COMMENTS ON EARTH SCIENCES: GEOPHYSICS
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Prospects for Geothermal Power

For many decades it has been recognised that an enormous amount of energy is locked up in subterranean geothermal sources. Some of this energy has been utilized directly in the form of the heating of houses near geothermal areas and, since the end of the last century, indirectly to generate electricity. These uses were rather haphazard until fairly recently.

Because of man's voracious appetite for cheap electricity there has been, in the last decade or so, a determined effort on a worldwide scale to stimulate interest and research into the location and economic exploitation of geothermal fields, both known and unknown. Progress to date and some exciting possibilities were discussed at a recent United Nations Symposium on the Development and Utilization of Geothermal Resources held during the last two weeks of September 1970 in Pisa, Italy.

This symposium was spawned by an earlier conference, again sponsored by the United Nations and held in Rome in 1961, on New Sources of Energy. At this earlier conference discussion was not limited to geothermal power since there was also a great deal of interest in wind and tidal generating stations; in retrospect the proponents of geothermal power were perhaps overly optimistic with regard to its rate of development. However, this is due as much to unexpectedly rapid development of cheaper methods of producing power from fossil fuels (often achieved by economics of scale) as by some rather tricky technological problems associated with the development of geothermal power. It is my purpose to discuss some of the more interesting present and possible future lines of developments discussed at the Pisa symposium.

The symposium itself was very well organized with authors being required to produce papers several months in advance of the meeting; these were then divided into a dozen different categories and allocated to rapporteurs who summarized the world wide picture in each section. Most of the summaries were printed and distributed to all participants prior to the meetings while the individual papers (totalling approximately 10 kg) were printed and distributed at the meetings. In these comments all references for 1970 refer to papers submitted to the symposium; therefore, they will be referred to only by author's name and date in the text and will not be included at the end; other works referred to will be classified in the normal manner. Copies of the papers given at the symposium will eventually be generally available through the United Nations.

What is a geothermal field? This was a question posed early in the symposium but even so it led to a considerable amount of argument because some geothermal areas can be exploited and some cannot. I am sympathetic towards the proposal that we follow the practice of the mining industry where a mine is simply defined as an economically exploitable ore deposit; a geothermal field (or reservoir) is therefore a geothermal area which can be exploited economically.

High temperature (>200 °C) geothermal fields can be broadly classified into two main types—those that produce dry steam and those that produce wet steam (i.e. a mixture of steam and water); there have been a number of attempts to produce a more detailed classification based upon the geologic environment (McNitt, 1970) but it was obvious from the discussion that there was far too little information available on a worldwide basis to permit general agreement on a well founded system of classification. Much more recently it has been realized that there is enormous potential in the relatively low temperature (<100 °C) water contained in many formations of sedimentary basins throughout the world.

For generating electricity, the energy from dry steam fields is much more efficiently used than that from wet steam fields; in the latter, steam must be separated from the water to avoid the highly abrasive and corrosive effects of high pressure-high temperature water which frequently contains significant quantities of dissolved salts, which can then attack the materials of the steam transmission pipes and turbine blades, or simply deposit silica or carbonates on them. With wet steam systems only about 5 to 10% of the available energy is actually used to generate electricity, the rest in the form of hot water is usually wasted either by injecting into a convenient river system or, as recently suggested to avoid pollution effects, reinjecting the unwanted portion back into the ground.

Even in well-developed countries such as the United States, dry steam fields can produce electricity at a cost per KWh that is only about 60 or 70% of that for a power system of the same capacity using conventional fossil fuels (Facca, 1970). On the other hand, for a wet steam field the savings are not so clear cut with the economic comparison between a geothermal power station and a fossil fuel power station depending upon such factors as whether the cost of fossil fuel is above the average for a particular area, the size of power station required etc. As might be guessed from the law of maximum cussedness, the frequency of occurrence of dry steam fields is much less than that of wet steam fields, about one in twenty (White, 1970).

