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WESTERN ENERGY RESOURCES AND THE ENVIRONMENT: GEOTHERMAL ENERGY

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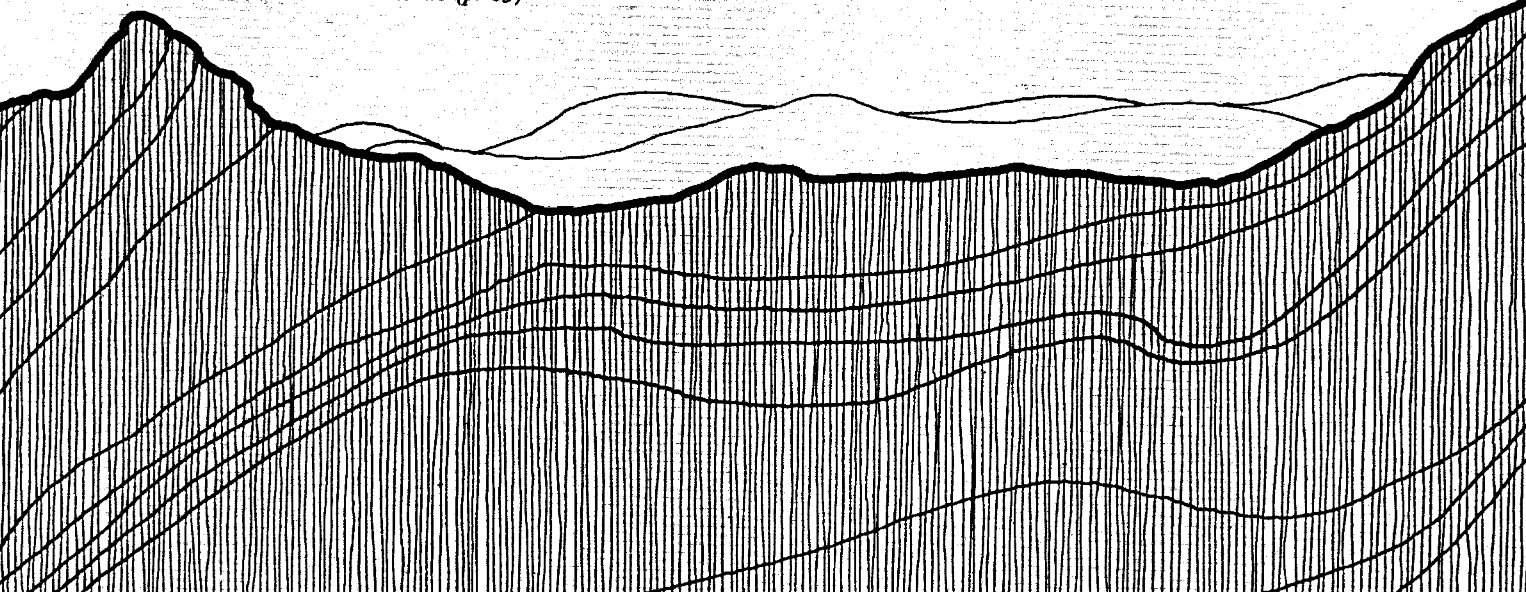

Western Energy Resources and the Environment

Geothermal Energy

prepared for
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This document on geothermal energy is the first in a series of summary reports to be prepared by the Office of Energy, Minerals and Industry (OEMI) of the Environmental Protection Agency (EPA). The purpose of the series is to describe what environmental effects are known or expected from new energy resource development in the western third of the United States. Throughout the series, we will emphasize those environmental impacts that currently are of greatest concern. We will indicate some of the research and development activities under way and review the nonenvironmental constraints to resource development. The series will serve as a reference for planners and policymakers on the entire range of problems and prospects associated with the development of new energy resources.

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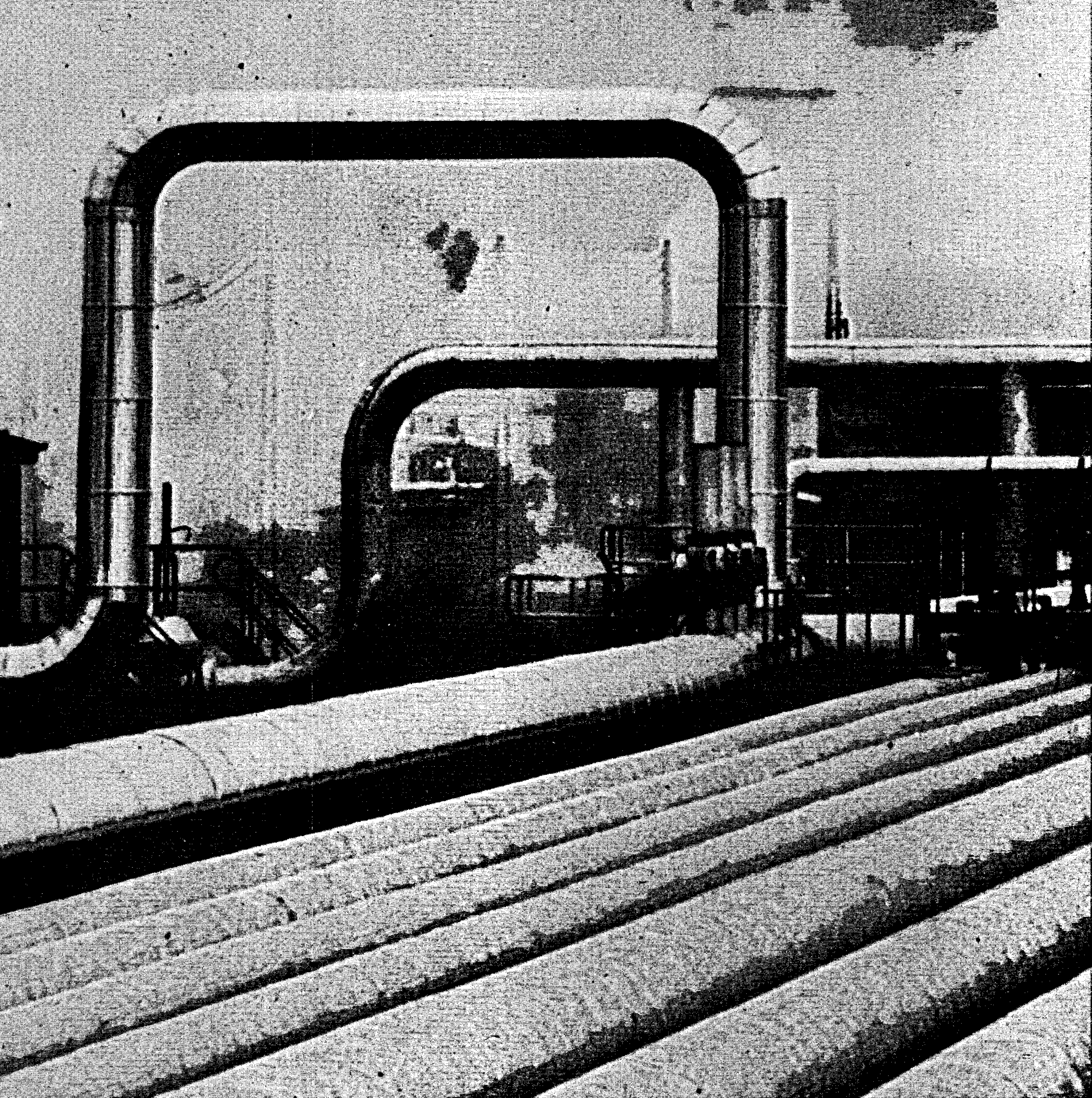


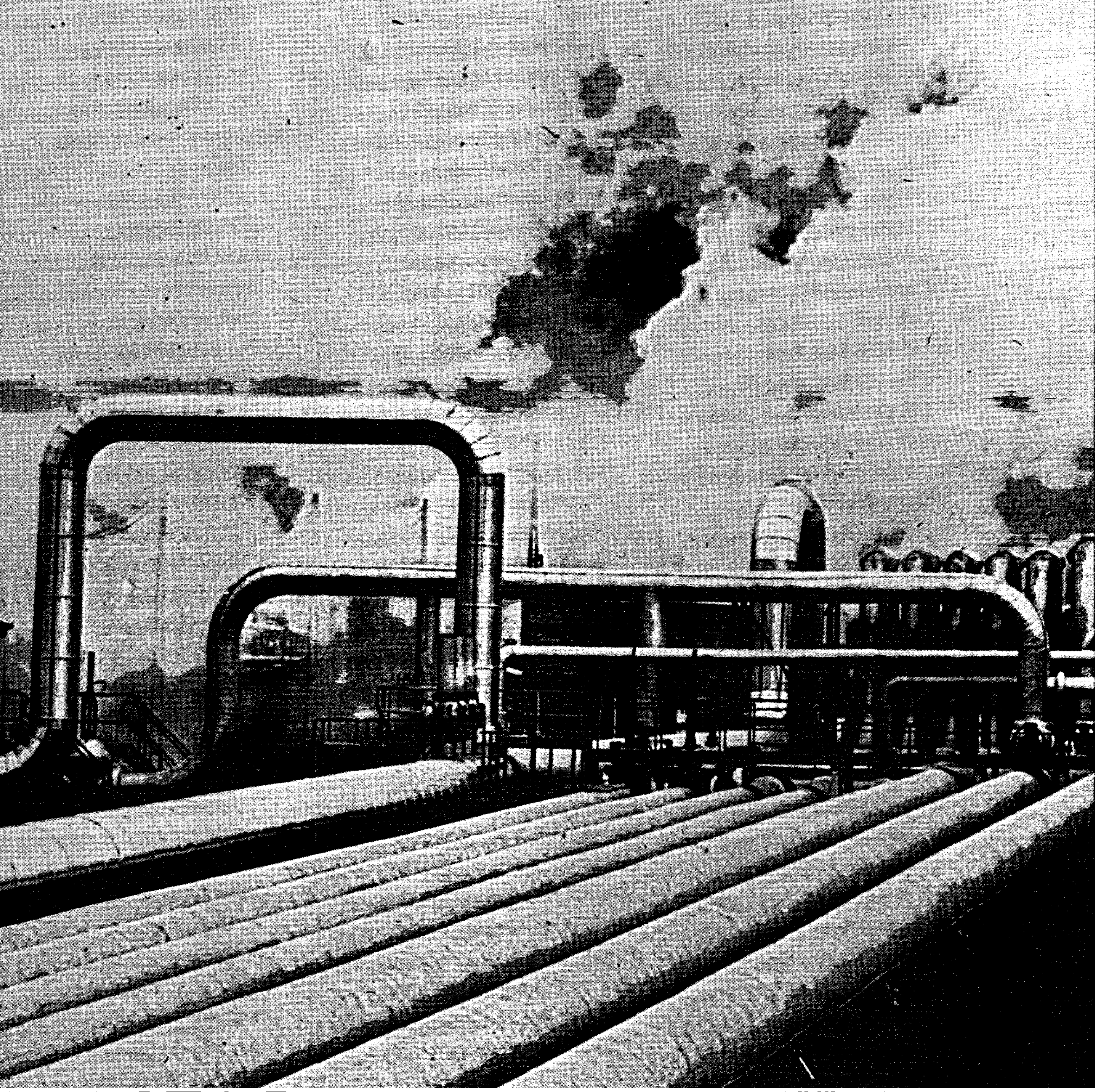
Introduction

Supplying the United States with "clean," affordable energy in the next 25 years has become a problem of considerable importance in the current climate of unstable petroleum imports, dwindling reserves of natural gas, higher energy prices, and an increasingly polluted environment. Numerous programs have recently been undertaken to conserve energy, substitute renewable resources for nonrenewable ones, develop domestic alternatives to imported fuels, and focus on resources that may present few environmental problems.

One of the resources receiving increased scientific and public attention in the United States is geothermal energy—the heat of the earth. Subsurface reservoirs of dry steam and hot water, called hydrothermal convection systems, are viewed as sources of low-cost steam for use in steam-electric plants. In other parts of the world, these systems have a long history of direct use for space heating and process steam.

The most commercially feasible type of geothermal resource is dry steam. However, only four commercial dry-steam generating plants are presently in operation throughout the world; and only one of these—The Geysers, in Sonoma County, California—is located in the United States. Although other geothermal resource types, primarily hot-water systems, are far more abundant, their commercial development is only now beginning in earnest. Worldwide, about a dozen hot-water systems are in some stage of commercial development or operation. In this country, however, no hot-water plants have yet been commercially developed.

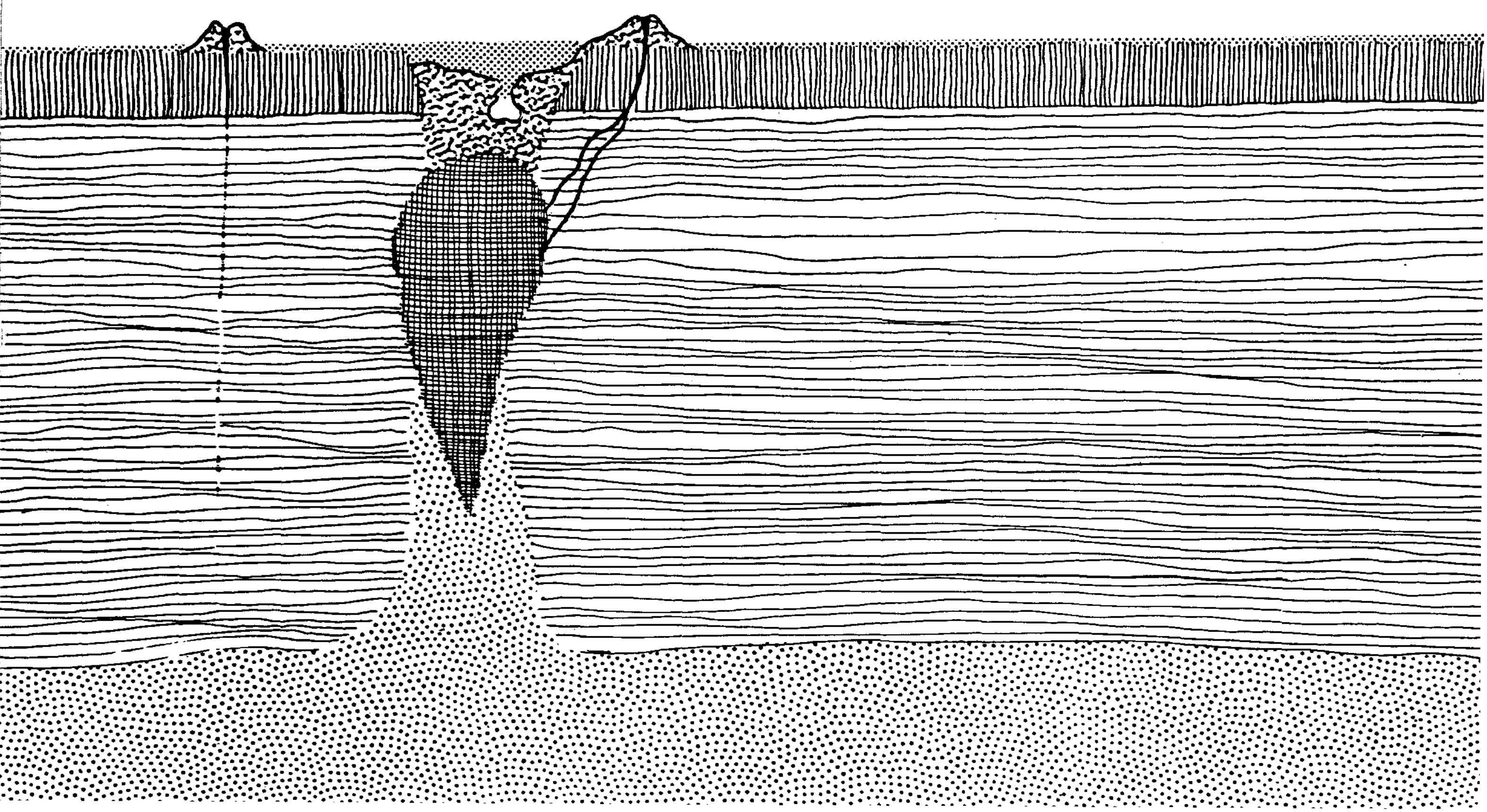
The cost competitiveness of the electricity provided by The Geysers system is proven, and demand is growing. What is not known is whether the hot-water systems now being developed experimentally will prove to be as inexpensive as alternative fuel sources.



Other important questions pertaining to geothermal energy remain unanswered, including: What share of the nation's energy needs can it realistically supply? What are the development costs? Can the technological requirements be met? Will legal and institutional factors retard development, and if so, how? What are the environmental problems and can they be addressed satisfactorily?

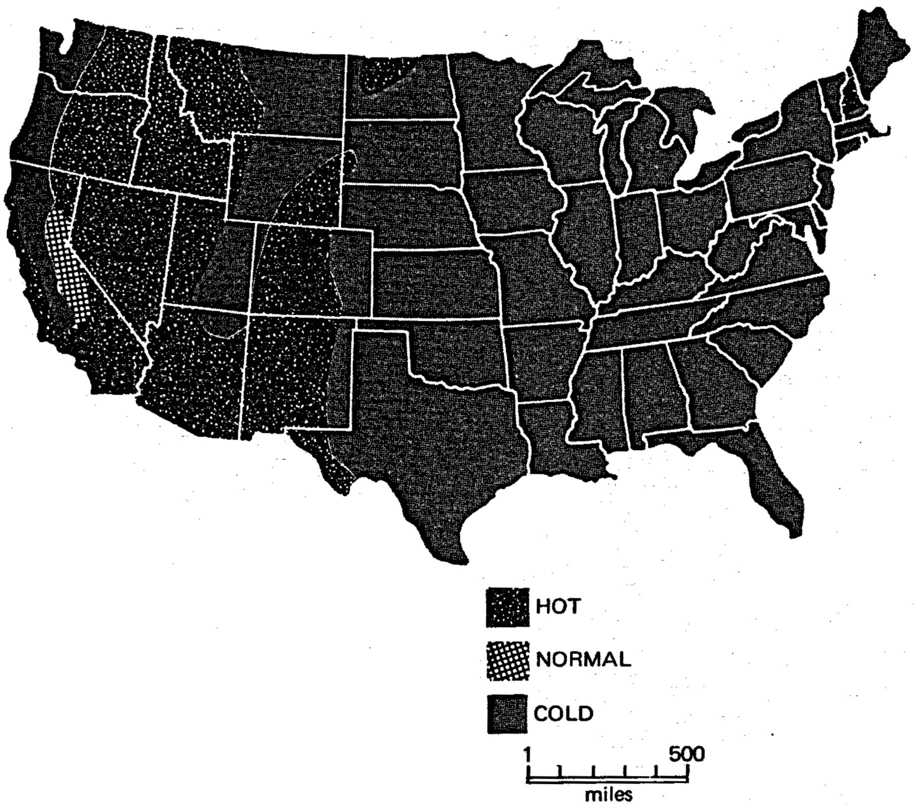
In this atmosphere of uncertainty, the federal government, primarily through the Energy Research and Development Administration (ERDA), has initiated a major effort to stimulate commercial interest in geothermal energy. ERDA has launched a program to identify and verify the potential of the geothermal resource, develop and test needed technology, and provide economic incentives to the private market. The thrust includes a research program to explore the potential environmental threats posed by development. At this early stage, a great many questions about possible adverse effects of geothermal energy have yet to be answered; evidence to date indicates that the potential is of sufficient magnitude to warrant further attention and implies the need for careful management and strict control.

This publication summarizes the state of knowledge about these possible environmental effects. It is not a technical document but a general reference intended as a guide to policymakers and the public. This document defines the extent and potential of geothermal resources, the technology available for development, and the constraints to growth. It highlights major research and development efforts being carried out by ERDA, EPA, and other federal agencies. In summary, this document aims to provide the reader with a balanced picture of the problems and prospects for the development of geothermal energy in the United States.



I.
Geothermal Resources: Their Energy Potential and Development Technology

Figure 1
Location of Hot, Normal, and Cold Crustal Regions of the United States



SOURCE: Nathanson, M. and L.J.P. Muffler, 1975, pp. 98, 99.

Overview

Geologists at the United States Geological Survey (USGS) recently completed an extensive investigation of areas in the United States where drilling data indicated variations in the temperature readings of different locations drilled to identical depths [*1*] (see Figure 1). They found the western third of the United States to be significantly "hotter" than the rest of the continent. This finding, combined with the region's history of volcanic activity, geologically recent mountain-building, and earthquakes provides the basis for the growing belief that the West offers significant potential for the development of geothermal resources.

Geothermal resources are generally defined as reserves of heat relatively near the earth's surface, created by the underlying geologic structure of the earth. (For a more detailed explanation, see the insert, "How Geothermal Resources are Created." The geothermal resource *base*—that is, the total amount of heat stored in the outer 10 kilometers of the earth—is enormous (calculated to be 3×10^{26} calories). [*2*] However, because the heat is diffuse, only a tiny fraction of that amount is recoverable.

The best known geothermal resources are the geysers and hot springs that dot the western part of the United States, giving rise to dozens of communities with names like Sulphur Springs, Thermal, and Devil's Kitchen. However, although these geothermal resources are the most readily identifiable, they do not represent the only geothermal resources, nor even those with the largest potential as sources of energy.

In addition to geysers and hot springs, which are the visible signs of ***hydrothermal convection*** systems, geothermal resources also include ***hot igneous*** systems and ***conduction-dominated*** systems. These three types of resources are distinguished by their geologic characteristics and the means by which their heat is transferred to near-surface areas.

Estimates of the near-term development potential of geothermal resources vary widely, depending on the assumptions used. The prevailing view is that geothermal energy is of greatest importance as a source of electricity, but only in certain local areas or more widely in underdeveloped countries seeking alternatives to even more expensive energy sources. The counterview is that the potential for geothermal energy is greatest in non-electrical applications—including desalination, agriculture, and space heating.

Table 1
Varying Projections of Electrical Generating Capacity from Geothermal Resources in the United States, 1985-2000
(in megawatts of electricity)

Source of Projections	By 1985	By 2000
Federal Power Commission, 1970 Power Survey December 1971	0	0
R. Rex (Senate Hearings) 1972	—	400.0
Bureau of Mines 1972	4.0	40.0
Department of Interior 1972	19.0	75.0
National Petroleum Council—I 1972 (high assumption)	19.0	—
National Petroleum Council—IV 1972 (low assumption)	3.5	—
W. Hickle, Geothermal Energy Report 1972	132.0	395.0
California Division of Gas 1972 (in Stanford Research Institute Report, 1973)	—	7.5*
Stanford Research Institute 1973 (separate report)	11.8	4.4*
D.L. Ray, Energy Policy Office 1973	20.0	80.0
Project Independence 1974 (high assumption)	34.0	—
Project Independence 1974 (low assumption)	4.0	—
ERDA 86, Geothermal Energy Definition Report 1975-1976	6.0	39.0
Electric Power Research Institute (EPRI) 1976	3.5	10.0

SOURCE: Federal Energy Administration, 1974, and The Mitre Corporation, 1976.

* Within California only
—No forecast

The conclusions of several recent studies have varied widely about the potential of geothermal energy as a source of electricity by the years 1985 and 2000 (see Table 1). The disparities result from different expectations of future technological breakthroughs, information on resource characteristics, and the future costs of alternative fuels. To develop a realistic assessment of the potential of geothermal energy, USGS has calculated the energy potential of geothermal resources based on the cost of extraction (see Table 2). USGS estimates that, disregarding cost, the potential is roughly equivalent to "140 Hoover dams or 140 average modern nuclear power plants." [3]

This chapter describes the distinguishing geologic characteristics of the three major types of geothermal resources, identifies their known or probable locations, projects their usable heat content, and briefly describes the development technology that must be applied to extract and use their heat.

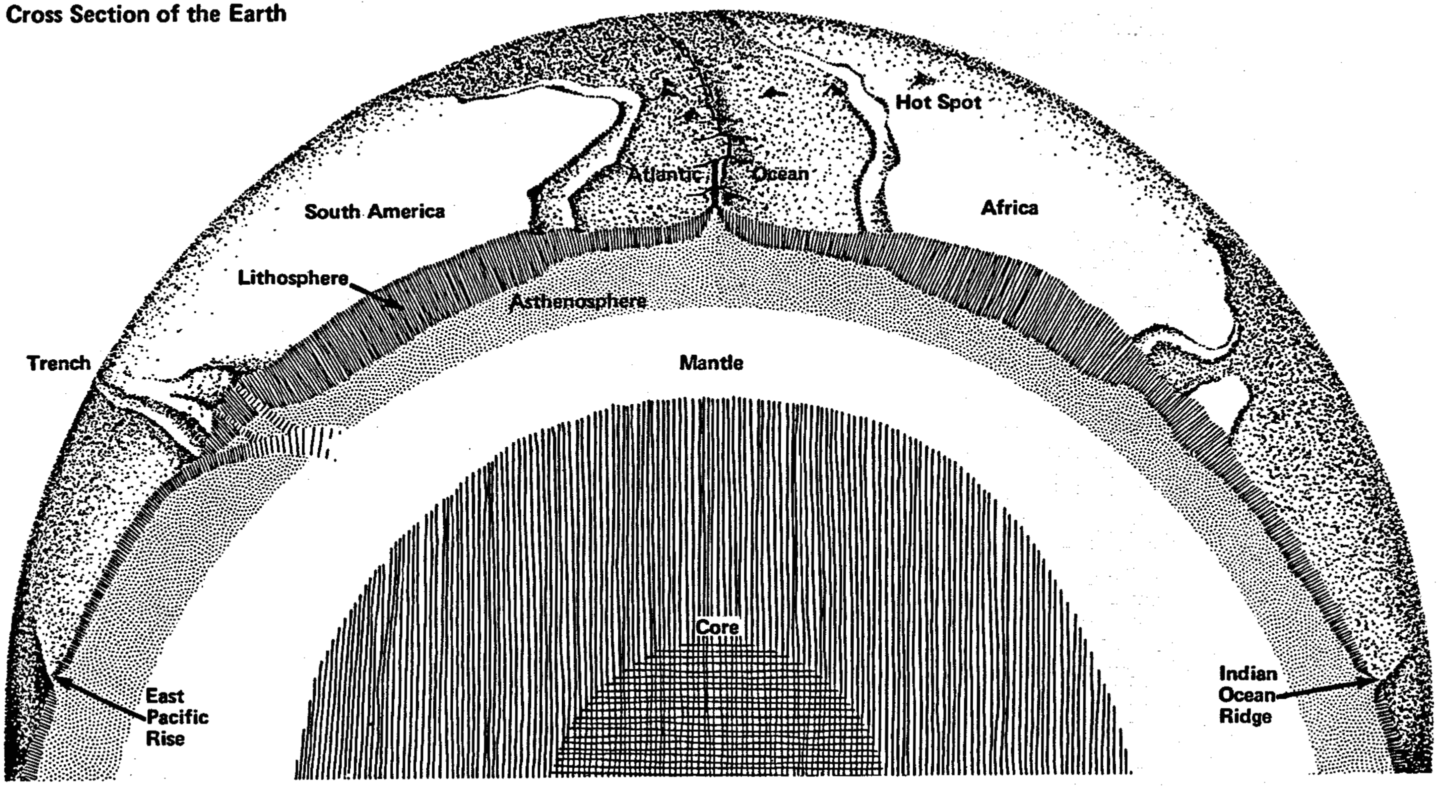
Table 2
USGS Estimates of Potential Energy Recoverable from U.S. Geothermal Resources with Current or Near-Current Technologies

Development Category	Type of Geothermal Resource		
	Hydrothermal Convection	Hot Igneous	Conduction-Dominated
Geothermal reserves (developable at competitive costs)	3,500 MW·c*	recovery technology undeveloped	
Marginal resources (developable at costs 1-2 times that of current alternatives)	3,500 MW·c		wide range of estimates; at least 25,000 MW·c
Submarginal resources (developable at costs more than twice that of current alternatives)	>1,000 MW·c		
TOTAL magnitude of geothermal resources recoverable with present technology, disregarding cost	>42,000 MW·c		

SOURCE: White, D.E. and D.L. Williams, 1975, pp. 147-155.

* 1 MW century (MW·c) is equivalent to 1000 kW produced continuously for 100 years.

Figure 2
Cross Section of the Earth



SOURCE: Burke, K.C. and J.T. Wilson, 1976, pp. 46-57.

How Geothermal Resources Are Created

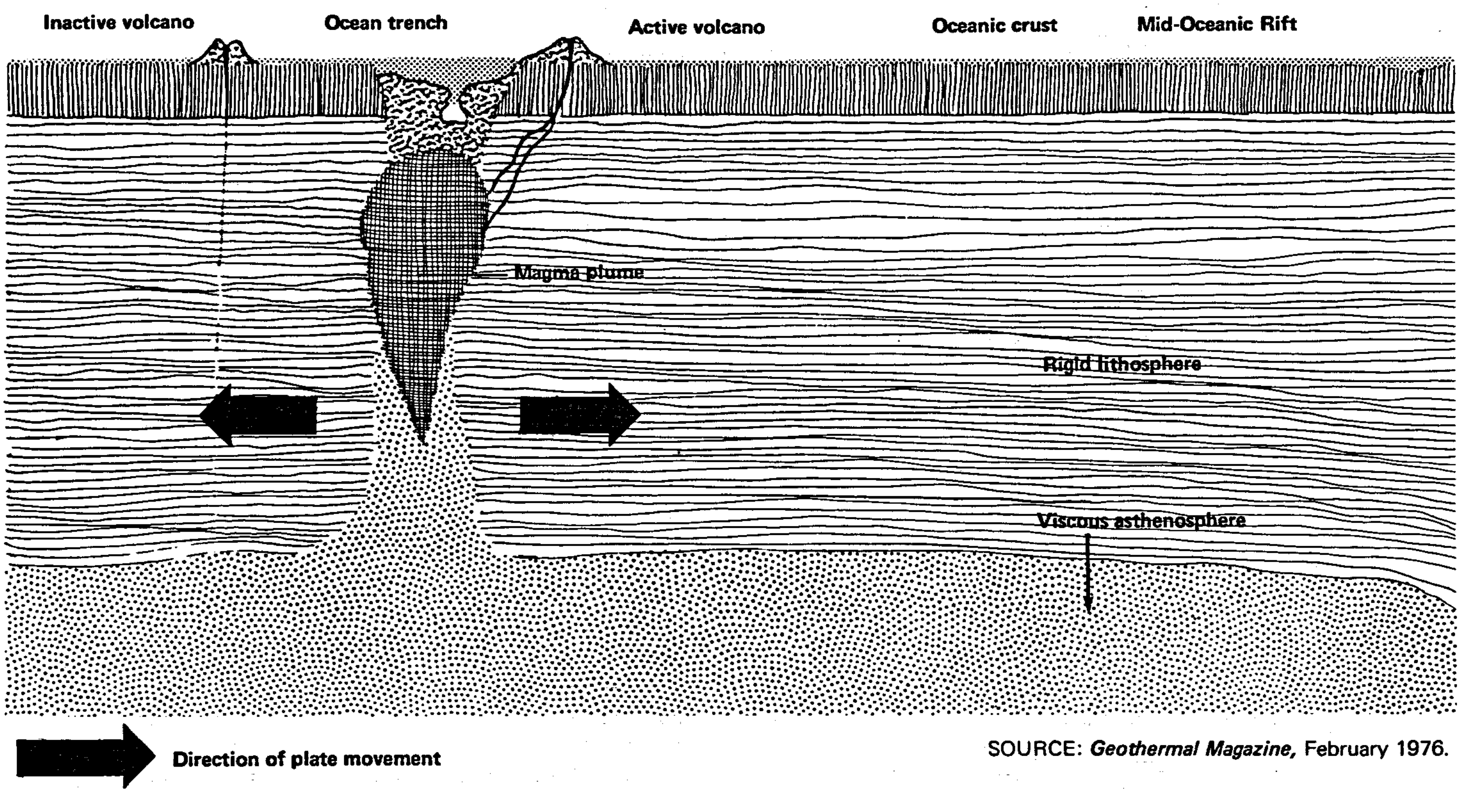
Current geologic theory purports that a cross-sectional diagram of the earth (Figure 2) would reveal a core of heavy metals such as nickel, iron, and cobalt, surrounded by zones of molten material, cooler near the surface than near the core. Between the outer core and the surface of the earth lies the mantle, a thick zone of molten rock (called magma). Above this is a relatively thin, cool layer, which extends to just below the earth's crust.

