ASPECTS OF ENERGY CONVERSION

Proceedings of a Summer School held at Lincoln College, Oxford, 14-25 July, 1975

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PREFACE

This publication contains texts of lectures presented at the Summer School "Aspects of Energy Conversion" together with edited transcripts of the discussions which followed each lecture and of the panel discussions which were held at intervals in the proceedings (we are grateful to the students for providing notes of many of the discussions). We must stress that the lecturers are not responsible for the accuracy of information given in these transcripts as, in the interests of early publication, we have not confirmed the validity of statements made therein; we do feel that the main points made in the discussions have been preserved, however. Some of the students felt stimulated to produce their own papers at the School and these are reproduced in the Appendix.

Our fellow-members of the School Organizing Committee are listed separately and we are indebted to them for helping to make the School and this publication possible. We also thank the staff of the Education and Training Department at AERE Harwell, in particular Ms. Julie Carpenter, whose painstaking secretarial work contributed greatly to the smooth running of the School, and Mr. Fred Major for his audio-visual aid, and the staff of Lincoln College and the Examination Schools, Oxford. We are grateful to Dr. George Kalmus for his interest and it is a pleasure to thank Ms. Judy Williams for her invaluable assistance with the massive effort needed to prepare the material for publication, Ms. Elaine Knowlton for her enthusiastic typing and, of course, Carol, Jill and Lynda.

Finally, we wish to express our gratitude to the lecturers for their cooperation in producing texts of their lectures for publication and to both lecturers and students for uniting to make the School a stimulating and informative experience. We hope that readers will derive similar benefits from these Proceedings.

I. M. Blair
B. D. Jones
A. J. Van Horn

INTRODUCTION

The recent massive increases in the price of oil have focused attention on the importance of energy in society. They have reminded us of the fact that our traditional fuel reserves are of finite extent, and that the continuous growth in their use over recent decades, due mainly to their relative cheapness, cannot continue definitely. There is, therefore, at the present time much concern over the wise husbandry of these traditional fuels, and over possible alternative energy sources to replace them. In particular the most imminent alternative source, nuclear power, is being subjected to a most detailed scrutiny.

It is most appropriate that the Science Research Council and the Energy Technology Support Unit at Harwell should collaborate at this time to hold a Summer School on "Aspects of Energy Conversion". The energy problem is complex, involving scientific, technological, economic, environmental, sociological and political issues. It is also international. We are pleased to note that all these facts have been borne in mind in the preparation and presentation of the School Programme, and that the material presented at the School can now reach a wider audience through these Proceedings.

W. Marshall

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Dr Walter Marshall
Chief Scientist
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SECTION 1

FUNDAMENTALS OF ENERGY RESOURCES AND CONSUMPTION

SECTION 2

FOSSIL FUELS

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NUCLEAR FUELS

SECTION 4

ALTERNATIVE ENERGY SOURCES

GEOTHERMAL ENERGY

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INTRODUCTION

The use of geothermal energy involves the extraction of heat from rocks in the outer part of the Earth. It is relatively unusual for the rocks to be sufficiently hot at shallow depth for this to be economically attractive. Virtually all the areas of present geothermal interest are concentrated along the margins of the major tectonic plates which form the surface of the Earth. Heat is conventionally extracted by the forced or natural circulation of water through permeable hot rock. Steam generated in this way is used in turbines for electricity generation. The many areas where impermeable hot rock is at shallow depth are not at present exploitable, but if current research into the generation of fissure systems by explosive or other means is successful, they may become so. The number of regions of geothermal interest would also be significantly increased by the development of commercially attractive vapour turbine cycles which were able to use low enthalpy waters for power generation. Low enthalpy waters ($\sim$ 100 cal/gm) are at present used for agricultural or domestic heating. If geothermal energy is used in Britain it will probably be in these latter ways.

Geothermal energy has been used to generate electricity at Larderello in northern Italy almost continuously since 1904 by using the energy of hot natural flows of water or steam. By 1972 Italy had installed geothermal power stations with a total capacity of 390 Mw at a capital cost of about $100/Kw. Total production costs are estimated at 5-9 US mills/Kwhour. In addition, both New Zealand and the United States have major geothermal power stations in operation and a dozen or more other countries are either actively exploring the possibility of such installations or have small schemes already working.

In this paper we review the main features of geothermal power and discuss its possible future development and limitations. We take the use of geothermal power to mean the "economic extraction of energy either for driving machines or direct heating, from naturally hot rocks in the upper part of the Earth's crust".

THE ENERGY SUPPLY

The Earth is believed to be close to a state of thermal equilibrium where the energy which is received at the surface by solar radiation is lost again at night, and the much smaller amount of energy which is generated by the decay of unstable isotopes of Uranium, Thorium and Potassium distributed within the Earth is balanced by the small continuous heat flux from the Earth's interior to the oceans and atmosphere.

Heat generation within the Earth is approximately 2700 Gw, roughly an order of magnitude greater than the energy associated with the tides but about four orders less than that received by the Earth from the sun. The mean surface heat flux from the Earth is about 1.5 Heat Flow Units (1 HFU = 10^{-6} cal cm^{-2} sec^{-1}).

Temperature distributions within the Earth depend on:

1) the mean surface temperature (which is controlled by the ocean/atmosphere system).
2) the abundance and distribution of heat producing elements within the Earth.
3) the thermal properties of the Earth's interior and their lateral and radial variation.
4) any movements of fluid or solid rock materials occurring at rates of more than a few millimetres per year.

Of these four factors the first two are of less importance from the point of view of geothermal energy. Mean surface temperatures range between 0° and $30^{\circ}C$, and this variation has a small effect on the useable enthalpy of any flows of hot water. Although radiogenic heat production in rocks may vary by three orders of magnitude, there is much less variation from place to place in the integrated heat production with depth. The observed range in depth-integrated heat production for the upper (and most variable) part of the crust is equivalent to about 1.5 HFU.

