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GEOTHERMAL ENERGY AND RESOURCES

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The population explosion coupled with man's accelerating desire for a higher standard of living has greatly increased his demand for energy in the past and there is evidence to expect a similar - if not greater - demand in the future. Historically, the majority of the countries of the world have satisfied this need through the conventional energy sources of wood, water, coal and hydrocarbons. Since the turn of the century, an ever increasing percentage of energy has been supplied by the fossil fuels - coal and hydrocarbons. In the highly developed countries these fossil fuels have provided over ninety percent of the total energy since 1900. Increasingly, concern has been expressed as to the wisdom and practicability of satisfying future energy demands with fossil fuels only. Such concern is founded upon the present reserves, recent discovery success and the ever increasing economic value of these fuels as petrochemicals and other products.

Hence, it is not surprising that increasing attention is being directed to the practical utilization of some of the more exotic energy sources such as nuclear, solar, tidal, wind, and geothermal. The expected future energy demand has spurred theoretical and applied research and industrial pilot installations relating to these exotic energy sources. Of particular significance is the rapid technological progress that has been made during the past decade in the nuclear field. Once this energy source becomes economic, wide scale industrial applications will follow rapidly, and should help greatly to meet future energy demands. Similar developments should be expected for other sources of energy. Another field in which there has been considerable recent interest and progress is geothermal energy, the subject of this paper.

In the most general sense, "geothermal energy" is concerned with the natural heat of the earth. However, this term has been used broadly to describe the useful energy extracted from naturally occurring water, either as a vapor (steam) or liquid (hot water). In the usual case, the geothermal fluid, steam or hot water under elevated pressure and temperature, is located by drilling and completing wells in the conventional manner. The fluid production is used to drive turbines to generate electric power or to provide heat for industrial and home use. In some cases, chemical by-products may be produced with the geothermal fluids.

Temperature anomalies, and consequently the source of heat found in geothermal areas, are believed to be related to the processes of volcanism and intrusive magma. Hence, the heat may be derived from deep buried, extrusive, igneous rocks, from relatively shallow intrusive magma which is still cooling, from volcanoes, from slip friction associated with faulting or from radioactive mineral decay.

Geothermal reservoir geology has not been satisfactorily described. However, it is generally agreed that some source of heat must be associated with the regional accumulation of the geothermal fluid. To date, the principal geothermal reservoirs in the world have been found in regions of Cenozoic volcanism and the best evidence supports that the heat is derived from intrusive magmas. Further, it is believed that this heat is transmitted to the geothermal fluid contained in an appropriate structural or stratigraphic trap. In all commercial accumulations identified thus far, the geothermal reservoir has an impervious cap. Structurally, these reservoirs are located in an orogenic belt which has undergone late Pliocene and Quaternary uplift or in deep structural depressions associated with late Tertiary and Quaternary displacements of 10,000 to 20,000 feet. The geothermal fluid is thought to be contained in the porous and permeable rock comprising the geothermal reservoir. The fluid is believed to have a meteoric origin and visualized as entering the geothermal reservoir through downward percolation and/or underground regional migration.

As has been mentioned previously, geothermal fluids may be comprised of vapor, liquid, and associated minerals. In general, vapor when located at relatively shallow depths has appropriate thermodynamic properties at the pressure and temperature to permit easy and efficient turbo-generator operation. When the geothermal fluid is liquid at reservoir conditions, additional facilities, either subsurface or surface, are necessary to process the fluid in order to secure the desired mass, and quality of steam. In general, this results in high liquid productions which after flashing, must be disposed of in an appropriate manner.

Quite often the geothermal fluids contain minerals such as salt, calcium chloride, potash, manganese, boron, iodine, bromine, lithium, sulfur, fluorine, potassium, arsenic, and yes, even copper, silver and gold. In some cases, the production of these minerals is such as to be commercial. In other cases, extractive processes have not yet been developed to make extraction commercial. Further, some of these minerals cause corrosion and scale formation in the operating equipment.

