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Geothermal Energy

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By Donald E. White

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ABSTRACT

The earth is a tremendous reservoir of heat, most of which is too deeply buried or too diffuse to consider as recoverable energy. Some large areas are higher-than-"normal" in heat content, particularly in regions of volcanic and tectonic activity. Recovery of stored heat from these large areas may be economically feasible in the future but cannot compete in cost now with other forms of energy.

Certain hot spring areas, commonly near active or recently active volcanoes, are discharging heat at rates per unit area of 10–1,000 times the "normal" (1.5×10^{-6} calories per square centimeter per second) heat flow of the earth; some of the largest and hottest areas have been explored for geothermal energy. These areas are characterized by high permeability, at least locally on faults, fractures, and sedimentary layers; this high permeability permits fluid circulation, most of the total heat flow being transported upward in water or steam. The circulation has produced reservoirs of stored heat closer to the earth's surface than is normally possible by rock conduction alone. Local near-surface thermal gradients are typically very high, but the gradient decreases greatly, and even reverses, at greater depths in any single drill hole.

Some other geothermal systems are here considered as a composite type. Near-surface caprocks are low in permeability, and temperatures in these rocks are therefore controlled dominantly by conduction. Beneath the insulating caprocks, permeable reservoir rocks may permit convective transfer of fluids and heat. Natural hot springs are small and relatively unimpressive in a composite system because little fluid escapes. Temperatures near the surface are low but increase steadily with depth, in contrast to hot spring systems that have vigorous near-surface circulation and, therefore, high near-surface temperatures.

Some undiscovered geothermal systems may be composite in type. Because the near-surface permeabilities are so low that no fluid escapes, the principal evidence of such a system will be abnormally high geothermal gradients and heat flows distributed over a relatively large area.

Geothermal energy stored in the upper 10,000 feet of many hot spring systems is 1,000–10,000 times the annual natural heat flow at the surface. Most of these hot spring systems, therefore, have appreciable age and stability relative to human activity. Energy is being recovered from some commercially developed hot spring areas at rates of five to more than 10 times their rates of natural heat flow prior to development. Such overdrafts, in at least some systems, can continue for many years, the excess heat being supplied from the heat reservoir. Eventually, depending on the characteristics of each individual system, the effects of sustained overdraft must become evident.

Present world utilization of geothermal energy is about 1 million kw (kilowatts) or 7.5×10^{15} cal/yr (calories per year), and this amount can probably be increased 10–100 times for at least the next 50 years. Potential reserves to depths of 3 km (kilometers) recoverable at or near present costs (1 percent of total assumed recoverable) are estimated to be 2×10^{19} cal; resources to depths of 10 km recoverable at much more than present costs are estimated to be 1×10^{22} cal. Of the total world resources of geothermal energy, probably 5–10 percent occurs in the United States; the areas of highest potential are in the Western States.

INTRODUCTION

Geothermal heat supplies only a very minor fraction of present domestic and world use of energy. In the United States, a geothermal steam powerplant generating 28,000 kw (kilowatts) of electricity (McNitt, 1963, p. 14) is now operating at The Geysers in California, and many other areas are being actively explored; hot spring water is also used locally for space heating. Total utilization of geothermal energy in the world today is roughly equivalent to a production capacity of 1 million kw, and approximately half of this total has been developed in the past 15 years. In the future, geothermal energy is expected to be of considerable local significance, and of a much greater total quantity than now, but it is not likely to rank as one of the major sources of energy.

This brief survey of geothermal energy is hampered by a serious lack of reliable data. Scattered bits of information, generally consisting of a few temperature measurements, are available for individual wells; heat flow has also been estimated or measured semiquantitatively in a few thermal spring systems.

In this report, four types of thermal systems are considered; each is gradational into at least one of the other types:

1. Areas of "normal" geothermal gradient and heat flow.

2. Large areas of higher-than-"normal" geothermal gradient and conducted heat flow.

3. Hot spring areas, characterized in their upper parts by convective transport of most of the total heat flow in circulating water or steam.

4. Composite hydrothermal systems involving in their upper parts convective and conductive heat transfer of types 2 and 3. Near the surface heat is transferred largely by conduction through rocks of low mass permeability that permit little or no discharge of water or steam. Temperatures immediately below the insulating layers are too high to be explained by conductive heat flow alone; circulating fluids are the indicated major agents of heat transfer.

Types 3 and 4, grouped together as the hydrothermal types, are particularly important for geothermal energy because they provide heat reservoirs relatively near the surface and because they also insure a natural fluid for transferring heat from the reservoir to the powerplant. The importance of this natural fluid is considered in a later section of this report.

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The author is indebted to many individuals. Particularly noteworthy have been contributions of Gunnar Bodvarsson of Iceland and James Healy and John Banwell of New Zealand. Arthur H. Lachenbruch of the U.S. Geological Survey has been very helpful in many ways, specifically suggesting the concept of volumetric specific heat. The author's opportunities to study relationships at depth in many different geothermal systems were made possible through generous cooperation of domestic companies and individuals, but the author takes responsibility for the interpretations contained in this report.

AREAS OF "NORMAL" GEOTHERMAL GRADIENT

The earth as a whole is a tremendous reservoir of thermal energy but most of this energy is too deeply buried or too diffuse to justify consideration as an energy resource. Calculations of internal earth temperatures and of total quantity of heat are very different, depending upon assumptions concerning the origin of the earth, the total amount and distribution of radioactivity, and other factors (Gutenberg, 1951; Birch, 1955; Jacobs, 1956; Verhoogen, 1960; Wyllie and Tuttle, 1960; Clark, 1961; Ringwood, 1962). Nevertheless, the general order of magnitude of thermal energy within the earth at depths now accessible by drilling, or that may become accessible, is of some value to the purpose of this report.

The global average heat flow is about 1.5×10^{-6} cal/cm^2/sec (hereafter referred to as 1.5 heat-flow units); the calculated continental average from sparse data is slightly higher (1.65 units) (Lee and MacDonald, 1963).

