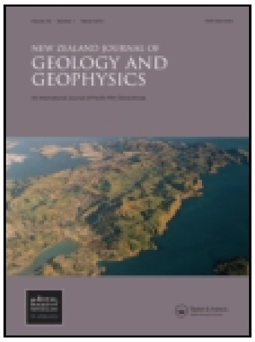

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Thermal energy from the earth's crust

Introduction and Part 1

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THERMAL ENERGY FROM THE EARTH'S CRUST*

INTRODUCTION AND PART 1

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ABSTRACT

The characteristics of the larger and hotter natural hydrothermal systems are discussed, and several different models of heat source and heat-transfer mechanism reviewed. It is shown that, with models depending on mixed conductive-convective heat transfer from a magma chamber, the observed heat flows require either a contact area of several hundred square kilometres for the conductive transfer link, or very small separations between a chamber of circulating magma and the convective hot water system. None of the models is entirely satisfactory, and the possibility of heat transfer by magmatic steam is reconsidered in the light of the new isotope evidence, which indicates that most of the water discharged is of surface origin. It is suggested that it would be possible for this surface water to penetrate to and become absorbed by heated rock or magma at great depths and pressures, and for it to be ejected from the rock by subsequent heating, or to escape under reduced pressure to provide a very efficient high-temperature heat-transfer medium that would mix with ground water near the surface.

The power potential of the various models is estimated by calculating the mechanical energy that could be obtained from an ideal heat engine taking heat from the rock or water and discharging the heat into a sink at a fixed temperature of 30°C. The results are plotted as graphs of available power per unit mass flow against temperature for saturated steam and water up to the critical temperature, and energy content per unit volume against temperature for steam, water, and rock. In nearly all cases, most of the stored energy is in the rock. The total energy content of the conductive and convective zones of the models discussed is estimated from their probable dimensions, and is found to be of the order of 10^6 to 10^8 megawatt years for the larger models. At the power drawoff rates of 250 to 350 megawatts involved in the Wairakei and Larderello power projects, these quantities of energy, if effectively drawn upon, would last at least several thousand years, and even the smallest probable model would supply these stations for some hundreds of years. If any of these models is in fact applicable to the areas concerned, it is unlikely that any appreciable impression on the storage will be made over several decades; and neither the Wairakei nor the Larderello areas are yet showing any sign of exhaustion of their heat supply, though there are indications that the water supply may become a limiting factor. Eventually, both these and other hydrothermal power projects may gain great advantages from control of the water supply and circulation by injection of recharge water.

INTRODUCTION

This series of papers is concerned primarily with estimates of the amounts of energy that it may be possible to extract from heat stored in the upper

*Parts 2 and 3 of this paper will be published in later issues of this *Journal*.

portions of the earth's crust, either by the direct exploitation of natural hydrothermal systems, or by more advanced methods which recent technological developments now appear to make practicable, or which promise to become practicable in the near future. Up to the present time, the approach to geothermal power development has consisted in drilling in natural thermal areas. This has proved very rewarding in at least two large areas (Larderello in Italy, and Wairakei in New Zealand), and there are many similar regions in various parts of the world showing similar promise; some of these are now in the early stages of exploration or development. These enterprises are a very important pioneering achievement, and, with proper management, some of them may make available energy resources much larger than some writers have been inclined to believe. The long-term behaviour of these systems is sure to throw further light on their mechanism, and will doubtless suggest new methods of heat extraction.

Although power from the larger natural hydrothermal systems may make a very useful or even a major contribution to the needs of certain favoured areas, it must be recognised that areas of this kind are rather thinly distributed over the earth, and their total output, even on the more optimistic estimates, does not seem likely to become an important fraction of world power requirements. Much more exciting prospects are offered by the more aggressive approach of establishing artificial hydrothermal systems in favourable areas. Apart from the neighbourhood of volcanoes and recent magmatic intrusions, there are considerable areas of the earth's crust where there is evidence to show that very large amounts of stored thermal power may be economically accessible. However, our present knowledge of the thermal and physical conditions even in the shallower parts of the crust is still too scanty to allow these areas to be fully mapped or even enumerated with certainty. Many parts of the crust do not appear to be promising at the present time, but the history of the oil industry shows that, given some initial success, the need, and enough determination, results can be achieved that would have seemed impossible to a preceding generation.

Part 1 deals with natural hydrothermal systems and current theories of their mechanisms and heat sources. The behaviour of some of the systems under exploitation and the nature and probable form of the heat storage will be discussed, with the object of predicting performance and determining at the earliest possible stage which of the models best fits the actual system. The importance of such early prediction for economic exploitation is obvious. In Part 2, conventional heat flow and thermo-dynamic theory will be applied to the special problems associated with the efficient extraction of heat from massive rock, and some relevant examples will be discussed in detail. These results have application both to natural and artificial systems, and an attempt will be made to predict the approximate quantitative behaviour of different models of natural systems under exploitation. Part 3 will deal with the thermal and physical conditions in the crust necessary for the presence of useful and accessible amounts of thermal energy, with methods of survey and preliminary assessment, and with possible ways of extracting the energy efficiently.

PART 1—NATURAL HYDROTHERMAL SYSTEMS

Recent accounts by various authors of the physics, geophysics, chemistry, and geology of most of the known geothermal areas were presented at the United Nations Conference on New Sources of Energy, held in Rome on 21–31 August 1961; no detailed description of these areas will therefore be attempted here, and individual references will be given only where they have some direct application to the point under discussion.

