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Autor(en): **Jaffé, Felice C.**

Objekttyp: **Article**

Zeitschrift: **Bulletin der Vereinigung Schweiz. Petroleum-Geologen und - Ingenieure**

Band (Jahr): **38 (1971)**

Heft 93

PDF erstellt am: **20.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-197907

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Bull. Ver. Schweiz. Petrol.-Geol. u. -Ing., Vol. 38, Nr. 93, Oktober 1971, S. 17–40

Geothermal energy, a review

with 5 figures and 7 tables

by Felice C. Jaffé*

Abstract

Natural surface manifestations of geothermal energy, such as hot pools, steam vents, geysers, etc., have been known since Antiquity, but the significance of natural steam in terms of economic development has been grasped only in recent years. Individual geothermal fields occur under a great variety of geological conditions, but they all have in common a deep magmatic source, an aquifer in a highly permeable reservoir rock heated from below, and an impermeable cap-rock which prevents the escape of the accumulated steam in significant quantities. The geological environment of eight selected fields is described in order to illustrate their common and individual characteristics.

Exploration methods such as those used for oil, gas and minerals have been applied to surface and subsurface study of geothermal fields. However, new specific methods have also been devised, which are increasingly employed. Particular drilling methods and problems are described. An indication of average costs is also given.

* Department of Mineralogy, University of Geneva.
11, rue des Maraîchers, 1211 Genève 4, Switzerland.

The main utilisation of geothermal energy is electric power generation. The total installed capacity will quadruple from 385 MW in 1960 to approximately 1,600 MW by 1975. Production costs per kWh compare favourably with those obtained by the use of conventional fossil fuels. At present, important geothermal power plants are in operation in Italy, Japan, New Zealand and the U.S.A., while production on a smaller scale is going on in Mexico and the U.S.S.R.

Natural steam is also harnessed for district and greenhouse heating, especially in Iceland, for cooling and air conditioning, as well as for various agricultural and industrial applications in many countries.

Future utilisation trends point to an increased and more efficient electric power generation. The countries which are currently small producers will intensify the use of their vast geothermal resources, and in the next decade several developed and developing countries will join the list of present power producers. More intensive geothermal steam utilisation in agriculture can also be forseen, as well as heavy water production, water desalinisation and extraction of brines and chemicals by geothermal methods. The harnessing of geothermal energy in many developing countries well endowed with this kind of natural resource, but lacking in reserves of conventional fuels, is being actively undertaken under the sponsorship of the United Nations.

Zusammenfassung

Natürliche Manifestationen geothermaler Energie an der Erdoberfläche, wie zum Beispiel heisse Tümpel, Dampfemanationen, Geysire, usw. sind seit dem Altertum bekannt. Die Bedeutung des Naturdampfes aus der Tiefe für die wirtschaftliche Entwicklung ist jedoch erst in den letzten Jahrzehnten erfasst worden.

Die einzelnen geothermalen Felder kommen unter sehr verschiedenen geologischen Bedingungen vor; sie haben aber alle einen tiefen, magmatischen Wärmeherd, einen wasserführenden Horizont in einem stark durchlässigen Speichergestein, das aus der Tiefe erhitzt wird, und schliesslich eine undurchlässige Deckschicht, welche das Entweichen grösserer Mengen des angestauten Dampfes verhindert. Die geologische Situation von acht ausgewählten Feldern wird beschrieben, um ihre gemeinsamen wie auch ihre individuellen Eigenschaften aufzuzeigen.

Die Methoden der geothermalen Oberflächen- und Tiefenprospektion wurden aus denjenigen entwickelt, die bei Öl-, Erdgas- und Lagerstättenprospektion angewendet werden; es wurden jedoch auch neue Methoden ausgearbeitet, die speziell auf geothermale Ziele gerichtet sind, und diese finden immer weitere Anwendung. Spezielle Probleme und Bohrmethoden werden beschrieben und ihre durchschnittlichen Kosten sind angegeben.

Die geothermale Energie wird vorwiegend zur Erzeugung elektrischer Energie genutzt. Die gesamten aufgestellten Anlagen werden ihre Kapazität von 385 MW im Jahre 1960 bis zum Jahre 1975 auf ungefähr 1,600 MW vervierfachen. Die Produktionskosten per kWh liegen günstig im Vergleich mit den Kosten, die bei Benutzung der üblichen fossilen Brennstoffe entstehen. Gegenwärtig arbeiten bedeutende geothermale Kraftwerke in Italien, Japan, Neuseeland und in den USA, während die Produktion in kleinerem Rahmen in Mexico und in der UdSSR stattfindet.