The latter two factors, however, are of great importance and show a wide range of variation. Their importance is clear from the relationship

$$\beta = \frac{q}{k}$$

where, for a steady state, β is the thermal gradient, q is the heat flux and k is the thermal conductivity. The first requirement of any potential geothermal source region is that β be large i.e. that high rock temperatures occur at shallow depth. Beta will be large if either q is large, or k is small, or both.

By comparison with most everyday materials, rocks are poor conductors of heat; values of conductivity may vary from 2×10^{-3} to 10^{-2} cal cm^{-1}sec^{-1} $^{o}C^{-1}$. Rocks are also very slow to respond to any temperature change to which they are exposed, i.e. they have a low thermal diffusivity, $K = \frac{k}{\rho C_p}$, where ρ and C_p are density and specific heat respectively.

Diffusivity values are of the order of 10^{-2} cm^{2} sec^{-1} and are so low that the effects of diurnal surface temperature variation are damped out at depths of less than a metre and effects of annual variation become insignificant at depths of about 3m. The effects of major and longer term climatic variations such as ice ages may be recognisable at depths over 1500m or more. However, these effects change temperatures by only a degree or so at that depth. Thus fluctuations in surface temperatures have little effect at depth, but the presence of a thick surface layer of low conductivity rock such as clay (Jurassic clay from the south-east English midlands has a mean conductivity of about 2.5×10^{-3} cal cm^{-1} sec^{-1} $^{o}C^{-1}$) has the effect of a surface insulating blanket which can maintain unusually high temperatures within and below it, although the heat flow itself may be of average value.

We turn now to variations in the Earth's surface heat flux, q. As indicated above, the heat flux ultimately derives from the Earth's radioactivity, and in consequence, regions with higher radioactivity will tend to have a somewhat higher heat flux. Very high heat fluxes, however, are related in a more

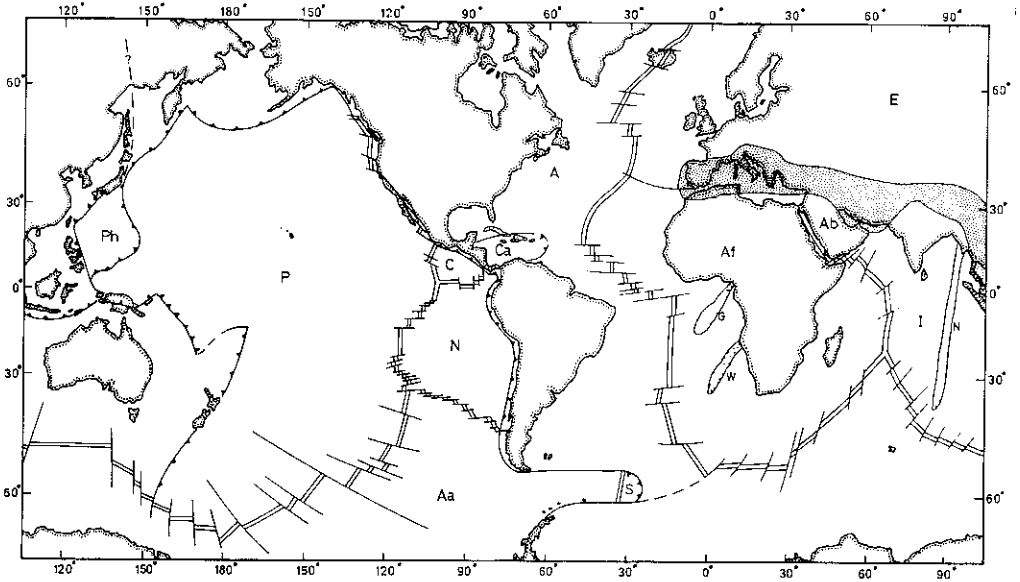


Fig. 1. - The main tectonic plates of the Earth's surface: Ph, Philippine plate; P, Pacific plate; Aa, Antarctic plate; Nasca plate; A, American plate; E, Eurasian plate; Af, African plate, I, Indian plate; Ab, Arabian plate. Toothed lines indicate zones of plate convergence, double lines zones of plate separation and single lines, plate margins along which plates slide past each other. Stippled area Alpine-Himalayan belt where two plates have recently locked.

indirect way to radioactivity.

It is now known that the surface of the Earth comprises a small number (a dozen or so) of relatively rigid tectonic "plates"; these have a thickness of the order of 100 km and lateral dimensions of the order of thousands of kilometres (fig. 1). These places are continuously in motion with respect to each other and form part of a large-scale, solid-state convective flow system which involves at least the outer 700 km of the Earth. This flow occurs because the interior of the Earth is unable to lose heat by conduction as rapidly as it is generated by radioactivity and consequential convective instabilities develop.

A variety of processes occurs through interaction between plates along their margins, which lead to partial melting in and below the crust (i.e. at depths from 15 to 200 km). The liquids produced in this way are about 10% less dense than the material melting to produce them, and in consequence these penetrate the surrounding rocks and rise rapidly (at rates of cm/yr to cm/day) towards the surface. Those which reach the surface give rise to volcanic activity, others may come to rest in the middle or upper part of the crust (i.e. depths less than 20 km) where they crystallise to form the intrusive igneous bodies familiar to geologists. Depending on their depth or origin and the exact composition of the material undergoing partial fusion, liquids (magmas) will arrive in the upper part of the crust at temperatures between 800° and 1200°C.