CLASSIFICATION

The division of natural hot water and steam flows into "low temperature" and "high temperature", proposed by Bodvarsson (1961) for thermal activity in Iceland will be adopted here. The low-temperature springs include hot water flows with base temperatures (i.e., temperatures at depth) up to about 150°C, and there is no difficulty in accounting for most of these springs, which are widely distributed over the earth's surface, by deep circulation of ground water along fault zones and heating by the normal geothermal heat flow. A few of these springs have heat flows large enough to make their inclusion in this class rather doubtful, and they may represent cases of new or dying high-temperature activity, or minor high-temperature springs heavily diluted by local ground water. Not many have temperatures and heat flows large enough to make them of interest for power production, though some are capable of providing significant quantities of low-temperature heat for other purposes.

High-temperature systems are generally characterised by the emission of both steam and water at the surface, often by geysers and boiling springs, by base temperatures in the range of 150 to 300°C, and by heat flows large enough to require some special mechanism to account for them. Although many of these systems are found near recent or present-day volcanic activity, and could be reasonably regarded as associated with it in some way, this is not always so. The precise connection between a major steam area such as Larderello and volcanism is far from clear, since there is no evidence of surface volcanism in the immediate neighbourhood, and no eruptive rocks have been found by drilling. The area is, however, located in a region of major tectonic activity, and this may have resulted in the presence of fluid magmas at relatively shallow depths, as well as in a generally high rock permeability, allowing the penetration of surface water to the vicinity of the magma and the escape of gases from the magma. A recent description of the geology of the Larderello field and its surroundings is given by Burgassi (1961).

THE HEAT TRANSFER PROBLEM

The natural heat discharge at the surface from a large high-temperature system is of the order of some hundreds of thousands of kilogramme calories per second, and this discharge is often concentrated in a surface area of a few tens of square kilometres. Bodvarsson (1961) refers to two areas in Iceland with heat outputs in the range of 125,000 to 750,000 kcal/sec, with areas of 12 km² and 100 km². At Wairakei, the original natural discharge of about 160,000 kcal/sec took place from an area of about 6 km² and most of it from an area of only a little over 1 km² (Banwell, 1961). Near the surface, the heat is carried by the convective flow of water and steam, and there are no special theoretical problems. Deeper in the system, it is quite possible that the heat flow is not so concentrated, but the magnitudes involved are nevertheless such that different forms of heat-transfer mechanism from the proximate heat source can be expected to make important differences to the quantity of heat stored in the system, and to its accessibility for uses such as power production. Conversely, the observed changes in the system when the heat flow from it is increased by exploitation should, in time, provide a useful means for discriminating between the various models of the system that may be proposed.

A useful illustration of the basic heat-transfer problems is provided by the group of hydrothermal systems comprising Wairakei, Rotokawa, and Taupo shown on Fig. 1, and by the proposed geological section given by

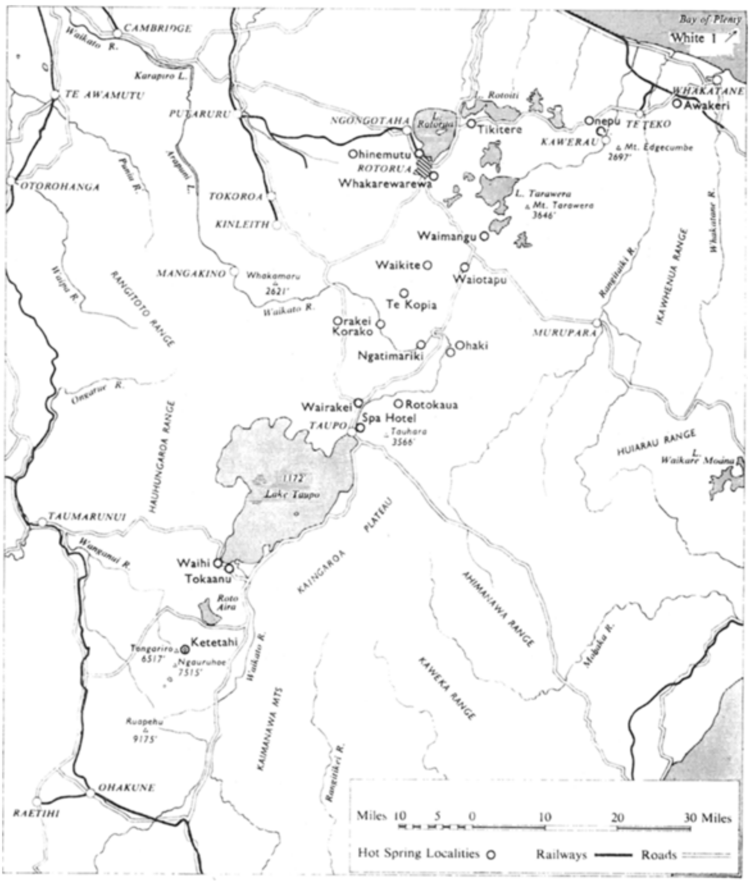

FIG. 1—Map of Volcanic Belt showing Wairakei–Rotokawa–Taupo area.

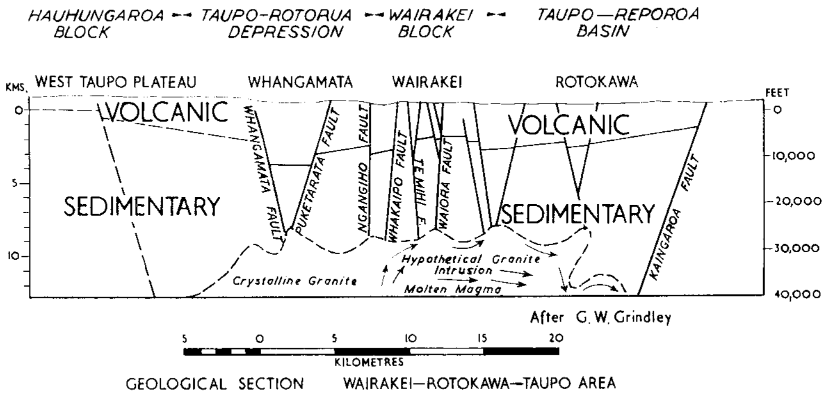

FIG. 2—Geological section Wairakei–Rotokawa–Taupo area.