The areas of the earth close to the surface are believed to consist of two layers: the "lithosphere," or outer layer, which is relatively cold and rigid; and the "asthenosphere," which is both very hot and capable of being deformed slowly. The asthenosphere, hence, is not liquid, but a solid that flows under stress, like the ice of a glacier. Temperatures in the asthenosphere range from 650°C (1200°F), the melting point of rock, to 1200°C (2142°F). This heat is radiated, or conducted, outward to the surface.

Under certain geologic conditions, deposits of magma from the asthenosphere are found quite close to the earth's crust. These conditions result from actions within the earth's interior that are often attributed to "plate tectonics," a recently developed theory that provides a unifying framework to explain events such as earthquakes, mountain-building, and volcanoes.

Briefly, the theory states that the lithosphere is broken into about a dozen plates in which the continents are anchored. These plates separate from one *another at the crests of mid-ocean ridges, where undersea volcanoes add new material and push them apart (Figure 3). The opposite process—the convergence and overlap of lithospheric plates—frequently occurs at the edges of continents (Figure 4). In these regions, called subduction zones, one plate plunges under another, and its leading edge is reabsorbed into the mantle. The frictional heat and pressure created by this movement can cause earthquakes, volcanoes, and the building of mountain ranges such as the Andes in South America. Although not yet thoroughly understood, the movement of the plate is thought to be a result of "convection currents" in the mantle—roughly circular movements of hot earth materials that rise from the depths and thus bring their heat close to the surface.*

Figure 3
Divergent Plate Boundary

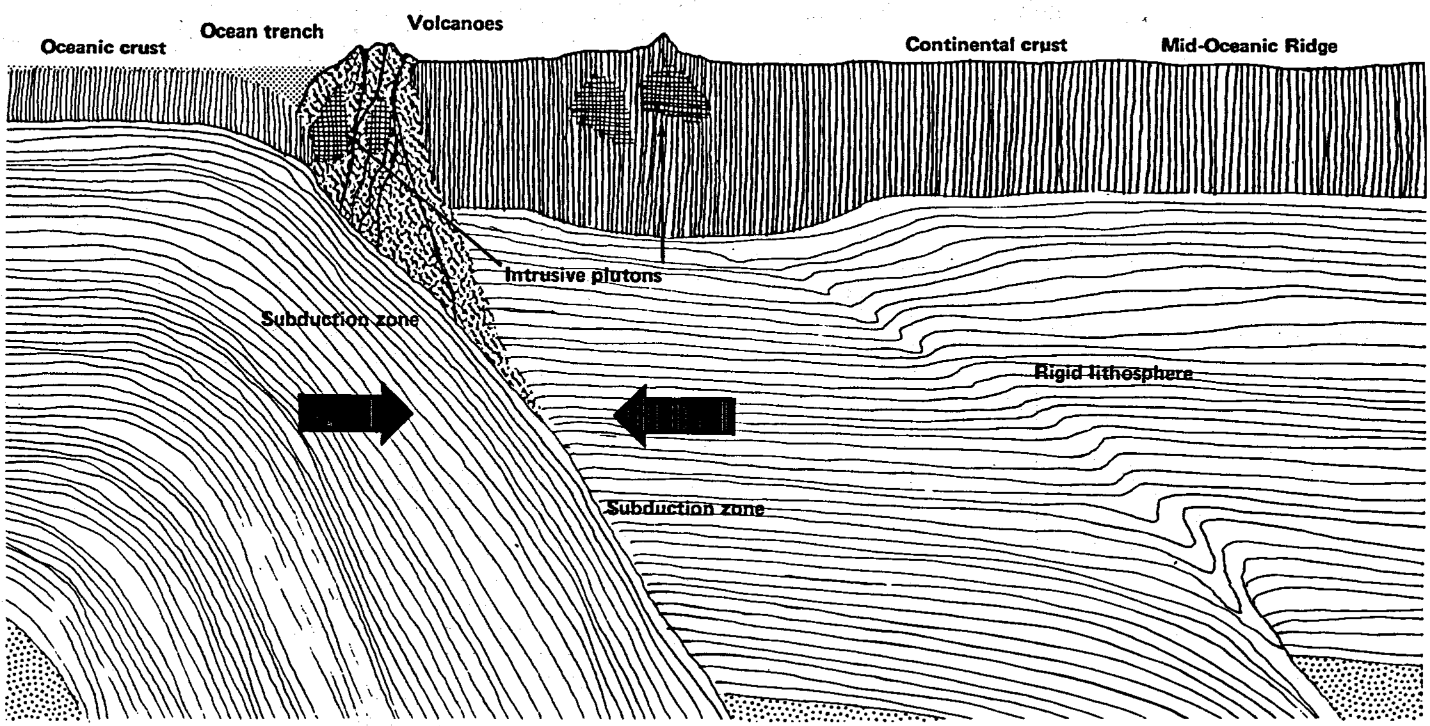


SOURCE: *Geothermal Magazine,* February 1976.

The location of geothermal resources is clearly controlled by the mechanics of heat transfer deep within the earth and by plate movement. As shown in Figure 5, many geothermal areas, including The Geysers, are located near the margins of the major lithospheric plates. Hotter-then-normal areas and volcanoes located in the middle of the plates have recently been attributed to the presence at depths of "plumes"—rising, columnar currents of hot material. The plumes heat surrounding material and produce magma near the surface.

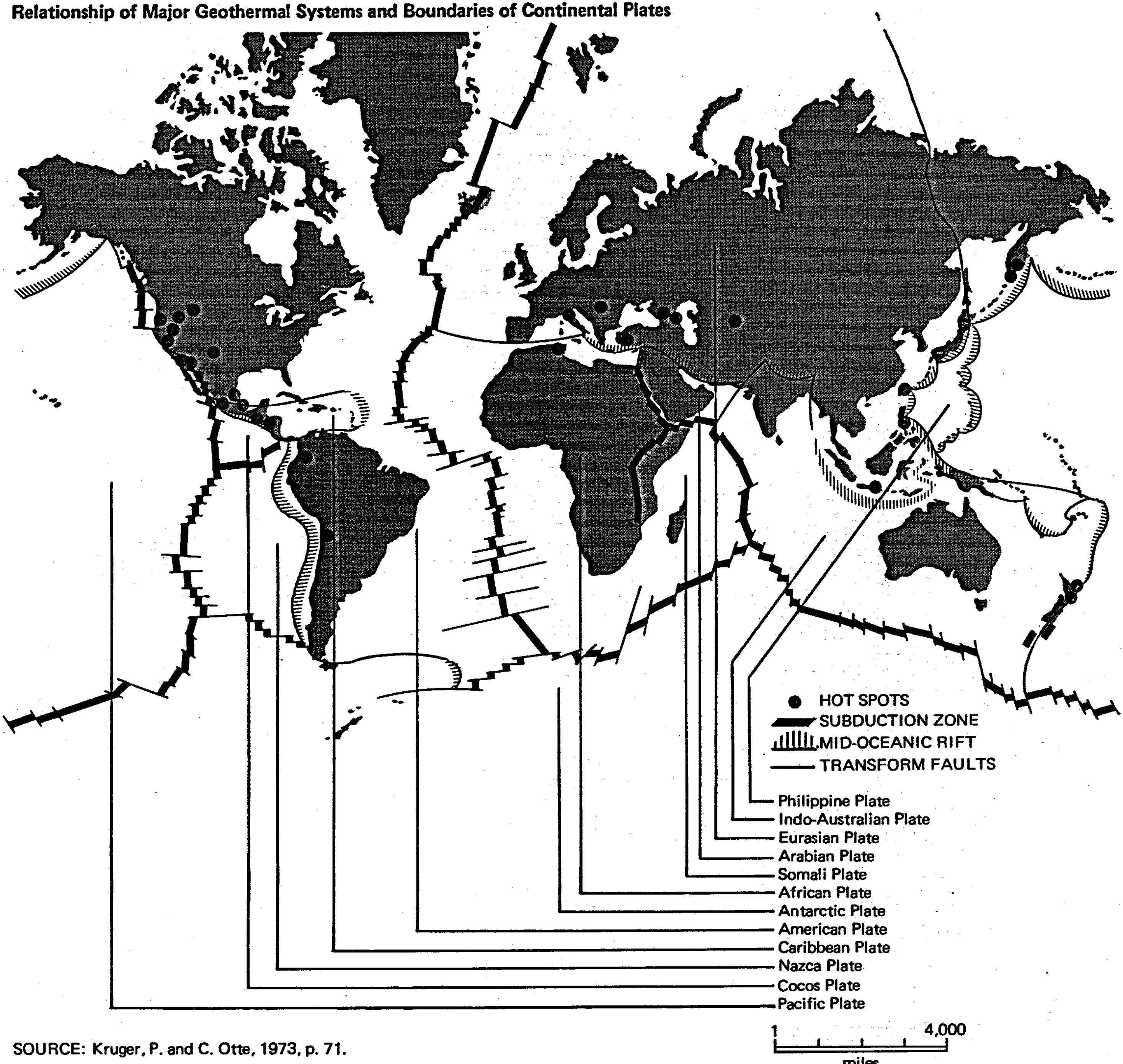
Improved knowledge of the history and mechanics of these processes could eventually enable geologists to predict the locations of commercially viable geothermal resources.

Figure 4
Convergent Plate Boundary



SOURCE: *Geothermal Magazine*, February 1976.

Figure 5
Relationship of Major Geothermal Systems and Boundaries of Continental Plates



SOURCE: Kruger, P. and C. Otte, 1973, p. 71.

1. Hydrothermal Convection Systems

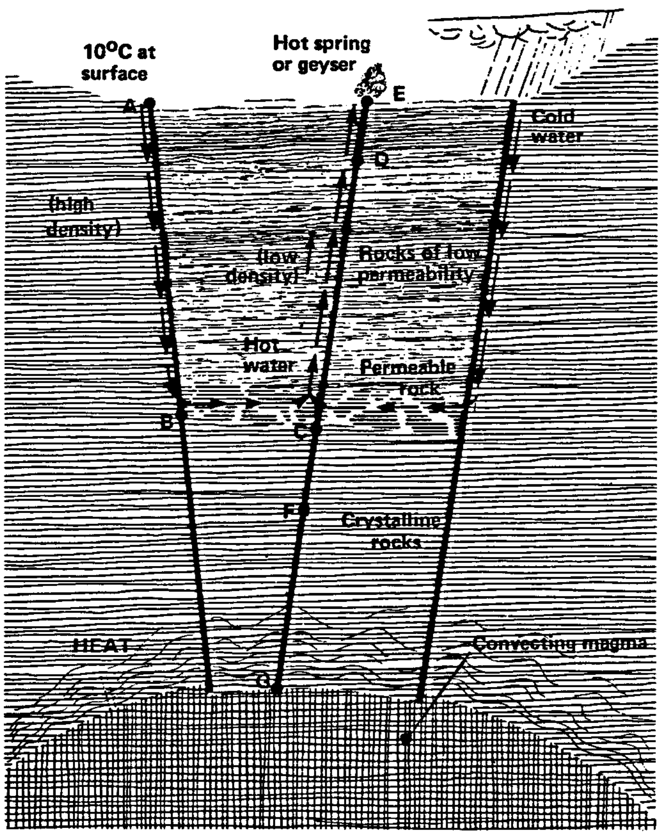
Subsurface reservoirs of steam or hot water, which may display such surface characteristics as boiling springs, sulfurous mud flats, and steam spouts, are categorized as hydrothermal convection systems. These systems are created by the concurrence of several natural geologic configurations (see Figure 6). The creation of a hydrothermal convection system begins with a source of heat, usually molten rock or magma, that lies relatively close to the earth's surface (usually at depths of 2 to 8 km). Overlying this magmatic deposit is a permeable rock formation containing water, which expands and rises upward as it is heated by the molten rock below. Above the permeable rock is a layer of impermeable rock, which traps the superheated water. If this layer contains cracks or fissures through which fluid can rise, the fluid will emerge on the earth's surface either as steam (a vapor-dominated system) or hot water (a liquid-dominated system).*

Hydrothermal convection systems are usually associated with tectonic plate boundaries and volcanic activity. (The locations, by state, of known hydrothermal convection systems are shown in Figure 7.)

---

* The structure of a hydrothermal convection reservoir varies depending upon whether it is liquid-dominated or vapor-dominated; however, the differences between the two are not fully understood. It appears that the porosity of the rocks, the rate at which the reservoir is "recharged" by water or steam condensate, and the geophysical features of the reservoir (whether it is a "flat" horizontal area, or a deep "columnar" area) influence whether the liquid vaporizes to dry steam or remains in a super-heated liquid state as it rises.

Figure 6
Structure of a Typical Hydrothermal Convection Reservoir



SOURCE: Austin, A.L., 1974, p. 15.

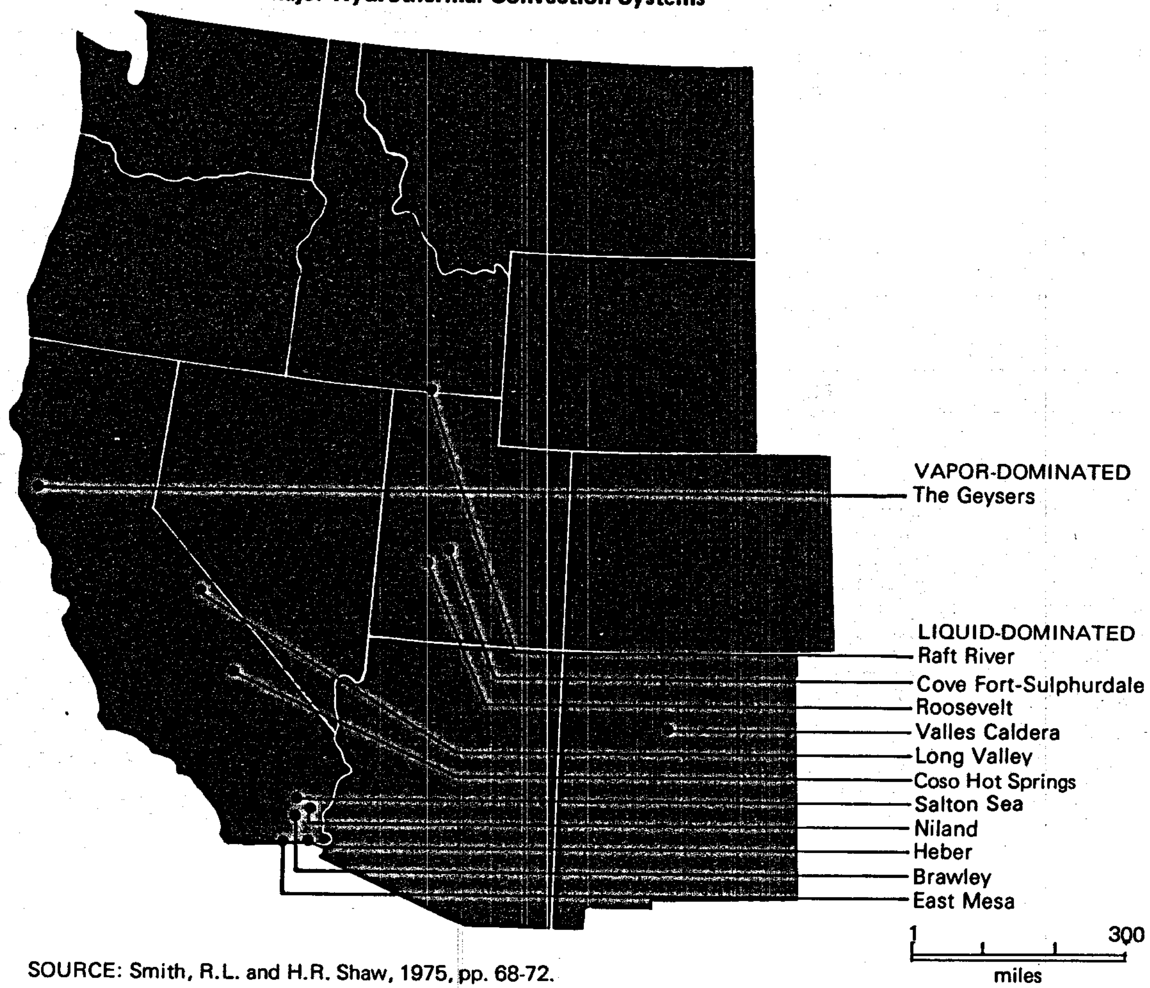
Based on 1975 USGS calculations and their reasonably cautious assumptions about the physical recoverability of known —but not yet developed—resources, hydrothermal convection systems are expected to "have an estimated electrical production potential of 8,000 megawatt century (MW·c) or 26,000 MW for 30 years."* [4]

However, only about half of the production from identified systems is expected to be from *reserves*, recoverable with present prices and technology; the rest is calculated from marginal and submarginal resources.** [5] Of these, 95 percent are from liquid-dominated and 5 percent from vapor-dominated systems. The USGS estimates that five times as much energy is available in undiscovered systems, with "a considerable fraction" recoverable at present prices and technology. Resources having intermediate temperatures which may be used for nonelectric purposes are estimated at 2.87 x 10^{21} calories. [6] The calculations are given in Table 3. Table 4 lists the power generating capacities of the major hydrothermal convection systems operating in the world as of 1972.

* Approximately 1,000 MW (the capacity of many modern nuclear power plants) are required to meet the electrical needs of an average city with a population of one million.

** *Marginal* is defined by USGS as between 2 and 3 times the cost of alternatives. *Submarginal* is defined as greater than 3 times the cost of alternatives.

Figure 7
Locations of Known Major Hydrothermal Convection Systems



SOURCE: Smith, R.L. and H.R. Shaw, 1975, pp. 68-72.

Table 3

USGS Estimates[a] of the Potential Energy Assumed Recoverable from Hydrothermal Convection Systems with Current and Near-Current Technologies

	Heat in Ground 10^{18} calories[b]	Heat at Wellhead 10^{18} calories[c]	Conversion Efficiency	Beneficial Heat[d] 10^{18} calories	Electrical Energy MW-century	MW for 30 Years[e]
High-temperature systems (>150° C; for generation of electricity)						
Identified resources	257	64	0.08-0.2			
Reserves					3,500	11,700
Marginal resources					3,500	11,700
Submarginal resources[f]					>1,000	>3,300
Undiscovered resources[g]	1,200	300	0.08-0.2		38,000	126,700
Intermediate-temperature systems (90°-150° C; mainly non-electrical uses)						
Identified resources	345	86	0.24	20.7		
Undiscovered resources	1,035	260	0.24	62.1		
Total	2,837	710		82.8	46,000	153,400

SOURCE: White, D.E. and D.L. Williams, 1975, p. 150.

a. Estimates exclude national parks.
b. 10^{18} calories is equivalent to heat raised by the combustion of 690 million barrels of oil or 154 million short tons of coal.
c. Assumed recovery factor is 0.25 for all convective resources.
d. Beneficial heat is defined to be thermal energy applied directly to its intended thermal (non-electrical) use. 10^{18} cal of beneficial heat, if supplied by electrical energy, would require at least 4,400 MW for 30 years; however, a user of this geothermal energy must be located or must relocate close to the potential supply. Insufficient data is available to predict demand or to subdivide into reserves, paramarginal, and submarginal resources.
e. Assumes that each MW-c of electricity can be produced at a rate of 3.33 MW for 30 years.
f. Small because systems with temperatures below 150° C have been excluded.
g. Perhaps as much as 60 percent will be reserves and marginal resources; costs of discovery and development are more speculative than for identified resources.

Vapor-Dominated Systems

These geologically complex dry steam systems are characterized by the high temperatures of the steam (240°C or 464°F) and the high pressures and volumes at which the steam is vented (35 kg/cm²). [7] Since the steam is usually of high quality—that is, it contains few particulates or other substances that must be extracted before use—it can drive conventional steam turbines to generate electricity.

To date, only three vapor-dominated systems have been identified in the United States: The Geysers in Sonoma County, California; the Mud Volcano system in Yellowstone National Park, Wyoming (Old Faithful); and a likely, although not yet confirmed, system in Mt. Lassen National Park, California. Only one of these systems, The Geysers, has been developed commercially.* (See insert for description of "The Geysers Dry-Steam Field.") Pacific Gas & Electric Company (PG&E) presently is generating about 502 MWe from this system, which is capable of supplying electricity to a city with a population of 500,000—equivalent to 74 percent of the electricity currently demanded by San Francisco.

Thus, prospects for additional electricity generated from vapor-dominated systems appear to be limited to the expansion of presently known steam fields. Neither the technology nor the requisite geophysical information exists to predict and locate new vapor-

Table 4
World Geothermal Power-Generating Capacity
1972

		MWe			
Country	Field	Operating	Under Construction	Vapor-dominated Systems	Hot-water Systems
Italy	Larderello	358.6		358.6	
	Monte Amiata	25.5		25.5	
United States	The Geysers	302.0	110.0	412.0	
New Zealand	Wairakei	160.0			160.0
	Kawerau	10.0			10.0
Japan	Matsukawa	20.0		20.0	
	Otake	13.0			13.0
Mexico	Pathe	3.5			3.5
	Cerro Prieto		75.0		75.0
Soviet Union	Pauzhetsk	5.0			5.0
	Paratunka	0.7			0.7
Iceland	Namafjall	2.5			2.5
Total		900.8	185.0	816.1	269.7

SOURCE: Kruger, P. and C. Otte, 1973, p. 71.

* Three other commercial plants are operating in Lardarello, Italy, and Otaka and Matsukawa, Japan.

dominated fields that do not have surface discharges. However, the potential for expansion at known sites is good. Pacific Gas & Electric expects to produce 1800 MWe from The Geysers by 1985, nearly a fourfold increase over the 1976 capacity. [8]

Once located, a vapor-dominated field is explored to determine its chemical and thermal characteristics. The processes used are based on oil and gas exploration and development techniques (see insert, "How Geothermal Resources Are Developed"). Actual utilization of the geothermal energy once the steam-bearing formation is penetrated involves the application of an existing technology: the steam turbine. Lines are attached at the well head to transport the steam to a centrifugal separator, where dust and corrosive particles are removed. The treated steam is then used to drive the turbine, which generates electricity (see Figure 8). Each of the generating units now being installed at The Geysers requires a throughput of 1 million lbs/hr. of superheated steam, from which 55 MW of electricity is produced. [9]

Liquid-Dominated Systems

The chemical and thermal characteristics of liquid-dominated or "hot water" systems, which are far more common than vapor-dominated, vary greatly by site. Temperatures range from 90°C to 250°C (194°F to 662°F), with an average of 150°C (302°F)—almost 100°C less than the average temperature of vapor-dominated systems. [*10*] The amount of total dissolved solids also varies considerably. Extremes of 26 to 35 percent dissolved salts have been found in the geothermal wells drilled near the Salton Sea in California.

Hot-water systems are usually grouped into one of three categories, based on the temperature of their natural working fluid:

High-temperature systems:	greater than 150°C (302°F)
Intermediate-temperature systems:	90°C to 150°C (194°F to 302°F)
Low-temperature systems:	less than 90°C (194°F)

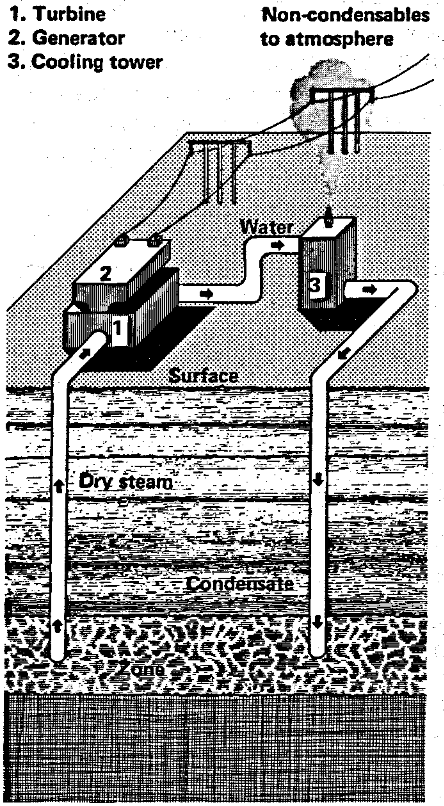
High-temperature systems may be further divided by the characteristics that affect their performance, such as the level of salinity, dominant chemical constituents, rate of rechargeability, structural and stratigraphic environments, and presence or absence of permeable reservoirs and insulating cap rocks. These characteristics are important to determine the commercial viability of a hot-water system, either for electricity or for other purposes.

Hundreds of hot water wells have been drilled throughout the world, and nine electric generating plants have been developed based on high-temperature hot-water systems. Most of these plants are located in New Zealand, Japan, and Mexico.

In the United States, a total of 63 high- and medium-temperature hot-water systems have been identified by USGS. [*11*] Federal policy initiatives and research funds are being focused on developing these systems by 1985. Hot water wells are attractive to the electric utility industry because knowledge about their development and use is relatively advanced and because most of the required technology, described below, can be provided in the near future.

Significant discoveries of high-temperature systems have been made at half a dozen sites in the western part of the United States. Most attention has been given to sites in the Imperial Valley of California, where a very large reservoir appears to be located. There the U.S. Bureau of Reclamation and the Office of Saline Water are conducting a pilot project to test the feasibility of producing both electricity and desalinized water. Nearby, at Niland, an experimental plant is being developed and is testing waste reinjection techniques. Closer to the Mexican border, at Heber, California, is the likely

Figure 8
Dry-steam System (The Geysers, U.S.A.)



SOURCE: Comptroller General of the United States, 1975, p. 22.

Figure 9
Flashed-steam System

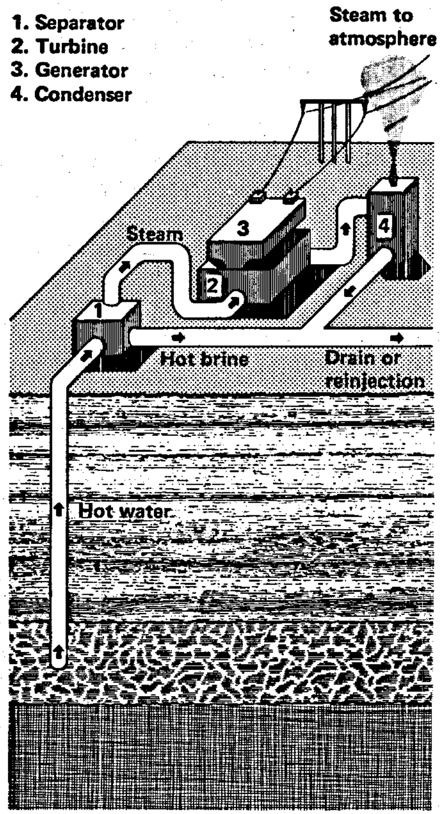
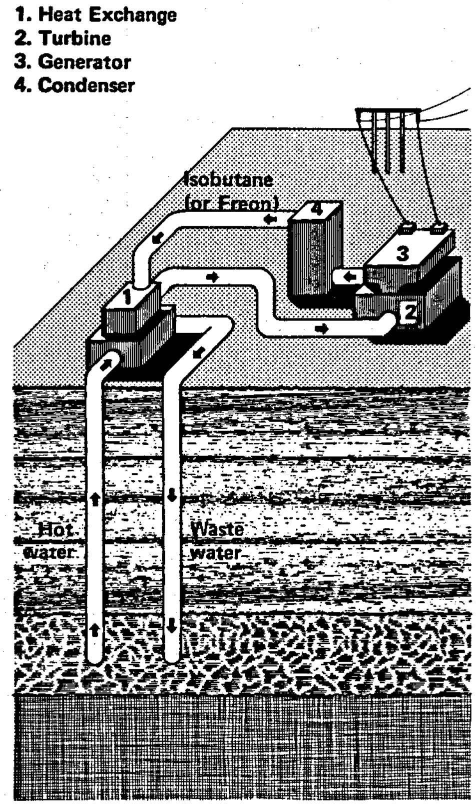


Figure 10
Binary-cycle System



site of the first commercial liquid-dominated electric generating plant in the United States. Although, currently, the combined power of these experimental systems is small, it is expected to grow significantly in the next decade.

Moderate and low-temperature systems are also being used around the world for nonelectric needs such as space heating, air conditioning, and industrial drying; particularly in Iceland, Japan, the Soviet Union, Italy, and the United States. In the United States, the best known project is at Klamath Falls, Oregon, where 350 wells supply heat for space heating. Elsewhere in Oregon—as well as at Calistoga and Desert Hot Springs, California; Boise, Idaho; and other localities in the West—geothermal waters are used to heat greenhouses, baths and resorts, farm buildings, and schools. In addition, 19 research institutions representing private industry, universities, and state and local governments recently were awarded contracts by the Energy Research and Development Administration (ERDA) to conduct demonstrations of the feasibility of using geothermal heat for nonelectric purposes.

The same exploration and development techniques used for vapor dominated systems are applicable to liquid dominated systems. However, the production technology differs significantly. Because of the temperature requirements for generating electricity from convection systems, only the high-temperature, moderate- or high-salinity system is being developed extensively. Two processes, the *flashed steam* and the *binary cycle* (or heat exchange), currently are used. A third system, the *total flow process,* is still in the design and testing stage, but holds promise for greater efficiency than the other two.

FLASHED STEAM. This technology (see Figure 9) takes advantage of a process that occurs naturally in some hot-water systems; that is, the hot fluid in a reservoir is usually under much higher pressure below the surface than at ground level. As the water is withdrawn and nears the surface, the pressure decreases, causing a portion of the fluid (approximately 20 percent in high-temperature fields) to boil and "flash" into steam upon reaching the surface. The steam is captured, passed through separators to remove certain particulates, and then used to drive turbines in an electric power plant. Any remaining water and condensed steam are disposed of through reinjection or surface drainage; noncondensables are vented to the air. The energy efficiency of this system is low; only 2 to 5 percent of the original stored heat of the hot-water system is actually converted to usable energy. This conversion efficiency drops to 1 percent if the steam must be passed through a separator.

