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TECHNOLOGY OF UTILIZING GEOTHERMAL ENERGY

by

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Technology of Utilizing Geothermal Energy

1.0 Introduction

The earth is a heat engine. The average heat flowing *conductively* out through the earth's surface is 0.07 watts per square meter. If we multiply this value by the total surface area of the earth (5.1×10^{14} square meters) we obtain the total heat flowing from the earth as 3.5×10^{13} watts or 35,000,000 megawatts. The state of Utah currently consumes about 1750 megawatts of electrical power, so that if all of the earth's heat could be converted with 100% efficiency to electricity, it would power 20,000 areas the size of Utah and a total population of 20,000 million people! These are fascinating figures but not currently meaningful, for we have yet to devise an economic means of extracting the earth's average outward heat flow. Fortunately, the earth has local "hot spots" where the *convective* heat flow can range up to a thousand times the average rate and where temperatures are sufficiently high at shallow depth (150°C to 350°C) to allow economic conversion of energy from heat to electricity. Geothermal fluids at temperatures less than 150°C are more efficiently used for direct heat applications, i.e. the heat is used directly and not converted to electricity.

Where does the earth's heat originate? Of several possible theories concerning its origin, the most plausible lies in radioactivity. When radioactive elements decay they release energy which is dissipated as heat. All rocks contain small amounts of radioactive elements. The only elements producing important amounts of heat are thorium, uranium, and potassium, and their decay products. Simple calculations reveal that there is no difficulty in accounting for the observed heat flow on the basis of heat given off in radioactive decay processes. For a granite, 3 microwatts per cubic meter of heat is generated through radioactive decay of uranium, thorium, and potassium; while for basalt, which is less rich in uranium, thorium, and potassium, 0.3 microwatts per cubic meter is produced. A granitic crust 20 km thick uniformly spread over the earth would produce all of the heat flow we observe today. Over a period of 4500 million years, the age of the earth, sufficient heat has been produced to heat (Fig. 1) the inner core to an estimated 4800°C, the outer core to 4000°C, the lower mantle to 3000°C-1500°C, and the upper mantle to 1500°C-1200°C. The inner core is solid nickel-iron, the outer core is liquid nickel-iron, the lower mantle is a nickel-iron-magnesium compound, while the upper mantle is largely a silicon-iron-magnesium compound and is a source of basalt lava.

The outward conductive flow of heat to the outer mantle causes it to form convection cells in which the material of the mantle rises slowly upon heating, becomes cooler as it nears the crust, and once cooler and denser, descends again. The precise configuration of these convection cells is not known, but we are able to deduce that the roughly cylindrical axes of some of them lie along relatively straight lines for thousands of miles. The rigid crust above this convecting mantle cracks above two counter-rotating cells to form steep valleys from which issue volcanic eruptions. Earthquakes accompany the cracking. The process is repeated and the two segments of crust on either side of the crack move apart at average annual rates of from 1 cm to 10 cm. This crustal splitting occurs along the mid-oceanic ridges (Fig. 2).

Transform faults offset the ridges in order to allow crustal adjustments. Mantle material rises along the cracks to form a thin oceanic crust of basalt; this crust is about 4 km in thickness. At certain plate boundaries the oceanic plates are thrust under the continent, or subducted by this thermal driving mechanism. The subducted lithospheric plate moves downward at an angle of about forty-five degrees, remaining intact to depths of 700 km. Below this depth the material of the plate is sufficiently hot to flow and becomes mixed with the mantle material from which it was derived. During this subduction process the top layer of the plate undergoes severe frictional heating, which remelts part of the plate. The melted rock rises buoyantly and gives rise to volcanic eruptions. Earthquake activity accompanies the subduction and volcanic eruption.

A third place where volcanism and earthquakes occur is in intraplate melting zones, where a local upwelling plume of hot mantle material causes the oceanic crust to thin and crack as the crust moves over the hot spot. The Hawaiian Islands are the prime example of this type of volcanism.

We have by now obtained a glimpse of the heat production mechanism in the earth, of the radial variation of temperature, of the heat-driven dynamic interior of the earth, and of the shaping of the terrestrial surface by thermal forces. Let us now look, on several scales, at the non-uniformity of heat flow from the earth.

We begin with the global picture (Fig. 3). Chapman and Pollack (1975) utilized more than four thousand measurements of surface heat flow, plus some ingenious reasoning, to arrive at a map of the heat flow from various small elements of the earth's surface. Generally they find high heat flow over the mid-oceanic ridges, behind the subduction zones, and over the intraplate melting anomalies. The outward heat flow over the terrestrial globe is not uniform, varying by at least a factor of four on a scale of a few thousand kilometers. The study concerned global, not local, features.

Now turning to the North American continent, we find that there is, in general, higher heat flow in the western half of the United States than elsewhere. This is due to the fact that the crust is thinner in the west than in the east and that the west has seen much more recent faulting and volcanism. Generally speaking the high heat flow occurs west of the Rocky Mountains and the Colorado Plateau, roughly lying west of the Wasatch Front in Utah. However, virtually all of Arizona has a high heat flow as does the Rio Grande Rift which extends northward from western New Mexico through mid Colorado. Within the western states there are local hot spots many of which are imperfectly delineated as of this date.

2.0 Types and Occurrences of Geothermal Resources

At the present time we recognize the following types of geothermal resources: convective hydrothermal, normal geothermal gradient, deep sedimentary basin, radiogenic, hot dry rock, geopressured, and magma. While many of these are related, their economic potentials by current judgment set them apart. We shall define them in the following.

Convective Hydrothermal

One assumes for the classical expression of this type of resource that a liquid or solidified magma serves as a source of heat (Fig. 4). Cold surface, or meteoric, water percolates downward through fractures and faults to the region immediately surrounding the heat source. Upon adequate heating the meteoric water becomes less dense and convects, via other fractures and faults, towards the surface. If no caprock or layer of low fluid permeability is present to contain it, the heated fluid will escape at surface as geysers or hot springs. However, a caprock often traps the hot fluid. At The Geysers in California and at Larderello in Italy, the fluid is *dry steam*, i.e. no liquid water vents with the steam. At Wairakei in New Zealand and at Cerro Prieto in Mexico the fluid is *wet steam*. Actually, in a wet steam reservoir the fluid is hot water, part of which flashes to steam in the wellhead. Fluid temperatures as high as 350°C have been encountered at Cerro Prieto while most of these resources exhibit temperatures of order 250°C. The reservoir may be the fractures containing hot water as at The Geysers, or it may be sedimentary beds as in the Imperial Valley in California.

normal geothermal gradient

Where the earth's crust is thin, meteoric water can be heated to temperatures as high as 200°C at a depth of just a few kilometers by the normal crustal temperatures, with no magma present (Fig. 5). Faults allow meteoric waters to percolate downward where they are heated and convect upwards as for a convective hydrothermal system. Most resources of this type produce surface hot spring waters which are of considerably lower temperature than for those classed as "convective hydrothermal" and hence we set them in a class by themselves.

deep sedimentary basins

Circulation of waters in rocks of high intergranular porosity, aided by fracture porosity, can be very deep in some sedimentary basins. Upon heating, the waters convect upwards. The Madison formation, a carbonate rock of widespread occurrence in North and South Dakota, Wyoming, and Montana is an example of this type. Temperatures typically are less than 90°C but occasionally run as high as 150°C.

radiogenic

When a uranium-rich granitic intrusive is buried beneath a few thousand feet of thermally insulating sediments, heat is generated in the granite due to radioactive decay and accumulates in the granite and in the sediments (Fig. 6). Drilling to the sediment - granite interface on the eastern seaboard of the U.S., where this type of occurrence is best documented, is expected to yield water temperatures as high as 80°C at a depth of 1500 m.

hot dry rock

Hot dry rock is defined as heat stored in rocks within 10 km of the surface from which the energy cannot be economically produced by natural hot water or steam. To extract the heat a well is drilled to a suitable depth, excess hydraulic pressure is applied to the well to fracture the rock surrounding it, a second well is drilled into the fracture zone, and finally, cold domestic water is pumped down one well where it is heated and pumped up the second well (Fig. 7). Heated water temperatures of approximately 135°C have been obtained at the one test site established at Fenton Hills, New Mexico.

geopressured

Sedimentary rocks in some oil fields, especially in Texas and Louisiana, contain waters under very high pressure and at temperatures ranging from 80°C to 180°C (Fig. 8). The mechanical pressure of the water and the heat are presumed to be extractible energy forms. In addition, these waters contain dissolved recoverable methane. A well is currently drilling at about 4000 m in Brazoria County, Texas and is targeted to reach 5500 m in the Nation's prime test of this resource possibility.

magma

Molten rock, or magma, exists near the surface of the earth in volcanoes such as at Kilauea Iki on the big island of Hawaii. These lavas are at temperatures of order 1200°C and are a readily available source of heat. However, the means for extracting this heat are by no means established. Some form of heat exchanger placed in the lava and using water as the circulating fluid is envisioned.