Geothermal reservoir fluid characteristics and productivity vary over a wide range. However, in commercial operations the maximum surface pressure observed is approximately 500 psia and the maximum bottom-hole temperature is 575°F. It is not uncommon for the wells to flow at rates greater than 100,000 lbs. per hour and hundreds of tons per day of minerals. Ordinarily, the most productive wells are those which have been drilled into faults. In general, minerals in geothermal fluid production have increased production and operating problems and costs.

Geological evidence covering millions of years and man's total recorded history are testimony to the presence of surface and subsurface geothermal activity. Centuries ago the Maori and Koreans used the heat from surface emanations for cooking and heating and later others used the minerals contained in the geothermal fluids for food supplements, medicines and other commercial purposes. In 1827, Count Francesco Larderel became interested in the geothermal activity in Italy and through his efforts a profitable chemical industry producing borax was developed. Various other power uses were made of the steam containing the borax, but it was not until 1913 that the first turbo-generator unit was installed. The capacity of this power generating installation has been progressively increased and the area is now appropriately called Larderello. From this humble beginning, continuing efforts have been devoted to develop the science that relates to geothermal prospecting, drilling, transportation and conversion of this fluid to the use of man.

Geothermal energy utilizes the heat in the earth's crust which may be located and produced economically. Geothermal prospecting is still in its infancy and the state of the art has progressed only slightly past the equivalent of that of oil seep exploration experienced in the initial stages of petroleum prospecting. Since it is generally conceded that geothermal energy is closely related to volcanism, those areas of the world in which there is evidence of volcanic action, earthquake and seismic activity have received the greatest attention in the search for this type of energy. Further, the state of the art of prospecting dictates that the principal attention be directed toward locating and producing geothermal energy in the form of vapor. Hence, discovery has been preceded by a long history of known temperature anomalies indicated primarily by surface hot springs, geysers and fumaroles in an area.

In Figure 1 is shown the principal volcanic and seismic activity areas of the world. Although it is not intended that this representation is complete, studies reveal that to this date, the principal geothermal prospects are located within these areas. It is important to note that much of this area is in countries that have little, if any, natural energy resources. During the last ten years, geothermal prospecting by various techniques has been greatly accelerated in countries throughout the world. The countries in which geothermal exploratory wells have been drilled include Argentina, Chile, Costa Rica, El Salvador, Fiji, Iceland, Indonesia, Italy, Japan, Java, Katanga, Kenya, Mexico, New Britain, New Zealand, Nicaragua, Philippines, United States, Soviet Union, Taiwan, Turkey, Uganda, and the West Indies.

Although the future holds much promise for this form of energy, there are only six countries at this time which are harnessing this energy to produce a significant amount of electric power. These countries are Italy, which is generating over 300 megawatts of power; New Zealand, 200 megawatts; the United States, Japan, and Mexico, 100 megawatts each; and the U.S.S.R., undoubtedly in the 100's of megawatts. A number of other countries have small electric power plants in the ten megawatt class. In many countries, including Iceland, U.S.S.R. and New Zealand, large quantities of geothermal fluids are being used for household heating and/or commercial purposes.

Without question, geothermal prospecting in the past has achieved, at best, only limited success and from an overall standpoint must be considered as a net economic loss. However, it must be realized that geothermal prospecting techniques are just commencing to be evolved. For the most part, the geothermal energy prospects of the world are unexplored. Even the two major geothermal areas, Italy and New Zealand, have experienced only limited, regional, areal reconnaisance. To the author's knowledge there have been only two geothermal wells drilled below 6,000 feet, six drilled below 5,000; few have been drilled below 4,000 and the great majority are less than 1,000 feet deep. Therefore, our depth perception for geothermal activity is very poorly defined even in areas that have received principal attention. Hence, the limited development and use of geothermal energy thus far should in no way serve to minimize the potential importance of prospects for the future.