Flashed steam plants currently are operating in eight different locations in the world. However, uncertainties about their efficiency and environmental safety have kept the process from being introduced commercially to the United States. The current best estimate for the utilization of flashed steam is the early 1980s. [*12*]

BINARY CYCLE (or heat exchange process). In this process, the hot water withdrawn from the reservoir is used to heat a second fluid (freon or isobutane) having a lower boiling point (see Figure 10). The vapor thus generated by boiling the second fluid is used to drive the turbine. Once used, the vapor is condensed and recirculated through the heat exchanger in a closed system, where it may be heated and used again. This system appears to be the preferred method for developing high-temperature, high-salinity reservoirs.

A 3.8 MWe binary plant currently is in use in Japan, and the Soviet Union is reported to be using a .75 MWe binary plant. Pilot plants in Long Valley and Imperial Valley, California are being constructed to test the applicability of this process to high-temperature systems of both high and low salinity.

TOTAL FLOW. The least developed of the three liquid-dominated systems, total flow utilizes the heat and natural pressure of both the steam and water in one generating process that combines a steam turbine and waterwheel. Two types of generators are being developed in the United States: the impulse turbine and the helical rotary screw expander.

The Geysers Dry-Steam Field

The Geysers geothermal field lies 75 miles north of San Francisco in the hilly and rugged Mayacmas Mountains (see Figure 11). In this sparsely populated area, the land is used, where at all, for cattle-grazing or hunting. In the past, however, Lake County had a more colorful atmosphere. Resort hotels were built in the late 19th century offering the attraction of "healthful and refreshing warm baths" piped straight from the bubbling hot springs which fed Big Sulphur Creek. In 1880, mercury was discovered and mines opened. They continued to operate until the 1950s. There never were any real geysers in the development area, certainly nothing as spectacular as "Old Faithful" in Yellowstone Park; however, numerous steam vents and hot springs testified to the presence of heat reservoirs. The odor of hydrogen sulfide inspired the early explorers to name the stream which flowed through the area "Big Sulphur Creek."

In the 1920s, entrepreneurs drilled in these hot springs and tried, unsuccessfully, to find a market for the electricity they thought they could produce. Then, in the middle 1950s, Magma Power Company and Thermal Power Company began drilling and eventually interested Pacific Gas and Electric (PG&E) in the project. In 1960, an 11 MWe power plant built by PG&E began operation. Today, Union Oil is in partnership with the other developers and owns 50 percent of the field; Magma and Thermal own 25 percent each. Other companies are exploring the surrounding land.

At present PG&E is the only utility generating electricity at The Geysers. Recently, however, a group of eight northern California cities, members of the Northern California Power Agency, announced plans to undertake a development program to ultimately produce 130-170 MWe of generating capacity in the Lake County portion of The Geysers.

The Geysers land is owned by federal, state, and local interests. Leaseholds have been acquired by firms that wish to search for and develop geothermal steam. These firms generally own easements and limited surface rights sufficient to develop geothermal resources.

Of The Geysers' total original 163,428 acres, 11,450 were federally owned. The Known Geothermal Resource Area (KGRA) has been analyzed several times. In January 1974, a competitive lease sale was held for 8,755 acres and bids totalling $5,526,827 were offered. Leases on these lands were issued in July 1974. Pursuant to the Stock Raising Homestead Act of 1916, the federal government holds mineral rights on an additional 14,000 acres within The Geysers. However, whether these mineral rights extend to geothermal steam is not legally clear. The federal government also owns lands adjacent to The Geysers that may be valuable for geothermal steam production.

To date, a total of more than 100 wells have been drilled at The Geysers and all but about 10 have produced steam. While the steam originally was found at depths of less than 1,000 feet, the increased need for steam to generate power has necessitated drilling to greater depths. Maximum well depth is now over 9,000 feet; average production depth is 6,000-7,000 feet.

Generating units in use at The Geysers are relatively small; an average site provides 110 MWe. About 15 to 20 wells are required to support a 110 MWe generating unit. As individual well pressure decreases, new wells must be drilled to maintain an adequate steam supply to the turbines. The average lifetime of a well is expected to be 15 years.

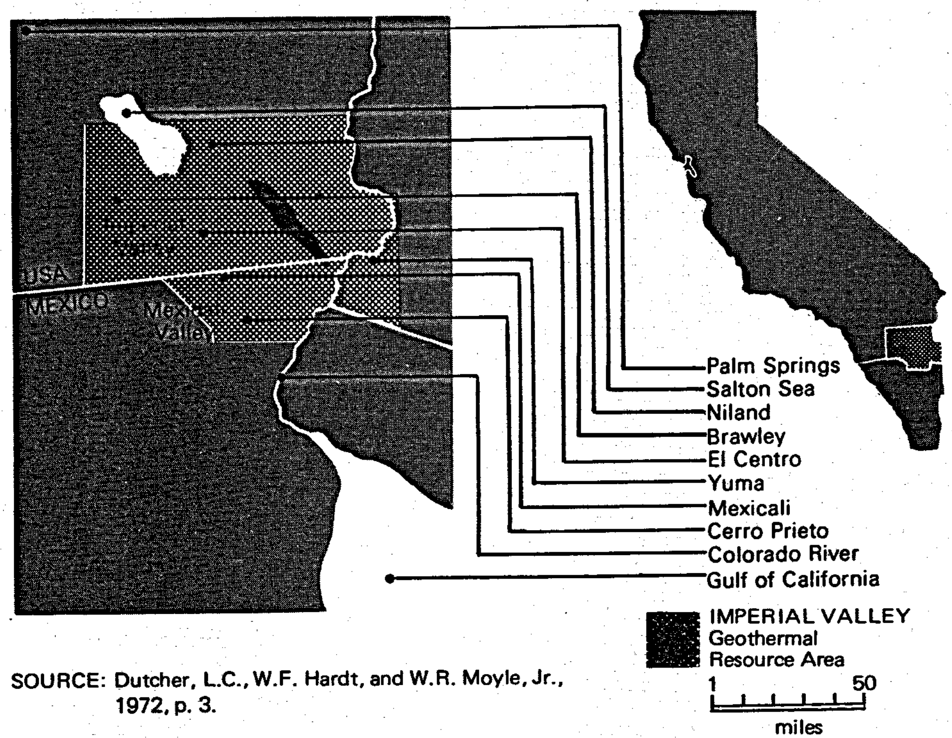
Seventy-five wells now produce steam for 11 turbines, producing more than 500 MWe. The wells average 150,000 lbs per hour of 350°F steam at 100 psi. The field is believed to be as extensive as 386 square miles (1000 km²) and capable of supplying as much as 10 times the current generating capacity. If this scale of development comes about, approximately 45 generating units will be functioning, supplied by 675 geothermal wells.

Figure 11 (opposite):
The Geysers Dry-steam Field

SOURCE: Pacific Gas & Electric Co.

Figure 12

Location of Hydrothermal Convection Resources in the Imperial Valley



SOURCE: Dutcher, L.C., W.F. Hardt, and W.R. Moyle, Jr., 1972, p. 3.

The Imperial Valley: The Next Generation of Development

The Imperial Valley holds the most promise as the site of the next major development of geothermal energy in the United States. It is part of a large structural basin that extends from the Coachella Valley to the Gulf of California, and south to the Mexicali basin in Mexico. The entire depression is called the Salton Trough and is filled with clay, silt, and sand deposited by the Colorado River as part of the delta created over many hundreds of thousands of years (see Figure 12).

This trough contains a thick layer of water-saturated sediment (as much as 20,000 feet), which in turn overlies a heat flow anomaly. Here heat flows range from 4 to 10 times the average gradient of the earth. The combination of the extensive body of porous, water-bearing rock and the high heat flows have created a series of related hydrothermal convection reservoirs, causing the Imperial Valley to be regarded as the first opportunity for the commercial development of a hot-water system.

The potential of the geothermal resource has been estimated at 10 to 15 million acre-feet of geothermal brine per year, and 20,000 to 30,000 MW of electric power (see Figure 13).

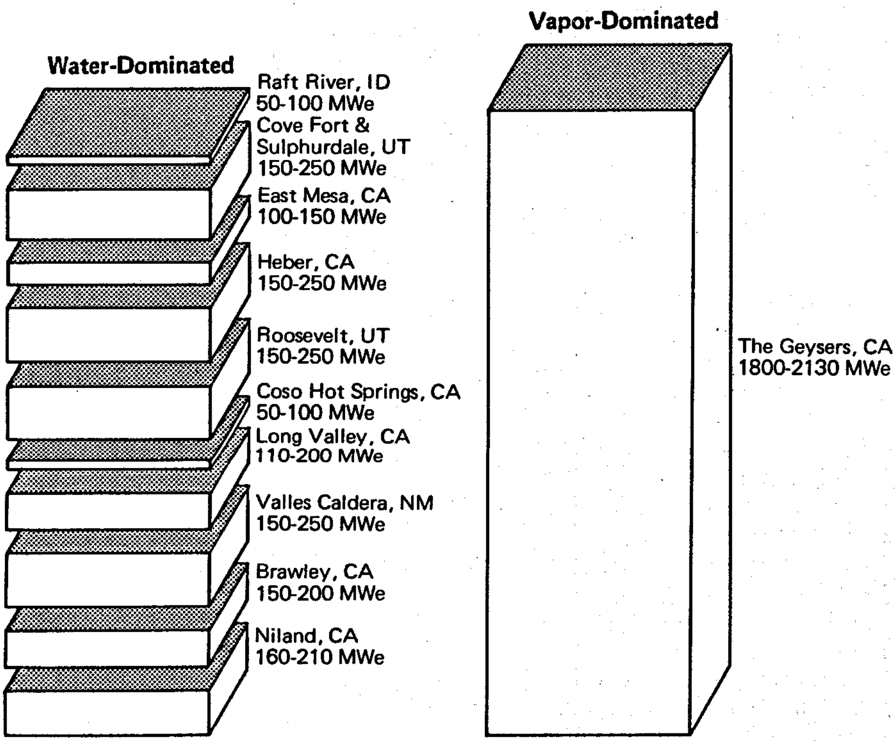
In addition, great interest has arisen in the large amount of underground water in this otherwise arid region, estimated at 1.1 billion acre-feet, with 100 million acre-feet at temperatures below 100°C. Studies are under way to determine the economic feasibility and environmental effects of removing some water for irrigation.

Deep wells have been drilled throughout the area and several have been the focus of extensive testing and development. A major steam field at Cerro Prieto, Mexico, has been tapped; a 75 MWe plant has been built and is now in operation. Niland, Heber, and Brawley, California are prime sites for the possible production of electricity. At Niland, near the Salton Sea, the Geothermal Test Facility of the San Diego Gas and Electric Company and ERDA is located. This facility, a 10 MWe binary fluid experimental power plant using highly saline brines, is complete and undergoing prestart-up tests; however, the high salinity of the geothermal fluid at this site may preclude its commercial development. Such uncertainties make it difficult to predict the rate of future development in the Imperial Valley. However, at Heber, the Standard Oil Company plans to develop a 50 MWe plant that could be in operation as early as 1978. It would be the first commercial hot-water plant in the U.S.

A large project to establish environmental baseline information on the entire Imperial Valley has also begun. The Lawrence Livermore Laboratory has been appointed by ERDA to lead this long-term project, which includes obtaining information on the impacts of water withdrawal on subsidence and induced seismicity; effects on the water supply and quality of the area; air quality problems from the highly-mineralized reservoirs; and effects on the fragile desert ecosystem of extensive development. Information is being obtained on virtually every aspect of geothermal energy through field monitoring and model development—on the hydrology, geology, ambient air conditions, vegetation and wildlife, seismicity, health effects, and possible socioeconomic impacts.

In addition to ERDA, EPA, the U.S. Bureau of Reclamation, and the U.S. Geological Survey are also conducting significant research in the Imperial Valley. When completed, an "integrated assessment" will be made of these studies and the relevant research of universities and other federal, state, and county programs. The combined information will be used to develop a strategy to protect the area environmentally before it is developed extensively.

Figure 13
Estimated Generating Capacity of Significant Geothermal Reserves in the West



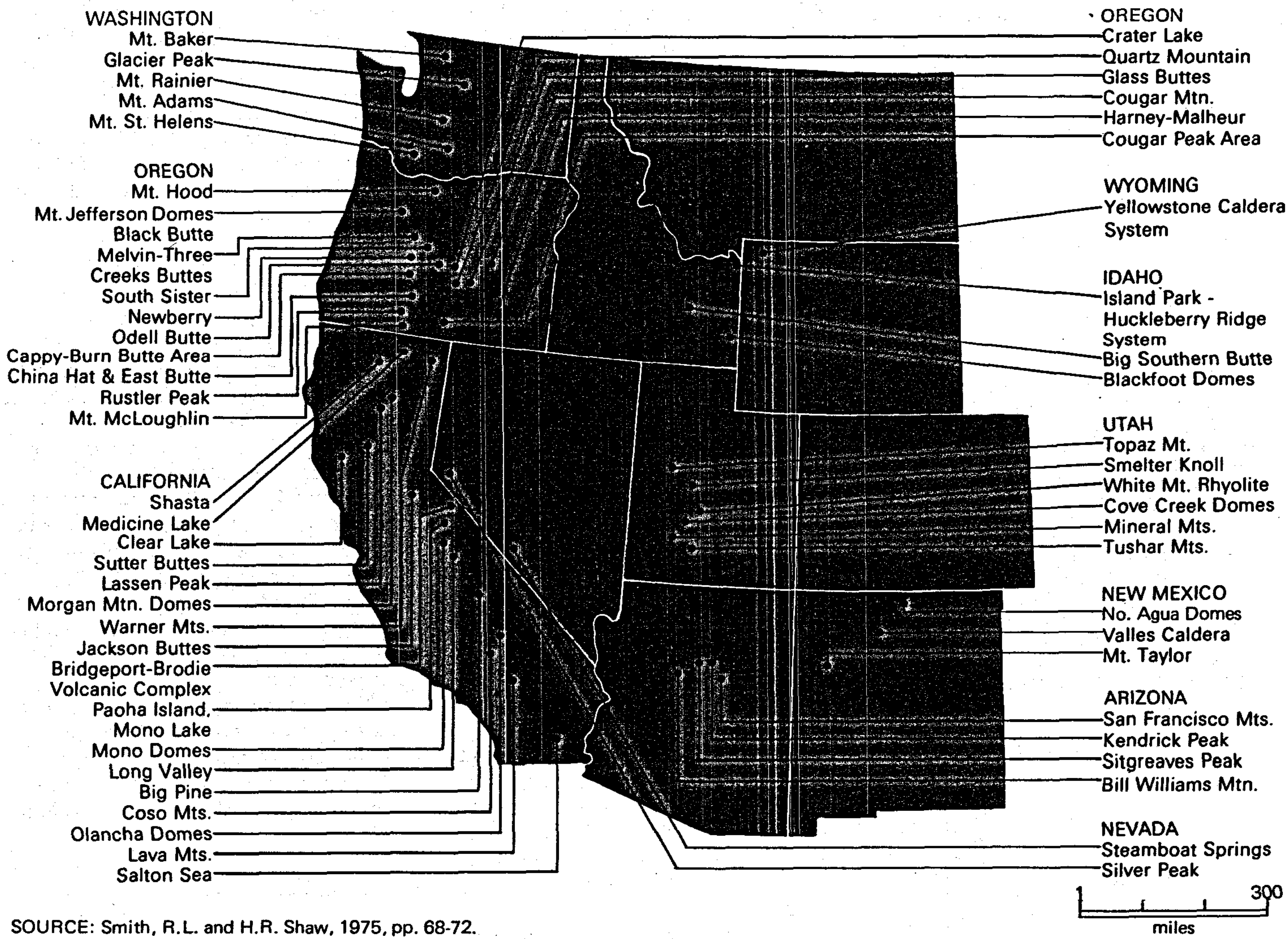
SOURCE: LaMori, P.N., 1976, p. 112.

2. Hot Igneous Systems

The second major type of geothermal resource is hot igneous, which includes both *magma* (molten rock occurring near the surface of the earth), and *hot dry rock* (the solidified margins around the deposits of magma and the overlying roof rock). Although hydrothermal convection systems are also heated by magmatic deposits, the rock formations in hot igneous systems are not sufficiently permeable to trap water. Thus, heat is transferred through a solid body rather than through a liquid.

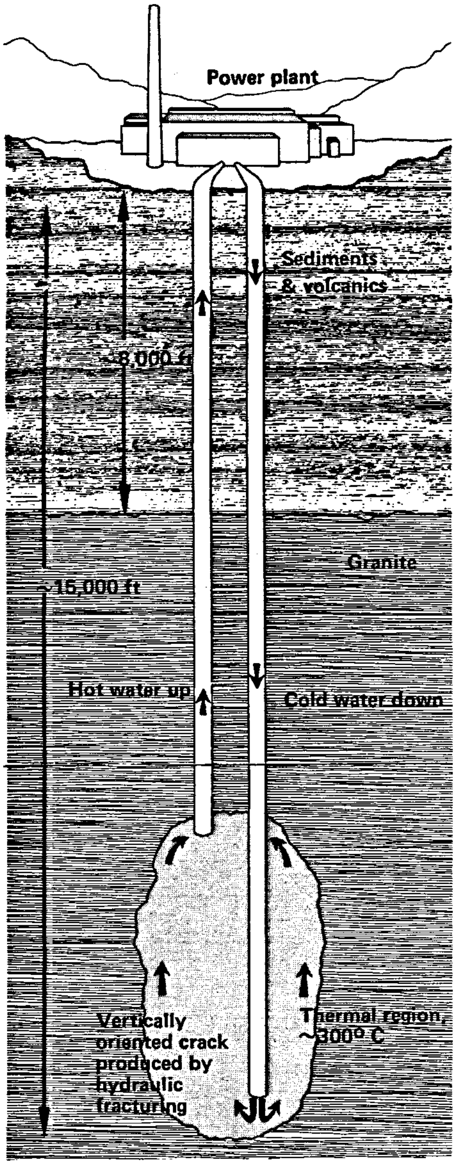
According to current geologic theory, volcanic rock of near-surface origin is silicic, rather than basaltic. Thus, inactive volcanic sites containing silicic rock are believed to signal the probable location of magmatic deposits at depths of 3 km to 10 km. On the basis of existing geological and geophysical data, USGS has listed 17 inferred molten bodies of silicic and intermediate composition in the coterminous United States, 24 bodies of mainly intermediate composition in Alaska, and 1 basaltic body in Hawaii. The total estimated heat energy in these systems is at least 25,000 x 10^{18} calories, 30 or more times the estimated heat content of all hydrothermal systems in the United States at depths less than 3 km. [*13*] USGS has further estimated that about half of this heat is in molten or partly molten bodies at temperatures between 650°C and 1200°C. USGS concludes, "the large inferred volumes and cross-sectional areas of a number of these bodies make them suitable targets for geophysical exploration." [*14*] (Figure 14 shows the areas identified by the USGS.)

Figure 14
Areas of Identified Volcanic Systems



SOURCE: Smith, R.L. and H.R. Shaw, 1975, pp. 68-72.

Figure 15
Technique for Developing Hot Dry Rock



SOURCE: Smith, M.C., 1974, p. 33.

Magma

The recovery of geothermal energy directly from magma is not yet feasible. Although some information has been developed on the location, temperature ranges and depths of magmatic deposits, many characteristics of the resource remain largely unknown and the technology for converting its energy to useful forms in commercial quantities is yet undeveloped.

Work is under way to develop drilling and extraction equipment and materials capable of withstanding the very high temperatures and corrosive properties encountered in a magmatic system. Preliminary research into efficient and durable heat extraction mechanisms also has begun. Sandia Laboratories is working on such a process, which would use a closed system heat-exchange device. Other techniques under consideration are aimed at improving the efficiency ratio of heat extraction. Field tests at the Hawaiian lava lakes or other suitable locations are planned.

Hot Dry Rock

The technology required to utilize hot dry rock is just beginning to be developed, and until several important technical problems are resolved, extraction of the stored heat cannot be considered feasible. The late 1980s is thus the earliest date projected for the utilization of hot dry rock as an energy source. [*15*]

Preliminary engineering approaches to tapping the energy potential are focusing on the design of a circulatory fluid flow loop through the rock (see Figure 15). First, a well would be drilled into the hot formation; then cold water would be injected under high pressure to fracture the formation, and a second well would be drilled to intersect the fractured zone.* Finally, cool surface water would be injected to the first well, passed over the hot dry rock, and withdrawn through the second well in the form of steam or hot water. The heated fluids generated could then be processed using either the flashed steam or binary cycle process.

ERDA recently announced the successful fracturing of hot dry rock using this technique at the Jemez Mountain site being developed by a Los Alamos Scientific Laboratory team. However, the commercial applicability of the system has yet to be proven.

A more exotic method of fracturing hot dry rock is under study by the American Oil Shale Corporation and the Nuclear Regulatory Commission as part of the Plowshare program. This method would employ multiple nuclear explosions to fracture the rock. Some of the energy from the explosions would be trapped as heat, and thus be recoverable for power generation.

No experiments of fracturing hot dry rock by this method have been conducted to date; where similar techniques have been used to stimulate natural gas wells, little success has been reported.

* Thermal fracturing may also result from the thermal stresses induced by the temperature change.

How Geothermal Resources Are Developed

The heat content of the earth cannot be considered to be an exploitable resource unless it is found in circumscribed areas large enough to justify the costs of exploration and drilling. Therefore, stored heat must be concentrated in a form similar to an oil or gas reservoir or a mineral deposit.

Locating a "heat pocket" is the first step in the development of a geothermal resource. Exporation begins with aerial surveys by small aircraft or helicopters equipped with modern aerial photographic equipment and sometimes aeromagnetic or infrared sensing devices useful for mapping surface heat.

Field measurements are then performed, beginning with regional geologic and hydrologic surveys, to search for evidence of tectonic activity and seismic disturbance, determine the distribution and age of young volcanic rocks, and locate any surface discharges of steam, water, or warm mud. Temperature and discharge measurements are taken, and a chemical analysis of the fluids is performed. The water table is measured and evaluated to determine the presence of water and to locate sources of recharge water. The results of these measurements are used to predict the geologic and hydrologic conditions likely to be encountered during drilling. Even vegetation and soil characteristics may provide an indication of the underlying type and character of a reservoir.

Next, geochemical reconnaissance involving the sampling and analysis of waters and gases from hot springs and fumaroles is conducted to determine whether the geothermal resource is liquid- or vapor-dominated. Following geochemical analysis, geophysical surveys are conducted to define specific target areas for drilling. At this point, physical measurements such as temperature, electrical conductivity, magnetism, and passive seismic recordings are taken. Seismic-noise detection and microearthquake measurements are especially useful in detecting reservoirs and developing a regional model of an identified reservoir. Deep drilling to test the temperature gradient and heat-flow of the rocks or fluids may also be conducted, usually by drilling to depths of 15 to 100 meters.

The final phase of gethermal exploration is the drilling of exploratory wells to depths of up to 3 km. Only through such drilling is it possible to determine the actual characteristics of the reservoir, including its salinity level and type of fluid, and thereby evaluate its potential as an energy resource.

Exploratory drilling is accomplished through the use of a rotating bit attached to the surface with a length of pipe called a "drill string." Either an air compressor or water is used for drilling. A "reserve pit" approximately 1,000 feet square and 8 feet deep is dug to store waste fluids flushed up during drilling. Cuttings from the drilling operations are removed from the well through the use of a fluid called "drilling mud," which is pumped down through the drill pipe and then circulated back to the surface in the space between the pipe and the well wall. In addition to removing cuttings, the drilling mud maintains the hydrostatic pressure in the hole, thereby preventing a "blow-out"—the unconstrained flow of liquids or gases from formation zones penetrated as the hole is drilled. Once the drilling reaches the resource, tests are conducted to determine flow rate and reservoir size.

Some Problems Related to Development Technology

Much of the technology needed to determine the location, magnitude, and geologic characteristics of geothermal resources is presently in some stage of research, design, or development. Therefore, only limited information is available, and that information relates only to known geothermal resources, most of which have visible surface discharges. Geologists currently are working to design techniques for locating underground geothermal resources, predicting their chemical characteristics, modeling their hydrologic and geophysical structures, and estimating their magnitude. In addition to locating and evaluating the resource, drilling and extracting steam or hot water pose difficult technological problems.

Drilling

Drilling rigs and surface pumps common to the petroleum industry can be used in geothermal drilling. However, much of the equipment borrowed from the oil and gas industry is inadequate. A list of some of the inadequacies follows.

Drilling bits. *The hard, abrasive rock surrounding geothermal resources is difficult to penetrate even with the best available bits, which are made of tungsten carbide. The composition of the rock slows drilling and causes excessive wear to bits, requiring their frequent replacement.*

Drilling mud. *Vital to the drilling process, this fluid lubricates and cools the drill string and bits, and is also used to remove cuttings as the well is drilled. However, drilling mud deteriorates rapidly at temperatures above 177°C (351°F), slowing the circulation rate of the cuttings being removed. Drilling fluids resistant to the high temperatures found in geothermal reservoirs have not yet been perfected.*

Logging instruments. *These monitoring instruments are used to record the temperature, flow rate, pressure, and physical characteristics of the geothermal resource during drilling. Currently available devices and instruments are accurate only to temperatures near 180°C. Logging and sampling in these high temperatures cause great problems. The requisite technology is lacking but is being studied.*

General drilling equipment. *Many of the basic parts of the equipment used in drilling (bits, casing, piping) are subject to breakdown, corrosion, and scaling caused by the high temperatures, high pressures, and varying salinities found in geothermal resources. Improved cementing compounds and elastomers (rubber-based substances) are being developed to help alleviate this problem. The high rate of precipitation of solids in drill pipes interferes with drilling and requires the pipes to be cleaned and replaced frequently.*

Research and development of improved materials and methods for addressing these technology-related drilling problems is under way. Improved drilling bits and fluids are expected to be available by the late 1970s, and most of the other technological problems should be resolved by the early 1980s.

Extraction

Once the geothermal resource has been tapped through drilling, the stored heat and energy can be extracted. However, much of the equipment necessary to extract that energy is presently in the design and demonstration stage. The equipment under development includes:

Downhole pumps. *These pumps are placed within the well during the binary cycle conversion process to increase the rate of fluid extraction and maintain the geothermal fluid under pressure.*

Heat exchangers. *Heat devices are used with high- and medium-temperature hot-water systems to transfer the heat in the geothermal fluid to a second fluid having a lower boiling point, thereby producing steam.*

Reinjection equipment. *This equipment is used to reinject the used geothermal fluid into the ground to prevent land subsidence and minimize the need for waste disposal.*

The essential features of all the equipment being developed are resistance to corrosion and scaling, and the ability to function effectively under a wide range of temperature and salinity.

3. Conduction-Dominated Systems

In hydrothermal convection systems, heat is transferred from the earth's interior to its surface by a circulating fluid; in hot igneous systems, heat is transferred through the near-surface intrusion of magma. However, most of the earth's heat is transferred from the interior towards the surface through solid rock—a process called *conduction*.

Where conduction is dominant, a temperature gradient exists within the earth such that temperatures increase proportionally with depth from the surface at a constant rate. This temperature gradient, or rate of heat flow, may be increased or decreased by the presence of fluids or low-conductivity rocks. The heat content is unrelated to plate tectonics. Both of the geothermal resources in this category are conduction-dominated systems, referred to as the normal gradient and geopressured geothermal reservoirs.

Normal Gradient

The rate at which heat is conducted through rock to the surface of the earth is expressed in *heat flow units*. Worldwide, the average heat flow rate is 1.5 heat flow units. [*16*] A range of heat flow between 0.8 and 2.0 heat flow units is considered to be the normal* gradient. At this rate, temperatures of 75°C exist at a depth of 3 km. In some areas, temperatures at 3 km have been above 75°C (at least one region, near Clear

* Normal is defined as the orthogonal, or perpendicular, rate of temperature change.

Lake, California, is believed to be as high as 100°C/km), but these are anomalies.

Areas of normal gradient are postulated to be sources of usable energy where only low-temperature heat is required. However, the extraction of energy from the normal gradient is not expected to be technically feasible for many decades. Rock that is permeable and thus capable of "holding" water at these depths must be located. Drilling costs are high, and the technology for drilling where temperatures are high is far from perfected. In addition, some type of heat exchange device that uses a transfer medium such as water must be employed. It is, therefore, highly unlikely that the normal gradient will be selected for development while more commercially feasible alternatives exist.

Geopressured Geothermal Reservoirs

Like the normal gradient, geopressured geothermal reservoir is conduction-dominated; that is, temperatures of the resource increase with depth at a constant, normal rate. However, a geopressured reservoir differs significantly from a normal gradient in being a formation of methane-saturated water trapped in layers of sand and shale beneath impermeable rock. The weight of the sediment creates extremely high water temperatures and high pressures.

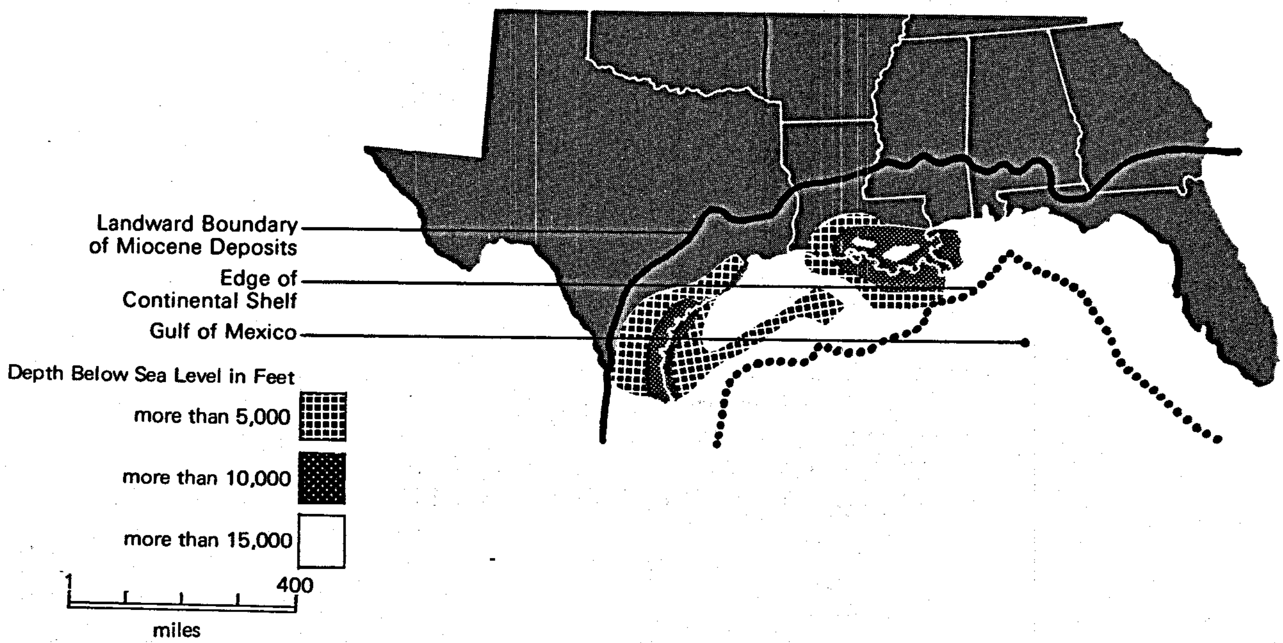
Geopressured zones are known to exist beneath an area of more than 278,500 km² extending from the Rio Grande in Texas to the mouth of the Peal River in Louisiana, into the Gulf Coast and out to the Continental Shelf (see Figure 16). An additional inland area of 52,000 km² has also been identified. Based on oil drilling (more than 300,000 wells have been drilled along the Gulf Coast) and inland drilling data, this area may offer significant potential for three types of energy; *thermal*—from the water, which has temperatures from 160°C to 200°C; *mechanical or hydraulic*—from the high pressures present in the formation; and *fuel*—from the water, which is believed to contain a high amount of dissolved natural gas (methane). The presence of methane deposits makes the zone especially promising.