Of the above types of geothermal resources, only convective hydrothermal and normal geothermal gradient are economic at present. Research on the feasibility and cost-effectiveness of the other resource types is proceeding under the auspices of the U.S. Department of Energy's Division of Geothermal Energy.

3.0 Electric Uses of Geothermal Energy

Dry steam is used to drive a turbine directly; the turbine drives a generator for the production of electricity (Fig. 9). If the geothermal fluid is *wet steam*, the water fraction is first removed in a centrifugal separator and the steam is used to drive a turbine as before (Figs. 10 & 11). The efficiency of the turbines is improved markedly if the spent steam is cooled. Natural evaporation in a cooling tower of some of the effluent from the turbine lowers the temperature of the remainder of the steam to convert it to water in a condenser. Some 25% of the condensate is wasted to the atmosphere in this manner. Scrubbers have removed gases such as hydrogen sulfide prior to water vapor release to the atmosphere. Water from the condenser, the cooling tower and from the centrifugal separator is then reinjected into the cooler fringes of the geothermal field where it serves as make-up water to replenish the reservoir. Natural hot water and steam at temperatures in excess of about 210°C can be used in this manner. World production of electricity by this process is listed in Table 1.

Below about 210°C, the direct utilization of the geothermal heat for generation of electricity becomes uneconomical. Between 150°C and 210°C, a *binary fluid* system can be used economically. The geothermal fluid is used to heat a gas, such as isobutane, in a heat exchanger (Fig. 12 & 13). The high vapor pressure isobutane is then used to drive a turbine which by virtue of the higher density of the vapour is more compact than a steam turbine. A 10 MW plant of this type is under construction at East Mesa, in the Imperial Valley of California. A 5 MW experimental binary cycle power plant, funded by the Department of Energy, is under construction at Raft River, Idaho. Many more installations of this type will be seen world wide. A variant on this basic unit assumes that the geothermal fluid flashes to steam which is then used in the heat exchanger to heat the butane. An experimental facility using this principal has been in operation at Niland, California since mid 1976 (Bishop et al., 1978).

4.0 Direct Heat Applications

Geothermal heat may be used directly, without conversion to electricity, in a variety of ways and at a variety of temperatures. Table

2 lists a number of the agricultural uses and indicates the temperature range required for each. The list of potential applications is growing daily.

Reykjavik, Iceland, pioneered in the use of geothermal water for district heating. Almost all of the homes in Reykjavik receive geothermal water for space heating. Reservoir temperatures range from 100°C to 150°C while the distributed water temperature is about 80°C. These waters are distributed as far as 25 km from the reservoirs. In Klamath Falls, Oregon, well over 500 homes, businesses, churches, schools, hospitals, swimming pools, etc. are heated by geothermal waters which range in temperature from 55°C to 110°C. Boise, Idaho has a municipal geothermal heating system providing 75°C water to about 160 homes and has many private geothermal heat installations. By far the greatest potential use of geothermal fluids is in direct heat applications.

Two types of heat exchangers are in use for most direct heat applications. The first involves a surface heat exchanger wherein the geothermal water is pumped from a well to radiators which dissipate the heat at the point of application and then the spent fluid is discharged into a reinjection well (Fig. 14). The second method involves a downhole heat exchanger wherein domestic water is pumped down and up a hairpin of pipe immersed in the geothermal water; the domestic water is heated in the process and then is used in radiators (Fig. 15). Corrosive or scaling geothermal fluids are best used in this latter manner.

Heat pumps are an attractive means of utilizing the natural earth temperatures between 70°C and 20°C. In the summer the heat is extracted from a building and pumped into the earth in the manner that a refrigerator pumps heat out of its interior to the room surrounding it. In the winter, the "refrigerator" cycle is turned backwards so as to take heat out of the earth and pump it back into the building. The L.D.S. Church Office Building in Salt Lake City accomplishes as much as 75% of its heating and cooling requirements in this manner; the remainder is contributed by conventional energy sources.

5.0 The Department of Energy Programs

The U.S. Department of Energy is stimulating the use of geothermal energy via a number of programs which include basic energy research, energy technology research, reservoir assessment, demonstration projects, user identification, user assistance, institutional problem studies and environmental studies. Information concerning any aspect of geothermal energy may be obtained from the Department of Energy, Division of Geothermal Energy.

The Department of Energy has set the goals of Table 3 for its program of convective hydrothermal energy development. These goals are completely realizable if a concerted effort is made to place geothermal energy in the forefront of currently acceptable and economic energy resources.

Problems currently inhibiting acceleration of utilization of low temperature hydrothermal resources are listed in Table 4. Our knowledge of the locations, shapes, sizes, and productivities of potential reservoirs is in its infancy. Until the public becomes totally aware of the potential of geothermal resources, the growth rate in identification of users will be stifled. Profitability must be demonstrated to any potential user.

Table 5 shows a somewhat different set of problems which is slowing the growth of electric power on line from high temperature hydrothermal resources. The utility companies will not finance new generating facilities unless the longevity of the reservoir can be demonstrated to be 30 years or more. Means for discovering and delineating the reservoirs are improving rapidly but this science is still in its infancy. Regulatory and other institutional problems are taking their toll on putting this energy source on stream as they are for all energy sources.

Considering the low environmental risk and relatively widespread occurrence of geothermal resources, the *nation* ought to expedite their exploitation.

6.0 Acknowledgements

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TABLE 1.

POWER GENERATION FROM GEOTHERMAL RESOURCES

UNITED STATES	The Geysers	608 MWe ~~502~~ MW	The Geyser Nov 30, 1979
	early 1980 ~~Late 1979~~	~~908~~ 798	
	1981	(1128)	
ITALY		417	
NEW ZEALAND		202	
MEXICO		78	
JAPAN		70	
USSR		6	
ICELAND		3	
El Salvador			

TABLE 2.

SOME DIRECT HEAT USES

TEMP.	BASIC USE	EXAMPLES
10-20°C	Ground Warming	Roads, Parking Lots, Crop Advancing
25-45°C	District Heating	Homes, Offices, Schools, Warehouses
45-55°C	Fish Culture	Prawns, Catfish
75-85°C	Greenhouses	Food Crops, Shrubs, Flowers, Trees
75-80°C	Crop Processing	Hay Drying
90-100°C	Vegetable Dehydration	Potatoes, Onions
105-115°C	Kiln Drying	Lumber
110-120°C	Food Canning	Fruits, Vegetables
120-130°C	Alfalfa Dehydration	Pellets
150-160°C	Gasohol Production	Alcohol from Sugar Beets

TABLE 3.

DOE GEOTHERMAL ENERGY GOALS

ELECTRIC POWER GENERATION

1985	3,000 MEGAWATTS	or	0.2 QUADS/YR
2000	20,000 MEGAWATTS	or	1.3 QUADS/YR

DIRECT HEAT

1985	0.2-0.3 QUADS/YR
2000	1.5-3.5 QUADS/YR

1 QUAD = 10^{15} BTU

CURRENT U.S. CONSUMPTION = 79 QUADS/YR

TABLE 4.

LOW TEMPERATURE HYDROTHERMAL RESERVOIR PROBLEMS

- RESERVOIR UNCERTAINTY
- USER IDENTIFICATION
- PUBLIC AWARENESS
- PROFITABILITY
- GEOTHERMAL DISTRICT DELINEATION

TABLE 5.

HIGH TEMPERATURE HYDROTHERMAL RESERVOIR PROBLEMS

- RESERVOIR LONGEVITY
- UTILITY PRIORITIES
- EXPLORATION & ASSESSMENT TECHNOLOGY DEFICIENCIES
- RESERVOIR DELINEATION
- GEOTHERMAL DISTRICT DELINEATION
- INSTITUTIONAL PROBLEMS

FIGURE CAPTIONS

Figure 1. The major units of the earth's interior: inner core, outer core, lower mantle, upper mantle, and crust. The crust and the upper 100 km or so of the mantle together form rigid lithospheric plates which shift on the earth's surface, causing continental drift.

Figure 2. Mid-oceanic spreading ridges (double lines), subduction zones at plate boundaries (heavy barbed lines), and transform faults (light lines off-setting double lines). Circles are locations of major geothermal systems. (After White 1973).

Figure 3. Global map shows heat flowing from the earth's interior on a regional scale. Contours are in milliwatts per square meter. (After Chapman and Pollack 1975).

Figure 4. Schematic illustration of a convective hydrothermal system (after White 1973).