The heat stored above surface temperatures in the outer 100 km (kilometers) of the earth is about 2×10^{28} cal.[1] This amount of energy is equivalent to the heat lost by conduction at the surface of the earth for nearly 100 million years, to solar radiation received by the earth for 10,000 years, to 2×10^{22} kwhr (kilowatt hours); or to the heat content of 3×10^{18} short tons of coal.

Wells have been drilled to depths of about 8 km and drilling can now attain a maximum of about 10 km. Heat stored under the surface of the earth to a depth of 10 km is about 3×10^{26} cal. Heat stored under the United States to the same depth is about 6×10^{24} cal, which is equivalent to conductive heat transfer from the United States for nearly $1\frac{1}{2}$ million years, or to solar radiation received by the United States for approximately 200 years; this heat is also equivalent to about 5×10^{18} kwhr or the heat content of 9×10^{14} short tons of coal.

The heat content of rocks in areas of "normal" geothermal gradient is an extremely low-grade source of energy. In the preceding calculation the heat is assumed to

[1] See section on "Assumptions, statistics, and conversion factors".

be dispersed through about 100 million cubic kilometers of rock underlying the United States. The average heat content available in excess of surface temperatures is about 60 cal/cm^3 of rock or approximately 20 cal/gram in the outer 10 km of the earth. This is only 0.3 percent of the heat content of 1 g (gram) of coal, and less than 0.01 percent of the heat equivalent of fissionable uranium and thorium in 1 g of average granite.

LARGE AREAS OF HIGHER-THAN-"NORMAL" GEOTHERMAL GRADIENT

Major regional differences have been found in the U.S.S.R. (Khitarov, 1956, 1959, 1961). Kraskovskiy (1961) concluded that the heat flow from large areas of old crystalline rocks of the world is only about 0.9 unit. Heat flow has been determined recently at 39 localities in the islands comprising Japan and at 12 places in the surrounding seas (Horai and Uyeda, 1963). The average heat flow on the islands of Japan is 1.55 units and at sea 1.48; both of these figures are very close to the global average of about 1.5. Heat flow is higher (>2.00 units) than the Japanese average on the concave (western) side of the arc formed by the Japanese islands, and relatively low (<1.00 unit) on the Pacific Ocean side of northeastern Honshu. The Precambrian shield of Australia has an average heat flow of 1.0 unit, and areas surrounding the shield average about 2.0 units (Howard and Sass, 1964). The Hungarian basin, which is composed of Tertiary and older rocks, is an isolated geothermal high (about 2.4 units) surrounded by areas of nearly "normal" heat flow (Boldizsar, 1964). Bodvarsson (1957) estimated a heat flow of 4.7 units in those parts of Iceland that lack Quaternary volcanism.

Prior to 1964, very little was published on regional variations in North America. Garland and Lennox (1962, p. 246) plotted the distribution of all values published prior to 1962. Heat flow from the Great Lakes region and the Precambrian Shield averages about 1.0 unit for four localities. Seven localities in western North America have an average of 1.4.

The structural trench of the Gulf of California extending northwestward from Mexico into the Imperial and Coachella Valleys of California is an example of a large area that has higher-than-"normal" heat flow. Von Herzen (1963) found a mean of 3.1 units for 13 measurements in the Gulf of California; this mean is about 2 times the global average. Throughout the Imperial Valley abnormally high temperatures have been reported in all deep oil-test wells for which data are available. At least 10 wells from 4,000 to more than 13,000 feet deep have been drilled southeast to west of Salton Sea (not including geothermal exploration wells). Reported temperatures in the oil-test wells range from only slightly higher to about 3 times more than temperature increases expected from an average geothermal gradient. The sediments of this basin area are largely fine-grained siltstones and claystones, and their thermal conductivities are probably somewhat lower than average. Nevertheless, a large area about 60 miles long and 25 miles wide within the United States probably has an average heat flow at least $1\frac{1}{2}$ times "normal".

A large "hot spot" on this broad geothermal high lies immediately southeast of Salton Sea and is a composite hydrothermal system, a type discussed in a following section.

Although volcanic eruptions are now rare in the United States, except in Hawaii and the Aleutian Islands, many areas in the Western States have had extensive volcanic activity in the last few million years. Each of these areas is a likely place for much stored heat in excess of "normal," and some areas may still have molten magma at depths of less than 10 km. The available heat of granitic magma in excess of the mean surface temperature is about 7×10^{17} cal/km^3 (See footnote 1), which is the heat equivalent of about 100 million tons of coal. Many old magma chambers, now cooled and exposed at the surface by erosion, are tens to hundreds of cubic kilometers in volume; the chamber supplying the Steamboat Springs, Nev., thermal system is calculated to have a minimum volume of 50 km^3 (White, 1957a, p. 1642) and an original heat content equivalent to at least 5 billion short tons of coal.

Brown and Silver (1956) suggested that granite may someday be mined for the energy of its contained uranium. Average granite is very unlikely ever to be mined for its uranium content, perhaps 4 ppm (parts per million), but after higher grade energy ores are exhausted, large volumes of rock with 10, 20, or 50 ppm of uranium may be utilized, as determined by future needs and economics. Similarly, if man ever has a critical need for geothermal energy, he can search for and find large areas of more than "normal" heat content.

If the recovery of heat from underground nuclear explosions is a possibility, the recovery of heat from magma chambers or from hot rocks is also likely. Some of the problems of recovery are considered in a later section.

HOT SPRINGS AREAS

Certain "hot spots" of the earth, generally near areas of Recent or Pleistocene volcanism, are discharging heat at rates of 10 to more than 1,000 times that of areas of "normal" heat flow of comparable size. These are hot spring areas characterized by physical transport of most of the total heat flow in water or steam. In such areas, much higher temperatures exist at and very near the earth's surface than is possible where heat is transferred by rock conduction alone.