Grindley (1960) and reproduced in Fig. 2. This section, and especially the deeper parts, must be regarded as a tentative model only, but it is reasonable in the light of the known geology. Of the three thermal areas, Wairakei has the largest natural heat flow (about 160,000 kcal/sec), Rotokawa a flow of approximately 90,000 kcal/sec, and the hot areas in and near the town of Taupo an estimated flow of 50,000 kcal/sec, giving a total of about 300,000 kcal/sec. Only the Wairakei group has been subjected to any important artificial withdrawal of heat, the others being still virtually undisturbed. In all the areas the heat flows are concentrated for the most part in small intensely active patches, and the whole complex can be enclosed in a circle of about 7·5 km radius. For the purposes of discussion, it will be assumed that the natural activity of these areas is maintained by heat transferred in some way from the magma chamber shown in the section of Fig. 2, or from certain variants of it.

CONDUCTIVE TRANSFER

If the magma chamber shown by the circulating arrows in Fig. 2 is considered to be circular in plan, its horizontal area is about 227 km^2. Assuming further that the top of the magma chamber is kept at a temperature of say, 1,300°C by active movement of the magma, and that heat is transferred by conduction through the rock forming the roof of the chamber to circulating water at 300°C, it is possible to calculate the thickness of the conducting layer for a given rock conductivity and heat flow. Since some gases of magmatic origin are believed to be present in the surface discharges, some transfer of heat from the magma by hot gases must be accepted, and it will be arbitrarily assumed here that only 250,000 kcal/sec (83%) is transferred by conduction. On evidence discussed below, the conducted fraction could be closer to 100%. The average thermal conductivity of the earth's crust will be taken as 4×10^{-3} cgs units, giving a theoretical thickness of 363 metres for the conducting layer. Since the upper surface of the magma chamber is likely to be irregular, thus increasing the effective area, and the thermal conductivity may be higher than that assumed, a reasonable estimate for the thickness of the conductive layer would be 0·5 km. Since the depth to the top of the magma chamber in the section is about 9 km, the system then consists of circulating magma of indefinite depth and volume, overlain by a thickness of 0·5 km of nearly impermeable rock through which heat is transferred mainly by conduction. This rock is in turn overlain by a thickness of 8·5 km of formations permeable enough to permit transfer of heat to the surface by convection of water with little further fall in temperature until the surface is approached and the pressure becomes low enough for the water to boil.

The validity of these calculations depends upon a faily uniform and continuous access of the circulating water to the heated rock of the conducting layer over the whole of the area. It would be quite insufficient for surface water to percolate down faults to a few parts of this area and return to the surface up the same or other faults. For the same heat flow, area of contact and thickness of conducting layer vary together, so that if the area were reduced by, say, a factor of ten (to about 23 km^2), the thickness would be reduced to only about 50 metres. It is very difficult to picture a fault or system of faults permitting the magma to be in contact with the country rock over an area even as great as 23 km^2, while at the same time leaving a shell only 50 metres thick between the circulating water and the magma. Any endeavour to avoid the necessity for liquid (and circulating) magma by postulating an intrusion or series of intrusions at appropriate intervals meets with serious difficulties in the total volume of material that would need to be injected over the life of the activity. Grindley (1961) estimates the age of the Wairakei field to be about 500,000 years, and if the general level of activity discussed above has been of the same order over most of this period, the volume of rock (initial temperature 1,300°C, final temperature 300°C) required to supply the necessary heat would be nearly 10^4 cubic kilometres. Within the Volcanic Belt shown in Fig. 1, the total volume of volcanic rocks overlying the basement greywacke is approximately $1{\cdot}5 \times 10^4$ cubic kilometres. Most of this was extruded at the surface and would not be able to supply the quantity of heat required. On this account, injection seems unlikely to have been the dominant heat-transfer mechanism.

Conductive Transfer over a Large Area

In the geological map of the Taupo sheet Grindley (1960) shows a volcanic formation, the Haparangi Rhyolite, which was ejected about the middle of the last glaciation, and which is scattered in patches of varying size over an area of nearly 1,600 km^2 on this map (similar material also occurs in regions beyond the northern limit of the map). These rocks are all sufficiently similar to the geologist to be classed together, which suggests that they are likely to have originated from a single and relatively well mixed magma chamber, which must have underlain at least a major part of the area where the rocks were erupted. On this evidence, it might thus be permissible to assume a heat-transfer area of the order of 1,600 km^2 or even larger, and if, as before, we are prepared to make the major assumption that surface water is able to circulate down to and spread more or less uniformly over most of this area, the thickness of the conducting layer for a heat flow of 250,000 kcal/sec is about 2·5 km. As before, this thickness might be increased if a more irregular upper surface for the magma chamber and a higher thermal conductivity for the rock were assumed. Hence, supposing that the top of the magma chamber lies at a depth of 9 km, the system would consist of a 2·5 km conductive layer overlain by a convective system 7·5 km thick. If we attempt to apply this model to the Volcanic Belt, the 1,600 sq. km is clearly insufficient to include the area covered by Haparangi rhyolite; and furthermore it would impinge on other thermal areas within the Volcanic Belt.

If conditions in the Volcanic Belt as a whole were represented by the large-area model, many of the superficially cool regions covering a large fraction of the graben area must be underlain by circulating hot water. It should be possible to test this by deep drilling in a few of the inactive parts of the graben.