Figure 5. Typical temperature versus depth curves for an area of normal heat flow and one of high heat flow. High temperatures are reached at shallower depths in the high heat flow area.

Figure 6. Pictorial representation of a radiogenic geothermal resource type. The thermally insulating sedimentary blanket traps the heat produced in the granitic intrusive by radioactive decay of potassium, uranium, and thorium.

Figure 7. Illustration of the principle of extracting geothermal heat by means of a hot dry rock experiment. A well is drilled and fluids are pumped down it at sufficient pressure to fracture the rock hydraulically . A second well is directionally drilled into the

fracture zone. Cold domestic water is pumped down one well, becomes heated, and is pumped up a second well.

Figure 8. Schematic of pressure and temperature in a geopressured geothermal resource. The water in the sand aquifer is at an elevated temperature, is subject to a fluid pressure above the hydrostatic head, and contains dissolved methane.

Figure 9. A dry steam power plant uses the steam directly to power a turbine which in turn drives an electric generator. Through a condenser and a cooling tower the spent steam is converted to water which is reinjected into the ground. The Centrafix is used to remove the occasional rock fragment brought up with the steam.

Figure 10. A single flash steam power plant separates the brine from the steam, utilizing the steam to drive the turbine and reinjecting the waste brine.

Figure 11. A double flash steam power plant operates the same as a single flash unit except that the waste brine from the first separator is allowed to flash to steam at a lower pressure and this steam drives the second stage or low pressure turbine. Efficiency is increased by this process but so are costs.

Figure 12. In a binary cycle power plant the heat of the geothermal fluid is transferred to the working fluid (isobutane) which is used to drive a compact turbine.

Figure 13. In a flash binary cycle power plant the flashed steam heats the working fluid which is used to drive a compact turbine.

Figure 14. Surface heat exchanger used in direct heat applications. The corrosive geothermal fluids are pumped to the surface to heat domestic

water which is then used in various forms of radiators (after Hannah, 1975).

Figure 15. Downhole, or hairpin, heat exchanger used in direct heat applications. The cold domestic water is fed down the first leg of the hairpin pipe where it is heated by the geothermal fluid and convects up the second leg of the hairpin pipe whereupon it is directed to various forms of radiators (after Hannah, 1975).

Fig. 1

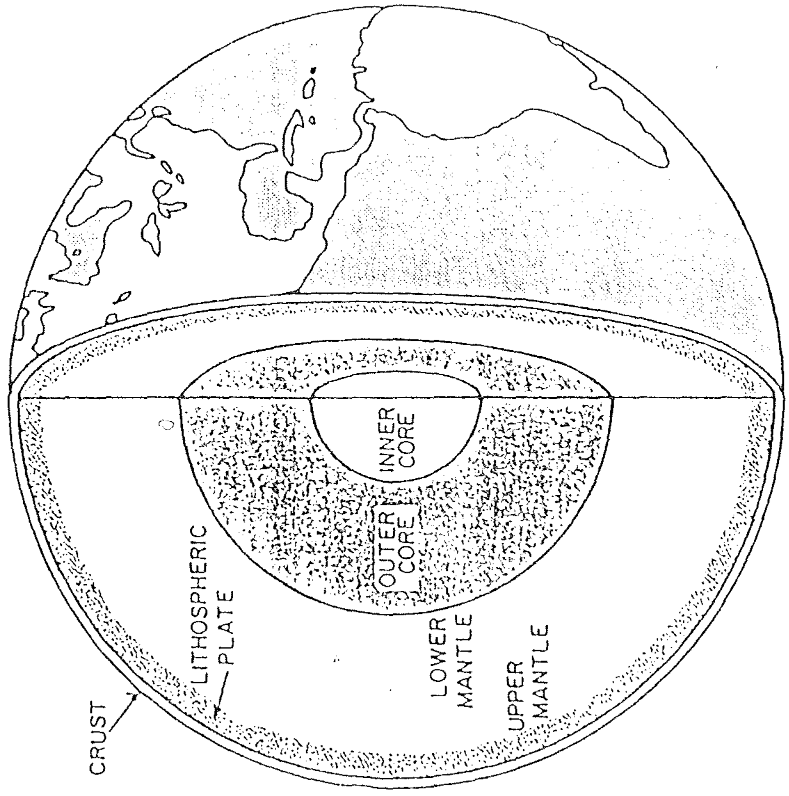
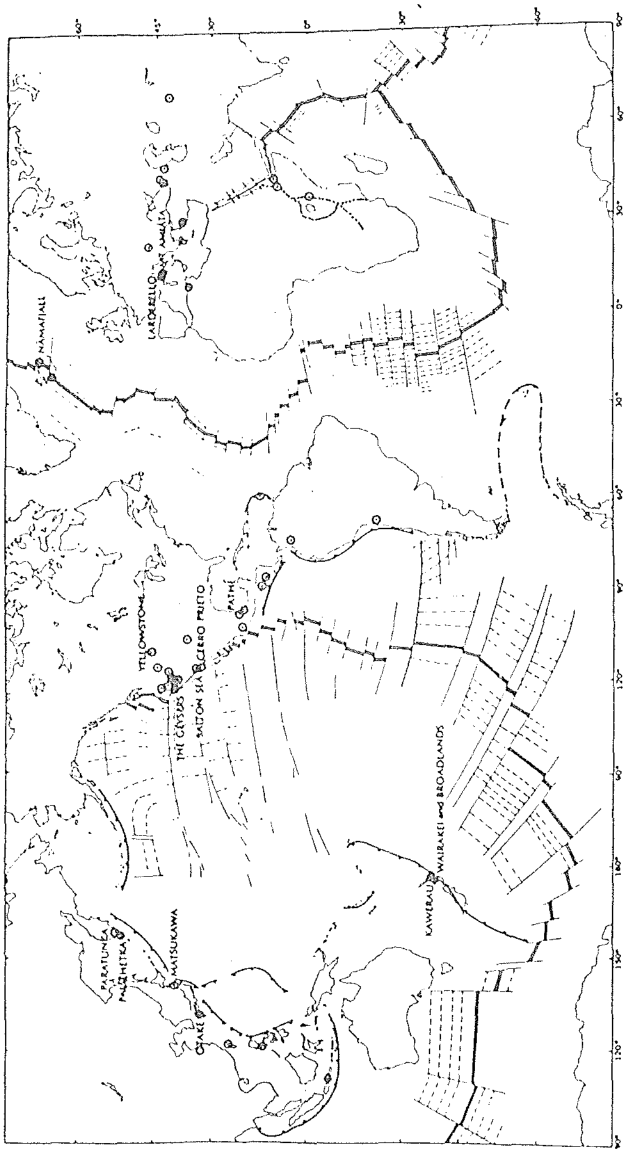

CRUST
LITHOSPHERIC PLATE
LOWER MANTLE
UPPER MANTLE
OUTER CORE
INNER CORE

Fig. 2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MT. AMIATA
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THE GEYSERS
SALTON SEA
CERRO PRIETO
PATHÉ
KAWERAU
WAIRAKEI and BROADLANDS
PARATUNKA
PAUZHETKA
MATSUKAWA
OTAKE

