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UNITED STATES MINERAL RESOURCES

GEOTHERMAL RESOURCES

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TABLE

ABSTRACT OF CONCLUSIONS

The geothermal resource base is defined as all the heat above 15°C in the earth's crust, but only a small part of this resource base can properly be considered as a resource. The magnitude of the geothermal resource depends on the evaluation of many physical, technological, economic, environmental, and governmental factors. The physical factors that control the distribution of heat at depth can be evaluated, at least rudely. More tenuous are the assumptions of technology, economics, and governmental policy. These assumptions are critical to geothermal resource estimation, and differences among them are in great part responsible for the vast range in magnitude among different geothermal resource estimates.

Utilization of a greater proportion of the geothermal resource base depends on achieving one or more of the following items:

1. Technological advances that would allow electrical generation from low-temperature reservoirs.
2. Breakthroughs in drilling technology that would permit low-cost drilling of holes to depths greater than 3 km.
3. Development of techniques of artificial stimulation that would increase the productivity of geothermal reservoirs.
4. Expansion of the use of low-grade geothermal resources for such purposes as space heating, product processing, agriculture, and desalination.

INTRODUCTION

Geothermal energy, in the broadest sense, is the natural heat of the earth. Temperatures in the earth rise with increasing depth. At the base of the continental crust (25–50 km), temperatures range from 200°C to 1,000°C (Lachenbruch, 1970); at the center of the earth (6,371 km), they range perhaps from 3,500°C to 4,500°C. Most of the earth's heat is far too deeply buried ever to be tapped by man. Although drilling has reached 7½ km and may some day reach 15–20 km, the depths from which heat might be extracted profitably are unlikely to be greater than 10 km. Even in this outer 10 km, most of the geothermal heat is far too diffuse ever to be recovered economically (White, 1965). Consequently, most of the heat within the earth, even at depths of less than 10 km, cannot be considered an energy resource.

Geothermal energy, however, does have potential economic significance where heat is concentrated into restricted volumes in a manner analogous to the concentration of valuable metals into ore deposits or of oil into commercial petroleum reservoirs. At present, economically significant concentrations of geothermal energy occur where elevated temperatures are found in permeable rocks at depths less than 3 km. The thermal energy is stored both in the solid rock and in water and steam that fill pores and fractures. This water and steam serve to transfer the heat from the rock to a well and thence to the ground surface. Under present technology, rocks with too few pores, or with pores that are not connected, do not constitute an economic geothermal reservoir, however hot the rocks may be.

Water in a geothermal system also serves as the medium by which heat is transferred from a deep igneous source to a shallow geothermal reservoir at depths shallow enough to be tapped by drill holes. Geothermal reservoirs are located in the upflowing parts of major water convection systems. Cool rainwater percolates underground from areas that may consist of tens to thousands of square kilometers. At depths of 2–6 km, the water is heated by contact with hot rocks (in turn probably in contact with molten rock). The water expands upon heating and then moves buoyantly upward in a column of relatively restricted cross-sectional area (1–50 km²). The driving force of these large circulation systems is gravity, effective because of the density differen between cold downward-moving recharge water a hot, upward-moving geothermal water.

EXPLOITATION

The primary use of geothermal resource to da is for the generation of electricity (fig. 27). Und existing technology, geothermal steam (after sep ration of any associated water) is expanded into low-pressure (5–7 bar) turbine which drives a co ventional electrical generator. Geothermal heat also used directly (table 49) in the heating and a conditioning of buildings, in the heating of h houses and soil for agricultural purposes, and product processing. In addition, warm waters fro springs and wells are widely used for bathing, re reational, and therapeutic purposes, particularly central Europe and in Japan (Komagata and othe