The cooling and crystallization of igneous bodies which quite commonly have characteristic dimensions of several kilometres or more, will give a very high local heat flux for thousands to hundreds of thousands of years depending on local circumstances. Although on an Earth time scale of 4.5×10^9 years these are very short lived phenomena, an area of present igneous activity and high heat flow can be expected to remain so on all time scales relevant to our present energy problem. Active igneous areas commonly have surface heat flux values of 10 HFU and occasionally 100 HFU or more.

To summarize, very high heat flux values and thus the majority of active geothermal areas, tend to concentrate around the margins of the major lithospheric plates (compare figs. 1 and 2). High thermal gradients can also be associated with abnormally low values of thermal conductivity; strata with these characteristics may be found on any part of a continent. Table 2 gives the characteristics of many of the geothermal fields shown in fig. 2.

TABLE 1

	lower	average	upper
q (HFU)	0.8	1.5	3.0 (non volcanic) ∿100 (volcanic)
k cal cm^{-2} sec^{-1} $^{o}C^{-1}$	2 x 10^{-3}	6 x 10^{-3}	12 x 10^{-3}
β ^{o}C/km	8	20	60 (non volcanic) ∿300 (volcanic)

Note these values are simple intended to give a general idea of the normal range of geothermal parameters. In volcanic regions, in particular, both q and β can vary considerably, and the upper values given are somewhat notional.

Values of Geothermal Parameters

TABLE 2

Field	Reservoir Temp., °C	Reservoir Fluid	Enthalpy, cal/g	Average well depth, meters	Fluid salinity, ppm	Mass flow per well, kg/hr	Non-condensable gasses, %
Larderello	245	Steam	690	1,000	<1,000	23,000	5
The Geysers	245	Steam	670	2,500	<1,000	70,000	1
Matsukawa	230	Mostly steam	550	1,100	<1,000	50,000	<1
Otake	200+	Water	∿400	500	∿4,000	100,000	<1
Wairakei	270	Water	280	1,000	12,000	–	<1
Broadlands	280	Water	400+	1,300	–	150,000	∿6
Pauzhetsk	200	Water	195	600	3,000	60,000	–
Cerro Prieto	300+	Water	265	1,500	∿15,000	230,000	∿1
Niland	300+	Brine	240	1,300	260,000	∿200,000	<1
Ahuachapan	230	Water	235	1,000	10,000	320,000	∿1
Hveragerdi	260	Water	220	800	∿1,000	250,000	∿1
Reykjanes	280	Brine	275	1,750	∿40,000	∿400,000	∿1
Namafjall	280	Water	260	900	∿4,000	400,000	6

Characteristics of Selected Geothermal Fields, from Koenig in Kruger & Otte,1973.

HEAT EXTRACTION

So far we have considered only the distribution of hot, near-surface rock. For such rock to provide a useful energy supply, however, the heat must be extracted by some form of heat-exchanger. In many geothermal areas natural heat-exchangers exist in the form of large scale, sub-surface water circulation systems, which commonly give rise to hot springs or geyser activity at the surface.

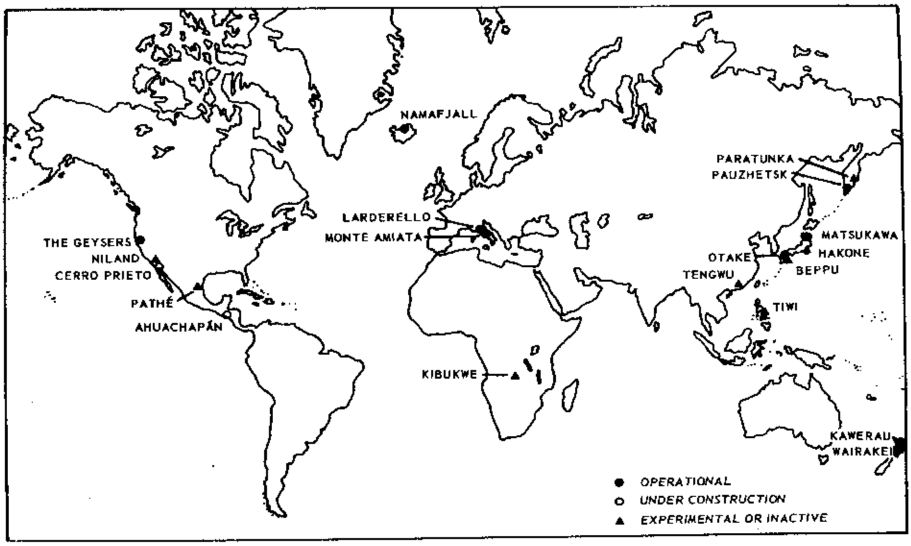
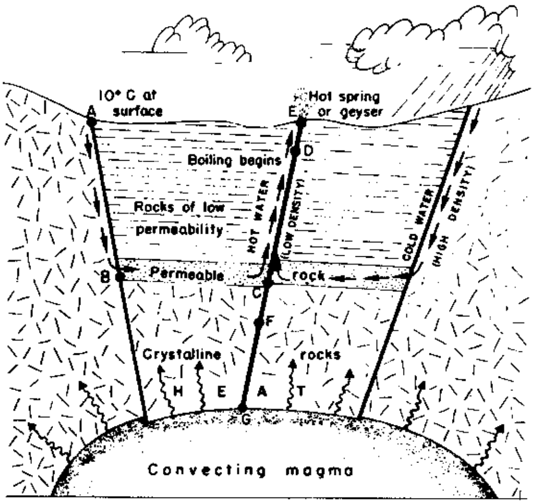


Fig. 2. - Geothermal electric power stations from Koenig in Kruger & Otte, 1973.