One of the most useful parameters of a hot spring system is its natural rate of heat flow before commercial development. This parameter is a first approximation of the minimum rate at which heat can be withdrawn in water or steam in a geothermal development (Benseman, 1959a; Bodvarsson, (1964a, b); it is also the most significant reference base for evaluating effects of accelerated withdrawal from a developed geothermal field. In low-temperature spring systems from which all circulating water is discharged at the surface and none escapes unseen below the surface, the approximate total heat flow is determined easily from discharge and temperature measurements. Fukutomi (1962) found that conducted heat flow from such low-temperature areas accounts for only 10 percent of the total and that discharging water accounts for about 90 percent. The total heat flow is much more difficult to determine where water escapes unseen below the surface (Benseman, 1959b), or where a large part of the total escapes in steam or by rock conduction (Benseman, 1959a; Dawson, 1964).

Table 1 contains almost all estimates and measurements of total heat flow published through 1962 for hot spring areas of the world. Some data are only approximate, and others, such as the later figures for Wairakei, New Zealand, are based on extensive study; even here, agreement among authors is not notably close. Some of the Wairakei data suggest that large withdrawals of hot fluids from wells result in at least a temporary increase in total "natural" heat flow from fumaroles and springs and by rock conduction. This situation is the reverse of what might be expected, but the author has observed an increase in "natural" heat flow after geothermal development at Steamboat Springs, Beowawe, and Brady Springs, Nev. This phenomenon can occur in a hot water system whose temperatures at depth are close to the boiling points for existing pressures. If discharge of fluids from wells results in a decrease in water level or hydrostatic pressure, the new temperature of boiling, at any given depth, is lower than the former temperature; excess heat previously stored in solid phases within the zone of change is now available to vaporize water. A temporary increase in flow of heat in activated fumaroles is eventually followed by a decrease if a steady-state relationship is again approached. The new steady-state "natural" heat flow (from all sources other than production wells) should be less than the natural heat flow prior to development of the area.

The large quantity of heat that has been stored in the heat reservoir of each hot spring system over a long period of time accounts for the fact that heat can be withdrawn from wells at a rate much greater than the natural heat flow. The heat content of the fluids does not decrease immediately if permeability and supply of fluid are adequate.

Only a very few estimates have been made of the magnitude of the heat reservoirs for individual hot spring systems. In some systems of very low discharge that have so little convective transfer of heat that heat conduction is the major mode of transfer, temperatures will rise continuously with depth (somewhat similar to fig. 3 of Donaldson, 1962). In most near-boiling hot spring systems, however, temperatures rise rapidly near the surface and then tend to level off as depth increases a few hundred feet (Banwell, 1963; Banwell and others, 1951; Bodvarsson and Palmason, 1964; White, 1964); little further increase in temperature is found within explored depths. The most reasonable explanation for the latter relations involves a large convection system of water that circulates below explored depths and attains a characteristic base temperature dependent on rates of flow of water and heat in the system (similar to the models of Donaldson, 1962, figs. 2, 6).

Table 1.—*Natural heat flows of some hot spring areas of the world*

[Estimates preceded by ~ are the author's and are based on published maps or other available data; other estimates are by the original authors. Hydrothermal areas of composite type in parentheses are not included in totals]

Area	Approximate size[1] (km^2)	Maximum recorded temperature[2] (°C)	Total heat flow[3] (10^6 cal/sec)	Source of data
British West Indies				
Qualibou, St. Lucia	~0.1	(S)185	8.6	Robson and Willmore(1955).
St. Vincent	~1	(S)>27	18	Do.
Dominica	~1	(S) 90	17	Do.
Montserrat	~.1	(S) 97	1.6	Do.
El Salvador				
Total of country	----------	----------	200	Durr (1964).
Northern belt, total	----------	----------	50	Do.
Southern belt, total	----------	----------	>150	Do.
Ahuachapán group	80	(D)174	80	Do.
El Playón de Ahuachapán	~.25	(S)boiling	.46	McBirney (1956).
Agua Shuca	~.25	(S)boiling	.32	Do.
Fiji Islands				
Savusavu	~1	(S)100	2	Healy (1960).
Iceland				
Steam fields, total heat flow	----------	----------	{ 630 1,000	Einarsson (1964). Bodvarsson (1964a).
Hengill, total	50	(D)230	55–80	Einarsson (1964).
Do	----------	----------	25–125	Bodvarsson (1964a).
Hengill, southern part only.	----------	(D)230	28	Bodvarsson and Zoëga (1964).
Torfajökull	100	(S)boiling	500	Bodvarsson (1964a).
Reykjanes	1	?	5–25	Do.
Trölladyngja	5	?	5–25	Do.
Krysuvik	10	(D)230	5–25	Do.
Kerlingafjöll	5	(S)boiling	25–125	Do.
Vonarskard	?	?	5–125	Do.
Grimsvötn	12	?	125–750	Do.
Kverkfjöll	10	?	25–125	Do.
Askja	25	?	5–25	Do.
Námafjall	2.5	?	25–125	Do.
Krafla	.5	(S)boiling	5–25	Do.
Theistareykir	2.5	(S)boiling	5–25	Do.
Low temperature areas; about 250 areas.[4]	----------	(D)146	100	Do.
Six lines of thermal springs, each.	----------	(S)100	5–25	Do.
Reykjavík	~5	(D)146	1.7	Bodvarsson and Zoëga (1964).
Reykir	~5	(D) 98	11	Do.
Deilartunga line, total	----------	(S) 100	25–125	Bodvarsson (1964a).
Deilartunga spring	----------	(S) 100	24	Do.

See footnotes at end of table.