The total capacity of generators operated by geothermal power is somewhere around 700 to 800 MW of which 60 to 70% is accounted for by the plants near Larderello, a dry steam area in Italy, and at Wairakei, a wet steam area in New Zealand; it is the pioneering development of these two areas that is showing the way for the rest of the world. These figures are insignificant compared with the total installed capacity of all forms but it is the potential for the future that is important. For instance, the greatest dry steam field in the world, at The Geysers in California, can support generator sets totalling 800 MW with an estimated capacity of over 3000 MW (Facca, 1970). Approximately 10 acres of producing area is required for each MW of capacity.

This leads to one of the problems concerning large scale development of geothermal fileds. To obtain power we need a steam producing area with appropriate bore-holes, a steam pipeline collection system and a power plant. Similar to the experience found in oil fields and normal hydrological technology, it has been found that there is an optimum borehole diameter beyond which significantly increased output cannot be obtained at a reasonable cost. Several boreholes are therefore needed, spaced sufficiently far apart that they do not interfere wth each others flow; typical spacing is somewhere between 70 m and 200 or 300 m, depending on the type of field (James, 1970). If the steam is to be used to drive turbines at a large centrally located power station then the cost advantages and convenience of having a central location must be balanced against the disadvantages of having a large number and long lengths of steam pipeline with the increased expense associated with both the capital costs and the heat loss, and therefore loss of power generating capacity, as the steam travels along the pipes. It is here that the conventional power stations using fossil fuel have a great advantage. Significant savings for fossil fuel powered stations can be obtained by taking advantage of economies of scale using such sophisticated techniques as high pressures, high super-heat temperatures, several stages of reheat and liquid cooled generator windings; these can all be concentrated into one station of several hundred KW capacity. However, from the nature of the beast it is unlikely that similar economies of scale can be practiced for geothermal power generating units; it has been estimated that the present limit to single generator capacity is somewhere between 50 to 80 MW and that not more than two of them can be economically placed in one building (Facca, 1970; Bradbury, 1970). Thus, for a large geothermal field the trend is likely to be to have a number of relatively small power stations being fed by steam pipelines of optimum length with the electricity generated being collected by transmission lines in the normal way. This system has the advantage that if some of the boreholes supplying steam dry up unexpectedly, it is relatively easy to dismantle the generator set and use it elsewhere.

In a recent article titled "Clean Power From Inside the Earth" it was assumed that geothermal power was free of pollution problems;[1] however, it was evident from discussions at the symposium that this might be one of the largest problems facing the future economic development of geothermal power. For instance, anyone who has visited Rotorua, N.Z., where many houses are heated by geothermal hot water, cannot fail to be impressed by the smell of hydrogen sulphide (with its inherent toxic dangers (Armstead, 1970)) that hangs over the town as well as by the beauty of its many geothermal phenomena. With geothermal power stations reinjection into the ground of unwanted water adds to the cost of operating the station but has the advantage that it reduces the depletion of the underground water supplies. On the other hand, if cold or relatively cool water is reinjected it might cause "fingering", that is, cold water might suddenly penetrate along a fissure to a production hole and ruin its potential. This could be overcome by reinjecting at a distant point but this again increases costs and, since it is being reinjected into a different system, does not help very much in the matter of conserving underground water supplies in the field that is being depleted.

All geothermal fields exploited to date have been discovered from obvious surface indications such as geyser or fumarole activities. In this respect the status of exploration for geothermal fields is analogous to that of the exploration for oil as it was roughly at the turn of the century when oil seepages were relied upon to give the first indications of a subterranean oil pool.