Fig. 3

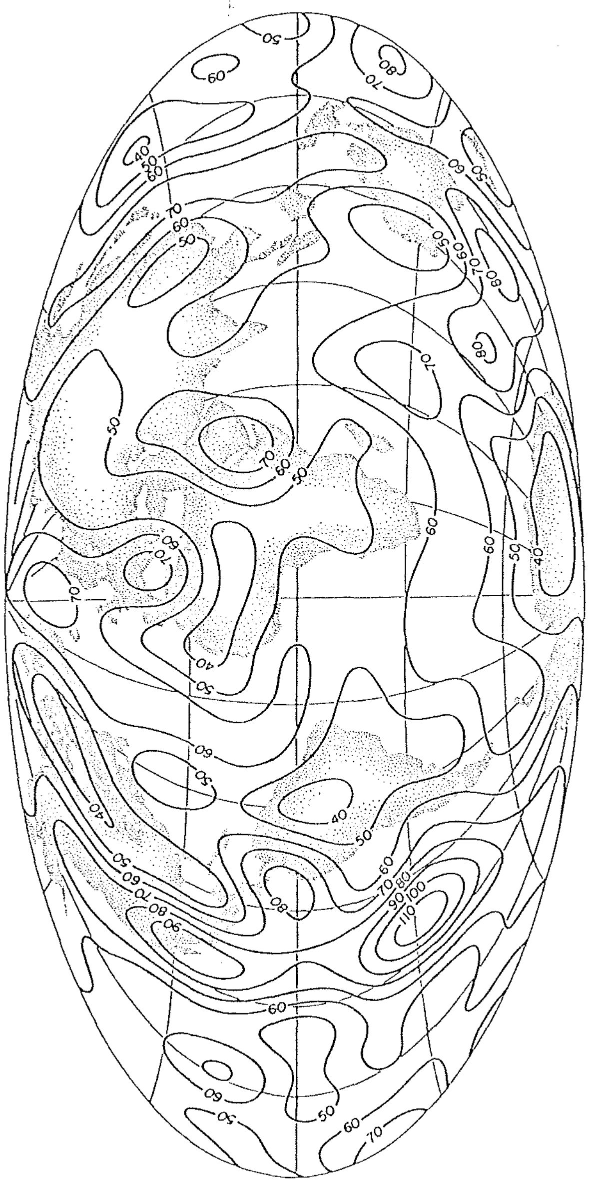

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Fig. 4

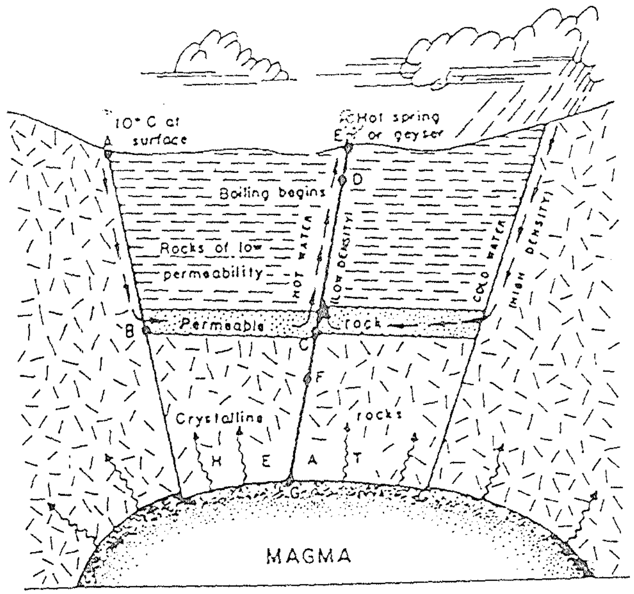
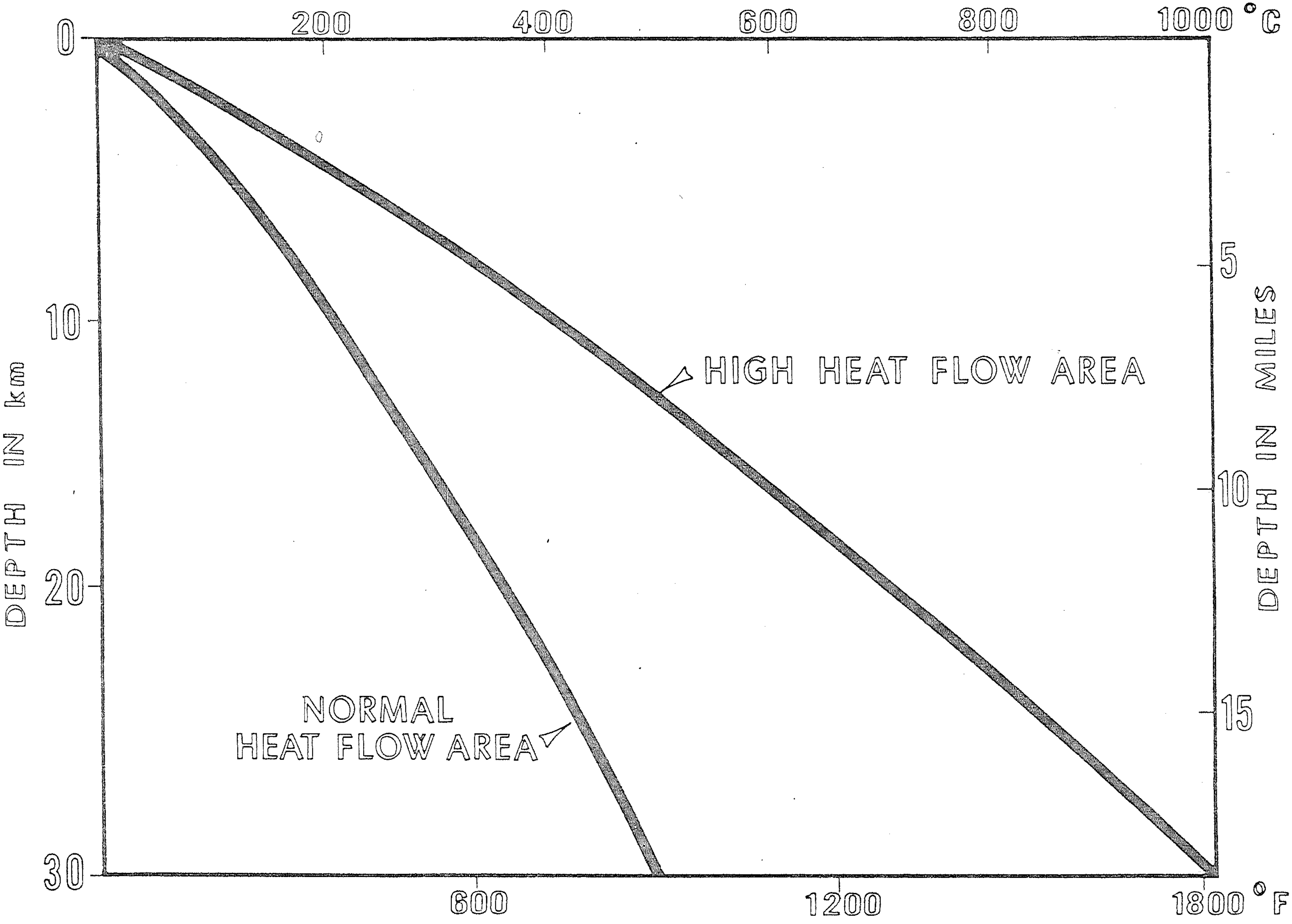

A
10° C at surface
E
Hot spring or geyser
D
Boiling begins
Rocks of low permeability
HOT WATER
(LOW DENSITY)
COLD WATER
(HIGH DENSITY)
B
Permeable rock
C
F
Crystalline rocks
H E A T
G
MAGMA