Conductive Transfer over a Small Area

This model is suggested by the fact that flows of rhyolitic lavas of varying sizes are common throughout the area, in many places forming separate and well defined dome-like masses indicating high viscosity. However, the presence of volatiles in a confined mass would reduce the viscosity considerably. Lavas of this kind are able to reach the surface fairly readily from some magmatic source below, and therefore it is possible that relatively small lava columns are present, which have not penetrated to the surface, but which extend well up from the parent magma body, while still remaining in convective connection with it. Ground water circulating round these columns in sufficient quantity could remove heat fast enough to prevent or delay their progress to the surface, and would discharge heat taken from the lava as surface hydrothermal activity. For the maintenance of a hydrothermal system such as Wairakei (which on this model would be considered as being separated from neighbouring areas in the group), a column with a diameter of a few kilometres, and exposing an area of 10 km^2 to the circulating ground water would be appropriate. To maintain the Wairakei heat flow (about 160,000 kcal/sec) the conducting layer between the circulating magma and the circulating water would then be only about 2·5 metres thick. A model with these dimensions might appear to lack strength and structural stability, but approximate hydrostatic equilibrium would be possible between the pressure in a magma of a not unreasonable composition and density, and the pressure of the surrounding rock. The depth to the top of the magma column in this model is not defined, since it will depend to a great extent on the actual density assumed for the magma, and the depth to which ground water is able to circulate freely. However, if the top rises to within a few kilometres of the surface, the volume of the convecting system above will be only a few tens of cubic kilometres at most, and the heat storage in this system will be relatively small.

CONVECTIVE HEAT TRANSFER BY MAGMATIC GASES

Consideration of the above range of models, all of which depend on thermal conduction as an important link in the heat-transfer process, shows that none is entirely free from doubtful or unattractive features. It is possible that the progress of observation or new developments will make the acceptance of one or other of these models, or something like it, nearly unavoidable, or else suggest some better alternative. Meanwhile, it appears worth while to consider the possibilities of a more nearly purely convective system, in which much of the heat is transferred from the magma by gases escaping from it.

Magmatic Steam

A model of this kind was considered by the writer in an earlier publication (Banwell, 1957), where it was shown that the heat flow from an area such as Wairakei could be accounted for by adding about 14% of magmatic steam to circulating ground water. The temperature required for the magmatic steam was rather high, but, in the model chosen, some of the heat from this steam was used for heating rocks prior to an eruptive phase. From recent surface-heat and mass-flow measurements at Wairakei, the probable maximum temperature of the circulating water deep in the system is about 340°C (it may be lower on certain alternative hypotheses assuming higher rates of internal circulation), and if this water is supposed to consist of ground water initially at 15°C in which magmatic steam initially at, say, 1,300°C has been condensed, the fraction of the latter in the mixture would need to be about 52%. Until recently there was little experimental evidence concerning the source of this steam and it was often supposed to consist of juvenile water (i.e., water incorporated in the primitive earth and escaping for the first time). However, as the evidence quoted below will show, magmatic steam is not necessarily juvenile steam. Craig (Craig, (Craig, Boato, and White, 1956), discussion) identifies "magmatic water" with "juvenile water" or "recycled water" although the term "magma" is itself commonly used in a non-committal sense. In this paper "magmatic steam" is used to refer to steam that has come from magma, whatever its ultimate origin.

Isotope Evidence

Some important restrictions on the probable origin of the water have been imposed by the work of Craig, Boato, and White (1956), who have shown that there is a close correspondence between the oxygen and hydrogen isotopic make-up of the hot water discharged from hydrothermal areas in a number of parts of the world (including New Zealand) and that of the local ground water. They conclude that the hot-spring water cannot contain more than a few per cent of water of non-local origin (e.g., of juvenile water from the magma, connate or metamorphic waters, or surface water from distant sources), and may contain only very small amounts. Their evidence is most conclusive for springs distributed across a large continental area such as North America, where there are well marked variations in the isotopic make-up of the local surface water, and is rather less definite for the New Zealand thermal area where, although the correspondence still holds, there is too small a variation across the country to provide a positive check. Nevertheless, there seem to be insufficient grounds for rejecting a conclusion based on firm evidence for other areas, and it appears reasonable to suppose that, in the New Zealand hydrothermal systems also, nearly all the hot water and steam discharged are ultimately derived from local surface water.

These results have sometimes been considered to favour conductive heating against heat transfer by magmatic steam, but, as the discussion below will show, a vapour phase that is effectively magmatic (though not juvenile) steam can be derived from surface water.

Turnover Time

The time since this water entered the hydrothermal system is not determinable directly from this evidence, but it may be suggested that the water must have left the surface when the climatic conditions were not greatly different from those of the present time. The New Zealand climate has not changed markedly since the last glaciation, which occurred 5,000 to 10,000 years ago. This period of time is long enough for important volcanic events to have taken place in the region as a whole, and it is therefore possible that the ground water has had time to penetrate deeply into the more permeable formations, and is being ejected again by heating and remelting due to magma movements.

Absorption of Meteoric Water by Magma

In view of the comparatively high solubility of water under pressure in rock melts, it is also conceivable that meteoric water gains access to magma deep in the system, becomes dissolved, and leaves the magma again when it has circulated to some higher level where the pressure is lower. In this way, very efficient transport of heat from the magma by the escaping water vapour would be possible, without the need for the large areas of contact required by conductive transfer. The water could penetrate to the neighbourhood of the magma through a few deep faults and there diffuse into the magma, and the vapour could escape and enter the ground-water system through other faults.