Based on a cautious drilling program and stringent environmental standards, the USGS has estimated that the combined thermal equivalent of the energy present in the onshore areas is 30,900 MW produced continuously for 30 years. [*18*]

While there is evidence of a large potential resource, a great many questions remain unanswered. Estimates of the porosity of the rock and the extent of the methane deposits are only preliminary and may be proved to be grossly overstated. A reliable assessment of the resource has yet to be developed. ERDA recently initiated exploratory assessments and is presently developing baseline environmental information. If the initial test results indicate that development is feasible, a resource could be developed during the 1980s and 1990s. However, drilling at the necessary depths may be economically infeasible. In addition, the possibility of subsidence (collapse of the surface) and the environmental effects of drilling pose serious potential hazards.

Figure 16

Locations of Known Geopressured Zones Having Geothermal Resources



SOURCE: Comptroller General of the United States, 1975, p. 14.

Section I

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Refer to bibliography at end of book for complete citation.

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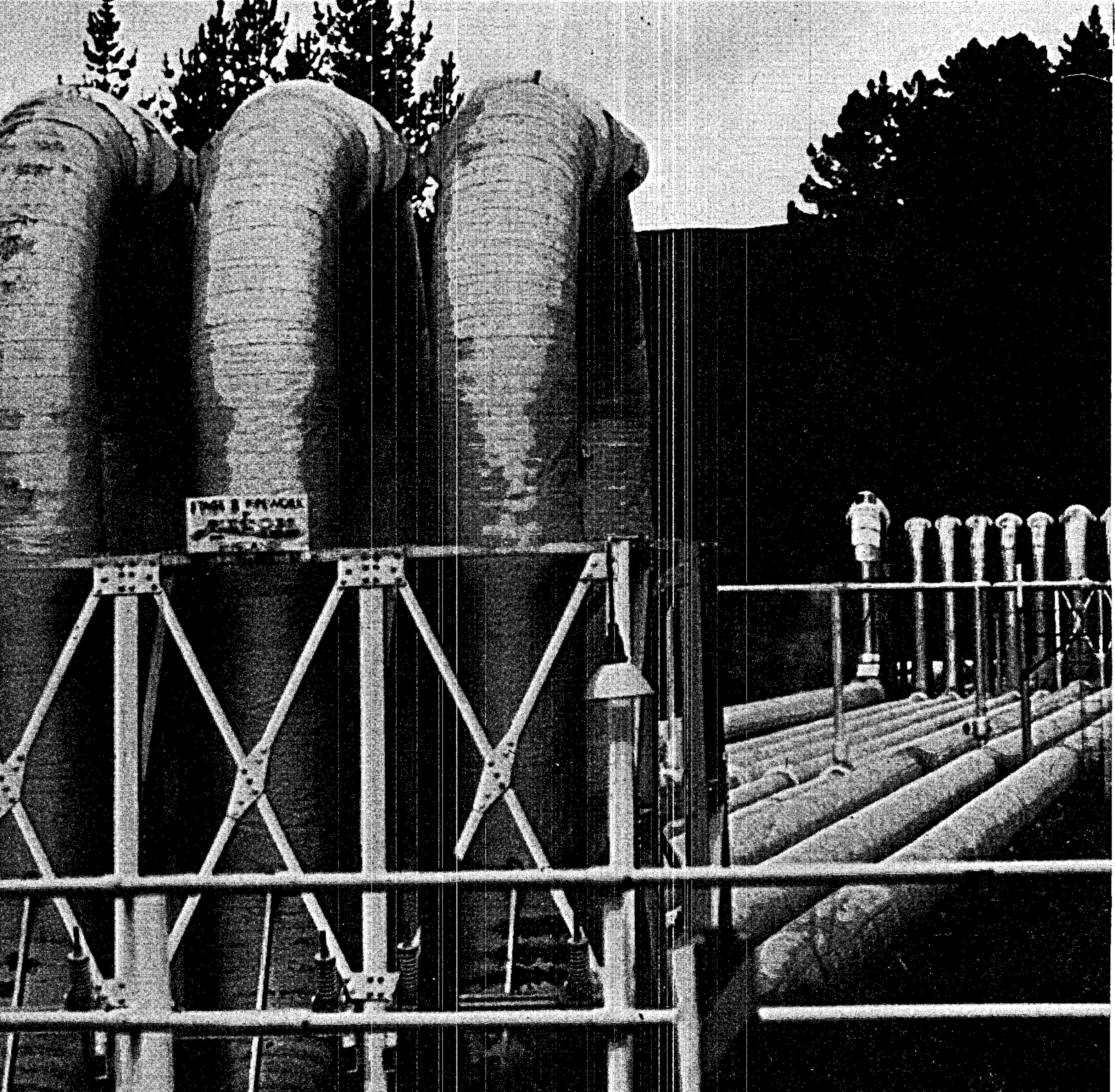
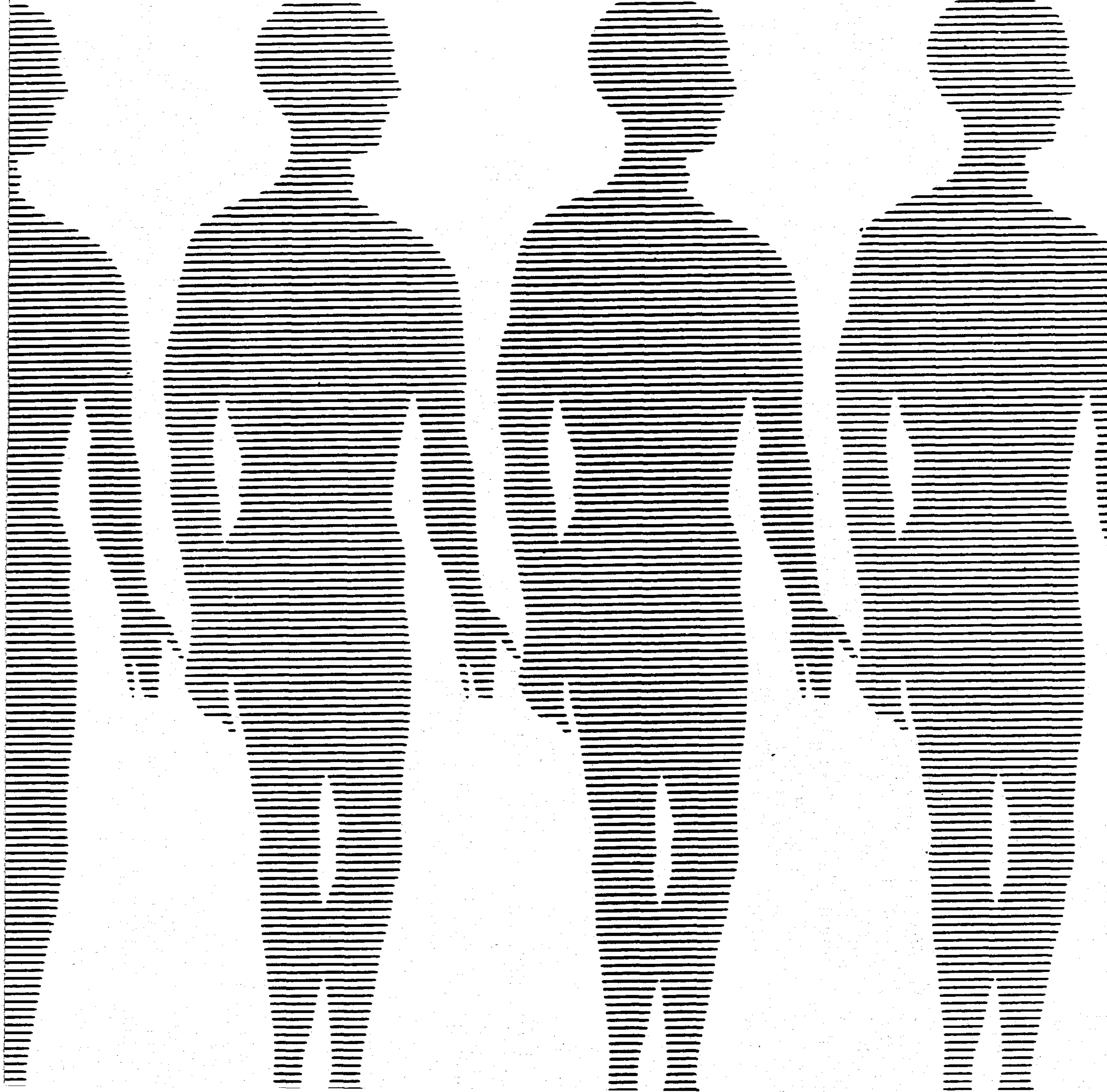
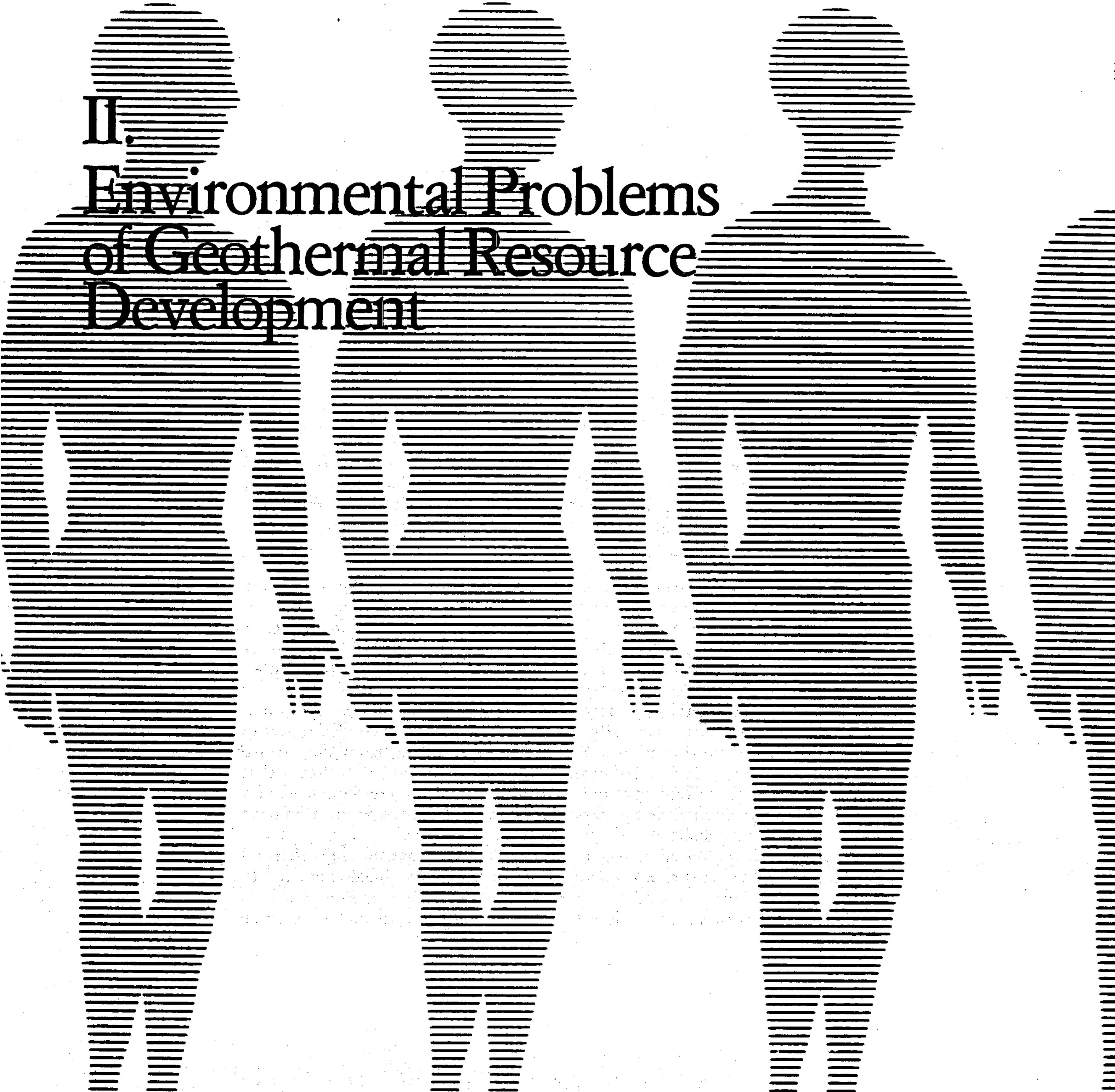




II. Environmental Problems of Geothermal Resource Development



Overview

The widespread belief that geothermal resources represent a relatively "clean," nonpolluting energy source recently has played an important role in heightening public interest in geothermal development. Although knowledge of the related environmental impacts is still incomplete, geothermal resources do appear to offer several significant environmental advantages over alternative energy sources.

Since geothermal energy must be utilized or converted in the immediate vicinity of the resource to prevent excessive heat loss, the entire fuel cycle, from resource extraction to transmission, is located at one site. Unlike fossil fuel or nuclear power production, in which large land areas are required for processes such as mining, refining, transportation, fuel processing, and waste disposal, geothermal energy is not a technology that requires a massive infrastructure of facilities and equipment and large amounts of input energy. Although geothermal development necessarily involves some disturbance of the earth's surface, the effects are not as severe as are those resulting from the surface mining of coal or uranium. Furthermore, the controversial safety issues that have been raised about underground coal mining and the consequences of a major accident during nuclear power production do not arise in connection with geothermal power production.

Another environmental benefit arises from the fact that those geothermal power plants that use steam as a working fluid to drive a turbine do not need an external source of water for cooling purposes, because the condensed steam is recycled for that purpose. Thus, they do not place additional demands on scarce water supplies.

In addition to these environmental benefits, the development and application of geothermal power would reduce the demand for alternative fuels currently in critically short supply (specifically, oil, natural gas, and uranium) and help to reduce the nation's dependence on foreign supplies.

Unfortunately, however, not all the potential environmental effects of geothermal energy are positive. Among the most significant adverse impacts of the exploration, development, and production of geothermal energy (see Table 5) are possible land subsidence, seismic activity, air pollution resulting from the discharge of noncondensable gases such as hydrogen sulfide, high noise levels of drilling and power plant operation, and mineral or thermal pollution of surface and ground waters. Other concerns include increased erosion and sedimentation resulting from site disturbance; possible climatic changes resulting from the release of heat, water vapor, and carbon dioxide; and disturbance of soils, vegetation, and wildlife.

The actual impacts of geothermal development can vary widely—probably more widely than the impacts associated with fossil or nuclear energy sources. For example, the chemical constituents of geothermal steam or hot water can differ significantly from site to site, causing markedly different air and water pollution emissions from power plants having identical generating capacities. The potential severity of the environmental impacts associated with geothermal development depends on several factors:

Table 5
Potential Environmental Impacts of Geothermal Power Production

Impact	Estimate of Probability	Technology/ Resource Type	Severity of Consequences
Land subsidence	moderate	hot-water	variable—can be high
Induced seismic activity (earthquakes)	low	all	high
Air pollution resulting from discharge of noncondensable gases (e.g., hydrogen sulfide, carbon dioxide)	high	all except hot-water binary fluid and other "closed-cycle" use of geothermal fluids	variable—depends on emission controls
High noise levels of drilling and plant operation	high	all; worst for vapor-dominated	moderate
Chemical or thermal pollution of surface and groundwaters	moderate	all; greatest probability with hot-water	high
Well blowouts	low	hot-water; vapor-dominated	moderate
Increased erosion and sedimentation resulting from site disturbance	high	all	moderate
Consumption of water for cooling purposes	high	hot-water binary fluid; hot dry rock	high
Consumption of land for wells, power plants, transmission lines	high	all	moderate
Short-term climatic changes resulting from release of heated steam and carbon dioxide	high	hot-water; vapor-dominated	low
Disturbance of habitat; alteration of ecosystems	moderate to high	all	moderate to low

- — Type of geothermal resource being developed
- — Chemical constituents of the geothermal fluid (steam or hot water) and subsurface rock
- — Overall characteristics (geology, hydrology, topography, vegetation) of the development site, both above and below the ground surface
- — Engineering design technologies used to produce energy and control pollution.

Depending on the site, geothermal power production could result in either equivalent or substantially lower pollution levels than those produced by a coal- or oil-fired plant of identical capacity. Thus, generalizations about the magnitude and significance of the likely environmental impacts resulting from geothermal development must be based on careful, site-specific analysis that takes each of these factors into account.

Both the likelihood and potential severity of the possible impacts of geothermal development warrant careful consideration in determining the significance of any impact. Even if the likelihood that a certain impact will occur is relatively small, it requires close attention if its consequences are potentially serious. For example, although at present it is considered unlikely that geothermal development would induce a major earthquake, the extensive damage that could result from such an event justifies its further investigation.

Because geothermal development has not been widely pursued, ***both the likelihood and severity of many impacts are still relatively unknown***. Extensive information is available for only a few sites, such as The Geysers and the Wairakei plant in New Zealand. Projections of impacts at other locations where development is planned are still preliminary and highly speculative. Since intensive research on environmental impacts is only just being initiated, it will be several years before a detailed understanding of actual impacts is developed.

This chapter describes the major impacts of geothermal resource development on various aspects of the environment. In each section, the anticipated impacts of developing the two most immediately promising types of hydrothermal convection systems—vapor-dominated and hot-water—are discussed in detail. Because available information on the other types of geothermal resources is limited, the probable impacts associated with their development are noted but not discussed extensively.

4. Land Use

The development of all types of energy resources, including geothermal, necessarily involves the use of land. However, the nature of the geothermal resource and the production methods employed in its development result in far less extensive land disruption than occurs with resources that require mining (coal, uranium), transportation over long distances (coal, gas, uranium, petroleum), extensive processing facilities (coal, petroleum, uranium), fuel storage areas, or aboveground waste disposal (coal, gas, petroleum). Unlike these, geothermal energy is not a technology that requires a massive infrastructure and large amounts of input energy. The entire geothermal energy cycle, from extraction to the transmission of electricity, occurs in one location.

The severity of the land disturbance required for geothermal operations also is far less than that of other alternatives, in particular those that require mining. Restoration of land used for geothermal development appears to be less expensive and more likely to succeed than reclamation of mined areas, in part because it is possible to drastically reduce harmful effects through proper management.

Although the extent and severity of land disturbance is relatively less than for other resources, geothermal resource development does have several significant land-use impacts. These impacts relate to: (1) the total acreage requirements for development of a geothermal field and the extent to which the land is disrupted, (2) the compatibility of geothermal development with adjacent land uses, and (3) protection of sensitive land areas. (Chapter 5 discusses impacts of geothermal development on the subsurface geology and soil stability, and Chapter 10 discusses the effects of land disturbance on vegetation and wildlife.)

Acreage Requirements

The development of a geothermal field requires the installation of drilling pads for supply and reinjection wells, sumps, by-product processing facilities, access roads, pipelines, generating plants, cooling towers, and transmission lines. (Table 6 offers figures for the average amounts of land required for each of these uses.) The total land area required to develop a geothermal reservoir is primarily a function of the electrical capacity of the generating plants, the number and density of supply wells (which are, in turn, dependent on the inherent characteristics of the reservoir), and the topography of the site. Impacts resulting from these requirements are inherent in the development procedure.

Factors Affecting Acreage Requirements

The first factor, electrical capacity, is the easiest to comprehend: the larger the generating plant, the more steam is required to attain a given level of output, and the more wells must be drilled.

The second factor, well spacing, is influenced by several considerations: first, wells must be drilled into specific target areas—zones of subsurface fracture where the heat reservoir is located—without consideration to topography, surface condition, or watersheds. Second, the initial rates of steam flow and the constituents of the steam may influence how many wells must be drilled and whether auxiliary facilities, such as those required for the reclamation of chemicals or condensation of steam for water supplies, are built. Third, whether the field development policy is rapid or slow has a marked effect on well spacing. Rapid development is achieved by drilling more wells per acre in a "cluster" arrangement, with relatively short pipelines feeding steam to generating units located at the center of the wells. With a slower rate of development, wells are more widely spaced, and relatively long main supply lines are fed by a more extensive network of feeder systems. [*19*]

The third factor, topography, can also influence acreage requirements. As the slope of the land increases, the total surface area required for development increases, because slope support must be provided and cut-and-fill banks stabilized. [20] Heavily sloped areas, as at The Geysers, often require double the acreage for a given activity. (Erosion and landslide effects relating to topography are discussed in Chapter 5.)

The amount of surface land disturbed in a geothermal development area ranges from 10 to 50 percent, with 20 percent as the average. [21] Scaling up from the acreage presently used at The Geysers (see insert description of The Geysers Steam Field, Chapter 1), a 1000 MWe facility consisting of ten 100 MWe units with a well spacing density of 1 well per 58 acres* would cover 2025 to 3645 hectares (5000 to 9000 acres) or 21 to 40 square kilometers (8 to 14 square miles) of land. Of this amount, an average of 20 percent, or 405 to 729 square kilometers (1000 to 1800 acres) of surface area would be disturbed physically through clearance of vegetation, grading, and paving.

Variability in Land Requirements

Figures on land requirements vary considerably from those recorded for the geothermal operations at Lardarello, Italy, and Wairakei, New Zealand. Based on 1970 figures at the dry-steam field of Lardarello, 13 generating units supplied a total capacity of 360 MWe from 467

* This current spacing at The Geysers is lower than will occur if additional wells are drilled to exploit marginal areas. In that case, acreage requirements probably will be greater, and perhaps they will double.

Table 6
Land Use Requirements for a Typical Geothermal Development Site

Phase	Surface Area
Exploration and Testing Phase	
Road construction	3 to 4 miles, graded and compacted
Drill pads	1 acre each, cleared and compacted
Mud sump	Each one requires an area 100′ x 125′ x 10′ deep to temporarily store up to 1,000,000 gallons of effluent and cuttings.
Full Field Development	
Road construction	Acreage varies. Access roads may be built to drilling pads, mud sumps, buildings for housing equipment and storage. Estimate: 30 acres of land cleared for every 15 wells.
Pipelines	Each pipeline is 10″ to 30″ in diameter, raised on supports rising no more than 12 feet. The area cleared for the pipeline is from 10′ to 300′ wide, depending on whether access roads are constructed.
Power generation facilities	Roughly 5 acres are required; most of the land must be paved or otherwise made impervious.
—turbine generators & condensors	Each is 150′ x 65′ x 60′ high.
—cooling towers	Each is 360′ x 65′ x 60′ high.
—transformer	Each is 100′ x 100′ x 55′ high.
Transmission lines	Lines consist of towers or poles at a height of 80 to 120 feet, with concrete bases 40 feet apart.

SOURCE: U.S. Fish and Wildlife Service, 1976, p. 144 ff.

wells distributed over 168 square kilometers (65 square miles)—a ratio of 1 well to 36 hectares (89 acres). In 1971, at the Wairakei hot-water field, 61 wells supplying a 160 MWe power plant were concentrated in a compact well field of less than 2.59 square kilometers (1 square mile)—a ratio of 1 well to 4 hectares (10 acres). Thus, a complete 1,000 MWe facility based on the much more densely developed Wairakei site would require 16 square kilometers (6.25 square miles) for 381 wells.

Wherever possible in this report, impacts are compared on a quantitative basis. However, a quantitative comparison of the total land requirements of geothermal energy and alternative energy resources is difficult to make because of the complexity of the fuel cycle for the alternatives. The specific acreage requirements for the equipment common to all types (such as power plants, cooling towers, and electrical transmission lines) are roughly the same for any 1,000 MWe facility. Moreover, specific geothermal equipment, such as drilling pads, do not usually take up more space than oil or natural gas drilling equipment. However, the difficulty in comparing alternatives arises in attempting to determine whether the *total* amount of land required for all other fuel types (fuel pipelines or transportation lines, processing facilities, storage and disposal facilities) can reasonably be attributed *solely* to providing 1,000 MWe of electrical power.

Compatibility With Adjacent Land Use

Another important land-use issue associated with geothermal development is the extent to which such development is compatible with surrounding land uses. Possible adverse effects to adjacent land could result from the changes in the use of the land at the site, human activity, and noise and pollutant emissions; furthermore, such impacts are likely to be long-term in relation to the life of a geothermal field.

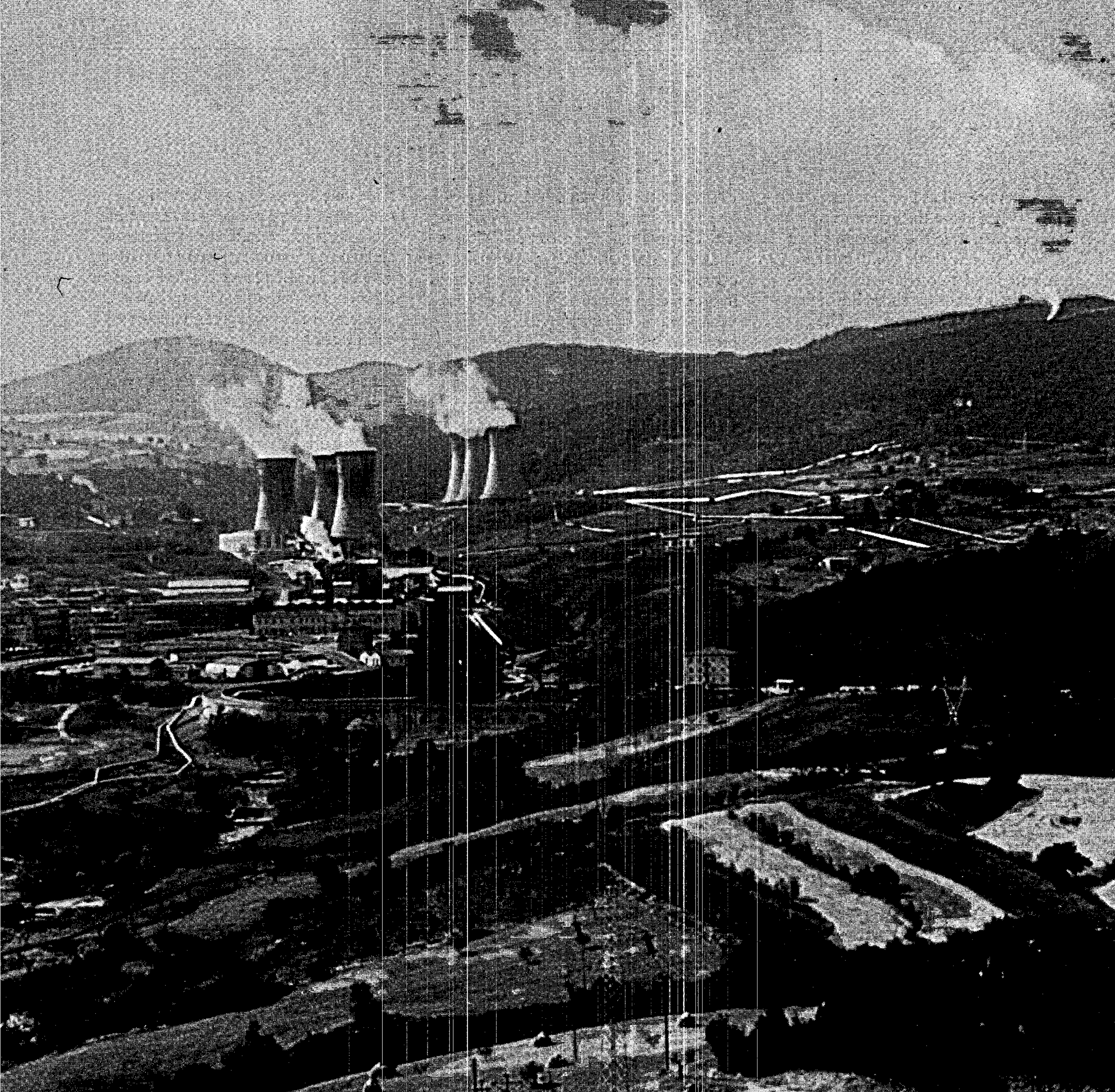
To date, the use of geothermal resources for the generation of electricity has occurred primarily on undeveloped lands. Consequently, geothermal development has radically altered passive multipurpose land uses such as wildlife reserves, cattle grazing, and watersheds. (Some potentially harmful consequences of this change, such as forage reduction, are discussed in Chapter 10.) As a result, whatever value these uses once gave to the land is now diminished. To the extent that the scenic and aesthetic characteristics of undisturbed landscape are replaced by noise, odor, built forms, or defoliation, the changes are not especially pleasing. Human activity in the area must sometimes be restricted, especially during testing, when the dangers of well blowouts are greatest—restrictions that could lead to the overuse of adjacent areas.

The impact of geothermal development on the productivity of adjacent lands is not yet fully known, but appears to be minimal. One important exception is the adverse effect of land subsidence, which results from the withdrawal of geothermal fluids. Subsidence of adjacent land is a major adverse impact that could drastically reduce the value of the land affected if easily damaged facilities, such as irrigation canals or buildings, are present. Subsidence is not rare. It has occurred at Wairakei, New Zealand, and Cerro Prieto, Mexico; but so far the economic effects have been limited by the relative remoteness of these areas. Both are hot-water fields, which are apparently more vulnerable to subsidence. If subsidence were to occur as extensively in the agricultural Imperial Valley, there would be major adverse economic impacts. To the extent that reinjection of geothermal fluids may prevent subsidence, the impacts would, of course, be less (see Chapter 5).

To date, the impacts of geothermal development on land fertility appear to be minimal. During most of the 60 years of field development at Lardarello, Italy, for example, the surrounding land has had varied agricultural uses. Today, pipelines traverse vineyards, orchards, and farmlands with no known detrimental effect (see Figure 17). At The Geysers, wilderness surrounding the development area has remained largely unaffected. Extensive studies are presently being conducted to identify additional effects on the surrounding ecosystems.

Figure 17 (opposite): The Lardarello Dry-steam Field

SOURCE: Pacific Gas & Electric Co.