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Table 1.—*Natural heat flows of some hot spring areas of the world*—**Continued**

Area	Approximate size[1] (km^2)	Maximum recorded temperature[2] (°C)	Total heat flow[3] (10^6 cal/sec)	Source of data
		Italy[5]		
(Larderello)	(~50)	((D)240)	(5)	(Composite type, see text; Burgassi, Battini, and Mouton, 1964; Boldizsar, 1963).
Ischia and Flegreian Fields	~10	(D)296	?	Penta and Bartolucci (1962).
(Monta Amiata)	(~3)	((D)165)	(?)	(Composite type, see text; Penta and Bartolucci, 1962).
Vulcano	~1	(D)194	?	Penta and Bartolucci (1962).
		Japan		
Otaki, Kyūshū	----------	(D)185	?	Saito (1964).
Atami, Shizuoka-ken	5	(D)180	16	Watanabe (1958).
Do	----------	---------	22	Murozumi (1960).
Ito, Shizuoka-ken	----------	---------	44	Do.
Obama, Nagasaki-ken	1.5	(D)180	57	Watanabe (1958).
Beppu, Ōita-ken	~10	(D)150	19	Do.
Kawayu, Hokkaido	.7	(S) 65	8	Do.
Yunokawa, Hokkaido	~1	(S) 66	4.0	Fukutomi (1962).
Yachigashira, Hokkaido	?	(S) 69	.5	Do.
Shikabe, Hokkaido	~.5	(D)113	1.2	Do.
Toyako, Hokkaido	~3	(S) 55	2.2	Do.
Noboribetsu, Hokkaido:				
Hot Lake area, total	~.2	(D)112	14	Do.
Jigokudani Valley (variable)	~.3	(D)160	~6–11.2	Do.
Matsukawa, N. Honshu	----------	(D)189	?	Saito (1964).
Onikobe, N. Honshu	~80	(D)185	?	Do.
Narugo, N. Honshu	----------	(D)175	?	Do.
		Mexico		
Pathé, Hidalgo	~2	(D)155	?	Penta and Bartolucci (1962).
Ixtlan, Michoacan	----------	(D)150	?	Anda, Isita Septien, and Ruiz Elizondo (1964).
		New Zealand		
Wairakei, 1951, 1952	7	(D)266	133	Banwell (1955, p. 50).
1954	7	(D)266	[6]82	Ellis and Wilson (1955).
1956?	7	(D)266	143	Benseman (1959a).
1958, 1959	7	(D)266	163	Thompson, Banwell, Dawson, and Dickinson (1964).
1958	7	(D)266	101	Fisher (1964).
Waiotapu	~15	(D)295	272	Benseman (1959a).
Orakei Korako	~5	(S)boiling	130	Do.
Tikitere	5	(S)boiling	40	Ruiz Elizondo (1964; original data not accessible).

See footnotes at end of table.

Table 1.—*Natural heat flows of some hot spring areas of the world*—Continued

Area	Approximate size[1] (km^2)	Maximum recorded temperature[2] (°C)	Total heat flow[3] (10^6cal/sec)	Source of data
New Zealand—Continued				
Tokopia	----------	---------	30	Ruiz Elizondo (1964; original data not accessible).
Waikiti	----------	(S) 91	20	Do.
Ngatamariki	~1	(S)hot	12.6	Gregg (1958).
Rotokaua	~5	(S)boiling	52	Do.
Ohaki	~1	(S)boiling	12.8	Do.
Taupo Spa	~3	(S)boiling?	36	Do.
Kawerau (Onepu) 1959?	?	(D)277	25	Healy (1964).
1962	?	(D)285	18	C. J. Banwell (written commun., 1962).
Rotorua	?	(D)>160	----------	Healy (1964).
Union of South Africa				
Seven scalding springs[4]	?	(S) 64	1.7	Kent (1950).
UNITED STATES				
California				
The Geysers	~1	(D)208	[7]0.4	McNitt (1963).
Sulphur Bank	~2	(D)136	[6].2	White and Roberson (1962, and unpub. data).
Wilbur Springs area	~5	(S) 69	.4	White (1957b, p. 1675).
Casa Diablo–Hot Creek	>25(?)	(D)180	[6]70	(8)
Alkali Lakes area	----------	---------	----------	
(Salton Sea)	(~50)	(D,>270)	(4)	(Composite type, see text; White and others, 1963).
Nevada				
Steamboat Springs	5	(D)187	[6]7	White (1957a and unpub. data).
Bradys Springs	~2	(D)168	?	Magma Power Co.,(written commun., 1963).
Beowawe	~3	(D)207	?	Magma and Vulcan Thermal Power Companies (written commun., 1961).
Wyoming				
Yellowstone Park, Wyoming	9,000	---------	----------	
Total, discharging water	~70	(S) 138	207	Allen and Day (1935, p. 136).
Total, calculated[9]	~70	(D)205	500	White (this report).
Norris Geyser Basin	~ 3	(D)205	8	White (1957a, p. 1642).
Upper Geyser Basin	~10	(D)180	90	Do.
Mammoth–Hot River	~ 8	(S) 73	34	Do.

See footnotes at end of table.

Table 1.—*Natural heat flows of some hot spring areas of the world*—Continued

Area	Approximate size[1] (km^2)	Maximum recorded temperature[2] (°C)	Total heat flow[3] (10^6cal/sec)	Source of data
U.S.S.R.				
Pauzhetsk, Kamchatka	~1	(D)195	[10]18	Averiev, Ivanov, and Piip (1960, p. 262); Piip, Ivanov, and Averyev (1964).
Total[11]			~2,700	

[1]The limits of a hydrothermal area are very difficult to define and meaningful criteria are difficult to apply. Depending upon the definition, the "limits" of an area can vary by at least an order of magnitude. The author's definition for use in this report is: "The rather broad boundaries containing specific areas with some surface evidence for abnormally high temperatures at depth. The evidence can consist of one or more of the following: hot springs, fumaroles, active hydrothermal alteration, and abnormally high near-surface geothermal gradient. Closely spaced 'hot spots' not separated by areas of approximately 'normal' gradient for the region are included in a single thermal area."

[2](S) indicates temperatures measured at the surface; (D) temperatures from drill holes.

[3]From data of original author, commonly converted from other units. Most heat flows are relative to mean annual surface temperatures but a few are relative to 0° or 4°C; such differences are small compared to the uncertainties and have not been modified. 1×10^6 cal/cm^2/sec approximates the "normal" heat flow from 60 to 70 km^2. (Lee and MacDonald, 1963).

[4]Heat transported in discharging water only. Other heat losses believed relatively small.

[5]Heat flows of many below-boiling springs recently summarized by Uyhara (1963).

