APPLIED MECHANICS REVIEWS

Geothermics*

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Introduction

The earth is a reservoir of immense heat energy. Part of it has been stored in its interior since the earth was formed; part is being continually generated by the buffeting the earth receives from its gravitational interactions with the sun and moon; and part develops as radioactive materials spontaneously change (Stacey, 1969). Most of it lies so deep within the earth that it is unlikely ever to be tapped by any foreseeable drilling technology or is far too diffuse to be extracted economically; however, there are many local hot spots throughout the world which can be tapped efficiently to extract useful heat. Although the number, distribution, and magnitude of them are poorly known, they are most prevalent along the belts of young volcanism that ring the Pacific Ocean and that follow the mid-oceanic ridges (Grose, 1971; 1972). Development and substantial utilization of geothermal power is underway in the United States (mainly in the West), Mexico, El Salvador, the Phillippines, Japan, Iceland, New Zealand, and Russia, and many smaller countries are exploring their potential geothermal resources (Kruge and Otte, 1973 United Nations, 1974).

Exploitation of geothermal heat has occurred at least since the hot baths of Roman times. Beginning about the turn of this century, it has been used in a limited way for space heating, chemical extraction, product processing, agricultural heating, and generating electricity—by far its most extensive application. Since 1950, the technology of geothermally generating electric power has progressed rapidly, with now more than 1,000 megawatts worldwide on line, about one-half from The Geysers in California. This power is equivalent to one fossil fuel plant. In cost it competes favorably with fossil fueled and nuclear power plants.

On the average, heat flows outward to the surface at the rate of 1.5×10^{-6} cal per cm^2 per sec (Lee, 1965), and at depths potentially accessible to drilling, down to 10 km, there appears to be stored approximately 10^{24} BTU (10^{27} joules) which could produce 10^{13} to 10^{14} megawatts of power. Except at hot spots, temperatures in a deep well or mine increase on the average about 25°C per km of depth so that at about 3 km depth the boiling point of water is reached. The increase at a hot spot is very much greater: Marysville, Montana, has an extreme temperature gradient of 175°C per km.

Search for Hot Spots

The problem of finding hot spots, especially wet ones, is similar to that of locating oil deposits and much of the know-how developed by the petroleum industry is being brought to bear on the geothermal problem. Surface seepage was used to locate the first oil deposits and, in the same vein, hot springs and geysers, volcanic activity, and abnormal amounts of silicon dioxide in and around waters are useful surface indicators of geothermal activity. However, subsurface indicators hold the most promise. Drilling is still the surest and most effective way to find geothermal wells and is being used extensively at present. It is expensive: at least $180,000 for a 1 km well.

There are several other geophysical indicators of geothermal activity. Early on, infrared photography was thought promising but studies have shown that it looks mainly at the surface and does not sense what is below.

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Above normal heat flow indicates high temperature gradients, suggestive of potential reservoirs. Fortunately, routine heat flow measurements have been made by the thousands during the past few years, using abandoned holes drilled for oil or minerals. Such measurements are made by placing two or more thermometers at spaced intervals down a drill hole and measuring the difference in temperature between them. The Marysville anomaly was found in this way.

Several potential resources have been located by electrical resistivity measurements. Wet rocks, being much better conductors than dry ones, exhibit easily identifiable resistivity anomalies (Kruger and Otte, 1973).

Ground-noise mapping is a new technique most particularly applicable to geothermal prospecting. Geophones capable of sensing ground vibrations survey the distribution, frequency content (of the order of 1 Hz), and amplitude of the motion of the surface of the ground over the area of interest. A geothermal area has a characteristic set of ground noises associated with it and using recognized geothermal basins as baselines, other fields can be delimited.

Gravity and magnetic surveys are successful only to a limited extent, mostly in complementing other types of surveys.

Geothermal Resources for Elpower Generation

There are five general types of geothermal resources that can be used to generate electric power:

(1) dry steam which streams from holes drilled to great depth (a steam-dominated system);

(2) wet steam which is generated when superheated water gushing from drilled holes partly flashes into steam (a water-dominated system);

(3) geopressurized reservoirs in which fresh water at high pressure is stored deep underground;

(4) hot water which flows from natural or man-made holes at a temperature less than its boiling point (a hot water system); and

(5) hot rocks, deeply buried, from which dry steam can be generated by dousing with water (a dry system) (Kruger and Otte, 1973).