Volume of Heated Rock

Convective transfer of heat from the magma by water vapour in the manner discussed above could result in the heating of only comparatively minor volumes of rock in permeable formations near the surface, since large quantities of steam under pressure could escape from the magma along a few very limited fissures, and a general permeability of the deeper rocks is not necessary. Even if large volumes of rock became heated by conduction from the steam in the course of time, it would be difficult to extract this heat at a rate fast enough to be of practical use unless the rocks were well broken up by joints or faulting. The closeness of joints, permeable channels, etc., necessary for efficient heat extraction over a reasonable period of time will be discussed further in Parts 2 and 3.

GENERAL CONCLUSIONS CONCERNING NATURAL HYDROTHERMAL SYSTEMS

To summarise the foregoing discussion, it may be said that the two conductive models with the larger heat-transfer areas first considered are likely to contain very large amounts of stored heat, and exploitation at the rate currently considered (i.e., by stations with power outputs of the order of 250 megawatts) represents such a small drawoff of heat in relation to their capacity that a very long period must elapse before there is any observable falling off in the heat supply. The chief objections to these models are likely to be raised by geologists, who may be disposed to reject the structures and rock properties demanded as geologically improbable.

The small-area conductive model, and that depending on magmatic steam for heat transfer, will tend to contain considerably less stored heat, and they are therefore more likely to demonstrate their presence by falling heat supply within reasonable periods under current production programmes. Quantitative results will be given below.

ENERGY CONTENT OF ROCK AND WATER

Definitions and Units

Energy content is defined here as the amount of mechanical work that can be extracted from unit mass or volume of a substance by means of an ideal reversible heat engine discharging heat into a sink (refrigerator) at a constant temperature of 30°C, and taking heat from the substance until the temperature has been reduced to 50°C. The sink temperature is chosen to correspond to that normally attainable in a reasonably efficient condensing steam plant, and the temperature of 50°C is taken as a limit of heat extraction below which it is seldom economic to go. The method is essentially the same as that described by Claude and Claude (1949), who give the equations used and a few numerical results. When the power available from a practical generating plant is considered, it will be necessary to multiply this ideal energy content by the efficiency of the plant (usually from say 25% up to 75% for a very efficient plant), by a factor to allow for transmission losses, and by a factor depending upon the temperature at which the heat is actually extracted from the substance. Consideration of this last factor provides an important criterion for determining the conditions desirable for heat extraction from rock masses, and for judging the efficiency of various extraction programmes. This aspect will be discussed further in Part 2. In the case of water, the variation in density and specific heat with temperature is taken into account, and the calculations are not carried above the critical temperature. In the case of rock, the density and specific heat are taken as constant over the whole temperature range.

With a few exceptions, which will be noted where they occur, the following physical properties for a typical rock are used in all calculations:

Density (ρ)	2·5 gm/cc.
Specific heat (c)	0·2 cal/gm °c.
Thermal conductivity (k)	4×10^{-3} cgs units.

These values are based on measurements of rock samples and should apply to the upper part of the earth's crust in the volcanic belt. It is not difficult to adjust the numerical results obtained to take account of rocks of different characteristics.

Units of energy content are either joules per cm^3, or megawatt years per cubic kilometre (MWY/km^3) where 10^4 MWY/km^3 = 315·6 J/cm^3. Where flows of water and steam are considered, the units are either kilowatts per kilogramme per second (kW/kg sec) or megawatts per 10^5 pounds per hour.

Power from Water and Steam Flows

Fig. 3 gives the power (energy per unit time) for flows of saturated water and steam up to the critical temperature. The full-line curve is the power from the ideal heat engine as defined above, and the dashed line that for an ideal heat engine with a sink at 100°c, and extracting heat down to 100°c (representing the norm of performance for a non-condensing steam engine). The depth and enthalpy scales at the bottom of the diagram refer to a model hydrothermal system in which the temperature at each depth is equal to the boiling point at that depth under hydrostatic plus atmospheric pressure. It is not uncommon for conditions in actual hydrothermal systems to approximate to this over significant ranges of depth; beyond this, the temperature either approaches a maximum at a certain depth or rises much more slowly. Apart from their use for rapid estimation of the power potential of measured steam or hot-water flows, the cuves of Fig. 3 allow the rates of circulation of water or steam in a natural or artificial hydrothermal system required for a given temperature range and rate of energy transfer to be found.

Energy of Hot Water, Steam, and Rock

Fig. 4 gives the energy content per unit volume of steam and water up to the critical temperature, and of rock up to 400°c. By means of these curves, the energy content of any hydrothermal system consisting of rock of given porosity and temperature distribution saturated with water or steam can be readily estimated by integration over the volume under consideration. Examples of the results obtained for such a system with two different values for the porosity are given in fig. 3 *in* Banwell (1961). From these curves, it is evident that, in the case of water-saturated rock, the value of the porosity is of secondary importance, because the energy content of rock and water are not very different on a volume basis. Since the porosity of typical rock seldom exceeds 30%, and generally diminishes with depth,