[6]Heat flow computed from rate of discharge of chloride (or boron), on the assumption that all water has cooled from a reservoir temperature equal to maximum temperature measured (Ellis and Wilson, 1955; White 1957a).

[7]Does not include heat losses by evaporation from ground-water body or by conduction from surface, which in total are considerably greater than discharging spring water.

[8]Heat flow computed from rate of discharge of boron by method similar to that of Ellis and Wilson (1955) for chloride. Close observation of boron contents in Los Angeles Aqueduct supply over many years indicates a discharge of about 200 short tons of boron per year from the Casa Diablo–Hot Creek–Hot Lakes area, in water averaging 11 ppm of boron (Goudey, 1936; L. V. Wilcox, written commun., 1957; G. I. Smith, oral commun., 1962). A discharge of 520 l/sec, or 8,300 gpm, is indicated for the total system; temperatures to as much as 180°C have been measured in wells at Casa Diablo (Magma and Endogenous Power Companies, written and oral commun., 1960, 1961), but a conservative reservoir temperature of 150°C is used for present heat-flow calculations. During and since the late Pleistocene, most of the boron from this system was incorporated in saline deposits of Searles Lake. Because of this, detailed studies of Searles Lake by G. I. Smith (oral commun., 1962) furnished a basis for concluding that the hot springs have been in existence for at least 50,000 years.

[9]Discharge of 2,900 l/sec of water according to Allen and Day (1935); all discharged waters are assumed to have cooled from 180°C at depth. This temperature is almost certainly incorrect for the low-temperature Mammoth–Hot River waters (700 l/sec) but is probably more than offset by large areas of steaming ground that have little or no discharge.

[10]Calculated from discharge of 100 l/sec and heat content at depth, 170–190 cal/g.

[11]Approximate total heat flow from those areas for which estimates have been made, excluding composite type in parentheses. An average has been assumed for those areas that have more than one estimate.

Most hard competent rocks are more highly fractured near the surface than at depth; therefore, mass permeabilities tend to increase upward, and active circulation in a hydrothermal system occurs up to the water table, which may be at or below the ground surface. The water rises by convection within the core of each system because of the lower density of the hottest fluid. Little change in temperature occurs in the rising water except where boiling occurs near the surface as hydrostatic pressure decreases. This picture is no doubt oversimplified for many systems but is supported by much of the evidence obtained from geothermal exploration to date; the assumed system provides a crude means of estimating the total heat content of a reservoir if the area underlain by the reservoir can be estimated and if a characteristic "leveling-off," or base, temperature is ascertained by drilling.

Rocks differ greatly in specific heats, depending on their composition, porosity, and degree of water saturation. This variance has made calculation of heat content of geothermal reservoirs by the usual methods impractical. Arthur H. Lachenbruch, U.S. Geological Survey, pointed out the important concept (oral commun., 1962) that specific heats tend to vary inversely with specific gravity and that most natural substances have volumetric specific heats that are similar enough to be useful for present calculations. Volumetric specific heats differ somewhat with temperature; in this report, 0.6 cal/cm^3 is assumed for temperatures near 100°C, 0.7 cal/cm^3 near 300°C, and 0.8 cal/cm^3 near 500°C.

By use of these concepts of volumetric specific heat and a reservoir temperature indicated by the "leveling-off" temperature, White (1964) estimated a minimum of 1.6×10^{18} cal of heat stored in the Steamboat Springs reservoir, Nevada, beneath an area of 5 sq km (square kilometers) and to a depth of 3 km. This storaged heat is equivalent to present natural heat flow for 7,000 years. Similar calculations for the Upper Geyser Basin of Yellowstone National Park, assuming the area and temperature listed in table 1, indicate a heat reservoir of 3.6×10^{18}. Heat content of a geothermal reservoir calculated by this method is likely to be a minimum content because the area of surface expression is commonly smaller than subsurface dimensions of hot ground and because hotter convection cells may underlie the explored cell.

By use of different assumptions and methods of calculation, C. J. Banwell (written commun., 1962) found a total heat content of 2.4×10^{18} cal to a depth of 2.3 km under the most active Wairakei area of 6.28 km^2. If this reservoir is assumed to extend to a depth of 3 km, a common base of other calculations of the present report, its heat content is about 3.2×10^{18} cal.

Bodvarsson (1964a) and Bodvarsson and Palmason (1964) have published estimates of recoverable heat content and efficiencies of recovery of heat from Iceland's geothermal reservoirs that lead to an estimate of about 1.1×10^{19} cal for total heat content. Specific dimensions assumed in these calculations are not stated.

The hot spring areas given in table 1 that show both surface area and heat flow are estimated to have a total area of about 500 km^2, and a total heat flow of 2×10^9 cal/sec or 6×10^{16} cal/yr (composite type not included here). Heat stored to a depth of 3 km in these hot spring systems—assumed to have an average reservoir temperature of 180°C above surface temperature—is about 2×10^{20} cal. Much additional heat is no doubt stored at depths greater than 3 km and at higher temperatures but is not included in these estimates. Vertical extension of the systems with depth is assumed here but many, and perhaps most, hydrothermal systems have a horizontal component of up-flow controlled by water-conducting structures.

The total stored heat of these crudely "measured" hot spring systems (2×10^{20} cal) divided by their present natural heat flow of 6×10^{16} cal/yr indicates an average age of at least 3,000 years. If heat stored at greater depths and heat discharged at the surface in the past are also considered, the average spring system must be at least 10,000 years old.

HYDROTHERMAL SYSTEMS OF COMPOSITE TYPE

The Salton Sea geothermal area and some of the Italian areas previously mentioned are characterized by low natural rates of discharge of water or steam at the surface. Drilling in these areas has demonstrated that temperatures near the surface are only slightly above atmospheric temperature but that they increase rather steadily with depth at rates perhaps 5–10 times "normal." In many of the Italian areas and also in the Salton Sea geothermal field, near-surface rocks are shale and other fine-grained sediments of low mass permeability; these rocks inhibit circulation of fluids. Temperatures of 250° to more than 300°C are characteristic of some of these areas at depths of several thousand feet. If these thermal systems were controlled entirely by rock conduction, temperatures close to the initial melting point of granite (600°C or higher, depending on water content) could be expected at about 10,000 ft. Deep drilling in Tuscany, Italy, has demonstrated that rocks below the capping shale are permeable and that temperatures show little additional increase with depth. The only reasonable explanation for such data is that heat is transferred through the intermediate permeable zone by circulating fluids.

