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FIVE LECTURES ON GEOTHERMAL ENERGY

H. Christopher H. Armstead

UNU Geothermal Training Programme, Iceland
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FIVE LECTURES ON GEOTHERMAL ENERGY

By

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OPENING REMARKS

When Dr. Fridleifsson and the Studies Board of the United Nations University Geothermal Training Programme very kindly invited me to be the second international guest lecturer at the Icelandic Geothermal Training School I felt very greatly honoured - the more so because I do not claim to be any kind of geothermal specialist. I am a simple engineer who have spent much of my professional life in the pursuit of energy and power supply problems. But my interests in such problems have not been only technical: they have also been philosophical. When the opportunity came to me, more than 25 years ago, of close involvement in an important geothermal development project, I became fascinated in the concept of what, to me, was then a totally new source of energy of which I knew virtually nothing and had heard no more than casual mention. Gradually, in the course of the last quarter-century, I have become more and more closely involved in geothermal affairs, and my interest has deepened. But the more I learned, the more conscious did I become of my own ignorance; for I soon discovered that geothermal development involves so many specialised disciplines, to master all of which would be beyond the capacity of any single individual. To this day I know very little of the earth sciences: I have been more concerned with the engineering aspects of the surface activities that must follow after the earth scientists have discovered thermal fluids and the drillers have brought them to the surface. But this one-sidedness of my experience has in no way damped my enthusiasm for geothermal development nor my deep interest in new concepts of gaining access to vast stores of heat as yet untapped. If, in a small way, I have been able to help the Geothermal Cause, it has perhaps been more in the rôle of a propagandist than as a technologist.

I understand that the subjects for this year's U.N. fellowships in Iceland are geology, geochemistry and geophysics. Let me confess at the outset that I can help none of you in these subjects, for you will all know far more about them than I do. But I am a great believer that knowledge and interests should be not only deep but wide. It is of the greatest importance that every specialist, besides having a deep knowledge of his own subject, should also look outwards to gain a wide understanding of the whole field of knowledge, of which his own discipline forms but a single, though important, component. In the course of my lectures I shall therefore be talking to you <u>not</u> about your own specialisations, but about others that collectively make up the present scope of geothermal science and - more important - about the probable shape of a tantalising future in which all of you will be deeply involved. Much of what I shall be saying may sound rather elementary, but it all forms part of a coherent whole branch of science in which every one of us is interested, and to the advancement of which we are all dedicated. I hope you may gain something of value - even if only a little - from my lectures. If so, then I shall feel that my visit to Iceland, apart from being a source of great pleasure to myself, will not have been in vain.

LECTURE ONE

APPLICATIONS OF GEOTHERMAL ENERGY

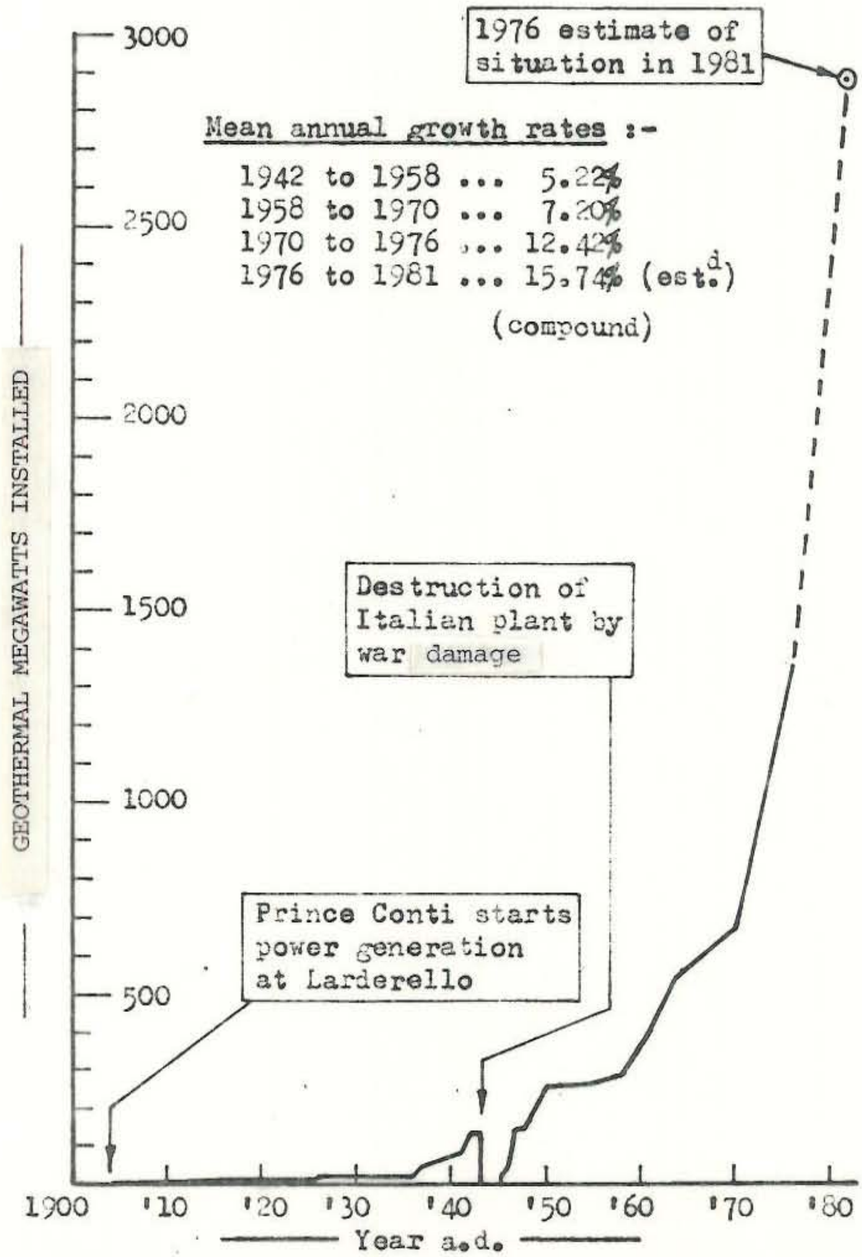
Just over one hundred years ago electricity was first made available to the public. It was hailed as the greatest single contribution to human material welfare since the invention of the steam engine, and its obvious benefits caused a rapid proliferation of electricity supply systems all over the the world. It was versatile; for it could be used for lighting, heating, motive power and other purposes. It was clean. It could be transmitted over long distances. It was readily marketable. As a new industry, electricity supply was assured of commercial success in almost every country of the world; and the marked improvement brought by electricity to living standards was self-evident.

Only about 25 years after the birth of public electricity supply a new form of energy appeared - geothermal energy, or earth heat. Strictly speaking, it was not really new, for it is true that man had used this form of heat in a small way for centuries in many parts of the world - for bathing, for the alleged healing properties of natural hot waters, even for space heating on a very small individualistic scale. But nowhere, until the twentieth century, had earth heat been used as a public service on a large scale. In 1904 an Italian nobleman of vision, Prince Piero Ginori Conti, perceived that it would be possible to use the natural heat of the Tuscan hills for generating electricity. After a few not very successful attempts, the prince and his successors gradually overcame the technical difficulties and built up an impressive electricity supply system based upon the geothermal field of Larderello. By the time of the Second World War this system was supplying 130,000 kW to the Italian State Railways - a very large amount of power by the standards of those days.

Other geothermal fields were known to exist in several countries besides Italy, so it was not unnatural that men's thoughts should turn to the possibilities of harnessing these fields also, for the generation of electric power - especially with the successful example of Italian experience before them. For whereas fuels can be transported by road, rail or ship, and productively burned hundreds or even thousands of kilometres from their place of origin, heat (as such) is not so easily or so cheaply transmitted. Most geothermal fields occur in places rather remote from large centres of population; so it made sense to convert the earth heat into electricity at the thermal field and to transmit the energy electrically to the nearest market. In this way, after about half a century of hesitation, several other countries began to develop geothermal power projects from the late 1950s onwards. Now, more than 2 million kW of geothermal power plant are installed, and the capacity continues to grow rapidly. The reason for the half century of hesitation was not so much nervousness of a comparatively new technolgy, but the continued availability of very cheap fuels. With oil at US$ 1.80 a barrel, why embark upon expensive programmes of geothermal exploration that could offer no positive assurance of a successful outcome?

With this rapid growth of geothermal power development - a growth that is being accelerated by the alarming and continuing rises in the prices of fuels - an unfortunate attitude of mind has also tended to grow in many countries, with one major and a few minor exceptions. This attitude is to regard power generation as the natural and obvious, even the <u>only</u>, application of earth heat. What it tends to overlook is that power generation is inherently a very inefficient way of using primary energy. <u>Convenient</u> it certainly is: <u>efficient</u> it certainly is not. Thermodynamic Law decrees, as you all doubtless know, that even the most perfect heat engine conceivable could never attain an efficiency exceeding $\frac{'T_1 - T_2'}{T_1}$, where $'T_1$ is the absolute temperature at which heat is supplied to the engine, and "T_2" is the so-called "sink temperature" at which the unusable part of the heat is ultimately discharged. This "ideal" efficiency is, of course, the Carnot efficiency. A typical admission temperature for a geothermal turbine is about 170°C, or 443°Absolute, while a typical "sink" temperature would be that of the turbine condenser - say about 52°C, or 325°Absolute. A <u>perfect</u> turbine working under these conditions could attain an efficiency of no more than 26.6%, while in practice about 16% might be achieved: the remaining 84% of the heat imput would be dissipated into a river or into the atmosphere, irrecoverable. The true situation is even worse than this typical figure of 16% efficiency would suggest; for after allowance has been made for transmission losses between the bores and the turbines, for the venting of steam as a means of controlling pressures and flows, for the inevitable wastage of steam during the development and testing of bores, and sometimes for the rejection of huge quantities of unwanted hot waters, the overall efficiency at which the original natural heat is used will sometimes be as low as 6 or 7%:

In an energy-hungry world this is a very extravagant way of using our dwindling resources.



WORLD CAPACITY OF GEOTHERMAL POWER PLANT INSTALLED

(Although this graph was drawn in 1976, the projection to 1981 is still fairly accurate).

Until 1970 the growth rate of geothermal power was less than that of the world's electricity consumption, which was then running at about 8 1/2% p.a. Geothermal growth after 1970 has rapidly overtaken electrical growth.

When earth heat is first converted into electricity and subsequently used by the consumer for heating purposes, the process may be described as indirect application of primary energy; for a double process of conversion is involved - from heat into electricity at the power station, and from electricity back into heat at the consumer's premises. Of course, electricity generation is both convenient and necessary for certain purposes such as lighting; also for motive power in factories, as it is obviously more sensible to use electric motors than to pipe steam to large numbers of small individual prime movers. Please do not think for one moment that I reject the need for geothermal power plants; they are very necessary despite their inefficiency. But much energy is required by the ultimate user in the form of heat, in which cases the use of electricity as an intermediary should be dispensed with wherever possible, as an undesireable extravagance. What I am advocating is not the abolition of the indirect application of earth heat by power generation, but the maximum possible use of direct application. For not only is it far more efficient than indirect application: it also enables good use to be made of low grade heat that would be worthless for power generation.

Even with direct application we cannot, for practical reasons, attain 100% efficiency as reckoned from the heat source at the bores to the point of use; but whereas the ideal attainable efficiency for indirect application is the Carnot efficiency - say 27% typically - the equivalent ideal for direct application is 100%. Of course neither ideal is attainable in practice: the approach to both is limited by economic and practical constraints. But by spending more and more money we can continually improve the efficiency of direct application until it no longer pays to spend any more:, whereas with indirect application through the intermediary of power generation we could never attain even the very poor Carnot efficiency however much money we spent. Thus direct application has an initial inherent efficiency advantage of something like 3 or 4 to 1 (100: 27 typically) over indirect application.

As to the use of low grade heat, even tepid waters can be of value for such purposes as fish breeding, balneology, zoology, fermentation, and the de-icing of roads in cold climates. Such waters would be valueless as a source of electric power. Even rather hotter waters that could productively be used for space heating could be applied to power generation only at very high cost and low efficiency, probably necessitating the use of binary fluids. Moderate temperature fluids can supply the bulk of the demands for certain applications, while heat pumps or supplementary fuel can supply the peaks, which often account for only a small proportion of the total energy requirements of an application having a fluctuating demand.

In referring to the prevalent attitude of mind that tends, in so many countries, to regard power generation as the natural, or even the only, way in which to make use of earth heat, I mentioned one major and several minor exceptions. The major exception is, of course, our host country - Iceland What Italy has done for geothermal power generation Iceland has done for the direct application of earth heat. Each of these two countries has been the pioneer in its own sphere. The reasons why they followed different roads were partly climatic and partly topographic. The harsher climate of Iceland by comparison with that of Italy created a demand for space heating, while the occurrence of natural hot fluids close to the capital city, and even within its boundaries, afforded the opportunity of satisfying that demand. Although it can also be cold in Italy the winters are of shorter duration; and the location of the principal Italian thermal field is fairly far from any city of moderate size. A further incentive to the direct use of earth heat in Iceland has been provided by the fact that the climate is such as to discourage the natural cultivation of fruits and vegetables. For that reason a prosperous greenhouse industry has grown up in this country to make it possible to grow not only the normal farm produce available in more temperate climates but also subtropical, and even tropical, delicacies that would be unobtainable except as highly priced imports. An abundance of cheap hydro power in a country of small population provided yet another reason for Iceland's greater interest, until recently, in direct heat application than in power generation.

A parallel example of the influence of climate and topography upon the path of geothermal evolution is to be found in the Western United States of America. The splendid thermal field of the Geysers is some 100 km from San Francisco - a city having a mild and comfortable climate. The combination of distance and the absence of a large heat market made power generation the obvious form of geothermal development of California. In the State of Oregon, however, where winters are harder and longer, and where hot waters are to be found at the very edge of Klamath Falls - a town of some 40,000 population - geothermal district heating and domestic hot water supplies have been the natural outcome. Klamath Falls is now well on the way to becoming a second Reykjavík, though on a smaller scale. Geothermal greenhouse heating and other forms of agriculture, horticulture and aquaculture are also developing rapidly in Oregon and in the neighbouring State of Idaho.

In many of the countries that are now developing their geothermal resources it is encouraging to note that space heating, domestic hot water supplies, greenhouse heating, soil warming, animal husbandry and other forms of direct heating are now belatedly being developed. But only in Iceland and Hungary does the demand for directly used earth heat for district heating and for farming (in one form or another) exceed 600 MW(th). [It is advisable here to draw attention to a world-wide estimate of directly applied earth heat which appeared in Table, 1, p. 4-9, of Special Report No. 7 of the Geothermal Research Council, 1979, in which a figure of 5,100 MW(th) was shown for agricultural and aquacultural application in the Soviet Union. If this figure were correct, it would account for nearly 92% of the world total of direct heat application; but it is open to some doubt. It appears to have been derived from a paper presented by Soviet authors at the U.N. Geothermal Symposium at Pisa in 1970. A critical analysis of geothermal information from the U.S.S.R. has been made in a Note (JSG - 80/04 gss) prepared by the Geothermal Division of the Icelandic Energy Authority (1980-07-22) which suggests that an arithmetical discrepancy is evident from other official Soviet data of hot water quantities and temperatures, and that in fact a more probable figure for the USSR direct heat application (excluding industrial uses) would seem to be about 360 MW(th) reckoned above 15°C]. Even in the U.S.A. this demand now amounts only to about 80 MW(th) - which is 11% of that of Iceland despite a population nearly 1,000 times as great. On a <u>per capita</u> basis, Iceland leads the U.S.A. in direct application of earth heat by a factor of 8,800 times! In most of the countries that are developing their geothermal resources there seems to have been a marked lack of interest in direct applications: efforts have been directed almost exclusively towards power generation.

Now I understand that at this year's training course there are Fellows from El Salvador, Honduras, The People's Republic of China and The Philippines. To all of you I would urge that when you return to your countries do not think only of power generation when your national plans for geothermal development take shape. Think also of direct applications so that you may put to good use your low grade heat resources and apply them, as well as your higher grade heat resources, at the best possible efficiency. Now the gentlemen from China come from a vast country with a very wide range of climate, and I think my message to them will be quite clear. But I can understand the gentlemen from Central America and The Philippines saying to themselves "What has this to do with us? We have no need for space heating; and all manner of fruits and vegetables grow naturally in our abundant sunshine without the aid of artificial heat". If you are saying that, you have a good point; but so far I have only mentioned space heating and farming. There is an other promising field for the direct use of earth heat, namely industry, and a great scope for this can be found in all climates. But before I discuss industry I would like to suggest that just as in cold climates is it possible to grow tropical produce by soil warming, so should it be possible in hot climates to grow the fruits of temperate countries - e.g. strawberries and other soft fruits - by soil cooling. However, let us now consider the more important matter of industry.

Many industries are very heat-intensive: that is to say, they require large numbers of calories for every dollar's worth of end product. Unfortunately I lack information about geothermal industrial activities in the Soviet Union, France and Hungary but outside those countries there are as yet only two major industrial developments using direct geothermal heat. The larger is at Kawerau, New Zealand, where The Tasman Pulp & Paper Company are consuming from 100 to 125 MW(th) of earth heat for the paper industry. The other is at Námafjall in Iceland, where about a quarter of that amount of geothermal heat is being used for the refinement and production of diatomite filter aids. These two industries together account for about 60% of all the industrial applications of earth heat outside the three excepted countries. The remaining 40% is accounted for by a variety of small industries such as brewing, timber seasoning and veneer fabrication, salt manufacture, suplhuric acid production, extraction of chemicals from geothermal fluids and sea water, the curing of light aggregate cement building blocks, the production of elemental sulphur, milk pasteurisation, food processing, boric acid production and various other processes. Last year the world total demand for geothermal industrial processes was estimated at only about 235 MW(th), or about 10 1/2% of the total direct earth heat applications. This is a regrettably small proportion, because the possibilities of using earth heat for industry by direct application are immense.

In a most instructive article by an Icelander, Mr. Baldur Líndal, which appeared several years ago in a UNESCO Geothermal Review which I edited, the author listed 35 random industrial processes and quoted in every case the quantities of heat required to produce a dollar's worth of finished product. Although subsequent inflation must have outdated the actual figures quoted then by Mr. Líndal, the relative heat intensiveness of the listed industries will probably have remained much the same. An interesting point to observe is that the Kraft process for producing paper pulp was 20th in his list of heat-intensiveness, with less than 1/7th of the heat-intensiveness of one of the processes quoted by him. Yet the most successful existing geothermal industry in the world - at any rate outside the Soviet Union, France and Hungary, for which countries I lack information - is using that process commercially by means of directly applied heat in New Zealand. It would seem that at least 19 other more heat-intensive industries could do better by using earth heat. Nor is Mr. Líndal's list by any means exhaustive, for there are many other heat intensive industries which he has not included in his list - e.g. synthetic rubber manufacture, textile factories, refrigeration, mineral extraction from geothermal fluids and from sea-water and many other industries that deserve close attention. There will be many occasions where geothermal fluids, although insufficiently hot for some particular process, can be used to save fuel by pre-heating before a final boost which may have to be supplied by fuel or electricity. There seems little doubt that the direct application of earth heat to certain industries could be most profitable; but progress in this direction has hitherto been inhibited by the prevalent tendency to think mainly in terms of power generation whenever geothermal energy is being harnessed. I would here add that it has just come to my notice quite recently that at Roosevelt Hot Springs, in the State of Utah, an aluminium reduction plant activated by geothermal heat is now under consideration. It is of interest to note that this industry is 3.34 times as energy-intensive as the Kraft pulp process used at Kawerau in New Zealand. Perhaps we shall here see a real breakthrough for geothermal heat into heavy industry.

I would like to pursue this theme further. Large areas of the world - especially in the Soviet Union, Canada and perhaps in Northern and Western China - are rich in minerals but are in the grip of permafrost, which makes operations almost impossible and living conditions very hard. If geothermal heat can be won in these areas it might be possible to use part of the heat to banish the permafrost and to render habitable and self-sufficient huge tracts of land that have hitherto been regarded as unfit for habitation or for human activities. This could ease the pressures of rising population upon the world's dwindling resources.

In another urgent field, earth heat could perhaps be used for the production of fuels from various forms of biomass, thereby creating a partnership between solar and geothermal energy for reducing our present dependence upon fossil fuels - especially for transportation. In the State of Oregon, U.S.A., an alcohol factory is planned and is in the design stage, for producing one million gallons of alcohol annually from potatoes. Many other forms of vegetation can also be converted into alcohol and other fuels with the aid of heat. The intention in the U.S.A. is first to dilute their gasolene with 10% alcohol to form "gasohol":, but in Brazil, motor vehicles are being designed to run on pure alcohol - suitably contaminated to discourage human consuption! I have been wondering whether Iceland, which could never produce very much bio-mass on land, could use seaweed as a raw material for hydro-carbon fuel production; or even emulate Oregon by using the potato which, I understand, will grow under natural condition in this country.

There are many other industries that could be supported by geothermal heat. Alumina can be produced from bauxite with the aid of steam. The textile industry needs large quantities of low grade humid heat. Sugar factories need heat; hitherto provided traditionally by the combustion of the by-product bagasse. But bagasse is becoming a valuable raw material for building boards, and it could be released for this purpose if earth heat were available for the process of sugar production. Another heat-intensive industry of the future in an increasingly "thirsty" world is the desalination of sea-water and brackish waters. Geothermal fluids are often even capable of self-distillation if sufficiently hot, but where sea or brackish waters are available they can more profitably be used to desalinate far more than their own weight of such waters.

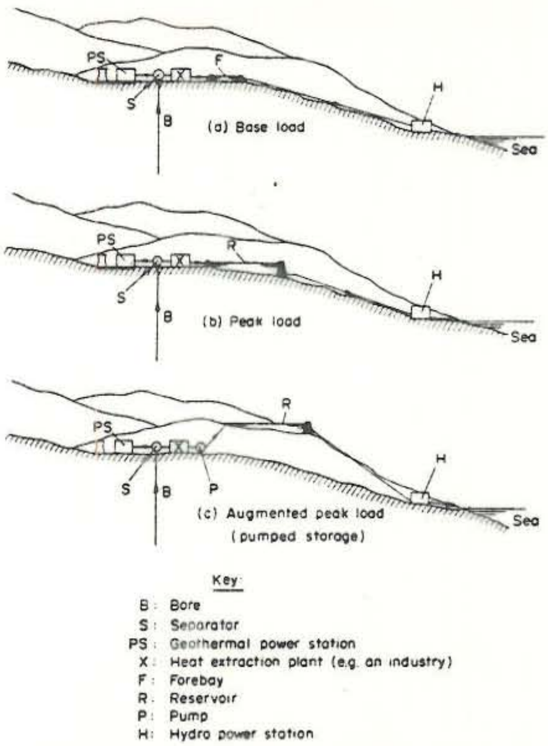
One of the reasons for the slow development of direct applications of earth heat for industrial purposes is simply that industrialists and developers just do not know about it. This may seem incredible, but for so long have people thought simply in terms of fuel or electricity when they need heat that their minds have been closed to possible alternatives. Of course at present earth heat is available only in relatively few parts of the world, but the quantities of heat in those parts are sometimes prodigious. Another attitude of mind that has inhibited the development of the direct application of earth heat is that which thinks solely in terms of labour, raw materials and markets. Industries are generally established at places as close as possible to the sources of labour and raw materials, or alternatively close to the markets. In either case energy is usually regarded as a secondary consideration - an element that can be bought in the form of electricity or fuel. There has, however, been one notable exception - the aluminium industry. This is one of the most energy-intensive industries known; so energy-intensive that for decades the producers have built their factories at sites chosen solely where cheap power is available, regardless of national frontiers. Thus an aluminium producing company may have its management and central organisation established in Zürich or London, for example; it may mine its ore in the Caribbean; ship it to a factory in Norway, Iceland or elsewhere where cheap power is available; and transport the finished products to markets all over the world. The commercial success of the industry has depended entirely upon the over-riding choice of a location of the industry at a place where energy is cheap. There is absolutely no reason why that principle should not equally be applied to many heat-intensive industries that could be located at geothermal fields, however remote. The necessary raw materials and labour could be transported to the field, even across national frontiers; a community could there be set up, self-sufficient in food and with adequate amenities and a high standard of living comforts; and the end products of the industry could be shipped to the markets, wherever they may be. In this way not only would many products become cheaply available: it might also be possible to populate certain parts of the world that have hitherto been regarded as uninhabitable, thereby easing the population pressures somewhat.

Earlier I referred to the fact that those who live in hot climates are not interested in space-heating; but they might well be interested in space-cooling. Air-conditioning, activated by electricity or gas, can greatly alleviate the discomforts of living in hot, humid climates; but this is a luxury that can generally be afforded only by large offices and stores and in the homes of the more prosperous section of the community. If geothermally activated municipal cooling could be distributed throughout certain tropical cities, much as heating is distributed in Reykjavík - but "in reverse", so to speak - more comfortable living and improved health could perhaps be brought to millions. It was an eminent Icelander Mr. Sveinn Einarsson, who proposed, after the devastating earthquake of 1972 in Managua, Nicaragua, that some benefit might at least be salvaged from that disaster by incorporating such a public cooling scheme during the reconstruction of the city, as a geothermal field lay close by. I seem to recall that the thermal field of Los Baños lies only about 40 km outside the city of Manila, the climate of which would be entirely suitable for district cooling.

I hope I have said enough to persuade you that there is much merit in the direct application of earth heat for many purposes. There is even greater merit in establishing, wherever possible, dual or multi-purpose projects. Different uses require heat of different grades, or temperatures. Where earth heat is available at moderately high temperature it may sometimes be possible to use the total available temperature spectrum for two or more different purposes - seriatim. For example, a geothermal power plant could perhaps use back-pressure turbines instead of condensing turbines, so that the discharged heat would be of sufficient grade to supply a district heating scheme or an industry, which in turn could perhaps reject low grade heat for soil warming, for a swimming pool or for a fish hatchery. Again, with wet geothermal fields that yield mixtures of steam and boiling water, it could sometimes perhaps be possible to use the steam for power generation and the hot water for an industry, district heating or farming purposes. The possible variety of combinations is immense.

Although the possibilities of dual or multi-purpose geothermal projects are very great, the actual number of such applications is pathetically few - again for the probable reason that the possibilities have not occured to those who could have benefited thereby. Some existing applications have the appearance of dual purpose projects, but are not so in the truest sense. At Larderello both power and boric acid are produced: at Námafjall power is generated and diatomite is provided; but these are not strictly dual purpose plants, for in each case the two products are from separate parallel processes operating side by side: they do not use the same fluid over two temperature bands in series for two different purposes. At Kawerau in New Zealand, exhaust steam from a turbo-electric generator is used as process steam for pulp and paper manufacture: that is an example of a true dual purpose application. So too is the combined power and heat establishment at Svartsengi, Iceland, and also the consecutive use of earth heat at Otake, Japan, for power generation, space heating and cooking, and finally for balneology: also the alligator farms in Japan, where greenhouse heating is in series with the warmed alligator pools and with soil warming installations for the raising of tropical flora. In Kamchatka, in the East of the Soviet Union, two small geothermal power plants discharge waste heat that is used in greenhouses and for soil warming. At Klamath Falls, Oregon, discharged warm water from the geothermal heating system at the Oregon Institute of Technology is used to cultivate prawns. In terms of heat, some of these schemes are very humble, but they make use of a sound principle that should be encouraged wherever possible. Dual and multi-purpose projects are not without their problems, for the magnitude and patterns of the heat demands of the different processes may differ considerably: and this may call for bypassing, storage facilities or even wastage. Nevertheless, full consideration should be given wherever possible to multi-purpose installations, especially where the use of very low grade heat can avoid wastage.

It is also sometimes possible to derive byproduct benefits from a geothermal installation - benefits that are not strictly in themselves of a geothermal nature. For example, the extraction of CO_2 from the non-condensible gases discharged from a geothermal power plant could perhaps be commercially justifiable for the production of dry ice or of methyl alcohol, or for providing effervescence to mineral waters or fruit juices. In wet fields situated at high elevations above sea level, huge quantities of unwanted bore waters are sometimes thrown to waste, perhaps because reinjection is impracticable for chemical reasons. Under favourable topographical conditions it may be possible to win substantial quantities of hydro power from these rejected waters, though obviously it would be desirable in such cases first to extract all the possible heat from them.