In Island dient natürlicher Dampf vor allem zur Heizung von Wohngebieten und Gewächshäusern. Naturdampf wird weiterhin in vielen Ländern genutzt für Kühl- und Klimaanlagen, wie auch für verschiedenartige landwirtschaftliche und industrielle Zwecke.

In der Zukunft wird eine erhöhte Erzeugung elektrischer Energie mit einem erhöhten Wirkungsgrad erreicht werden. Länder, die gegenwärtig kleine Produzenten sind, werden in der nächsten Dekade die Nutzung ihrer ausgedehnten geothermalen Energiequellen verstärken, und weitere Industrie- und Entwicklungsländer werden die Liste der heutigen Produzenten ergänzen. Eine intensivere Nutzung geothermaler Dampfvorkommen ist mit grosser Wahrscheinlichkeit anzunehmen für die Landwirtschaft, wie auch in der Herstellung von schwerem Wasser, zur Meerwasserentsalzung und zur Extraktion von Solen und Chemikalien. Die Vereinigten Nationen fördern besonders aktiv die Nutzbarmachung geothermaler Energie in Entwicklungsländern, welche mit dieser Art natürlicher Energiequelle reich versorgt sind, denen jedoch Reserven konventioneller Brennstoffe fehlen.

1. Introduction

For well over a century, natural resources have been divided, somewhat arbitrarily, into mineral fuels, metals and non-metals. The history of their exploration and exploitation can certainly be regarded as one of the most important and fascinating chapters in the history leading to the etablishment of our present industrial society and culture.

Energy production from conventional and exotic raw materials has an increasingly significant bearing on our modern life, in spite of the puzzling side effects which the industrial revolution imposes on mankind.

The development of oil, coal and water as energetic raw materials is historically well established. However, the recognition that energy, as well as valuable mineral byproducts, can be obtained economically from natural steam, abundantly available in nature, is quite a new concept. Its importance has only been realized in recent decades.

The study of geothermal energy, with its challenging theoretical, scientific, technical and practical implications is a field which has not as yet caught the attention of a wide public. Moreover, it has been neglected to some extent even by geologists and earth scientists in general. However, there can be little doubt that their involvement with this subject will increase rapidly in the near future. The purpose of this article is to present a commented general picture of the field of geothermal energy. In the writer's opinion, the moment for such a synthesis is well chosen, because of the increasing importance of the subject itself, and the quantity of information which is now available.

2. Historical Background

It is difficult and somewhat superfluous to establish exactly when the existence of natural steam was described for the first time. To a large extent, ancient as well as recent history of geothermal energy and its byproducts can be linked to steam manifestations occuring in the Larderello region of Tuscany. In this region, references to natural steam date back to Roman poets, such as Tibullus and Lucretius, and to Roman geographers. It is not surprising to find a reference to Larderello's soffioni in the most exhaustive inventory of knowledge established during Middle Ages: Dante's Divina Commedia.

Industrial use of boric acid, a byproduct of Larderello's natural steam, was probably achieved for the first time by the Etruscans for making the splendid enamels with which their vases were decorated (ENEL, 1970). Small scale use of borates is said to have continued through the Middle Ages. The first records of its modern extraction date back to 1818, when a plant was built for this purpose by a French engineer, François Larderel, in honour of whom the village of Larderello located near the plant was named in 1846. 1904 is an important date in the history of geothermal energy. In this year, Prince Ginori Conti, Larderel's son-in-law, lit five light bulbs with electricity produced by a small turbine driven for the first time by natural steam. The power production was continously expanded thereafter. Up to World War II, the Larderello field was for all practical purposes the only field in which natural steam was harnessed on an industrial scale for the production of electric power and borates.

After the last war, during which the Larderello installations were destroyed to a large extent by the retreating German army, power production was resumed and increased, whereas the production of borates was discontinued.

Also after World War II, many new geothermal fields were discovered, studied and brought into production, leading to the present utilization pattern.

The first international meeting of scientists and engineers involved with geothermal energy convened in Rome in 1961, as a section of the United Nations Conference on New Sources of Energy (UNITED NATIONS, 1964). In 1970, the United Nations Symposium on the Development and Utilization of Geothermal Resources was organized jointly by the United Nations and the Italian Government in Pisa. The attendance of over 200 specialists from different countries can be considered as supplementary proof of the importance which geothermal energy has been assuming in recent years.