In the Salton Sea area, details of temperature distribution have not been released by the companies involved, but the very high geothermal gradients of the upper 3,000 feet are unlikely to persist to much greater depths (White and others, 1963). The demonstrated fluid-producing capacity of recently drilled geothermal wells is indisputable evidence for at least local high mass permeability. Convective transfer of heat by circulation of the saline brine of the area is likely to be very important if permeable channels are interconnected in a three-dimensional system.

The heat content of the Salton Sea geothermal reservoir is, by rough calculation, at least 2×10^{19} cal. The volume here assumed is equivalent to a cylinder 7 km in diameter and 3 km in thickness, having an average temperature of 250°C, and an average volumetric specific heat of 0.7 cal/cm^3. This heat reservoir is about 6 times larger than that of Wairakei, one of the largest of the explored hot spring systems, primarily because of the larger surface area assumed for the Salton Sea reservoir.

Heat flows measured across the Larderello geothermal area in Italy (Boldizsar, 1963) range from 6 to 14 heat-flow units, 4–10 times the global average (Lee and MacDonald, 1963). If an average of 7 times "normal" or 10 heat flow units is assumed for the conducted heat flow from the exploited 50 km^2 of the Larderello field (Burgassi and others, 1964), the total conducted heat flow of the field is 5×10^6 cal/sec. The proven size of the Salton Sea geothermal field is somewhat less; if a surface area of 40 km^2 and a heat flow of 10 units is assumed, the total conducted heat flow of this field is 4×10^6 cal/sec.

The heat flow from each of these composite hydrothermal areas is less than that from many hot spring systems having permeable upper parts (table 1). Near-surface rocks of low mass permeability are evidently very effective in insulating a geothermal reservoir and in fostering high temperature and large size.

Some geothermal systems of composite type in very tight rocks may have little or no upward leakage of water or gases. The principal evidence useful in discovering such a system will be abnormally high geothermal gradients and heat flow, distributed over a large area. The optimum environment for a composite geothermal system is a large heat source, such as a magma chamber at depth; permeable rocks, preferably at depths of more than 2,000 feet, to serve as the heat and fluid reservoir; and a cap of impermeable rocks to provide an insulating cover.

GENERAL PROBLEMS OF UTILIZATION

At the present time, the geothermal areas of the earth that can most hopefully compete economically with other sources of energy are the "hot spots" that discharge steam or hot water as the heat-transporting medium or that have a permeable reservoir of hot fluids beneath near-surface rocks of low mass permeability. The essential requirements are relatively high temperature and permeable structures that can yield heat-transporting fluids to a well. Hot volcanic rocks or magma chambers at or near the surface but lacking heat-transporting fluid are also possible commercial sources of energy; however, effective recovery of heat from such reservoirs has additional problems not yet solved commercially.

The very low thermal conductivity of rocks imposes a restriction on effective recovery, especially if mass permeability is also low. The heat immediately adjacent to a well drilled in impermeable rocks can be withdrawn easily by circulating a cold fluid, but the amount of heat recovered is small and steadily decreases as rocks adjacent to the well are cooled. This low yield of heat is comparable to the low flow of an oil-test well in impermeable shale of high fluid hydrocarbon content. In contrast, large amounts of oil are obtainable from a single well in an oil pool in very permeable rocks. The possibilities for finding or creating high thermal "permeability" in reservoir rocks of low mass permeability seem limited to the following:

1. Each well is drilled deep enough to intersect one or more highly permeable channels or aquifers that, in total, will yield commercial quantities of the hot water already present in the rocks; however, in most crystalline rocks and many sedimentary rocks, permeable channels are narrow or widely spaced and are likely to be less numerous at great depth than near the surface.

2. The rocks adjacent to a well are artificially fractured to such an extent that the heat of a large volume of rock can be tapped. Natural permeable channels in the surrounding area must be made accessible to the newly broken ground to permit adequate discharge of existing deep water, or a transporting fluid must be introduced from the surface to recover the heat. Fracturing by buried nuclear explosion has also been proposed (Carlson, 1959), the nuclear energy providing additional heat.

Most deep waters are saline and are likely to contain high but uneconomic concentrations of elements such as boron, arsenic, sodium, and chloride; these elements constitute disposal problems. Some elements, including boron, potassium, lithium, cesium, and iodine have been considered for recovery to pay for part of the costs, but actual quantity and value of these elements are generally much below costs of recovery. The Salton Sea area of California is an outstandingly promising exception (White and others, 1963), and other similar areas may be found.

In some developed geothermal fields, heat in being withdrawn in considerable excess over the natural heat flow. Computed rates of withdrawal are four times the natural flow for Wairakei, New Zealand (Banwell, 1964a), three times for Reykir, four times for Hengill, and nine times for Reykjavik, Iceland (Bodvarsson and Zeöga, 1964), and at least 10 times for Larderello (calculations based on data from Boldizsar, 1963). McNitt (1963) estimated an excess withdrawal of 170 times for The Geysers, Calif. This excess over the natural heat flow is far greater than the indicated overdrafts of other geothermal areas; thus, additional studies should be made.

The quantity of stored heat that can be withdrawn from a reservoir without serious decline in quantity or quality of the heat-transporting fluids will be very different for each area, depending on the magnitude of the whole reservoir, the overdraft relative to natural heat flow, and the physical characteristics of the reservoir rocks. Yield from a large volume of rocks of high porosity and mass permeability, as in much of the Wairakei and Larderello fields, should decline less quickly than that from a heat reservoir in crystalline or sedimentary rocks of low permeability. In crystalline and sedimentary rocks, circulation of fluids is localized in faults, fractures, or the more permeable sedimentary layers; the total surface area of rocks in direct contact with migrating fluids thus is relatively small, and recoverable stored heat of the reservoir must be transferred to the circulating fluids by conduction through relatively large distances.