The two resources, The Geysers in California and Larderello in Italy, which produce the most power, about 500 megawatts each, are steam dominated; other large producers, Wairakei in New Zealand and Cerro Prieto in Mexico, are water dominated. Any classification is not clear cut; one type blends into another. In fact, at Wairakei, one of the producing fields, as the water was exhausted, changed from a water-dominated system to a steam-dominated one.

The geology of these regions is only partially understood but the features of most importance in evaluating a geothermal reservoir are:

(1) an adequate heat source, and hopefully, a large and porous reservoir with channels connected to the heat source near which water can circulate and then be stored: and

(2) capping rocks of low permeability that inhibit the flow of water and heat to the surface.

The three main producing areas, Wairakei, The Geysers, and Larderello, of which the geologies are well defined, all have these characteristics. Wairakei yields at depths ranging from 120 to 600m 250°C water, of which about 15 percent flashes to steam as it enters the turbines. The Geysers yield dry steam at 7Kg/cm^2 and 205°C from depths ranging from 600 to 3000 m. Larderello is a similar dry-steam operation.

Overpressured waters located at great depth, 2000 m. to 3500 m., particularly in the Gulf Coast, are potential sources of electrical power. They are being actively developed in at least three areas in South Texas. Geopressurized deposits of water occur in continuous belts, are bounded by regional faults, and extend hundreds of miles. Thermal diagenesis of clays has liberated bound and intercrystalline water. The water is fresh and contains large quantities of dissolved oil and gases which, at present, are being extracted on a limited basis. Temperatures range from 150°C to 180°C; well-head-pressures range from 250 kg/cm^2 to 400 kg/cm^2; and production rates could be several million gallons of water per day for each well (Dorfman and Kahle, 1974).

Binary systems have been designed to utilize hot water sources by extracting the contained heat in hot water from a range of 148°C down to a point of condensation of approximately 38°C. The operation involves the use of a low-boiling-point gas, freon or isobutane, in much the same way as it is used in refrigeration. The heat fluid vaporizes and the gas is used to power turbines that drive generators. This scheme would lower production costs and could utilize the large quantities of hot water at shallow depths which, at present, are of little value. A plant of this type at Raft River, Idaho, is being developed and the first drill hole was successful. Two freon pilot plants have been operated for more than eight years in the USSR. They use water at a temperature of 91.5°C in their 0.34 megawatts plant, and 180°C in one producing 0.75 megawatts.

Extraction of heat from hot dry rocks is being pursued by the Los Alamos Scientific Laboratory. The ultimate plan is to sink twin wells as deep as 6,000 m to hot rocks underlying the extinct volcano, Valle Grande, in New Mexico. Clean water, pumped down one hole, would be heated by the hot rock and would return up the other as steam. Hydrofracturing, an established oil well practice of opening up fractures, will be used to increase the surface area with which the water can come in contact and absorb heat. Tests on a 3,000 m deep well in the Jemez Mountains, New Mexico, have demonstrated the feasibility of the hydrofracturing technique. If the overall scheme works, the energy could provide all the additional power the nation will require until thermonuclear fusion and solar sources are developed.

Environmental Problems

Once a geothermal resource has been located, the problem of acquiring rights to it is similar to that of any other mineral resource; however, since the laws are new and not yet tested, many legal questions are arising. These are taking literally years to work out.

Geothermal energy is not so free of undesirable environmental consequences as some of its proponents suggest. Its impact will vary widely with the quality of the steam and water that emerge and will be dependent on whether subterranean pressure prevents returning them to earth. In this case, the problem of disposal may be formidable, although having adequate water for cooling is an asset and relatively pure water may find agricultural and other uses.

In large sedimentary regions such as the Imperial Valley in California, where a very active geothermal development program is underway for a desalinization project, extraction of fluids could easily lead to subsidence of the land to such an extent that flow through irrigation ditches is affected.

In most respects, hot dry rock seems the most environmentally satisfactory source of geothermal energy, although substantial quantities of surface water will be required. An original fear that the hydrofracturing would produce earthquakes or other geological instabilities has lessened as more has been learned about earthquake initiation.

Noise and odor pollution may be serious in populated areas, although not insurmountable. Steam escaping under high pressure is ear splitting and the frequent presence of hydrogen sulfide, unless extracted, will fill the air with the odor of rotten eggs. At The Geysers, the odor is pervasive. A 1,000-megawatt installation there discharges about the same amount of H_2S as would be given off by a fossil fuel plant of the same size.