There are in fact, many other similarities between geothermal reservoirs and oil reservoirs. Many geothermal fields are capped by impervious rock which has to be penetrated by a borehole in order to tap into the steam or hot water. Occasionally this cap rock is breached by tectonic activity thus allowing steam and hot water to escape to the surface where it is readily visible. For a geothermal reservoir to be exploitable it must have sufficient permeability either in the form of sufficiently thick layers of porous-permeable media or, as seems to be more generally accepted at least for the wet steam fields, in the form of cracks and fissures of sufficient width; in fact, Grindley[2] states that if high pressure production is to be sustained, wells must be sited to intersect fissures formed on the subsurface extensions of the major faults cutting the aquifer supplying hot water. Reservoirs being exploited, often at a changing withdrawal rate, are being watched in order to estimate current performance and hopefully predict future performance; even with all the experience of the oil industry there are still considerable difficulties in predicting reservoir performance so it is only to be expected that the much younger geothermal industry would also have considerable difficulty.

One of the principle concerns is recharge of the reservoir. What little is known about this process comes from an examination of the O^{18} and deuterium content of the water and indicates that the water is meteoric in origin (White, 1970) and that recharge can and does take place. Independent evidence comes from gravity observations at Wairakei which indicate that from 1961 to 1967 between 20 to 35% of the water withdrawn was replaced (Hunt, 1970); this information on total anomalous masses can be deduced from the gravity data by a simple application of Gauss's theorem. Ideally, discharge should be matched to recharge in order to make maximum use of the energy stored underground. The problem here is that as water and steam is withdrawn the reservoir characteristics change and since experience over the life of a reservoir is so limited there is a great deal of uncertainty as to how to control the performance. For instance, further gravity data for Wairakei from 1967 to 1968 suggests that the discharge is now matched by the inflow but the reasons for this are not clear.

Ultimately, of course, the reservoir will become exhausted since after a few cycles of recharge the heat stored in the rocks and transferred to the recharge water is gradually dissipated. A useful minimum time span to aim for would be about 20 years since this is often considered to be the time span of a generator (James, 1970), thus the plant and the field would be well matched.

We now come to the problem of locating geothermal fields without surface expression. This requires the application of geophysical and geochemical techniques. So far geochemistry has proved extremely useful in giving information concerning geothermal fields that have surface expression. For instance, there are many indicators of sub-surface temperatures in hot water systems. The amount of silica (SiO_2) is useful since it precipitates as water cools to about 180 °C; Na/K ratios in the waters are also used to predict underground temperatures; the presence of sinter precipitated from hot springs usually indicates temperatures greater than 180 °C either now or in the past;[3] sinter occurs in every known geyser area but it is also found in some areas without active geysers. These indicators, which are useful for water dominated systems, are not nearly as useful for vapor dominated systems. However, this is not too critical because in vapor dominated systems the thermodynamic properties of steam predict that initial water temperatures will be somewhere between 236 to 240 °C with pressures from 32 to 35 $kg\,cm^{-2}$ (White, 1970). All these indicators require surface expressions of a geothermal field. Geochemistry is therefore useful in the development and exploitation of a field but it is at present difficult to see that it has any significant use in the location of fields without surface expression.

Even geophysical methods have been used mainly to investigate the extent of fields located from surface expressions rather than to locate unseen fields.

In order to make good use of geophysical methods we require a good understanding of the geological occurrence of the existing fields. This we do not yet have mainly because the area so far sampled is a very small fraction of the earth's surface with the selection based entirely on obvious surface activity.

In discussing possibilities of discovery by geophysical methods it is necessary to have some idea of the target size. Considerations of such aspects of exploitation as the most economic size of a power station, length of steam collection lines etc. suggest that even under favourable conditions of temperature and permeability, the minimum volume of an economically useful field would be around 2 km^3 (Banwell, 1970). In terms of a structurally probable slab model this would have a shape of $\frac{1}{2}$ km thick $\times$ 2 km $\times$ 2 km; fields five or ten times this size are already known. Again, the maximum depth at which such a field could be exploited would be about 2 km. Numerous geophysical methods are available and a special session for discussion of geophysical methods was held during the symposium.