Fig. 5

TEMPERATURE VS DEPTH IN EARTH



RADIOGENIC GEOTHERMAL RESOURCE

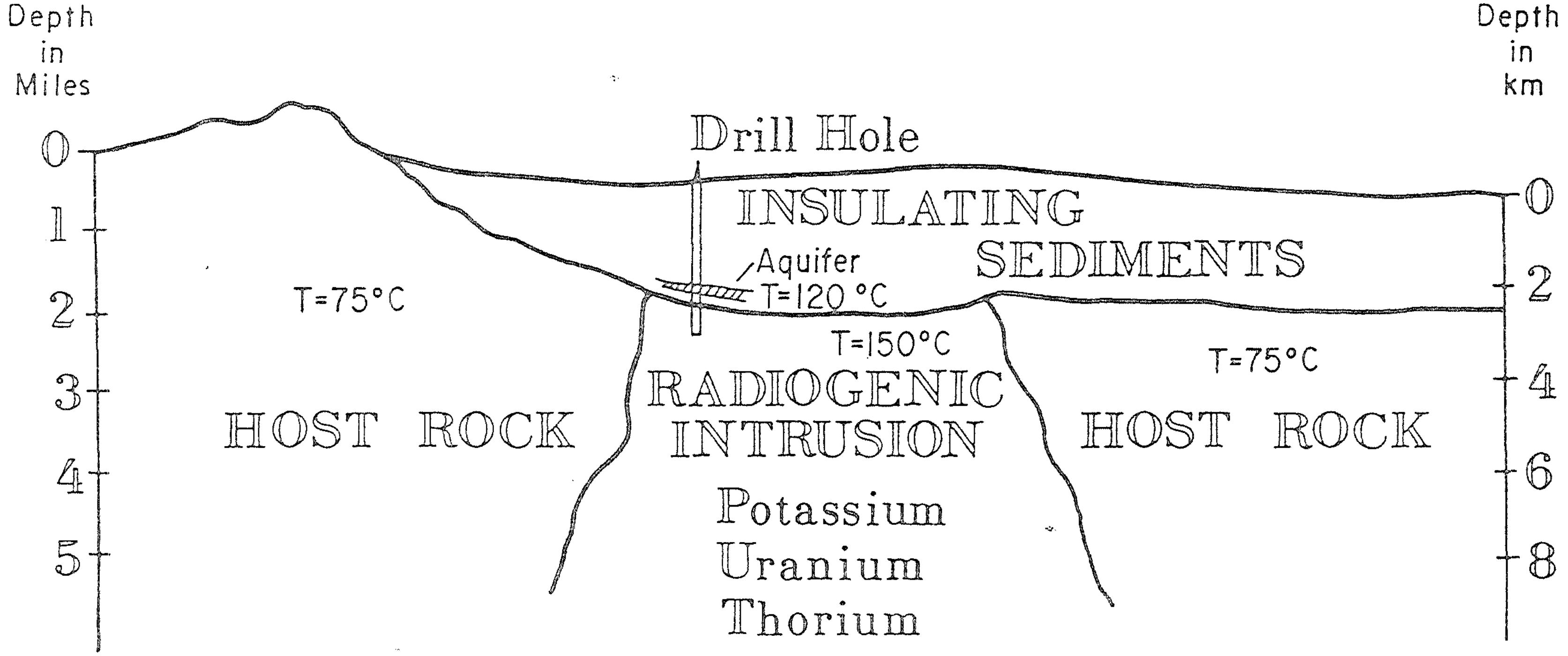
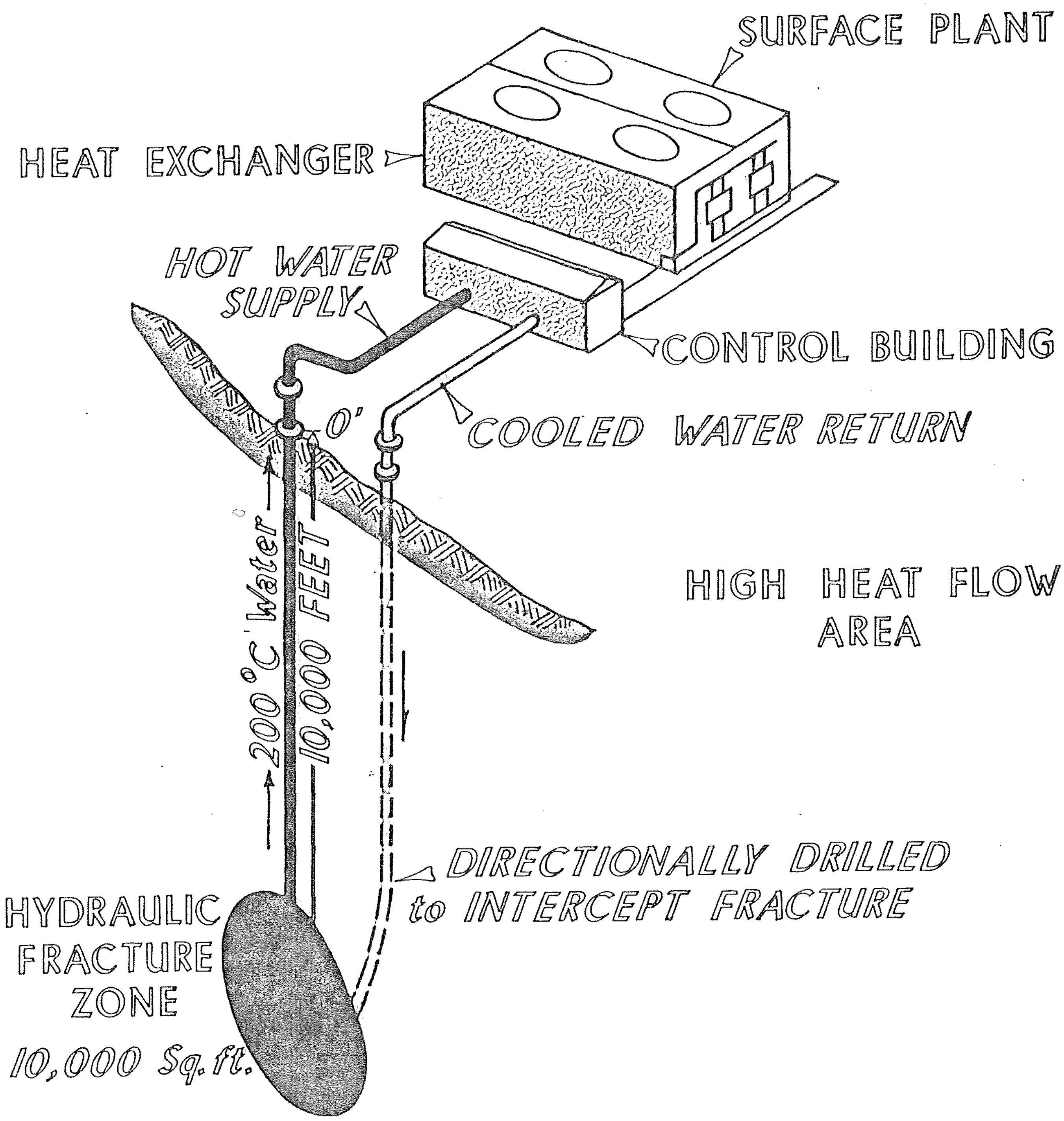
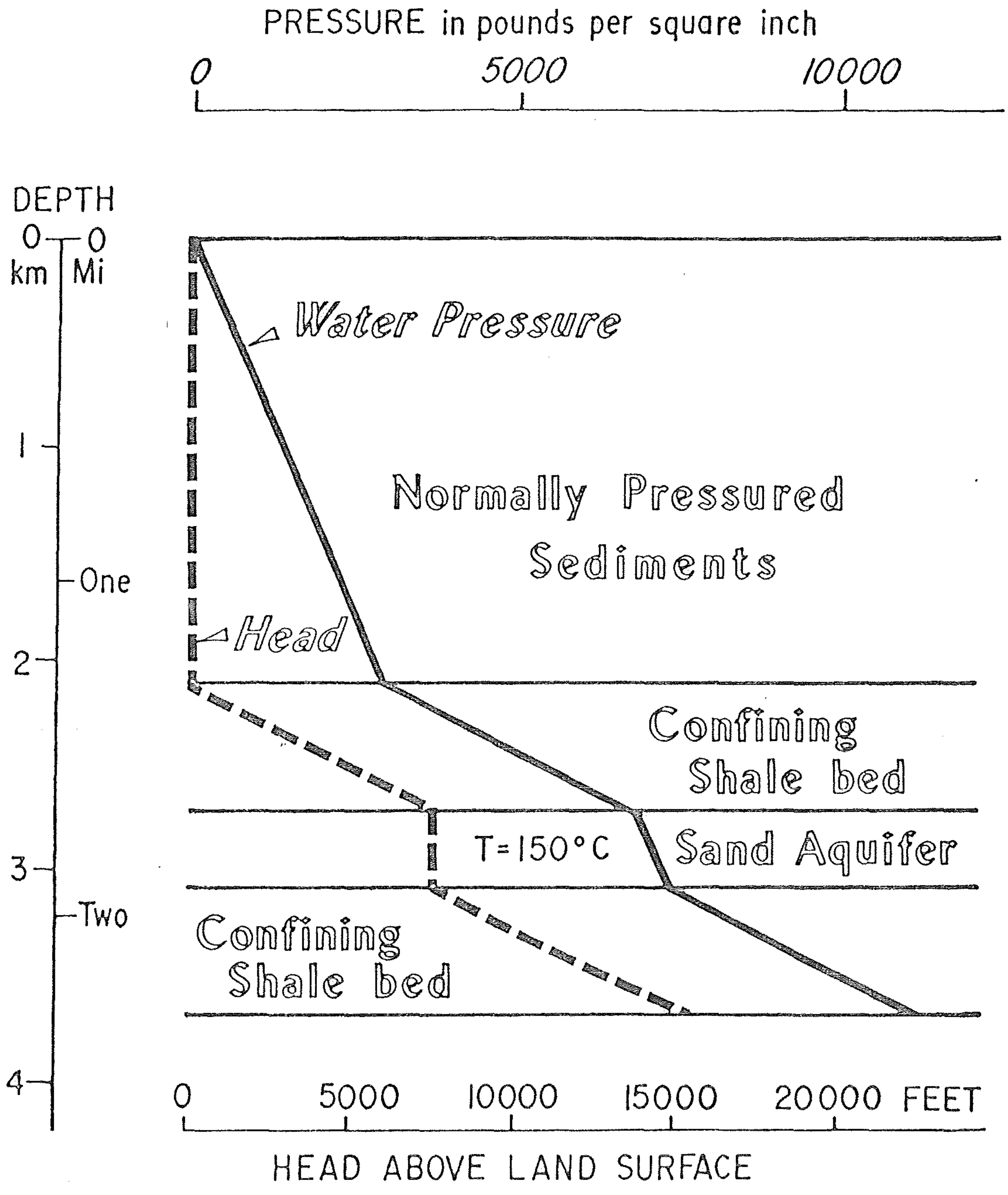