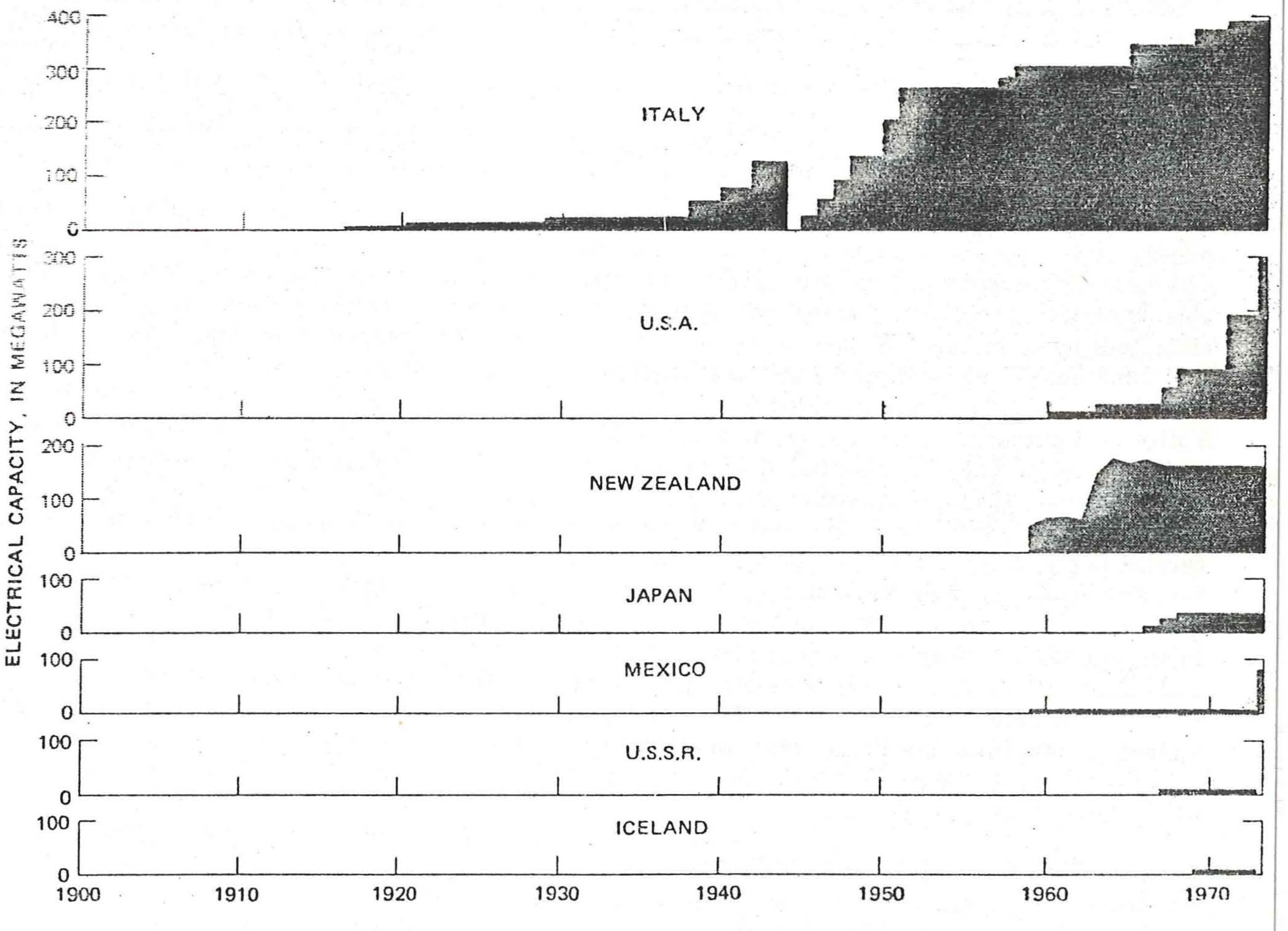

FIGURE 27.—Growth of geothermal generating capacity by countries 1900–72. Sources—Italy: [Italy] ENEL, [1970]. U.S.A Bruce (1971). New Zealand: McKenzie and Smith (1968); Smith (1970). Japan: Hayashida and Ezima (in press); M (in press). Mexico: Alonso-Espinosa and others (1968). U.S.S.R.: Tikhonov and Dvorov (1970); Facca (in press). I land: Ragnars and others (1970).

Mountain Arsenal well in Colorado by Healy, Rubey, Griggs, and Raleigh (1968).