Some concern has been expressed at The Geysers about the extent to which improved access to the wilderness area provided by new roads would increase residential and industrial growth, especially over the extended life of the field. To date, development of The Geysers has spurred neither residential nor industrial development. However, the question remains important because the development of geothermal sites in remote areas of the West is certain to contribute to a change in the social and economic character of these lands.

Federal leasing regulations [22] require that developers identify adjacent land uses, assess their productivity, and predict the effects of geothermal development on the value of the land. The regulations stipulate that geothermal activities on leased land must be conducted in a manner that prevents "unreasonable interference with the multiple uses of the land." [23] Effective emission controls, noise muffling, proper plant and equipment design, and continual monitoring of adjacent areas—in other words, comprehensive planning and conscientious management—can contribute significantly to the prevention of adverse effects.

Protection of Sensitive Lands

The Geothermal Steam Act of 1970 precludes the geothermal development of certain environmentally fragile land areas in order to protect their special land-use values or unique characteristics. The protected lands are generally public lands acquired with federal funds, and include lands reserved for Native American Indians, lands administered by the National Park Service (including Yellowstone National Park), lands within national recreation areas, lands used for fish hatcheries, wildlife refuges, wildlife or game range lands, wildlife management areas, waterfowl production areas, lands registered in the national wild and scenic rivers system, and lands reserved to protect and conserve species threatened with extinction. The possibility that geothermal developoment will cause damage to certain types of sensitive or critical land areas—such as valuable farmland, mature or near-mature forest, or historical and archeological sites—has also resulted in various leasing restrictions. Certain lands administered by the Department of Agriculture and lands withdrawn under the Federal Power Act (16 USC 818) may be leased only with the consent of, and under the conditions prescribed by, the governing legislation. [24]

Research Needs

An implicit issue facing geothermal developers is the trade-off between the use of land for geothermal energy versus its use for recreation, watersheds, or agriculture. In some areas of the country, this trade-off may be a central barrier to the rapid development of geothermal resources. There is a need to determine more specifically, in terms of economic and natural resources, what productivity may be lost when lands are developed for their energy potential. Disruption of aquifers, emission of potentially toxic substances, erosion, and subsidence—each of these may pose a threat to the long-term productivity of adjacent lands. Learning to measure the potential for harm, and adequately considering this through the instrument of the environmental impact statement, is a primary research need.

The potential also exists for geothermal development to beneficially affect the productivity of adjacent lands. For example, geothermal development may facilitate water reclamation in semi-arid and arid regions. This and other possibilities need to be identified.

Finally, a clearer statement of the potential for social and economic change resulting from successful, widespread development of resources in the now scarcely-populated areas of the West should be attempted. The Integrated Assessment activity now ongoing in EPA should advance knowledge on these matters. The synergistic effects of multiple resource development projects (for coal, uranium mining, and oil shale, for example) and the role of geothermal development in this problem needs to be more carefully examined.

5. Geology and Soils

The stability of surface soil and subsurface geologic formations can be affected in a number of ways by the activities related to developing geothermal resources. Among the most significant potential adverse effects are: surface soil erosion, land surface subsidence, and inducement of seismic activity.

Erosion

The exploitation of any geothermal resource necessarily involves site clearing, which disturbs the land surface, particularly during the initial stages of development. On steeply sloping sites, extensive earth-moving, or "cut-and-fill," may also be required for the construction of access roads, drilling sites, steam pipelines, power plants, and electrical transmission lines. Such activities invariably remove protective vegetation and thereby accelerate erosion of exposed soil by storm water runoff if protective measures are not taken. The eroded soil is carried into streams and subsequently deposited, raising suspended solids levels and causing sediment buildup on stream bottoms. Both increased levels of suspended solids and sedimentation can be harmful to fish and other aquatic species. Although erosion is most severe when the soil is exposed during construction, significant erosion from cuts, fills, roadsides, and culverts continues throughout all development stages. Earth-moving activities may also disturb national drainageways and slopes.

While some increase in the rate of erosion and sedimentation can be expected with virtually all types of geothermal development, the extent of the increase varies widely, depending on particular site conditions and development practices. At The Geysers steam field in Northern California, for example, the combination of steep slopes, poor soil structure, and high seasonal rainfall and runoff rates renders the soils highly erodible. Because a steep slope is also a site condition that requires substantial earth-moving, extensive erosion has occurred in the past. Frequently, fill material has slumped and soil and rock slipped above cuts into hillsides following the construction of drill pads and roads, particularly when built on active landslide areas. Degradation of nearby streams by siltation has also occurred.

In contrast, at the development sites having flatter terrain and less erodible soils, the impacts of geothermal development have been less severe. Moreover, since the land disturbance associated with geothermal development is not nearly as severe as that caused by the surface mining of coal or uranium, a smaller total amount of erosion is likely to occur.

The impacts of soil erosion and earth movement during geothermal development can be mitigated significantly by applying readily available erosion control techniques. Drains, mulch, and matting can be installed; revegetation measures can be taken; and the total land area disturbed can be minimized. Such techniques are currently being used on all federal lands, because federal leasing regulations require that disturbance to vegetation and natural drainage be minimal.

At The Geysers, the state of California has recently begun to carefully regulate earth-moving activities on the lands it owns, thus markedly reducing the severity of erosion-related impacts and highlighting the need for site planning prior to development.

Subsidence

Land subsidence resulting from the withdrawal of geothermal fluids from the earth is among the most serious of the potential impacts of geothermal development. Vertical subsidence and associated horizontal ground movement can occur whenever support is removed from beneath the ground; such movements have occurred throughout the United States as a result of the pumping of groundwater in numerous locations, as well as during the development of mines and oil fields.

Whenever subsurface fluids, such as oil or water, are withdrawn, the cause of the resulting subsidence is the same: a reduction in the fluid pressure that supports the overlying rock causes a marked increase in effective stress and subsurface compaction, or the collapse of pores in the rock structure. In petroleum fields, which are areas of unconsolidated or semi-consolidated sedimentary rock containing pore spaces, subsidence has occurred but has been successfully controlled by injecting water around the periphery of the field to maintain fluid pressures.

Likelihood of Subsidence

Land subsidence has not occurred during the development of the two existing vapor-dominated geothermal fields at The Geysers and in Lardarello, Italy. The lack of subsidence has been attributed to the geologic conditions under which such systems form. One of the fundamental conditions considered necessary to formation of a vapor-dominated system is a "competent" host rock; that is, rock not subject to compaction and, therefore, not subject to subsidence. [25]

In contrast, hot-water systems are expected to behave more like petroleum reservoirs and subsidence is more likely to occur unless subsurface pressures are maintained through fluid reinjection. In Wairakei, New Zealand, where geothermal water is discharged to a river rather than reinjected after being used to generate power, total vertical movement has exceeded 3.7 meters (12 feet) since 1956, affecting an area of over 25 square miles (65 square kilometers). Horizontal movement also has been recorded. [26]

Significantly, the area of maximum subsidence occurs *outside* the production field, which means that subsidence could affect the property of adjacent landowners more than the immediate development area.

In Cerro Prieto, Mexico, a hot-water field located near the Imperial Valley in California, subsidence was recorded some seven miles outside the well field even before extensive production began. [27] At this site, geothermal waters have been discharged to an evaporation and sedimentation pond rather than reinjected.

Land subsidence has serious implications for the future development of the Imperial Valley's geothermal resources. Potentially one of the most promising geothermal areas, the valley is tectonically active and may be subsiding naturally. Since most of the valley is a flat, fertile plain with extensive agricultural irrigation systems, subsidence induced by geothermal development could cause serious damage.

Concern about this issue has led to extensive studies by the U.S. Geological Survey and the state of California's Division of Oil and Gas. To monitor the extent of subsidence caused by both geothermal development and naturally occurring processes, surface benchmarks have been measured since 1971. Research to develop a reliable computer simulation model of the subsurface environmental effects of geothermal development has been funded by the National Science Foundation and is currently nearing completion.

Subsidence is also a concern in developing geopressured reservoirs such as those located along the Gulf Coast. However, two conditions are expected to reduce the likelihood of subsidence there: the deep location (frequently more than 10,000 feet or 3,000 meters) of the reservoir suggested by preliminary engineering proposals, and a seal of cap rock above the reservoir. Furthermore, the previous withdrawal of oil and gas from these zones has not yet resulted in detectable subsidence. [*28*]

Control of Subsidence

The primary technology available to prevent subsidence is the reinjection of geothermal fluids to deep wells following power production. While highly promising, the application of this technique may be limited by at least six unresolved problems.

First, while some compaction is elastic and reversible, the withdrawal of fluids can cause the irreversible collapse of some of the air spaces or pores.

Second, geothermal fluids sometimes contain a large amount of dissolved solids, such as silica or calcium. If the lower temperatures of the reinjected fluid cause these dissolved solids to solidify or precipitate, the reinjection pipes could become clogged; thus reducing the permeability of the aquifer. Concern about this problem has prevented the use of reinjection at the Wairakei power plant, where the geothermal water has a high content of dissolved silica. Such problems could be solved by placing chemical additives in the hot water to keep dissolved solids in solution; however, their use may create another problem: because additives increase the ability of the hot waters to dissolve solids (i.e., the "solubility coefficient"), they dissolve more solids in the host rock once reinjected. Subsequent use of the geothermal hot water containing increased dissolved solids would, in turn, worsen pipe clogging. This type of problem represents a major uncertainty in the development of geothermal energy.

Third, reinjection could lower the temperature and hence the energy potential of subsurface geothermal waters.

Fourth, only part of the geothermal fluid may be available for reinjection because part of the fluid used in the electrical generating process may be discharged as water vapor from a cooling tower.

Fifth, while reinjection, particularly of the concentrated brines characteristic of the Imperial Valley, may not always be practical at the site where the fluids were withdrawn, reinjection at too great a distance may induce seismic activity and consequent earth movement at the surface.

Sixth, the cost of creating reinjection wells for hot-water systems can be quite high relative to other, less environmentally desirable means of fluid disposal, thus increasing the cost of geothermal power. [*29*]

Further research will be necessary to evaluate the likelihood of subsidence for varying resource types and under different geohydrologic conditions, as well as to resolve the potential problems of reinjection as a control technology.

Seismic Activity

Seismic activity induced by the withdrawal or reinjection of geothermal fluids is a potential hazard of geothermal development. A connection between subsurface fluid pressures and earthquakes has been suggested recently. A series of earthquakes recorded at the Rocky Mountain Arsenal near Denver, Colorado, for example, followed the injection of waste fluids to crystalline rocks at a depth of three miles (5,000 meters). At Rangely, Colorado, earthquakes have been associated with the injection of fluids to oil fields as a way to increase production. It is hypothesized that similar events could occur as a result of geothermal development.

Natural Relationship with Geothermal Resources

Geothermal resources and seismicity occur naturally at the same locations; the unstable conditions in the earth's crust that create geothermal resources are the same conditions that produce faults and earthquakes. In fact, the presence of seismic activity is commonly used as a prospecting tool in the search for geothermal resources. As noted previously, most of the geothermal resources currently being developed are located in zones of recent volcanic or tectonic activity, which are often located along the margins of major crustal "plates." Active faults in some geothermal areas appear to create zones of high permeability that permit conduction of heat to the surface and keep open the cavities in which geothermal steam forms.

Micro-earthquakes—that is, earthquakes with magnitudes of less than 4 on the Richter scale—have been observed near many major geothermal areas around the world, including The Geysers and the Imperial Valley. Available data suggest that geothermal zones experience more frequent micro-earthquakes than do immediately adjacent areas. However, earthquakes having magnitudes greater than 4.5 and the potential to cause significant surface damage have rarely been observed in geothermal areas, although they may occur nearby.

The apparent difference in seismic activity within geothermal areas and outside is exemplified by the Imperial Valley earthquake of 1940, one of the largest to occur near a geothermal area. With a magnitude of 7.1, it caused faulting, which extended most of the distance between the geothermal fields just south of the Salton Sea, California, and those near Cerro Prieto, Mexico; but never *into* the geothermal areas. [*30*]

One possible explanation of this distinction is that the frequent micro-earthquakes in geothermal areas act to relieve regional tectonic stress, thus reducing the possibility of a major earthquake. In immediately adjacent areas, where no continual stress release occurs, major earthquakes appear to be more common. [*31*]

To date, there is no evidence to indicate that geothermal activity has increased the seismicity of an area; both The Geysers and the Wairakei sites have been monitored and no effects reported. However, because data are insufficient to reach any reliable conclusions, detailed seismic monitoring is being conducted at The Geysers and the Imperial Valley.

Underground nuclear detonation, which is currently under consideration as a technology for fracturing hot dry rock formations, has been related tentatively to the inducement of seismic activity. Underground experiments with nuclear detonation at the Nevada test site of the Plowshare Program have created small aftershocks, which represent the release of natural strain energy. Even at substantial distances, damages have been reported to buildings as a direct result of the shocks caused by these underground nuclear detonations. Based on these reports, the use of nuclear fracturing near populated areas is probably impractical. [*32*]

The rock formations of the Gulf Coast geopressured reservoir, the third type of geothermal resource, are highly porous and permeable. The faults in this area are not tectonic, but result from relatively minor ground settling due to continuing deposition of sediment. Under these geologic conditions, fluid withdrawal or reinjection at geopressured reservoirs is not expected to induce seismic activity. However, conclusive information for this assumption is not yet available.

Monitoring and Prevention

Operating procedures that would reduce or eliminate the possibility that geothermal development could induce seismic activity are not well known and will require careful investigation if further research indicates a probable seismic hazard. For the present, structures in geothermal areas, particularly those housing super-heated steam and water, should be designed to withstand naturally occurring, local earthquakes. Since this type of design is often expensive, the likelihood and potential magnitude of an earthquake should be determined before design criteria are established. If additional research shows that earthquakes of magnitudes greater than 4 or 5 are highly unlikely to occur in a geothermal development area, only moderate attention would need to be directed to structural precautions, except where faulting may occur near the surface. [33]

Research Needs

Although the erosion-related impacts of geothermal development can be significant, they are predictable for a proposed site and can be controlled with available technology. Consequently, little additional research needs to be undertaken. The possibility of land subsidence or induced seismicity at a particular site, however, is difficult to predict; and the adequacy of available control measures—such as reinjection of geothermal fluids—is uncertain. Extensive research is currently under way to develop adequate control measures, and actual effects are being monitored at development sites leased by the federal government to private operators.

Most programs to monitor subsidence have established local and regional networks of interconnected surveying (leveling) stations. Elevation is measured repeatedly at these stations to determine the degree of subsidence over time. The instruments used include tiltmeters, which measure surface deformation, and extensometers, which can be used to differentiate deep subsidence resulting from the withdrawal of geothermal fluids and shallow subsidence resulting from groundwater pumping.

The interagency Imperial Valley Subsidence Detection Committee is presently monitoring subsidence in the Imperial Valley. One monitoring technique not being employed that could provide useful data is a gravity reading. While not as accurate as detailed, "first-order" leveling, gravity measurements can be performed rapidly and inexpensively. Moreover, when taken in conjunction with first-order leveling, gravity readings permit estimation of the net losses of geothermal fluids from a reservoir and the surrounding area. Both are important parameters in determining the ultimate life of the field and the optimum level of production.

A wide variety of techniques can also be used to investigate seismic effects. Prior to geothermal development, portable, high-frequency seismographs should be used to establish levels of background seismicity, locate areas unsuitable for reinjection, and help locate the geothermal resource. Remote sensing techniques, such as SLAR (side-looking radar), and false-color infrared and conventional aerial photographs, can also be employed to identify surface features that indicate active faulting. During the actual development of new geothermal fields, a network of permanent seismographs can be installed to identify any induced seismicity. Such a network is presently being installed in the Imperial Valley and should be installed in other prospective geothermal areas as well.

A variety of research is currently under way to evaluate the feasibility of reinjection at geothermal sites. While these studies appear to address most of the important questions, at least one additional problem should be investigated: how to prevent reinjection-well plugging. To understand the chemical reactions that occur between geothermal fluids and the geologic formations into which they are injected, basic research on the precipitation of silica, calcium carbonate, and other dissolved minerals is needed first. Applied research should be conducted on the prevention of well-plugging and the related problem of mineral deposition on operating equipment. Based on this research, the potential for both stabilizing geothermal fluids against the precipitation of minerals and deliberately inducing precipitation before the fluids are reinjected should be assessed. Laboratory studies should be conducted based on actual samples from proposed development areas.

6. Water Resources

Geothermal development raises three primary concerns related to water resources: water pollution, effects on hydrology, and impacts on local water supplies. Water pollution may result from the disposal of fluids withdrawn from subsurface geologic reservoirs following their use for testing wells or generating power. Large-scale withdrawal and disposal of geothermal fluids may also alter both the surface and subsurface hydrology of an entire development area. Finally, geothermal development may affect local water supplies in the largely arid American West.

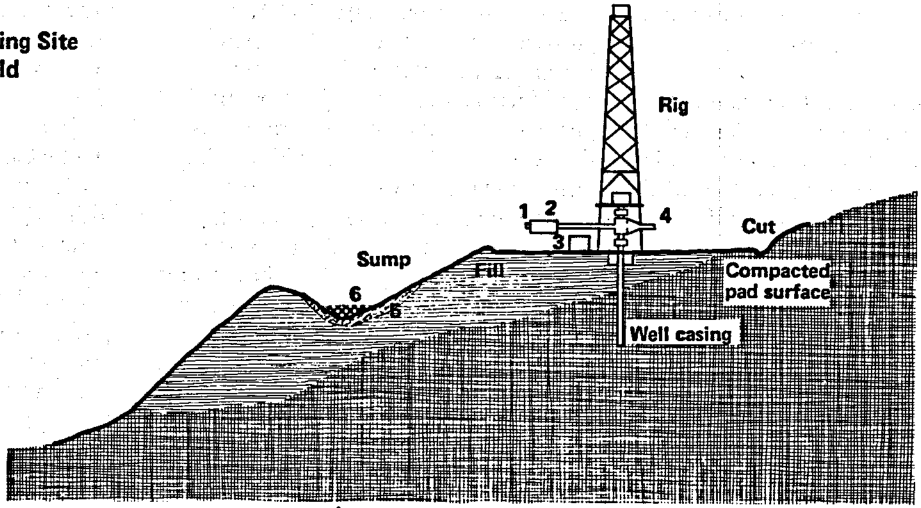
Water Pollution

The pollution problems associated with vapor-dominated systems are generally more manageable than those associated with hot-water systems, because the water from the geothermal steam is often relatively low in pollutants. However, water pollution can occur during any stage in geothermal development—well drilling, construction, or power plant operation.

Sources of Pollution

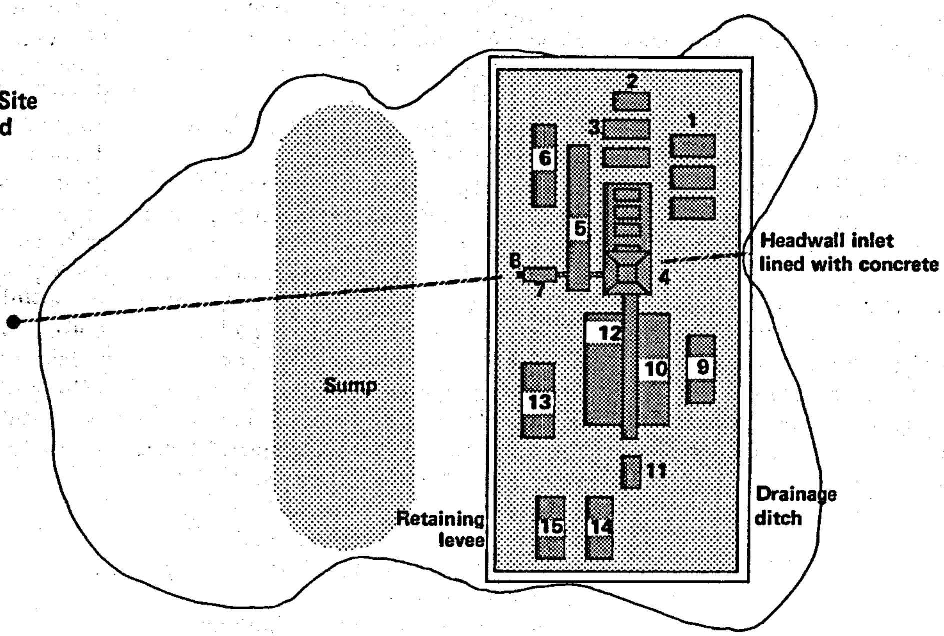
Muds used during the early stages of well drilling may contain various substances harmful to water quality. To prevent the contamination of surface waters, these substances, together with rock dust and the wastewater used in the drilling operation, must be isolated. At The Geysers, sumps with an impervious lining or steel tanks are currently used to store drill cuttings and waste fluid during drilling operations (see Figures 18 and 19). Nontoxic wastes may be permanently disposed of in a sump if it is protected

Figure 18
Cross Section of a Typical Drilling Site at The Geysers Geothermal Field



1. Blow line
2. Muffler
3. Mud mixing tanks
4. Blowout prevention equipment
5. Clay liner
6. Mud

Figure 19
Plan View of a Typical Drilling Site at The Geysers Geothermal Field



1. Air compressors
2. Generator
3. Mud pumps
4. Drilling rig
5. Mud mixing tanks
6. Tank
7. Muffler
8. Blow line
9. Office
10. Pipe rack
11. Blowout prevention hydraulic system
12. Catwalk
13. Mud logger
14. Change room
15. Parts

SOURCE: Reed, M.J. and G.E. Campbell, 1975, p. 1409.

from erosion; however, toxic wastes must be transported to an approved waste disposal site.

Well blowouts could also create water pollution. The California Division of Oil and Gas requires that blowout prevention equipment be used during the drilling of all geothermal wells as a control if pressure conditions become unfavorable. Only one well has blown out during the drilling phase at The Geysers. Well "Thermal 4" blew out in September 1957; as of 1975, it was discharging about 80,000 kg/hr (176,000 lb/hr) of steam and noncondensable gases to the atmosphere. Since the discharge is steam, air pollution is a greater concern than water pollution. However, the harmful substances being released to the atmosphere, such as mercury vapor, may contribute to local water pollution if removed from the atmosphere by rainfall.

Erosion and sedimentation associated with the construction of drilling pads, roads, transmission lines, and power plants can have a significant effect on the quality of nearby surface waters unless careful monitoring and preventive control measures are implemented. Recently, state and federal agencies have directed that increased attention be accorded to limiting erosion and sedimentation at The Geysers. These efforts have proven successful in reducing the pollution of nearby surface waters.

The most serious water pollution problems are likely to develop during power plant operation. The Geysers uses a production method in which relatively pure steam passes through turbines, is then condensed by contact with cooling water, and is finally evaporated in a cooling tower. However, the rate of evaporation from the cooling towers is slower than the rate at which the steam is fed into the turbines. Some of the steam condensate must consequently be removed in another fashion. On the large injection wells. Figure 20 shows the expected water pollutants contained in the condensate return water of 1,000 MWe of generating capacity at The Geysers. [36]
average, 80 percent of the steam is evaporated through the cooling towers, leaving 20 percent as "blowdown" water. [34]

From 1960 to 1971, the blowdown wastewater at The Geysers was discharged directly into a stream. [35] There, the ammonia and boron contained in the condensate caused some surface water pollution and harm to aquatic life. Since 1971, the wastewater has been reinjected to the steam reservoir rocks.

Of the various disposal methods, reinjection is considered to be the most advantageous because the pollutants in the wastewater do not come into contact with relatively pure surface waters and groundwaters. To ensure safety, reinjection wells must be carefully encased to prevent the leakage of geothermal brines to shallow aquifers.

Once introduced to the subsurface reservoir, the wastewater boils and produces steam, in effect artificially recharging the reservoir. Because it has proven to be effective in preventing both surface and groundwater pollution, it will be used in future expansion at The Geysers.

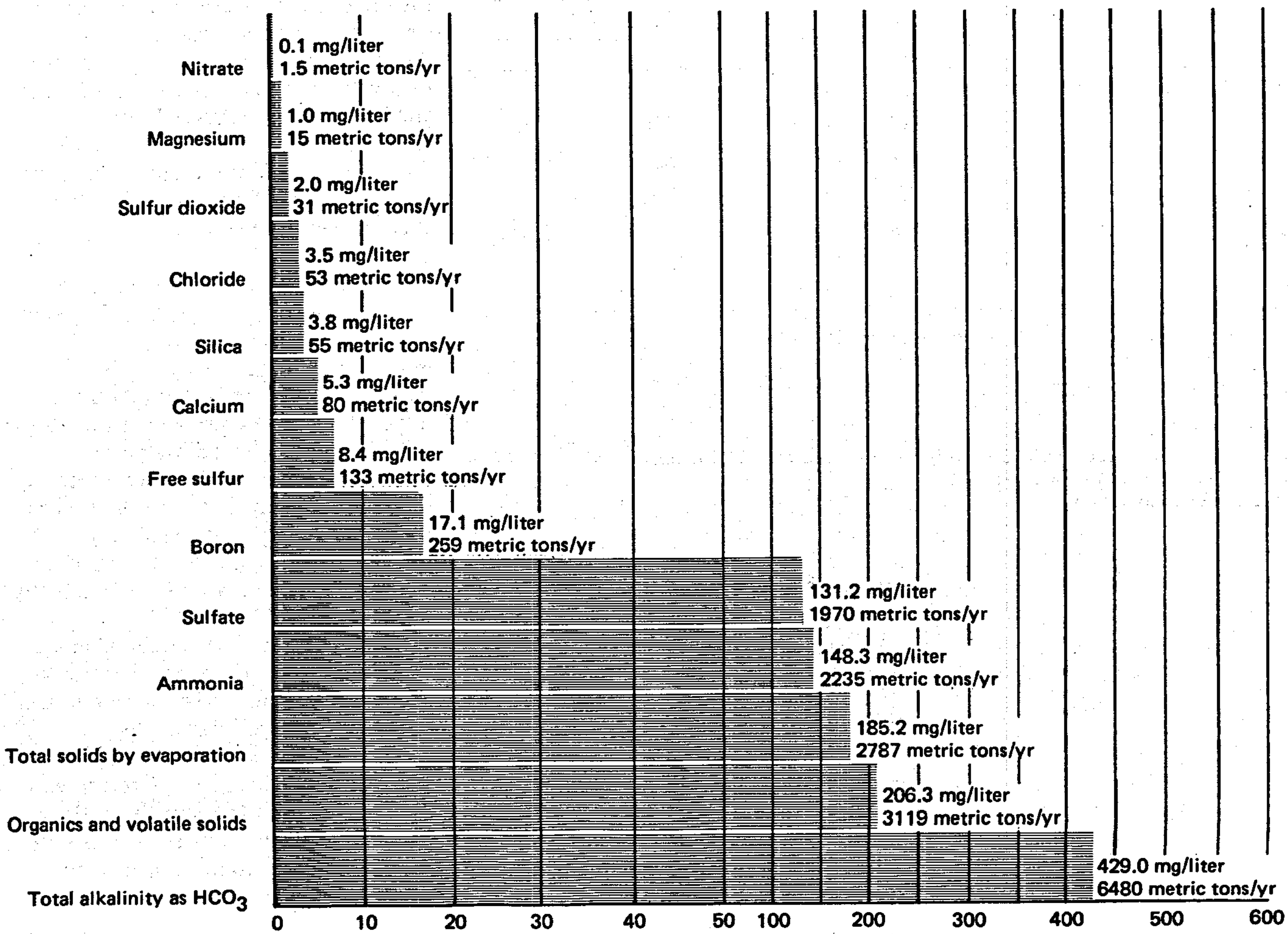
Each 100 MWe of generating capacity at The Geysers produces a relatively small wastewater flow of over one million gallons (3,785 cubic meters) per day—volume that can be handled adequately by one large injection well. An expanded 1,000 MWe of generating capacity would produce over 10 million gallons (37,850 cubic meters) per day, requiring 8 to 10

Power plant operation at The Geysers produces wastewater containing a moderate amount of total solids. The quantity of total solids produced during power generation is higher than that produced by nuclear or fossil fuel plants. However, these technologies also generate large amounts of pollutants during mining and processing, which are not involved in geothermal energy production (see Table 7). Moreover, the technology of reinjection to the geothermal reservoir—now being applied at The Geysers and planned for hot-water development sites in the West—would, if successful, almost eliminate the major cause of water pollution.

Hot-water systems pose far more difficult water pollution problems because wastewaters from testing and production are more abundant, more water pollutants

Figure 20

Composition and Yearly Quantities of Major Pollutants in Condensate Return Water of a 1000 MWe Plant (The Geysers)



SOURCE: Resource Planning Associates, Inc.

Table 7

Expected Water Pollution Emissions for Alternative Electrical Generating Processes, 1000 MWe Plant
(metric tons/year, rounded to nearest fifty)

Process	Suspended Solids		Dissolved Solids	
	A	B	A	B
Nuclear (light-water reactor)	0	0	0	0
Coal	500	4,000	500	2,600
Residual fuel oil	500	n/a	550	100,000[a]
Natural gas	500	n/a	550	0
Low Btu synthetic natural gas (from coal)	500	n/a	550	2,600
Geothermal (The Geysers)	n/a	n/a	2,800[b]	n/a

NOTE: Column A under each process includes total pollutants generated during power plant operations; Column B includes total pollutants during all other steps (mining, etc.).

SOURCE: Teknekron, Inc., 1975, 1976.

n/a—not available

a. Produced by a hypothetical 500,000 bbl/day refinery of which 34,000 bbl/day are residual fuel oil to supply a 1,000 MWe power plant.

b. Total solids by evaporation.

are contained in the geothermal fluid, and large amounts of cooling water are used. At Wairakei (a 143 MWe plant), approximately 30 million gallons (113,600 cubic meters) of wastewater are disposed of each day from the condensed effluent and the excess water not flashed to steam. This is a far greater proportion than is produced at The Geysers. Such large amounts of wastewater must be disposed of in an environmentally safe manner.

Characteristics of Geothermal Fluids

The quality of geothermal hot water—its physical and chemical characteristics, including impurities such as total suspended solids—varies widely. While some geothermal hot waters contain relatively few pollutants, most contain a relatively large amount of dissolved solids and heavy metals because the high temperatures of the brines increase the dissolution rate of solids and heavy metals in the rock. [37] Radioactive elements such as radium and radon also may be present.

The geothermal hot waters at Cerro Prieto, Mexico, contain 1.5 to 2 percent total dissolved solids (15,000-20,000 mg/1, compared to a value of about 35,000 mg/1 for sea water). At the Imperial Valley in California, about 75 miles north, geothermal waters are substantially more saline at most locations; brines with dissolved solid concentrations (typically over 25,000 mg/1 and sometimes reaching 260,000 mg/1, or 26 percent of the total) are found in many wells. [38]

In sharp contrast, at certain other locations in the West geothermal hot waters are sufficiently pure to be used for agriculture and industry. For example, geothermal waters are used for stock watering in Klamath Falls, Oregon, and for domestic hot water supplies in Boise, Idaho. In Iceland, geothermal waters are widely used for both municipal heating and domestic purposes. [39]

The Special Problem of Waste Disposal

Based on the variability in the amount and type of dissolved solids in geothermal fluids, a number of different methods for disposing of wastewater from drilling and power plant operation have been tested and used. These include direct release to surface water bodies, evaporation, surface spreading to shallow aquifers, desalination with subsequent water reuse, and reinjection to the producing reservoir by use of deep wells. The selection of a disposal method has depended on local hydrologic conditions, the quality of the wastewater, and environmental regulations.