Fig. 6



HOT DRY ROCK GEOTHERMAL RESOURCE

GEOPRESSURED GEOTHERMAL RESOURCE



DRY STEAM POWER PLANT

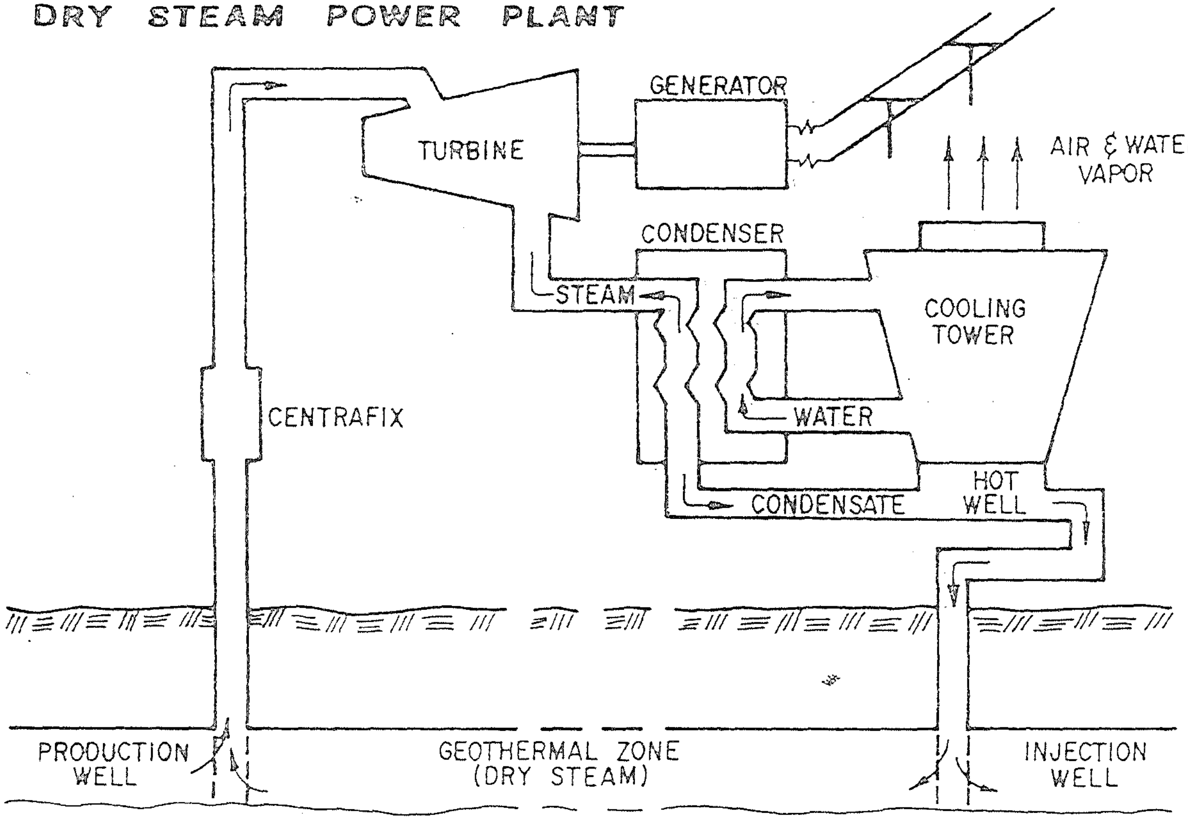


Fig. 9

FLASH STEAM POWER PLANT

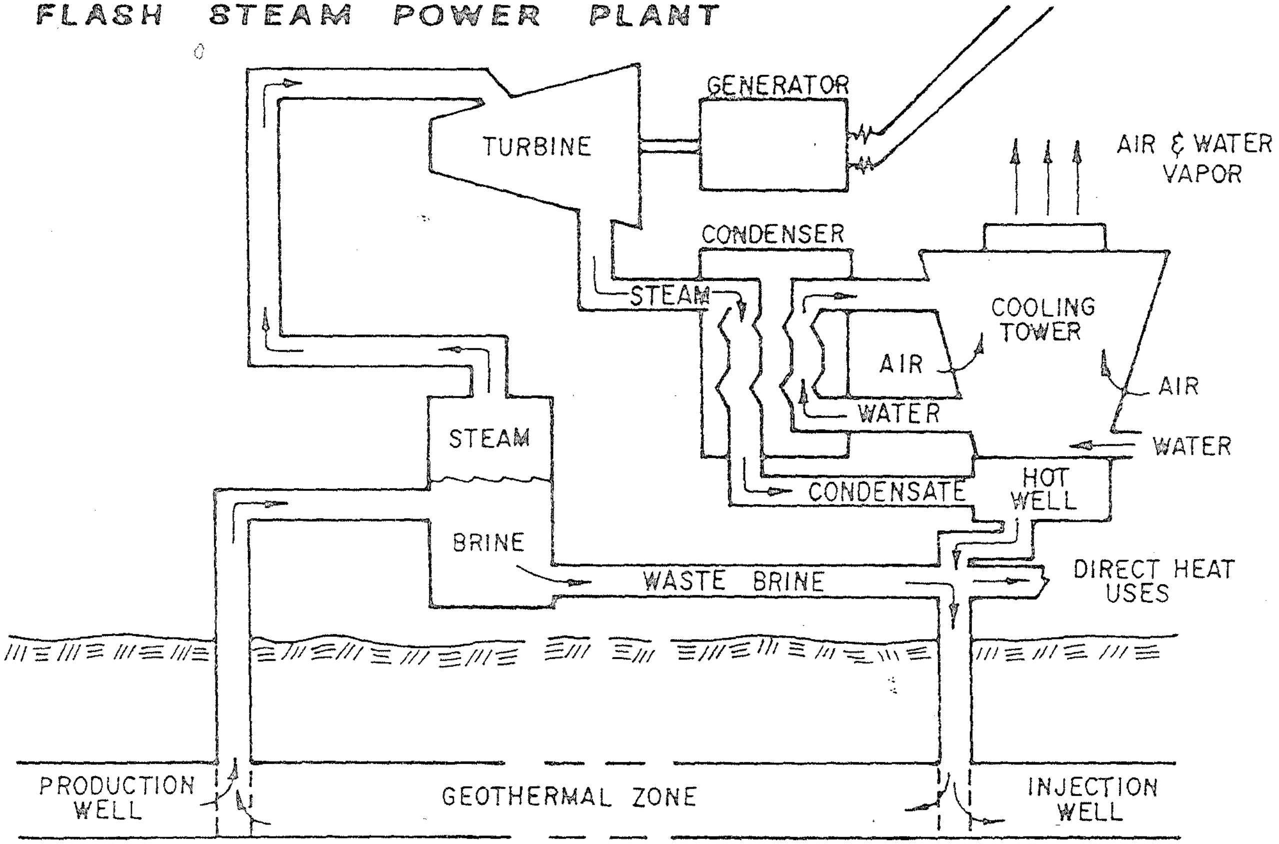


Fig. 10

DOUBLE FLASH POWER PLANT