Bowen (1973) correctly pointed out that "To understand properly the impact of the production of electric power on the environment, it is necessary to evaluate more than just the power plant, whether it is geothermal, nuclear, or fossil fueled; the entire fuel cycle from mining, processing, transportation, and the disposal of spent wastes must be considered." When viewed in this light, the environmental impact of geothermal generation does indeed appear to be minor compared with fossil-fuel or nuclear generation. The environmental impact of geothermal generation is restricted to the generating site, whereas much of the environmental impact of other modes of generating takes place at other sites (mines, processing plants, disposal sites) and is commonly neglected in the evaluation of environmental impact of a power plant.

GEOLOGIC ENVIRONMENTS

Geothermal reservoirs are the "hot spots" of larger regions where the flow of heat from depth in the earth is about 1½–5 times the worldwide average of 1.5×10^{-6} calories per square centimeter per second. Such regions of high heat flow commonly are zones of young volcanism and mountain building and are localized along the margins of major crustal plates (Muffler and White, 1972, fig. 1). These margins are zones where either new material from the mantle is being added to the crust or crustal material is being dragged downward and "consumed" in the mantle. In both situations, molten rock is generated at depth and moves buoyantly upward into the crust. The resultant pods of igneous rock provide the heat that is then transferred by conduction to the convecting systems of meteoric water.

There are two major types of geothermal systems: (1) hot water (White, 1970, 1973) and (2) vapor dominated ("dry steam") (White and others, 1971; Truesdell and White, 1973; White, 1973). In a hot-water geothermal system, the fluid in the rock at depth is water alone. Steam is produced by boiling as the fluid moves up a well to the surface, and a mixture of steam and water is produced at the surface; the water must be removed from the steam before the steam is fed to a turbine. Vapor-dominated geothermal systems, on the other hand, contain both water and steam in the reservoir at depth. With decrease in pressure upon production, heat contained in the rock dries the fluids first to saturated and then to superheated steam, which can be piped directly into a turbine. Among geothermal systems discovered to date, hot-water systems are perhaps 20 times as common as vapor-dominated systems (White, 1970).

Potentially recoverable geothermal resources also occur in some regions where the normal heat flow of the earth is trapped by insulating impermeable clay beds in a rapidly subsiding geosyncline. For example, along the gulf coast of the United States, temperatures of 150°C–273°C are found at depths of 4–7 km in geopressured zones (Jones, 1970). Waters in these geopressured zones are not circulating meteoric water; they are produced by compaction and dehydration of the sediments themselves.

RESOURCES AND PROBLEMS

Estimates of the geothermal resources of the United States and of the world differ by as much as six orders of magnitude. White (1965, p. 14) stated that "existing worldwide utilization equivalent to about 1 million kw * * * probably can be increased at least 10 times [that is, to 10^4 Mw] under present economic conditions and maintained for at least 50 years." Banwell (1967, p. 155) estimated a potential heat production of 2×10^9 kg-cal/sec from geothermal energy associated with "Pacific type volcanism." At 14 percent thermal efficiency, this rate of heat production could sustain electrical generating capacity of about 10^6 Mw. Rex (1971a, p. 54) stated that he and his colleagues " * * * are estimating the western [conterminous] U.S. geothermal potential from 10^5 to 10^7 megawatts." White (1965) and Muffler and White (1972) estimated that the world geothermal resource to a depth of 3 km for electrical generation by proven techniques is approximately 2×10^{19} calories (equivalent to 58,000 Mw for 50 yr). Rex (1972a) stated that " * * * the present recoverable [geothermal] resource for the western third of the continental United States, excluding Alaska, is of the order of 10^8 megawatt-centuries. This figure could be expanded by another factor of 10 by the inclusion of the eastern two-thirds of the United States and another factor of 10 [that is, to 10^{10} megawatt-centuries] by improvements in technology." [1] John Banwell and Tsvi Meidav (oral presentation, Ann. Mtg. Am. Assoc. Adv. Sci., Philadelphia, 1971; ms. supplied by Tsvi Meidav) stated that "The geothermal energy reserves of the world are orders of magnitude greater than the total reserve of any other form of fossil energy."

The wide variance among these resource estimates reflects several factors—predominantly, the defini-

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[1] If one assumes 14 percent thermal efficiency (as in Rex, 1972b), this electricity is produced from 4.93×10^{25} cal. or approximately eight times the estimate of White (1965, p. 2) for the total heat stored under the United States to a depth of 10 km.

productivity are unlikely to be abundant. White (1965) estimated resources recoverable as electricity to 3 km to be 2 × 10^{19} calories ($=2.32\times10^{13}$ kwhr). This energy is less than one ten-millionth of the total amount of heat above 15°C in the outer 10 km of the earth (White, 1965, p. 2).