The only extensive commercial experience with hot-water system waste disposal has been outside the United States, and some of the methods used in other countries are not acceptable here because of their harmful environmental effects. For instance, at Wairakei, New Zealand, wastewaters are discharged into a river near the plant, substantially increasing the arsenic, sulfur, and mercury levels of the river. At Cerro Prieto, Mexico, production wastewaters are separated from the geothermal fluid and then stored in a large evaporation and sedimentation pond (8 sq. km. or 3 sq. miles in size for the existing 74 MWe plant). As the waters in the evaporation pond become highly saline, developers plan to discharge them into nearby waterways having high natural salinity.

A major concern in the Imperial Valley of California is the salinity level of the Salton Sea and various shallow aquifers. Local water supplies are limited and in great demand for agriculture. Because water supplies already contain large amounts of dissolved solids, additional salinity must be prevented. The state of California has prohibited the discharge of waste fluids with high dissolved solids content into either surface waters or shallow aquifers.

In complying with this restriction, wastewaters produced during test drilling at the Imperial Valley are stored in plastic-lined holding ponds from which the water evaporates. This disposal method prevents infiltration to groundwater and has thus far proven effective. However, the very large volume of wastewater generated during actual power plant operation limits its use; the rate of evaporation is not fast enough for large volumes of wastewater. As a rough indication of the magnitude of the problem, a 1,000 MWe plant in the Imperial Valley is estimated to require the disposal of approximately 50 billion gallons (18,900,000 cubic meters) of brine per year containing 50 million tons of solids. [*40*] Thus, the most probable long-term disposal method for wastewater from power plant operation seems to be reinjection to deep wells. Initial tests of reinjection have proven promising. In a year-long experiment, 2,727 liters (600 gallons) per minute were successfully injected into a single well without reducing the ability of the formation to receive water. [*41*] However, a number of complex technical problems remain to be solved (see Chapter 5).

Desalination, which has the additional benefit of producing usable fresh water for a locality, is another alternative for wastewater disposal. Currently, desalination is being tested by the Bureau of Reclamation at its East Mesa test facility in the Imperial Valley. However, because the expense of desalination increases with the salinity of the water, the technology is probably limited to waters with dissolved-solids concentrations below 35,000 mg/1. This excludes a large proportion of the Imperial Valley brines. [*42*] The economic feasibility of desalination in the Imperial Valley has also been questioned recently because the temperatures of geothermal brine at East Mesa are lower than originally anticipated. If less heat is extracted from the brines, less electric power can be produced. Hence, at relatively low temperatures a tradeoff exists between the production of power and the availability of fresh water.

Hydrology

Geothermal development at The Geysers has not as yet altered the area's surface hydrology significantly. However, continued withdrawal of geothermal fluid could reduce the amount of water in the deep steam reservoir and in the rate of water flow and possibly change the temperature or chemical characteristics of nearby thermal springs.

Pressure decline tests indicate that The Geysers reservoir is almost a closed system; that is, it is not being recharged with water at a rate sufficient to prevent a decline in steam pressure as energy is produced. Although some of the fluid is restored through reinjection, geothermal steam at The Geysers should be viewed as a depletable, rather than a renewable, resource.

Large-scale extraction and reinjection of hot-water geothermal fluids in the Imperial Valley also may cause changes in the subsurface hydrologic system. Effects such as alterations in groundwater recharge rates have been extremely difficult to predict quantitatively for the valley. To better understand the mechanisms of groundwater recharge in this highly complex hydrologic system, local, state, and federal agencies are closely monitoring the water quality and quantity in the valley.

The lack of comprehensive, reliable data on subsurface hydrology makes impossible the determination of whether long-term power production would ultimately deplete the geothermal resources of the Imperial Valley or other hot-water systems in the United States. Investigations at Wairakei, New Zealand, suggest that geothermal energy could be developed at a rate that permits production for an indefinite period of time. [*43*]

Reinjection could also help to maintain the long-term productivity of the geothermal resource. Research involving computer simulation of resource behavior is under way to identify the most effective long-term production strategy (including the rate and method of withdrawal and reinjection) for both hot-water and geopressured reservoirs.

Water Supply

Geothermal power production may also require the use of water for cooling purposes. At The Geysers and other vapor-dominated systems, water can be supplied by the geothermal resource in the form of condensed steam, thereby eliminating the need for an external source of water. A similar cooling system can be used in a flash turbine hot-water plant. However, in a binary fluid system, because the geothermal hot water is reinjected directly to the geothermal reservoir once it has passed through a heat exchange device, it is not available for use in cooling the freon or isobutane used to drive the turbine, and an external source of water is needed.

Current Alternatives for Cooling

The cooling water can be provided to a geothermal site in one of three ways: with a "once-through" cooling system, in which external water, frequently from a river or lake, is utilized once for cooling, and then discharged to its source; with an evaporative or "wet" cooling tower, in which the external water is evaporated to the atmosphere; or with a "dry" cooling tower, in which the fluid is cooled by air and continually circulated in a closed system.

The water requirements of these systems may vary widely. "Once-through" systems and wet cooling towers require substantial amounts of water; dry cooling towers very little. Their environmental impacts also vary substantially (see Chapter 9).

A once-through cooling system is currently used at Wairakei, New Zealand; however, the potential for thermal pollution of surface water limits the applicability in the United States.

New Designs for Still-Undeveloped Resources

Preliminary designs prepared by Bechtel Corporation for a 10 MWe demonstration binary power plant with an evaporative or "wet" cooling tower indicate that 830 gallons per minute of makeup water is required, of which about 20 percent is "blown down" and reinjected to the reservoir. At this rate, for a 1,000 MWe plant, 83,000 gallons per minute (almost 134,000 acre-feet, or 165 million cubic meters per year) are required. This amount is substantially greater than that needed by alternative power generation systems because the thermal efficiency of a geothermal plant is low. Such large quantities of water may not be available in many locations in the predominantly arid western states, or may preempt scarce water resources needed for other purposes. Alternatively, a dry (air-cooled) cooling tower could be used. Based on present prototype designs, dry cooling towers are expected to be 30 to 40 percent more costly than evaporative towers, [44] and may reduce the already low thermal efficiency of the power plant.

A moderate quantity of makeup water is required to operate hot dry rock systems. Requirements are estimated to be about 26,500 gallons (100 cubic meters) per day for wells supplying 100 MWe of thermal energy; at this rate, 1,325,000 gallons (5,015 cubic meters) per day (1,484 acre-feet, or 1,830,000 cubic meters per year) would be needed to supply a 1,000 MWe plant, assuming that a binary power plant with 20 percent efficiency is used. [45] Additional cooling water would, however, be required to cool the isobutane or other working fluid.

Research Needs

In any geothermal development area, impacts on water quality, hydrology, and local water supply can be predicted only on the basis of comprehensive, site-specific data. Baseline environmental data on water quality and hydrology are presently being collected as part of ongoing research programs in potential geothermal development areas, such as ERDA's Imperial Valley Environmental Project.

Geologic and hydrologic data are usually obtained from deep test wells drilled during exploration for geothermal fluids. Insufficient data are often obtained from such wells at shallow and intermediate depths. Data on the vertical variation of water level, depth, temperature, and pressure; and on rock permeability, porosity, and cementation, should be collected in each zone to the extent required by USGS for wells drilled by leaseholders on federal lands. To provide a thorough understanding of local hydrology and determine whether reinjection is likely to be successful, test wells should also be drilled on the periphery of geothermal areas, where temperatures decrease rapidly and rock cementation occurs.

In many geothermal areas, data on rock porosity and permeability are insufficient to assess the hydrologic nature of the reservoirs. Well-logging techniques using radioactivity (including gamma-gamma and neutron logs) provide the most reliable means of estimating porosity and permeability. Where appropriate, such techniques should be applied to new wells (both deep and shallow) in geothermal areas.

To assess impacts on water quality, data should be collected not only on the standard water quality parameters (e.g., dissolved solids) but also on the local hydrologic systems and the characteristics of geothermal waters that would disclose their presence in surface and groundwaters. Data would be particularly useful on hydrogen and oxygen isotopes present in water samples from surface waters, shallow groundwaters, and geothermal reservoirs. Detailed laboratory analysis of the chemistry of geothermal fluids, similar to that performed to determine potential reinjection problems, would also be helpful in determining potential water quality problems.

The liquid wastewater disposed of during geothermal operations often contains a variety of chemical compounds. Because wastewater is a potential source not only of water pollution, but also of water supply and commercially valuable chemical by-products, high priority should be assigned to developing economical methods of producing fresh water (desalination) and extracting valuable chemicals such as boric acid and sulfur compounds.

7. Noise

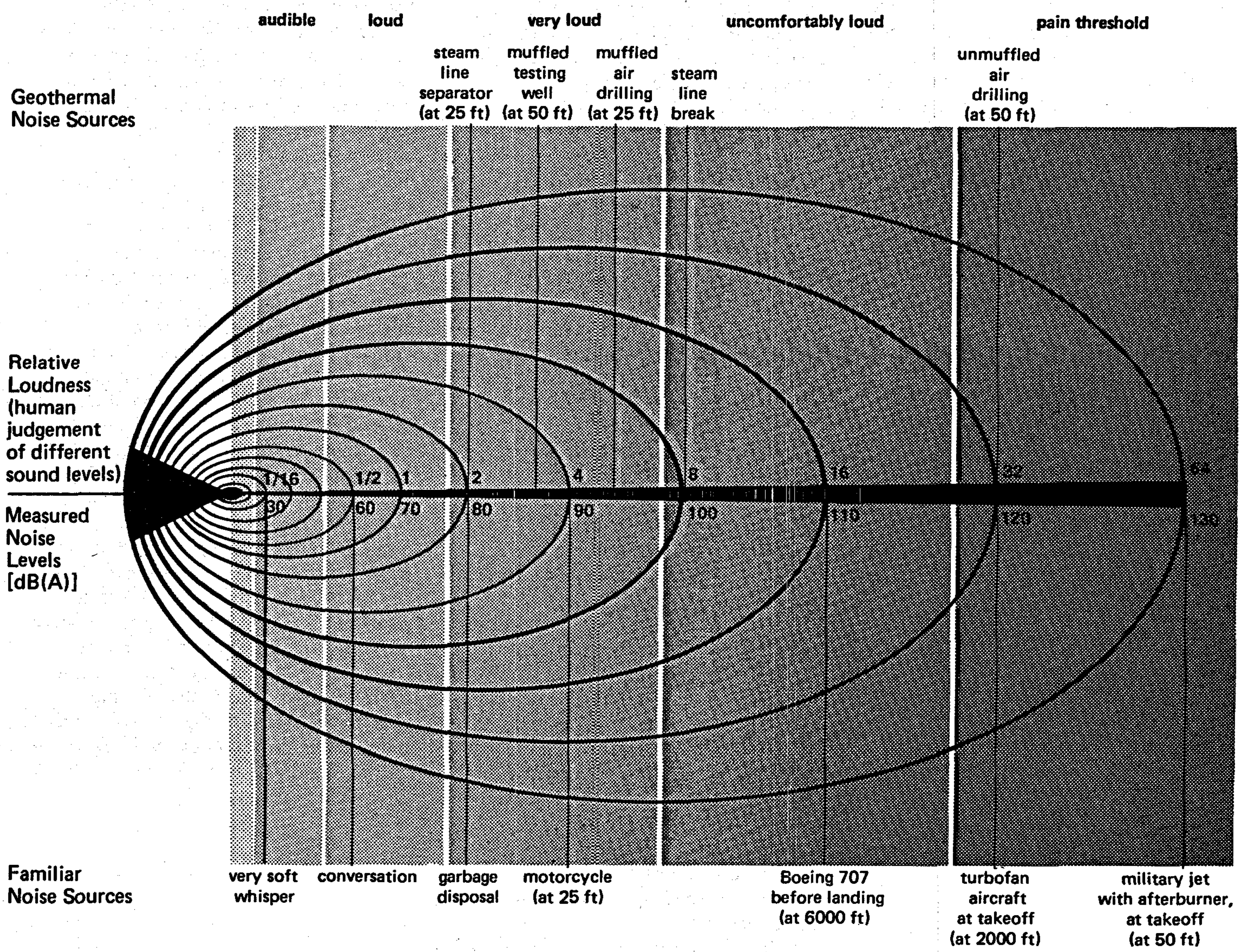
Perhaps the most ubiquitous environmental disturbance associated with geothermal development is noise. Loud, continuous noise occurs during both the drilling and production testing of geothermal wells and the operation of the plant. Nevertheless, noise does not represent as immediate a concern as do some of the other environmental impacts of geothermal development because its effects are limited to the immediate area under development. And because the health and welfare effects of noise are well documented, this section reviews those effects only briefly and then focuses on the sources of noise at a site.

Effects of Noise

The harmful health and welfare effects of exposure to excessive noise levels or vibration over a prolonged period of time range from the relatively minor, such as temporary task interference and irritation, to the severe and permanent, such as sleep loss, physiological stress, speech impairment, and hearing loss (see Figure 21). Since the extent of harm is related directly to the frequency and duration of exposure to high noise levels, workers at a geothermal site experience the highest risk. Noise standards established by the Occupational Safety and Health Administration (OSHA) require that exposure of workers to unmuffled noise at levels above 95 dB(A) be limited. [46] Several geothermal development activities produce noise at levels close to, or substantially higher than, this level. Persons in the vicinity of a geothermal site may be exposed to continuous noise at levels varying from 60 to 120 decibels, depending upon the ongoing development and distance from the noise source.

Figure 21

Noise Levels of Geothermal Operations at The Geysers Compared with Those of Familiar Sources



SOURCE: Reed, M.J. and G.E. Campbell, 1975; U.S. Department of the Interior, 1972; Ecoview, Inc., 1974.

In addition to direct health and welfare effects, the noise generated by geothermal development may have other adverse impacts. In communities with little industrial development, residents may regard the continuous noise associated with geothermal development—even at a relatively low level—as an intrusion into their previously quiet environment.

Until recently, for example, noise related to activity at The Geysers had not led to strong efforts by nearby residents to limit noise. However, a new power plant (unit No. 13) is currently planned for construction close to a residential community (1.7 miles), the village of Anderson Springs. In response to concern expressed by residents, Lake County, California, is considering enacting noise control standards.

Animal behavior also is affected by excessive noise, which has been shown to cause changes in the size, weight, reproductive activity, and behavior of farm animals. In some wildlife species, changes in mating behavior, predator-prey relationships, and territorial behavior have been observed (see Chapter 10).

Sources of Noise in Geothermal Development

High noise levels are produced during each of the major phases of geothermal development: well drilling and production testing, construction, and plant operation. Table 8 lists typical noise levels occurring at The Geysers for these activities, which are summarized below.

Well Drilling and Production Testing

The process of drilling and testing geothermal wells is comprised of a number of separate operations of varying duration in which steam under high pressure escapes to the atmosphere, generating high noise levels. Some of these operations can be effectively muffled, others emit essentially unavoidable noise.

At vapor-dominated sites like The Geysers, only the shallow portion of a well can be drilled by using mud as the circulating fluid. For much of the procedure, compressed air must be used as the circulating fluid when penetrating the probable steam zone to avoid clogging or damaging the steam-producing rock fractures. Air drilling is much louder [120 dB(A)] than mud drilling [75-80 dB(A)], primarily from the horizontal pipe ("blow line" or "blooie line"). The engines operating the air compressor also produce a deep resonant sound that carries for considerable distances. Of the total drilling period of two to three months (during which drilling is conducted 24 hours a day), about one-third of the time is spent drilling with compressed air.

Drilling companies have experimented with a wide variety of methods for controlling air drilling noise at The Geysers and have tested several types of mufflers. Recently, significant reductions in noise have been achieved by directing the discharge of the blow line into a large "air sampler," a large chamber designed to capture loose rock cuttings. Injection of water into the air sampler, a method originally developed to increase the amount of rock captured, also reduced noise. [47] These techniques have been employed extensively in recent well drilling at The Geysers.

Once drilling is completed, the noise levels associated with extraction do not drop significantly. A well must first be allowed to "blow" freely for three to six days until the accumulated dust and rocks are removed. Noise levels during the procedure approach 118 dB(A). It is generally considered infeasible to muffle this operation, because only large rocks blown up under pressure would damage currently available muffling equipment.

Following the clean-out, the well is tested to evaluate the steam reservoir and production rate by releasing steam from the well to the atmosphere. The accompanying noise level is high [approximately 118 dB(A)]. Several types of mufflers have been used in an attempt to control testing-related noise. One of the most effective, a "rock muffler," significantly reduced the noise level by 29 dB(A), from 118 to 89 dB(A), according to tests by Union Oil Company. [48]

A completed test or production well is discharged or "bled" continuously into the atmosphere through a small diameter pipe (bleed line), which permits releases of 5 to 10 percent of the total potential steam flow. The noise associated with bleed line discharges is relatively low—about 86 dB(A)—and can be lowered to 65 dB(A) by venting the line into a rock-filled ditch. While this discharge continues until the power plant is operational (possibly more than a year if delays are encountered), an attempt is usually made to limit this source of air and noise pollution by timing the completion of production testing to coincide with the completion of the power plant.

Occasionally, wells are allowed to vent at full pressure for several hours to prevent the buildup of condensate Because this operation is not usually muffled, it produces about the same noise levels [118 dB(A)] as do unmuffled test wells.

Well blowouts, or unanticipated venting, rarely occur during the drilling phase of geothermal development. The noise emitted when they do occur, however, is extremely loud, probably as loud as an unmuffled test well. If not controlled, blowouts can continue to be sources of air and noise pollution for extended periods of time. At The Geysers, "thermal" well No. 4 "blew out" in September 1957 and is still discharging some steam into the atmosphere; however, this blowout has been partially controlled and is no longer a significant noise source.

Table 8
Noise Levels of Geothermal Operations During Development Phase at The Geysers

Operation	Duration	Noise Level [dB(A)]	Distance [ft]
Well Drilling			
Mud drilling	60 days/well	75-80	50
Air drilling, including	30 days/well		
blow line		120*	25
blow line with air sampler		95*	25
blow line with air sampler & water injection		85	25
Well cleaning; open well	3-6 days	118*	50
Well testing; open well	14 days	118*	50
Rock muffler		89	50
Well bleeding before connection to generator	variable		
open hole		86	5
rock-filled ditch		65	5
blowouts	variable (infrequent)	118*	50
Construction			
Operation of construction machinery (trucks, bulldozers, etc.)	1-2 years	70-90	50
Plant Operation	20-30 years		
Steam line vent (muffled)	intermittent	90	100
Jet gas ejector	continuous		
unattenuated (old design)		117*	5-10
with acoustical insulation		84	5-10
Steam line separator	continuous	80	25
Steam line breaks	brief, infrequent	100*	50
Cooling tower	continuous	80-90	5-10
Turbine-generator building	continuous	70	outside

SOURCES: Reed, M.J. and G. Campbell, 1975; U.S. Department of the Interior, 1972; Ecoview, Inc., 1974.

* Noise level is at or above OSHA standard of 95 dB(A).

Drilling noise levels pose less of a problem in hot-water than in vapor-dominated systems. Well drilling and production testing for hot-water systems is a far less noisy operation than for vapor-dominated systems because mud, rather than air, is used as the circulating fluid. Also, the period of time required for drilling in hot-water systems is somewhat shorter—30 to 45 days rather than 2 to 3 months.

The most significant noise associated with hot-water wells is that emitted during production testing for power generation, when 20 to 25 percent of the hot water is flashed to steam. If unmuffled, the noise of the expanding steam could reach a level as high as 100 dB(A) at 50 feet. [49] Well blowouts could also produce high noise levels. Following the testing period, the wells are completely capped and thus cease to be a source of noise.

Construction Activities

Full development of a geothermal field involves construction of access roads, steam pipelines, generating plants, and electrical transmission lines. Construction of generating plants requires the longest period of time—up to two years at The Geysers. During this period, the operation of earth-moving and construction equipment—such as large trucks, bulldozers, tractors, cranes, and cement mixers—generates noise levels familiar to anyone who has experienced a city building-construction site. Noise associated with construction activities can often be controlled through the use of engine mufflers and other abatement techniques. However, construction equipment is generally operated at the same time that production wells are being drilled and tested; the simultaneous field development and plan construction phases cause high noise levels.

Plant Operation

Operation of a geothermal power plant also creates high noise levels. At The Geysers, the most significant continuous noise sources are the cooling towers and jet gas ejectors, which release noncondensable gases from the condenser. The noise created by the fans in the cooling towers is continuous, but is confined by the structure to the immediate vicinity of the plant. [50] While the jet gas ejectors on older units at The Geysers emit considerable noise, newer units are acoustically insulated and are therefore considerably quieter. Installation during late 1976 of improved air pollution control equipment designed to transfer gases from the jet gas ejectors to other locations in the plant for the removal of hydrogen sulfide may also reduce the noise currently emitted from the ejectors. The particle separators and the movement of steam through the steam lines also represent significant sources of noise. Another loud but intermittent noise source is the venting of steam lines during plant shutdowns and accidental steam line breaks.

Research Needs

The noise levels produced by any type of geothermal development are largely determined by the actual equipment used and the operating procedures followed. While the geothermal industry has conducted extensive research and experimentation on noise control, much of this research has taken the form of "troubleshooting" aimed at controlling individual operations such as well drilling at a specific site. A need clearly exists for comprehensive research on noise control and the development of appropriate equipment and operating procedures.

Ambient noise levels at new geothermal sites should be monitored to determine noise intensity, frequency, and duration before and during development. In addition to site-specific data collection, a more general, comprehensive engineering study should be undertaken to analyze in detail each geothermal operation that produces noise in the development of both vapor-dominated and hot-water fields. Existing equipment and procedures used to reduce noise levels during each operation should be compared in terms of effectiveness, reliability, cost, and environmental impact, and specific procedures and equipment recommended for use. Such a study could also explore the need for federal R&D to control the noise of operations that cannot be muffled with existing technology, such as noise produced development and plant construction phases cause high noise levels.

8. Air Quality

Noncondensable gases and particulates accompany the geothermal steam released to the atmosphere during well drilling, production testing, and plant operation. At sufficiently high concentrations, several of these substances—particularly hydrogen sulfide—can have harmful effects on human health. The odor of hydrogen sulfide can also be regarded as aesthetically objectionable.

To date, no significant health effects resulting from emissions of hydrogen sulfide or other air pollutants during geothermal power production have been documented, either at The Geysers or at geothermal power plants in foreign countries. However, relatively high emission levels of various air pollutants have been recorded at geothermal power plants in other countries, and moderate emission levels of hydrogen sulfide have been documented at The Geysers.

Since data on health effects, air pollutant emission levels, and ambient air quality at geothermal development areas are still incomplete, the air quality impacts that will result from full-scale geothermal development at sites currently in the early stages of exploration and development cannot be predicted accurately. However, because the concentration of air pollutants in geothermal fluids (and hence, of the steam released to the atmosphere) varies widely from site to site, the development of better methods to evaluate and control emissions is generally considered to be one of the most important environmental issues associated with geothermal development.

The following sections identify the types of pollutants emitted during geothermal power generation, describe their potential health hazards, and discuss the major sources of emissions at existing geothermal power plants.

Types of Pollutants

The types of pollutants likely to result from geothermal development are primarily determined by the chemical composition of the geothermal fluid at a site. Both the total quantity of gases in the fluid and the relative concentration of their constituents depend on the geochemistry of the underground reservoir. The chemical composition of the geothermal fluid can vary substantially in different reservoirs, at different wells within the same reservoir, and even during the lifetime of a single well. Thus, the levels of pollutants emitted during geothermal operations can also vary widely overall. Table 9 compares the composition of geothermal steam at The Geysers and Wairakei.

The gaseous emissions associated with the geothermal production of electricity differ considerably from those associated with nuclear and fossil-fuel production. Since geothermal processes operate without combustion, the resulting gaseous emissions are the reduced compounds (primarily hydrogen sulfide, ammonia, and hydrocarbons such as ethane and methane) of elements contained in the geothermal fluid. In the burning of fossil fuels, these elements are found in oxidized form as sulfur oxides, nitrogen oxides, and carbon dioxides.

In vapor-dominated systems and in the "flash" steam process used with hot-water systems, the geothermal steam contains an assortment of noncondensable gases. Carbon dioxide represents the main component (75-95 percent); ammonia, methane, hydrogen sulfide, and nitrogen typically are present in smaller quantities; and gases such as radon, mercury vapor, and argon are present in trace amounts. [*51*] Small quantities of minute particulate matter (including rock dust, heavy metals such as lead and silver, and boron) are also likely to be in suspension in the steam. Measurements at sites throughout the world indicate that because the chemistry of geothermal fluids in both vapor-dominated and hot-water systems can vary so widely, neither type of system inherently results in more air pollution than the other.

Potential Health Hazards

Several of the noncondensable gases emitted during geothermal power generation pose potential health hazards. To date, the emission levels associated with existing geothermal power plants have generally not been high enough to cause most of the effects; however, because the nature of the geothermal fluid varies considerably from site to site, serious effects could occur at new development sites.

Hydrogen sulfide and ammonia present the greatest *potential* hazards; carbon dioxide, although usually present in higher concentrations, is somewhat less significant. Mercury and radon are of concern because they are toxic even at low concentrations.

Hydrogen Sulfide

Hydrogen sulfide (H_2S) is a highly toxic gas. Its direct effects on humans range from a noxious, "rotten-egg" odor and eye irritation at low concentrations to respiratory damage and even death at high concentrations. [*52*] Although atmospheric dilution of geothermal steam generally prevents ambient hydrogen sulfide from reaching dangerously high levels in the immediate vicinity of steam releases, concentrations may be sufficient to create an occupational health hazard for workers. The potential hazard of this gas is increased by the fact that it cannot be detected by smell at the high concentrations which are most dangerous.

Hydrogen sulfide is chemically reactive, and readily converts to other compounds of sulfur, such as sulfur dioxide, sulfur trioxide, sulfuric acid, and particulates (metal sulfides and sulfates). Conversion is particularly likely to occur in urban areas where ambient oxidant levels are high. [53] Recent research shows that this conversion frequently occurs within hours or at most several days following introduction of the gas to the atmosphere. Figure 22 presents data on the physiological effects of hydrogen sulfide. The other sulfur compounds into which hydrogen sulfide is converted also have significant negative health effects on humans, including increases in irritation to the respiratory system.

Although the odor of these compounds does not constitute a nuisance as does hydrogen sulfide at similar concentrations, they are of greater national significance overall as air pollutants because they are emitted in large quantities by "stationary sources" such as fossil-fuel-burning power plants. Hence, geothermal emissions of hydrogen sulfide contribute to raising ambient levels of sulfur oxides regionally. This is particularly important because sulfur dioxide (SO_2) is one of the "criteria pollutants" for which EPA sets and enforces national ambient air quality standards under the authority of the Clean Air Act and its 1970 amendments. Geothermal emissions of hydrogen sulfide may also contribute to regional climatic problems, such as increases in the acidity of rainfall.

Table 9
Comparison of Noncondensable Gases in Steam from Wells at Two Geothermal Power Plants

Gas	Range of Concentrations Measured (ppm)			
	Geysers			Wairakei
	Low	High	Average	Average
Hydrogen sulfide	5	1,600	222	40
Carbon dioxide	290	30,600	3,260	600
Methane	13	1,447	194	5
Ethane	3	19	–	1
Ammonia	9	1,060	104	8
Nitrogen	6	638	52	3
Hydrogen	11	213	56	10

SOURCES: Reed, M.J., and G. Campbell, 1975; Axtmann, R.C., 1976.

Ammonia

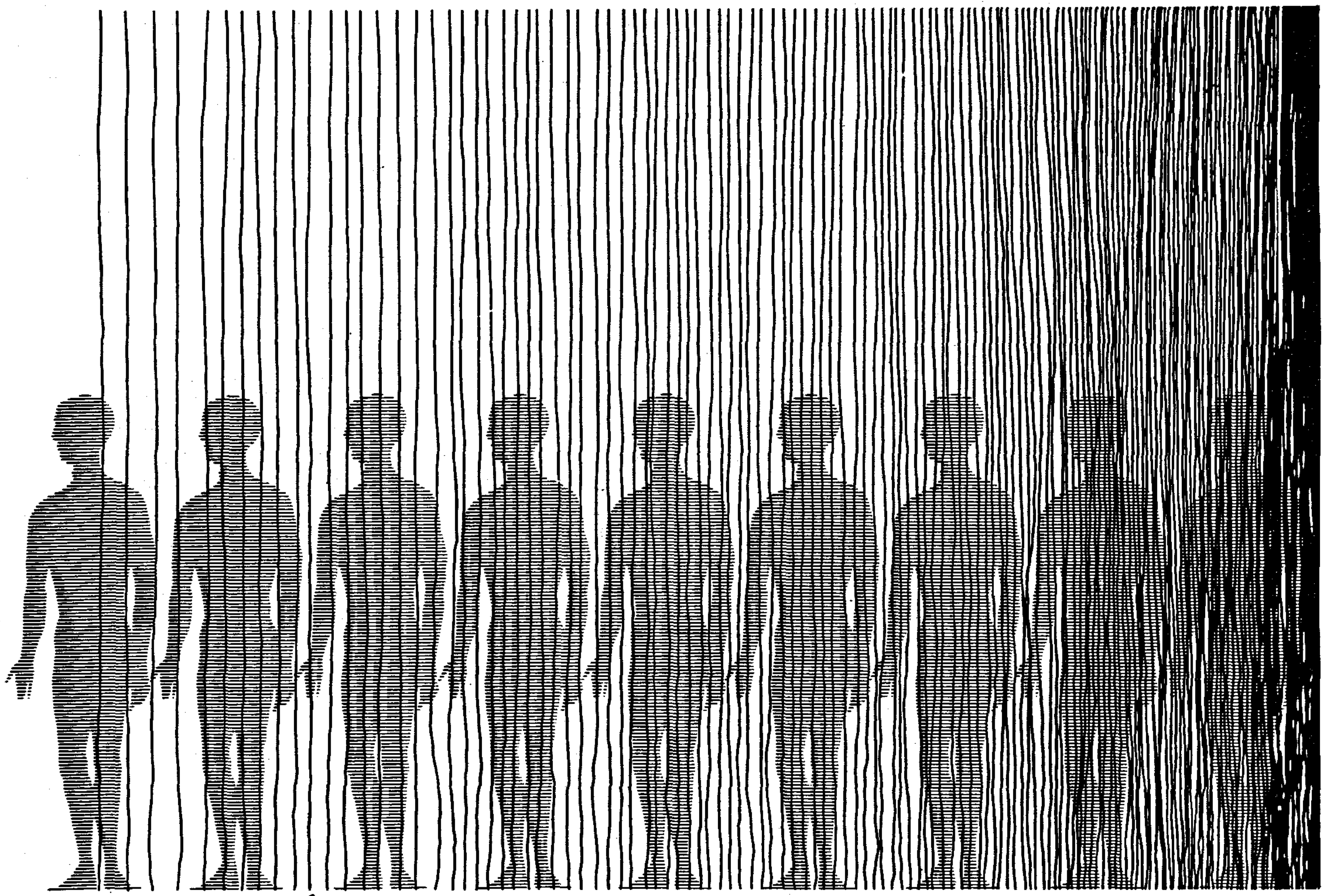
Most geothermal steam contains ammonia at levels too low to pose a direct health hazard. Moreover, as with hydrogen sulfide, atmospheric diffusion rapidly lowers ammonia levels to acceptable values. Inhalation of high concentrations (1000 ppm) of ammonia, which can cause extensive irritation of the eyes and upper respiratory tract, coughing, and vomiting, is thus a rare occurrence. However, if ammonia reacts with other chemicals to form more toxic compounds (such as with hydrogen sulfide to form ammonium sulfate), harmful environmental impacts on human health and certain plant and animal species may result. [54]

Carbon Dioxide

Carbon dioxide is present in undiluted geothermal steam in quantities more than twice its toxic level. Because it is a normal component of the atmosphere, it tends to diffuse rapidly and therefore does not usually pose a major danger. However, the accumulation of carbon dioxide in terrain depressions (which can occur as a result of its greater density than air), may result in high concentrations in the ambient air.