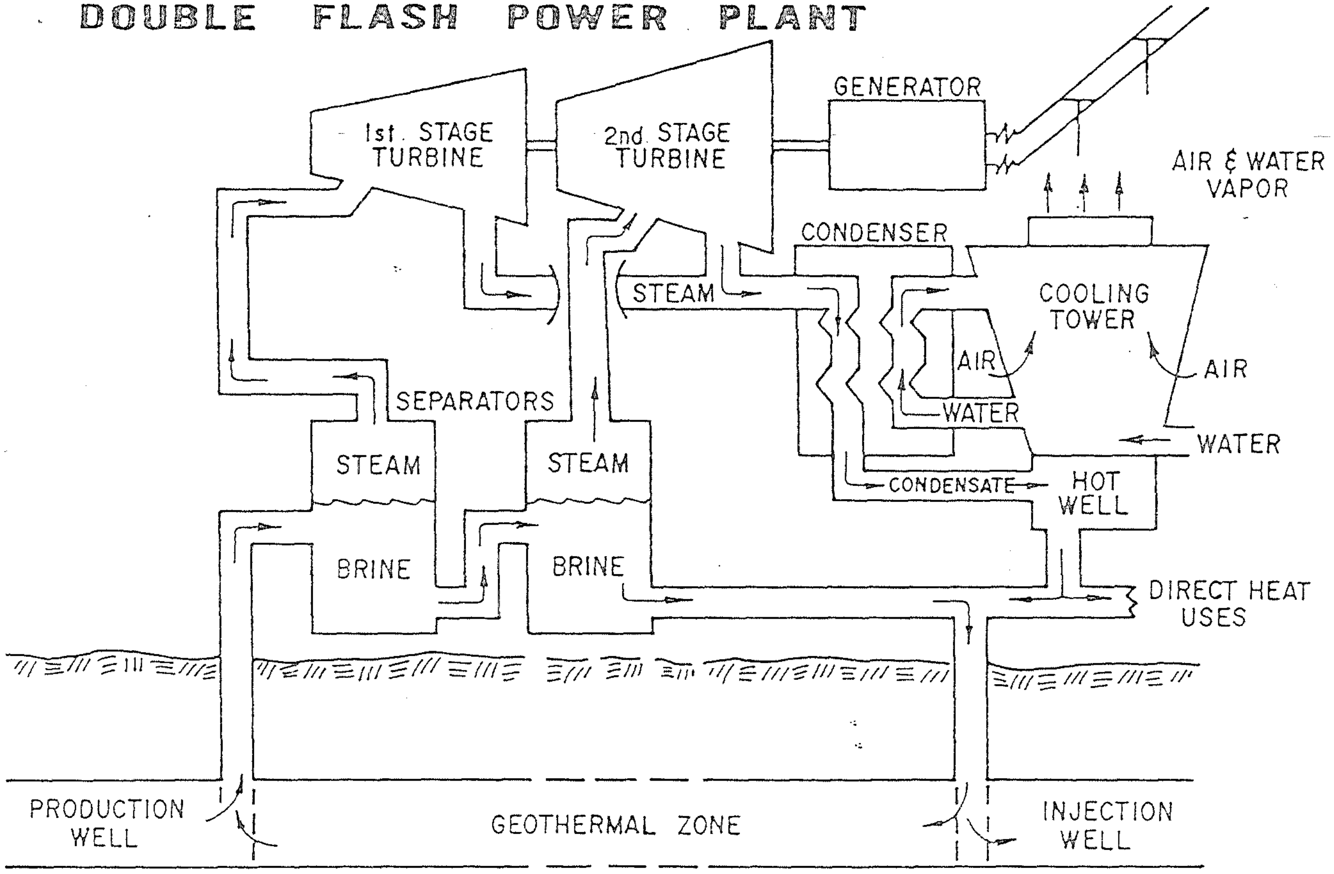


Fig. 11

BINARY CYCLE POWER PLANT

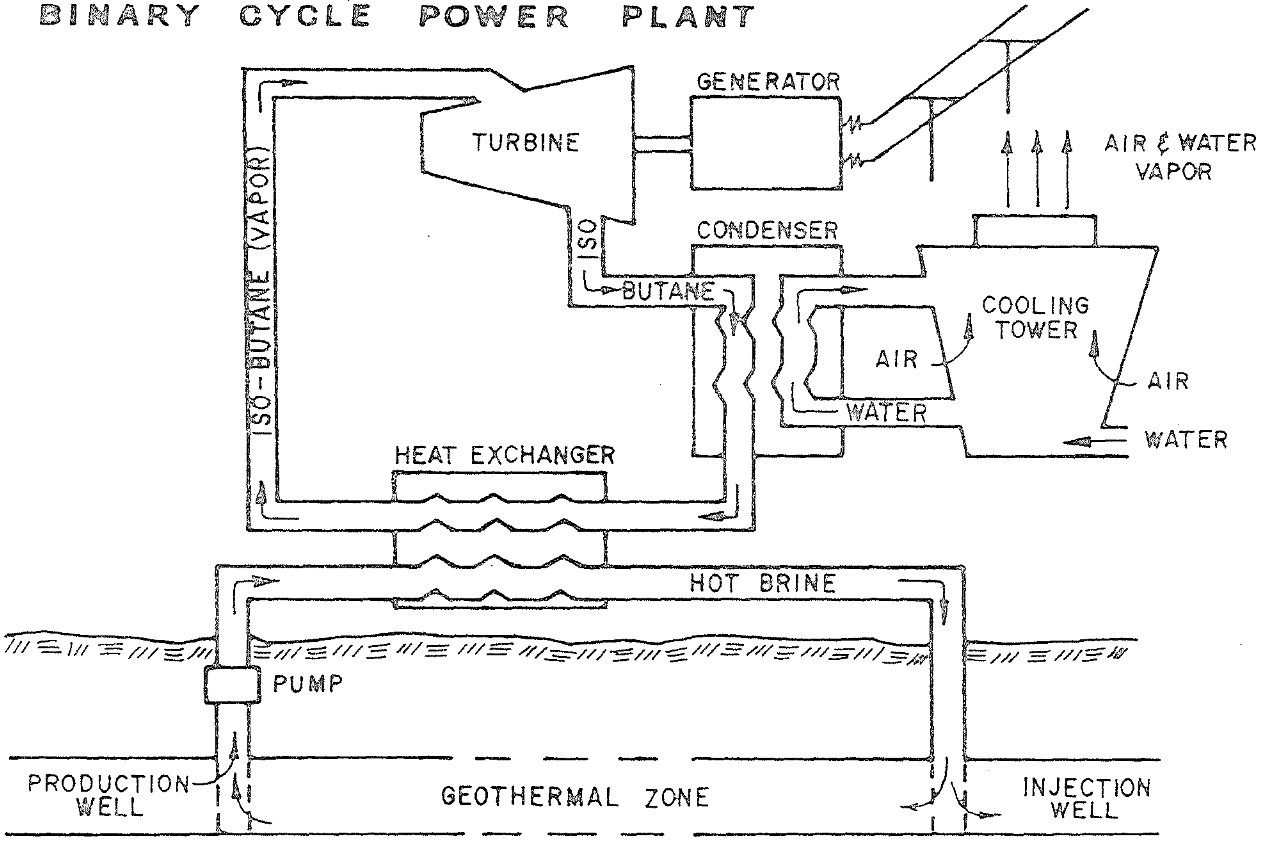


Fig. 12

FLASH BINARY POWER PLANT

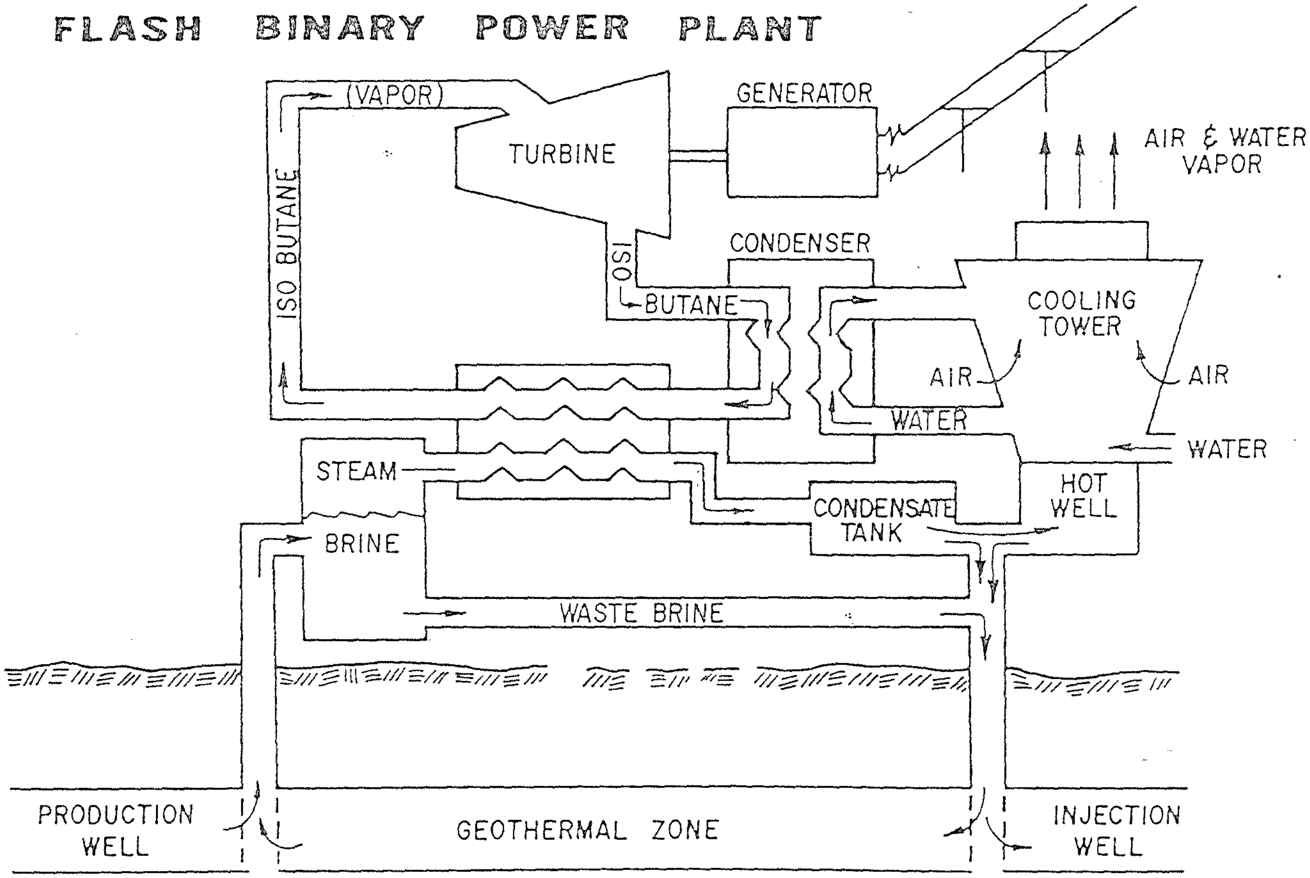
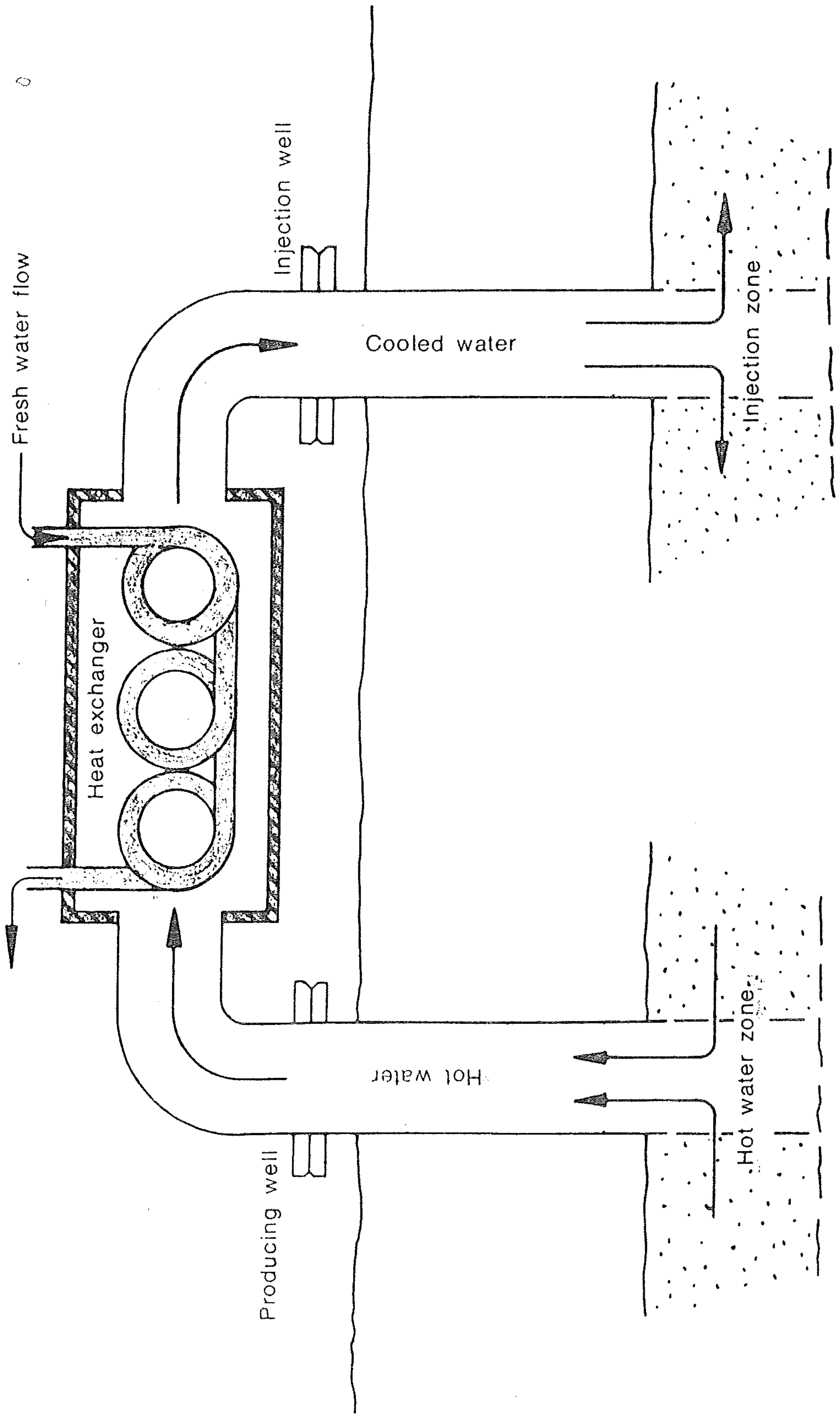


Fig. 13

Fig. 14


Fresh water flow