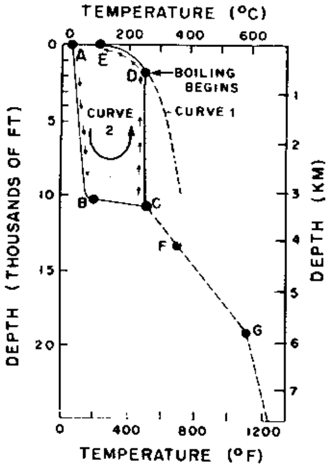
It is at once evident that if heat is to be extracted either by natural or artificial means the hot zone must be permeable, and at present this further requirement prevents the exploitation of a number of otherwise promising areas. We return to this problem later, but for the present we consider the characteristics of permeable regions in more detail.

Fig. 3 shows an idealized system. A large body of slowly crystallizing magma lies at a depth of six kilometres or so below the surface. This has penetrated rocks which are for the most part impermeable. In the region immediately above the magma body the impermeable (crystalline) rocks are overlain by a localized pocket of permeable strata. These strata are bounded by and cut by steep faults (fracture zones along which some relative motion has occurred - shown as heavy black lines on the diagram).

The upper levels of the permeable strata are less permeable than the lower. In nature this could occur by chance through original variation in rock properties. More commonly, however, it will be the result of the precipitation of dissolved solids from ascending hydrothermal fluids. Water in the



3a



3b

Fig. 3a. - Schematic representation of a geothermal system.
Fig. 3b. - Schematic temperature distribution expected in a); curve 1 is the boiling curve; see text for discussion. From White in Kruger & Otte, 1973.

temperature range 150° - 300°C readily dissolves silica and a number of other rock constituents. Hydrothermal waters tend to be unusually rich in SiO_2, Cl, B, Na, K, Li, Rb, Cs and As; occasionally they may contain significant amounts of H_2SO_4. Therefore, the effect of hydrothermal circulation is often to increase permeability by solution in the deeper, high temperature zone, and to reduce permeability by precipitation in the cooler, lower pressure, near-surface region. Thus many hydrothermal areas have a convenient self-sealing property which means that after circulation has gone on for some time, surface flows may be largely or entirely restricted to places where holes have been drilled for the purpose.

Fig. 3a shows the convective circulation of ground water; it circulates downwards from the surface along the marginal fault zones, moves laterally and is heated passing through the permeable layer and finally rises to give a hot spring or geyser at E. The permeable layer is heated by conduction of heat from the magma chamber. The variation of temperature around the system is shown in fig. 3b. Note that the gradients which are governed by convection (AB, CD and G downwards) are much shallower than the conductive gradient (CG).

We now examine the shallow depth behaviour of the ascending flow by reference to fig. 4. The heavy curve shows the variation of the boiling point with depth of pure water under hydrostatic pressure. In nature the curve will be modified through the effect of salts in solution and in many cases the pressures will not be hydrostatic. As the heated water rises, it undergoes relatively little temperature change (CD, fig. 3b). Provided that its "base temperature" (C, fig. 3b) is significantly above 100°C, at some depth its temperature path will intersect the boiling curve (e.g. A, fig. 4) and the water will begin to boil.

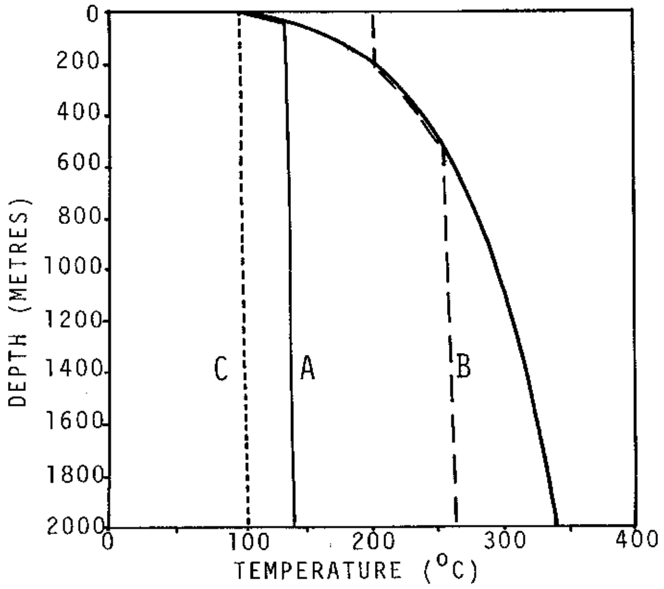


Fig. 4. - The boiling curve (heavy); see text for explanation of A, B and C; after White in Kruger & Otte, 1973.

As it continues to rise its temperature drops, following the boiling curve, with the generation of more steam. It now becomes clear that natural hydrothermal systems fall into three groups:-

1) Dry steam systems: these have a relatively high base temperature and a deep intersection of the boiling curve; all water is converted to steam which is super-heated when it reaches the surface (e.g. fig. 4 curve B). Both Larderello and the Geysers field in California are of this kind.
2) Wet steam systems: the boiling curve is intersected at shallower depth

but not all the water has been converted to steam by the time it reaches the surface, where there are commonly violent geyser eruptions of water-steam mixtures (e.g. fig. 4 curve A).

3) Hot water systems: in these the boiling curve is not intersected, or at most only in the upper few tens of metres. Hot springs are the normal surface manifestation (e.g. fig. 4 curve C).

In nature, however, the situation is rarely as simple as represented here. In cases where the near surface layers have been sealed by precipitation of silica, pressures may be significantly higher than hydrostatic at shallow depth. As discussed below, drilling into such systems may allow the controlled flashing of the hot water. With highly permeable surface layers, on the other hand, boiling may occur at lower temperatures and/or greater depths than indicated by the boiling curve. Because the hydrostatic assumption is no longer valid, once boiling has begun in a system which is in communication with the atmosphere, the pressure is controlled not by the weight of a column of water, but by the weight of a column of mixed water and steam.