By-product hydraulic power from a wet geothermal field

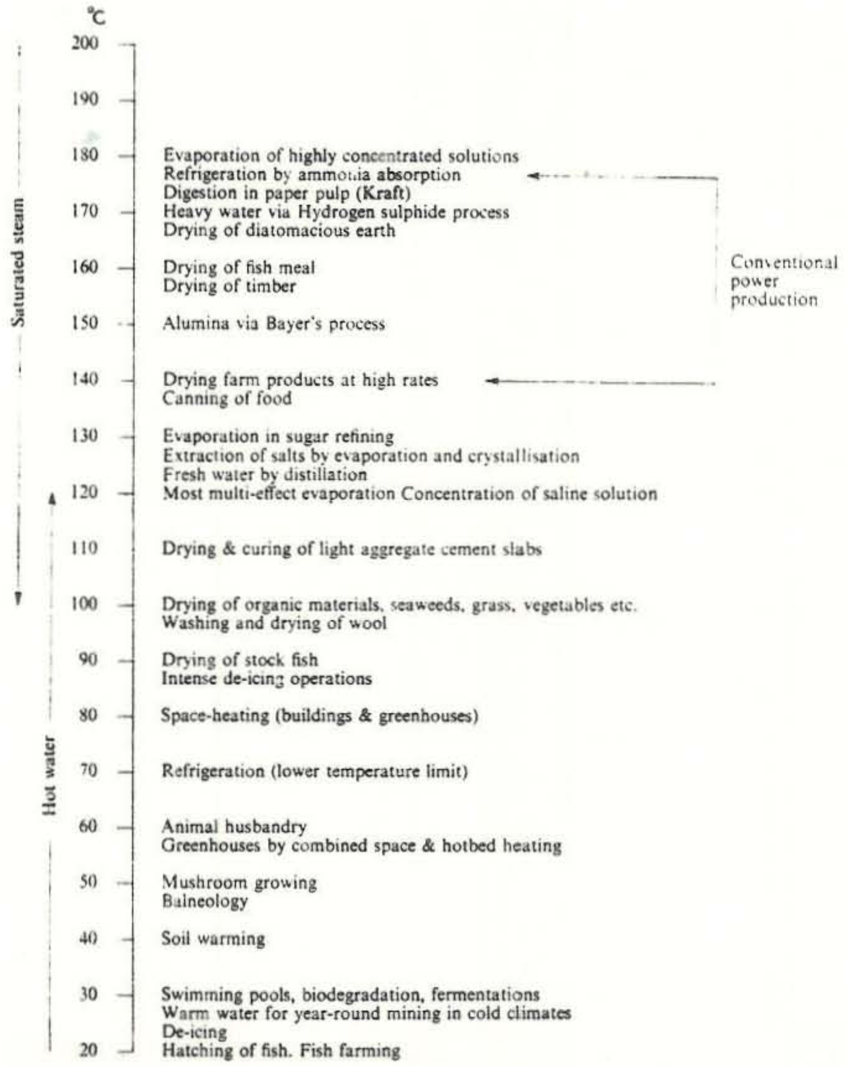
Unwanted bore water could theoretically be used to generate base load, peak load or augmented peak load (pumped storage) electricity, as shown in this diagram. In New Zealand for many years a byproduct bonus of about 2 1/2 MWe continuous base load has been earned in this way, because the unwanted bore waters have been rejected into the Waikato River which flows through a series of hydro power plants on its way to the sea. This gained byproduct power has been equivalent to about 2% of the truly geothermal output from the Wairakei plant. Unfortunately in this case the rejected water has been very hot. When I visited Ahuachapan in El Salvador, early in 1969, one of the problems that was then causing concern was the disposal of huge quantities of unwanted bore water that could not be discharged into the local water courses owing to a hazard of contaminating downstream water supplies with toxic ingredients rejected from the bores. At that time, the practicability of reinjection had not yet been proved; so I proposed that advantage could perhaps be taken of the height of Ahuachapan above sea level, and of the presence of higher hills close by, to introduce a pumped storage system that would have benefited the national power network. The discharged bore water could perhaps have been pumped for about 20 hours per day into a high level reservoir and released during the peak load hours through turbines into the sea, which lay beyond the local catchment area. Probably the proposal would have cost too much in civil engineering works: at any rate it was not adopted.

The latest estimate of direct application of geothermal heat for the whole world, which appeared in Special Report No. 7 of the Geothermal Resources Council, 1979 (amended to take care of the suspected error in the case of the USSR), put world demand at 2,250 MW(th). This figure was incomplete in that it omitted figures for industrial processes in the Soviet Union, Hungary and France: it may therefore be regarded as a cautious evaluation. The estimate, in summary, was as follows:-

Space heating	1,424 MW(th)	... (63.3%)
Agriculture and aquaculture	591 MW(th)	... (26.3%)
Industries	235 MW(th)	... (10.4%)
Total	2.250 MW(th)	

When this figure is compared with the 2,000 MWe(approx.) of installed geothermal <u>power</u> plant in the world, which I mentioned earlier in this lecture, you may be wondering why I have been deploring the slow rate of development of direct heat application by comparison with that of geothermal power generation; for it would appear to have developed quite as rapidly as the latter. 2,250 MW is of the same order of magnitude as the more than 2,000 MW of the world's total geothermal power plant capacity. But it is necessary to allow for the widely different efficiencies of direct and indirect applications. For whereas 2,250 MW(th) of direct heat use probably requires something of the order of 2,700 MW(th) of <u>extracted</u> heat, more than 2,000 MWe of power would need at least 20,000 MW(th) of extracted heat, as the average efficiency of geothermal power generation is not likely to exceed about 10%. The world is therefore probably extracting about 7 1/2 to 8 times as much heat for power generation as for direct application. That, though not accurate, is a more realistic comparison.

It is obvious that geothermal fluids cannot provide the answer to <u>all</u> our energy needs, even by indirect application through the intermediary of electricity. At present, transportation by road, rail, ship or air is mostly dependent upon fuels. Reistad, in an interesting paper presented at the U.N. Geothermal Symposium in San Francisco, 1975, showed that at least 40% of the energy needs of an industrialised country could be satisfied geothermally if the resource were available; but with increased electrification, the successful development of the electric car, and the possible advent of a hydrogen economy, this proportion could be very greatly raised. Fortunately, a fair proportion of human needs can be satisfied by low grade heat, as is illustrated by this very much quoted diagram of Mr. Baldur Líndal.



APROXIMATE TEMPERATURE REQUIREMENTS OF GEOTHERMAL FLUIDS FOR VARIOUS APPLICATIONS. (Baldur Líndal. p. 146, UNESCO Geothermal Review, 1973)

To summarise, the benefits of direct heat application are as follows: -

i) High conversion efficiencies are possible - sometimes as much as 80 to 90% - by comparison with about 16% (at best) for power generation.

ii) Low temperature sources, useless for power generation, can be put to good use; and these resources are thought to be far more plentiful than high temperature sources.

iii) It requires less exotic equipment, such as turbines fitted with special materials.

iv) Development times are usually much less than for power projects.

v) Low temperature fluids require less expensive well development (and often shallower bores), and are usually - though not always - less corrosive than high temperature fluids.

vi) Hot water can be transported economically over much greater distances than steam.

vii) It is virtually pollution-free.

There is one possible disadvantage in the use of low temperature sources, in that more land would be affected for a given quantity of heat extraction, since the bulk of fluid would have to be much greater than in the case of high temperature fluids; but this is seldom likely to cause any problems as low temperature processes usually involve less heat extraction. As with high temperature wet fluids used for power generation, the risk of ground subsidence must be considered if reinjection is not practised.

To conclude, my advice to those of you who are studying here under U.N. Fellowships is not to think exclusively in terms of electric power as the only, or even the best market for such geothermal resources that your countries may possess. Seek low temperature as well as high temperature fields. Confer with your Ministries of Commerce and Industries and of Agriculture, and with your Chambers of Commerce, so as to discover what heat markets may exist in your countries. Confer also with the Commercial Attachés of foreign embassies to discover whether enterprises from other lands could use your natural heat to your mutual advantage, thus giving local employment and enabling your countries to earn valuable revenues for your national exchequers. In short, advertise on a world-wide basis if you should possess large and cheap heat resources. But if you succeed in attracting big business from abroad, may I suggest (even though this may have political overtones) that your countries avoid the temptation to nationalise successful geothermal enterprises operating on leased geothermal rights: the repercussions of doing that could discourage much needed foreign aid in other fields.

LECTURE TWO

ENVIRONMENTAL ASPECTS OF GEOTHERMAL ENERGY

Until about a century ago pollution was a very local problem. Certain cities were afflicted with choking fogs due to the excess burning of coal, or they suffered from squalid, disease-ridden slums caused by poverty and over-crowding. Here and there the landscape was being spoiled by the growth of mining and heavy industries. But while a few people were concerned about the affected areas the great majority of the human race, including the intellectuals, scarcely gave the matter a thought. The world was then regarded as a vast place, and a few local imperfections were only to be expected - often as the price to be paid for the material prosperity bought by industry. What was not properly understood was that environmental decline had in fact been going on in many parts of the world for centuries, but so slowly that the changes occurring within a lifetime were almost imperceptible. Deforestation and the ravages of the goat had been steadily encouraging erosion, with the result that the deserts were continuously encroaching upon what had formerly been rich farming lands. The discharge of untreated sewage from growing cities into small rivers was slowly destroying fish life. Certain species of animals and birds were gradually disappearing from lands where they had once flourished, conquered in their struggle for life by their inveterate enemy - MAN. Nevertheless, in the latter part of the nineteenth century most of the world differed but little from what it had been for many generations past. The advent of the railway and the steamship scarcely affected the status quo.

Then came the motor-car, the aeroplane, the explosive growth of industries, the centripetal migration of people from the countryside into the cities, the oil age, the proliferation and use of weapons capable of ever-increasing devastation. Added to all this came the terrifying growth of population, running now at an excess of live births over deaths at a rate of about three human beings every second. (In my own lifetime the world population has almost trebled,) As a result, our planet is becoming polluted at an accelerating rate, despite a few encouraging improvements. But whereas 100 years ago pollution was mainly a local phenomenon, it is now only the improvements that are local. For example, I myself vividly remember the London of my boyhood, when every winter we experienced fogs so thick that day was turned into night, with the street lights (themselves only visible from a distance of 2 or 3 meters) burning at noon. Now, that is a thing of the past, and the air of London is almost as clean as that of the countryside. Here in Reykjavík, thanks to geothermal energy, you have a city with air of impeccable cleanliness. Legislation concerning the discharge of toxic wastes into water courses has resulted in the return of fish life to rivers that only a few years ago were almost devoid of all life except bacteria. But unfortunately these few encouraging signs of improvement amount to no more than a gentle breeze by comparison with the hurricane of world pollution that threatens the quality of life in every quarter of the globe. Pollution is now occurring at such an alarming rate that the whole world is being affected, even in places thousands of kilometres remote from where the evils are actually being perpetrated. The world can no longer be regarded as a vast place: metaphorically it has shrunk, and it continues to shrink.

Then, soon after the Second World War, there slowly started to appear signs of a public conscience in the matter of pollution. Sufficient numbers of people were becoming alarmed at the trends for the subject to merit the attentions of governments and institutions. At first, concern was mainly focussed upon the hazards of radioactivity. Anxiety about nuclear bombs was entirely understandable. Anxiety about nuclear power stations was perhaps tinged with too much emotionalism and technical ignorance; but that is a very controversial subject that I do not intend to pursue. What is relevant to my theme is the rapidly increasing atmospheric pollution arising from combustion, probably the worst single offender against the environment. Since the beginning of this century the world's consumption of primary energy has increased by a factor of about 13 times. All but a tiny fraction of this has been provided by the combustion of fuels. Even more alarming was the fact that the mean annual growth rate of combustion during the 1950s and '60s was more than double the rate for the first half of the century; so that the consumption of fuels was not merely accelerating, but was accelerating at an accelerating rate. In short, the growth of combustion was hyper-exponential. Only since the Middle East crisis of late 1973 has there been a decline in the growth rate of combustion. It is true that that crisis, and what followed after it, has played havoc with the economies of many nations, but at least it has had a sligthly beneficial effect on the rate of deterioration of the world environment. Nevertheless, combustion is still on the increase, though at a slower rate than formerly.

Why is combustion so undesirable, environmentally? For several reasons: -

i) Much of the burnt fuel is consumed inefficiently, resulting in the emission of black smoke that is damaging to human health, vegetation and buildings.

ii) Many fuels are sulphurous and contain other toxic ingredients that are harmful for the same reasons.

iii) Combustion produces huge quantities of CO_2 which, though not toxic, may have an adverse effect upon the world climate. In recent years the CO_2 content of the atmosphere has been rising at a compound rate of 0.7% p.a., which implies a doubling in less than a century. Now CO_2 has "greenhouse effect" upon the atmosphere: it lets in solar energy but inhibits the outward radiation of heat at night, so that gradually the climate of the world will tend to become warmer. If continued unabated, the polar ice caps will start to melt, the sea levels will rise and land will be inundated; if the process continues indefinitely, conditions on earth could gradually approach those of the planet Venus, long before which all life would have perished.

iv) About 30% of the world's primary energy is already supplied by coal. If we are to depend upon a combustion economy for many more decades a greater share of the burden will have to fall upon coal, the reserves of which are far greater than those of oil. The coal mining industry will therefore be compelled to expand: and this is an industry with a poor record in terms of environmental deterioration and of danger to life and health, in spite of greatly improved working conditions.

Public concern about the environment led to the establishment in the 1970s of a United Nations Environmental Programme, with Headquarters in Narirobi, and to the convening of an international conference on the subject in Stockholm. Many national governments set up Ministries for the Environment. Almost coincidental with the dawn of public concern about pollution came the sudden upsurge of geothermal development. Enthusiasts claimed that this form of energy was entirely pollution-free and that every effort should be made to halt, and to reverse, the growth of combustion and to substitute earth heat in its place. Now it is perfectly true that by comparison with combustion geothermal energy is far less pollutive; but it is not true to say that it is entirely pollution-free. Moreover, the exploitation of geothermal energy by means of existing technology could never contribute more than perhaps 2 or 3% of the world's total needs of primary energy; so even an all-out world-wide campaign to develop earth heat resources wherever possible could only slightly alleviate, but never solve, the world problem of combustion pollution until the scope of geothermal technology has been greatly widened. A good cause is not well served by shutting one's eyes to the facts or by making exaggerated claims. People's hopes were unjustifiably raised by the geothermal enthusiasts.

Geothermal energy, though relatively innocent, is not entirely blameless in causing pollution. Nevertheless, certain precautions can be taken that can render it so innocuous as to be entirely acceptable. Hence there is no doubt that the more rapidly geothermal energy is developed, the greater will be the extent to which pollution is mitigated, though with existing technology this can never be to a very marked degree on a world scale. However, this fact does provide an additional incentive to the rapid development to the world's resources of earth heat.

In the early days of geothermal development, in Italy and New Zealand, its minor pollutive side-effects were considered to be so unimportant by comparison with fuel combustion that for some time a laissez-faire attitude was adopted: the side effects were more or less ignored. But when geothermal power projects started to proliferate in the 1960s and '70s, realisation came that the sheer scale of development made it impossible to turn a blind eye indefinitely. Some of the countries possessing geothermal resources introduced legislation to impose pollutive constraints upon the developers of those resources. In principle, this was to be welcomed; but it can happen that a wide gulf of misunderstanding may separate those who legislate from those task it is to develop energy resources. The legislators, perhaps under public pressure, tend to be perfectionists; whereas the developers know that in this imperfect world it is often necessary to compromise between the ideal and the attainable. To illustrate this, I would mention that the Government of California have imposed constraints upon the emission of H_2S from the power installations in the

Geysers field that are so stringent that Nature herself is sometimes guilty of breaking the Law! Before Man interfered with Nature in the Geysers area a strong smell of H_2S was noticeable there, as so often occurs in thermal areas all over the world. The Californian Government has seen fit to specify that the concentration of this gas near the development works shall not exceed 30 parts per billion. This concentration, though well above the threshold of odour, is by no means obtrusive - less so, in fact, than often occurs in undeveloped natural thermal areas. It is less than 1/300th part of the concentration at which irritaion to the eye is experienced, and 1/20,000th of what is generally regarded as a lethal dose. This amounts to an excess of zeal, for Nature herself was less fussy before exploitation began, and the local ecology had attained a happy balance without the aid of legislators. The task of conforming with the law may be achievable, but only at immense cost in money, time and effort.

At geothermal power plants H_2S will occur in the highest concentrations at the gas ejector discharge points, and to a lesser degree over the cooling towers. In the early days of geothermal power development it was deemed sufficient to disharge the ejector gases at high level above the ground, and to rely upon their high temperature to produce the necessary buoyancy for their wide dispersal. However, it must be remembered that although H_2S occurs naturally in most thermal fields, exploitation concentrates and increases the release of this gas into the air. Also the scale of development in certain fields has now become so great that proper precautions have become necessary quite apart from statutory obligations. At the Geysers field, if no precautions had been taken, about 50 tonnes of H_2S would now be discharged daily into the atmosphere. At Cerro Prieto in Mexico about 110 tonnes of this gas are already being released daily into the air, and by 1984 the figure could reach 450 tonnes per day if adequate steps are not taken. Already the field and station staff there have to wear gas masks for certain tasks and in windless weather. Clearly it is necessary to take precautions against the H_2S hazard, even if in California the Law has been over-zealous in this respect.

At first in the Geysers field the discharged gas was burned to form SO_2 and then scrubbed with cooling water. This practice was not entirely satisfactory, so an iron oxide treatment was then tried, which success-fully removed the H_2S but at an unacceptable cost in damage and dirt. A heavy sludge of iron sulphide choked the cooling towers, reducing their performance and sometimes causing the splashfills to collapse; while contaminated spray covered buildings, substations, insulators and local vegetation with red dirt. Later, the cleaner Stretford process was introduced - a British form of treatment that had been found highly satisfactory in industry. This process is very efficient provided that the H_2S occurs in an acid environment; but the bore steam at the Geysers contains ammonia which, of course, is alkaline. In consequence, about 30% of the H_2S escaped capture, and the statutory limitations could not be met. Hence it has now become necessary to introduce a secondary abatement process after the Stretford plant: its efficacy has yet to be proved. Meanwhile experiments are being pursued with sulphuric acid injections into the condensers so as to neutralise the ammonia. Thought is also being given to upstream treatment of the steam before it enters the turbines, by methods involving further cost and loss of thermal efficiency; and with no absolute certainty that the methods will be successful. It would scarcely be an exaggeration to say that as a result of the Law, the Geysers power stations are evolving into chemical plants with incidental power units as appendages!

It will now be seen into what a complicated entanglement the Californians have been landed through striving after perfection. What the end will be it is not yet possible to say. Perseverence will almost certainly bring ultimate success, which will be of immense benefit to geothermal developers in other parts of the world; but at what terrible cost to California! Let us try to count this cost: -

i) The Stretford process and secondary abatement equipment have added greatly to the capital cost per kilowatt, while the recurring costs of chemicals and of maintenance have inflated the production costs per kilowatt-hour. It is also necessary to consider the very substantial past expenditure on methods of gas abatement that have been tried unsuccessfully, and also the continuing costs of experimenting with further alernatives.

ii) The adoption of the Stretford process has meant abandoning a feature that has hitherto contributed to the cheapness of geothermal power - the direct contact jet condenser - which is not only much cheaper in capital cost than the surface condenser which now has to be used, but also enables a better vacuum to be attained with the same quantity of cooling water.

iii) Additional man-power has to be employed to operate the chemical plants, and the extra costs in the engineering projects office have been heavy.

iv) More important is the fact that the annual plant factor on the Geysers plants, which could probably have been maintained at 90% or more without all these complications, has dropped to about 70%.

v) Worse still is the loss of time. Time is of immense importance in geothermal development for countries that have to import fuel. The construction of the Geysers plants has been delayed by at least a year because of the need to comply with the statutory requirements on pollution. Every kilowatt of base load geothermal plant can save the importation of about 2 tonnes of oil fuel per annum. With oil at $175 per tonne, or thereabouts, one year's delay raises the effective cost of a geothermal plant by about $350/kW, which is at least three-quarters of the present actual cost of the newest Californian plants. Thus a delay of 16 months effectively doubles the cost per kilowatt of geothermal power in California, even if the additional (and very considerable) interest charges during construction be disregarded. The extended use of oil fuel during the period of delay also affects the trade balance of the State and of the whole country, and it perpetuates the pollution from fuel-fired plants which is greater than would have been caused by the geothermal plants had the time been saved by imposing less stringent pollution standards.

As a result of all this, geothermal power in California, which only a few years ago was the cheapest form of generation within the large integrated system of the Pacific Gas & Electric Company and which cost 25% less than nuclear power, now costs 24% more than nuclear power - a 40% decline in competitiveness. Developers are being discouraged because they now have to wait for so many years before they start to earn any revenue on their heavy investments; and since their income from the sale of steam is proportional to the number of kilowatt-hours generated, that income (when it does start to flow) is heavily cut by the decline in the annual plant factor. Geothermal power is undeservedly earning a bad name - just at a time when there is such a desperate need for it.

Even this long catalogue of woe is not the end of the story; for the Californian Government have warned the power company that until they succeed in abating the H_2S to conform strictly with the Law, no more licences will be granted for the various geothermal power extensions that have been planned and <u>for which steam is already available</u>. That is not the way to encourage geothermal development.

Would it not have been wiser from the start if, instead of seeking near-perfection, the authorities had been willing to compromise with what was practically attainable? Environmental legislation is most necessary and desirable; but it is even more important to keep our priorities in proper perspective. We are living at a time of acute anxiety about energy shortages, energy costs and balances of payments. One would have thought that the first priorities for California should have been to develop the State's indigenous resources, to win them as <u>quickly</u> as possible, and to win them as <u>cheaply</u> as possible: but both speed and cost have been sacrificed quite unnecessarily for the sake of avoiding a harmless smell! In my opinion the New Zealand Government have approached this problem in a more flexible and pragmatic way. They introduced a Clean Air Act in 1972, under which neither the emission nor the ambient air quality standards are precisely specified. Instead, permissible concentrations of H_2S are <u>negotiated</u> on an <u>ad hoc</u> basis at the time when a plant is licensed, taking into consideration the local circumstances, past custom and evidence of "public nuisance". In 1975 H_2S emission at Wairakei was limited by Law to 5 p.p.m. - 167 times the ambient concentration decreed for the Geysers area. It is true that there is a big difference between concentrations at points of emission and in the local ambience; but in the absence of public complaints no coercion is applied by the Government on the generating authority. Should evidence later be produced of public nuisance, the Government might well introduce more stringent limitations. I do not know if anything has happened in this respect in the last five years, but until 1975 the Wairakei geothermal power stations were not burdened with the trouble and expense of costly abatement precautions, even 17 years after the stations were first commissioned.

All this, of course, is a question of policy. Very possibly the Government of California has been subjected to great pressures from the environmentalists to place drastic restrictions upon toxic discharges of all kinds - and that is indeed a most laudable aim. But I cannot help thinking that a more gradual approach would have been possible and preferable. The sort of policy I would favour would be to come to terms with the art of the possible; lay down standards that are strict but practically attainable (provided that public health is not endangered); and give warning that these standards will be made more stringent after a lapse of so many years. This would give operators and industry time in which to perfect methods of improved abatement without incurring crippling costs, constant harassment and disturbance to the smooth and efficient running of power plants.

This lecture is about environmental problems associated with geothermal development. I have devoted most of it to just one of these problems - H_2S pollution - partly because it is usually the most serious one, and partly because it has afforded an opportunity to emphasise the importance of adopting a wise policy in such matters. I hope that those of you who are here on U.N. fellowships will take my remarks to heart. If your Governments construct a geothermal power plant in some remote situation, I would suggest that they do not apply the same rigid standards of perfection that would be appropriate for a plant situated in a densely populated area. Adopt a flexible, but not lax, policy that is in the best interests of your countries and of the world.

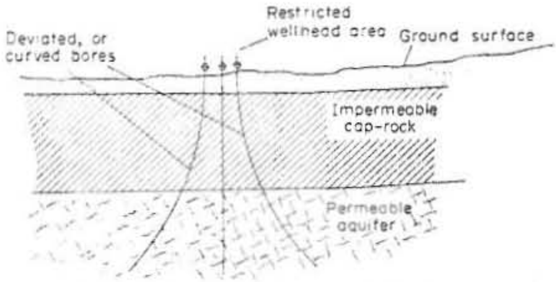
Having dealt at some length with H_2S I must now devote a little time to other forms of geothermal pollution that can occur. First there is CO_2, which quantitatively forms by far the greatest part of the non-condensible gases associated with bore steam. This gas can escape into the atmosphere or into local water courses. Apart from the climatic threat to which I have referred, this gas, when dissolved in the waters of streams and rivers, can encourage weed growth. The quantities of CO_2 released at the sites of geothermal power plants are usually, though not always, far less than would have been produced by combustion in a conventional power plant of the same capacity. For example, at Wairakei in New Zealand the CO_2 emitted per kilowatt-hour is about 1/60th of that emitted from the nearest coal-fired power station at Huntly. On the other hand the Broadlands field, also in North Island, has 20 to 30 times the CO_2 content in the steam by comparison with Wairakei, so that the advantage when compared with Huntly would be only 2 or 3 to 1 - but still a positive advantage in favour of geothermal power. Only in rare exceptional fields, such as Monte Amiata in Italy, is the CO_2 discharged greater than it would be from a fuel-fired plant of equivalent capacity; though usually this condition persists only for a year or two, after which the proportions of the gas drop to a far lower level. In so far as the displacement of combustion by geothermal power is concerned, the net result would certainly be a reduction in CO_2 emission; but as hyperthermal fields could never replace more than a small fraction of combustion plants in the world as a whole the net benefit would be very slight. The various possible commercial uses for CO_2 to which I referred in my first lecture, though perhaps desirable economically, would not help from the pollutive aspect, for in every use suggested the gas would be returned to the atmosphere after use. I am unable to say whether some permanent method of CO_2 fixation can be devised by the chemists, or whether, if so, it would be economic; but I do not regard the problem as an urgent one. For where the direct application of low grade earth heat is involved, no CO_2 problem arises at all. Moreover, if heat mining should ever assume a major rôle in meeting our energy needs - and I shall be talking about this in my fifth lecture - again there would be no CO_2 problem, and the emission of this gas would steadily decrease. Finally, it should be remembered that for millions of years forest fires have occurred on a devastating scale: it is therefore probable that the CO_2 concentration in the atmosphere has fluctuated. The curtailment of these fires resulting from the reduced areas of afforestation and through the exercise of care may well do as much to restrain the rise of CO_2 in the atmosphere as would ever be undone by the release of that gas from exploited geothermal fields. On balance, I do not regard CO_2 from geothermal exploitation as a serious pollutive hazard.

After H_2S, heat pollution can sometimes cause the most trouble from geothermal exploitation: it can also be very wasteful. The necessary adoption of moderate temperatures for geothermal power generation must result in low efficiencies and therefore the rejection of far more waste heat than in conventional thermal power plants of equivalent capacity. Where cooling towers are used, nearly all this low grade waste heat passes harmlessly into the atmosphere, while that contained in the small quantity of cooling water spill can be reinjected belowground. Where waste heat from condensers is rejected into rivers the practice differs only in degree from that which is followed in fuel-fired power plants, and is again more or less harmless. What can be serious, however, is the discharge of huge quantities of unwanted boiling, or near-boiling, bore waters into rivers; for this can damage fisheries and encourage unwanted weed growth. Even at Wairakei, where this practice has been followed for many years, and where the volume of discharged water was thought to be too small a proportion of the very large cold flow of the Waikato River to be harmful, adverse effects on river life have been observed. At mean flow the effect of the hot water discharged at Wairakei is to raise the river temperature, after mixing, by only 1.3°C; but under drought conditions, with very low river flow, temperature rises of well over 6°C have been observed. The normal range of temperature variation of this river is about 10 to 20°C; so the degree of heat pollution is obviously not very serious for such a large river with a power plant of the size of Wairakei. With smaller rivers or larger hot water discharges the effects would of course be worse. The important point about this form of heat pollution is that it should never be allowed to occur, if only because of its terrible wastefulness. From what I said in my first lecture it will be understood that wherever possible a useful application should be found for the rejected heat; but where this cannot be done the unwanted hot water should be reinjected into the ground.

Reinjection can, in fact, provide at least a partial and simultaneous solution to several pollution problems, first among which is heat pollution; for much of the unwanted heat would thereby be returned to the aquifer whence it came. Water-borne poisons from effluents containing boron, arsenic, mercury or other toxic substances could be disposed of by reinjection before they could damage downstream fisheries, crops or drinking water supplies. Ground subsidence, caused by the removal of huge quantities of underground waters from wet fields, can be greatly mitigated by reinjection, simply by replacing much of what has been withdrawn. Other environmental hazards, to which I shall shortly refer, can also be alleviated by reinjection. In my fourth lecture I shall have more to say about the practice of reinjection, but today I am simply stating that it can provide a means of combatting several undesirable environmental effects of geothermal exploitation.

I have now referred to H_2S, CO_2, heat pollution, water-borne poisons and ground subsidence. These, unfortunately, do not exhaust the list of potential forms of adverse side effects of geothermal exploitation. Others are: -

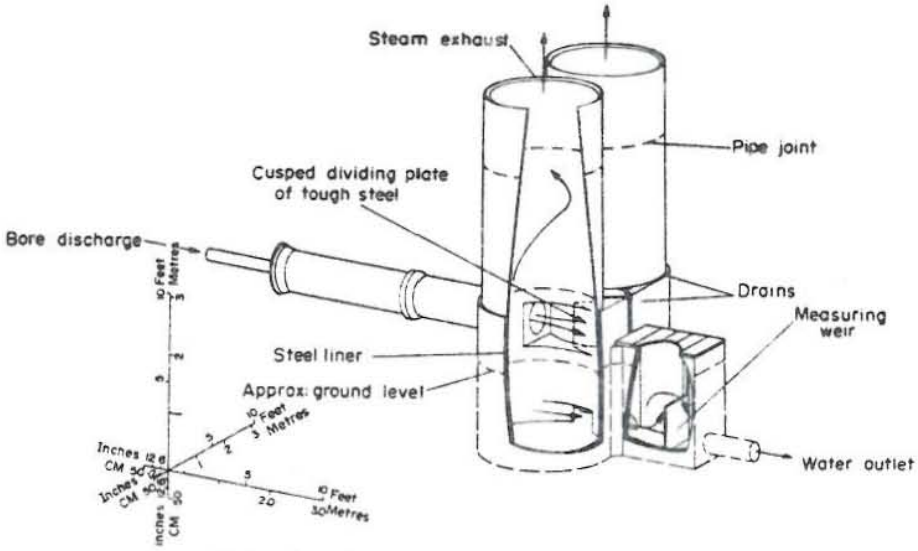
Land erosion in localities that are naturally prone to landslides and washaways. The artificial levelling of the ground to accommodate field works, roads, power plants, substations, etc. can aggravate erosion, especially if steep gradients have been formed in the earthworks, or if the removal of local vegetation robs the ground of the binding action of the roots. Careful site selection, improved construction methods and the replanting of shrubs and grasses can cure this trouble. The use of deviated bores, enabling two or more wellheads to be accommodated within a single levelled area of limited size can reduce the amount of surface earthworks, while allowing the aquifer to be tapped at widely separated points, so: -



Suggested method of using deviated, or curved bores to tap an extended producing zone from a restricted wellhead area.

The use of splayed bores can also offer a solution to the problem of gaining access to steam or hot water beneath lands that are being used for agricultural, building or other purposes and which cannot be disturbed on the surface. It has been reported (p.10, ETSU Report N2-77 by J. D. Garnish, Jan. '77) that directional drilling in Paris has added only 28% to the drilling costs as compared with vertical bores; but the savings in surface pipework and of having only one drilling pad and rig have more than offset this.