Bodvarsson and Palmason (1964) suggested that recovery of only 10 percent of the stored heat is a reasonable assumption for Iceland's heat reservoirs, which consist largely of plateau basalts having few permeable channels. Banwell (1964a), however, concluded that recoveries of 70–90 percent can be achieved over drawoff times of 20–100 years, provided that channel spacing is less than about 200 feet. Banwell's theoretical discussion of this subject is very useful, but several of his important assumptions need comment:

1. Efficiency and percent of heat recovery refer only to heat stored above 100°C (rather than to that stored above mean surface temperature, which is commonly used by others). Banwell's calculated efficiencies are therefore correspondingly high.

2. Banwell's idealized models assume all faults and fractures to be so permeable that permissible rates of fluid withdrawal or circulation have no restrictive upper limit; his model also assumes a uniform rate of flow across all surfaces.

Geologists familiar with permeability variations along veins, faults, and fractures in ore deposits will recognize the danger of accepting the latter assumption without modification. Flow rates are not stated for Banwell's models, but if 80 percent of stored heat is to be recovered in 20–100 years from a reservoir of heat content equal to at least 1,000 years of natural heat flow, fluid must be withdrawn at rates at least 10–50 times that of the natural discharge of the system. Any increase in circulation rate will be localized along interconnected channels of highest permeability and will result in excessive withdrawal of stored heat adjacent to these few channels and eventually in degradation in heat content of the recovered fluids.

A hot spring system prior to development probably approximates a steady-state equilibrum relative to its recharging water supply, the pressure drive from recharge to discharge parts of the system, and frictional resistance along its channels of circulation. A highly permeable spring system that has unlimited recharge potential will have achieved a steady state characterized by very high discharge and relatively low temperature; the latter is a consequence of the low thermal conductivities of rocks. A high-temperature geothermal system, on the other hand, can persist for thousands of years only if the recharge potential or the permeability of the most restrictive parts of the system is low. If the most impermeable part of a geothermal system is near its discharge end, as seems probable for the Larderello and the Salton Sea fields, wells can be drilled through the caprocks into the underlying more permeable rocks and the rate of through-flow of fluids can be increased significantly. In a thermal spring system in competent crystalline rocks, however, high permeability is likely to occur near the surface, and channels of lower permeability are characteristic of deep parts of the system. Compare, for example, the open textures of most shallow epithermal ore deposits with the tight structures of most mesothermal and hypothermal ore deposits. The tightest restrictions or bottlenecks, along channels of flow are likely to be deep in a hot spring system, below the shallow reservoir. Production at rates that exceed the natural discharge of fluids may prove to be short lived. Water levels, temperatures, and pressures are then likely to decline, and the accelerated withdrawal may be balanced only in small part by increased circulation through the system.

The hydrodynamics of hot spring systems are very complicated and not yet well understood. Each system differs in at least some respects from all others. Until testing proves otherwise, it is hazardous to assume that the natural discharge of many hot spring systems can be as much as doubled for more than short periods of time. In the testing of a new field, nonproducing observation wells are essential to monitor and evaluate changes in water level, temperature, pressure, and water composition. The adequacy of fluid supply is likely to be more critical than adequacy of the heat reservoirs in limiting future utilization of geothermal energy.

Other engineering problems related to utilization of geothermal energy are discussed in excellent reviews by Smith (1964; Bodvarsson 1964b). Total cost of geothermal power is presently considered to be about 8 mills per net kwhr in Iceland, and about 4.5 mills in New Zealand. G. Facca and A. Ten Dam (written commun., 1964), computed total generating costs for Italy as about 2.4–3.0 mills per net kwhr. At The Geysers, Calif., the cost of steam delivered at the powerplant is 2.5 mills per net kwhr of electric energy delivered to the transmission line (Bruce, 1964), but the overall cost, including power generation, has not been published.

Corrosion of equipment and deposition of mineral matter constitute problems in utilizing the heat of many thermal areas (Smith, 1964). Corrosion is likely to be more serious than deposition in the dry steam areas, but this problem evidently has been solved or adequately controlled in Italy and at The Geysers, Calif. Deposition of calcium carbonate or silica is characteristic of many, if not most, of the hot water areas. The chemistry of deposition has been discussed by Ellis (1964), White (1964), and others.

DOMESTIC AND WORLD RESOURCES OF GEOTHERMAL ENERGY

The total amount of heat above surface temperatures stored in the outer 100 km of the earth, as mentioned previously, is on the order of 2×10^{28} cal, which is equivalent to the heat content of 3×10^{18} short tons of coal. Heat stored under the United States to a depth of 10 km is about 6×10^{24} cal or equivalent to the heat content of 9×10^{14} short tons of coal. Most of this heat is in areas of "normal" geothermal gradient and is contained in rocks that are extremely low-grade sources of energy.

Areas of abnormally high geothermal gradient can be classified into three types, at least in part overlapping: (1) areas in which geothermal gradient is significantly higher than "normal" but where notable hydrothermal activity is absent; in some of these areas, molten magma may exist within accessible depths; (2) hot spring areas, in which natural thermal fluids are discharged at the surface; and (3) hydrothermal areas of composite type that have little surface expression but with high-temperature fluids that existing beneath capping rocks of low permeability.

In the first type of geothermal area, heat contents and thermal conductivities are so low, and drilling costs for very deep wells so high, that heat is probably not recoverable economically even at 10 times present values. In the future, with research and experience, some energy probably can be recovered from heated rocks or magma if the value of the energy is sufficiently high, but no attempt is made here to compute resources of this type.