Further complications arise in connection with the balance between flow of hot water out of the system, and the recharging of the system from groundwater. When the latter is inadequate to compensate for the surface losses, the nature of the system will gradually change. As the volume of water available for heating decreases, fluid pressures will tend to fall, boiling will occur at greater depths and the system may evolve from a wet-steam to a dry-steam type.

EXPLOITATION OF GEOTHERMAL AREAS

In general, exploitation requires the drilling of a number of holes at carefully selected sites in a geothermal field which has previously been delineated and evaluated by geological and geophysical methods. Steam, hot water or both are then piped as short a distance as possible to a power station.

Economic viability depends largely upon the number, diameter and depth of holes which have to be drilled and the useable enthalpy and ancillary characteristics of the geothermal fluid. Drilling is an expensive business (fig. 5), and much effort has been devoted to securing the hole profile which optimises the fluid discharge/unit drilling cost ratio. At the Geysers field holes are typically about 2 km deep with a surface diameter of about 51 cm reducing by degrees to about 22 cm for the lower third of the depth.

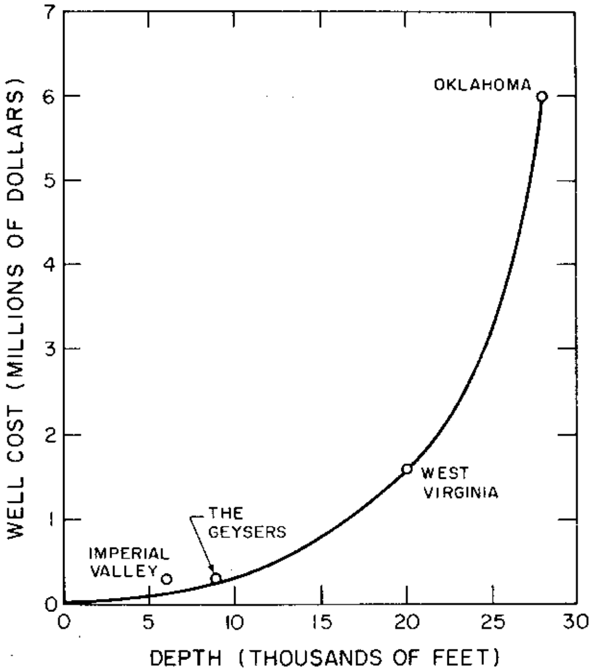


Fig. 5. - Drilling costs increase rapidly with the depth of the well (from Anderson in Kruger & Otte, 1973).

At the power station the treatment of the geothermal fluid largely depends upon its character. In general, the higher its temperature the better. In the commercially attractive, high-temperature ($T > 200^{o}C$) dry steam systems, such as Larderello or the Geysers, the steam may be expanded directly through a steam turbine, to generate electricity. Fields of this kind are rather rare but produce over 70% of the world's geothermal electricity output at present.

In wet steam, sealed systems suitably located and pressure regulated wells may make it possible to control the depth at which flashing occurs; the steam may be separated from the water at the surface and again used to drive a turbine.

In both wet and dry systems there are various operational difficulties, although in the latter they are rather less. Dry steam at high pressures tends to have high velocities and to carry with it particulate material which can coat pipes and turbine blades; coarse fragments can damage the installation. Wet steam and the water associated with it can be very highly corrosive because of the dissolved impurities, and it is sometimes necessary to put it through a heat exchanger rather than into a turbine directly. In addition, cooling of the fluid leads to precipitation of the impurities, which in time leads to serious problems of furring of the pipes and other parts of the installation.

In recent years considerable attention has been devoted to plants using a heat exchanger and a vapour turbine cycle. The heat exchanger accepts liquid water from the well and uses it to heat a low boiling point fluid such as propane or freon, which in turn is expanded through a turbine and then condensed and reused. The schematic layout of such a scheme is shown in fig. 6.

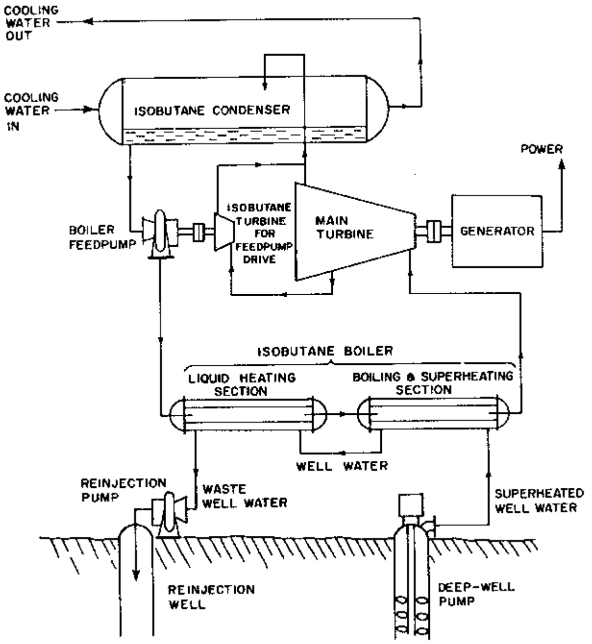


Fig. 6. - Schematic representation of a vapour-turbine cycle; from Anderson in Kruger & Otte, 1973.

The economic viability of such systems is as yet unproven although a small freon-based system has been in operation in the USSR for several years. Their advantage is that they may permit the profitable exploitation of much lower enthalpy geothermal fluids than is at present possible.