The two most successful commercial installations in the world utilizing geothermal energy are located at Larderello, Italy and Wairakei, New Zealand. Quite surprisingly, these two operations represent the probable extremes of reservoir fluid conditions that may be found in geothermal reservoirs. For a moment let us look at these reservoir fluid conditions and the probable effect they will have on the production history of the reservoir. This is best done by considering the so-called vapor pressure curve, shown in Figure 2, in which pressure is plotted versus temperature. A curve, originating at approximately atmospheric pressure (15 psia) and 212°F., the boiling point of water, and terminating at 3206 psia and 705°F. is drawn. Simply stated, this curve represents the boiling point temperature of water at the corresponding pressure. Hence, at temperature and corresponding pressure conditions (point B) that lie on the curve, vapor and liquid will co-exist, as in a teapot. At pressure and temperature conditions (points E and C) that lie above the curve, only liquid will exist. Further, only vapor will exist for conditions that correspond to pressures and temperatures (point A) that fall below the curve.

The reservoir fluid conditions reported at Larderello are approximately 500 psia and 475°F., which corresponds to a superheated steam falling below the vapor pressure curve. Hence, wells drilled into the reservoir produce steam at relatively constant temperature. In contrast, the reservoir fluid conditions at Wairakei are approximately 760 psia and 480°F., corresponding to a superpressed liquid. Hence, wells drilled into the reservoir would be expected to contain liquid, to the depth at which the water will boil as pressure is reduced. Consequently, wells could produce hot water, saturated steam, dry steam or admixtures. Usually, steam and hot water are produced simultaneously. It is quite evident that the structural position of the wells, the nature of the completion, that is, whether the well is completed in the matrix rock or in faults and the design of the flow string can materially affect the quality of the fluid productions.

In the United States, virtually all of the area west of the eastern slope of the Rockies, shown in Figure 3, is considered as a potential area for geothermal prospecting. Over 1,000 geothermal surface evidences are recorded in this region and geologic evidence suggests that other areas are prime geothermal prospects. To this date, the principal success has been experienced in the Big Geysers area in Sonoma County north of San Francisco, California. As early as 1921, a well was drilled in this area to prospect for steam. However, it was not until the late 1950's that a planned drilling program was initiated and later accelerated. Many relatively shallow wells have been drilled encountering high quality steam at a temperature of 410°F. and a surface pressure of 150 psi, approximately. Over 100 megawatts of power are now being produced in this area and plans are underway to further expand this operation. This success has attracted considerable attention and has resulted in greatly expanded interest and exploration activity in the western United States.

Another U. S. area which has received considerable attention is Imperial County, California, south of the Salton Sea. Wells drilled to depths of approximately 6,000 feet have reported bottom-hole temperatures of 572°F. One well drilled in this area had a productive capacity exceeding 500,000 lbs. per hour with a mineral content of twenty percent. This corresponds to a daily mineral production of 1,200 tons. Hence, both the energy and mineral potential of this area is being investigated.

To a considerable extent, geothermal exploration and development has been deterred not only by the present state of the art, but by the absence of sufficient information on which to make economic decisions. Specifically, cost estimates for prospecting, producing, transporting, converting energy, and estimates for fluid in place, recoverable fluid and fluid production rate are needed.

With respect to exploration and development costs, it may be surprising that such data are not readily available from the rather extensive Larderello and Wairakei installations. However, it must be remembered that for all practical purposes these two operations are essentially government controlled. Quite frankly, from personal experience, appropriate economic data are not only difficult to obtain, but to interpret.

Economic data reported by Italian geothermal experts are shown in Table 1. These data indicate a most favorable advantage of geothermal energy over other forms of energy. However, this summary does not provide an adequate economic analysis for energy prospectors in the U. S. since some question may be raised concerning the plant factor, U. S. tax structure, and other considerations.

Kaufman has analyzed and converted the aforementioned data in accordance with U. S. practices and has prepared the summary shown in Table 1. From these studies he concluded that geothermal energy is competitive with other conventional means of generating electricity.

For many reasons, the author does not feel that either of these two analyses are representative of the relative value of geothermal energy in generating electrical power. To cite a few reasons, in the past only the most elementary prospecting techniques have been employed; modern drilling methods such as air and gas drilling have not been employed; subsurface and surface well equipment and lease and transport lines have been overdesigned; wells have been amortized on the basis of a relatively short life of ten years and turbo-generating plants and other field facilities on a twenty-year life with no salvage value. All of these factors contribute to increasing costs of geothermal power generation and are the result of the youth of the industry, inexperience, excessive safety precautions and ultra conservatism. Further, no cost of land acquisition has been included in any of the economic appraisals.