Noise is an inescapable nuisance associated with the development of hyperthermal fields; but the compulsory wearing of ear-plugs or muffs can protect the human ear from damage at places where the high-pitched scream of escaping fluids cannot be avoided during construction. Elsewhere the use of silencers at all regular fluid escape paths can be very effective in reducing the pitch and intensity of the noise. The accompanying sketch shows a simple and effective design of silencer developed in New Zealand, and now used in many other fields: -



Twin cyclone silencer, as used at Wairakei

By introducing the bore discharge into a larger openended pipe, air is sucked into the silencer by injector action so that condensation of the flash steam starts before the fluid enters the main body of the silencer. The twin tangential cylinders are of concrete, but a tough divider plate of manganese steel is inserted at the point at which the discharged bore water impinges, thus splitting the flow into two streams and directing it tangentially against the cylinder walls and protecting the concrete from erosion. The kinetic energy of the hot fluid is dissipated in friction as it swirls round the cylinders; the noise is directed skywards at reduced pitch; and the bore water, after surrendering its flash steam to the atmosphere, passes over a measuring weir to give an appoximate corroboration for checking flow estimations, after allowing for the flashed steam.

The use of temporary sound barriers can sometimes be helpful during construction. Drilling operations tend to be noisy, but no worse than road works, and they are of fairly short duration. Noise can also arise, as with conventional thermal power plants, from the whirr of machinery; but control rooms and offices can be sound-proofed so that most of the attendant personnel are protected.

Seismicity could conceivably be induced by prolonged exploitation triggering off earthquakes in formations that may already be in a state of high shear stress; especially if reinjection, involving fairly large temperature differentials, is practised. However, no serious trouble from this cause seems yet to have arisen in practice. Swanberg ("Physical aspects of pollution related to geothermal energy development", p. 1441, Vol. 2, San Francisco UN Symposium proceedings, 1975) states that injection will not trigger off earthquakes unless practised in places where high shear stresses already exist - i.e. at active faults. He further states that among thousands of injection wells in the USA only two well authenticated cases of seismic effects resulting from them have been reported. However, in hyperthermal areas it could occur. Nevertheless, reinjection is being practised in El Salvador, Japan, California, New Zealand and probably elsewhere, and as far as I know no seismic troubles have been reported from this practice.

Air-borne poisons escaping from cooling towers, ejector exhausts, silencers, traps and drains, bores under test, "wild" bores and control vent-valves could pollute the air with toxic substances (besides H_2S) - e.g. compounds of mercury and arsenic, and radioactive elements. Alarming though these substances may sound, their occurrence is usually in such tiny proportions as to constitute no threat to human, animal or vegetable life. Non-toxic, but noxious, emissions of rock dust and silica-laden spray can be air-borne and sometimes have given trouble. Some forest trees at Wairakei, New Zealand, and some coffee plantations in El Salvador were damaged by silica in the early days of exploitation. At Cerro Prieto, México, salt deposition on buildings and crops caused some trouble, while at Wairakei the deposition of hard silica on car windscreens, carried by the wind from the spray emitted by the silencers, caused some nuisance.

Fog. Large volumes of warm vapour escaping from cooling towers, or of hot vapour from silencers, vent-valves, bores under test and dump lagoons can give rise to thick clouds of billowing fog that can cause traffic hazards. This is seldom serious in dry warm climates, where the vapour is quickly absorbed into the air; but in cold damp climates the fog can persist and be troublesome; and sometimes ice precipitation can occur. Warning signs and traffic diversion routes can often mitigate the nuisance:, but the best remedy, where possible, is to limit the discharge of hot waters by extracting the heat for some useful purpose, or to reinject. This would not entirely eliminate the fog hazards, as cooling tower vapour plumes and occasional unavoidable discharges of steam would remain. In practice, however, no serious inconvenience has arisen from what amounts to a purely local and minor nuisance, with which we must come to terms, as with the weather.

Scenery spoliation. This is too subjective a matter for firm pronouncements to be made. In California great trouble was taken to camouflage the steam pipelines and to render the power plants inconspicuous. Unfortunately, as I have already mentioned, these good intentions have temporarily been frustrated by the unsightly deposition of red dust from the iron oxide treatment for H_2S abatement; but this trouble will disappear when success has been achieved with other forms of sulphide suppression. Some people would argue that the presence of huge volumes of billowing vapour - indicative both of waste and pollution - enhances, rather than spoils the scenery by imparting a majestic and mysterious quality to the view. Be that as it may, it will be conceded by most people that on balance a geothermal power plant is far less unsightly than a fuel-fired power plant with its obtrusive chimney stacks, smoke (in many cases), ungainly coal and ash handling equipment, boiler house, coal storage yard or oil storage tanks. Scenery spoliation, given reasonable care, need not constitute an environmental nuisance.

Ecology. Finally there is the question, as yet not fully proven, as to whether geothermal development disturbs the local ecology. The discharge of chemicals into the air and water courses, and thence into the groundwater; small, but detectable local changes of temperature and humidity; noise; and perhaps a degree of deforestation; all these influences could conceivably disturb the natural balance of nature that prevailed in a thermal area before exploitation. Research is being pursued on this question - and quite rightly - but no positive conclusions have yet been reached. On present evidence there seems little to show that the local fauna and flora have anywhere been detectably affected by geothermal development; with the exception of minor effects on river life in New Zealand resulting from heat pollution and dissolved CO_2: but it is well that this potential hazard should be continuously monitored and studied. Here again, reinjection could greatly help.

In conclusion, I think it may reasonably be claimed that geothermal development can arrest the environmental deterioration that has for so long been caused by the combustion of fuels, and that with persistence it could lead to an ultimate amelioration by reducing atmospheric and water pollution to negligible and acceptable levels. However, I would urge that enthusiasm to attain what is ultimately desirable should not be allowed to bring about just the reverse effect by delaying urgent geothermal development at immense and avoidable cost.

LECTURE THREE

SOME ECONOMIC ASPECTS OF GEOTHERMAL DEVELOPMENT

Today I face the most difficult of my tasks for this week - to talk to you about the economic aspects of geothermal development. The title of my subject may encourage you to expect that I shall be giving you a lot of geothermal cost information, but if you think that I fear you will be disappointed; for all I can hope to achieve today is to discern a few economic patterns and to deduce some cost relationships between different ways of developing geothermal resources, and between geothermal energy on the one hand and fuel energy on the other hand. I shall be quoting a few actual costs; but taken in isolation they are not of very great significance. However, the word "economics" has a far wider connotation than mere costing - important though costs will always be. Such considerations as national self-sufficiency, environmental impact, social repercussions and energy conservation may sometimes overshadow considerations of cost.

I should like to start by stressing the importance of national self-sufficiency. It is important to recognize at the outset that the days of cheap energy and of a wide choice of competitive suppliers departed in November, 1973, when politically motivated swingeing increases in oil prices rocked the economies of many nations and set off an inflationary trend in the prices of alternative fuels also. Energy has now become an expensive commodity; but it cannot be regarded as a luxury, for we could not survive without it. Have it in abundance we must: so it may sometimes be necessary to pay a higher price for it from a reliable source than a lower price from an unreliable source. Simple competitive price comparisons are no longer enough. Hence the growing importance of national self-sufficiency in a world where dependence upon some other country for our energy supplies can perhaps put us to the risk of being held to ransom. If the supply of energy can just be turned off, as though by a tap, at the whim of some other country or bloc of countries either for political or commercial reasons, then every nation owes itself a duty to acquire, or at least to attempt to acquire, energy self-sufficiency in so far as it is able to do so. No one, either an individual or a nation, likes to be placed in the invidious position of having to bargain under duress: it is both expensive and undignified. Hence the development of indigenous energy sources wherever possible has become a matter of pressing urgency.

Deplorable though the energy crisis of the last seven years has been - and it will continue for much longer - it has at least injected an element of urgency into the quest of many nations to develop such geothermal resources as they may possess.

The task of putting a price on geothermal energy is fraught with many difficulties. Someone - unfortunately I forget who it was - once aptly likened the problems of electricity cost accountancy to those of a merchant who buys by the cubic metre and sells by the tonne a commodity whose specific gravity is both difficult to determine and constantly changing. Geothermal cost estimation is just about as forbidding. With any energy source many uncertain factors can arise between the moment of intent to develop and the moment when the energy starts to flow. With geothermal energy the task of predicting its cost is rendered even more difficult by its own peculiar uncertainties; and the instabilities of modern times have aggravated these difficulties. Exploration costs can seldom be foretold with any precision; the costs of exploratory drilling are particularly hard to foresee, for the success ratio can vary so greatly: it is hard to foretell to what depth bores will have to be sunk to reach productive horizons (and drilling costs are notoriously dependent upon depth): the quality of rock to be penetrated can never be certain: the bore density per square kilometre and the bore characteristics are quite unknown in advance, as are the chemical properties of the bore fluid. These and other uncertainties ordain that there will nearly always be a high risk element in geothermal development as now practised - except perhaps when extending a field that has already been proven.

Until 1973 it would have been very roughly true to say that wherever earth heat had been exploited it usually cost only about 1/5th as much, or even less, as oil fuel heat. This is not the same thing as saying that the relative cost of earth heat would everywhere be so low, but at that time only a few fields had been developed, and I refer to them only. It could be argued that other fields has not then been developed simply because they were not expected to show nearly such a favourable price advantage. Be that as it may, it would be true to say that developed geothermal heat invariably cost only a small fraction of fuel heat; and the same would probably have applied to heat obtainable from many undeveloped fields, the failure to exploit which was due to many reasons other than unfavourable estimated heat costs. In fact the estimated heat costs had often never even been studied at all.

For direct applications the effect of this great price advantage was very profitable for all heat-intensive activities. I understand that here in Reykjavík, even after adding the costs of the extensive city reticulation system, the cost in 1973 of geothermal heat delivered to consumers was something between 50 and 60% of the cost of heat supplied from oil fuel burned in small domestic boilers.

For power generation, however, the relative cheapness of earth heat was to a large degree offset by the fact that geothermal plants were compelled to operate at much lower pressures and temperatures than conventional fuel-fired plants. This burdened the geothermal plants with the handicaps of lower efficiency and the inability to use such large power units:, which meant that their capital cost per kilowatt was higher. Despite this, it would have been roughly true to say that in 1973 geothermal power, wherever it was developed, usually cost only about 60% - or even less - of fuelled power, thanks to the extreme cheapness of the heat.

Since 1973 the whole pattern of power costs has changed. Oil fuel prices have risen by a factor of about 13 (which implies an annual price growth rate of about 44% compound). Labour and materials also have inflated very much in the same period, and to different extents in different countries; but on average they have increased by a factor of 2 to 2 1/2 times. To avoid overstressing my argument I shall here assume that labour and materials have risen in price by a factor of 3 in those seven years. One other important financial factor has also greatly changed in the same period: interest rates in most countries have risen sharply: and while this has had a modifying affect on sinking fund charges for meeting depreciation, it is probably true to say that the rate of capital charges as a whole have about doubled since 1973.

Now what has been the combined effect of all these changes on the relative costs of geothermal power to conventional thermal power? The following figures may be taken as fairly typical of the make-up of the production costs from power plants of each type in 1973: -

oil-fired		Geothermal	
Fuel	63%	Labour and	
Labour and materials ...	11%	materials ... 20% of 60% =	12%
Capital charges	26%	Capital	
	100%	charges ..... 80% of 60% =	48%
			60%

After taking into account the inflationary factors already mentioned, the relative costs of power today from these two sources of energy will have changed approximately to the following: -

oil-fired		Geothermal	
Fuel............... 63% x 13 =	819%	Labour and	
Labour and materials 11% x 3 =	33%	materials ... 12% x 3 =	36%
Capital charges 26% x 3 x 2 =	156%	Capital	
	1008%	charges.. 48% x 3 x 2 =	288%
			324%

Thus while oil-fired power is now costing more than 10 times what it cost only seven years ago, geothermal power is apparently costing only $\frac{324}{60}$, or 5.4 times as much. The relative advantage in favour of geothermal power has improved from 60% to $\frac{324}{1008}$, or 32.14%. This represents an improvement in competitiveness by a factor of 60/32.14, or 1.867. Now of course these figures make no claim to precision, but they do show how the relatively greater rate at which oil prices have inflated by comparison with labour, materials and interest rates has immensely improved the competitiveness of geothermal power, although of course all forms of power are now costing far more than previously. So long as fuel prices grow more rapidly than other commodities and services, geothermal power will tend to become relatively more attractive; and this tendency will very probably continue for many years. When we consider geothermal heat for direct application, its relative advantage over fuels will of course be far greater. For example, I understand that domestic geothermal heating in Reykjavík is now costing only about 12% in terms of real money (i.e. after discounting the oil subsidies paid to those to whom geothermal heat is not available) of what domestic oil heating would cost - an improvement of about 4 1/2 times comparison with 1973 in competitiveness. It is not surprising that so many countries are now actively seeking to develop their geothermal resources as rapidly as possible. In California, where geothermal development has been hampered with the costs of complying with the environmental laws - to which I referred in my second lecture - the relative cost of geothermal power vis-á-vis oil-fired power will be less favourable than these rough calculations would suggest. However, even there it has recently been estimated that by next year geothermal power will cost only about 34% of oil-fired power, which is not so very different from the 32% I have deduced from rough assumptions. The fact that these two figures do not differ more is probably because the Californian fuel-fired plants too have been subjected to very stringent environmental constraints.

It may be asked "Why, if geothermal power can be so cheap, has its development not been more rapid?" It is indeed surprising that with the splendid example of the Italian developments at Larderello it took several decades for other countries to do anything about it; and even then progress was very slow until the 1970s. The caution observed by most countries until recently lay partly in the comparative rarity of hyperthermal fields and the remoteness of many of them; also in the fact that the potentialities of low grade heat had not then been fully appreciated outside Iceland. Another factor was that several countries that possessed geothermal resources were also well endowed with cheap alternative energy sources that could be developed without risk by well established technologies involving no more than conventional engineering practices. New Zealand, for example, was abundantly blessed with large hydro resources as well as coal and natural gas. Even Iceland was comparatively slow to develop earth heat for power purposes, thanks to her rich reserves of hydro power. Another inhibiting factor in the past was the philosophical conflict of ideas between "risk capital" on the one hand and "safe development" on the other hand. Geothermal exploration entailed the investment of risk capital; and until recently men thought of electric power as the natural product of geothermal development. But electricity supply had been a safe and assured market that could then be supplied from very cheap fuels without entailing any risk whatsoever. Investors in risk capital expect a high return on their money if their enterprise is successful; but the power market, being a public service, is apt to be intolerant of high profits. There was thus a conflict of ideas that inhibited geothermal development. But now, the energy market is increasingly favouring geothermal development, while at the same time the risk element of exploration is being reduced by improved exploration techniques. And so this conflict has now largely been resolved, and geothermal development can be expected to go from strength to strength.

I would now like to talk about the form or nature of geothermal costs, as distinct from their magnitude. It is usual to treat the costs of producing anything, whether a manufactured product, industrial heat or electrical energy, in two components. There are the fixed costs of setting up and maintaining the means of production, and the variable costs that are incurred more or less in direct proportion to the quantity of the product. With conventional thermal power production the fixed costs consist of the capital charges (interest and amortisation) on the total investment, and the costs of management, attendance and most of the repairs and maintenance; while the variable costs will consist almost entirely of fuel, plus some other secondary costs more or less directly related to the energy output from the power plant. The fixed costs are usually expressed in $ p.a./kW and the variable costs are expressed in cents or mils/kWh. The consequence of two-part costing in this manner is that the average cost per kWh will depend upon the annual load factor at which the power plant operates; for if, for a given kilowatt capacity, only a few kilowatt-hours are generated, then th fixed costs must be borne by those few kWh and the average cost/kWh will be greater than if the plant operated at a high load factor and produced more kWh during the year.

All this is of course very elementary, but how can two-part costing be applied to geothermal power production? The absence of a fuel component would suggest that all annual recurring costs should be treated as fixed, since the total annual expenditure is scarcely affected by the output in kWh. For most purposes this is a valid argument, and it is in fact the normal custom to treat as fixed all the annual costs incurred in the operation of a geothermal power plant. However, where the steam supply and the power generation are undertaken by two separate enterprises, as in California, it may happen that the price charged for steam - instead of an annual fixed sum - is at so-much per kWh generated; in which case steam may then be regarded, from the cost accountancy aspect, as fuel, and therefore as a variable component of costs. But where a single authority undertake exploration, drilling, steam supply and power generation, as in New Zealand, the general custom has been to assume zero variable costs. Although this is usually good enough for practical purposes there is a minor flaw in the argument, for there is one cost component that should more logically be treated as variable. I refer to the service charges on the exploration costs. This is because the reward of succesful exploration is the discovery of a field containing a finite quantitiy of non-renewable energy which may be squandered quickly in a large plant or eked out slowly for a longer time in a small plant: it may be used wastefully in an inefficient plant or economically in an efficient plant. However used, that energy has a value attached to every usable heat unit: and that value is determined by the amount of money spent in discovering the energy. For example, let it be assumed that $10 millions are expended in exploration resulting in the discovery of a field of estimated usable capacity of 3,265 MWyre. Let it further be supposed that the $10 millions have been raised by a loan @ 10 1/2% interest, repayable in 25 years. The corresponding amortisation rate on a sinking fund basis would be 0.943% p.a. so the total charges on the loan would be 10.5 + 0,943, or 11,433% p.a. Thus to serve the loan over 25 years would cost 25 x 0,11443 x 10,000,000, or $28.6 millions. Then the variable cost component could be expressed at ...

$$\frac{28.6 \times 10^6 \times 1{,}000}{3265 \times 8760 \times 1000}, \text{ or } \underline{1 \text{ mil/kWhe}}$$

Now the assessment of this variable cost would be very difficult in practice, because the evaluation of the ultimate useful productive capacity of a field will always be uncertain. Moreover, exploration is often an activity that continues for some time after a project comes into service, so that the total expenditure on exploration will at any one time be difficult to define. All we can hope to do is to make the best possible attempt at estimating both the total useful exploitable energy and the total exploration expenditure so as to arrive at an approximate variable cost component.

Now all this may seem to be of little but academic significance because the conventional development of a hyperthermal field for power generation will normally be for base load operation so as to spread the high fixed costs over the greatest possible number of kilowatt-hours. Moreover, the theoretical variable cost component will usually form only a small fraction of the total production cost. Were it possible to save heat in large quantities when operating a geothermal power plant on light load, as with a fuel-fired plant, then the variable component would have a greater significance; but for practical reasons it is not easy to curtail the rate of heat withdrawal from belowground, for well-throttling can cause instability. In practice, therefore, the reduction of load on a geothermal power plant will result in the blowing of steam to waste. This gives an added reason for base load operation. However, the significance of a variable cost element can be seen in the study of what is generally known as the "scale factor". With conventional thermal power plants the capital cost per kilowatt installed is sensitive to this factor; that is to say, a very large plant will tend to cost less per kilowatt than a small plant of similar type. An approximate empirical formula to this effect which broadly applies to conventional thermal plants is ...

Total capital cost proportional to kilowatt capacity^{0,815}

Thus if plant 'A' has 10 times the capacity of plant 'B', its total cost would be about 6 1/2 times that of plant 'B' and the cost per kW of plant 'A ' would be about 65% of that of plant 'B'. This advantage in favour of the large plant is partly due to the spread of overheads over a greater number of kilowatts, partly to other general economies of large scale manufacture, and partly to the fact that the larger plants can use higher pressures and temperatures which are conducive to better efficiencies.

With geothermal power plants the scale factor is much less pronounced (with a reservation which follows) for two reasons. Drilling costs are roughly proportional to the installed capacity; and the moderate temperatures and pressures available limit unit capacities and efficiences. The corresponding scale factor formula for geothermal power plants would be more like ...

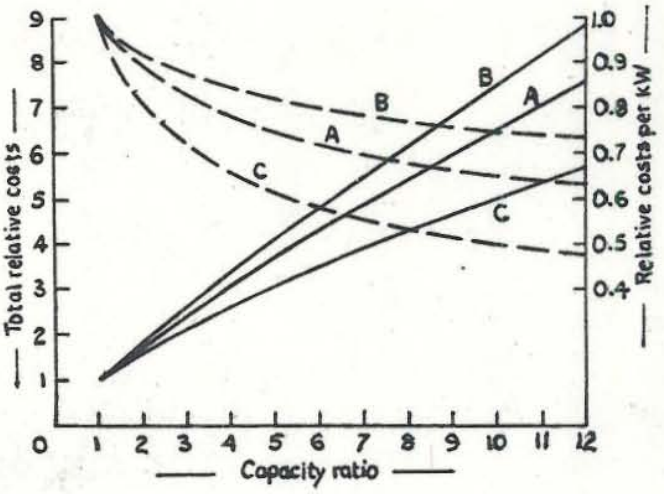
Total capital cost proportional to kilowatt capacity^{0,875}

Thus if plant 'A ' has 10 times the capacity of plant 'B' its total cost would probably be about 7 1/2 times as great and its cost per kW would be about 75% of that of plant 'B'. The advantage of size is therefore less marked with geothermal than with conventional thermal power plants. However, this is true only if a variable cost element is assigned to the energy, whether per kilocalorie or per kWhe, as a means of spreading the capital costs of exploration. If the exploration costs were treated simply as capital expenditure, the scale effect of a geothermal power plant would be greater than for a conventional thermal power plant, and the formula would become something like this ...

Total capital cost proportional to kilowatt capacity$^{0.7}$

Thus if plant 'A' were 10 times the size of plant 'B' its total cost (including exploration) would be about 5 times as great and its capital cost per kW would be about 50% of that of plant 'B'.

All these three formulae, which are here shown graphically, should be regarded as indicative only, rather than factual - particularly the third, since exploration costs can vary widely form project to project. They serve to show, however, that it would seem to be more logical to treat exploration costs as a variable element so that the scale factor is less pronounced. The alternative of treating exploration costs as part of the total capital investment would mean that if only a small installation were first adopted, then the exploration costs (unless partly allocated to a suspense account to be charged against expected future development) would have to be fully recovered from that first installation, and a large quantity of residual "free heat" would remain in the ground for use in future developments which, when realised, would quite illogically be exempted from any share of the exploration costs.



APPROXIMATE COST SCALE FACTOR

'A' — Conventional thermal power plants

'B' — Geothermal, excluding exploration

'C' — Geothermal including exploration

——— Total relative costs

- - - - Relative costs per kilowatt

It is now of interest to consider a curious paradox that arises with geothermal power generation. The normal method of exploiting a hyperthermal field for power generation is to pipe the steam from a number of bores to a central power station, where electicity is generated by means of condensing turbines. This practice is followed because of the greater efficiency of such turbines by comparison with atmospheric exhaust turbines. An alternative way of developing the field would be to install a number of small non-condensing turbines close to the wells and to interconnect them electrically. This would effect great savings in pipework, and the small power units would need only the simplest of foundations and weather protection, no condensers and no cooling water system. Furthermore, by siting the turbines close to the wells there would be savings in heat losses of transmission, and it would be possible to adopt higher turbine admission pressures with consequent improved thermal efficiency. Alternatively, we could use the same turbine admission pressures and obtain a greater kilowatt output by using more steam from the same number of bores. It is true that the non-condensing turbines would require perhaps about 70% more bores in order to achieve the same total output as a central condensing plant, but the cost of these can be more than offset by the various savings I have mentioned. It is in fact possible to effect a saving of about 12 to 14% in capital costs per kW and about 10% in the production costs per kWh by adopting the non-condensing arrangement. Why then is it that all the existing major geothermal power developments have been designed for central power stations with condensing turbines? The answer is that production costs per kWh, though important, are not the only criterion on which the choice of a system should be based. Energy conservation and long term profitability can be even more important. Let us consider a hypothetical example.

Suppose that a field has been discovered with an estimated total exploitable energy capacity of 3,400 MWyre based on the use of condensing turbines. If non-condensing turbines were used, consuming, (say) 70% more steam per kWh than condensing turbines, the field capacity would be reduced to 2,000 MWyre. Let it further be assumed that the production costs with condensing and non-condencing turbines are 20 and 18 mils/kWh respectively - i.e. 10% less in the case of non-condensing turbines. Would it be right to squander 1,400 MWyre (3,400 - 2,000) for the sake of a 10% saving in production cost per kWh? This question can best be answered by considering the most nearly competitive alternative source of base load energy. Let us suppose that this competitive source is a fuel-fired thermal power station with a production cost of 35 mils/kWh. Over the life of the field, the savings effected by using geothermal power rather than fuelled power would be ...

For a central condensing plant ... $3400 \times 8760 \times 1000 \times \frac{(35 - 20)}{1000} = \underline{\$446.8\ m}$

For non-condensing plants .... $2000 \times 8760 \times 1000 \times \frac{(35 - 18)}{1000} = \underline{\$297.8\ m}$

Difference .... $\underline{\$149\ m}$

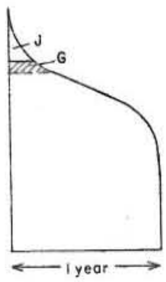
Thus, although the non-condensing plants would save 17 mils/kWh as against only 15 mils/kWh for the condensing plant, by comparison with the alternative fuel-fired source, the larger saving could be applied to a far smaller number of kWh; with the result that the long term profitability of using costlier condensing plant would show a gain of $149 millions. This, of course, is an over-simplification, for it assumes a constant value of money over the life of the field. In an inflationary market of the type now prevailing, in which fuel prices are inflating more rapidly than other costs, the long term saving in favour of the condensing plant would be far greater, if the alternative to geothermal power were fuel-burning. In spite of all this, non-condensing power units have their uses: -

i) where geothermal steam has a gas content exceeding about 10%; because the cost of gas exhaustion then becomes prohibitive, and

ii) as small pilot plants, where field study is the prime objective, and generated power may be regarded simply as a useful spin-off.

Let us consider further the economics of pilot plants. In the early days of developing a hyperthermal field it is customary for the first few successful bores to be blown to waste at high output for a considerable time in order to study the bore behaviour and the field characteristics. A pilot plant could put this steam to good use. Since the steam thus used would otherwise be wasted, it could be of greatest value if consumed by a plant in almost continous operation, so that it could contribute its mite towards the system base load. Pilot plants are of an experimental nature, installed to foster confidence and to gain experience. They should be cheap in capital cost as their function is comparatively ephemeral; so non-condensing units would be suitable for the purpose. They can be quickly installed, and as they would make use of a single bore, or at most a very few bores, they would be of fairly small capacity - say from 2 to 5 MWe. As they would use steam that would otherwise be wasted, they should not be expected to bear any share of the costs of bores or well-heads; these being primarily provided to serve a later and larger permanent plant. Nor, for the same reason, should they be burdened with any variable costs incurred by exploration. However, if a pilot plant is to enjoy these exemptions, it would be unfair to compare its production costs (as computed on the basis of these exemptions) with the full production costs of other plants. It would be more logical to compare them only with the direct incremental savings earned by the generated output of the pilot plants. For practical purposes these savings may be taken as the value of the fuel that would, but for the pilot plants, be burned in any conventional thermal plants that may be contributing energy to the integrated electricity system. As I mentioned in my second lecture, every kilowatt of base load geothermal capacity can save about 2 tonnes of oil fuel per year (or equivalent of other fuels). Even in 1980 it should be possible to operate a non-condensing geothermal pilot plant at an annual cost of perhaps $150/kW or thereabouts; so such a plant would not only pay for itself but would also contribute some modest excess revenue if the price of oil fuel were more thatn $75 per tonne - a condition likely to be found in all non-oil producing countries. The fact that a pilot plant may have served its original purpose within 2 or 3 years of its installation need not mean that its life is finished after that period. It could be shifted to a new field for further pioneering work, retained in situ as an emergency generator, or even used to make a small contribution to the system peak load.

I have already mentioned that geothermal power is eminently suited to the supply of base load. Nevertheless, it can be argued that to a small extent it could perhaps sometimes be used for contributing towards peak load requirements. It is well known that in an integrated power supply system cheap kilowatts can sometimes be as valuable as cheap kilowatt-hours. Non-condensing geothermal turbines have some of the characteristics of peaking plants, in that their cost per kW is low while their heat consumption per kWh is high. If a cost comparison be made between power supplied by a non-condensing geothermal turbo plant and some conventional type of peaking plant - e.g. a jet expander gas turbine - it will be found that the former will have the lower production cost per kWh at all but very low annual load factors. The higher the cost of heat, the smaller will be the break-even annual load factor for these two types of plant. This means that in theory, although non-condensing geothermal turbines could never compete with jet expander gas turbines for carrying the extreme peak loads, they could compete for carrying secondary peak loads; by which is meant flat-topped 'slices' of load in the upper part, but not at the very top, of the load duration curve; as shown in this sketch.



'J' represents the extreme peak, for which a jet expandor gas turbine or some other type of peaking plant would be best suited

'G' represents a 'slice' of secondary peak load, for which geothermal power could perhaps theoretically compete.

The practical objection to using non-condensing geothermal plants for non-base load purpose is the difficulty of bringing bores into use for short periods and shutting them off again when they are not needed. Such treatment is not conducive to bore stability and must be ruled out. This problem could of course simply be solved by bypassing the unwanted steam to waste at off-peak times; but this would be wasteful of a non-renewable source of energy and it could give rises to environmental problems. The best circumstances in which geothermal power could make a substantial contribution to the system peak load would be if a commercial use could be found for off-peak steam for some non-power purpose, possibly with the help of thermal storage. If a market could be found for such steam, it is quite possible that the power element of a dual purpose project could more profitably be used for supplying secondary peaks or loads at intermediate load factor than for base load. Non-condensing geothermal turbines could, however, supply a very small element of peak load if installed as closely as possible to the wells in a field that is primarily supplying a base load condensing plant. So long as the steam demand of the non-condensing units forms such a small proportion of the total bore steam that the disturbance to the system pressures on starting up or shutting off these units is small, bore instability can perhaps be avoided. However, a more promising future for the use of geothermal power for non-base load purposes may perhaps be realised when the use of submersible well pumps - about which I shall be speaking in my fourth lecture - becomes standard practice; for then it should be possible to withdraw a variable flow from the wells without affecting their stability: geothermal plants could then perhaps be used to supply electricity at any required load factor, both practically and economically. Another possibility which I have recently been examining is that of condensing unwanted off-peak steam in a pressurised condenser and reinjecting the mixture of condensate and heated cooling water into the aquifer. Pressurising the condenser would nimimise the amount of cooling water required.