A significant contribution to the history and the overall knowledge in this field is the publication of a comprehensive bibliography, covering over 10,000 titles (SUMMERS and SCHWAB, 1971).

The Centro Internazionale per le Ricerche Geotermiche* carries out basic and applied research in Italy (in co-operation with the Ente Nazionale Elettricità – ENEL) and abroad. It organizes annual courses in geothermal science and technology for students from developing countries, and publishes a new international periodical, Geothermics. The proceedings of the United Nations conference held in Pisa will be published in the 1971 special issue. Future regular issues will contain articles and information pertaining to various aspects of geothermal energy.

3. Characteristics of geothermal fields

The existence of an economic geothermal field is based on the following geological and economic conditions:

1) A magmatic heat source at relatively shallow depth (1–10 kilometers).

2) An appropriate aquifer at drillable depth. This aquifer must be in a highly permeable reservoir rock, sufficiently thick and heated from below to generate and to maintain a system of convection cells.

3) A primary or secondary impermeable bed rock above the aquifer.

4) An economic extraction and utilization of dry or wet steam and its byproducts, if any.

5) The disposal of hot water and other waste products.

Among the conditions of existence enumerated above, two important notions are used which need to be more fully defined.

First, the distinction between dry and wet steam is based on the temperature of the vapor, for a given pressure. In dry or superheated steam, for a given pressure, its temperature is higher than the temperature of saturation of the steam-water system. In wet steam on the contrary, the two temperatures are equal, hence steam and water coexist. At lower temperatures, the hot water phase becomes dominant. Detailed information on steam-water systems at different temperatures and pressures are given by Mollier diagrams (SCHMIDT, 1963). Dry steam is desirable, because it has a higher enthalpic (or heat) content than wet steam, and consequently a higher thermodynamic yield. In actual practice, dry steam is rare in nature, and is being produced in significant quantities only in The Geysers and Larderello.

Secondly, a distinction must be made between primary and secondary cap-rocks. A primary cap-rock is a well defined original rock formation, such as for example the «argille scagliose» formation in Larderello. In a secondary or self-sealing cap-rock, the originally permeable rocks above the aquifer have been sealed by the action of hydrothermal fluids. The main self-sealing process is probably silica deposition filling the fractures and the pores. However, calcium carbonate at depth and argilisation at shallow depth may also play an important role. The presence of a self-sealing cap-rock was first recognized in The Geysers field (FACCA and TONANI, 1964 and 1967; FACCA, 1969).

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* Lungarno Pacinotti 55, Pisa, Italy.

4. Short geological description of selected fields

The existence of numerous geothermal fields has been recognized in many different countries (see fig. 1). Their exhaustive description exceeds the purpose of this article. Thus, only the characteristic features of some major fields will be indicated.