The hydrothermal areas mentioned, including both types 2 and 3 offer the greatest immediate possibilities for economic development because high temperatures occur relatively near the surface and hot natural fluids are present as energy-transporting media. Geothermal heat is now competing successfully with other sources of energy in Italy, New Zealand, Iceland, and The Geysers in the United States. Experience at some localities indicates that heat can be withdrawn at rates of four to more than 10 times the natural rate of heat flow for at least 10 years without serious effect. The heat withdrawn in excess of the natural flow is derived from reservoirs of previously heated rocks. As mentioned previously, however, many other geothermal areas, especially of the hot-water type in rocks that are at least in part of low mass permeability, have not been tested adequately; serious degradational effects may become evident in shorter times and at lower withdrawal rates.

The total heat flow from hot spring areas for which estimates of natural heat flow have been made (table 1) is about 2.7×10^9 cal/sec (or 1×10^{17} cal/yr). Table 1 is probably reasonably complete for Iceland, New Zealand, and El Salvador but in most other countries only a few of the known areas are included. Almost none of the thousands of hot spring areas of low to moderate surface temperature (Waring, 1965) are considered, and hydrothermal systems of the composite type that are much more difficult to recognize are very inadequately represented. The world's total natural heat flow from all hydrothermal areas is probably at least 10 times that of the estimated areas, or about 3×10^{10} cal/sec (or 1×10^{18} cal/yr).

The total stored heat of the crudely "measured" hot spring systems of table 1 (excluding the composite type) is estimated to be about 2×10^{20} cal to a depth of 3 km.

Total heat stored in other hot spring systems is difficult to estimate. Some systems of high discharge and low temperature may have less stored heat than comparable volumes of "normal" earth. Others may prove to be hydrothermal systems of composite type, having meager surface discharge of fluid but high geothermal gradients in near-surface caprocks of low permeability.

Heat reservoirs of hydrothermal systems of the composite type may be relatively large because their heat has been largely preserved by good natural insulation rather than dissipated by convective discharge at the surface. The heat content of the Salton Sea geothermal area, as previously stated, is crudely estimated to be 2×10^{19} cal to a depth of 3 km (or 10,000 ft), and the Larderello system may be similar in magnitude. No sound basis exists for predicting how many large undiscovered systems of the composite type exist in the world, but 40 of the magnitude estimated for the Salton Sea area is not unreasonable. In addition, some hot spring systems of shallow circulation may be underlain at intermediate depth by rocks of low mass permeability, and these rocks in turn may be underlain by one or more circulation systems of composite type.

A very crude estimate of 2×10^{21} cal is suggested as the total stored heat of all hydrothermal systems to depths of 3 km, and 1×10^{22} cal to 10 km.

Geothermal energy has been utilized for such a short period of time that estimates of the proportion of heat commercially recoverable from hydrothermal reservoirs are of doubtful value, but 1 percent is viewed as a conservative estimate. On this basis, estimated recoverable reserves are:

	Heat content (calories)
Potential reserves to depths of 3 km, recoverable at or near present costs	2×10^{19}
Additional resources to depths of 10 km, recoverable at much more than present costs	1×10^{22}

Existing worldwide utilization equivalent to about 1 million kw, or 7.5×10^{15} cal/yr, probably can be increased at least 10 times under present economic conditions and maintained for at least 50 years. The author may be too conservative in these estimates, but many technical and scientific problems are not yet solved, and great optimism is not warranted until these problems clearly can be solved. Although geothermal heat is now only of minor importance as an energy source, the quantities available in hydrothermal systems are large and with additional research and development, recovery is likely to increase greatly.

The western half of the conterminous United States, Hawaii, and parts of Alaska are particularly favorable for local concentrations of geothermal energy. Of the total global resources of geothermal energy underlying land areas, probably 5–10 percent is in the United States.

ASSUMPTIONS, STATISTICS, AND CONVERSION FACTORS

Surface area of earth, 5.1×10^{18} cm^2; surface area of United States, 9.3×10^{16} cm^2.

Assumed temperature at 100 km depth, 1,100°C; average temperature of the outer 100 km of earth, 550°C above surface temperature; average volumetric specific heat, 0.8 cal/cm^3; latent heats of any phase transitions are disregarded.

Temperature gradient of outer 10 km, 20°C/km (or 1°C/160 ft); average temperature in the outer 10 km, 100°C above average surface temperature; average volumetric specific heat assumed 0.6 cal/cm^3. The assumed gradient is probably too low for orogenic areas and is almost certainly too high for stable continental areas having low heat flow and higher than average thermal conductivities.

Global average heat flow about 1.5×10^{-6} cal/cm^2/sec or 2.5×10^{20} cal/yr from the earth's surface. For geothermal considerations, heat flow in the range of 0.8–2.0 $\times 10^{-6}$ cal/cm^2 sec may be considered within the "normal" range. Thermal conductivities of most rocks range from about 3 to 10×10^{-3} cal/sec/cm °C. Within these extreme limits, temperatures could increase with depth at rates ranging from 50 to 410 feet per 1°C; the average is about 160 feet per degree.

1 cal (mean) = 0.001 kcal (kilocalories) = 0.00116 watt hr = 1.16×10^{-6} kwhr = 0.00397 BTU (British thermal unit) (mean) = 4.186 joules.

1 year = 365 days = 8,760 hrs = 5.26×10^5 min = 3.5×10^7 sec.

Coal is assumed to have a heat content of 13,000 BTU/lb = 6.5×10^9 cal/short ton = 7.2×10^3 cal/g.

Average rock of outer crust is assumed to contain 4 ppm uranium and 12 ppm thorium; uranium and thorium in 1 ton of such rock is equivalent in heat content to 50 tons of coal (Brown and Silver, 1956, p. 95).

Solar energy striking earth, 17×10^{14} kw or 1.3×10^{24} cal/yr (Weinberg, 1959); United States assumed to be average.

Heat available from granite magma, assumed liquid at 900°C, then crystallizing and cooling to 500°C, is about 175 cal/g or 4.7×10^{17} cal/km^3. If cooled to mean earth-surface temperature, nearly 300 cal/gm or 7×10^{17} cal/km^3 is available. Heat content of molten basalt at 1,100°C is about 375 cal/g, relative to surface temperatures.

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