I have already mentioned the fact that steam production and power generation may sometimes be undertaken by two different authorities, as in California for example. It might be thought that such an arrangement would result in higher priced electricity than if only a single authority were involved; for each partner in the joint enterprise will expect to derive some financial benefit from the risks and efforts he has contributed. This is not necessarily so, for if each participant is a highly experienced specialist organisation in the particular activity concerned, it is quite possible that the end product, electricity, may even cost less than if only a single entrepreneur were responsible for everything; for it would be necessary for such an entrepreneur to contract out for much of the work involved - e.g. for drilling. At the Geysers in California the field is parcelled out into a number of concessions, each leased by different enterprises for developing steam supplies that are delivered to another enterprise - the Pacific Gas & Electric Company - who is responsible for building and operating the power plants and transmitting and distributing the electricity to the consumers. On the whole, the arrangement works satisfactorily for the benefit of all concerned. The price charged for the steam is not fixed, but is variable according to an agreed formula relating the steam price to the costs of alternative energy sources such as fuels and hydro power. This linking of steam price to the costs of alternative energy sources is not without its critics, for it is argued that the OPEC countries have only to raise their oil prices and the steam supply concessionnaires will immediately collect more revenue for supplying exactly the same quantity of steam without their costs in any way having been affected by the action of OPEC. The argument in favour of the arrangement; however; is that the higher the price of oil rises the greater becomes the need to provide an incentive to encourage further exploration for geothermal steam; and the "unearned" revenue derived from oil price rises provides the concessionnaires not merely with a fair reward for the risks they have taken but also with funds with which to finance further geothermal exploration. The purchaser of the steam - The Pacific Gas & Electric Company - is also satisfied with the arrangement because the price formula is so framed that the steam price will always be such that geothermal power will cost <u>less</u> than alternative thermal power from fuel-fired plants. The origin of this rather curious steam purchase arrangement lies in the historical development of the electricity supply industry in the U.S.A. In the early days of natural gas, fixed cheap prices were agreed which made natural gas economically attractive by comparison with other fuels, so the whole nation more or less shifted to a gas economy. Although the developers did fairly well out of it for a time, there was no extra reward to encourage further exploration. They therefore lost the incentive to develop more gas just to have it rigidly controlled in price, so they invested in other more rewarding ventures or did nothing at all. Suddenly the country found itself geared to a gas economy and running out of gas. Despite clear warnings the country had failed to develop its coal industry and other energy sources because of the artificially low gas prices. The Pacific Gas & Electric Company do not wish to see history repeating itself: they prefer to observe the rules of the market place and to make sure that they will get geothermal steam for as long as it is available at a competitive price rather than no steam at all. At one time when the steam price was low, the concessionnaires of the Geysers field showed signs of losing interest in continuing exploration because they found better and more rewarding ways of investing their capital. Furthermore, since some of them were also involved in oil prospecting they diverted all of the then scarce steel tube supplies to that more rewarding effort. Another factor that has justified the increased revenue to the steam suppliers is the big rise in drilling costs. Some of the earlier wells cost only about $50,000 each. More recently, typical well costs have reached the $1 million mark, partly because of inflation and partly because it is now becoming necessary to penetrate into deeper and more difficult formations. Yet another factor is the long waiting times induced by bureaucratic delays of one kind or another: a 7-year wait from a "Notice of Intent", and 11 years from the start of reconnaissance before the revenue starts to flow is nothing unusual now. Hence the steam price formula is not a matter of condoning profiteering, as might at first be thought by those who are unfamiliar with the historical facts and circumstances. As I mentioned in my second lecture, the steam supplies in the Geysers field are not metered: the charges are based on the number of kilowatt-hours generated. In the early days of development this arrangement was a great simplification, acceptable alike to the steam suppliers and the power company, because an annual plant factor of 80 to 90% was more or less assured. But since the enforcement of rigid H_2S concentration levels, which has necessitated the retro-fitting of abatement plant, the annual plant factor has dropped and the steam suppliers have suffered accordingly. Their revenues have not been won too easily despite the price increases that have occured. In 1960, when the first power plant was commissioned in the Geysers field, the power company paid the steam suppliers only 2 mils/kWh. Now, the price is 18.63 mils/kWh - an increase of more than 9-fold, equivalent to a mean annual price growth rate of 11.2%. The latest price, however, includes a charge of 1/2 mil/kWh for reinjection costs.

One of the greatest influences upon the cost of geothermal heat arises from drilling operations, the costs of which can vary very widely from site to site for the following reasons: -

1) A drilling contractor must incur substantial "mobilisation" costs for acquiring his equipment, transporting it to where it is needed

preparing his drilling sites, providing access thereto, hiring a team of skilled men (who must be paid even when no active drilling is in progress) and providing them with temporary housing and other social facilities in out-of-the-way locations. He may also have to provide water supplies and construct wellhead cellars which may, or may not, be included in his contractual obligations. Hence, very substantial sums of money must be spent before even a single metre of borehole has been sunk. This is particularly true of small developments in remote sites. Time is the essence of reducing the total costs of perforating a field with bores. Delays of all kinds can increase drilling costs enormously.

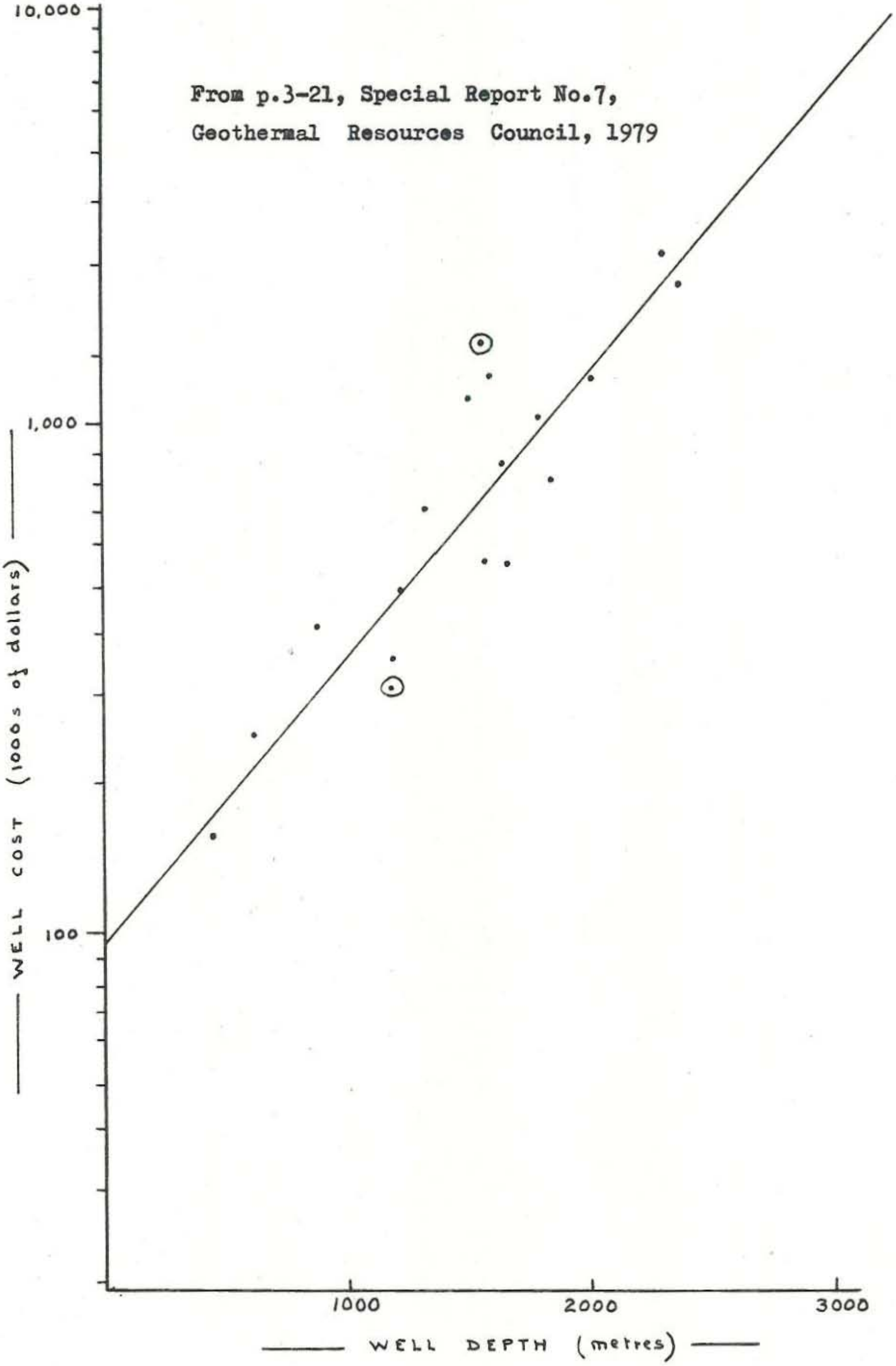
ii) Exploration holes may be 2 or 3 times as expensive as production holes of the same depth, because of the need to take cores and to make frequent downhole measurements.

iii) Drilling costs are very sensitive to depth, mainly because of the greater proportion of unproductive time, as the depth increases, spent on the increasingly laborious work of changing bits and of dismantling and reassemling drill stems. I shall be discussing this sensitivity to depth later.

iv) Drilling costs depend greatly on the nature of the rock to be penetrated. A hole 3,000 m deep drilled in granite could perhaps cost 3 times as much as if drilled in sedimentary rocks.

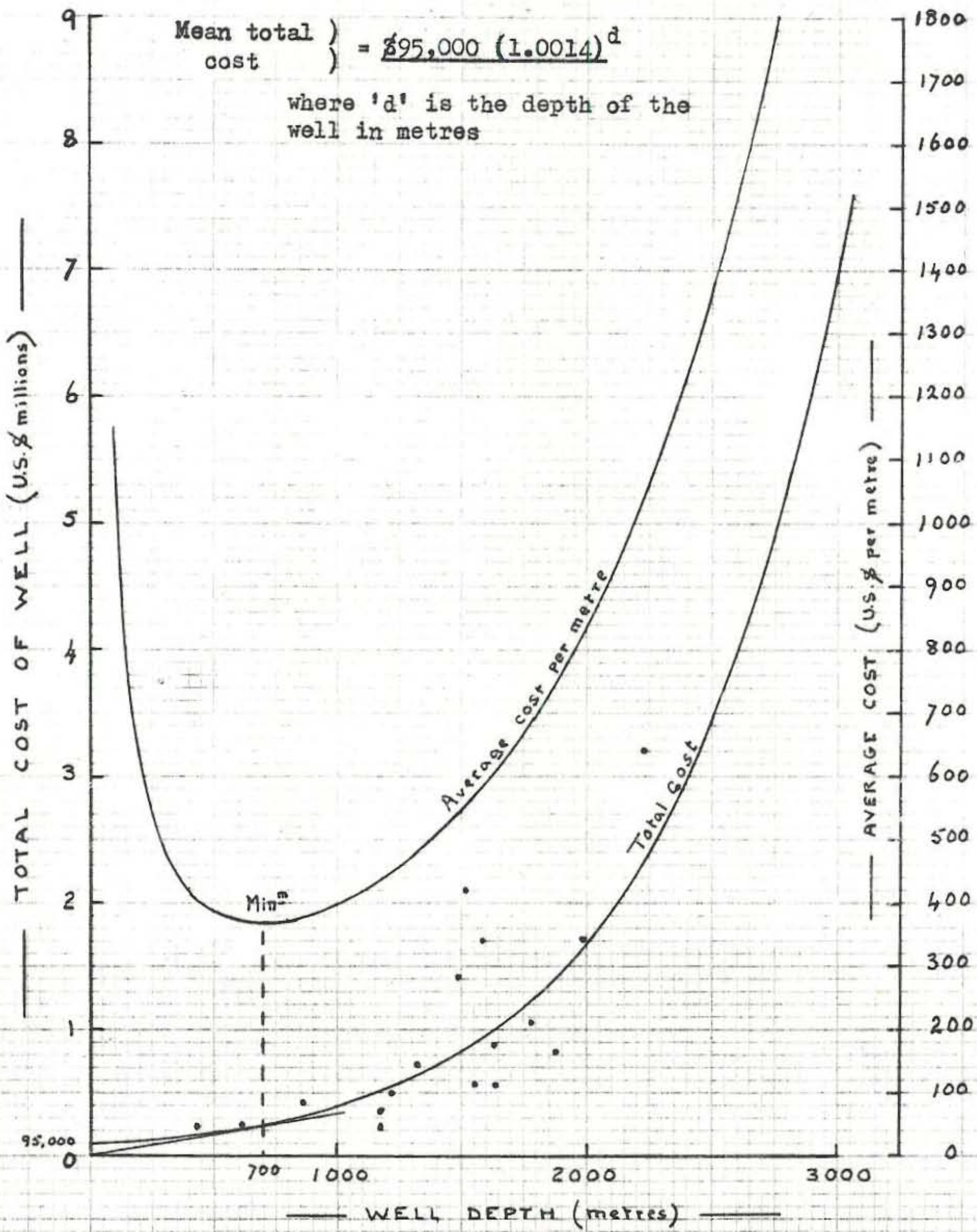
v) Drilling tends to be far cheaper in those countries or regions where there are already extensive drilling activities, and where rigs, skilled crews and contractors abound. At a remote site, unaccustomed to such operations, all the necessary facilities must either be imported, or at least moved over great distances.

Recently published in Special Report No. 7 of the Geothermal Resources Council, p. 3-12, was a graph which claimed to show the broad trend of drilling costs in the U.S.A. for low and medium temperature holes. I reproduce the significant parts of that graph. All the holes are suitable for the direct application of earth heat: bores in hyperthermal fields are excluded. Since the vertical scale appears to be logarithmic, and since a straight line has been drawn through the data points, the implication is that the costs tend to follow an exponential relationship with depth. The use of logarithmic scales is a well known device



<u>TYPICAL AMERICAN WELL COSTS</u> (in 1979 dollars)

for low to medium temperatures.



TYPICAL AMERICAN WELL COSTS (in 1979 dollars)

for low to medium temperatures

for trying to detect a relationship between points that show a wide degree of scatter when plotted against linear coordinate scales, and in this case the sloping straight line certainly looks like a reasonable mean trend. But although the scatter about that line looks moderate, the upper ringed point lies above the line by a factor of 2.77, while the lower ringed point lies below it by a factor of 66%. Such is the distortion caused by the use of a logarithmic scale. To complicate matters, the vertical scale of this graph has not been drawn truly logarithmically; the reason for this is not known. However, if we take the extremities of the sloping line and accept their apparent coordinates, the equation becomes ...

$C = 95{,}000\ (1{,}154)^D$ where 'C' is the total cost of bore, and 'D' is the depth in 100s of metres.

or alternatively ...

$C = 95{,}000\ (1{,}0014)^d$ where 'd' is the depth in metres.

This shows an exponential relationship, a fixed cost of $95,000, and a cost increment of 15,4% for every 100 metres drilled.

The next graph shows the interpretation of this formula to linear coordinate scales; and on the same graph is shown a curve of the average cost per metre as a derivative of the total cost curve. The scatter of data points now makes the total cost curve look like wishful thinking. The average cost per metre reaches a minimum at a depth of about 700 metres, where a straight line from the origin is tangential to the total cost curve. To show how misleading such curves can be, I would mention that recent bores in the Geysers field for typical depths of 2000 - 2500 m have been costing around $1 million each, which is considerably less than half of what this curve would suggest, despite the much higher temperatures encountered at the Geysers. In the Imperial Valley, California, also at high temperatures, bores of 2000 - 3000 metres depth are costing around $200 per metre. At Klamath Falls, Oregon, drillings at moderate temperature are costing not much more than about $100 per metre for depth of 100 m or so. These figures are far below what the curves would suggest. It may be that different costing methods have been adopted in these cases, but personally I have little faith in logarithmic interpretations of widely scattered points unless the fit is far better than that shown by the first curve. Even the very form of the implied equation is not rational; for the zero-depth cost of $95,000 would logically represent the typical cost of setting up a rig and having everything in readiness for the start of drilling operations. But there is no reason why the actual penetration costs incurred thereafter should be a function of that setting-up cost, which is what the equation implies. It would be more rational to seek some fixed setting-up cost as a first term of a two-term equation, with a second additive term expressed as some function of the depth. There is no particular reason why, even to a logarithmic vertical scale, the total cost curve should be a straight line. For instance, if we treat the $95,000 as a fixed "setting-up" cost and deduct this amount from the costs shown by the straight line figure, the point at zero depth would drop to minus infinity, while at the upper end (as drawn) it would drop only to $7,405,000 from $7,500,000; and the second term would become a curve assymptotic to the zero-depth vertical and to the sloping line: possibly a hyperbola, but no longer exponential. Very possibly, for any one hole, the cost may be an exponential function of depth, but as a basis for statistical law for covering a wide variety of circumstances, it would be too much to expect that a simple exponential formula could ever be devised. The probable fact is that drilling costs are so complex that no simple statistical relationship with depth can be detected - certainly not from a mere 18 data points. I greatly regret that I can offer you no simple formula for estimating, even approximately, what drilling will cost anywhere. It could in fact cost almost anything because of the many variable factors that contribute to the total cost. I would only suggest that for the U.S.A. as a whole, the curves I have shown you are probably pessimistic, except for rather isolated sites.

The most recent costs that I can quote for geothermal power are those of the Pacific Gas & Electric Company who, with various steam suppliers, are exploiting the Geysers field in California. Their 1980 estimate of the average cost of geothermal power is 31 U.S. mils/kWh, including 18.63 mils/kWh for the purchase of the steam and reinjection. Thus the steam cost accounts for about 60% of the total. This cost of 31 mils/kWh has been inflated by the expenses and side-effects of H_2S abatement, and also by the fact that the steam price (under the terms of the purchase agreement) partly reflects the rise in fuel prices. On the other hand the scale factor for an undertaking with over 900 MWe installed will have helped to restrain the cost. A 1973 estimate of the Geysers production costs was 9.2 USmils/kWh for 80% annual plant factor and 9.7 USmils/kWh for 70% plant factor. As the plant factor is now running at about 70% only, this shows a cost increase of 3.2 times in 7 years, equivalent to an annual mean cost growth of 18%. By comparison, production costs in California from alternative sources are now as follows:

Nuclear .... 25 mils/kWh, or 80.6% of the geothermal costs
Coal-fired .... 44 mils/kWh, or 142% of the geothermal costs
Oil-fired ..... 91 mils/kWh, or 294% of the geothermal costs.

I have also just received information that the electricity production costs at Cerro Prieto, México, are now estimated at USmils 36/kWh for a 75 MW installation (2 x 37 1/2 MW). Considering the modest size of the plant, this compares favourably with the Californian production cost of 31 mils/kWh, although México has not yet been plagued with the same expensive gas abatement costs. A 1974 estimate for Cerro Prieto production cost was 12.56 USmils/kWH; so the apparent escalation rate works out at about 19% p.a. Although slightly more than for the Geysers, it should be remembered that the earlier Mexican figure was only an estimate made in advance of actual experience; and, like so many advance estimates, could well have been on the low side.

I regret I have no other production costs of geothermal power.

When assessing these costs it is important to remember that different lives should be allowed for different assets. In the early days of geothermal power development, when there was still some uncertainty as to its reliability, a cautious life of 20 years was considered "safe" for the power plants; but now that confidence has been gained, it is usual to allow for a life of at least 25 years, and often 30 years for power plants. As to bores, however, a 10-year life is usually considered advisable although individual bores may serve for much longer periods. The fact is that most bores in hyperthermal fields tend to yield less fluid as time passes, owing to calcification, silica deposition or other causes of reduced formation permeability, so that after some years they have to be replaced, as their wellhead equipment and branch line pipework could be more usefully employed on a newer bore of greater output. When interest rates were low, this reduced life allotted to hyperthermal bores had a marked influence on power production costs, but with high interest rates this influence is relatively less. For example, at 5% interst it is necessary to allow 1 1/2% for a 30-year life but nearly 8% for a 10-

year life for amortisation on a sinking fund basis. In the case of the bores, amortisation would account for 61 1/2 of the capital charges. Now that interest rates may be as high as perhaps 16% p.a., the amortisation rate for a 10-year life is only 4.69%, forming about 20.7% of the capital charges. With low temperature bores for direct heat application, much longer bore lives are usually permissible unless some peculiarly virulent chemical problem is experienced. For power plants to which a 30-year life is assigned, the amortisation rate at 16% interest is only 0.19%, which forms a very small proportion of the total capital charges. (1.2%). Another very important factor in power production costs is the annual plant factor, to which those costs are inversely proportional. Factors of 90% or even more are often attainable; but the fact that the Geysers plants are now operating at only about 70% annual plant factor is adding about 28% to that part of the production costs that excludes the steam purchase price.

For low grade heat, the latest figures I have for Iceland will now be very much overtaken by inflation, for they are those quoted by Mr. Sveinn Einarsson in 1975 as approximate estimates only. These were as follows: -

Water temperature	100°C	120°C	
Production cost at bores	2.1	1.6	USmils/kWht
Distribution costs	3.8	3.8	" / "
	5.9	5.4	" / "

To which must be added transmission costs ranging (according to pipe diameter)

from .. 0.12 to 0.23 ..... 0.1 to 0.17 USmils per kWht per kilometre.

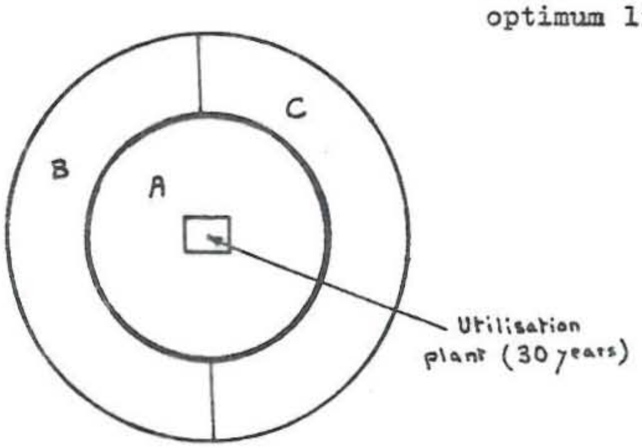
I am sure there must be several people here today who will be able to quote updated figures after this lecture, and I eagerly look forward to hearing them.

The only other up-to-date cost <u>indications</u> I have for low grade heat are implicit in a statement that in Klamath Falls, Oregon, a 90% saving is now claimed for geothermal space heating by comparison with oil heating; but as the oil heating costs would, for fair comparison, include capital charges and maintenance costs on the heating equipment as well as the actual fuel costs, it is not possible to deduce from this statement the delivered costs of geothermal heat per kWh(th). Nevertheless, the claimed saving is very impressive.

As to heat extracted from hot dry rocks, about which I shall be speaking to you in my fifth lecture, it is too early for any firm figures to be quoted yet, as the art is still in the experimental stage only; but at Los Alamos, New Mexico, they are tentatively talking of a prototype cost in the range of 3 to 4 US cents per kWh(th); while in the United Kingdom a price of 2 to 3 pence per kWhe - say 4.7 to 7 cents/kWhe - has been cautiously mentioned. I do not know on what size of installation either of these figures is based; but they are beginning to look as though they could make commercial sense. Moreover, the figures are sure to fall in terms of real money as the technology improves and the scale of development increases. The cost of hot dry rock heat is very dependent upon the time over which exploitation is effected, and the financial pattern of heat recovery activities is curious; for an exploited mass of rock will contain a finite total of recoverable heat. Thus, if inflation be discounted, the total revenue that could be earned from that mass of hot rock would be fixed. Hence, within limits, the shorter the life assigned to the project the greater will be the financial return on the investment, though for a <u>very</u> short life the amortisation rate becomes substantial. More important, however, is the fact that the capital cost of the <u>utilisation plants</u> - whether power stations, factories or whatever - large enough to "swallow" the total available heat within a very short life becomes very great. As a result, there will be an optimum number of years for which the best financial return will be obtained on the investment. The <u>shape</u> of the profit and loss curves for hot dry rock heat, if the <u>total</u> investment be considered - i.e. including the bores, fracturing operations <u>and</u> the utilisation plants - would be somewhat as here shown: -

The curves are intended to be typical only of shape - not of magnitudes. The optimum returns shown by these curves would probably be at too short a life by comparison with the much longer practical lives of some of the assets - e.g. about 30 years for a power station. This difficulty could probably be overcome by allowing the heat extraction investment to operate over its own short optimum life for one zone of exploitation, and then to extend the zone peripherally outwards in two or three stages, each with its relatively short life, while retaining the utilisation plant in a central position and merely extending the pipework to serve it from the extended areas, so: -

Zones 'A', 'B' and 'C' of equal area, with optimum life of 10 years each.



However, all this theorising could be rather academic, as the rate of heat extraction will be limited by practical considerations that will almost certainly prevent us from fully exploiting the hot rock within the theoretical optimum life, so that a higher price would have to be charged than would have been possible with more rapid heat extraction.

I fear that today's lecture may have disappointed you. With the best of intentions it is virtually impossible to indicate typical geothermal costs because there are too many variables. Each exploitation must be considered as a very individual enterprise. Operators are generally reluctant to quote cost figures, knowing well that they are likely to be outdated so soon by external influences over which they have no control. Even spot figures can only be of limited value because of the wide variations in purely local circumstances: and so, as I said at the beginning of this talk, I have only been able to discuss cost patterns, influences and trends, rather than actual figures.

LECTURE FOUR

SOME ENGINEERING PROBLEMS IN THE PLANNING OF GEOTHERMAL PROJECTS

So many engineering problems are involved in the application of geothermal energy to practical uses that I can only touch upon a few: some of these have been high-lighted in recent years.

I shall start with energy transmission. It is generally true to say that whenever energy is transported from one place to another an energy loss is incurred, also that the larger the quantity of energy to be moved by any particular method, the lower will be that loss proportionally.

If energy be transported in chemical form - that is to say as fuel - the intrinsic loss in the actual fuel transported should be nil; but nevertheless some external energy has to be expended in propelling the tanker or wagon by road, rail, sea or air. Fuel transportation is the most energy-efficient way of moving energy around, with the result that it is commercially feasible to send coal, oil or liquid petroleum gas all over the world.

Electrical transmission of energy can be very convenient and, if in sufficiently large blocks, can cover distances of some hundreds of kilometres with only a few percent loss.

But when it comes to heat transmission, energy is far less mobile. As with other forms of transmission, the greater the quantity of energy to be moved, the larger the distance that can be economically spanned; but distance limits cannot be precisely defined. They will depend on the quality and the quantity of heat and upon a host of local conditions.

If steam is the transmission medium, 2 or 3 km. is about as far as it would propably pay to move energy from one point to another; for energy losses are also incurred through drains and traps if the steam be saturated. The transmission of superheated steam raises few technical problems other than the need to make adequate provision for thermal expansion and contraction - a need that will apply to all forms of heat transmission - but it involves the making of two principal economic compromises. The first is between excessive pressure drops on the one hand, and large expensive pipes on the other hand. The second is between incurring high head losses on the one hand (and possibly squandering the superheat), and the provision of expensive lagging on the other hand. When transmitting saturated steam, however, an added problem arises from the fact that no wellhead separator can operate at 100% efficiency: with wet bores there will always be very small quantities of bore water that escape capture and get carried over with the steam into the pipelines. Bore water usually contains salts in solution, such as chlorides, that must not be allowed to enter turbines except in the most minute concentrations lest they damage the blades in the presence of H_2S. Turbine makers may specify that chloride concentrations at turbine entry shall not exceed 10 p.p.m. in the droplets of the water. Thus if the steam were, say 0.5% wet, the gravimetric chloride concentration in the steam would have to be kept to within 50 p.p.b. If slightly wet steam has to be transmitted over distances of more than about 1/2 km, this constraint can easily be complied with; for it does not pay to spend too much on lagging the piplines, because condensation on the pipe walls can have a beneficial effect by acting, in conjunction with traps, as a very efficient means of scrubbing the steam and diluting the salinity to almost infinitesimal concentrations. Heat losses through imperfect lagging cause condensation, which dilutes the condensation of dissolved salts carried over with the steam from the wellhead separators. The placing of a trap after 100 m. or so from the wellhead will effect the removal of a large proportion of the diluted saline water from the pipeline. That part of the diluted saline water that is not removed by the trap is again diluted by further condensation that occurs on the pipe walls over the next 100 m or so to the next trap, where the process is repeated. In this way, repetitive dilution and draining can effect a rapid and high degree of purification that improves, in geometrical progression, with the length of the pipeline and the number of traps; so that the steam entering the turbines - though perhaps 1/2 of 1% wet - will contain scarcely any trace of the harmful salts carried over from the bores. The action of a long pipeline in this way, resembles the process of repeated rinsing. After about 1/2 km of pipeline it is possible to effect removal of about 99.7% of the salts that first entered it, while after 1 km the removal factor could reach about 99.9997%. These figures assume a trap spacing of 100 m, a trap removal efficiency of 75%, and a condensation between consecutive traps of 0.5% of the steam.

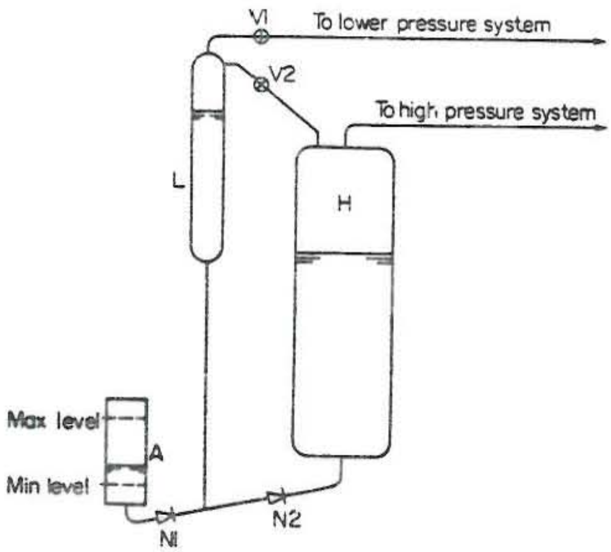
Sometimes, however, the configuration of a wet field may be such that steam transmission distances are very short. Although this would be fortunate in that the cost of steam pipework would be low, the beneficial scrubbing effect of long pipelines would largely be lost; for even if very little lagging were provided so as to increase the amount of condensation between traps, the trapping efficiency would be reduced if the traps were placed too close to one another. This is because turbulence occurs after each trap, and this requires a fair length of pipe in which to allow the suspended droplets to settle along the bottom of the pipe. If the spacing between traps is insufficient much of the suspended liquid is carried past the next trap instead of being removed. In these circumstances it may be necessary to install scrubbers between the pipelines and the turbines, unless a pipeline deviation should prove to be the cheaper alternative.