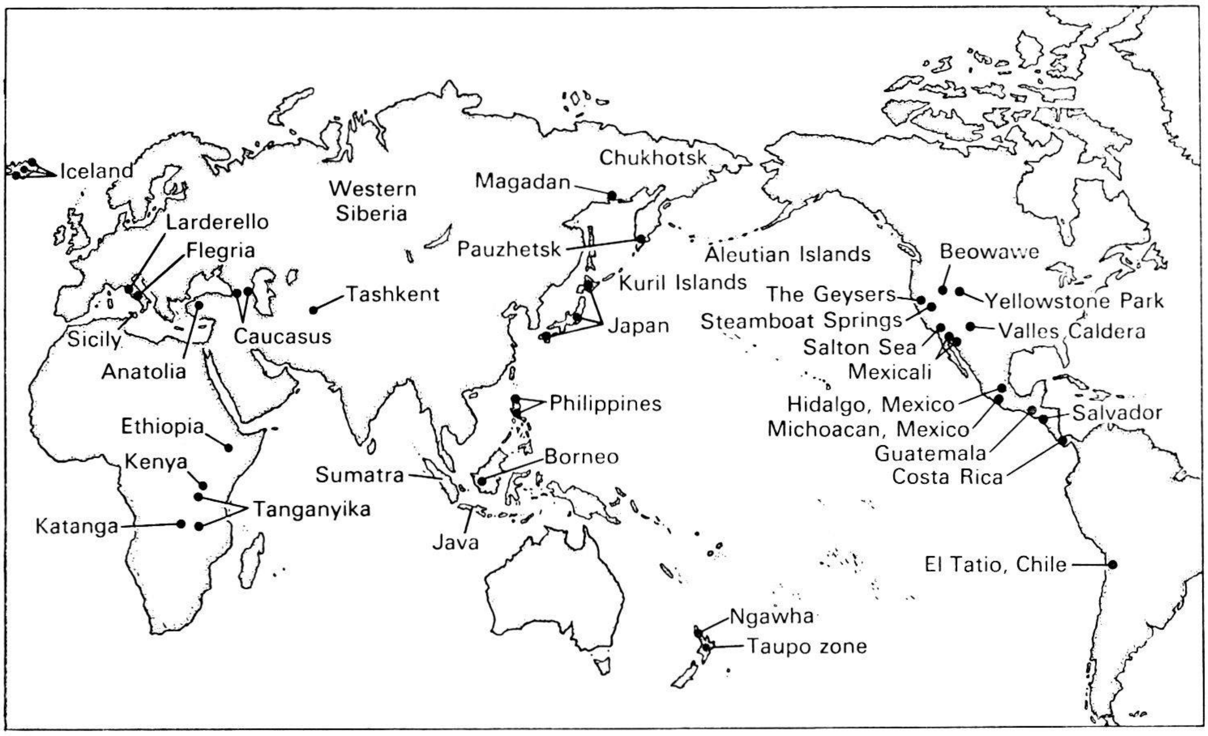

Fig. 1: Map of well known geothermal areas of the world (Ellis, 1967).

Even this condensed description shows that geological formations, structures and ages, as well as heat sources, recognized or postulated,vary greatly.

A comprehensive classification of the known fields is hampered both by their great variety, and in many cases by the lack of detailed geological subsurface information. Several classification systems have been suggested, partly based on genetic considerations (Makarenko *et al.*, 1971; Bonarenko *et al.*, 1971; McNitt, 1971). They should be considered tentative at best. Indeed they were put forward without sufficiently taking into account the nature of the heat sources, and the position of each field in relation to major features of deep tectonics.

Hence, no new classification is being proposed. Eight well known fields have been chosen to show the great possibility of variation in geological environment.

Larderello, Italy.

The Larderello region is the classical example of a field with a permeable reservoir rock formation (Tuscan series) covered by primary impermeable argilitic cap-rock (Ligurian series) (see fig. 2). The porosity of the reservoir is due to dissolution cavities in the Upper Triassic dolomitic limestone and anhydrite (see table I). Where the contact between the Tuscan and the Ligurian series intersects the topographic surface, the «soffioni» or natural steam vents used to exist. Since the field has been under intense exploitation, they have practically disappeared.

Contrary to a widespread belief, the Larderello field is not in a volcanic belt. Indeed, the nearest volcano, the Monte Amiata is about 75 kilometers away. The abnormal heat gradient in the Larderello region is probably due to a deep-seated Tertiary granitic batholith, similar to the Monte Capanne batholith on the Island of Elba (Marinelli, 1964).

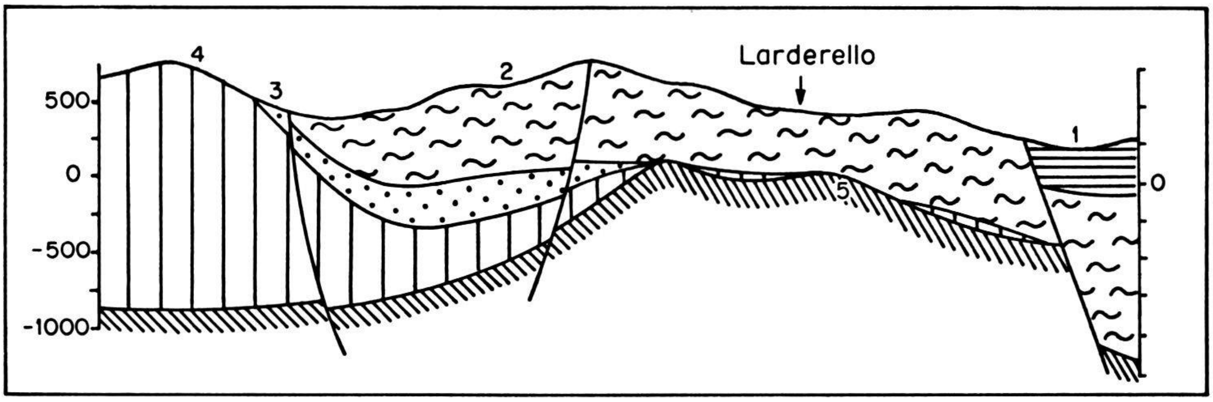

Fig. 2: Cross-section of the Larderello geothermal field (Enel, 1970). Scale in meters.
1. Pliocene – Miocene. 2. Ligurian series – cap-rock (Upper Paleocene – Upper Jurassic). 3, 4 and 5. Tuscan series: 3. Macigno (Oligocene); 4. Predominantly Mesozoic sedimentary sequence, including dolomitic limestones and anhydrite – reservoir rock (Eocene – Upper Trias); 5. Verrucano s. 1. (Upper and Middle Trias).