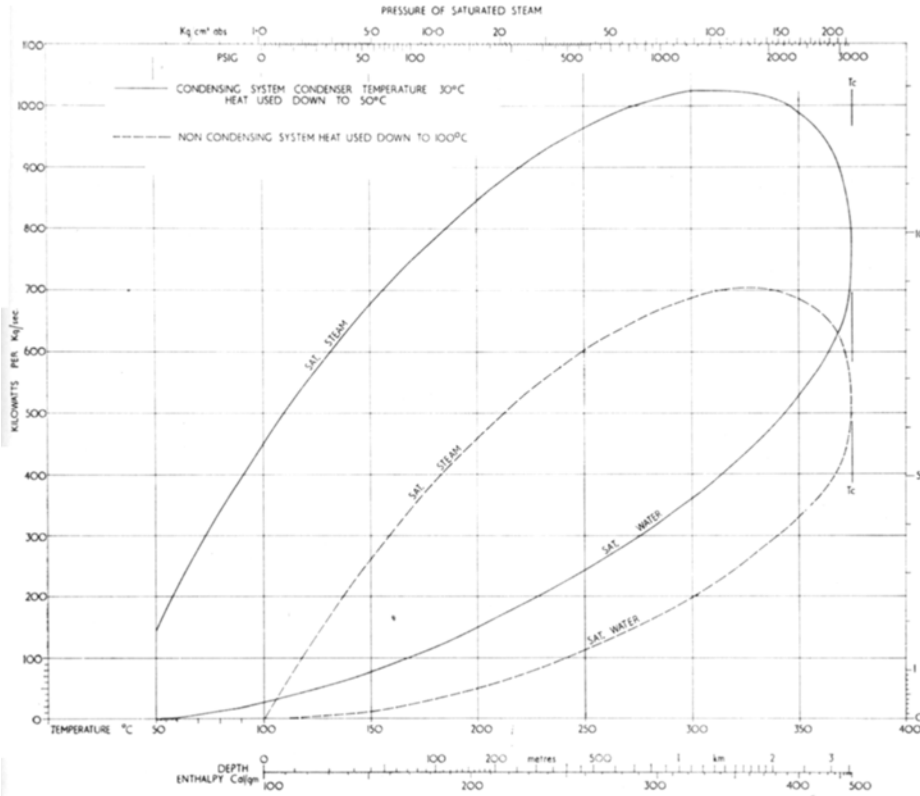

FIG. 3—Power potential of saturated water and steam.

most of the stored energy in a hydrothermal system will be in the rock. Reference to Fig. 4 of this paper shows that the energy content of saturated steam per unit volume is comparatively insignificant until the critical temperature is approached, so that if the rock pores are filled with steam near its saturation temperature, the relative importance of rock storage is even greater.

Energy of Rock and Magma

Fig. 5 gives the energy content per unit volume of rock over an extended temperature range up to complete fusion of basalt at atmospheric pressure. The melting range shown for basalt should be treated as approximate only, both limits being liable to modification by factors such as mineral composition, pressure, and volatile content. The lava is assumed to freeze progressively and to give up its latent heat at a uniform rate over the whole freezing range. It is unlikely that real lavas will behave in this simple manner, since different solid mineral constituents can be expected to form

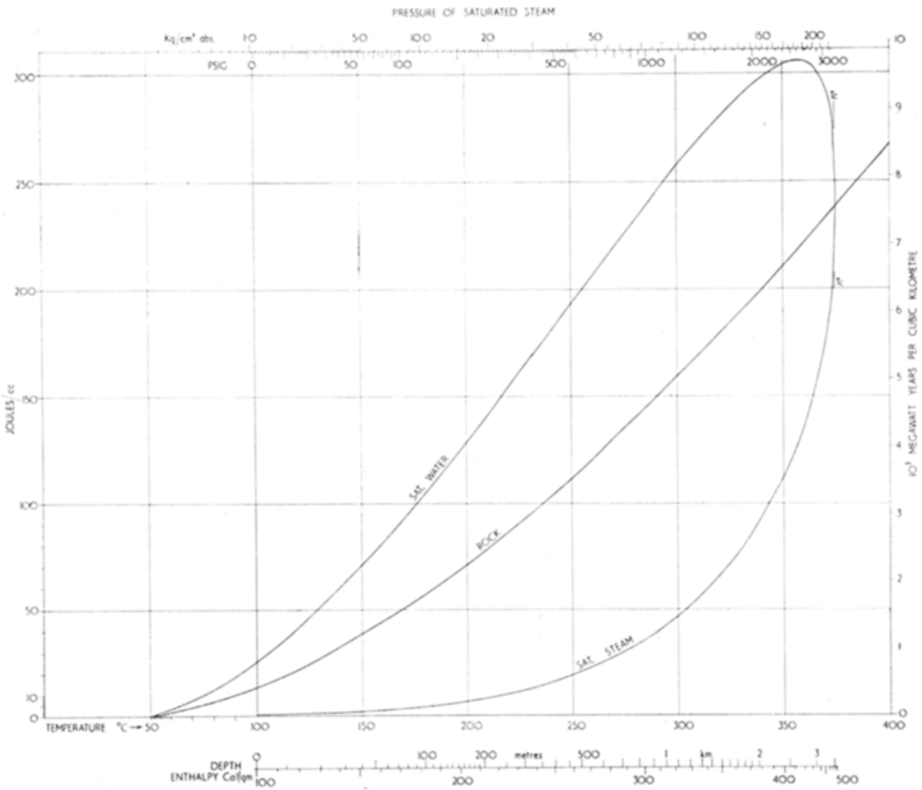

FIG. 4—Energy content of rock, saturated water, and saturated steam.

over small parts of the freezing range and give out very variable quantities of heat as they solidify, and important quantities of volatiles may separate. However, these differences are not important where the total energy content only is being considered, and if the problem of extracting energy from an actual lava is involved, such as that discussed by Kennedy and Griggs (1961), experimental data for the lava concerned are obviously desirable. These authors assume a latent heat of freezing of 100 cal/gm for the lava, whereas the curves of Fig. 5 are calculated for 75 cal/gm, so the energy contents given here are possibly conservative. There do not, however, appear to be any well-established and precisely defined experimental values for the latent heats of freezing of typical lavas, still less for their total heat content with different amounts of volatiles in solution.

The remaining notes in Fig. 5, concerning the melting range of granites in the presence of water and changes in elastic properties with temperature, will be discussed below.