Scientific and professional opinion has thus far seemed to be directed to establishing the fact that the estimation of reserves and the energy content of geothermal reservoirs is not possible and that the source of energy is infinite. In the opinion of the author, this is most unfortunate since this has created unnecessary controversy relative to the definition of the fluid productions from such reservoirs and the reservoirs eligibility for depletion allowance.

The author has recently completed a geothermal reservoir engineering study of the Wairakei Field for the Commonwealth of New Zealand. In this study he attempted to estimate the fluids in place and the future productivity of the field utilizing methods used in the petroleum industry, after appropriate modifications. However, due to the complexity of the geology of the volcanic region, and the lack of subsurface data, it was not possible to estimate fluids in place by geologic subsurface methods. However, through the use of materials and heat balance equations and a high speed IBM 7094 digital computer, the initial fluids in place, the optimum initial reservoir temperature and pressure and the future performance of the field were estimated. The details of these techniques are beyond the scope of this paper, but have been presented in a paper delivered at the Society of Petroleum Engineers Fall Meeting at Houston, Texas, in October, 1967, and will soon be published in the Journal of Petroleum Technology. However, without detailed explanation, the initial fluid in place, temperature and pressure were optimized and estimated with confidence. As an indication of the high accuracy of such estimates, the actual fluid production history of the Wairakei reservoir is compared with the calculated performance in Figure 4. The results indicate that the reservoir fluid was initially superpressed and that the reservoir pressure has declined to that corresponding to the vapor pressure at the reservoir temperature. Hereafter, the reservoir pressure should remain approximately constant with fluid production. Without question, this geothermal reservoir is of the depletion type and should be entitled to depletion allowance in accordance with that permitted for depletable water and/or steam resources.

The initial fluid estimated in this reservoir contains approximately the same amount of energy as the proved petroleum resources of the world. Recently the U.S.S.R. stated that Soviet scientists had found a vast underground fluid reservoir in western Siberia in which they estimated the fluid in place to be equivalent to 10,000 times that which the author estimated for Wairakei. Although these estimates may seem to be astronomical in magnitude, the author feels that they simply are indicative of the future potential which may be available from geothermal energy.

A few pictures of the Wairakei geothermal operations are shown in Figure 5.

In summary, the science of geothermal energy is in its infancy and prospecting, drilling, well completing, producing, transporting and energy converting techniques are in the experimental phase and much progress is needed to optimize these operations. Although some progress has been made in estimating the quantity of fluids in place, fluid productivity, ultimate fluid production, and economic factors considered in appraisals, much work also remains to be done in these areas to improve accuracy and confidence. During the past decade, limited development drilling throughout the world, based primarily upon cursory surface indications, has established that geothermal reservoirs are potential sources of great quantities of energy. It is the author's fervent hope and expectation that man's ingenuity will be applied to exploit this energy to the use of man and the continued improvement of his standard of living.

TABLE 1.

ECONOMICS OF GEOTHERMAL POWER

Energy Source	Mils/KWH (1)
Geothermal	2-3
Conventional Thermoelectric	5.47-7.75
Nuclear	5.42-11.56
Hydroelectric	5-11.36

(1) 92 Percent Plant Factor

Energy Source	Mils/KWH (2)
Geothermal Plant, Producing Own Steam	6.70
Geothermal Plant, Purchasing Steam	7.43
Coal-Fired Plant	6.96
Oil-Fired Plant	6.74
Gas-Fired Plant	7.04

(2) 51 Percent Plant Factor and Adjusted to Present Tax Structure of U. S.