This session was rather disappointing since it suggested that many people did not fully understand the potentialities and disadvantages of the geophysical methods they were using. For instance, at one stage of the proceedings one person disparaged the seismic method on the grounds that if he set a charge off at point A and recorded at point B and then set off a charge at point B and recorded at point A he did not get identical traces!

Most of the standard well developed geophysical techniques can, of course, be used to give structural information in practically any environment. However, at the present stage of geothermal power development the standard methods are usually used simply to give more detailed information in an area where the existence of a geothermal field of unknown extent and temperature is already known. In seeking methods capable of locating potential geothermal areas which do not have obvious surface expressions of geothermal activity, emphasis is being placed upon various airborne methods. One of the most interesting of these, suggested some years ago,[4] is the airborne infrared survey. There are many complications in interpreting the results mainly because the pre-dawn period of radiation balance is so short, although there are ways of getting around this difficulty. There are also many other complications but it might be possible to locate a region where, for instance, a warm spring discharges into a larger river. At the present stage of development it is probably reasonable to say that the airborne infrared survey is capable of mapping relatively strong anomalies in special circumstances but that the many disturbing influences do not at present make it a very sensitive detector for geothermal purposes; this is quite apart from the usefulness of the method in helping to construct geologic maps together with evidence from other types of aerial photography.

Airborne magnetic and electromagnetic methods may also be useful, the latter because saline hot water has a low electrical resistivity which, in conjunction with rocks which are sufficiently porous to make a field worth exploiting, can produce a detectable anomaly. To date, resistivity mapping has generally been carried out on the ground and has been the most successful geophysical method for indicating the extent of a geothermal field.

Magnetic surveys have not proved to be so reliable because although hydrothermal alteration of rocks can convert magnetite to pyrite, which would produce a magnetic low in the region where some of the magnetite is not altered, one cannot always be sure that the magnetic low is not caused simply by a deficiency of magnetite. However, it might be possible to test this with the Induced Polarization method.

Surprisingly enough, neither in the papers submitted nor in the discussion was reference made to the potential use of I.P. methods.[4] This is effective in detecting disseminated sulphides and should therefore be useful in differentiating magnetic lows due to hydrothermal alteration of magnetite to pyrite, from those due simply to a lack of magnetite. It would also be useful in detecting the presence of conducting clays, also non-ohmic, which frequently interfere with the DC resistivity measurements. Since one of the parameters determined in an I.P. survey is the resistivity, whatever electrode arrays are being used, it is somewhat surprising that no one appears to have tried using this method. Of course, it is one of the most expensive ground methods available and this may explain some of the reluctance to use it since the amount of money being spent on geophysical methods applied to exploration for geothermal fields is infinitesimal compared with the amount spent by the mining and oil industries.

Furthermore, even if I.P. methods proved to be successful in mapping hydrothermal systems by the presence or absence of pyrite, it is always possible that its presence might be due to an old, and therefore cold, hydrothermal system. In the final analysis a geothermal field must be proved by geothermal methods.

Geothermal surveys are perhaps the most commonly used in the business. Both temperatures and heat flows can be mapped. Since the diurnal and annual temperature variations at the surface are usually damped out at depths of about 2 and 20 m respectively, if a survey is made in a time which is short compared to a year (say 2 or 3 weeks) a reasonable set of temperature gradient determinations which need not be corrected for surface temperature variations can be made if a depth range of 3 or 4 to 6 or 7 m is used. In many areas a relatively simple thermistor probe can be pushed into unconsolidated ground; in other areas an auger can be used.

If a group of small scale geothermal surveys have to be tied together then one deeper hole, say about 50 to 100 m deep, would have to be drilled in each area to obtain a gradient that is undisturbed by the annual temperature variations. This is necessary because, in effect, one is making measurements with reference to a slowly moving isotherm which may be regarded as stationary if the time span of a survey is small enough. Instead of drilling boreholes one could apply corrections but these are usually difficult and unreliable.