Heat rejection is another significant local environmental effect. If the ten 1,000-megawatt geothermal plants are installed as contemplated in Imperial Valley, the total rejected heat to a 1,000 square mile area would equal 5 percent of the solar energy reaching that area. This might influence local weather patterns significantly.

Geothermal electricity, as with other forms of onsite generation, must be carried to where it is needed. This means an expansion of transmission lines, with their attendant problems of land use, visual pollution, and energy loss.

The main objection voiced by environmental groups is the modification of the existing terrain by the wells, pipelines, and power plants of a producing geothermal field. However, The Geysers and Larderello are not particularly out of harmony with their surroundings and at Larderello, the land amidst the installation is being used for agricultural purposes. The chief impact comes during the construction phases but is confined to the area of the field and causes nothing like the disruption produced by strip-mining coal.

Potentials of Geothermal Power

Geothermal power offers a gigantic potential and the field of Geothermics is booming. The USSR estimates that their geothermal potential is probably equal to their reserves of petroleum. According to a National Science Foundation study in 1973, the United States could, by the end of the present century, generate as much power geothermically as is used today, 395,000 megawatts. While the former Atomic Energy Commission's estimate for geothermal power is only 5 percent by the year 2000, the U.S. Geological Survey estimates that as much as 10 percent of the nation's energy might come from geothermal sources by 1985.

One of the biggest unknowns is the lifetime of the resource. There is some indication that the production of steam at The Geysers and Larderello is diminishing somewhat. At Wairakei, the rate of evolution of hot water and steam has decreased considerably. The exact location of the source and extent of the water residing in the basins is obscure, although geologists seem to feel that the supply will last at least 30 years, if not much longer. At present, production is maintained by drilling additional wells.

Development in the United States has been very slow. The uncertainties are largely economic, although there are other unknowns. Many of these problems were discussed at the Second United Nations Geothermal Energy Symposium held in San Francisco in May 1975 and attended by about 1300 scientists and engineers. One full week of the two was devoted to geology and geophysics, the main tools used to locate resources. The several geophysical prospecting techniques discussed above have all now been applied widely. While drilling is still the only certain way to establish a resource, the geophysical techniques used in combination, and combined with geological knowledge, are appearing more and more promising as indicators.

Areas for Future Research

If the hot water binary system and the hot dry rock technique can be proved in Idaho and New Mexico, and as of now this appears promising, geothermal energy in the future is bound to form a major segment of the energy needs.

The challenge to the engineering scientist lies in the need for him to provide a firm scientific and engineering basis on which future development can rest.

Two prime new areas of concern are heat transport in geological structures, involving both conductivity and mass transfer, and possible modifications of mechanical characteristics of the system, produced both by natural forces such as earthquakes, subsidence, and earth tides, and by man's tampering with the system.

Perhaps the most pressing problem is the development of an appreciation for the flow characteristics of hot, nonisothermal fluids through porous and fractured media. There are only a very few previous studies in this area which are applicable to the geothermal problem. The extensive previous studies of flow through porous media have been largely limited to isothermal fluids flowing through isotropic materials. Clearly pronounced temperature gradients occur in the fluids contained within geothermal basins and mechanically they are highly heterogeneous. The fluidity of water increases rapidly with increasing temperature, the viscosity varying by a factor of 6 over a 200°C temperature span. Thus, at great depth, the high water temperature span. Thus, at great depth, the high water temperature can change flow patterns in a marked way.

A major problem is the definition of a realistic mechanical model upon which to base analyses and calculations. Early investigators treated the basins as more or less isotropic porous masses, allowing more or less unconstrained convection patterns to develop. At the Second United Nations Geothermal Energy Symposium almost a hundred engineering scientists convened a special session to exchange thoughts on appropriate geological models to use. New geological, analytical, and numerical studies discussed at that session demonstrate convincingly that much of the flow takes place through fractures that channel and modify the flow.

The newer geological models will also be extremely helpful in analyzing response to applied mechanical stresses. The activities of geothermal basins are not constant, being perhaps, most strongly influenced by earthquakes. These often occur along the faults that permit the flow of fluids. Earth tides and subsidence also have noticeable effects. Once a field is in production, extraction of fluid will cause the basin to change. A number of engineering scientists are now looking at these new and important problems.

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