Although the major interest in geothermal power must stem from its potential for generating electricity, there are also a number of schemes in operation by which geothermal water too cool for electricity generation by present methods is used directly for town or agricultural heating purposes. Such waters which tend to be cooler than 150°C have relatively low impurity levels and are generally not seriously corrosive. Systems of this kind are in operation in Iceland, Oregon USA, Hungary, the Soviet Union and a number of other places. Where hot waters are available close to urban areas, they often offer a very inexpensive form of heating. In all probability, it is in this way that geothermal energy will be used in Britain. Some comparitive cost information is given in Table 3.

TABLE 3

Geothermal field	Geothermal production	Local average, other fuel
Electricity, U.S. mills/kwh		
Namafjall, Iceland	2.5 - 3.5	-
Larderello, Italy	4.8 - 6.0	∿7.5
Matsukawa, Japan	4.6	∿6.0
Cerro Prieto, Mexico	4.1 - 4.9	∿8.0
Pauzhetsk, U.S.S.R.	7.2	∿10.0
The Geysers, United States	5.0	7.0
Space heating, U.S.$/Gcal energy		
Reykjavik, Iceland	4.0	6.7
Szeged, Hungary	3.0	11.0
Regrigeration, U.S.$/Gcal energy		
Rotorua, New Zealand	0.12	2.40
Drying diatomite, U.S.$/ton		
Namafjall, Iceland	∿2	∿12

Selected Comparative Cost Data for Geothermal Energy, from Koenig in Kruger & Otte, 1973.

RESERVES

As with any other naturally occurring commodity, reserves may be estimated in two ways: we may estimate the absolute abundance of that commodity without regard to its concentration, or alternatively we may regard as reserves only those occurrences which, under prevailing economic conditions and with present technology of extraction, appear capable of profitable exploitation.

To view the Earth's thermal reserves in the first way is meaningless because although the Earth's total heat content is enormous ($\sim 10^{35}$ cal) nearly all of it is inaccessible to us and likely to remain so. On the other hand, to apply the latter criterion at present is almost equally meaningless because of the relatively small amount of effort which, until recently, has been devoted to developing the technology of heat extraction from the Earth. It is most unlikely that there remain many high temperature dry steam geothermal areas to be discovered; their surface manifestations are so obvious that in populated areas (where they are likely to be of use) they would have almost certainly been discovered. Fig. 7 shows the major undeveloped geothermal fields of the world which by present criteria (i.e. high temperature and permeability) have potential for power generation. If this represents the limit of the Earth's commercially exploitable geothermal resources, geothermal energy is unlikely to increase its share of the energy market (at present about 1% in the United States).

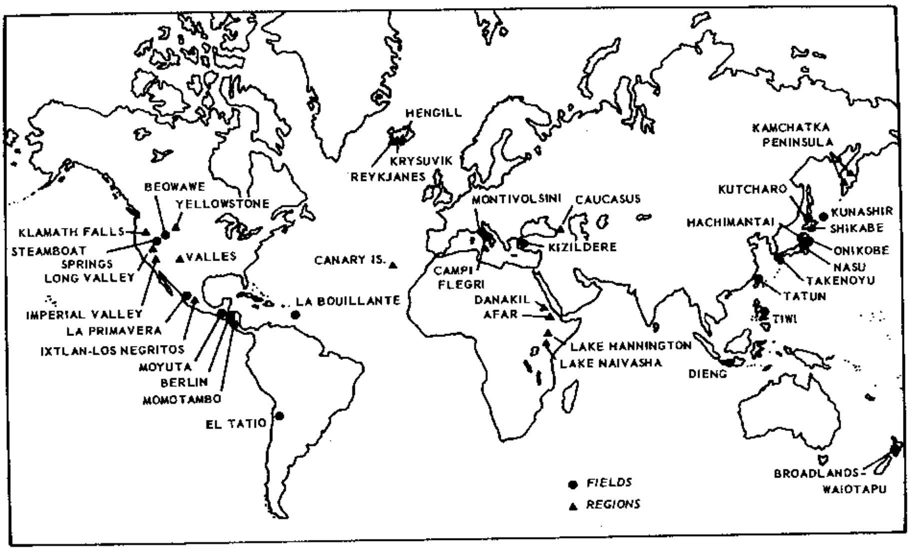


Fig. 7. - Major undeveloped geothermal fields or regions under active exploration; from Koenig in Kruger & Otte, 1973.

Although cautious, such an assessment of the future is perhaps unduly pessimistic. Technological advances in three areas could together or separately considerably improve the prospects of geothermal power, although its economic attraction will as always remain dependent upon a comparison with other energy sources available at the time.

The first possible area of advance is that of generating fissure systems in otherwise impermeable rocks and thus allowing heat to be extracted from extensive areas of high geothermal gradient which cannot be exploited at present because water cannot circulate through them. A number of different techniques are being used. Hydraulic fracturing by generating very high pump pressures at restricted depth intervals in holes has been used for a number of years in the oil industry to increase rock permeability. By itself this method appears inadequate to generate fissure systems sufficiently extensive for geothermal purposes. There is, however, now the possibility of causing fractures generated in this way to undergo self-propagation as thermal contraction cracks as heat is extracted by circulating fluid. Alternatively, the fracture system may be initiated by chemical or nuclear explosions down the hole. In some systems of this kind it might be necessary to force the circulation of the fluid by surface pumping, particularly in the early stages. If techniques of the kind outlined above became fully developed and were routinely and relatively cheaply employed, the present geothermal resources (as defined at the end of the previous paragraph but one) would be increased by a factor of between one and two orders of magnitude.

The second area of advance has already been mentioned above. At present, enthalpies of > 200 cal/gm are sought for power generation and > 100 cal/gm for direct heating. The lowering of one or both of these requirements by the use of vapour turbine cycles or other methods would enormously increase the volume of resources. The amount of increase would be related to the degree of lowering of the requirement, but halving the power generation requirement should again increase reserves by one to two orders of magnitude.