Injection well
Cooled water
Injection zone
Heat exchanger
Hot water
Hot water zone
Producing well

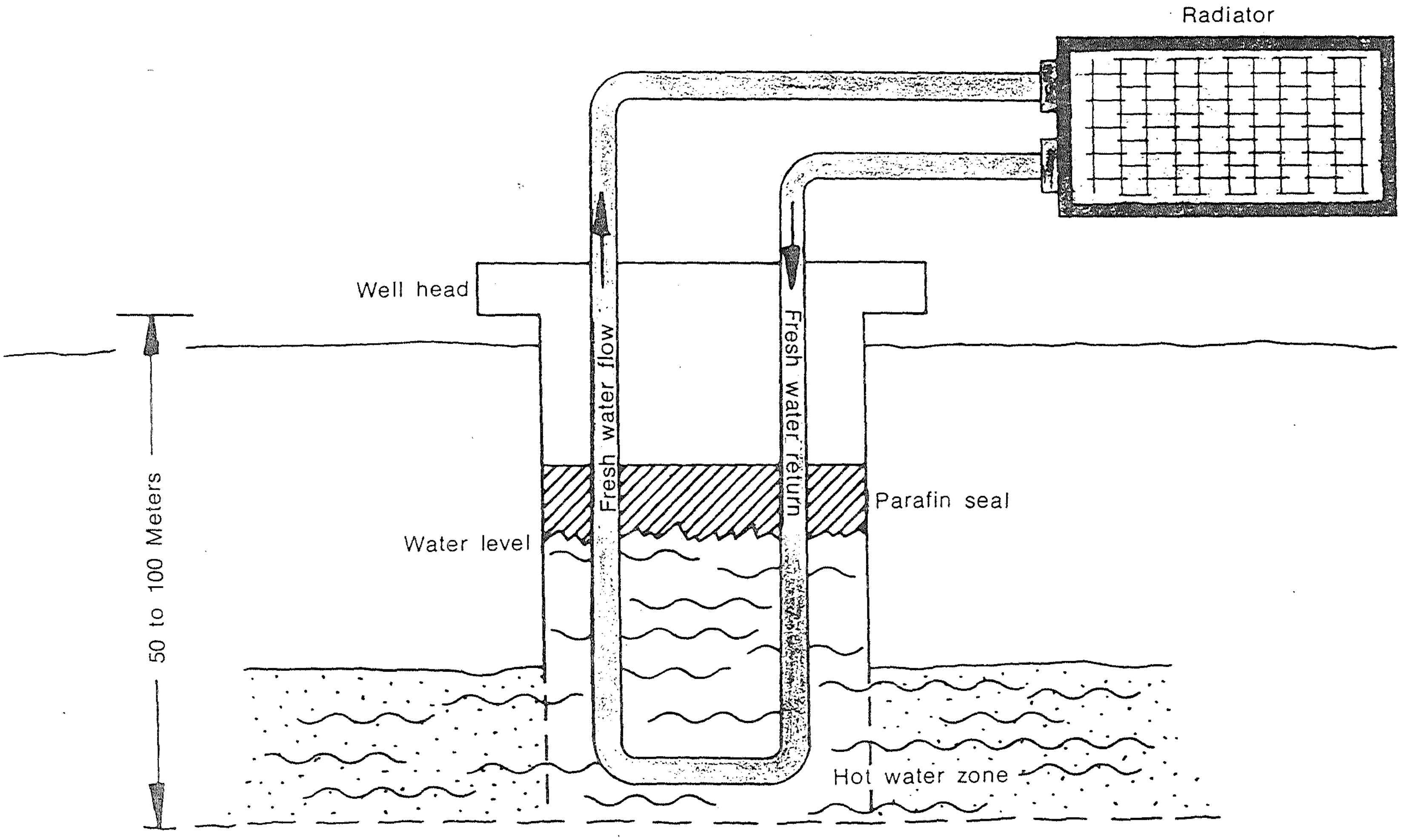

Radiator
Well head
Fresh water flow
Fresh water return
Parafin seal
Water level
Hot water zone
50 to 100 Meters

Fig. 15