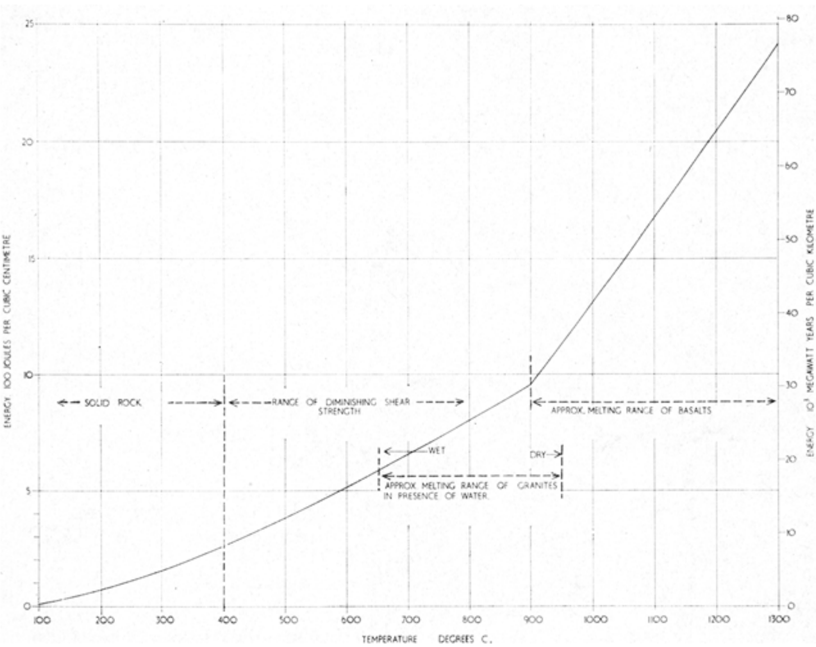

FIG. 5—Energy of rock and magma.

ENERGY CONTENT OF MODEL HYDROTHERMAL SYSTEMS

Medium Area

By means of Figs. 4 and 5, the approximate energy contents of the conductive and convective zones of a given hydrothermal model can be readily found. Taking first the conductive zone of the medium-area (227 km²) conductive-transfer model discussed above, the volume of this zone is 82·4 km³ if the smaller theoretical thickness of 363 metres is used. Assuming the rock in the conducting zone to be completely solid under the pressures prevailing, no latent heat will be available, and a reasonable estimate of the mean energy between 300°C and 1,300°C from Fig. 5 is about 2×10^4 MWY/km³. The total energy content of this volume of rock is then $1{\cdot}65 \times 10^6$ MWY.

The temperature in the convective zone above the conductive layer cannot be assumed to be everywhere equal to the value of 300°C used in the heat-flow calculation, since some parts of the volume must be cooled by descending water, and steam separation will occur, with consequently falling temperature, when the rising fluid comes within about 1 km of the surface, For the calculation of energy content, the convective zone will accordingly be taken to have an area one-quarter that of the conductive zone, a thickness of 7·5 km, and a uniform temperature of 300°C over this volume.

Unless the porosity is high, which is improbable, the contribution of hot water to the energy storage will be small, and the whole volume can be treated as consisiting of rock only. From Fig. 4, the energy content of rock at 300°C is about 5×10^3 MWY/km³, so the energy content of the convective zone is about 2×10^6 MWY, or roughly the same as that of the conductive zone.

Large Area

Since the area and thickness of the conducting zone increase together for a given heat flow, the volume is proportional to the square of the area assumed, so that the energy content of the conducting zone with an area of 1,600 km² will be about $(1{,}600/227)^2 \times 1{\cdot}65 \times 10^6 = 8{\cdot}2 \times 10^7$ MWY. The volume of the convective zone will be proportional to the area, so that the energy content, assuming the same general temperature distribution as for the medium area, will be about $1{\cdot}4 \times 10^7$ MWY.

Small Area

The volume of heated rock in the conducting zone surrounding the small (10 km²) intrusion will evidently be almost negligible as far as heat storage is concerned, and only the convective zone above is worth consideration. This volume will depend on the depth assumed for the top of the intrusion, which must remain somewhat arbitrary in the absence of any definite criterion. For the purpose of illustration here, this depth will be assumed to be 3 km, which does not appear to be unreasonable. Since there may be some heating of incoming ground water at the sides of the intrusion, and considerable recirculation of hot water, it will be assumed here, as a possibly generous estimate, that the temperature is uniformly equal to 300°C over the whole area of 10 km² to within 1 km of the surface, so that the volume of principal storage will be 20 km³, and the energy storage 10^5 MWY.

RESPONSE TO DRAWOFF FOR POWER PRODUCTION

Larderello

Up to the present time, the only hydrothermal system where a substantial rate of drawoff has been maintained for any considerable time is in the boraciferous region at Larderello. Burgassi (1961) gives a total steam discharge of 792 kg/sec at a maximum temperature of 245°C from the 160 wells now in production and feeding electrical and chemical plants. Not all this steam is used for power production, but it will be convenient to express the flow in terms of power, and for purposes of comparison both the initial steam temperature and mean rock temperature will be taken to be 250°C. The gross power equivalent of the steam, neglecting generating losses, is then 764 MW. Some of the wells are stated to have been producing for about 40 years, though the flow has now fallen to about one-tenth of its initial value, and it will be assumed here that the integrated drawoff of all the producing wells drilled in the area since development began is equivalent to the present drawoff maintained for a period of 20 years, representing a total of about $1{\cdot}5 \times 10^4$ megawatt years. This figure may be on the high side, but this is not serious for present purposes. Considering now the geological section given by Burgassi (1961) in fig. VII, the most probable local source of stored heat is the permeable anhydrite series in the up-faulted block beneath Larderello. The anhydrite formation extends over a much larger area, but if attention is first confined to the section defined by the local marginal faults, the thickness is about 400 metres and the width in the section about 4 km. Assuming the block to be square in plan, the volume is therefore about $6{\cdot}4\ km^3$, and the energy content of the rock at 250°C about $2{\cdot}3 \times 10^4$ MWY.