To obtain heat flow contours the thermal conductivity of the strata should also be determined. In some areas this may not be necessary since the conductivity variations are not too great and contouring of temperature gradients will give the same pattern as a heat flow map. In areas where the variations in thermal conductivity are too great to be ignored, either an in situ method[5] or a laboratory method[6,7] of measuring conductivity should be used.

With the present state of the art there seems little doubt that geophysical methods are at present only useful in mapping fields already known from surface activity. Banwell (1970) suggests the following as an optimal exploration program. It is assumed that basic topographic, meteorological and geological information is already available.

The first stage is essentially a geochemical survey. The primary objective is the sampling of surface activity in order to find concentrations and ratios of the significant elements, compounds and isotopes present. This gives information on the temperature in the reservoir and its classification into a wet or dry steam field thus allowing the second stage of the program to be properly planned.

The second stage consists mainly of a temperature and heat flow survey of the area from which the enthalpy (the amount of heat per unit mass) of the surface discharges can be calculated and compared with similar evidence from the geochemical survey.

The third stage consists of a resistivity survey using electrode arrays giving depths of penetration up to 2 km. In addition, exploratory boreholes are drilled deep enough to avoid undue temperature disturbance due to near surface ground water movement so that reliable temperature gradients are reasonable depths can be obtained; these holes may be anywhere from 100 to 300 m deep.

The fourth stage might consist of using other geophysical methods to give additional information. These methods, include magnetic, gravity, seismic, geological, infrared, electromagnetic, ground noise, and microseismicity. However, this stage is often eliminated altogether because use of these methods does not seem to be required to bring the investigation to the point where a deep exploratory hole can be planned and sited.

The fifth stage is the drilling of a deep exploratory hole from which detailed temperature, geological and engineering information can be obtained.

If the data so obtained proves that the geothermal area is exploitable further work is better classified as development although some other more detailed geophysical surveys might be carried out to give additional information on the geological structure of the area.

Although geophysical methods are at present confined to fields with surface expression, there seems to be little doubt that if geothermal fields become obviously economic as a means of supplying power, electrical or otherwise, there will be a massive application of funds comparable with that used in the mining industry, and perhaps in the oil industry, diverted to geophysical exploration programs. When this happens I am confident that the geophysical technique will be responsible for the discovery of many fields which do not at present have any surface expression.

So far we have concentrated on the production of electrical power from geothermal fields, mainly because conversion to electrical energy allows it to be transported over long distances with relatively little loss whereas, as noted earlier, the energy cannot be transmitted as thermal energy over large distances without significant economic loss.

This applies to other methods of utilising geothermal energy. Thus, considerable use has been made of available sources of heat in a number of different ways but in each case the source of geothermal energy must be very conveniently located with respect to the sink.

The most obvious and most used alternative is for direct space heating. For instance, in Iceland several district heating systems supply geothermal water to heat and provide hot water to the houses of 40% of the population, nearly all public and commercial buildings, schools, community centers, swimming pools etc. (Einarsson, 1970). Water is obtained from various sources with temperatures ranging from about 50 °C to 180 °C. In Reykjavik alone it is estimated that the volume of space in houses heated is approximately 10^7 m^3. It is also estimated that in order to produce the same amount of heating in Iceland as a whole using conventional fuels it would require approximately 1 ton of fuel oil per head of population (Palmason and Zoega, 1970); therefore, by using geothermal resources there is a very considerable saving in imported fuel oil.

In Hungary, wells as deep as 2 km and penetrating the Upper Pannonian Series (Lower Pliocene) supply water at about 85 °C to heat about 0.5 m^3 of housing and public building space at a cost that is about a quarter of that for a comparable coal heating system (Boldizsar, 1970); the electrical energy equivalent is about 440 MW. Because of this tremendous saving it had been planned to heat the whole city of Szeged; these plans were abandoned only after the discovery of an oilfield and cheap natural gas nearby.