The third and, perhaps, least likely area for advance lies in drilling technology. Advances here are least likely only because much more time and effort has been devoted to drilling methods over the years than to the other problems. If, however, new and cheaper methods were developed (e.g. drilling by rock melting is at present being tested), the depth range over which it was profitable to extract heat from rocks could be considerably increased. Most geothermal wells in use at present are less than 2 km deep. If this range could be increased by a factor of two or three without large cost increases, and if fluid circulation could be maintained at those depths, perhaps half the area of the continents would be underlain by rocks capable of yielding water with enthalpy of 100 cal/gm.

In summary, it is at present not reasonable to count on a major contribution to the world's energy budget from geothermal sources. Advances in one of several fields of technology could, however, abruptly change the situation.

PRACTICAL DIFFICULTIES

There are various practical difficulties and disadvantages associated with the use of geothermal power. Some of these have been touched upon in the previous sections and will only be recapitulated here.

1) The geothermal fluid is often highly chemically corrosive, or physically abrasive as a result of the entrained solid matter it carries. This may entail special plant design problems and unusually short operational lives for both the holes and the installations they serve.

2) Because the useful rate of heat extraction from a geothermal field is in nearly all cases much higher than the rate of conduction into the field from the underlying rocks, the mean temperature of a field is likely to fall during exploitation. The rate and significance of such temperature reductions will depend on local conditions (Larderello has operated successfully for 70 years and at an increasing power output). In some low rainfall areas there may also be a problem of fluid depletion. Ideally, as much as possible of the geothermal fluid should be reinjected into the field. However, this may involve the heavy capital costs of large condensation installations. Occasionally, the salinity of the fluid available for reinjection may be so high (as a result of concentration by boiling) that is is unsuitable for reinjection into the ground. In that case, it must either be diluted before reinjection, purified, or

disposed of elsewhere. Occasionally the impurities can be precipitated and used, but this has not generally proved commercially attractive.

3) Transmission: geothermal power has to be used where it is found. In Iceland it has proved feasible to pipe hot water 20 km in insulated pipes but much shorter distances are preferred.

4) Environmental problems: these are somewhat variable and are usually not great. Perhaps the most serious is the disposal of warm high salinity water where it cannot be reinjected or purified. Dry steam plants tend to be very noisy, and there is release of small amounts of methane, hydrogen, nitrogen, ammonia and hydrogen sulphide; of these the latter presents the main problem. At the Geysers field it is present in the vented steam at the level of about 225 ppm; this is equivalent to about one quarter the rate of release of a coal fired power station (using coal with 1% sulphur) and the same power output.

   Changes in porosity and fluid pressure in geothermal reservoirs could give rise to small amounts of seismicity especially if the rate of inflow of water is much less than the rate of withdrawal. It is thought that this kind of problem can be monitored and controlled fairly easily.

CONCLUSIONS

At present geothermal energy makes a very small, but locally important, contribution to world energy requirements. This situation will not change unless important technological advances are made. Environmentally it is probably the least objectionable form of power generation available at present with the exception of hydro-electric methods.

Although geothermal exploration of Britain is at a fairly early stage, all the signs indicate that the only resources available are likely to be low enthalpy, relatively pure waters. These may locally offer the possibility of very inexpensive agricultural or even domestic heating. The extent of such resources in Britain is not yet known and there is little in the way of domestic technology available for their exploitation. If any of the major technological advances mentioned earlier occurred, the position in Britain would be dramatically changed.

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DISCUSSION

Question: What would be the costs of drilling to extract geothermal heat?

Answer: It would be about one million US dollars for a 4.5 km bore-hole based on costs in 1972. Present day costs are undoubtedly greater but it does not seem more economical to drill several small diameter holes instead of a single large hole.

Question: Is a systematic geothermal survey being made of U.K.?

Answer: A map showing the geothermal character of the U.K. does not exist yet, but work is active in this respect and a map should be available in a few years. Unfortunately, the cost of drilling exploratory bore holes 300 m deep is high and so progress on mapping has been slow. Holes drilled for other purposes have been used but often the requirements for these conflict with those necessary to make geothermal energy use worthwhile. This is particularly so for oil drilling which, for obvious reasons, is not carried out near the geological faults at which the magma approaches the surface. The magma is, of course, at such a high temperature that effective use for it cannot be found in our present technology. Should there be a likelihood of magma rising up the bore hole, evacuation of the drilling area might be necessary. There have been some geothermal surveys in the Paris basin which consists of fairly thin alternate layers of permeable and non-permeable material. Low enthalpy sources probably exist there which would be ideal for direct domestic space heating with water at about 50 - 60°C but the generation of electricity is extremely doubtful.

When the U.K. geothermal map is complete, we should then be able to predict the possibility of district heating schemes with water temperatures up to about 80°C. An alternative procedure using a heat pump could be envisaged in which the geothermal energy is used to create a heat reservoir for the pump of, say, 40°C; however, solar energy absorbed within the first 3 m or so of the earth's crust could be used for the same purpose, provided that diurnal temperature variations could be accepted or attentuated.

Question: Will there be any seismic effects from heat extraction from deep holes?

Answer: Seismic effects might occur especially if equilibrium is not maintained between hot water extraction and cold water input to the permeable layers. These effects would probably be small. Underground nuclear explosions to increase permeability could be dangerous but little is known about this at present.

Question: Why is East Africa considered a potential site as it lies in the middle of a plate?

Answer: Because the edges of geological plates are the ideal locations for geothermal energy use, the interest shown in East Africa seems at first sight to be unlikely. It is now thought that, in time, a fault similar to that under the Red Sea will develop in a southerly direction from the Mediterranean Sea through East Africa causing an upwelling of magma.