Figure 22

Physiological Effects of Hydrogen Sulfide



Effect	ppm	mg/m³
odor nuisance	0.067	0.1
loss of sense of *smell*	0.067–0.67	0.1–1
eye irritation, fatigue	0.67–6.7	1–10
eye irritation, photophobia after several hours	6.7–100	10–150
eye and respiratory irritation within 1 hour, possible death within 43 hours	100–200	150–300
eye and respiratory irritation within 30 min.; slight systemic effects within 4-8 *hours;* dyspnea, hemorrhage, and death within 48 hours	200–334	300–500
slight systemic effects within 4 hours, hemorrhage and death within 8 hours	334–467	500–700
slight systemic symptoms within 1 hour, death within 4-8 hours	467–600	700–900
death within 1 hour	600–934	900–1400

SOURCE: Sheiler, L., Woodward-Clyde Consultants, 1975.

Mercury

Mercury, which can be toxic to living tissue, is a known constituent of some geothermal fluids in trace amounts. Because of its natural tendency to vaporize, mercury can be emitted to the atmosphere through natural releases of steam as well as those caused by geothermal development, and can be washed from the atmosphere by rainfall. Mercuric compounds are soluble in water and thus can be absorbed by living organisms directly from water or indirectly through the food chain. Because of its recorded toxicity in living tissue (inhabitants of the Minamata Bay area of Japan have suffered nerve diseases and death as a result of eating fish and shellfish highly contaminated with methyl mercury released from a plastics factory), standards have been set by the U.S. Public Health Service for mercury concentration in air, water, and foods such as fish and shellfish.

Radon

Radon-222, the only radioactive gas, is found in trace amounts in the noncondensable gas portion of geothermal steam. It is produced by the decay of uranium in the rocks of the geothermal reservoir.

Although only a minute amount of radon is present in geothermal effluents, its very presence has caused considerable concern. Once introduced to the atmosphere, radon acts as a source of highly toxic decay products. While radon itself does not accumulate in human beings, it has a relatively short half-life of 3.82 days, and breaks down into "daughter products" that readily attach to other particles in the atmosphere. These particles can, in turn, attach to human tissue. Increases in lung cancer at industrial sites have been associated with exposure to radon and its daughter products. A concentration standard of three picocuries per liter has been set by the state of California for the radon-222 concentration in the air.

Sources of Air Pollutants

The major sources of air pollutants emitted during geothermal power production are (1) direct releases of geothermal steam during all stages of development and (2) releases of noncondensable gases during plant operation (see Table 10).

Table 10
Sources of Steam and Noncondensable Gas Emissions During Geothermal Development

	Relative Importance as Pollution Source
Steam discharge during well drilling and clean-out	Moderate
Production testing of wells	Moderate
Well blow-outs	Low
Venting or "bleeding" of test wells prior to power generation	Low
Steam line vents during power plant operation	Moderate
Accidental steam line breaks	Low
Venting of wells during plant shutdown	Low-Moderate
Power plant operation	High

Vapor-dominated Systems

In vapor-dominated fields such as The Geysers, dry steam is released to the atmosphere when the steam-producing zone is penetrated, during subsequent well cleanout, and again during production testing. Results of extensive tests at The Geysers indicate that the average initial steam flow of a well is 68,000 kg/hour (150,000 lb/hour), although initial steam flow rates as high as 172,000 kg/hour (378,000 lb/hour) have been recorded. [55] An average well producing 68,000 kg/hour of steam with an average hydrogen sulfide content of 222 parts per million (as shown in Table 11) would result in the emission of 15 kg/hour (33 lb/hour) of hydrogen sulfide during well testing. A successful exploratory well at The Geysers will be cleaned and tested for approximately 20 days; during this time an average of 7,200 kg (15,800 lb) of hydrogen sulfide is emitted per well.

Following production testing, the well is discharged continuously through a bleed line until it is connected to the power plant. The average steam and hydrogen sulfide flows through a bleed line are small—450 kg/hour (990 lb/hour) and 0.1 kg/hour (0.221 lb/hour), respectively; however, the time period of discharge is variable, and can be as long as several years. The total estimated quantities of air pollutants released to the atmosphere *prior to* power plant operation for 1,000 MWe of generating capacity located at The Geysers are shown in Table 11. These quantities represent combined *total* emissions from well drilling, clean-out and production testing, and not rates of emissions per unit of time. Noncondensable gases currently are not controlled at The Geysers during these stages, although emissions of particulate matter are controlled through the injection of water into the "blowline" and the use of mufflers (see Chapter 7).

Table 11

Expected Total Air Emissions at The Geysers Prior to Operation of Geothermal Wells for 1000 MW of Generating Capacity

Constituent	Total, Metric Tons*
Steam	12.09×10^6
Carbon dioxide	9.55×10^4
Ammonia	8.46×10^3
Methane	6.04×10^3
Hydrogen sulfide	6.04×10^3
Nitrogen and argon	3.63×10^3
Hydrogen	1.21×10^3

SOURCE: Teknekron, Inc., 1975.

* Calculation assumes that well testing continues for approximately 2 months per well.

Uncontrolled blowouts, which have occurred infrequently during well drilling and production testing, also represent a source of air pollution. One such uncontrolled blowout at The Geysers (well "Thermal" 4) has resulted in total releases to the atmosphere of 4,000 tons (3630 metric tons) of hydrogen sulfide, 5,000 tons (4535 metric tons) of ammonia, and 6,000 tons (5440 metric tons) of methane between 1957 and 1975. This is about one-eighth the total that would have been emitted by a 100 MWe generating unit operating at The Geysers over the same period without special emission controls.

Power plant operation represents the most significant source of air pollution associated with geothermal power production. The solids and particulates are removed in a "centrifugal separator" built into each steam line. In existing units, the steam is cooled in direct contact with circulating cooling water. About one-third of the total hydrogen sulfide, and most of the other noncondensable gases in the steam, are continuously emitted to the atmosphere.

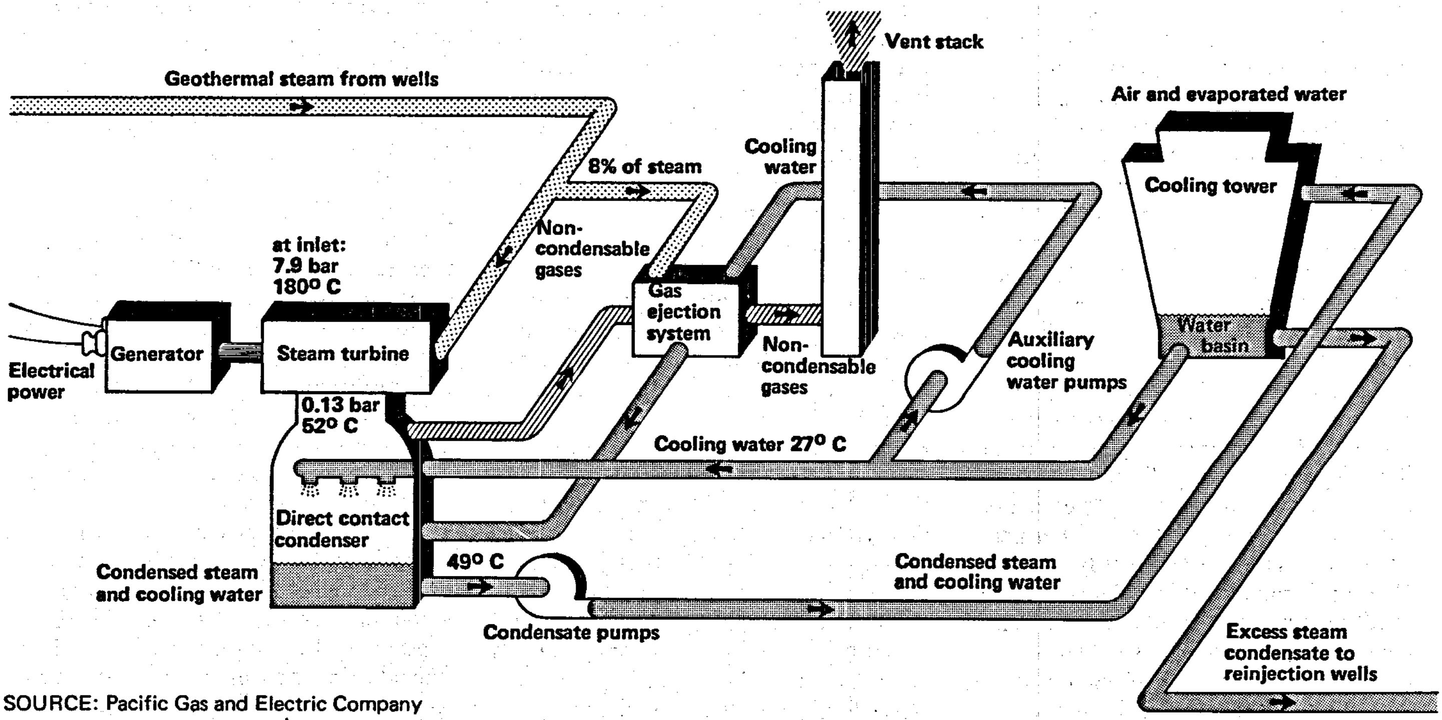
A portion of the gas, including about two-thirds of the total hydrogen sulfide, is dissolved in the condensed geothermal fluid, circulated to the cooling tower, and then released to the atmosphere, along with the evaporated water. [56] A small amount of the hydrogen sulfide (less than 10 percent of the total) is naturally oxidized to elemental sulfur and sulfates in the cooling tower and is reinjected to the subsurface reservoir along with the excess condensed water (Figure 23). [57]

Concentrations of hydrogen sulfide as high as 0.87 ppm have been recorded in the ambient air at a sampling station located close to a cooling tower near The Geysers; the average of 44 measurements taken was 0.126 ppm. Of 1,218 measurements taken at 37 sampling stations in the area, 84 percent recorded hydrogen sulfide levels lower than the California standard of 0.03 ppm. [58] However, residents in the area have complained about the noxious odor produced by the emissions. Systematic air quality sampling and statistical analysis to determine average ambient levels of hydrogen sulfide are currently being conducted, and PG&E is currently undertaking an extensive program which should significantly reduce emissions of this gas within the near future.

At The Geysers, emissions of gases other than hydrogen sulfide are generally low enough so that they neither constitute a significant problem nor

Figure 23

Typical System Cycle of Units 5 to 10 at Pacific Gas and Electric Company's Geysers Power Plant



SOURCE: Pacific Gas and Electric Company violate state and federal standards. For example, California Department of Health standards require that radon concentrations in uncontrolled areas be less than 3 picocuries [a quantity equivalent to 2.04×10^{-20} kilograms per liter (1.273×10^{-18} lb/cubic foot)]; measurements show that the standards are not exceeded in areas of normal human access. [59] Sampling to determine emission levels in mercury and other heavy metals, and their concentrations in air, water, soils, and vegetation, is also currently being conducted at The Geysers, Cerro Prieto, and the Imperial Valley.

Table 12 compares the total air pollution emissions that would be generated by a 1,000 MWe geothermal plant located at The Geysers with air pollution emissions from fossil-fuel and nuclear power plants.* The comparison shows that geothermal power plants are not necessarily "cleaner" than fossil fuel plants. Furthermore, the odor of hydrogen sulfide emitted by geothermal power plants creates a nuisance that does not occur with the sulfur dioxides and sulfates emitted by fossil fuel plants. Experience at The Geysers indicates that it is technically feasible to reduce hydrogen sulfide emissions during power plant operation by as much as 90 percent. The use of such controls is assumed in Figure 24.

* The relative significance of each of these sources can be assessed in terms of the total weight of polluting substances released. Calculations of this weight are based on the average steam flow for each source, size of the power plant, period of operation, and concentration of noncondensable gases in the steam.

Hot-Water Systems

As previously noted, geothermal steam derived from hot-water systems may contain either more or fewer air pollutants than does steam from vapor-dominated systems. The likely emissions resulting from development of a new hot-water system can only be estimated based on (1) detailed, site-specific analyses of the chemistry of its geothermal fluid, (2) monitoring of emissions and ambient air quality.

During well drilling and production testing, steam flashed from geothermal hot waters may represent 20-25 percent of the total fluid, depending on its temperature. For comparable levels of electricity generated, the total quantity of steam released to the atmosphere during these phases is probably comparable to that emitted at The Geysers. The resulting air pollution is strictly a function of the amount of noncondensable gases in the steam. Since the hot-water wells can in some fields be "capped" or completely shut off after production testing, well "bleeding" prior to power plant operation may not represent a source of air pollution. [60]

During operation of a flash-turbine power plant—the system currently used at both Cerro Prieto, Mexico, and Wairakei, New Zealand—noncondensable gases are vented to the atmosphere; thus, air pollution control techniques similar to those at The Geysers should be applicable. In the binary-fluid type of generating unit, the geothermal hot waters would be reinjected directly to the production reservoir following use and no air pollution emissions would occur. However, binary-fluid systems are still experimental.

At Wairakei, New Zealand, geothermal steam is relatively "clean"; it contains only about one-fifth as much hydrogen sulfide as steam at The Geysers. This 145 MWe plant discharges about 14 kg/hr (30.8 lb/hr) of hydrogen sulfide to the atmosphere at concentrations of about 5,000 ppm in the stack gas. About five times this amount is transferred to the plant's cooling water and discharged into a nearby river. [61] In contrast, geothermal steam at Cerro Prieto, Mexico, contains substantially more hydrogen sulfide; emissions of this gas from a 37.5 MWe unit have been measured at 355 kg/hr (780 lb/hr). [62] Figure 24 shows the expected annual hydrogen sulfide emissions from a hypothetical 1,000 MWe power plant at both those locations and at The Geysers.

Preliminary estimates indicate that steam from the geothermal fluids of the Imperial Valley will also contain large amounts of hydrogen sulfide. [63] At the experimental 10 MWe generating unit at Niland, flashed steam will be "scrubbed" to remove the polluting gas. However, available data are insufficient to assess accurately the total quantities of hydrogen sulfide and other air pollutants that would be emitted from a geothermal power plant in this area. Current research and monitoring at this and other potential geothermal development sites should soon provide better answers to this important question.

Table 12
Air Emissions of Alternative Electrical Generating Processes, 1000 MWe Plant
(metric tons/year)

Process	SO_x	NO_x	CO_2	CO	Hydro-carbons	NH_3	H_2S	Particulates
Nuclear (light-water reactor)	50	42	0			8		
Coal	54,000	38,000	n/a	2,000	600			23,000
Residual fuel oil	37,000	25,000	n/a	700	470			150
[a]	20,000	18,000	n/a	4,300	20,000	2,000		
Natural gas	20	20,000	n/a	neg.	34			5
	900	267	n/a	20	11			
Low Btu synthetic natural gas	5,600	13,000	n/a	neg.	neg.			n/a
(from coal)	1,600		n/a	550	5		12	5,000
Geothermal (The Geysers)	0	0	250,000	0	15,000	15,000	1,700 [b]	0
[c]	0	0		0				0

NOTE: The first row under each process defines emissions during power plant operation; second rows define emissions during other steps (mining, transportation, etc.).

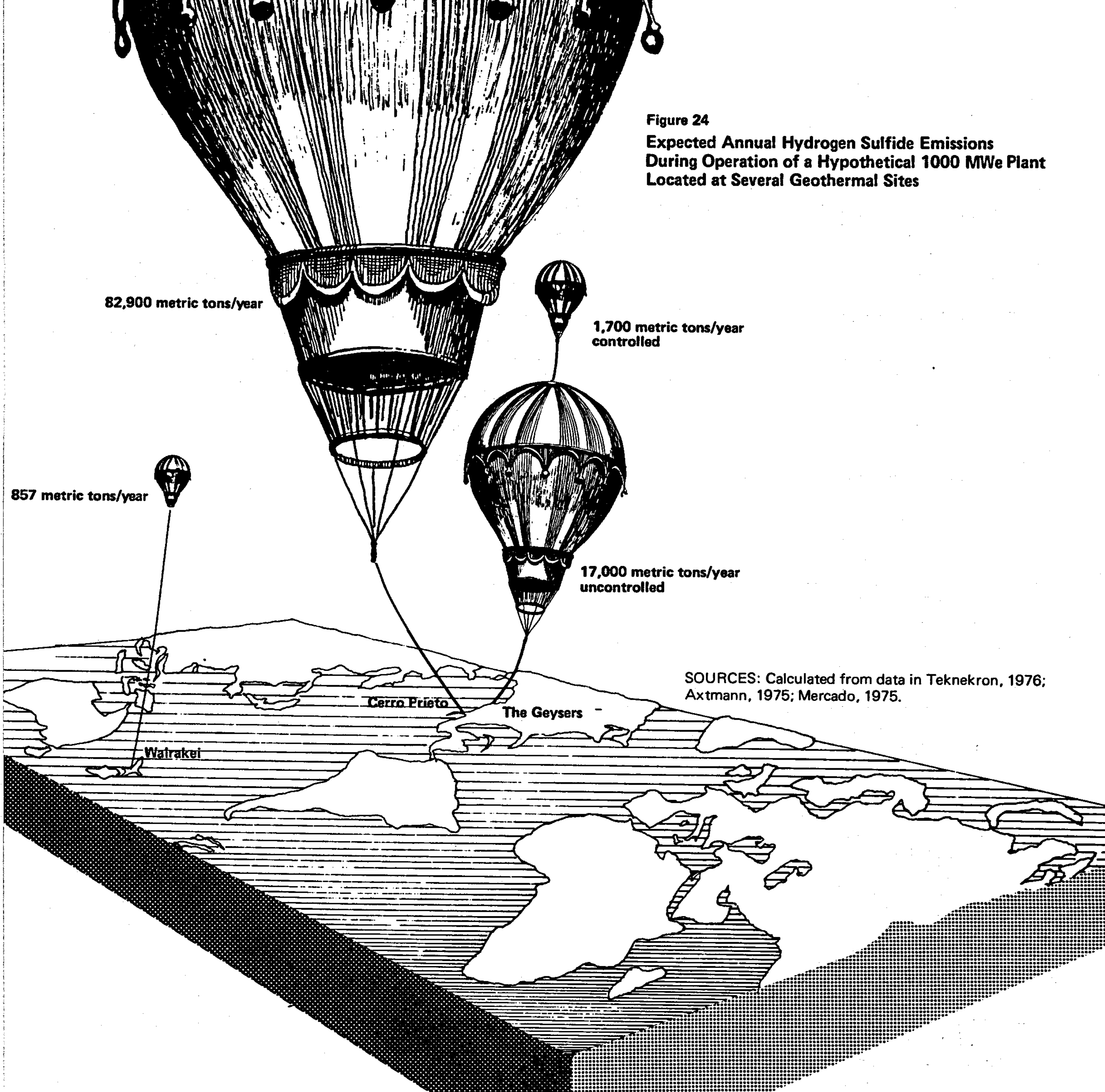
SOURCE: Teknekron, Inc., 1975.

neg.—negligible
n/a—not available

[a] Emissions from a hypothetical 500,000 bbl/day refinery which produces 34,000 bbl/day residual fuel oil to supply a 1000 MW power plant.
[b] Assuming 90 percent reduction of uncontrolled hydrogen sulfide emissions due to use of hydrogen sulfide abatement equipment (uncontrolled emissions are 17,000 metric tons/year).
[c] See Table 11 for total pollutant emissions from wells prior to power plant operation.

Figure 24

Expected Annual Hydrogen Sulfide Emissions During Operation of a Hypothetical 1000 MWe Plant Located at Several Geothermal Sites



SOURCES: Calculated from data in Teknekron, 1976; Axtmann, 1975; Mercado, 1975.

Research Needs

The air pollution problems currently receiving the greatest attention are those related to hydrogen sulfide emissions. ERDA, the Pacific Gas and Electric Company, and other public and private organizations are examining various ways to control hydrogen sulfide during power plant operation. Most of these approaches focus on treating hydrogen sulfide after it reaches the turbine in the power plant and do not provide for pollution abatement during periods when the plant is shut down for maintenance or repairs. Increased emphasis should be placed on controlling hydrogen sulfide before it reaches the turbine; not only would this control pollution at all times, but it could improve the operating efficiency of the plant as rock, dust, and other foreign particles are removed from the geothermal steam.

While hydrogen sulfide is known to be harmful at high concentrations, little is known about the possible health effects of long-term exposure to low concentrations. As these effects could include irritation of the respiratory system and interference with the transport of oxygen in the human body, they should be thoroughly investigated. Research should also be conducted into the time required for hydrogen sulfide to oxidize to sulfates and sulfuric acid under varying topographic and climatic conditions.

The development of control technologies for other air pollutants, such as arsenic, ammonia, mercury, and radon, will be important if the modeling and monitoring efforts currently under way show that these compounds would be released in significant quantities at geothermal development sites. For example, researchers in New Zealand are currently experimenting with removing silica and arsenic from geothermal waste-waters by adding slaked lime to precipitate calcium silicate. The applicability of such techniques in the United States should be investigated.

Increasingly precise and systematic techniques must be developed to monitor air pollution in geothermal development areas. Sophisticated chemical and radio-chemical sampling methods must be developed, for example, to determine the concentrations of all harmful substances at a site and to distinguish between the effects of naturally-occurring and development-related pollutant discharges. EPA recently sponsored technical conferences to evaluate ongoing research on geothermal sampling techniques.

Removal of harmful air pollutants from the gases discharged at a geothermal facility may create solid waste disposal problems. The ideal solution is the development of an economically feasible technology to recover waste materials in usable form. To encourage this solution, high priority should be assigned to the development of hybrid geothermal facilities that combine chemical production and power generation.

Control Of Hydrogen Sulfide At The Geysers

In recent years, concern about the effects of hydrogen sulfide emissions at The Geysers has increased, based on its toxicity, noxious odor, and relatively high concentrations; and air pollution control technology has been directed primarily at lowering these emissions.

The California Air Resources Board standard for hydrogen sulfide is its odor threshold—0.03 ppm for ambient air. Since the "rotten egg" odor of hydrogen sulfide is noticeable in the vicinity of The Geysers, the State Air Resources Board and the Northern Sonoma County Air Pollution Control District have been issuing temporary variances for the hydrogen sulfide emissions from the power plants.

PG&E has conducted extensive research and testing to develop an effective program to control hydrogen sulfide emissions at The Geysers. A variety of methods for control have been tested. The current abatement program planned for the 11 existing generating units will install a ducting system on all existing units that transfers the gases emitted from the jet gas ejectors to the cooling tower. An iron catalyst will be added to the cooling waters to promote oxidation of the hydrogen sulfide to elemental sulfur. The solid elemental sulfur thus remains in the cooling water, and is ultimately removed from the excess condensate reinjected through the use of sand filters. However, in tests the iron catalyst has caused corrosion; and while this method is capable of reducing hydrogen sulfide emissions to 10 percent of their original levels, it does not reduce other gaseous emissions.

New units built at The Geysers will use an improved system. Noncondensable gases from the jet gas ejector will be transferred directly to a sulfur removal unit ("Stetford plant"), which will reduce hydrogen sulfide emissions slightly more (up to 98 percent). Both processes planned for use at The Geysers generate large quantities of elemental sulfur, which must be disposed of at an approved solid waste disposal site.

These control systems treat gases after they reach the turbine. If the turbine is shut down, the hydrogen sulfide-laden steam is vented directly to the atmosphere. Because 24 hours are required to shut down a well and additional time required to reopen and clear out pebbles and rocks that can be picked up by the steam and damage the turbine, it is impractical to shut down the well when the turbine is shut off.

Treating steam before it reaches the turbine may prove feasible, and would permit control during shutdown. ERDA-sponsored laboratory studies are presently exploring the possibility of using regenerable copper sulfate to convert the hydrogen sulfide in geothermal steam to copper sulfide and sulfuric acid.

9. Thermal Pollution and Climate

Geothermal development can also have a variety of thermal and climatic effects. The most serious are caused by the release to the atmosphere of waste heat, water vapor, and carbon dioxide from geothermal wells, steam lines, and power plants.

Geothermal power plants emit larger amounts of waste heat than do fossil fuel or nuclear power plants because of their lower "thermal efficiency"; that is, less of the total heat energy contained in the geothermal fluid is converted to electrical energy. For example, a typical generating unit at The Geysers utilizes about 785 MWe of input energy to produce 110 MWe of electrical output, for a "primary efficiency" of 14 percent. At the Wairakei plant in New Zealand, the primary efficiency is approximately 8 percent. In comparison, fossil fuel and nuclear power plants have primary efficiencies ranging from 32 to 42 percent, thereby producing markedly less waste heat (see Table 13).

Waste heat and water can be discharged either to the atmosphere or to water. In terms of environmental impacts, an important tradeoff is involved: while the discharge of waste heat and water vapor to the atmosphere can have negative climatic effects, discharge to bodies of water can have harmful biological effects. Since water quality effects are commonly considered the more harmful, the trend in power plant construction has been toward atmospheric discharge with the use of cooling towers.

Cooling tower designs for any type of power plant, including a geothermal, are

Table 13
Expected Waste Heat Emissions During Power Plant Operation for Alternative Electrical Generating Processes, 1000 MWe Plant (kilowatt-hours/year)

Process	Total Waste Heat ($\times 10^{10}$)
Nuclear (light-water reactor)	1.86
Coal	1.2
Residual fuel oil	1.2
Natural gas	1.2
Low Btu synthetic natural gas (from coal)	1.2
Geothermal: The Geysers	4.5[a]
Wairakei	9.7[b]

SOURCES: Teknekron, Inc., 1975; Axtmann, R.C., 1975.

a. Discharged to air.
b. 4.3×10^{10} is discharged to air. 5.4×10^{10} is discharged to water.

of two basic types: the conventional "wet" or evaporative cooling tower, and the dry cooling tower. In the former, the steam from the turbine enters a condenser, where it is re-converted to water. The steam heat is transferred to circulating water, and the warm water then transferred to the wet cooling tower, where it is brought into contact with a flow of air, which causes evaporation. Since the cooling water is lost through evaporation, the supply must be replenished continuously.

In a dry cooling tower, the water circulates in a closed system. It is cooled by a flow of air created by either mechanical or natural draft, as in an automobile radiator. Only the heat is transferred to the atmosphere. Since water is not lost through evaporation, a dry cooling tower does not require a continuous source of cooling water; consequently it may be more desirable environmentally than a wet cooling tower in localities having limited water supplies (see Chapter 6).

Dry cooling towers are significantly more expensive than wet, and may reduce the operating efficiency of the power plant as well. This is why only wet cooling towers have been constructed for large power plants to date. Their effects at fossil-fueled power plants have included a slight heating of the atmosphere in the vicinity, increased humidity, and occasional fogging. These impacts are generally considered to be minor and local in scope.

At The Geysers, about 80 percent of the geothermal steam is discharged from wet cooling towers as water vapor containing waste heat; the remainder is reinjected to the steam reservoir. The result is a slight heating of the atmosphere in the vicinity, increased humidity, and occasional fogging. A greater incidence of plant disease resulting from higher humidity has been noted in some nearby areas. Some vegetation has also been "scalded" by direct releases of steam from wells and steam lines.

At Wairakei, a liquid-dominated field, the water of a nearby river is used for cooling the geothermal hot waters (a once-through cooling system). The wastewaters remaining after steam separation are also discharged to the river. About half of the total waste heat remains in the river; the other half enters the atmosphere along with the water vapor. This method has resulted in a heating of the river and extensive ground level fogging near the plant. [*64*] It is thus unlikely that this system would be used at new geothermal power plants.

In general, the climatic effects associated with existing geothermal and conventional power plants using cooling towers are considered to be relatively insignificant in comparison with other environmental impacts. However, their significance will increase as larger plants are built. Moreover, if a geothermal resource is located in an area whose topography and local meteorological conditions limit adequate atmospheric dispersal of heat and moisture, the problem of local weather modification could be significant. Preliminary analyses of the potential for weather modification resulting from geothermal development in Lake County, California (adjacent to The Geysers) indicate that ten 55-MWe generating units utilizing wet cooling towers could increase the moisture content in a small closed basin by almost 50 percent, probably leading to some increase in fog and icing. [65]

Larger-scale climatic effects are also thought to be possible from geothermal development. The emission of large quantities of hydrogen sulfide might increase the acidity of rainfall in a region which would lead to corrosion and harmful effects on vegetation and wildlife; and the emission of carbon dioxide could trap heat in the lower atmosphere, thereby raising the earth's temperature (the so-called "greenhouse effect"). While the scale of geothermal development worldwide is unlikely to be large enough to cause such significant effects, the advantages of monitoring the climatic effects of geothermal development are clear.

Research Needs

Research into the thermal and climatic effects of geothermal development has to date been assigned relatively low priority because these effects appear to be less significant than other environmental effects. However, certain potential impacts are serious enough to warrant further investigation. In particular, changes in the acidity of rainfall should be carefully monitored throughout the regions surrounding geothermal development, and any resulting damage to aquatic species and terrestrial vegetation and wildlife assessed. The pH and sulfate levels of rainfall should be analyzed, not only near geothermal development areas but also in the surrounding region, both prior to and during geothermal development.

If extensive geothermal development is planned in areas where topography and local weather conditions limit atmospheric diffusion of the heat and moisture released from cooling towers—as it does in narrow, closed valleys—extensive, local climatic data should be collected. A data base for predicting the likely extent of weather modification should include ambient wind speed and direction, rainfall frequency, humidity, and temperature. Similarly, if the development of a particular geothermal site involves significant thermal discharges to lakes or streams, monitoring data on ambient water temperatures, flow rate, and currents should be collected.