Utilization of a greater proportion of the heat stored in the outer 10 km of the earth depends on achieving one or more of the following items:

1. Technological advances that would allow electrical generation from low-temperature reservoirs.
2. Breakthroughs in drilling technology that would permit low-cost drilling of holes to depths greater than 3 km.
3. Development of techniques of artificial stimulation that would increase the productivity of geothermal reservoirs.
4. Expansion of the use of low-grade geothermal resources for such purposes as space heating, product processing, agriculture, and desalination.

Several of these breakthroughs may occur in the reasonably near future; if they do, the recoverable resource estimates of White (1965) will have to be revised upward to reflect the major changes in basic assumptions. Four possible breakthroughs deserve specific mention:

1. Much attention is currently being paid to the possible generation of electricity from low-temperature geothermal waters, using a system whereby the geothermal heat is used in a heat exchanger to boil a secondary fluid such as isobutane or freon. This low-boiling fluid (as a gas) drives a turbine, is condensed, and then returns to the heat exchanger (Jonsson and others, 1969). A generating unit based on the heat-exchange principle and using intake water at 81°C is reported to be in pilot operation at Paratunka, Kamchatka, U.S.S.R. (Facca, in press). U.S. industry interest in this generating mode is high (Anderson, 1973), although no pilot or prototype plant has yet been built.
2. Successful demonstration of the technical feasibility of geothermal self-desalination (U.S. Bur. Reclamation, 1972) could greatly enhance the economic position of geothermal resources. Particularly in water-short parts of the world, geothermal energy may be the preferable energy source for desalination, either of the geothermal brine itself or of other saline waters near the geothermal development.
3. Research at the LASL (Los Alamos Scientifi Laboratory) has recently been focused on th development of a nuclear drill that would bor holes in rock by progressive melting rathe than by chipping, abrading, or spalling (Smith, 1971). If development of this "nuclear subterrene" is successful and its use is relatively inexpensive, extraction of geothermal energy from depths as much as 10 km may become feasible.
4. One possible application of the nuclear subterrene proposed by LASL is to drill to depths greater than 5 km in regions where temperatures may be abnormally high but where permeability is low. LASL proposes to hydrofac the hot rock to increase permeability and expects that extraction of heat by water circulated through the crack will result in thermal-stress cracking and a continuously enlarging crack system (Aamodt and Smith, 1973; Harlow and Pracht, 1972). Geothermal reservoir stimulation by various methods (including nuclear devices) was recently the subject of a symposium of the American Nuclear Society (Kruger and Otte, 1973).

Another confusing aspect of geothermal resource estimation involves the units of energy in which the estimates are expressed by various authors. Geothermal energy is heat, and the resource and reserve estimates therefore should be expressed in calories, joules, or Btu's. But historically the major use of geothermal energy has been to generate electricity, and resource estimates commonly have been expressed in units of electrical energy (kilowatt-hours or megawatt-years) or in terms of installed electrical capacity (kilowatts or megawatts). In converting from calories to kilowatt-hours, however, one cannot blindly use the energy conversion factors given in standard tables (for example, Handbook of Chemistry and Physics). These conversion factors, although mathematically and physically accurate, do not take into account the thermodynamic inefficiencies in converting heat to electricity via a turbine and generator. For example, in units 3 and 4 at The Geysers, Calif. (a vapor-dominated geothermal system), only 14.3 percent of the energy delivered to the turbine is actually converted to electricity (Bruce, 1971). Almost all the remaining 85.7 percent is discharged as heat to the atmosphere, with only a small fraction of heat being returned to the reservoir in condensate from the cooling towers.

The best fossil-fuel generating plants in the United States have a thermal efficiency of about quantitative importance cannot be evaluated without making some estimate of the rate of exploitation of the reservoir. If exploitation is very rapid, recharge will have little significance, but if exploitation is very slow, recharge will be significant; thus, establishment of a steady balance between extraction and recharge (both heat and water) may permit the geothermal system to be exploited indefinitely.