Question: Would there be any advantage in locating heat exchangers underground?

Answer: This would be impractical because of the difficulty of removing furring from the exchanger surfaces. Although noxious gases would be suppressed, the heat transfer efficiency would undoubtedly be low.

Question: Can the water be used after heat has been extracted?

Answer: Common salt is obtained in California together with fresh water from condensation.

Question: What contribution could geothermal energy make to our power requirements?

Answer: Prospecting methods are still being developed and radon and micropulsation techniques still need to be made more reliable. When geothermal sources can be assessed with fair accuracy, it is reasonable to expect that, on the basis of present technology, some 1500 MW of geothermal power could be used to generate electricity by the year 2000. The widespread use of hydrofracture could increase this power by a factor of 3 or 4. It we could use low grade heat, this factor could be increased to 10 - 100, however, this might not be feasible because we cannot presently utilize the vast quantities of low grade heat rejected by power stations.

SECTION 5

TRANSMISSION AND STORAGE OF ENERGY

SECTION 6

POSSIBLE DEVELOPMENTS IN ENERGY USE

SECTION 7

ENVIRONMENTAL AND SOCIO-ECONOMIC ASPECTS OF ENERGY USE

SECTION 8

ENERGY ANALYSIS

SECTION 9

CONCLUDING PAPERS

EPILOGUE

I. M. Blair

Energy Technology Support Unit, Harwell, and Chairman of the School

It would not do justice to such a wide ranging and intensive a School as this to produce a summary in a few pages. I shall not even attempt to do so. I shall content myself by setting down just a few of the residual impressions left on me by the School following two weeks of continuous exposure. I should emphasise that these are personal impressions and do not necessarily reflect the views of the Energy Technology Support Unit or the Department of Energy.

During the School one noticed two, apparently incompatible, themes:-

(1) The "Establishment" view, linked with continually advancing life style and increasing energy consumption, hell-bent on ever higher technology, particularly committed to an intensive nuclear programme.

(2) The "Anti-Establishment" view, pressing for a low energy, low technology, life style, and bitterly opposed to nuclear power.

On the face of it, this is not a likely scenario for a profitable discussion but in the event it proved manifestly to be so. It became clear that they were but facets of an exceedingly complex problem, whose solution must emerge as a linear combination of them both. When intelligent people gather to discuss a problem, the diachromatism of polarised opinion merges into the continuous spectrum of consensus.

The Establishment/Anti-Establishment conflict appeared to be rooted in the mistaken impression that our affairs are being run by a ruling class, peopled by a race of infallible supermen, impervious to the wishes and opinions of we mere mortals. Intensive research which I have conducted over nearly four decades has failed to produce any evidence for the existence of such a class; when I have met certain persons charged with the responsibility of making decisions on our behalf, they have looked remarkably like us. They need, and seek, advice and opinion from anyone competent to give it to enable them to discharge their responsibility effectively.

Though this leads to a "weighted egalitarianism" which might cause offence to those with excessively pure ideals, it is clearly right to give more credence to the opinion of those who have devoted themselves to a study of the issue in question than to those whose expertise lies elsewhere.

Such was the consensus which appeared to me to arise from discussion at the School. Though it might inspire relief it should also inspire responsibility. Let each of us, within our sphere of competence, make sure that our views are forcefully and rationally presented. Perhaps the imperfections in our society are due not to "them" but to "us".

The debate on nuclear power became progressively more productive as mutual understanding of differing views increased. Even the strongest advocates were by no means unaware of the problems involved in this technology, nor were the strongest opponents suggesting that these problems were so severe that all reactors must be switched off forthwith. Thus no-one would seriously object to one reactor, it is only when large numbers of them are envisaged that the debate hots up. The problems associated with nuclear power, such as safety, capital cost and energy intensiveness, were balanced against the consequences of not having nuclear power. Thus a consensus view emerged, not for or against nuclear power in an absolute sense, but rather that an optimum balance point must be reached. The issues involved would thus dictate the scale and rate of growth of a nuclear programme.

How much energy do we actually need? This was the crucial question around which much of the debate on energy consumption and the sources we must develop to meet it revolved. It involved issues which, though important, were difficult to quantify, such as quality of life, personal expectations, etc. Intuitively one feels that quality of life is not a monotonic function of rate of energy consumption, but rather must pass through some optimum value. One is reminded of Professor Thring's much-quoted adage:-

"Happiness is three tons of coal equivalent"

Much concern was expressed over the ever increasing demand in the developed countries for energy and other manifestations of material wealth. It was questioned how much longer this could continue, and, even if it was desirable, that it should. It was suggested that such a life style, based on selfishness and greed, should be replaced by a simpler but more satisfying life style based on a lower material standard in which all people could share equitably. This touches upon moral and ethical issues which were not, unfortunately, included in the formal presentations though they were discussed informally. What is being asked for is nothing short of a change in human nature, and on a scale comparable to a religious reformation the like of which the world has never seen. Let the reader form his own view on the probability of this happening, and hence the wisdom or otherwise of using this as the basis on which to build an energy policy. Of course it might happen, but I have yet to meet a man who would bet ale on it.

So what happens next? We have indulged in much interesting talk and discussion. Let us hope that this was not merely an enjoyable intellectual exercise, for when all the assessments, paper studies, scenario building, etc., etc., have been done what is required at the end of the day to solve the problems is real practical hardware that works in the real world to exploit new energy sources, to make our existing technology safer, and to make more effective use of our conventional fuels. Who is going to produce it? The participants in this School represent a cross-section of our young energy technologists on the threshold of their careers. If they, and others who might read these pages, have been so inspired to determine to convert what they have learned here into practice, then the venture has been well worthwhile.

Aspects of Energy Conversion

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