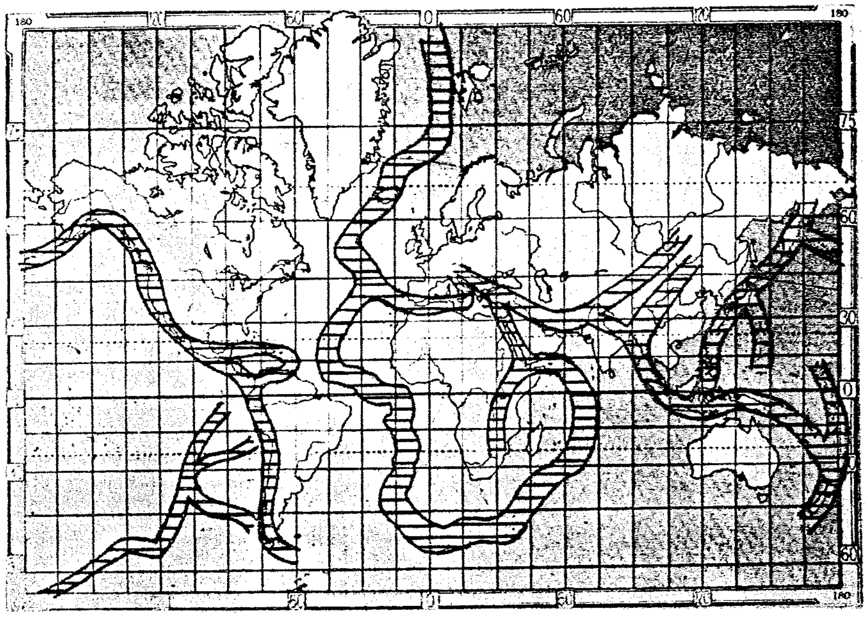

Fig. 1 World Volcanic and Seismic Areas

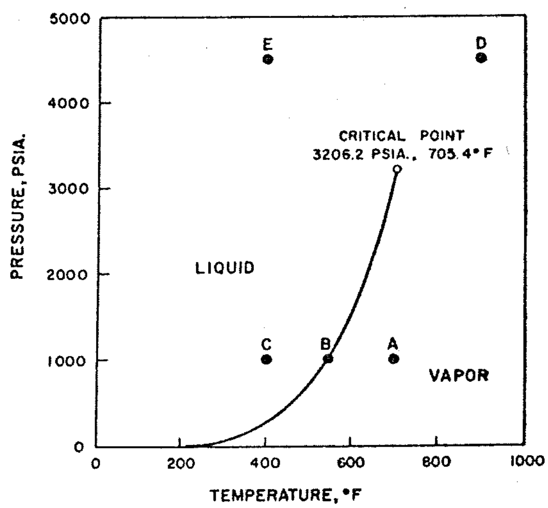

Fig. 2 Pressure-Temperature diagram for Water

Fig. 3 U. S. Geothermal Prospecting Areas

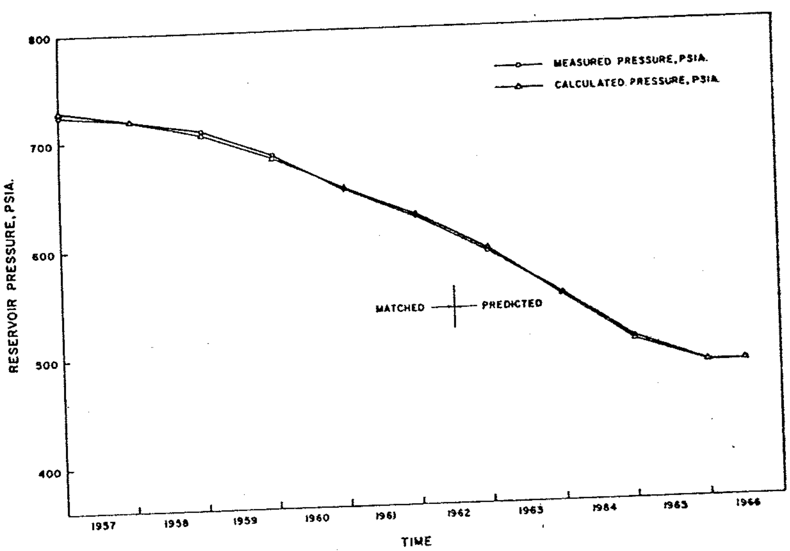

Fig. 4 Prediction of Geothermal Reservoir Performance