With hot water transmission, heat in fairly large quantities can be moved economically over some tens of kilometres. The reason for this difference between hot water and steam transmission is that the much higher density of water more than compensates for its lower enthalpy and for the lower permissible velocities through pipes: temperature drops of a fraction of 1°C/km can be achieved without excessive lagging costs. The transmission of hot water, however, requires far greater care than in the case of steam; that is, unless the water temperature is well below the boiling point corresponding to the pressure at which it is being transmitted. In wet fields, where the hot water is collected from wellhead separators and is to be transmitted over some distance to be flashed or otherwise used as the receiving end of a pipeline, care must be taken to prevent boiling from occuring at any point in the pipeline, as the formation of steam pockets and their subsequent collapse could cause dangerous and unpredictable pressure shocks that could perhaps rupture the pipe. It should be remembered that pressurised boiling water has explosive properties, and a burst pipe could have disastrous consequences - far worse than with a burst steam pipe at the same pressure. For example, a vessel containing water at 200°C in expanding to just above atmospheric pressure will have 12.3 times the capacity for doing work as the same vessel containing steam at the same temperature. For although the isentropic heat drop of the water is only 11.17% of that of the steam, its density is 110.11 times as great; and isentropic heat drop may be taken as a measure of capacity for doing mechanical work - i.e. of explosive capacity.

When transmitting pressurised boiling water it is therefore necessary to ensure that at no point in the pipeline is the hydraulic pressure permitted to fall below the vapour pressure. At the point of collection these two pressures are the same - namely the saturation pressure corresponding to the temperature; but as soon as pipe friction is incurred there will be a loss of hydraulic pressure. This can sometimes be made good by a gain in height head if the pipe runs down a sufficiently steep surface gradient; but over level ground, pipe friction will constantly tend to encroach upon any marginal excess that the hydraulic pressure may have over the vapour pressure. Apart from the pressure changes arising from gradients and friction, it is also necessary to allow for pressure change caused by acceleration or deceleration of flow resulting from the opening or closing of a valve at the receiving end of the pipeline. Valve closure will cause flow deceleration which, if not too sudden, will bring about a harmless pressure rise that will help to suppress any tendency to boil; but the opening of the valve will cause flow acceleration, and this will give rise to negative pressure surges that could result in the hydraulic pressure falling below the vapour pressure, with consequent boiling, unless suitable precautions are taken. The net effect of the combined influences of ground gradients, pipe friction and valve movement can so be controlled as to prevent boiling under all conditions by pressurising, by attemperation and by the careful avoidance of rapid valve movements. Pressurising can be effected by pumping. Valve movements can be controlled by means of a suitably devised mechanism. Attemperation is not so simple. It means the deliberate reduction of the water temperature, and therefore the vapour pressure, so as to increase the safety margin of hydraulic pressure for the suppression of boiling. Attemperation should be adopted only in certain circumstances. Obviously the injection of cold water would have the desired effect of avoiding boiling, but it would degrade the heat value of the transmitted hot water. What is permissible is to inject water at a lower temperature than that of the water primarily to be transmitted, but not less than the temperature at which flashing is to occur at the receiving end of the pipeline. Only in rare instances will water of the right temperature be available. At Wairakei, New Zealand, where there are two separate steam collection systems operating at widely different temperatures and pressures, it was possible to use the hot water issuing from the lower pressure bores for attemperating the hotter water from the high pressure bores, at the same time adding something to the quantity of useful transmitted energy; but a convenience of this sort is seldom likely to be available.

Unless an unnecessarily high pumping pressure is applied to a hot water transmission system it will seldom be possible to use vertical expansion loops, as the loss of pressure at the top of the loops might well be more than could be afforded: axial bellows pieces would be the preferable way of allowing for thermal expansion.

As a possible way of avoiding pumps for the transmission of hot water, with their attendant problems of maintenance and the use of special materials, I proposed many years ago a system of vapour pumping or, to use a less scientific but graphic term - "pumpless pumping". As far as I know this system has not yet been used; and as other methods of fluid transmission are now coming to the fore (as I shall later explain) it may never be used. Nevertheless, as it is just possible that it could still be of practical use, and not merely of academic interest, I shall now explain it.



The author's proposal for vapour-pumping (or 'pumpless' pumping) for imparting static head to a hot water transmission system.

A collection tank 'A' is provided at each well, while a static "head tank" 'H' serves a whole group of wells. Associated with each individual well is a lift cylinder 'L' connected as shown. The water level in the collection tank is allowed to rise and fall alternately between pre-designed maximum and minimum levels. When the level rises to its maximum height, a level-sensitive device opens a valve 'V_1', thus exposing the lift cylinder 'L' to a low pressure. Valve 'V_2' at this time is closed. The pressure in 'A' impels its content of hot water into the lift cylinder, passing on its way the non-return valve 'N_1', and the water level in 'A' will fall. As soon as the water in 'A' drops to the prescribed minimum level, a signal causes valve 'V_1' to close and valve 'V_2' to open, thus equalizing the pressure in 'L' and 'H' so that the water in 'L' will fall by gravity into 'H' through the nonreturn valve 'N_2'. Meanwhile, the collection tank starts to refill and the cycle is repeated indefinitely. At Wairakei, where two pressure systems were in operation, the intention was to connect the lift cylinder to the lower pressure system so that the vapour from 'L', though degraded in pressure, would still be conserved; but in general the atmosphere could serve in place of the lower pressure steam system, though at reduced efficiency. The head tank 'H' would just ride on the water trasmission pipe so as to provide a reasonable head for the suppression of boiling, and the vapour space in its upper part would be vented to the higher pressure steam system. The net effect of the assembly would be to raise, at every operation of the cycle, into the head tank without the use of pumps, a quantity of hot water equal to the capacity of 'A' between the maximum and minimum levels. Meanwhile, a similar cycle is operating with other wellhead collection tanks and their associated lift cylinders. Since the operation of the various control valves is actuated solely by water levels in the collection tanks, there is nothing to prevent a group of wells being connected to the same lift system even if they are at different ground levels. With pumping, differences of ground level would require different characteristics for each pump. Standard collection tanks could be provided for each well, and those wells having larger outputs of water would simply operate at a higher cycle frequency than those of low yield. The process would of course consume some steam, since energy is needed to raise the hot water: some would be discharged through valve 'V_1', some would condense on the cooler water surfaces, and some would flash off in the lifting cylinder. Although the equivalent expenditure of energy would be greater than with pumping, the extreme mechanical simplicity would make this well worthwhile. At Wairakei it was calculated that the steam losses of this system would amount to only about 1 1/2% of the transmitted energy in the hot water - a very cheap price to pay for mechanical simplicity.

At Wairakei, an experimental hot water transmission system was established in 1963 primarily to transmit the bore water from a group of high pressure wells to the power station, where it was flashed twice consecutively to produce lower pressure steam for passing through turbines. Some of the bore water from lower pressure wells was injected so as to achieve attemperation. All the water was pressurised by pumping it into a head tank which provided a net margin of about 40 feet over the saturation pressure at the high pressure wells. The water level in the tank was allowed to fluctuate so as to stabilise the pumps, absorb changes of bore water yields and act as a means of controlling the position of the valve admitting the hot water into the flash vessels, thus regulating the flow to match the yield of bore water.

Hot water transmission is cheaper than high pressure steam transmission, which in turn is cheaper than low pressure steam transmission. But in claiming cheapness for hot water transmission I refer to the pipework alone; by the time that the costs of the terminal works have been added - i.e. pumps, head tank, controls and scrubbers - hot water transmission can sometimes be relatively expensive, except over long distances (more than about 3 or 4 km) where the proportion of the costs of the terminal works to those of the actual pipeline becomes relatively small. In wet fields it is possible to avoid the transmission of hot water while still deriving some partial benefit from its energy content, by flashing at the wellhead and transmitting the low pressure steam to the utilization plant; but this is seldom commercially attractive because of the high cost of low pressure steam transmission. However, it has been done at Wairakei because of the existence of two separate steam transmission systems serving two different groups of wells. Hot water from the higher pressure bores is flashed near the wells into the lower pressure steam pipe system. If this lower pressure system did not exist, it would almost certainly not have been worth constructing one for the purpose.

Until now I have treated the transmission of steam and of hot bore water as two separate procedures, each with its own problems. It had been obvious for many years that if the two fluid phases from wet bores - hot water and steam - could be transmitted together through a single pipe instead of two, great mechanical simplification would have resulted. No wellhead equipment would have been necessary other than an emergency bypass and silencer, suitable valving and some very simple instrumentation.

Wellhead separators would have become superfluous and the whole bore outputs, both water and steam, could have been transmitted through a single pipe to the utilization plant from a group of wells. On arrival at the receiving end, the two phases could be separated in a single, or very few, large separator(s) which would cost far less than a big number of individual wellhead separators with their associated pipework, owing to the scale factor, and which could be more easily and cheaply maintained at a place close to the main plant than if scattered around the field in remote situations. However, engineers were apprehensive about the risk of water-hammer. In a steam pipe, an excess of water can cause dangerous water-hammer: in a hot water pipe the presence of steam can cause water-hammer. It seemed that each fluid jealously required its own pipe without the presence of the other, and it was thought that a pipe containing a water/steam mixture must certainly be subject to very severe water-hammer. Then a puzzling thought arose. Do not water/steam mixtures travel up bores and through short lengths of pipework at the wellheads, before separation, without noticeable evidence of water-hammer? Why then, should it not be possible to bend a bore from the vertical into a more or less horizontal position and extend it overground all the way to the utilization plant? Could not the bore and the surface transmission pipe become one and the same tube? Tests were carried out in New Zealand and Japan, and it was discovered that this was, in fact, perfectly possible. Although some vibration occurred at times, the transmission of steam and water in a single pipe was feasible, without noticeable water-hammer. The explanation of this rather surprising discovery seems to be that two-phase fluid flow, between certain maximum and minimum proportions of water to steam, is of the annular pattern, where the water mainly clings to the pipe walls and the steam passes through the middle - each interfering but little with the other. With slightly wet steam the water tends to flow in a channel along the bottom of the pipe, and there is a risk that sometimes it may be swept up by the faster flowing steam and thrown in gulps, like projectiles, against the downstream pipework, thus causing water-hammer. Occasional steam formed in hot water pipes occurs in large bubbles along the top of the pipe, and their collapse causes the displacing water to strike the roof of the pipe very forcibly - again giving rise to water-hammer. But with a wide range of mixtures of the two fluids, between extreme limits, such as are yielded by wet bores, the two fluids seem to be capable of flowing in harmony by adopting, to a large extent, the annular pattern. Whether these theories can be mathematically substantiated I do not know: the important thing is that two-phase flow is possible. A possible explanation which I tentatively put forward, but without firm conviction, is that with a small quantity of water in a steam pipe, flowing along the bottom, the ratio of mean depth to surface area is very small at the edges of the channel. These edges would therefore offer little resistance to being blown away by a wind of fast-moving steam. Their removal would be replaced by the re-spreading of the surface, and in this way the whole channel would soon be swept along with the steam in "gulps". With annular flow, there would be no such edges at which this process could be focussed.

The discovery that two-phase fluid transmission was practicable was important. This form of transmission is now being adopted as standard practice in the newer Japanese power plants served by wet fields, and I have now seen it in operation here in Iceland: it will probably become common practice elsewhere in the world. Since my arrival in Iceland I have been interested to see that two-phase flow pipes are being used at Svartsengi and Hveragerdi: I hear also that this form of transmission is being adopted at Krafla. The rather higher pressure drops incurred necessitate larger pipework than for dry steam, but the cost of this is more than offset by the savings effected in wellhead equipment and in separate hot water transmission systems. Two-phase flow pipes can also negotiate moderate uphill gradients. The relative levels of different bores would be of no consequence, and mixed fluids discharged from several bores may be merged into a single main pipeline. The simplified field equipment would also provide an aesthetic gain by comparison with large numbers individual and complex wellhead equipments.

The ultimate in bore fluid transmission would be to pressurise the fluid so that it may be transmitted all the way from the aquifer to the point of use as water. This has long been recognized as an ideal, preferable even to two-phase flow; for it would enable much smaller pipes to be used and it would neatly side-step every conceivable occasion for water-hammer. No separation would be needed except that which occurs in flash vessels if steam is needed for power generation; and these vessels could be placed close to the power plant, supported by scrubbers. To achieve pressurized flow, a down-hole submersible pump is needed in each bore;

for in water-dominated fields flashing occurs before the fluid has risen far up the bore. The pump would therefore have to be positioned just below the depth at which flashing naturally occurs, so as to ensure that the fluid is preserved in the form of water throughout its journey from the aquifer to the point of use.

Only five years ago the submersible pump was little more than a dream; (I do not refer to downhole pumps for moderate temperatures used for direct heat application, such as are in service here in Reykjavík, but to those for high temperature bores in "wet" fields used for power generation) but certain manufacturers declared that they were on the point of producing one. Now, three types of submersible pump are available on the market; some of which claim to be able to work reliably at temperatures of 300 or even 350°C. These temperatures are equivalent to saturated pressures of 1230 and 2380 psig respectively. It would, I think, be too early to claim that any of these pumps can yet be regarded as a standard product assured of trouble-free operation. Each type is susceptible to its own peculiar sources of potential trouble; but it should be remembered that I am talking of new products. There is no reason to suppose that one or all of these three types of pump should not soon be perfected to a high degree of reliability. This would virtually provide the best and ultimate solution of the problem of transmitting hot bore fluids. The three types of pump, and their "heels of Achilles", are as follows: -

1) Line-shaft pumps with electric driving motor at ground level, a long torque-shaft descending the bore and a submerged multi-stage pump as far down the bore as may be necessary. This type of pump's vulnerability lies in the need to support the long line-shaft with bearings at intervals of about 5 ft. to prevent the shaft from whipping. Lubrication and maintenance of these bearings can be troublesome.

11) Submersible electric pumps, in which the driving motor is directly coupled to the pump and placed deep down the well. This, of course, overcomes the need for a line shaft and bearings, but the difficulty is in producing a reliable motor with efficient sealing against the ingress of bore fluid and with insulation capable of withstanding

the high temperatures to which it is subjected. The cost of this type of pump is something like half that of the line-shaft pump.

iii) Turbine-driven pumps, consisting of a down-hole direct-coupled turbine and pump unit. The turbine may be driven by steam or by a binary fluid. With a steam turbine a separate water supply has to be led down the bore to a heat-exchanger that collects bore heat to generate the steam: its exhaust is led up the bore to atmosphere. With a binary fluid turbine it would be necessary to pipe the exhaust vapour to a surface level condenser before returning, as liquid, down the bore to be reheated into vapour at high pressure. This type of pump is the most expensive of the three, but it could perhaps prove to be the most reliable.

I confidently expect that down-hole pumping and pressurised hot water transmission will ultimately take the place of all other forms of geothermal fluid transmission in wet fields. Another advantage of the down-hole pump is that it would enable varying quantities of fluid to be extracted from a bore instead, as at present, of having to keep the flow fairly constant in order to avoid well instability. This would enable a geothermal power plant to follow demand variations as they occur, rather than being compelled to operate on base load. I referred to this aspect of pressurized transmission in my third lecture.

After the technical problems of transmitting bore fluids it would seem logical to pass on to the problems of their disposal. With dry fields the bulk of the used steam, where power generation is concerned, passes as vapour into the atmosphere by way of the cooling towers, or into a river where direct cooling is adopted. With cooling towers, the quantity of turbine exhaust is rather greater than the amount of vapour emitted; so a small surplus of somewhat impure liquid has to be disposed of. Also, where chemical treatment is used for reducing the emission of pollutive substances, there will be an unwanted effluent. In wet fields there is a much bigger problem, for enormous quantities of hot water accompany the steam; and even if the hot water is flashed to produce a power increment, there will still be a very large residual quantity of water - probably at or near 100°C. Ideally it would be desirable to extract as much heat as possible from this water for some useful application; but whether or not this is done, a large mass of water will remain. Thus, both in dry and wet hyperthermal fields, waters of various qualities and grades will have to be disposed of. What can be done with this water? In my first lecture I mentioned the possibility of gaining some incremental power by means of hydro turbines where a geothermal field is suitably sited at a high level above the sea; but although this is better than nothing it is by no means always practicable, and in any case it would do nothing to solve the problem referred to in my second lecture - namely, ground subsidence that can result from the continuous removal of huge quantities of underground waters. Clearly it would be better to reinject all unwanted waters into the aquifer, if possible, surrendering any hydro power dividend that could perhaps be gained in a few instances, but thereby mitigating the subsidence problem. In all fields reinjection would provide a convenient way of solving, at a stroke, problems of heat pollution, water-borne posions, the disposal of noxious chemical effluents from gas abatement plants, much of the noise problem, fog, scenery spoliation and ecological imbalance. The reasons for including noise, fog and scenery spoliation in this list of benefits is that in wet fields most of the noise usually comes from the discharge of high temperature bore water to waste; and this discharge is the greatest contributor to fog, while the presence of large numbers of silencers (which are only <u>partially</u> successful in suppressing noise) is generally regarded as unsightly.

Reinjection could therefore provide a comprehensive solution to several problems. At Wairakei, where the first large scale development of a wet field took place, reinjection was debated some 20 years or more ago:, but anxieties were felt for several reasons. Would the permeability of the formation at the base of a reinjection bore be sufficient for the acceptance of huge quantities of water without incurring pumping losses? Would the silica, which is present to saturation in the Wairakei bore water, precipitate on the walls of a reinjection bore and within the interstices of the underground formation to an extent that would necessitate the frequent abandonment of reinjection bores and the sinking of new ones? Above all, would the introduction of <u>relatively</u> cool waters into the aquifer adversely affect the quantity and quality of the production bores? Because of all these uncertainties it was decided <u>not</u> to reinject; and for many years the unwanted bore water has been discharged into the river. It is true that about 2 1/2 MWe of continuous base load power was gained thereby from augmented hydro power, but this has been at the expense of heavy ground subsidence - which might have been serious, though in fact it did scarcely any harm - and a certain amount of river pollution, though fortunately not on any disastrous scale. At Cerro Prieto, México, they just spilled the unwanted water onto the ground to form a huge evaporation lagoon. As the ground there was more or less desert land, the method was cheap; but it caused fog problems, and in the course of time there will be a huge salt deposit there.

By the end of the 1960s and in the early 1970s other wet fields were being exploited in El Salvador and Japan. In El Salvador there was a particularly acute problem to which I referred in my first lecture, that the bore water contained contaminants (particularly boron) which made it most undesirable that the water should be discharged into the natural water courses. Reinjection experiments were carried out both in Japan and in El Salvador; also in California where the quantities of impure water were not so great, as the field produced dry steam, but where the legal enforcement of pollution constraints made it urgently necessary to solve the water disposal problem. It was soon found that fears about the ability of an aquifer to accept great quantities of water without large pumping efforts were not justified: a gravity feed is usually sufficient. More recently, further reinjection experiments have been performed in New Zealand; and here too pumping is seldom required. As to the risk of silica precipitation, it has been observed in New Zealand that if the bore water is denied contact with the air, and if the temperature is maintained at a reasonably high level - say, 150°C - no silica deposition in the reinjection pipework is experienced. More surprisingly, the acceptance permeability of the aquifer to the reinjected water has actually shown a marked increase with the passing of time. This could be due to the cracking of the formation on contact with relatively cooler water, or perhaps to the negative buoyancy of this cooler water causing its rapid removal from the point of reinjection, or even to the conversion of a two-phase zone round the base of a reinjection bore to a single phase zone. Whatever the cause, reinjection has actually improved the permeability of the formation at the point of reinjection. This would certainly suggest that no fears need be entertained of silica deposition belowground which might necessitate the frequent abandonment of reinjection bore sites. Moreover, the well known ability of silica to remain in a state of super-saturated solution is apparently ensuring that no silica precipitation is occurring before the fluid enters the aquifer, where the higher temperature will restore the solution to a state of normal saturation.

Chemical treatment has also been tried in New Zealand for the removal of silica, by dosing the bore water with slaked lime to precipitate calcium silicate. It has been found that in the presence of air, less lime dosage is required if the bore water is allowed to "age" for a few hours, rather than if it is treated "fresh". So "aging tanks" were provided to hold up, or delay, the water before treatment, and settling tanks were provided for the collection of the precipitated calcium silicate. This treatment has been found effective in removing the silica, but it is rather expensive in itself, and it furthermore creates a new problem in the disposal of huge quantities of silicate sludge. Enquiries are being made to discover whether this substance could have any commercial value, but it seems doubtful if it could ever bear the costs of removal and transport to the nearest market, even if such a market were to be found.

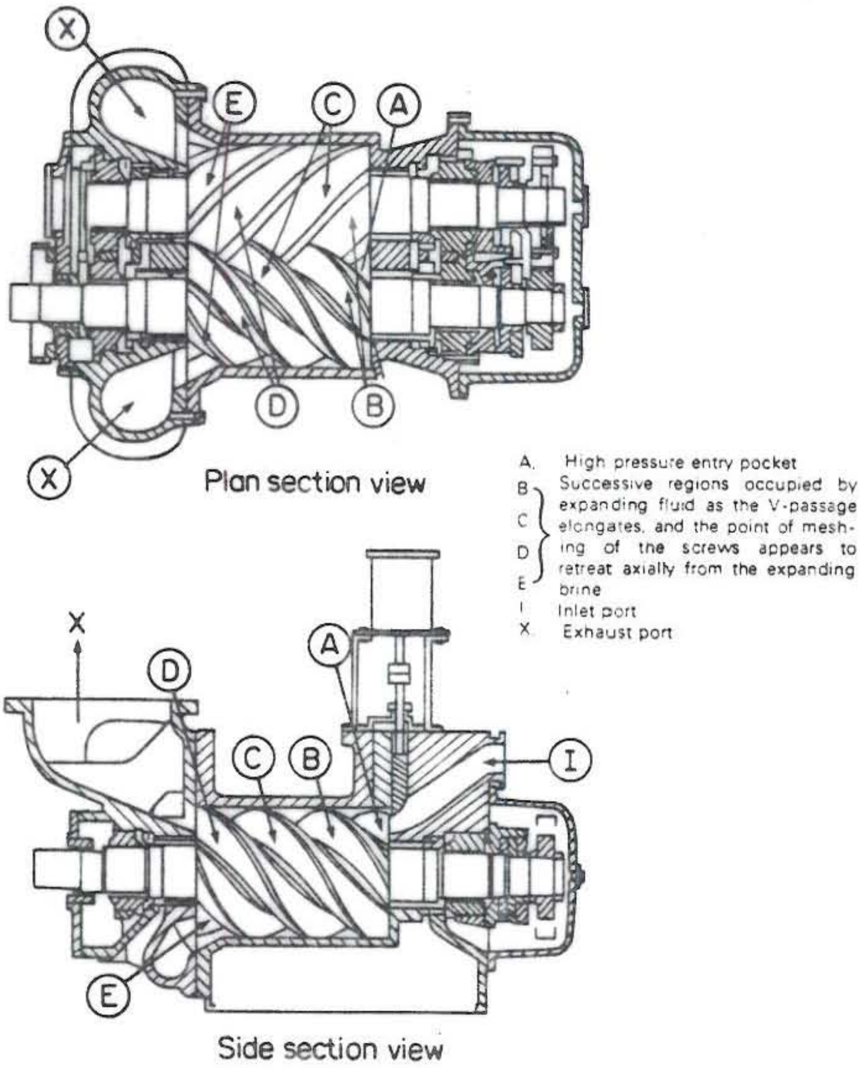
Thus it would seem from New Zealand experience to date that immediate, hot, reinjection is preferable to chemical treatment. However, experimentation in New Zealand continues; and it would be rash to argue that what is possible and advisable in one field will necessarily be suitable for others: the chemistry of bore waters can differ considerably from field to field. No trouble has been reported of silica deposition in reinjection wells in the Geysers field, but of course the quantities to be reinjected in a dry steam field are very much less. I have no recent news of reinjection experience in El Salvador or in Japan.

As to interference by the reinjected water on the production bores, this has not yet been noted in New Zealand even though the two classes of bore chosen for experiment were close to one another, and even though tracer isotopes did show as much as 14% re-appearance of reinjected water from a production bore. Obviously it would be unwise to reinject close to production bores, as interference would undoubtedly be observed after some time; but if reinjection bores are sited with care, the field performance could probably be improved by well planned reinjection. This is where the expertise of the hydrogeologist is needed; for he must predict the underground flow patterns sufficiently well to ensure that there will be no short-circuiting between the relatively cool reinjected water and the production bores. The removal of fluids from a hydrothermal field must always cause the inflow of external waters from beyond the confines of the field to replace that which has been removed. Normally this replacement water will be cool, as it will have originated from meteoric waters falling upon some permeable replenishment area connected with the aquifer through underground voids, fissures and porous rock formations. This inflowing cool water encounters the hot rock, from the interstices of which the original hot fluid has been removed by exploitation, and is heated up thereby - but not to the original temperature, because of the cooling effect of the replacement waters. In this way the quality of a field must slowly decline with exploitation until its temperature falls too low to justify further exploitation. The life of such a field will of course depend on the capacity of the original hot aquifer and the rate of exploitation. But if we return to the aquifer the reinjected bore water which, though less hot than the original fluid yielded by the production bores is nevertheless fairly hot - at any rate by comparison with inflowing cool meteoric waters; and if we ensure that reinjection is effected near the periphery of the field close to where inflowing meteoric replacement waters would be expected to flow under natural conditions, and not in the heart of the production area, then clearly the rate of temperature decline of the aquifer should be less than if replenishment were from cool waters only. Thus, judicious reinjection could actually prolong the life of a hydrothermal field. It would act somewhat in the capacity of "boiler feed" in a conventional thermal power station. Moreover, the reinjection of fairly hot bore water would lessen, though not remove, the economic desirability of adopting the flashing process to gain some incremental power from lower pressure flash steam, or of finding some other useful application for the heat content of the bore water. Instead of an immediate dividend from the hot water, reinjection would be earning a future dividend in the form of prolonged field life.

It is now becoming normal practice to reinject bore water in wet fields, either with or without flashing first: also to reinject all effluents and surplus cooling tower water.

I now come to the question of making the most profitable use of the hot water that issues from wet fields. We can of course reinject it into the ground as an investment in the future; but there is a general commercial principle to the effect that it is preferable to extract the maximum immediate use from an investment so as to get the highest and quickest return on the money spent. Future dividends are certainly better than nothing, but present dividends are still better. As an alternative to reinjection we can, in theory, use the water for district heating, farming, industry or other non-power purpose; and if our best efforts to find a heat market for any of these purposes should fail, then we can perhaps flash the water in one or two stages to produce steam at lower pressure(s) with which to generate a moderate amount of supplementary power. Power from flash steam can be commercially worthwhile, but it is not so economically attractive as power from the bore steam at higher pressure and temperature. This is partly because of the poor efficiency of low pressure power generation; partly because of the rather high cost of flash vessels and scrubbers; and partly because the capital cost of low pressure turbines, or augmented low pressure stages of mixed pressure turbines, is intrinsically greater than that of high pressure turbines. Even if we flash the bore water for supplementary power generation, we are still left with large quantities of residual hot water - probably at or near atmospheric boiling point - but this could be reinjected if no non-power use can be found for it.

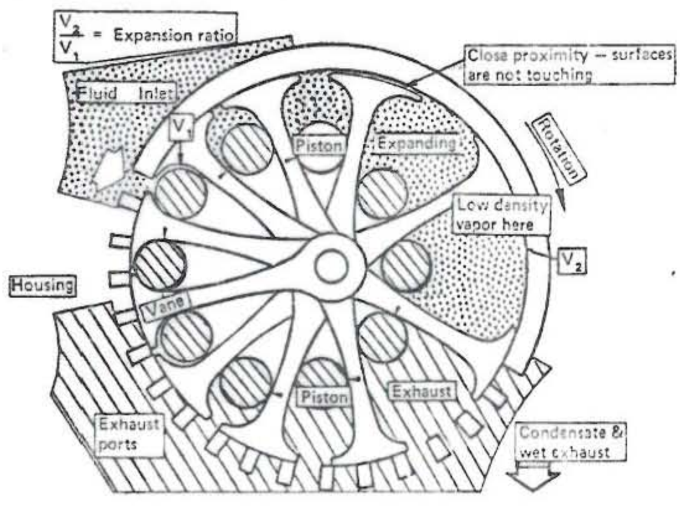
Considerations of this sort led to the concept of the total flow heat engine, that could make the greatest possible use of the steam and the hot water yielded by the bores in a wet hyperthermal field. One interpretation of this idea is to pass the whole of the bore fluid - water and steam - through a heat-exchanger to energize a binary fluid capable of extracting far more heat from the bore fluid than would be possible with flash generation; thus enabling the expended bore fluid to be rejected at a much lower temperature. (In this case, of course, although the unwanted water could be disposed of by reinjection, the thermal gain of prolonged field life would of course be lost). This, however, is not a true total flow heat engine, the object of which is to extract energy directly from the two phases of the bore fluid as they pass through the engine itself. Positive displacement heat engines can do this. One such is the Sprankle double helical machine, which is virtually a helical compressor operated in reverse. The bore fluid, in passing from the entry through helical passages to a vacuum exhaust,



The Sprankle (Hydrothermal Power Company) double helical hot brine expander. (From H.P.C. Brochure.)

undergoes a continuous reduction of pressure and temperature so that flashing occurs, and the fluid exerts a pressure on the helical vanes and produces a rotary motion. I have seen one of these machines in operation, but I have not yet seen any test results; so I cannot quote its thermal efficiency or say how its costs or its power/weight ratio compare with other prime movers. Probably the best application for this machine would be for the extraction of power from boiling brines, such as are to be found in the Imperial Valley in South California.

Other positive displacement heat engines are the Robertson engine and the KROV (Keller Rotary Oscillating Vane) engine. The latter is a somewhat fanciful assembly of pistons, radial arms and ports, as shown in the illustration.