10. Natural Biological Systems: Fish, Vegetation and Wildlife

The development of geothermal resources inevitably causes some disturbance to natural biological systems in the vicinity of a development site; primarily, land disruptions, air and water polluting emissions during well testing and power plant operation, and increased levels of noise and human activity. The extent, severity, and long-term consequences of the disturbance vary considerably from site to site, depending upon the geochemistry of the geothermal resource and the development technology employed. Conscientious application of sound management techniques and pollution controls can reduce, but not eliminate, the disturbance. Nonetheless, the disturbances to biological systems caused by geothermal development are less severe than is the development of alternative fuels that require large land areas for mining, transportation, and processing.

Types of Impact

Geothermal development may affect natural biological systems by reducing the diversity (the kinds of species in the ecosystem) or the total number of plants and animals in an area. These impacts may be of concern if the species endangered are rare or if the disturbed habitat is important to a large population. For example, extinction of the Devil's Hole Pupfish (a species believed to have existed in the West for several million years) would be regrettable because of its rarity, antiquity, and unique characteristics; but the loss would not affect any other species. On the other hand, destruction of an estuary would have far-reaching consequences for numerous species.

In addition, certain species may be valued for their beauty, for the recreational opportunity they provide, for their economic value, or for all these reasons. Snow geese, deer, and redwood trees are examples of species which may be valued for any or all of the reasons cited.

An extensive body of legislation protects certain categories of wildlife from disturbance. The most far-reaching, the *Rare and Endangered Species Act of 1973*, grants the Department of the Interior authority to prevent development in areas where threatened species of plants and animals will be adversely affected.

Little information presently is available on species existing in the areas of the West where geothermal development is likely to occur. Without adequate baseline information, maps of critical areas, and knowledge of the interrelationships of the plants and animals in the area—especially in a desert ecosystem—substantial harm can occur inadvertently. During the past fiscal year, the Fish and Wildlife Service of the Department of the Interior and the Environmental Protection Agency have embarked on several studies aimed at filling the information void. For example, FWS is working closely with the Bureau of Land Management to develop baseline information for use in government management programs. This information will also be used by the U. S. Geological Survey to conduct the federal geothermal leasing program.

Sources of Adverse Impacts

The causes of adverse biological impacts associated with geothermal development that could lead to a reduction in the diversity or population levels of species are: land disruption, erosion and sedimentation, water effluents, air pollutant emissions, noise, and human activity.

Land Disruption

The removal of earth and vegetation from an area to accommodate geothermal development can reduce habitat; kill small rodents, reptiles, or birds living on the land surface; and cause erosion. An average of 20 percent of the total land leased for geothermal activities is cleared [66] and is changed sufficiently in character to affect habitat (see Chapter 4). Of this 20 percent, approximately half is needed for permanent buildings and facilities, such as roads and power plants, which require original vegetation to be replaced with impervious surfaces. In addition, land along steam lines and immediately surrounding drilling pads, permanent buildings, and facilities may be temporarily cleared of vegetation. [67]

The clearing of a site for geothermal development usually has the following adverse effects on an area's natural biological systems: [68]

- The nutritional support for the area is altered as the physical aspects of the habitat are altered.
- Specific types of habitat (such as an "edge"*), dependent upon complex interrelationships, are severely affected.
- Lower population levels may result until the site revegetates.
- Surface soil temperature and moisture are altered.
- Erosion may be accelerated.

The recoverability of vegetation varies by species, soils, climatic conditions, and severity of disturbance. [69] In cool,

* An "edge" effect occurs when two levels of vegetation adjoin one another, as when a shrub layer abuts a grassland. An "edge" makes the environment doubly valuable. For instance, many small game species can browse on grasses and find protection in the shrubs.

moist, mountainous regions, areas dominated by grasses and shrubs recover relatively quickly; forested areas, however, require a much longer recovery time. In dry regions, where the ecosystems are fragile, the amount of time needed to restore a site is far longer. During the recovery period, however, the land is not totally sterile; some animal species can forage on germinating seedlings.

Careful plant design and road placement can avoid excessive disruption of the land surface during geothermal development. Avoidance of the "edge" and critical areas such as breeding grounds, salt licks, wetlands, and surface water bodies can help keep the immediate environment biologically productive.

Erosion and Sedimentation

Disturbance of the surface soil of an area through erosion interferes with the fertility of the soil and its ability to retain moisture. Topsoil, the most fertile part of the soil structure, is often covered over or dumped. Small root systems are turned over and soil structure is altered, causing additional erosion as the soil is loosened. Erosion lowers soil fertility and thus reduces the food available to support the surrounding environment. Soil erosion also increases sediment loads in surface waters, which, in turn, reduces the quality of streams and their capacity to support aquatic organisms. Nutrients in the soil are leached away to the streambeds, accelerating stream eutrophication.*

Sedimentation in critical parts of streams, such as spawning areas, can increase turbidity, which reduces the penetration of light in the water. This makes it difficult for fish to find food and for aquatic vegetation to grow. In addition, concentrations of mercury and other trace metals frequently found in sediments have been related to concentrations found in fish and aquatic vegetation living nearby.

The problems of erosion and the resulting sedimentation of waterways have proven to be particularly troublesome at The Geysers, because the drilling sites are located on steeply sloping hillsides which receive high rainfall. But even in this setting, the adverse effects can be greatly reduced through measures designed to control erosion, preserve the topsoil, channel any runoff into an appropriate treatment system, and quickly restore the vegetation of temporarily cleared sites.

* Eutrophication is the process by which nutrients build up quickly in a waterway, nourishing the growth of vegetation and depleting the oxygen supply needed to support fish life.

Water Effluents

Water pollutants resulting from geothermal activity—drilling muds, geothermal fluids, and heat from condensed steam—can have severe effects on aquatic animal life and vegetation if runoff or discharges enter streams. Numerous elements and compounds, particularly hydrogen sulfide, chlorine, ammonia, boron, arsenic, mercury, and such heavy metals as lead and silver, are toxic to aquatic vegetation and fish at varying concentrations. Each of these may be present in geothermal fluids or drilling muds. Most freshwater fish are also sensitive to rapid changes in pH or temperature.

Drilling muds and cuttings normally are disposed of in a sump during test drilling and production. Accidental discharges may, however, occur, and reach bodies of water. The severity of their effects depends largely upon their chemical constituency and the duration of the discharge. [*71*]

Geothermal fluids, particularly in hot-water fields, are often highly saline, contain heavy metals, and have very high temperatures (see Water Quality). In Wairakei, New Zealand, a hot-water field where reinjection techniques are not practiced, the composition of disposal in the nearby river and lake was recently analyzed. [72] High levels of arsenic, mercury, sulfur dioxide and hydrogen sulfide were found in the water, the aquatic vegetation, and the fish (e.g., mercury compounds at levels toxic to humans, 0.5 mg/kg or 0.5 ppm, were found in trout weighing more than 1.25 kg). Two large fish kills have been noted in the nearby lake and the number of trout in the immediate area of the plant has been reduced, although they have become more abundant just upstream and downstream. Lake Aratiatia, below the Wairakei plant, has fewer phytoplankton and zooplankton species—the first links in the food chain for fish in the lake.

The development of adequate reinjection techniques for hot-water systems will help protect the environment from the adverse effects of geothermal fluids. The development of an adequate reinjection technology will be particularly significant in areas where economically valuable or sensitive fish, wildlife, or vegetation exist, such as in the tidal basins along the coast of Texas and areas of the West where fragile desert ecosystems can be disrupted easily and restored only after long periods of time, if ever.

Air Pollutant Emissions

Gaseous emissions from dry-steam fields contain a number of potentially dangerous products—including hydrogen sulfide, carbon dioxide, and trace amounts of radioactive gases (see Air Quality). Studies to measure the buildup of these emissions in vegetation, aquatic organisms, and animals are just being initiated. Recent studies of the egg and fry of rainbow trout, for example, indicate that this species is vulnerable even to very low concentrations of hydrogen sulfide (above 0.006 ppm). [73] In-stream concentrations of hydrogen sulfide at Wairakei have probably exceeded these limits; botanists have reported filamentous sulfur bacteria, which thrive only in the presence of sulfide growing in nearby lakes. Recently completed studies supported by the National Science Foundation and the Fish and Wildlife Service report previously unsuspected damage by hydrogen sulfide to coniferous trees and some types of shrubs and plants. They also report highly variable sensitivity in vegetation; the most sensitive appear to be immature plants and plants under stress from aridity. [74, 75]

Sulfur dioxide, in particular, could have especially adverse effects in humid areas, where it oxidizes to sulfur trioxide and sulfuric acid. Millions of research dollars have been spent to determine the detrimental effects of sulfur compounds in the atmosphere. Compounds have been shown to "acid rain" or "acid snow" (a reduction in the pH of precipitation), which can burn the leaves of trees and shrubs, as well as heighten the acidification of water bodies. The acidification of lakes has, in turn, been related to the widespread destruction of fish habitats. [76]

Another possible hazard results from trace amounts of radioactive elements present in geothermal emissions. While radon and other radioactive elements have been studied to determine their effects on humans and animals, the possibility of radioactive substances becoming concentrated in the fatty tissues of organisms and transmitted through the food chain as a result of geothermal development has not been investigated. The probability of such an occurrence is, however, judged to be moderate or slight. [77]

Steam emissions can also have more direct and immediate effects. Trees in The Geysers area have been scalded; birds and other wildlife that come in contact with the steam are also in danger of being burned.

The outlook for the improved control of sulfur emissions is promising. The recently developed "Stretford" process, which is to be installed at new generating units at The Geysers, is expected to remove 85 to 90 percent of the sulfur prior to release (see Air Quality). This process is expected to work on the "flashed-steam" hot-water system as well. (The binary system involves no release of pollutants.) Research projects are ongoing to determine the threshold levels of various species of fish, wildlife, and vegetation to toxic gases, acid rain, heavy metals, and steam; and to gauge the effects of long-term exposure at sublethal levels.

Noise and Human Activity

The impacts of noise on natural biological systems have not yet been researched extensively. Some studies have uncovered no evidence of effects on animals in their natural habitats at a reasonably short distance from the site. [*78*] However, other studies are being conducted to measure subtler changes, including those of behavior and physiology. [79] Of particular importance is the possibility that noise in frequency ranges inaudible to the human ear may affect animals adversely. Loud, continuous noise may also affect animals who depend on acute hearing for protection, hunting, or mating. Particularly sensitive species need to be identified. If animals were to permanently abandon their habitat as a result of noise, the ecosystem would probably be affected adversely as well.

The impacts of human activities on natural biological systems are even more difficult to measure. Intrusion may pose a severe threat to some species, but relatively little to others. Associated dangers such as fire, litter, and garbage may pose threats to foraging animals. Yet, at The Geysers, deer and other animals have been reported to graze near the drilling site and steam pipelines, where they find warmth and forage in the winter. Desert ecosystems may be threatened more severely by human intrusion than upland forests and grasslands. That possibility is one of many under study by the Fish and Wildlife Service.

Research Needs

To maintain the diversity, productivity, and stability of an ecosystem subject to intrusion from geothermal development, extensive, site-specific examinations of existing ecosystems must be conducted in potential geothermal areas prior to development. Such investigations are vital to the development of management plans for those activities that can reduce harmful effects to the biota. Among the baseline environmental information which must be collected are: [*80*]

— Identification of plant and animal species present, their distribution, and population sizes
— Determination of critical ecological characteristics, that is, characteristics of the environment that play a unique or particularly important role to a species and thus are critical to their survival
— Identification of any species present classified as "endangered" or "threatened" by the U.S. Department of the Interior or state agencies
— Life cycle characteristics
— Nutritional requirements and susceptibility to disturbances of any critical, threatened, or endangered species present.

Examination of the environment prior to development must be followed by monitoring to detect possible changes during development and subsequent operations. The early identification of impacts can prevent unnecessary and extreme harm, and the information gathered can be of potential use in other research areas.

This type of environmental information is beginning to be gathered in many areas of the West by the U. S. Fish and Wildlife Service. More widespread understanding of the importance of early study and more diligence in applying sound management practices appear to be the greatest needs in protecting natural biological systems.

Section II

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Refer to bibliography at end of book for complete citation.

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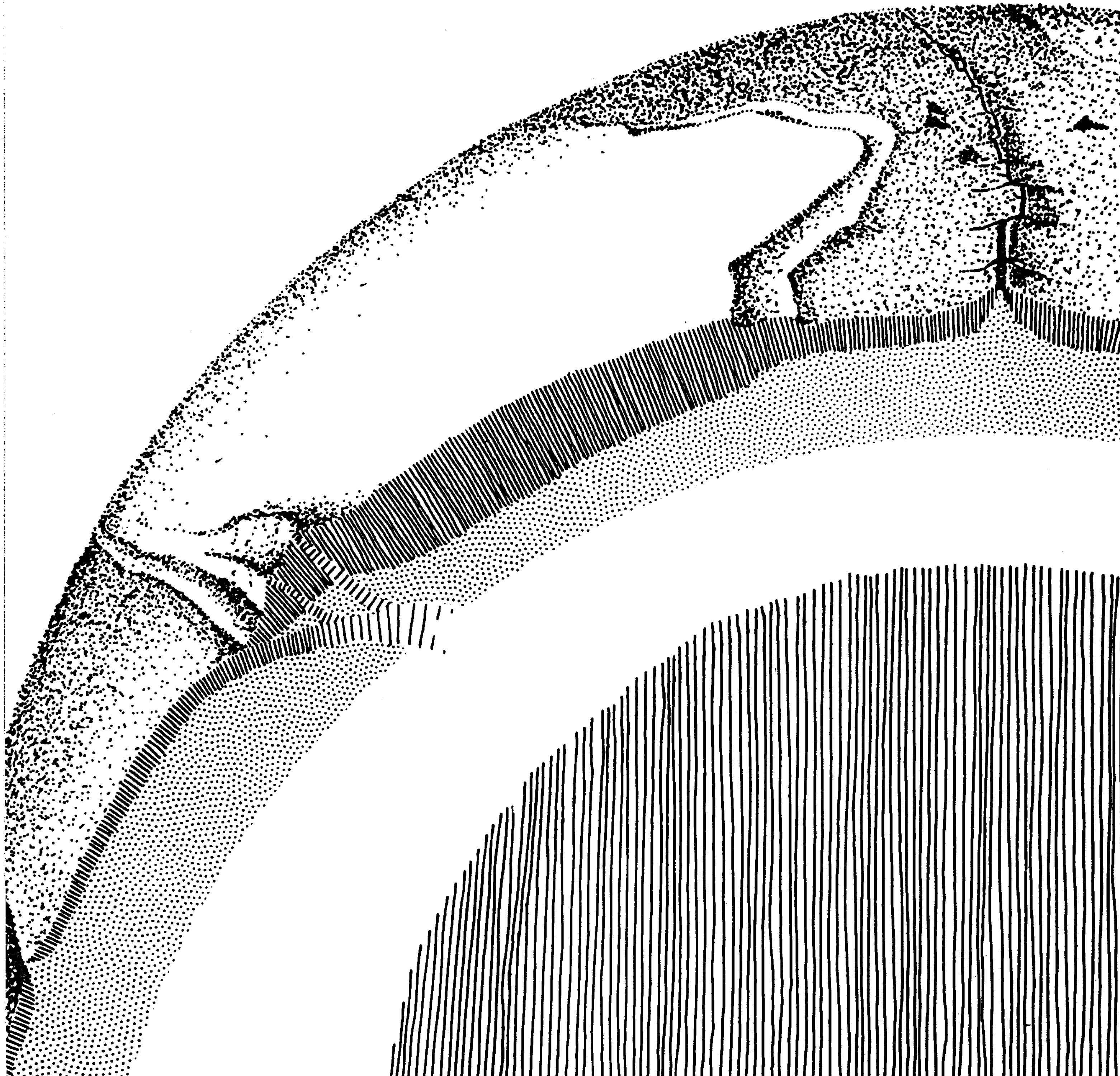

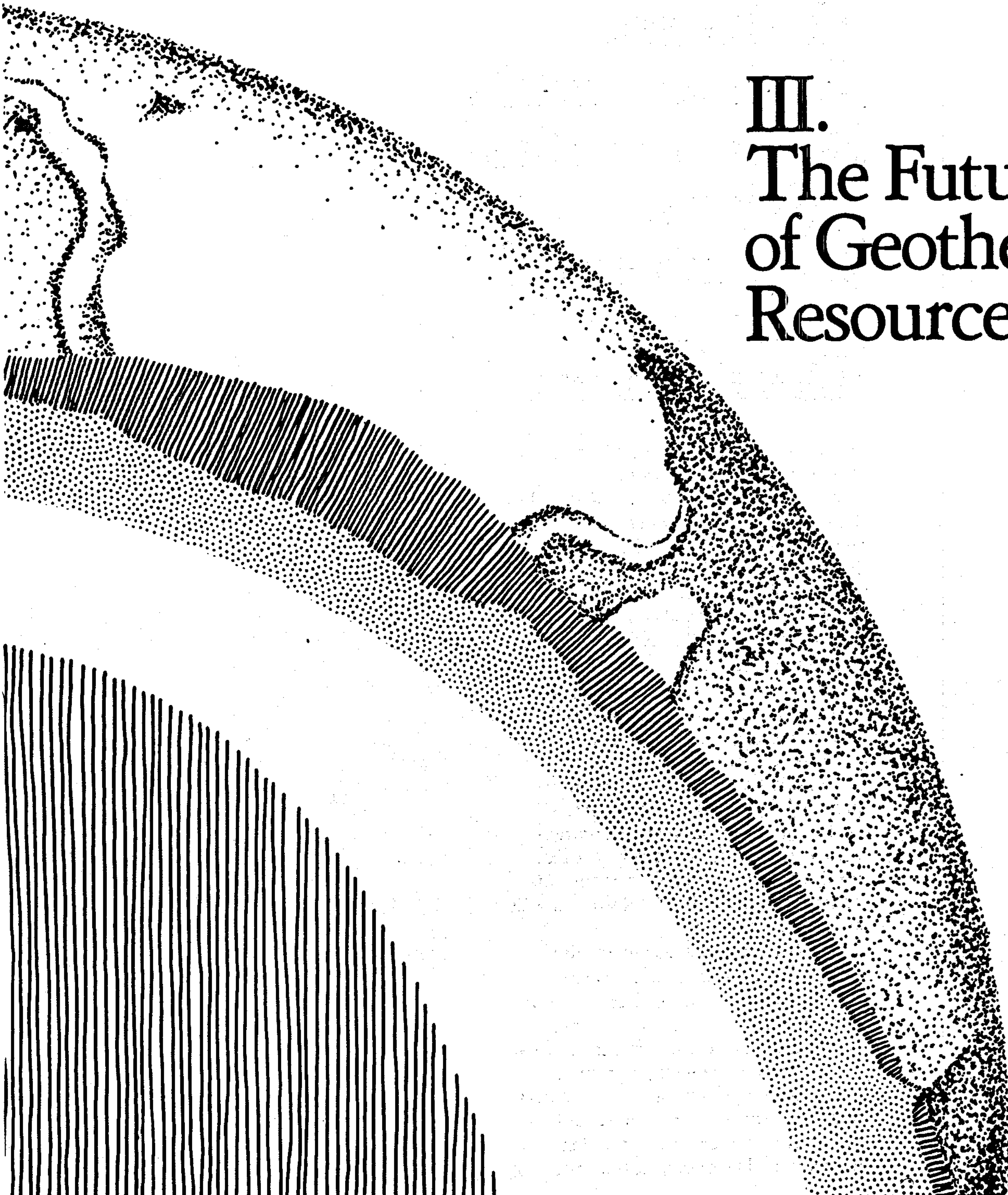

III. The Future of Geothermal Resources

11. Federal Environmental R&D Activities Related To Geothermal Resource Development

Over the past two years, funding for environmental R&D related to geothermal resources has doubled, as has funding for the development of geothermal technology. Much of this increase has been directed to research programs that address the environmental effects of hydrothermal convection systems, which are believed to offer the most rapid development potential. Table 14 offers current estimates of federal expenditures for environmental R&D. Research on geothermal technology and resource assessment, although not specifically performed with "environmental" R&D funds, also generates significant information about environmental effects. Unfortunately, the data needed to calculate a dollar amount that accurately reflects this "hidden" subsidy are not available.

In 1974, Congress designated the Energy Research and Development Administration as the lead agency in the development of geothermal resources. Under ERDA's coordination, the federal geothermal development program has been organized into seven areas: environmental control and institutional studies, resource assessment and exploration, hydrothermal technology, demonstration projects, advanced technology applications, engineering research and development, and resource development funding. R&D specifically focused on *environmental* activities related to geothermal development is now being undertaken by ERDA and the Environmental Protection Agency (EPA), the National Science Foundation (NSF),* and several divisions of the Department of the Interior, particularly the Fish and Wildlife Service (FWS). In addition, a Federal Interagency Energy/Environment R&D Program that coordinates large-scale R&D activities contributes to geothermal research. The following sections describe the activities of these agencies.

Table 14
Federal Environmental R&D Budgets for Specially Focused Geothermal-related Research
($000)

	1975	1976[a]	1977[b]
National Science Foundation	1,500	600	0[c]
Environmental Protection Agency[d]	340	365	636
Energy Research & Development Administration	0[e]	2,000	2,300
Fish and Wildlife Service	300	300	1,500
Total	2,140	3,265	4,436

SOURCE: Information for the budget figures was obtained through personal communication with senior officials in the agencies listed.

a. *Includes Transitional Quarter funds.*
b. Budget requested for 1977 fiscal year.
c. NSF is phasing out all focused geothermal environmental R&D, as ERDA takes on full responsibility.
d. The annual budgets for the Interagency Energy/Environment R&D Program for 1975 and 1976 were $134 and $100 million, respectively. However, since an insignificant fraction of these amounts was specificially directed to geothermal R&D, it has not been included in these calculations. The numbers for the other agencies include any funds from the EPA "pass-through" that are being used for geothermal research.
e. *ERDA did not begin funding this activity until its first full year in operation.*

Energy Research and Development Administration

The bulk of ERDA's environmental-related geothermal R&D is being funded by its Division of Biomedical and Environmental Research. The largest single current program is being conducted in the Imperial Valley of California by ERDA's Lawrence Livermore Laboratory. Valley-wide assessments are being made of potential subsidence and seismic problems associated with the development of large-scale hot-water systems.

ERDA is testing the air, water, vegetation, and wildlife impacts of emissions and effluents from geothermal conversion plants at San Diego Gas and Electric Company's experimental facility. ERDA is also studying the environmental

* In January 1975, NSF transferred nearly all its solar and geothermal energy research to ERDA; only some NSF-RANN projects remain in specialized areas.

and socioeconomic impacts of The Geysers plants in California. Preliminary studies on the effects of developing hot dry rock formations in the Jemez Mountains of New Mexico are being conducted at the Los Alamos Scientific Laboratory.

Through its work on new energy technologies, ERDA's Division of Geothermal Energy is also involved in environmental research. It has defined two specific goals for fiscal years 1976 and 1977: (1) development of baseline information to determine the need for environmental impact assessments, and (2) development of effective controls for hydrogen sulfide emissions. Monitoring guidelines and facility siting methodologies are planned for development in fiscal year 1978.

Environmental Protection Agency

To date, EPA's role in the federal geothermal R&D program has involved research on the air, water, noise, and health effects of geothermal development. Several major research projects currently are under way.

EPA's Las Vegas Laboratory is monitoring heavy metals and other air emissions and water quality effects resulting from the operation of experimental facilities at five sites in the west: The Geysers and Imperial Valley, California; Klamath Falls, Oregon; Rio Grande Rift, New Mexico; and Roosevelt Hot Springs, Utah. Plant and soil uptake of emissions from geothermal power plants is being analyzed by fixed and mobile stations. The effects on groundwater of accidental or planned disposal methods are also being studied.

EPA's Industrial Environmental Research Laboratory (IERL) is surveying the environmental regulations pertaining to geothermal development, analyzing the pollution hazards associated with geothermal power, and investigating the need for better control technologies.

National Science Foundation

The NSF's program focuses on a few specific problems. Several projects presently are being conducted on the environmental effects of the extraction and disposal of geothermal fluids, including the potential for subsidence. In this connection, NSF is experimenting with a technique to trace geothermal effluents in surface bodies by developing a "fingerprint" of the geothermal fluid.

In another study, NSF has been investigating the effects on birds and animals of the noise generated by geothermal power plants and interference with flight caused by transmission lines. The overall environmental effects of geothermal energy production are being examined in an effort to identify other research needs.

Fish and Wildlife Service

As part of its work to establish a five-year R&D priority plan, the Fish and Wildlife Service of the Department of the Interior is currently compiling information on the potential effects of geothermal development on natural biological systems. FWS is also working at the five western sites where groundwater is being monitored by EPA to determine its effect on the fish and wildlife in those areas. Their study aims to develop techniques for predicting the probable effects of geothermal energy development on fish and wildlife.

In response to increasing interest in developing the geopressured reservoirs of the Texas Gulf Coast, FWS has undertaken a research project to identify the possible environmental consequences to the area. As part of this work, the FWS is compiling an inventory of the area's ecological system.

12. Legal, Institutional and Economic Constraints To Geothermal Resource Development

Despite the existence of several promising hydrothermal systems with temperatures in the range practical for electrical generation, their commercial utilization has been slow to develop. In addition to the lack of resource information, unsophisticated technologies, and environmental difficulties, several legal, institutional, and economic constraints seem to be impeding more rapid growth.

Legal Constraints

The lack of a consistent, generally accepted definition of geothermal energy has led to widely varied interpretations of laws governing ownership, regulation, and taxation. Examples of some significant complications include:

Ownership. A recent California Superior Court decision (*Geothermal Kinetics, Inc. v. Union Oil of California, et al.*) defined geothermal resources as "minerals," rather than "water," based on the fact that the superheated steam withdrawn was not used as water has traditionally been used (that is, for agricultural purposes and as a water supply), but as an energy source. The court found that Geothermal Kinetics, which had purchased the mineral rights of 408 acres known as The Geysers, "owned and was entitled to the possession and control of all the geothermal steam and power and geothermal resources in and under the subject property." The owner of the surface rights, and also the water rights (Union Oil of California), thus had no claim to the steam from the geothermal reservoir underlying the land.

Regulation. Depending on the accepted definition of geothermal energy, the owner of a geothermal field may be subject to a variety of regulations that affect development decisions. If geothermal energy is classified as a "mineral," the owner must comply with a complex set of mining regulations; if it is classified as "water," the owner must comply with complicated local, state, and federal water control and use laws.

In response to water supply problems, many western states have enacted legislation that prohibits the diversion of water for uses outside the state without the state legislature's authorization. Whether or not these statutes are applicable to developers of electricity produced from geothermal resources defined as "water" is an issue yet to be resolved.

Taxation. In a 1972 case, *Reich v. Commissioner of Internal Revenue*, the court held that a geothermal resource that was primarily steam was classified as a "gas" within the meaning of the IRS code. Developers of the resource were therefore eligible to take depletion allowances and write off intangible drilling costs on their tax returns. Such tax benefits do not accrue to the developers of water resources.

Institutional Constraints

The current overlap in administrative and regulatory procedures among local, state, and federal agencies significantly impedes geothermal development. The problem of overlapping authority is greatest in issuing licenses and permits and approving environmental impact assessments.

The administrative problems associated with geothermal development begin with the leasing conducted under the Geothermal Leasing Program. The procedure by which lands are designated as Known Geothermal Resource Areas (KGRA) is impeded by inconsistent criteria and inadequate resource information. And while competitive bids are not required to lease lands *not* designated as KGRAs, the Federal Geothermal Leasing Act permits the reclassification of land as a KGRA if two or more lease applications in a locality overlap by 50 percent or more. The reclassified lands must then be reopened to the public on a "lease sale" or competitive bid basis. This procedure often delays the exploration and development of geothermal resources.

Once a tract of land has been leased, a lengthy and complicated procedure is required to obtain the necessary licenses and permits to initiate and conduct geothermal exploration, field development, and construction. While most of this procedure occurs locally, state and federal land use commissions, environmental agencies, and other regulatory bodies are involved to some extent. In Imperial County, California, for example, more than 40 steps extending over a long time period must be taken to obtain the needed permits and approvals for the commercial development of geothermal resources.

Once the geothermal field is developed sufficiently to produce electricity, other regulatory agencies become involved. Permits must be granted by the Federal Power Commission and comparable state and local agencies, and proposed rate structures reviewed by public utility commissions.

Economic Constraints

Substantial costs are involved in the development and production of geothermal resources, primarily (1) the high capital costs per installed power unit, and (2) operational costs per unit of energy produced. Capital costs include investments for exploration, drilling, and completion of wells; steam gathering lines; waste disposal systems; power plants and transmission lines (electric applications); distribution systems (nonelectric applications); and environmental control equipment. Operational costs include operating and maintaining the facilities. Actual costs usually depend on the specific characteristics of the reservoir, the size of the installed power plants, and the applicable taxes.

Given the limited information about the basic characteristics of geothermal resources—including their location, magnitude, lifetimes, distribution, geochemical characteristics, and energy potential—their development is regarded to be a high-risk, long-term investment. A geothermal reservoir capable of supporting 200 MW of electrical generating capacity is considered to be the smallest development economically viable. Uncertainty about the costs involved in the discovery of a reservoir of even this minimal capacity is reflected in the developers' widely varying estimates, which range from $3 million to $13.5 million. Once a site of sufficient potential has been located, expenditures of $11 to $15 million are required for drilling (roughly two to three times the cost per well of drilling for petroleum). Southern California Edison estimates a total development cost of $700 to $800 per kilowatt of capacity, bringing the total cost for a 200 MW plant to between $140 and $160 million.

This large investment may be increased by economic constraints external to geothermal development and by production factors, the most serious of which are generally believed to be:

- The uncertain exploration costs involved in the replacement of wells
- The time lag between investment in geothermal energy development and the realization of a return
- Uncertainty about cost-competitiveness of hot-water versus fossil-fuel systems.

Furthermore, developers believe the incentives offered for development of geothermal energy are fewer than those offered for the development of other energy resources. Taxation policies and depletion allowances are most often cited.

Several federal programs have been established to stimulate private investment in geothermal development. Perhaps the most significant is the Geothermal Loan Guaranty Program,* which provides guarantees against loss of principal and accrued interest on loans made for the following purposes:

- Determination and evaluation of the commercial potential of geothermal resources
- Research and development relating to extraction and utilization technologies
- Acquisition of rights in geothermal resources
- Development, construction, and operation of equipment or facilities for the demonstration or commercial production of energy for electricity or space heating, for example.

The limit on guarantees is $25 million for single projects and $50 million for single borrowers, subject to certain performance and environmental criteria.

Investment in geothermal energy development could be encouraged further through a number of financial mechanisms, including tax incentives, depletion allowances, favorable rent and royalty provisions for the leasing of land, write-offs of intangible drilling costs or dry holes, and cost-sharing for pilot and demonstration programs. The feasibility of these alternatives is presently being investigated by the federal government.

* Authorized under Title II of the Geothermal Energy Research, Development and Demonstration Act of 1974 (PL 93-410).

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