At Klamath Falls, Oregon the closed circuit system is an unusual departure from the normal procedure of house heating. What is essentially a long

U-tube is inserted into each cased and perforated well; this system not only eliminates scaling, a common and irritating phenomenon requiring the frequent reaming of boreholes, but it also prevents depletion of the water reserves and hence the water table.

Geothermal steam has been used, either directly or indirectly for the pulp and paper industry (Smith, 1970), drying diatomites (Lindal, 1970a), operating a refrigeration system at a tourist hotel (Reynolds, 1970), the treatment of sewage for disposal in a river (the hot brine killing all bacteria), sterilizing instruments in a hospital, and solution mining of potash from one formation by leaching with warmer water from a lower formation. These are uses to which geothermal steam and water of high and low temperatures, can be put without converting the energy to electrical energy.

A number of proposals requiring the siting of a plant near a source of geothermal power producing cheap electrical power have been made for producing various chemicals (Lindal, 1970b), for the production of heavy water (Valfells, 1970), for the production of fresh water from sea water[8] for drying seaweeds and many other possibilities too numerous to mention. Of course, hot water springs have been used for thousands of years for therapeutic purposes.

The existence of vast quantities of hot water in the Hungarian Basin is of considerable interest for a number of reasons. First, although the Basin is largely rimmed with evidence of Cainozic volcanicity, near the region being exploited there is no extensive evidence of this type of activity which is associated with nearly all the fields that have been exploited to date (McNitt, 1970). Second, although in the Hungarian Basin there are formations of suitable permeability for exploitation, in other areas of the world where the permeability is not suitable, the permeable characteristics might be improved by underground explosions. Third, there are real possibilities of obtaining electricity from these relatively low temperature waters. Basically, this requires a two cycle generator utilizing a heat exchanger whereby heat is transferred from the hot or warm water to vaporize a low boiling point fluid, the vapor being used to drive a turbogenerator, the turbine being in the closed vapor circuit. More research is obviously needed, but already in the U.S.S.R., where Freon is favoured as the intermediate fluid, a 680 KW generator has been operated satisfactorily using 82 °C water; in the United Kingdom a 2 MW Water-Freon generator is being developed. In the U.S.A. a 10 MW plant is under construction, at a cost of $160/KW (Facca, 1970), utilizing Isobutane as the boiling fluid; this is for use at somewhat higher temperatures, but still below the 200 °C minimum temperature required of a hot water geothermal reservoir for economic use in driving steam turbines directly, with geothermal fluid inlet temperatures being between 135 and 200 °C and the discharge temperature at 55 °C.

Since the construction of 2 cycle generators presents no serious technological difficulty, and the cost seems to be comparable with that of generators of similar size operating directly off geothermal steam (Facca, 1970; Bradbury, 1970), this is probably the most exciting information to come out of the symposium. The enormous reserves in the Hungarian Basin, and probably in similar basins across the world, mean that there may be virtually unlimited geothermal energy available for the generation of electricity.

A. E. Beck

References

1. J. Lear, Saturday Review, 53, 5th December (1970).
2. G. W. Grindley, New Zealand Geological Survey Bulletin, p. 75 (1965).
3. D. E. White, W. W. Brannoch and K. J. Murata, Geochim. Cosmochim. Acta **27**, 10 (1956).
4. A. E. Beck, La Scuola in Azione **6**, 166 (1964).
5. A. E. Beck, F. M. Anglin and J. H. Sass, Can. J. Earth. Sci. **8**, 1 (1971).
6. A. E. Beck, J. Sci. Inst. **34**, 186 (1957).
7. R. Von Herzen and A. E. Maxwell, J. Geophys. Res. **64**, 1557 (1959).
8. H. C. H. Armstead, Intl. Conf. on Water for Peace, Washington (1967).