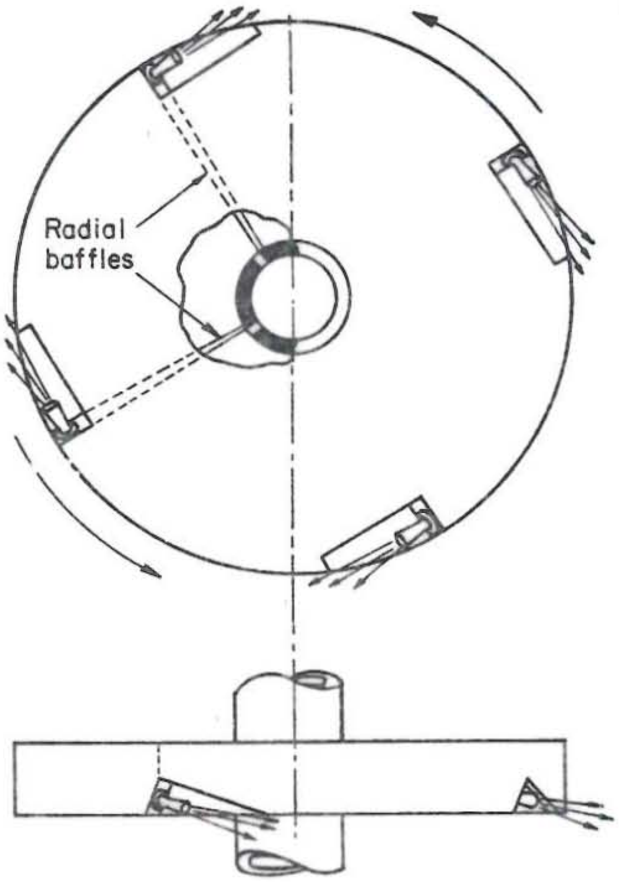
Diagrammatic representation of the KROV (Keller rotor oscillating vane) positive displacement machine.

Proposals for applying the total flow concept to turbines, which of course are not positive displacement heat engines, have also been made. One such is the bladeless turbine, which consists of an assembly of metal discs mounted on a hollow shaft, with narrow spaces between the discs. A water/steam mixture is admitted to these spaces from the periphery and directed in a spiral inward flow towards the central exhaust ports in the hollow shaft. The driving force is derived from frictional boundary layer drag between the fluid and the disc surfaces. Cheapness of construction would be an advantage, but the efficiency would be very poor. Another version of the total flow turbine is simply an axial flow impulse turbine, onto the blades of which impinge a jet of water/steam mixture expanding through a nozzle. Rather surprisingly, this concept has received considerable financial support from the Lawrence Livermore Laboratory of the University of California. I say "surprisingly" because, in my opinion, both it and the bladeless turbine are based on a fallacious principle. All heat turbines derive their power from the kinetic energy of a fluid subjected to a heat drop. Ideally a fluid jet attains maximum velocity, and therefore maximum kinetic energy, if expanded isentropically; and the formula for the ideal jet velocity thus approached is ...

$v = 91.4 \sqrt{\Delta H}$, where 'v' is the jet velocity in metres/sec., and 'ΔH' is the heat drop in cal/gram.

For a given temperature drop across a nozzle, the value of 'ΔH' will be far greater for steam than for boiling water. Hence the ideal velocities of the two fluids will differ widely. For example, in expanding through a nozzle from 149°C (300°F) to 101°C (214°F), 'ΔH' would be 60.17 and 3.03 cal/g for steam and boiling water respectively. The corresponding jet velocities would be 709 and 159 m/s for steam and boiling water respectively. Now the blade of an impulse turbine cannot move at a speed to suit two widely differing velocities simultaneously. Moreover, the relative movement of the steam to the water would induce a drag of (709-159), or 550 m/s, which would be dissipated in friction; and that could only lead to a loss of efficiency. If the water were finely atomised, the two fluids would soon attain the same velocity, at a value equal to their combined momenta divided by their combined mass. For example, a 4 : 1 water/steam mixture (mass ratio) would attain an equalised fluid velocity of 269 m/s. Now the kinetic energy of the steam and water expanding separately would be 66.9% greater (in this example) than that of the mixture travelling at the equalised velocity: so even the ideal nozzle efficiency could only be 1/1.669, or about 60%. A reaction turbine would not solve the difficulty, for if the rotating blades moved at a speed suited to the steam jet velocitiy they would be moving too fast for the water; and the acceleration of the water to the higher velocity would act as a brake on the reaction force from the steam. The same inherent inefficiency would apply to the bladeless turbine, disregarding the mechanical inefficiency of the machine. Basically, the fallacy of the total flow turbine as conceived in either proposal, is that the expansion of a water/steam mixture could never be isentropic, or anywhere near isentropic. In the wet range of a conventional steam turbine at the low pressure stages, where the wetness factor might be a few percent, this inherent inefficiency is still present, but to a far lesser degree because of the very small proportion of water.

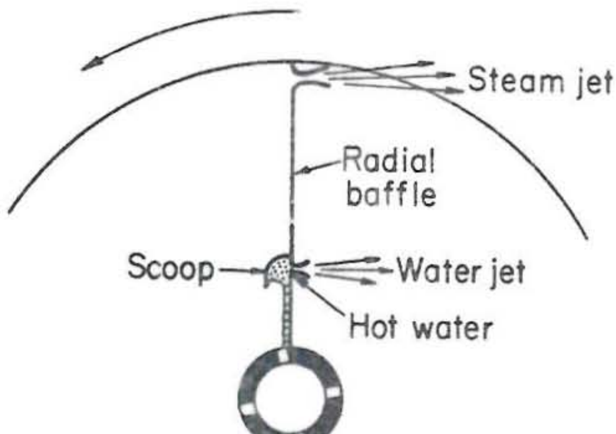
In an attempt to overcome this defect, I myself once proposed a very simple and cheap turbine based on the 2,000-year old Hero principle, in which the two fluids are separated by the motion of the rotor and the inertia of the water, and each is discharged at a radius appropriate to its ideal jet velocity. The machine would certainly not be efficient, but it would be extremely cheap, and could serve as a mobile pilot unit for recovering some energy from newly blown bores in a field while it is under development. If the water were not intercepted at a point part-way out from the axle, it would have a retarding effect due to the acceleration necessary to force the water to the perimeter of the rotor, there to be discharged through the peripheral steam nozzle.



Hero engine: disc rotor with four recessed nozzles, for use with dry steam.

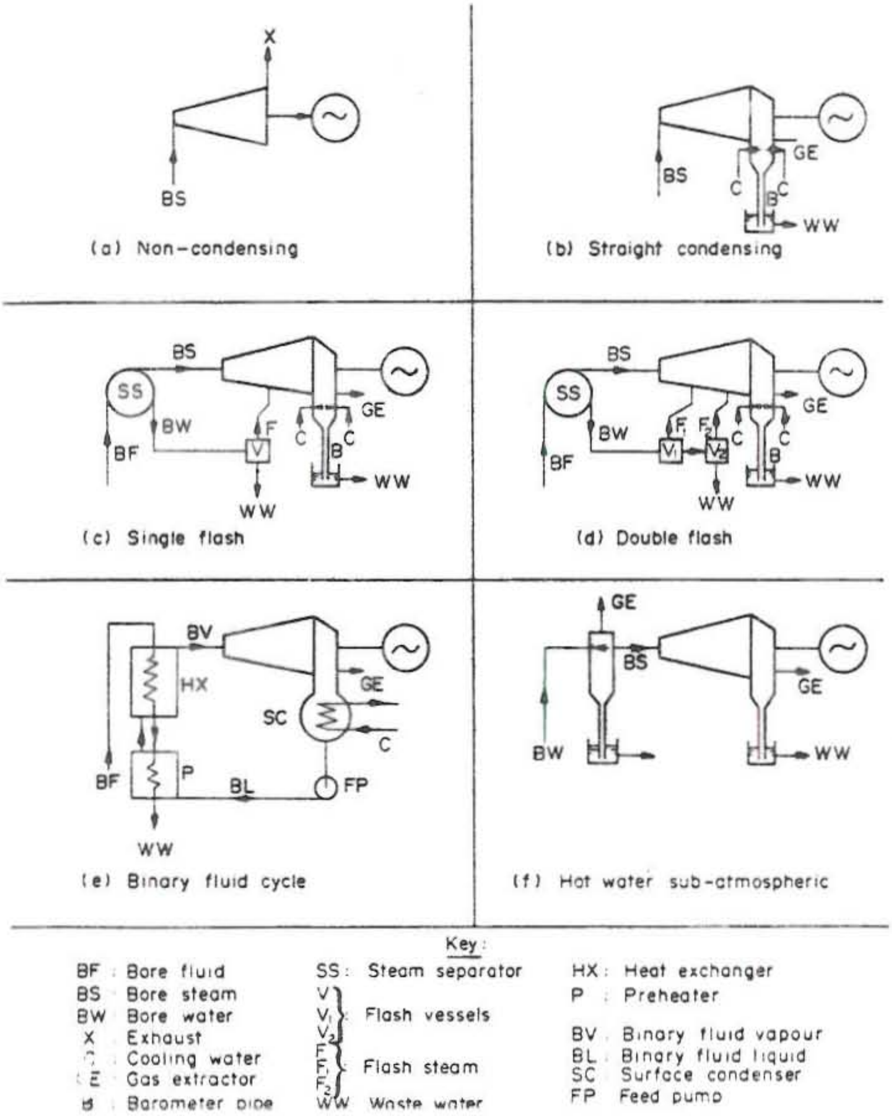
Let me explain this in greater detail. The rotor would be a simple flat hollow cylinder mounted on a hollow shaft. The fluid mixture would be admitted to the rotor through this shaft, and the steam would be ejected through nozzles at the periphery, raked at a slight angle so as to impart an axial component to the discharge velocity in order to remove the exhaust steam away from the rotor along an axial cowling (not shown). The inertia of the water would cause it to cling to the sides of radial baffles, and a scoop would prevent the water from travelling more than a fraction of the radial distance. The water would be discharged through bell-mouthed orifices, which have the well known property of allowing a wide range of discharge flows without flooding on the one hand, or the loss of seal on the other hand. Jets could be replaceable to allow for different flow rates and flow proportions. The ideal speed would be when the nozzle velocities are almost the same as the fluid jet velocities. If everything were perfectly adjusted, the fluids would just "drop out" of the rotor with no tangential velocity at all - the whole of their kinetic energy having been expended. A run-away speed at no load would be twice the ideal speed; and governing would be necessary to prevent this from being attained, and the rotor from bursting.

Here engine adapted for use with wet steam.



Suggested arrangement for water separation within a Hero turbine, and for the separate discharge of steam and hot water through differently placed nozzles.

I have mentioned binary cycles for power generation. In its simplest form the binary cycle is as shown in diagram (e) of the accompanying figure. The bore fluid is used to heat a refrigerant fluid having a very low boiling point and a high vapour density - e.g. isobutane, propane, and freons - in a closed cycle embodying a pre-heater, boiler, turbine and feed-pump. The theoretical advantages of the binary cycle are: -



<u>GEOTHERMAL POWER GENERATION CYCLES</u>

a) Non-condensing

b) Straight condensing

c) Single flash

d) Double flash

e) Binary fluid cycle

f) Hot water sub-atmospheric

i) It enables more heat to be extracted from geothermal fluids by rejecting them at a lower temperature.

ii) It can make use of geothermal fluids that occur at much lower temperatures than would be economic for flash utilisation.

iii) It uses higher vapour pressures that enable a very compact self-starting turbine to be used, and avoids the occurence of sub-atmospheric pressures at any point in the cycle.

iv) It confines chemical problems to the heat-exchanger alone.

v) It enables use to be made of geothermal fluids that are chemically hostile or that contain high proportions of non-condensible gases.

vi) It can accept water/steam mixtures without separation.

There are, however, the following disadvantages: -

a) It necessitates the use of heat-exchangers which are costly, wasteful in temperature drop and can be the focus of scaling.

b) It requires costly surface condensers instead of the cheaper jet type condenser that can usually be used when steam is the working fluid.

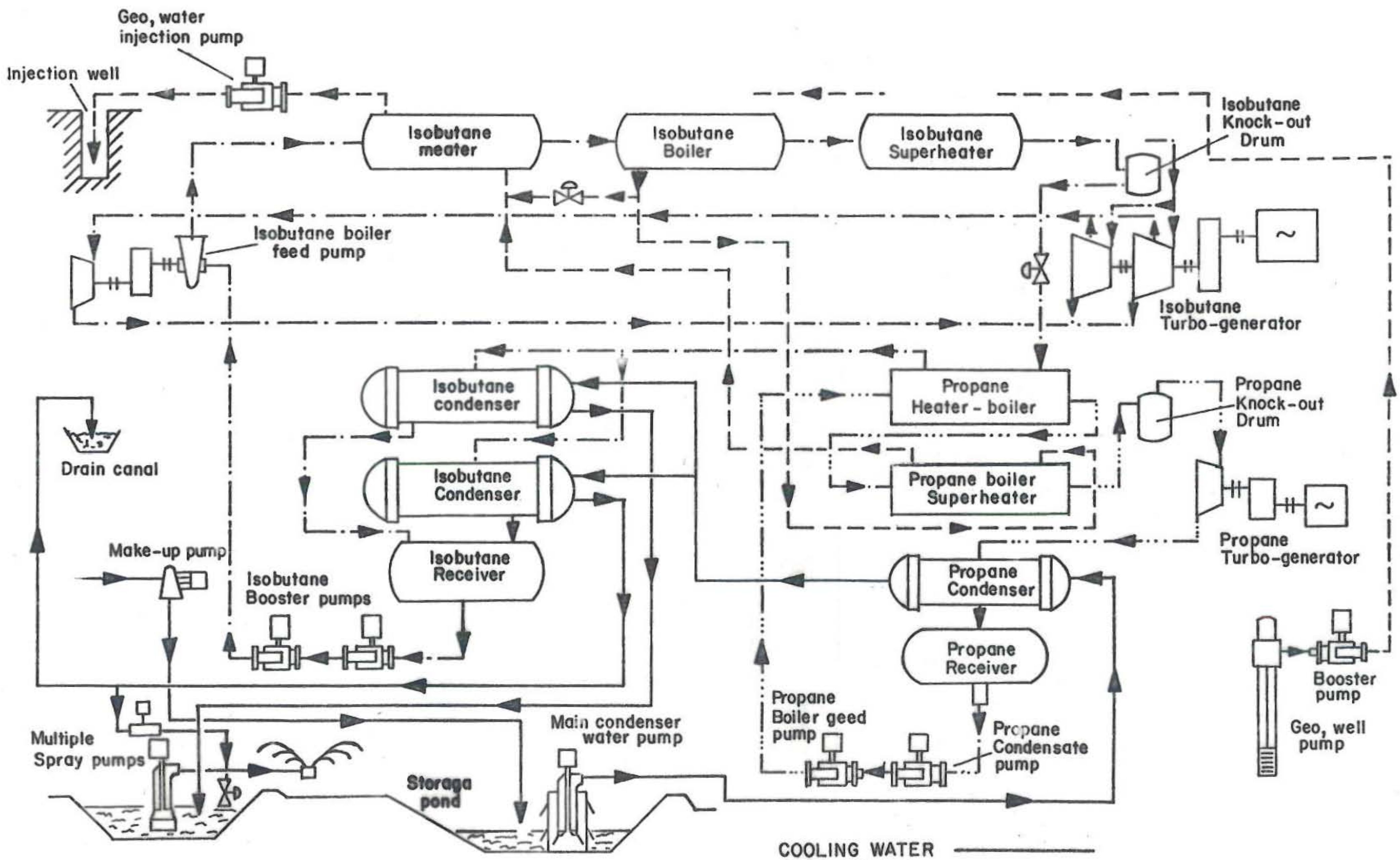
c) It needs a feed-pump, which costs money and absorbs quite a lot of generated power.

d) Binary fluids are expensive, volatile and sometimes toxic, and must be very carefully contained by sealing.

e) Makers are generally inexperienced, and high development costs are likely to be reflected in high plant prices - at any rate unless and until the cycle becomes commonly adopted in practice.

The disadvantage that necessitated the introduction of rather costly heat-exchangers and the acceptance of an inevitable and wasteful temperature drop across them has now been largely overcome by the advent of the direct contact heat-exchanger, in which the primary and binary fluids, being immiscible, are brought into intimate contact in a tubeless chamber. The binary cycle has not hitherto enjoyed very much support from geothermal developers, but this innovation could well boost its popularity. There is one very interesting and novel binary cycle plant that has recently been commissioned in the Imperial Valley in South California, where the extremely high salinity of the bore fluids make them very difficult for direct use. This plant, owned by the Magma Power Company, makes use of a dual binary cycle, as illustrated in the accompanying diagram. It uses bore water, isobutane, propane and cooling water in consecutive loops in which heat is transferred, with a falling temperature, from one loop to the next. It will be noted that the use of a submersible pump ensures the delivery of the hot bore fluid in liquid form to the plant, without the generation of steam at any point. After yielding its heat, the cooled bore water is reinjected into the ground. There are two turbo-alternators. The main unit is of 10 MWe capacity and is driven by isobutane. The secondary unit is of 2 1/2 MWe capacity and is driven by propane. The secondary unit is sufficient to supply all the auxiliaries, so that the full 10 MWe of the main turbo-set are available for net electrical output. The isobutane boiler feed-pump is driven by intermediate pressure isobutane bled from part-way down the main turbine. Both binary fluids are heated in boilers and superheaters, consecutively.

There is another innovation which, strictly speaking, is not a purely geothermal matter, but is closely related thereto; for it could be used in conjunction with combined heat and power co-generation projects. I refer to the possibility of heat storage within hot aquifers. It is of course well known that the availability of large scale thermal storage capacity would greatly help the economics of co-generation projects by providing means of correcting the mis-match of supply and demand arising from diurnal and seasonal load fluctuations. Hot water not required at times of light load would simply be discharged into a suitable aquifer and withdrawn from it at times of high demand. Obviously the practice could only be applied where a suitable aquifer within the right tempera-



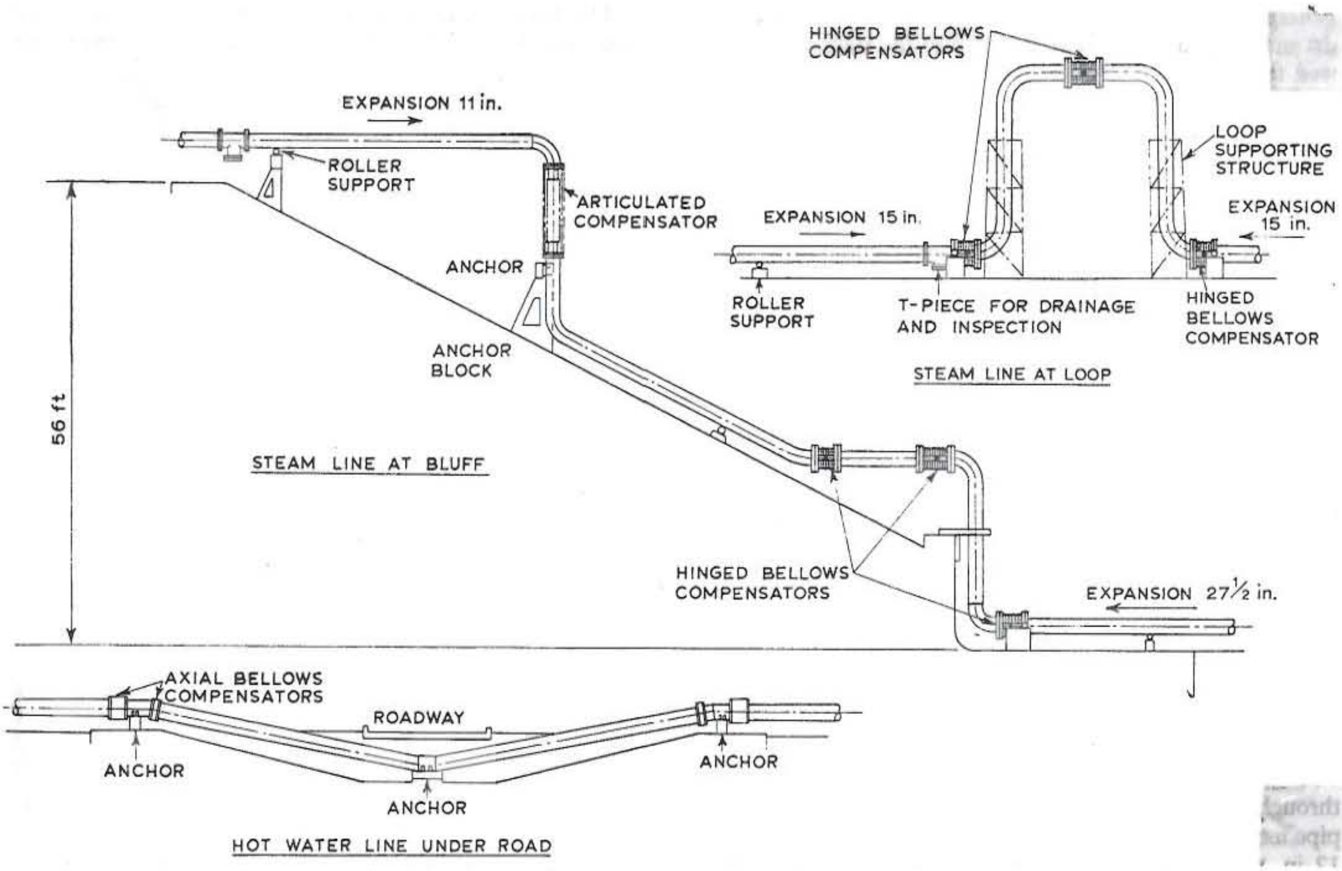
MAGMA POWER COMPANY'S

DUAL BINARY CYCLE

ture range is to be found close to a load centre; but there could be occasions where the principle could be applied to great advantage. I do not know of any operating examples of this principle, but the idea has been the subject of experiment and perhaps it could have quite a promising future.

There are many other points of engineering interest on which I could perhaps have spoken - such as methods of pressure and flow control, pipe expansion arrangements, directional drilling, the adaptation of geothermal heat for feed-heating in conventional thermal power plants to name but a few - but time is pressing and I think I have raised enough problems for one occasion. There are doubtless many very interesting problems associated with district heating, but I would not dare to speak of these in Iceland, where probably more is known about such matters than anywhere else in the world.

The lecturer showed some slides to illustrate the various methods used at Wairakei, New Zealand, to allow for pipe expansion, some of which are shown in the accompanying sketch. He stated that when assembling a pipeline cold, half the total movement was taken up in initial tension, so that under hot conditions an equal and opposite compressive stress would result.



USE OF BELLOWS COMPENSATORS FOR ABSORBING PIPE EXPANSION MOVEMENTS

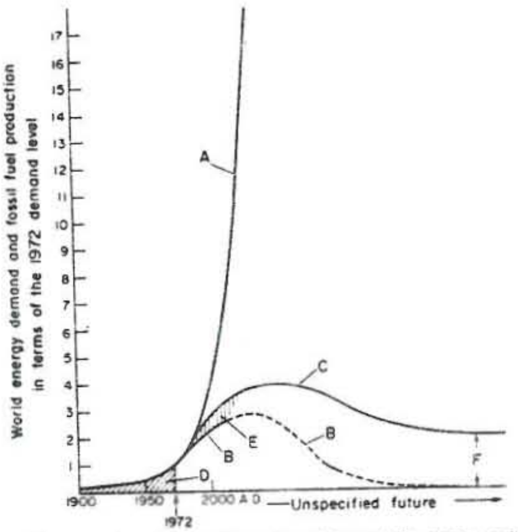
AT WAIRAKEI, NEW ZEALND.

(Haldane & Armstead. p.605, Proc. Instn. Mech. Engs., 1962, Vol.176, No. 23)

LECTURE FIVE

FUTURE GEOTHERMAL PROSPECTS: HEAT-MINING

In the first 73 years of this century the world's annual rate of primary energy consumption rose by a factor of 11.15 times. This represents a mean annual compound growth rate of 3.35%; but whereas the mean growth rate in the first half century was 2.56% it had doubled to 5.12% over the next 23 years, 1950-1973. Energy demand had, in fact, been growing hyper-exponentially. Clearly this escalation could not have lasted indefinitely. Nevertheless until 1973 no real difficulty had been experienced in matching energy supplies with demands. This fantastic expansion was partly due to a 2.7-fold rise in world population, but was more attributable to the fact that the energy consumption per capita had more than quadrupled during the 73 years (1900- 1973) as a result of higher living standards and increasing industrialisation.



Key:
A: actual world supply and demand for energy up to 1972, and the extrapolated future demand assuming 5% annual exponential growth.
B: probable shape (not to scale) of future fossil fuel production
C: probable shape (not to scale) of future world energy demand if disaster is to be avoided.
D: total world energy consumption from 1900 to 1972 (about 2% of tfe WPC 1968 estimates of world's fossil fuel reserves
E: deficit between world energy demand and fossil fuel availability, to be met from new energy sources and economies.
F: ultimate stability when world's energy demand can be met from renewable sources alone

Some years ago I produced this diagram which was intended to be a qualitative prophesy of the shape of things to come in world energy supply and demand. The vertical scale, expressed in terms of the 1972 demand, applies only to curve 'A' which, for the period 1900-1972 is factual, and from 1973 onward has been extrapolated at an arbitrary exponential growth rate of 5% p.a. In view of the fact that growth from 1950-1972 had been running at 5.14% p.a. (average), extrapolation at 5% did not seem to be excessive from the point of view of those - and there were many - who believed that maintained exponential, or even hyper-exponential, growth was some kind of Law of Nature. One glance at the diagram shows that such a growth pattern would be unthinkable; for the area enclosed beneath the growth curve is a measure of total energy consumed cumulatively. Thus the area 'D' represents the world's total energy consumption during the first 72 years of this century - which would differ only slightly from the total energy consumed since the dawn of history. Moreover, between 98 and 99% of the area 'D' had been supplied from fuels. It is inconceivable that exponential growth could be sustained indefinitely by means of fuels, even if nuclear fuels be included; for the world is a finite place with a finite stock of fuels, whereas the area enclosed beneath curve 'A' would rapidly expand towards infinity.

You all probably know the legend of the Chinese traveller who, centuries ago, introduced to the Moghul Emperor in Delhi the game of chess. The emperor was so delighted with the game that he invited the Chinese to name his own reward. The Chinese said that he would gratefully accept one grain of rice for the first square of the chessboard, two for the second, four for the third, and so on - doubling each time. The emperor thought him mad to demand such a trifling reward, until he discovered that the whole world did not contain enough rice to satisfy the request. The effects of sustained exponential growth are not unlike those grains of rice. My belief was, and is, that world fuel supplies would follow some pattern such as shown by curve 'B', which is not intended to be to scale, but only of a shape indicative of probable future trends. This curve shows a continuing increase in fuel supplies, but at a falling growth rate, until they reach a peak - perhaps fairly early in the next century; after which they would gradually decline in a curve assymptotic to zero. The gap between curves 'A' and 'B' could obviously never be satisfied by any conceivable form of energy after only a few years. Hence it must be concluded that the true world energy supply curve would have to depart drastically from curve 'A'. It would, as it were, be necessary to "bend" curve 'A' into some shape such as that of curve 'C', which could lie above curve 'B' only to the extent that "non-fuel" energy can be won. The deficit 'E' by which curve 'B' falls short of curve 'C' represents the amount of energy that must be found from sources other than fuels. I repeat that it is only the shapes and not the scales of curves 'B' and 'C' that are of significance. The more rapidly we can exploit new energy cources, the higher can we permit curve 'C' to rise above curve 'B', and the more comfortably shall we be able to live. Ultimately, in the remote future, a time must come when all non-renewable energy resources will have become exhausted, and we shall have to learn how to live within our means of renewable energy sources, 'F'.

That is the general pattern I foresee. You may ask why I chose 1972 as the point of departure from fact to surmise. This was partly because at the time I drew the diagram the latest available world statistics did not extend later than 1972, and partly because it was in 1973 that the first great Middle East fuel crisis arose; so that 1972 was the last full year to be uninfluenced by the events of 1973. Now we have world energy statistics up to and including 1978, which show that although energy consumption continued to grow after 1973 it did so at a mean annual rate over those five years of only 2.14% p.a. - a mere 42% of the growth rate over the preceding 22 years. It looks as though curves 'A' and 'C' are already drifting apart, as the diagram foretells.

Now energy consumption is a rough measure of living standards. It follows therefore that the discomfort of readjusting our way of life to a more restricted energy supply pattern will be mitigated to the extent by which we can harness new energy resources - 'E' in the diagram - to our service. It seems fairly clear that if we are to avoid a disastrous decline in living standards there is a very urgent need to win new, and very large, sources of energy very rapidly. I put no figures to my diagram; but the pattern of our needs is clear, and the difficult time for humanity will be the next few decades, during which our rate of re-adustment will have to be at its greatest.

Now were are we to find - and find quickly - a vast source of energy on a scale comparable with our present rate of consumption? I include nuclear fission energy with fuels; for whatever the protesters my say, the alternative to not developing nuclear power is so grim that such risks as there may be will just have to be taken; but while fissile fuels could offer us a valuable breathing space, even they are not inexhaustible. Hydrothermal fields, which represent the "cream" of the earth's geothermal resources, could probably never contribute more than about 2 or 3% of the world's total energy needs. This does not imply that hydrothermal fields are of no importance. Indeed they can be of immense importance to countries who are so fortunate as to possess them, but we cannot look to them for a solution to the world's long term enrgy problem. The other options that come to mind are solar, wind, wave, hydro and tidal energy - all renewable. This is not the occasion for debating the merits of these resources. Each has a valuable part to play, no doubt, but personally I do not believe that either separately or collectively they could ever fill the energy gap that must be spanned within a few decades. Only two sources, in my opinion, are large enough to solve our desperate needs - controlled thermonuclear fusion and crustal heat. If we can master the problems of winning either of these resources, our battle will be won. Both must be pursued simultaneously, for we cannot yet be sure of either. Although I am inclined to believe that ultimately we shall succeed in both quests, I think that crustal heat at present lies more nearly within our grasp. That is the resource that I wish to talk about now.

The heat content of the mantle and cores of the earth is probably between 1,000 and 2,000 times that of the crust; yet the crust alone contains enough heat to satisfy the world's probable energy needs for a very long time. And as this crustal heat is obviously far more accessible than the heat contained below the Moho, it makes practical sense to be satisfied for the present with the recovery of crustal heat alone - or at least with as much of that heat as can be won. Obviously deep magmatic heat would have the advantage of grade - i.e. high temperature - over crustal heat, and this could be useful for such applications as high efficiency electrical generation. Nevertheless, since the difficulties of penetrating into the mantle are so formidable, it would be as well to ignore everything beneath the crust - at least for the time being. Furthermore, it is suggested that we rest content for the present with the heat beneath the land surfaces of the crust only. Even if, as it well may, it should ever become practicable to recover off-shore crustal heat, access to the heat beneath the land surfaces would obviously be cheaper (except perhaps in the comparatively rare instances where use could conceivably be made of abondoned off-shore oil or gas bores).