The geothermal resources of the world, therefore, lie somewhere between 2×10^{19} cal (White's 1965 estimate of potential reserves to 3 km recoverable as equivalent electrical energy using present technology) and $5\text{–}10 \times 10^{25}$ cal (calculated from Rex, 1972a). Of these geothermal resources, perhaps 5–10 percent are in the United States (White, 1965). The differences among the various resource estimates will not be resolved until there is (a) better knowledge of the distribution of geothermal energy in the earth's crust, (b) clarification of the technological limitations upon geothermal resource exploitation, and (c) definition of uses.

PROSPECTING TECHNIQUES

The first step in reconnaissance geothermal exploration involves outlining broad regions where the heat flow is significantly greater than 1.5×10^{-6} cal cm^{-2} sec^{-1} (for example, Sass and others, 1971). Most of these regions of high heat flow are in zones of young volcanism and tectonic activity, and most are characterized by abundant hot springs.

Techniques for identifying potentially economic concentrations of geothermal energy within broad regions of high heat flow are not well developed. Important considerations include distribution of hot springs, evaluation of volcanological and tectonic setting, and chemical analysis of hot-spring fluids. In particular, the content of silica (Fournier and Rowe, 1966) and the ratios of sodium, potassium, and calcium (Fournier and Truesdell, 1973) provide information about the minimum subsurface temperature to be expected.

Several geophysical techniques have proved useful in the final delineation of geothermal targets (Combs and Muffler, 1973; Banwell, in press). Of these techniques, perhaps the most unambiguous is the direct measurement of temperature gradients at depths of 25–100 meters (Combs, 1971; Burgassi and others, 1970). Temperature measurements at shallower depths, however, can be very misleading, owing primarily to the effects of seasonal changes in temperature and to the shallow movement of ground water (Banwell, in press). Thermal infrared surveys detect surface temperature anomalies, but these anomalies can be caused by many factors other than geothermal heat flow (Banwell, in press; Watson and others, 1971).

Several techniques that measure the electrical conductivity at depth have had great success in geothermal exploration. The conductivity at depth varies directly with temperature, porosity, salinity of interstitial fluid, and content of clays and zeolites. All these factors tend to be higher within good geothermal reservoirs than in the surrounding ground, and consequently the electrical conductivity in these geothermal reservoirs is relatively high. Electrical conductivity at depth can be measured by electrical (galvanic) or electromagnetic (inductive) methods. Among the electrical techniques, only direct-current methods are reliable, owing to skin effects attendant to alternating-current methods; direct-current electrical arrays commonly used are Wenner, Schlumberger, and dipole-bipole (Banwell and Macdonald, 1965; Hatherton and others, 1966; Risk and others, 1970; Macdonald and Muffler, 1972; Zohdy and others, 1973). Electromagnetic methods (audiofrequency magnetotellurics, electromagnetic coil surveys, and loop-loop or wire-loop induction surveys) have certain theoretical advantages (Keller, 1970; Harthill, 1971) and are becoming more widely used.

Passive seismic methods are proving of use in locating fractured and permeable zones in geothermal areas. Microearthquakes at relatively shallow focal depths are concentrated along fracture or fault zones in many geothermal areas (Ward, 1972; Ward and Björnsson, 1971; Hamilton and Muffler, 1972). In addition, some geothermal areas appear to have a high level of seismic ground noise (Whiteford, 1970); analysis of the areal distribution of this noise may outline prospective zones of geothermal production (Goforth and others, 1972).

Several other geophysical techniques have proved useful in special circumstances. Gravity surveys may in some areas define positive anomalies that are caused by alteration or metamorphism of subsurface rock (Hochstein and Hunt, 1970; Biehler, 1971), but in other areas they may define a negative anomaly that may represent an intrusive mass at depth (Calif. Div. Mines and Geology, 1966). Magnetic surveys in some areas define negative anomalies that are caused by alteration of magnetite to pyrite (Studt, 1964), but in other areas they define positive magnetic anomalies that are caused by intrusions of magnetic igneous rock (Griscom and Muffler, 1971). Active (explosion) seismology is useful in defining subsurface geologic structure (Hochstein and Hunt, 1970; Hayakawa, 1970), and analysis of seismic attenuation across geothermal

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