Comparing this with the total drawoff calculated above, it is evident that this formation could not have provided this amount of energy without a very considerable fall in temperature, which has not occurred. Chierici (1961) states that in a period of 40–50 years the steam, which was initially saturated, has become superheated and its temperature has risen about 40°C. There can be little doubt that the heat reservoir supplying Larderello must be much larger than the minimal areas considered here, and the bores must be able to draw from a far larger area of permeable and heated aquifer, or else from some deeper and possibly hotter source.

Since the "boraciferous" area at Larderello covers an area of some $450\ km^2$, and much of this is marked by thermal activity, there is no serious difficulty in finding a large enough area of aquifer to supply the present drawoff for a very long period, though only about $70\ km^2$ of the area has so far been explored by drilling (Burgassi, 1961). The falling steam output that occurs with most drillholes in the course of time is probably due to an insufficient supply of surface water to replace the water removed as steam, and the underground hydrostatic level at Larderello has decreased by several hundred metres in 40 years (Chierici, 1961). A failing water supply will also limit output indirectly by accelerating blockage of holes in permeable formations by mineral deposition. At the present time, the output of the Larderello field seems more likely to be limited by a shortage of the heat-exchange medium rather than by the amount of stored heat.

Wairakei

The projected power output for the final Wairakei station is approximately 250 megawatts, or about 400 megawatts gross, after taking expected station efficiency into account. Although the generating station is still considerably below this capacity, bore output reached a level about 25% above that required to supply the final station in February 1960; since this date the output has been reduced by shutting down many of the drillholes not required for production, and in January 1961 the drawoff was rather less than half the peak value. The total drawoff by drillholes from the start of development up to Januay 1961 is equivalent to about $1{\cdot}3 \times 10^3$ MWY gross (Banwell, 1961), and is thus only about one-tenth the total Larderello drawoff as estimated above. It is only a little more than 1% of the estimated energy storage of the small-area system discussed above, so that little observable effect on such a system is to be expected. Even at full production, the estimated energy storage of 10^5 MWY would supply the station for some 250 years, so that, unless the system is still more limited in depth or dimensions, little observable change in temperature could be expected within 10 or 20 years. If the medium-area model is considered, it would be capable of maintaining the 250 MW station for about 5,000 years, and any changes observed in the system are more likely to be due to spontaneous changes or volcanic events, rather than to disturbance by artificial drawoff. Evidently, a 250 MW station would produce a drawoff far too small for its direct effects on the heat supply to be of much experimental value in the case of the larger systems.

The only changes so far observed in the Wairakei area that appear likely to be the consequences of drawoff are well marked falls in hydrostatic pressure in the producing aquifer and some parts of the outer area (Studt, 1958), and increases in the size of the areas of natural activity and in the intensity of the activity (Thompson *et al.*, 1961). There is no evidence of any steady general decline in temperature deep in the system, and some signs of current increases (Banwell, 1961). Except for the increasing surface activity, these changes resemble those observed at Larderello over a much longer, period, and the symptoms in both areas suggest an impending deficiency of water to transfer heat tc the surface.

IMPORTANCE OF WATER SUPPLY

It has been suggested by White (1961) that the differences between hot-water areas, of which there any many examples, and steam areas such as Larderello, are due primarily to the relation between the supply of ground water and the heat supply. A restricted water supply will give rise to fumaroles and superheated steam, and a more lavish supply to hot-water systems of varying temperature. In the hot-water areas (and perhaps in some of the steam areas also) it is possible that much of the water flows in a closed convective path within the system, shedding only a part of its mass as steam and water as it nears the surface. If the entry of replacement water is limited by low permeability in the available recharge paths, drillhole drawoff will produce pressure falls within the system, and, if it begins to deplete the supply of circulating water seriously, to rises in temperature, increasing proportions of steam, and eventually, to a restricted heat output. At Larderello, where the existence of natural fumarole activity indicates an already limited water supply, there is evidence of diminishing returns from further local drilling. At Wairakei, where drillholes produce much water with the steam, a fall in the amount of water present would have appreciable engineering advantages, apart from possible side effects such as further undesirable increases in surface activity, or blocking of some feed areas by mineral deposition from increasingly concentrated solutions. At the present time, it is difficult to decide whether it is desirable to permit a hot-water system to develop into a steam system as a result of drawoff, or if so, whether the transition can be expected to proceed smoothly.

CONTROL OF WATER CIRCULATION

Up to the present time, there has been no report of any attempts to maintain the water supply in any of the hydrothermal systems under development, either by water injection through drillholes or by other means. In this respect, the water circulation can be said to be uncontrolled, in that only the rate of removal of water or steam is modified, while corresponding changes in the rate of replacement are left to be determined by factors such as pressure changes, spontaneous changes in natural surface supplies, and feed-channel permeability. It seems probable that a point will be reached in some systems where the power available can be greatly increased by judicious control of the water supply, and it may indeed be that certain comparatively insignificant natural systems can be made into important power-producing areas by suitably augmenting their water supply. It is evident that a good understanding of the structure and thermal characteristics of the system is necessary in order to determine the best rates and locations for water injection for maximum efficiency and safety, and it will be the purpose of Part 2 of this series to establish some of the quantitative factors that are likely to be of importance in such an undertaking.

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