To avoid over-estimating the crustal heat reserves, all hyperthermal fields and active volcanic areas will here be discounted; and I shall assume for the sake of simplicity that all the land areas of the world are "non-thermal" - i.e. possessed of temperature gradients of not more than 25°C/km of depth. Although the geological "mix" of rocks at different depths will vary from place to place, an order-of-magnitude estimate of the specific crustal heat may be made by assuming homogeneity, or at least the same pattern of stratification everywhere throughout the crust. If a mean crustal density of 2.7 g/cm^3, a mean crustal specific heat of 0.2 cal/g°C and a mean crustal thickness of 35 km be assumed, then the specific crustal heat may be expressed as about 2,500 MWyr(th) per km^2 of surface area per °C of average cooling. Doubtless there will be errors in the assumptions made, but this figure should be of the right order of magnitude.

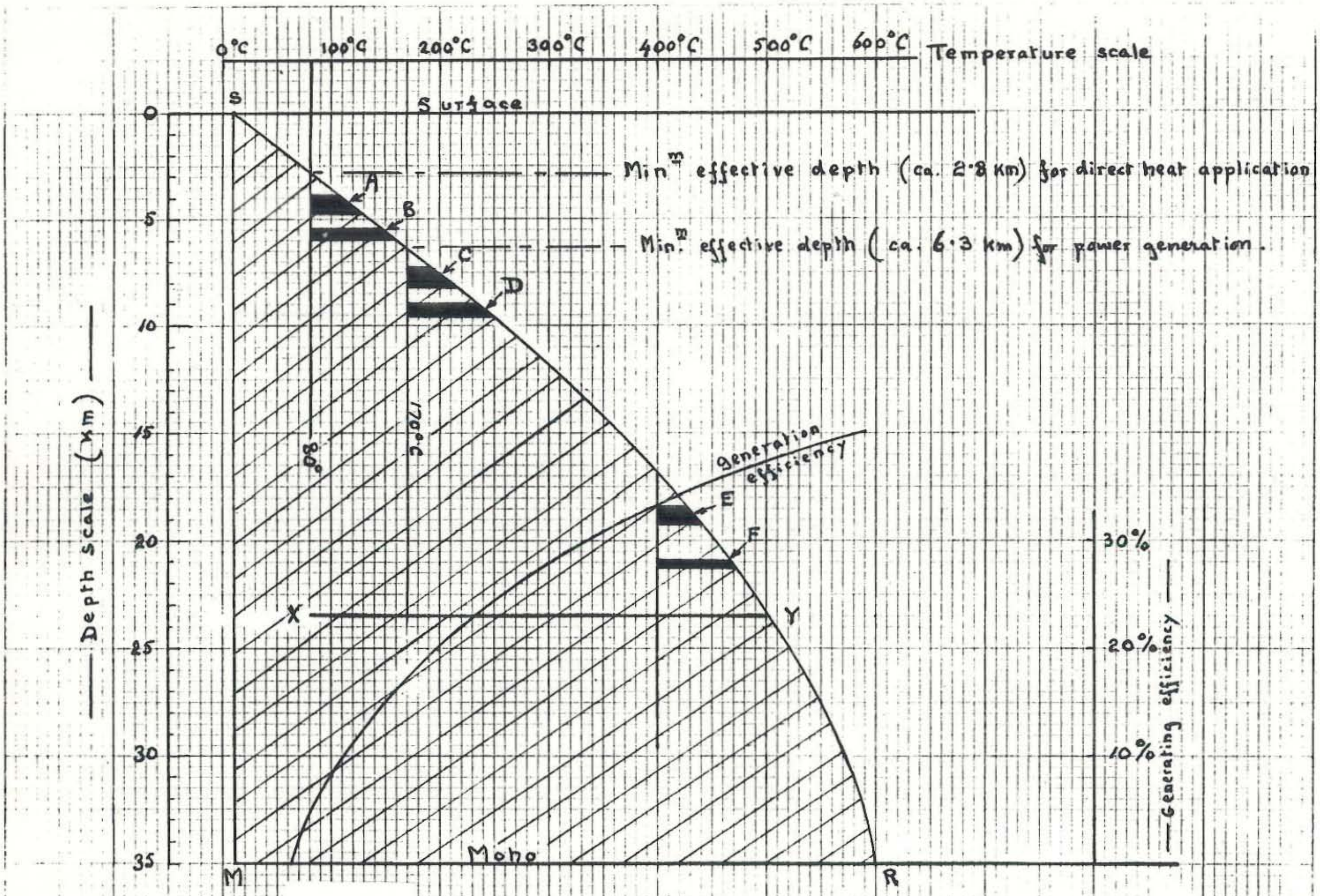
The total land masses of the world cover about 148 million km^2; so that if we could cool the crust beneath those areas through 1°C (average) we could recover about 3.7×10^{11} MWyr(th). In 1980 the total world consumption of primary energy is likely to be about 9 million MWyr(th); so by cooling the crust through 1°C we could recover enough heat to supply our present energy needs for more than 41,000 years. This figure, I must confess, is not a very honest one for two reasons. It takes into account neither growth nor grade. Even a very slow continued rate of exponential growth can reduce the life of a resource drastically; but if my pronostication diagram is even vaguely correct, the mean growth rate over future centuries could be very small or even negative. However, the roughly estimated figure I have just quoted is equivalent to somthing like 1,500 times the total energy consumed by the world in the last 80 years - i.e. since the year 1900. Does not this suggest that here perhaps is to be found the vast energy source we so desperately need? The question of grade is a more serious matter, for some of our heat requirements are at high temperatures that could not be obtained from crustal heat. However, there would seem perhaps to be enough heat in the crust to supply at least a large proportion of our requirements for a very long time, while our remaining resources of fuels. perhaps aided by magmatic heat, to which I shall refer later - could perhaps be used for our high temperature processes.

The first question that arises is "How much of the land masses could be used for crustal heat recovery?" In theory the amount would be limited only by accessibility; for crustal heat is ubiquitous and could be exploited wherever it is needed, once we master the necessary technology. We could mine the heat even in Antarctica and permafrost areas of the world, for part of the recovered heat could be used to create a local mini-climate to render habitable and self-sufficient large areas of the world that are now uninhabitable. It is worth noting that even if we were to use only a small fraction of the land areas - say 10% for example - we could probably recover enough energy to last us for centuries, even by effecting only one degree of cooling.

What is more important is "By how much could we reduce the average temperature of the crust without creating unacceptable conditions, through such causes as shrinkage, seismicity or climatic influence?" Could we cool a local area through an average temperature drop of as much as 1°C, for instance? If not, then my estimate of 2,500 MWyr(th)/km^2/°C would lose much of its impact. It is not easy to give a clear answer to this question; but it is worth noting that at Wairakei in New Zealand something like 45,000 MWyr(th) have been extracted from the field since exploitation began about 30 years ago. The horizontal projected area of the Wairakei field is about 18 km^2, so the total extraction to date has amounted to about 2,500 MWyr(th)/km^2. - i.e. just about the equivalent of 1°C average cooling. Moreover, it is probable that the crustal thickness at Wairakei is much less than 35 km, so the average cooling of the crustal column embracing the field has already probably been well in excess of 1°C. Yet heat extraction continues there, and many years of useful field life are confidently expected. The only adverse noticeable effecs at Wairakei are the reduced activity of neighbouring surface thermal manifestations - and that would be irrelevent in non-thermal areas - and ground subsidence, which has been due to water extraction and not to thermal shrinkage. It would seem quite likely that average crustal cooling of "perhaps a few degrees" - I cannot be more specific - might be permissible. This extent of heat extraction over quite a small proportion of the earth's land areas should be able to provide us with our energy needs until Man has either learned sense or destroyed himself.

The extraction of crustal heat may be described as "heat mining". The use of the term "mining" serves as a reminder that we are talking of a resource which, to all practical intent, is <u>non-renewable</u>; for it would take thousands of years for a mined zone of cooled rock to recover its temperature, even if cooled through 1°C. Geothermal exploitation, as already practised, is of course a form of heat mining, but as it so often involves also the extraction of fluids - i.e. of <u>matter</u> as well as heat - I prefer to reserve the term "heat mining" for the extraction of <u>heat alone</u> from deep rocks.

The figure overleaf represents a presumed temperature/depth distribution curve through a section of the crust. It makes no claim to precision, but it may be taken as a not unreasonable approximation, for it com-



TOTAL CRUSTAL HEAT AND MINIMUM EFFECTIVE DEPTH

(A SIMPLIFIED CONCEPT ONLY)

plies with the following conditions, all of which are believed to be fairly typical of non-thermal areas in the land masses: -

i) a crustal thickness of 35 km

ii) a mean ambient surface temperature of 10°C

iii) a temperature gradient of 25°C/km at the surface

iv) a Moho temperature of 600°C

The shaded area "SRM" represents the total heat content of the crust reckoned above the surface temperature. As drawn, it measures about 12,000 km°C. (As an approximate heat unit, the kilometre-degree is a useful expedient, though it lacks scientific precision). The cooling by 1°C of a crustal column 35 km in height beneath 1 km^2 of land area would of course be equivalent to the removal of 35 km°C of heat, which is only 0.3% (or thereabouts) of the total crustal heat; so in talking of "perhaps a few degrees" of crustal cooling I am referring only to a small fraction of the total crustal heat. Let us examine further the implications of 1°C average crustal cooling. I shall later be talking about proposed methods of heat mining, but here I need only say that the process will almost certainly be to pump water through underground fractures in hot rocks so as to enable their heat content to be extracted by conduction and brought to the surface. For practical reasons it is necessary to allow for certain inevitable temperature drops; also for the fact that heat mining would almost certainly not be a commercial proposition if aimed at the recovery of very low grade heat only. As a working hypothesis I have assumed the following: -

Minimum temperature of commercially useful directly applied heat (e.g. for space heating)	60°C
Add temperature drop at surface heat-exchanger	5°C
Add temperature drop at the underground rock/water interface	5°C
Add temperature drop from the core of the hot rock to the nearest rock/water interface	10°C
Minimum useful rock temperature	80°C

By shifting the vertical "base temperature" line from 10°C at 'SM' to 80°C, about 20% of the total crustal heat would be lost; but this is unimportant, as it is not suggested that we ever try to win more than a small fraction of the total crustal heat. According to this curve, the minimum depth at which rock at 80°C would be reached would be 2.8 km, and obviously if a reasonable quantity of heat is to be extracted we must penetrate a good deal deeper. Heat extraction to the extent of 1°C crustal cooling (average) is represented by the zone 'A', having an area of 35 km°C. This would imply the cooling of a pocket of rock 1 km in thickness through 35°C. Alternatively, zone 'B' represents the extraction of the same amount of heat by the cooling of a pocket or rock of 1/2 km thickness through 70°C. An infinite variation of pocket thicknesses and temperature drops could yield the same quantity of heat, and it is clear that the deeper we penetrate the thinner could be the cooled pocket of rock that could yield the same amount of heat.

Now let it be assumed that our aim is not the direct application of heat but power generation, for which a minimum temperature of 150°C at turbine entry may arbitrarily be assumed. (This could enable power to be generated at about 15% thermal efficiency). Adding the same 20°C margins as before for temperature drops, this means that a rock temperature of no less than 170°C would be required. Thus the mining of zones 'C' and 'D' of thicknesses 1 km and 1/2 km, through temperature drops of 35°C and 70°C respectively, as well as any number of variants having the same area, 35 km°C, would also result in an average cooling by 1°C in the vertical crustal column containing these zones. This would mean penetrating to depths of at least 7 3/4 km. Likewise, for power generation af higher efficiency, say 22 1/2% or thereabouts, it would be necessary to mine heat from zones 'E', 'F' or equivalent at depths of at least 18 3/4 km. All this, of course, is only illustrative - not precise. Actual pocket thicknesses, depths and temperature drops would depend on the exact shape of the temperature/depth curve and on the density and specific heat of the rock; but I hope I have made clear the principle.

If we ever succeed in penetrating very deeply, a good way of mining heat would be to exploit a thin zone through a large temperature drop for different applications seriatim; for example, the zone 'XY' having a thickness of 83 metres only could be cooled sequentially through 420°C for high efficiency power generation, lower efficiency power generation and finally for direct heat application - all resulting in cooling the local crustal column through an average drop of 1°C.

It should be noted that there is no reason why an area should be mined of its heat content at one mean depth only. It would be possible for two or more pockets of exploitation to lie vertically above one another; the uppermost being developed first for low grade heat application and the other, or others, lying at much greater depths and being developed for higher grade heat extraction at a later date when our ability to penetrate more deeply improves. An advantage of several relatively small pockets of heat mining activity could be that possible shrinkage or seismic effects would be avoided. A pocket of hot rock, initially in a state of compressive stress, would, in the process of cooling, gradually pass through states of declining compression and perhaps into tension while slowly transferring the weight of its overburden onto the surrounding rock without showing any detectable surface evidence of shrinkage. Cracking could ultimately occur in the cooled pocket (and this would incidentally aid the mining process) and at the moment of initiation a crack could perhaps give rise to a micro-earthquake, but its extension with further cooling should pass unnoticed.

The advantages of heat mining, if we succeed in mastering the technology, would be impressive: -

i) It could be practised in any part of the world where energy is wanted, in normal non-thermal areas.

ii) It would put an end to the present situation of "have" and "have not" countries in the context of energy. This alone should greatly ease international political tensions.

iii) The process would be virtually pollution-free.

iv) It would save the immense costs now incurred in <u>transporting</u> energy over great distances, either by electrical transmission or by the physical transportation of fuels by rail, road or sea, and would reduce the terrible problem of marine pollution resulting from the wreckage and sludging of super-tankers. This would simply be because the energy could be mined at, or close to, the point of need.

v) With pressurised water circulating through the hot rock, the flow could perhaps be varied to match fluctuating demands, so that the process would not have to be used for base load purposes only. No energy would be wasted at times of low load. However, the extent to which this will be possible must depend on the permissible variations of temperature in the injection and withdrawal bores.

How is heat mining to be effected? It will be necessary to master two problems: -

A. We must perfect the art of rock-fracturing, and
B. We must discover methods of penetrating very deeply into the crust at acceptable cost.

The first of these problems is already well on the way to being solved. The second poses greater difficulties; but many investigators are working on it. However, even the solution of the first problem will bring within our grasp huge quantities of energy and will thus gain for us valuable time in which to find the solution to the second problem. For although the simplified analysis I have just outlined has been based on the pessimistic assumption that all the land masses of the world are uniformly of a non-thermal quality, it is a fact that quite a considerable part of them exhibit temperature gradients well in excess of the normal figure of 25°C/km that I assumed. If at first we confine our efforts at heat mining to these semi-thermal areas, beneath which useful temperatures may be encountered at moderate depths, a large harvest of heat can be reaped as soon as the art of rockfracturing has been mastered. A still larger harvest will follow after we have succeeded in penetrating the crust cheaply to very great depths.

Let us consider the first problem - the perfection of the art of rock-fracturing.

Hydrothermal fields are exploitable because they have a permeable layer of rock at depth, capable of containing large volumes of water that serve to collect crustal or magmatic heat by conduction and to permit its conveyance to the ground surface through bores sunk into the permeable layer, or aquifer, for the purpose. Such aquifers, at suitable depths, are unfortunately comparatively rare. Most parts of the upper crust are almost impermeable except close to the surface, where useful temperatures are not encountered in non-thermal or even in semi-thermal areas. Of the three methods whereby heat can be transferred from one place to another - conduction, convection and radiation - it is clear that in solid rock, deep in the crust, neither convection nor radiation could be of use in transferring the heat to the surface. Conduction too would be useless if reliance were placed on the natural rock overlying the deep-seated hot zone, for all rocks are poor conductors of heat.

The only practical way of extracting the heat would seem to be to imitate as closely as possible the provisions of Nature in a hydrothermal field; that is to say, we must create permeability where none exists and supply water artificially to circulate through the man-made aquifer thus formed. A natural aquifer is a system of intercommunicating voids, fissures and porous rocks through which water can flow or percolate. To imitate this we must artificially form underground voids or fissures - we cannot imitate porosity - and force water through them so as to collect the crustal heat by conduction from contact with the hot rocks, and bring the heated water to the surface. If use can be made of convection currents in the process, then so much the better.

What is ideally required for heat mining is an underground labyrinth, formed in the heart of a mass of hot rock and having the following properites: -

i) The water/rock interfaces should have the greatest possible contact area so as to facilitate heat transfer from the hot rock to the water.

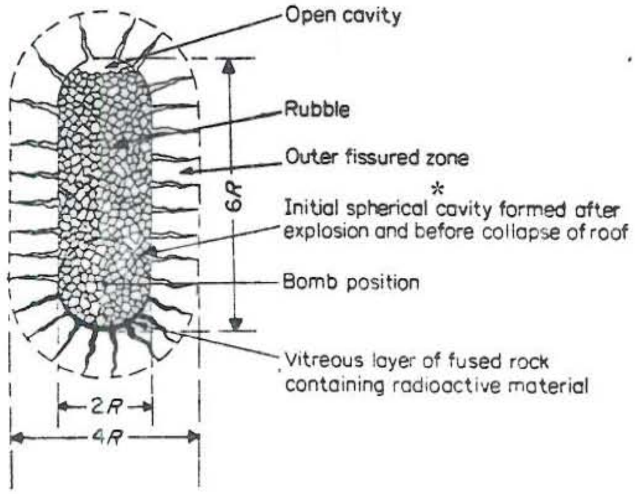
ii) The volume of voids and fissures should be as large as possible to ensure that the circulating water passes at a low velocity over the hot rock, so facilitating the extraction of a maximum quantity of heat during its passage.

iii) The configuration of voids and fissures should be such as to offer the minimum resistance to flow.

iv) Wide inequalities of flow resistance through alternative "parallel" flow paths should be avoided as far as possible, lest parts of the labyrinth become over-cooled before other parts have had time to surrender more than a fraction of the heat available.

v) Every point within an exploited pocket of hot rock should be as close as possible to a water/rock interface, so that heat conduction paths shall nowhere be too long. This calls for a high degree of fragmentation.

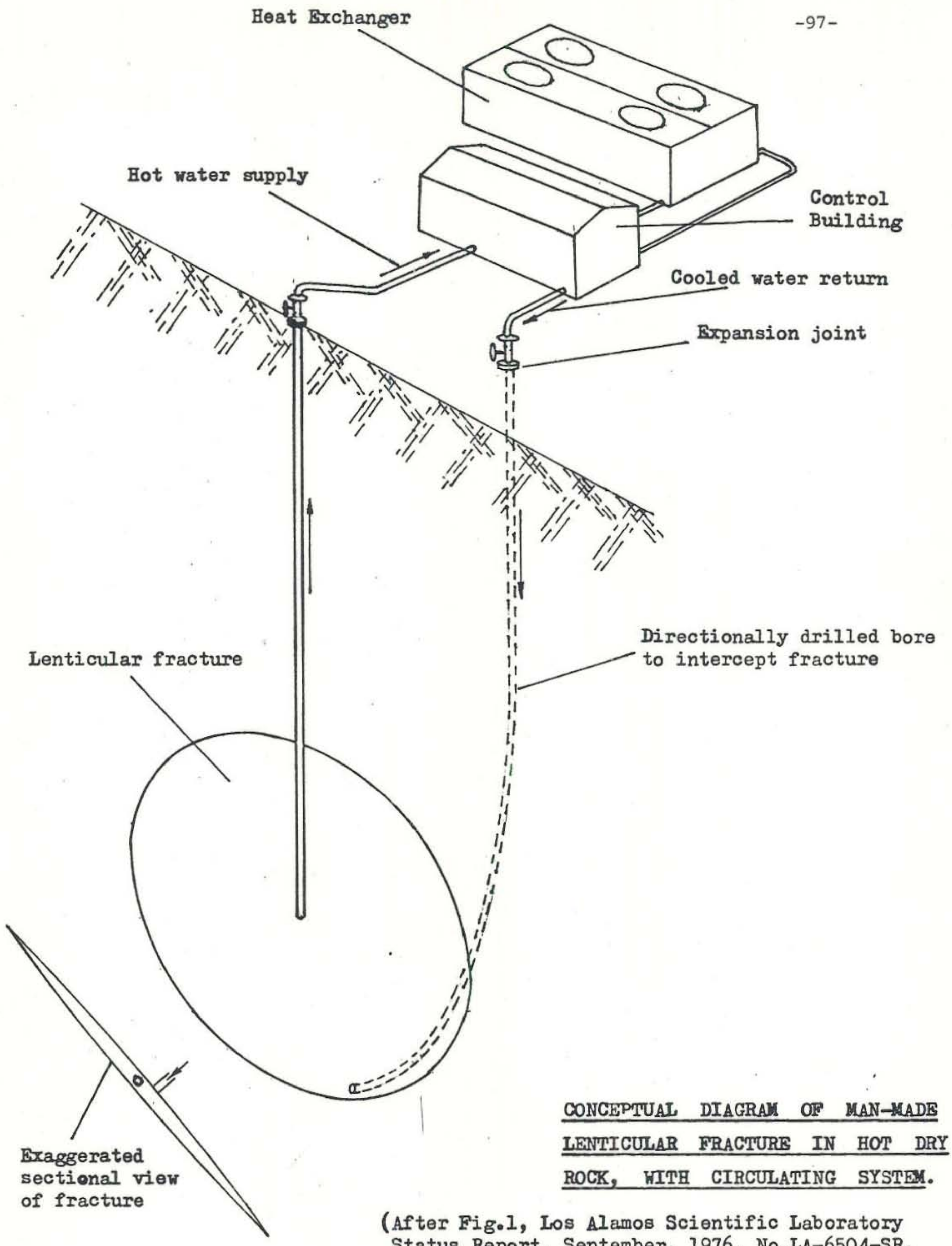
It is by no means easy - in fact probably impossible - to create an underground labyrinth that simultaneously satisfies all these requirements. The nearest approach to the ideal is that obtained by means of underground nuclear explosions, which create large rubble-filled cavities with a high proportion of voids, more or less as shown in the accompanying figure. However, political objections and the risk of seismic damage to buildings and other surface structures virtually rule out the use of such explosions except perhaps in a few rare situations. The theory is that wihtin a split second of the explosion the expanding gases will have formed a spheroidal chamber of such a size that the gas pressure just balances the lithostatic pressure of the overburden. *(It would be spheroidal, rather than spherical - as shown in the figure- because the horizontal component of the lithostatic pressure is less than the vertical). Thereafter, the roof of the chamber would collapse until the rise in height of the rubble thus formed would effectively support the roof against further collapse.



Rubble-filled 'chimney' formed by underground nuclear explosion (approximate proportions only are shown).

The art of labyrinth formation more or less resolves itself into finding the best compromise between costs on the one hand and the fulfilment of as many as possible of the five desirable properties.

Hydro-fracturing is a practice that has been used in the oil and natural gas industry for many years as a means of increasing bore yields. It is effected simply by applying a steady hydraulic pressure at a chosen point in a bore, where it is uncased. When the pressure is sufficiently high a disc-shaped crack, usually in a vertical plane, will be formed more or less concentrically with the point at which the pressure was applied - see sketch overleaf. This method is being used for heat mining at the Los Alamos Scientific Laboratory of the University of California,

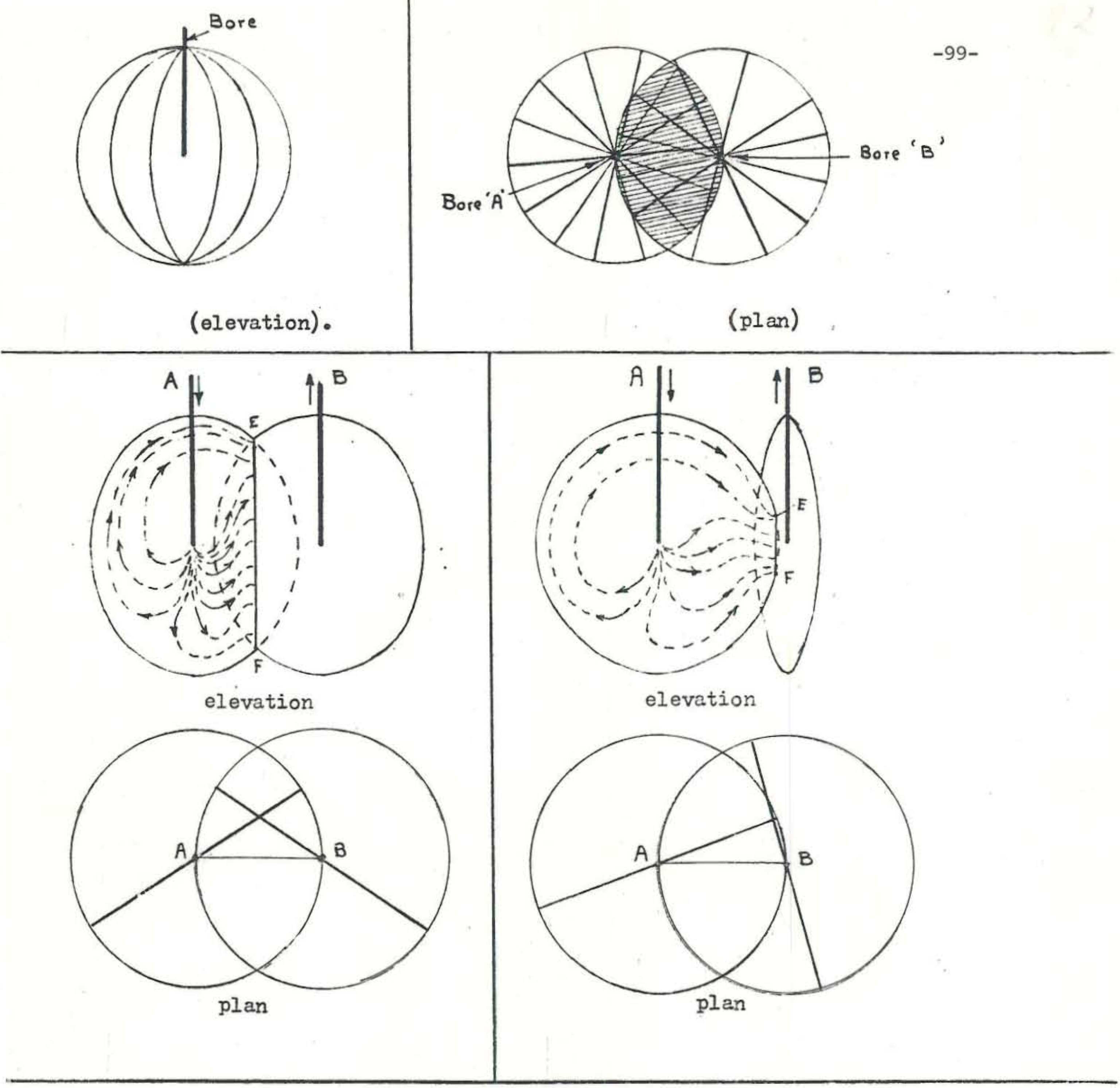


CONCEPTUAL DIAGRAM OF MAN-MADE LENTICULAR FRACTURE IN HOT DRY ROCK, WITH CIRCULATING SYSTEM.

(After Fig.1, Los Alamos Scientific Laboratory Status Report, September, 1976, No.LA-6504-SR, compiled by Roland A. Pettitt).

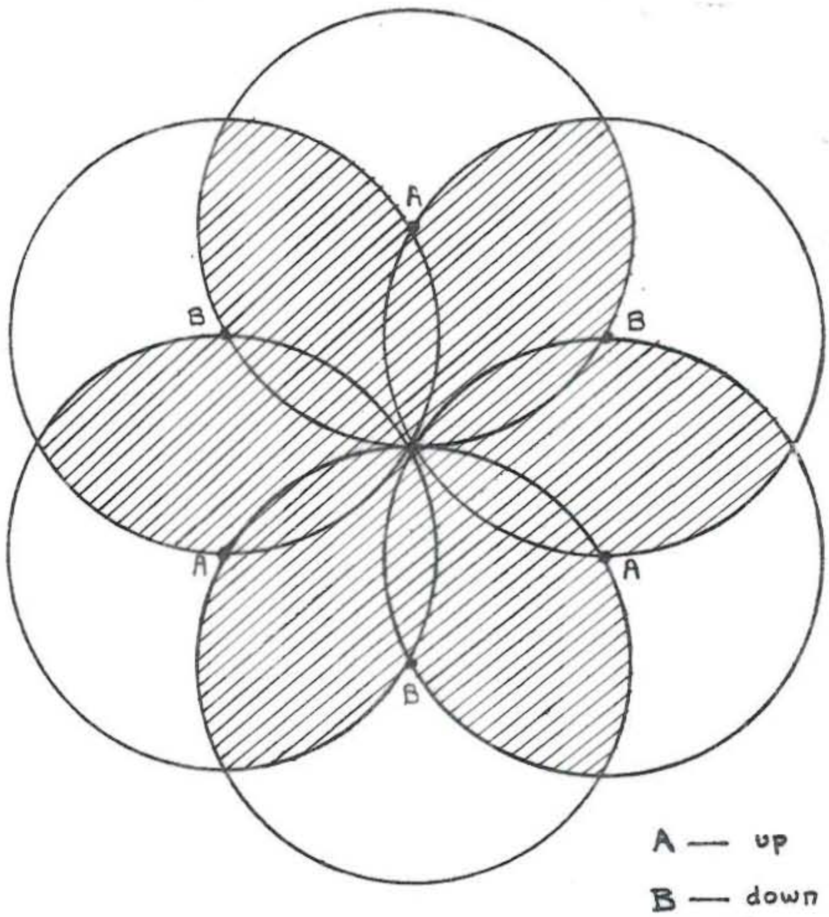
sited in New Mexico State, U.S.A., where a semi-thermal area exists having a temperature gradient of about 62°C/km - about 2 1/2 times "normal". A disc-shaped fracture of not less than 600 m diameter and about 2 mm average thickness was formed by applying pressure at the base of a vertical bore. A directional, or deviated bore was then sunk to strike the disc fracture near the lowest part of its periphery. Water is pumped down the second bore: it swirls round the disc-shaped crack, picking up rock heat by conduction, and rises up the vertical bore to the surface. For the experimental loop a heat-exchanger dissipates the mined heat in a cooling tower: but in a commercial installation the heat would of course be put to practical use. It was expected that the size of the thin disc-shaped crack would be increased somewhat by chemical leaching, by thermal cracking resulting from the contact of cooler water against the hot rock walls, and by "propping" from dislodged particles of rock dropping into the crack when distended by pressure and preventing it from fully reclosing when the pressure was released. Experience suggests that the second of these effects at least has helped. Thermal cracks would tend to form vertical grooves in the crack walls, because the horizontal compression in the crack walls is less than the vertical compression; and the change from compressive to tensile stresses would occur in vertical planes earlier than in horizontal planes. The first experimental loop at Los Alamos used a vertical bore almost 3 km deep, at which depth a rock temperature of 200°C was encountered. Circulation has been maintained for many months, and heat has been extracted continuously at a steady rate of about 7 1/2 MW(th), with a water recovery temperature of 131°C. A second and deeper loop is now being prepared with the intent to extract about 50 MW(th), for which some practical use will probably be found. (Within the last 3 or 4 months part of the recovered heat from the first loop has been used to generate 60 kWe by using a small binary cycle turbine, actuated by Freon R114; so the ability to use heat mining both for direct application and for power has already been demonstrated).

The properties of a disc fracture are far from the ideals that I have quoted. Nevertheless, even this crude form of "labyrinth" has produced results that have exceeded expectations. The weakest feature of the disc fracture is that it is 2-dimensional, so that the heat capture zone is confined to a thin flat slab of rock only. If we could succeed in forming 3-dimensional, or triaxial, fractures the scope for heat



Intersecting 3-dimensional spherical fracture patterns formed at the base of two adjacent bores.

extraction would be greatly improved. At the top left-hand side of the accompanying sketch is shown a spherical concentric assembly of disc fractures, formed like the segments of an orange. At the top right-hand side are shown, in plan view, two such assemblies side by side. It will be seen that some of the disc fractures intersect one another, thereby forming the rudiments of a true labyrinth, so that water would be forced down one bore and raised up the other after passing through several fracture paths in parallel with one another. It might at first be thought that only the intersecting cracks fractures could contribute anything to heat recovery; but even those radiating cracks that have the appearance of culs-de-sac can permit the formation of slow convection currents, as shown in the lower sketches. Another objection might be raised in that most of the water would tend to flow through the shortest paths offering the least resistance to flow, so that excessive local cooling would occur in the vicinity of those paths before the rest of the fractured zone would have time in which to contribute any useful share of the heat. Although this objection is partly valid, the difficulty is mitigated by the fact that the viscosity of water falls rapidly with rising temperatrure; with the result that the greater apparent impedance of the longer paths is largely offset by the lower viscosity of the hotter water, so the system would possess some degree of self-regulation.



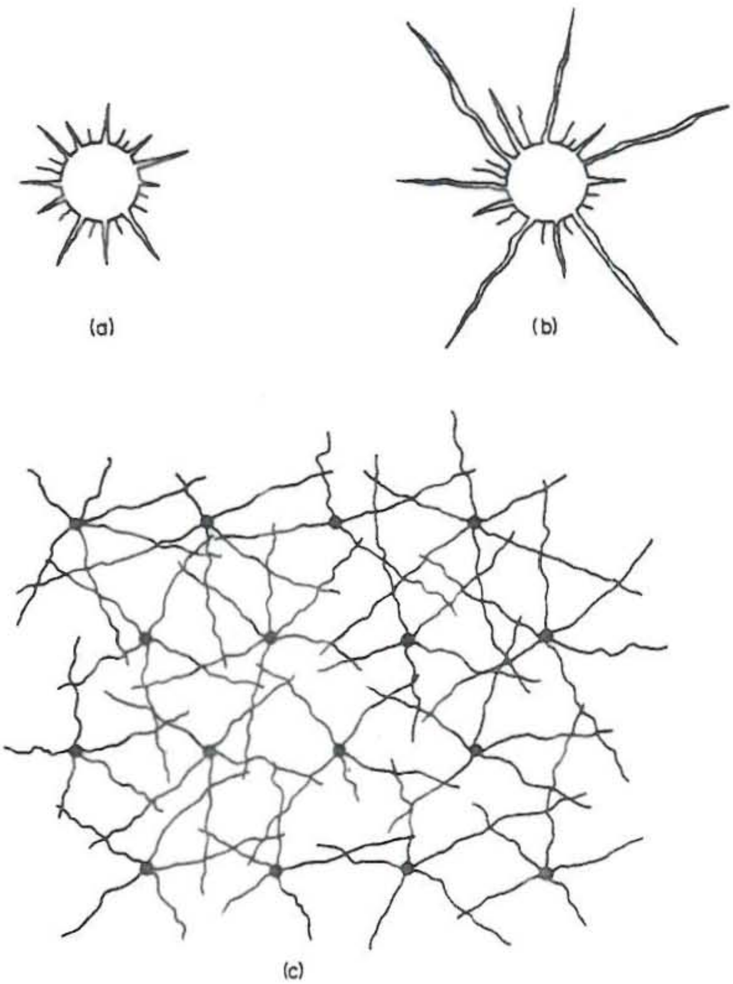
(Overlap zone of intersecting fractures shown shaded)

Far better than a two-bore assembly of radiating fractures would be a hexagonal cluster of bores, as here shown; for the overlapping of the spherical patterns would be more effective, with a smaller proportion of culs-de-sac, and the labyrinth would thus become more intricate. Alternate up-flowing and down-flowing bores would ensure a good flow distribution through the fractured rock.

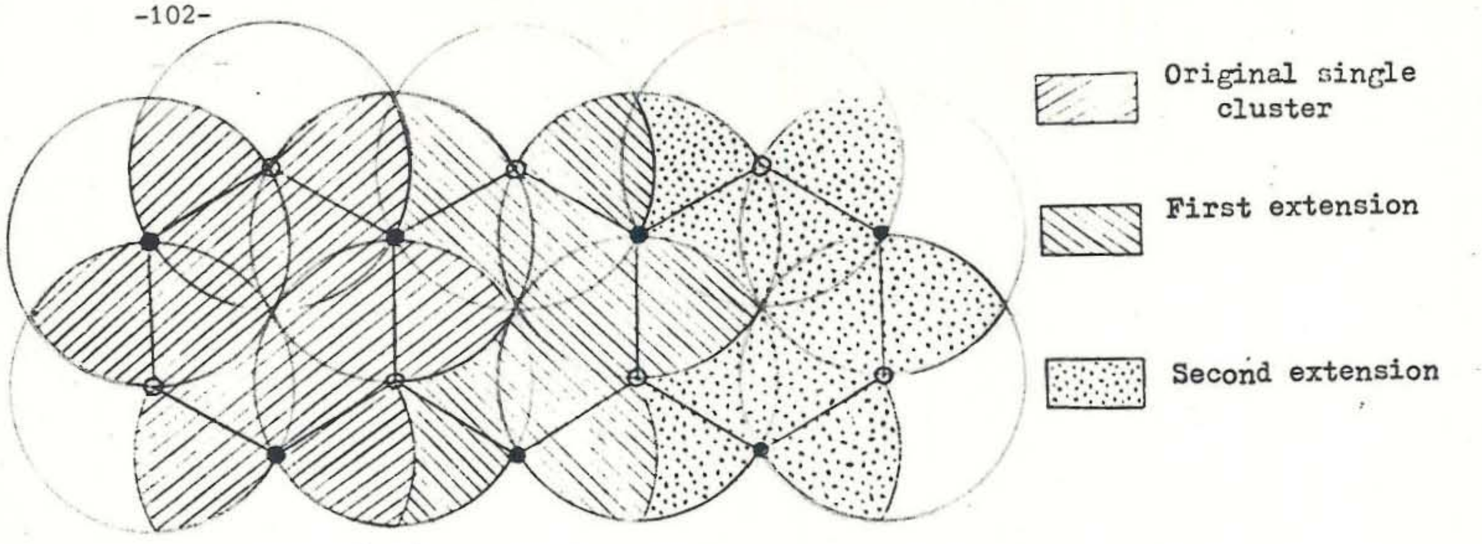
HEXAGON CLUSTER OF BORES AND SPHERICAL FRACTURE ZONES

Such an arrangement could be extended indefinitely, as shown in the figure on the following page, either undirectionally or peripherally, while still preserving the alternating flow directions in adjacent bores and further improving the labyrinthine nature of the crack system. Extensions of either type would bring an immediate economic gain; for the second hexagon collects an additional 78.55% of overlap zone volume at a cost of only 66.7% additional bores. Hence the economy of a double hexagon of ten bores over a single hexagon would be 1.7855/1.6667, or 7.13%. With each subsequent extension of further hexagons, unidirectionally, the gain rises, approaching 17.8% in the limit with an infinite number of hexagons. With peripheral extension, the same gain of 17.8% would be achieved with the completion of the first ring of 18 additional bores. At the same time as overlap area is gained, the proportion of culs-de-sac falls.

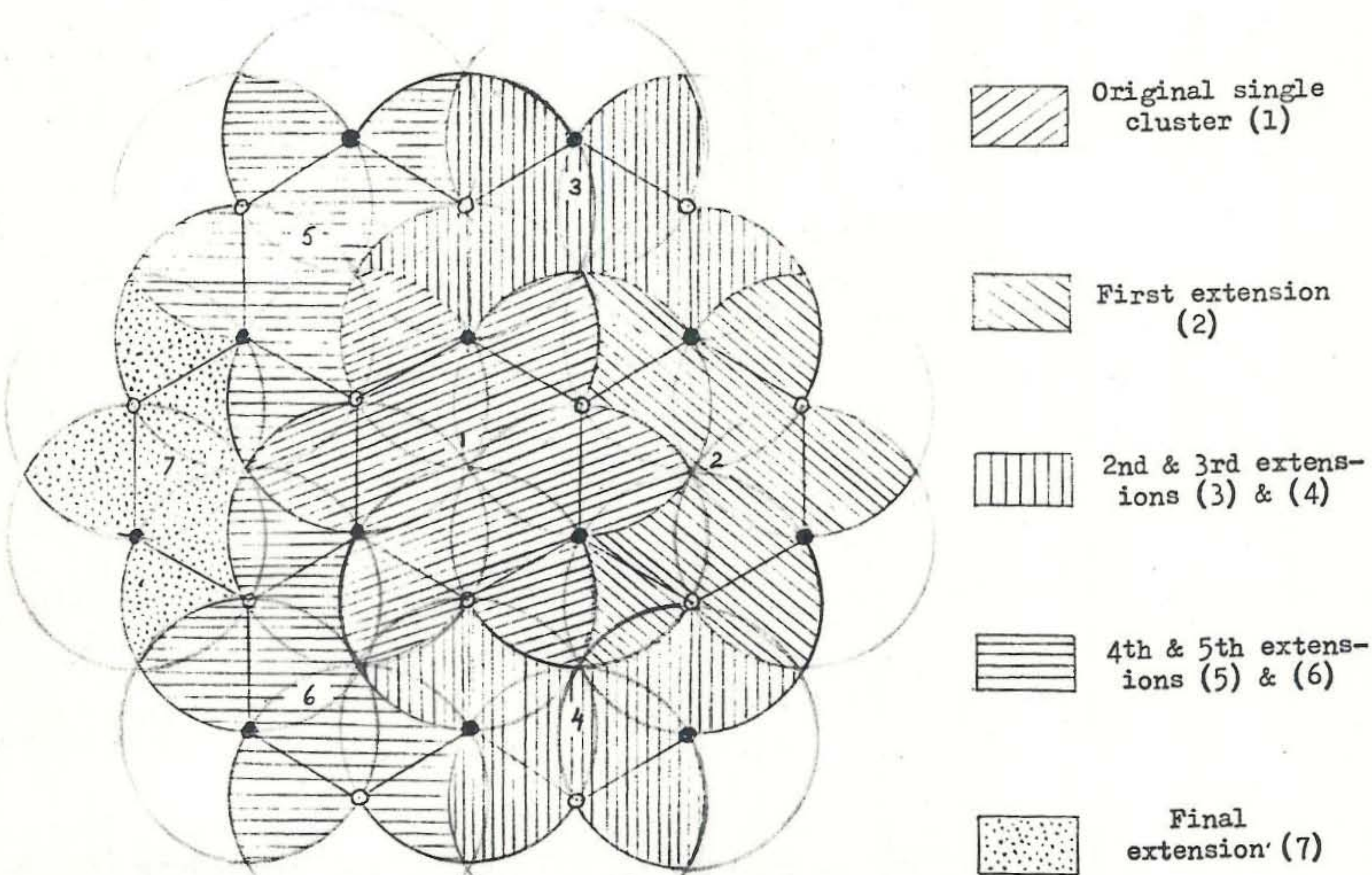
At the Camborne School of Mines in Cornwall, England, under the supervision of Dr. A.S. Batchelor, experiments are in progress aimed at producing triaxial fractures of the type I have described, in granite. It has been found that by detonating an explosive placed in an uncased part of a bore, radiating multiple fractures can be initiated, which can later be extended outwards by the simple application of hydraulic pressure, as here seen. If several bores are used, it should be possible to form a labyrinth,



Formation of multiple radial fractures by means of conventional explosions at the base of bores, their subsequent selective extension by means of hydro-fracturing, and the ultimate build-up of a labyrinth. (a) Initial formation after explosion (b) Extension of cracks along weaker planes by hydro-fracturing (c) Network of bores with radial cracks to form 3-dimensional labyrinth.



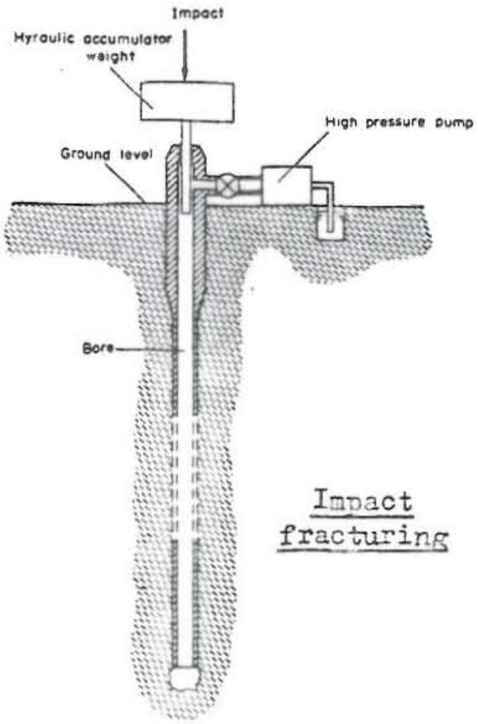
UNIDIRECTIONAL EXTENSION OF HEXAGONAL CLUSTERS



PERIPHERAL EXTENSION OF HEXAGONAL CLUSTERS

Downward-flowing bores ..... ●
Upward-flowing bores .... ○

somewhat as shown here. The success of this method depends on the fact that an explosion can supply energy more rapidly than it can be dissipated in a single propagating fracture, so that other fractures must be formed to dissipate the momentary high pressures created by the explosion. Hydro-fracturing by pumping cannot supply energy quickly enough for this.

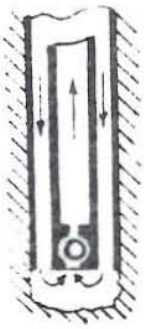


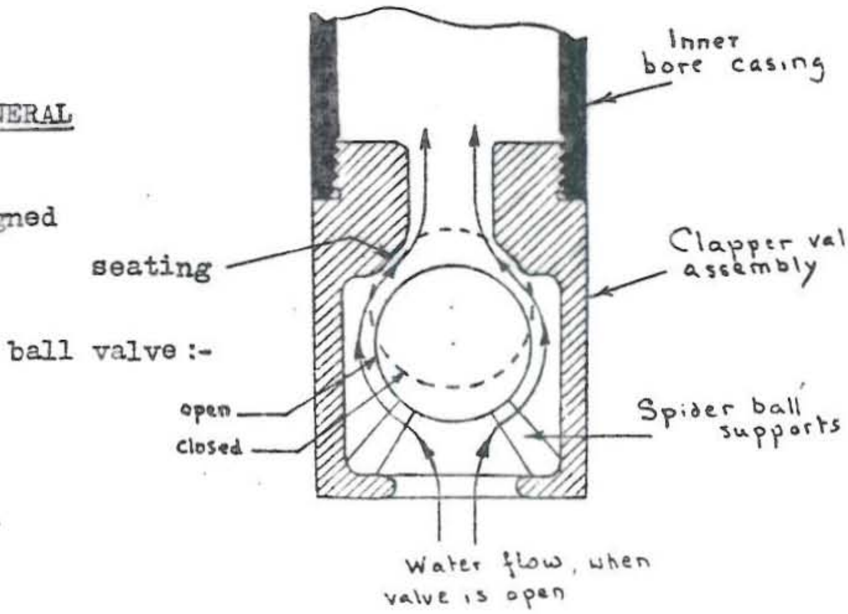
Impact fracturing

I myself have proposed two alternative ways of creating triaxial fractures, which I record only as a matter of passing interest, because the mathematicians tell me they would be unlikely to succeed. The first proposal, shown here, was to mount a hydraulic accumlator at the top of a vertical bore, cased to within a short distance from the bottom. By administering a dynamic blow with some device resembling a pile-driver to the top of the water column I had hoped to transmit a schock wave of explosive intensity to the bottom of the bore so as to create 3-dimensional fractures in the rock. The method would be to pressurise the bore by means of the pump to about 85 or 90% of the calculated fracturing pressure. At this point the weight would be so sized as to lift. The valve would then be closed so as to isolate the pump from shock, and the blow would be applied. Only 10 or 15% of the fracturing pressure would be needed in the form of dynamic shock in order to crack the rock. I am told that the attenuation of the shock would be too great. My second proposal, also illustrated here, was to generate a hydraulic shock at the exact point where it is needed, by creating water-hammer at the base of the bore. This was to be done by fitting a tube concentrically into the bore casing, so dimensioned that the annular area between the two tubes is equal to the sectional area of the inner tube. In this way water flowing down the annulus and up the inner tube would attain the same veolocity. A ball-valve was to be fitted at the base of the inner tube. By pumping water down the annulus at an increasing rate, a critical

SUGGESTED GENERAL FORM OF CLAPPER-VALVE.

(Not to scale, nor designed in any detail).



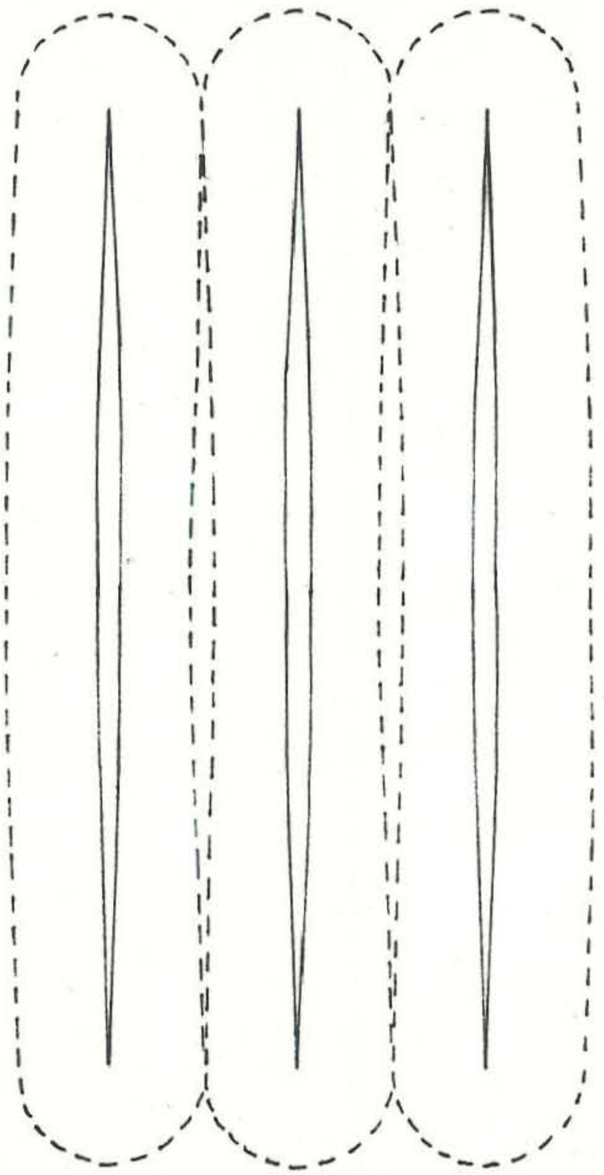


water velocity would be reached at which the Bernoulli forces over the ball would cause the ball to lift and interrupt the flow almost instantaneously. I had hoped that the water hammer forces created locally would have a sufficiently explosive effect to cause 3-dimensional fracturing. (Suitable anchoring arrangements (not shown in the sketch) would be needed to resist the fierce upward thrust on the inner tube). Again I am informed that the forces would not be sufficient. I mention these stillborn efforts lest the same ideas sould occur to others; and I would like to save them from wasting their time.

Both the impact and the water-hammer methods would certainly <u>fracture</u> the rock, and would enable pumps of lower pressure to be used; but the fractures would probably be two-dimensional only.

At Los Alamos the intention is to try out an arrangement of paralled disc fractures placed fairly close together so that their individual limited heat capture zones would overlap, in the manner shown in the sketch overleaf. This is another approach to the 3-dimensional concept, though no true labyrinth would be formed.

I could talk for much longer about rock-fracturing, but time presses; so I shall now pass on to the second of the two great obstacles to universal heat mining, - the discovery of a cheap method of very deep penetration into the crust.



CONCEPTUAL ARRANGEMENT OF PARALLEL DISC FRACTURES
WITH OVER-LAPPING HEAT CAPTURE ZONES

As I explained in my third lecture, the cost of conventional drilling rises very rapidly with increasing depth: some maintain that the cost/depth relationship is more or less exponential. As a result, it is found that after penetrating 3 or 4 km it simply does not pay, with our present skills, to drill more deeply for heat, except in the form of high calorific value petroleum or natural gas. What is needed is an entirely new method of penetration with a totally different cost/depth relationship. More than 30 novel methods of penetration are now the subject of research, and some of these may actually show a falling incremental cost per metre with increasing depth; so that although at shallow depths they may be prohibitively expensive, the cost curve of such methods will cross the curve for conventioanl drilling so that at great depths further penetration, though costing more in absolute terms, becomes relatively and progressively cheaper. In a short lecture covering such a wide subject I can do no more than just mention some of these novel methods of deep penetration: -

Melt-drilling techniques, using lasers, electron beams, electic arcs, and even the nuclear-heated subterrene.*

Thermal spalling methods by means of gas jets, rocket exhaust application, etc.

Chemical drills

Mechanical methods, using explosives, pellet impacts, ultrasonics, etc.

Changeable bit methods, to save time in retracting drill stems.

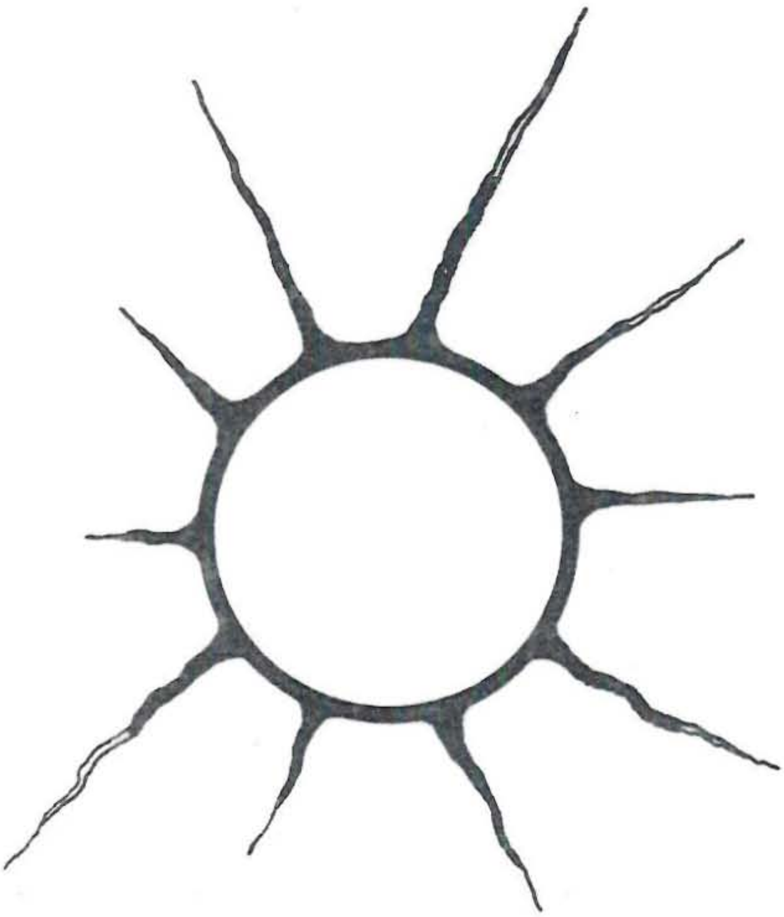
Projectile drills

Erosion drills, such as high pressure water jets.

Very little has been publicised about all this research, so there is not much I can tell you about them; but it is a fact that a great deal of effort is being made to find the most practical and economical method. Very probably, one method may be better than another for one particular class of rock whereas a different type of rock might favour another. Progress may be slow, but I see no reason to doubt that success will ultimately be attained.

Earlier I mentioned the question of the grade of mined heat. The spectrum of grades available is most unlikely to match that of the demands. This difficulty could perhaps be met to some extent either by mining heat at

* see accompanying sketch



VITREOUS BORE LINING FORMED BY MELT DRILLING, AND INTIMATELY BONDED WITH THE SURROUNDING ROCK

(Robindson *et al*. "A preliminary study of the nuclear subterrene", L.A. S.L. Doc. LA-4547, 1971).

The "subterrene" penetrates by melting the rock. Although near the surface it consumes about twice as much energy as conventional rotary drilling, the amount of added energy falls with increasing depth owing to the rising temperature of the rock. Its merits arise partly from the time saved in avoiding the need to retract the drill steam for frequent bit renewals, and partly from the fact that no steel casing or grouting is necessary. This second advantage is due to the extremely tough vitreous lining formed by the molten rock, which is intimately bonded with the surrounding formation in the manner shown. Hitherto, electrically heated subterrenes have been used for experiment, but the proposal was to make one with a nuclear head. At the 1975 U.N. Symposium in San Francisco it was confidently prophesied that by the mid-1980st it would be possible to penetrate several miles into the crust with holes of "some metres" in diameter; but less has been heard of it recently. The device was intended to be used for tunneling and mining, as well as for geothermal penetration.

different depths or by exploiting a single pocket of hot rock for different purposes at different times, always using the high grade heat first so as to avoid the wasteful degradation of heat. The more serious problem of grade is the absence of very high temperatures in the earth's crust. Modern fuel-fired thermal power plants make use of higher temperatures than can be found in "normal" parts of the crust, so if crustal heat is to be used for power generation it would have to be at some sacrifice of efficiency. This would not necessarily matter if the energy were sufficiently plentiful and cheap; but there are certain processes, such as smelting, glass making, pottery industry, etc. that just must have very high grade heat. This could of course be supplied by rather inefficient electrical generation from fairly low grade crustal heat; or it could still be supplied by fuels, for which there will be a declining demand as heat mining becomes more widely established. However, there is another possible form of heat mining to which I have made only passing reference earlier in this lecture. Whereas the analysis I have presented covers only normal "non-thermal" areas of the land masses, there are known to exist in several parts of the world magmatic chambers at temperatures of 1,000 to 1,100°C at far shallower depths than the 35 km or thereabouts at which the Moho usually occurs in the land masses. It has been estimated that in the U.S.A. alone the heat capacity of magma chambers is equivalent to about 5,000 times the present annual energy needs of that country. Active research is in progress in the U.S.A., Japan and, I believe, in the U.S.S.R. with the aim of devising a practical and economic method of tapping this huge resource of high grade heat. As far as I know, little information has yet been released as to the nature of these activities, but I understand that one project is to insert a heat-exchanger into the magma and another is to generate hydrogen gas by the dissociation of injected water. I regret I have no details. It must be remembered that whereas low grade heat mining could be universally practised at almost any place in the world, high grade heat recovery from magmatic chambers would be confined geographically to limited areas - just as with hyperthermal hydrothermal fields.

As to the cost of heat mining it is far too early to prognosticate anything positive, though I have heard unofficially that a cost of around 3 to 4 U.S. cents per kWh(th), at 1980 price levels, is being talked of for heat extracted by the simple Los Alamos type of disc fracture loop. What may seem expensive today may come to be regarded as cheap tomorrow.

Oil heat is now around 1 1/2 cents/kWh(th), and to make it useful it is necessary to provide some kind of heating equipment such as a boiler; so the actual price gap is not so very great even now, and this gap would of course be greatly reduced if heat mining were practised on a very large scale, and it must be expected that fuel prices will continue to rise. Before long it could well happen that heat mining will become competitive even in the simplest and most unsophisticated form. One cost advantage possessed by heat mining over the exploitation of hydrothermal fields is that the drilling success ratio should be about 100%: the risk element of drilling in geothermal fields would be obviated.

The days of cheap energy have departed. For the next two or three decades at least the cost of energy will almost certainly continue to rise - even though, as happened recently, there may be occasional temporary downward movements as a result of over-stocking or of trade slumps. Rising energy costs will undoubtedly cause severe economic, social and polictical strains. But at some time, perhaps not too far into the next century, I foresee the dawn of a new age of very cheap and abundant energy. The commercial and technical mastery of controlled thermonuclear fusion may well be achieved: let us hope so, for it is always preferable to have alternatives available. But I am confident that heat mining will in any case become an established activity before very long. I personally am desperately keen to see the coming of large scale heat mining, for I am convinced that it could avert untold human suffering. But, to be honest, that is not my only reason; for the winning of heat from the hot crust of the earth offers a tremendous challenge that must surely arouse response in many of us. The motivation that impels us to seek access to this immense source of energy is not only humanitarian: it is not unlike that which tempts men to do creative work or to overcome obstacles for the sheer satisfaciton of doing so. You all doubtless know the story of the Tibetan lama who asked the mountaineer, Mallory, why he wanted to climb Mount Everest. Mallory's simple answer was "Because it is there". That, to some of us, is as good a reason as any. Crustal heat "is there". Hence we seek to win it. The fact that we also need it is an additional incentive. Surely it cannot be beyond the wit of Man to overcome the two obstacles that now stand in the way of fulfilment? Let it not be forgotten that the miracles of nuclear fission and of space travel were accomplished within incredibly short times by virture of concentrated effort and will. Necessity is the Mother of Invention; and we are indeed faced with a very pressing necessity.