Table I: Stratigraphy of the Larderello geothermal field (Giannini *et al.*, 1971, slightly modified.)

Main rock types	Age	Tectonic unit
Clays, sandstones, conglomerates	Pliocene – Miocene	Neoautochtonous
Argilitic-calcareous flysch with associated ophiolites «Argille scagliose» Impermeable cap-rock	Upper Paleocene – Upper Jurassic	Alloctonous Ligurian series (overthrusted over Tuscan series)
Sandstones («Macigno»)	Oligocene	Autochtonous Tuscan series
Marls, radiolarites, limestones («Scaglia»)	Eocene – Jurassic	
Dolomitic limestones and anhydrites Permeable reservoir	Upper Trias	
Phillites, quartzites and conglomerates («Verrucano s.l.»)	Upper and Middle Trias	
Carbonaceous shales and quartzites	Permo-Carboniferous	Hercynian basement

Monte Amiata, Italy.

The sedimentary sequence in the Monte Amiata region, and in particular the well developed Tuscan series, is similar to the one described in the Larderello region. Dolomitic limestones and anhydrites of Upper Triassic age act as reservoir rocks. The predominantly argilitic flysch-like «Albarese-Pietraforte» series (Lower Cretaceous (?) – Lower Eocene) represents the impermeable cap-rock.

All these sediments were intruded during the Pleistocene by volcanic rocks of predominantly acid, quartz-latitic to trachytic composition, which formed the Monte Amiata volcano. The three small steam fields are only 3 to 5 kilometers in distance from the central Monte Amiata plug and are partly covered by ignimbritic flows. Thus it may be surmised that the anomalous heat gradient is related to the last cooling stages of volcanic activity.

The only surface manifestations which can be related to a concealed geothermal field are a few thermal springs, a common feature indeed in any volcanic region. Italian geologists deserve considerable credit for the detailed and successful studies of subsurface geology, involving geological, hydrogeological, geophysical and geothermal gradient investigations. Subsurface heat and conductivity measurements were carried out in over 200 boreholes on an average depth of 35 meters (range: 25–80 meters) (CALAMAI *et al.*, 1970).

The distance between the well known hydrothermal Monte Amiata cinnabar deposits and the geothermal fields is of only 2–4 kilometers. At this point, one should remember that probably more than 10 percent of all mercury deposits in the world are associated with thermal and mineral waters, with abnormally high subsurface temperatures, and with notable amounts of CO_2, H_2S and other gases, which in turn are common secondary manifestations in geothermal field (ELLIS, 1970; WHITE, 1971).

Hence, in this case the association between hydrothermal mercury mineralisation and geothermal activity may be to some extent genetic and not only spatial.

Matsukawa, Japan.

The Matsukawa region, on the Northern Honsyu Island, the main Japanese island, is located in a volcanic region of Miocene and Pliocene age composed essentially of dacitic and andesitic lavas and welded tuffs emitted by various volcanos. Hydrothermal alteation is very pronounced both on the surface and at depth. Steam production originates mainly from well developed cracks in hard welded tuffs which were emitted by the Marumori volcano (NAKAMURA *et al.*, 1971). The heat source is not specified, but in a predominantly volcanic region it can certainly be traced to lava formations which are still in the cooling stage.

Otake, Japan.

The Otake region, on the Northern Kyusyu Island is also located in a predominantly volcanic region, like practically all the numerous Japanese geothermal fields. Hot springs and fumeroles are abundant. A 700 meter thick Quaternary sequence of relatively viscous hornblende and pyroxene andesites with tuff breccias intercalations has been recognized. Hydrothermal alteration is so well developed and intense that six separate alteration zones have been mapped according to their predominant secondary mineral (YAMASAKI *et al.*, 1971). The heat source is not known with precision, but the same remarks made about the Matsukawa field apply also in this case.

Wairakei, New Zealand.

This field is in the center of the Taupo volcanic zone, a 15 to 25 kilometers wide belt extending for over 300 kilometers in a north-eastern direction in the center of North Island. The important Broadlands field is about 20 kilometers to the North-East.

Fumeroles and hot springs are frequent surface manifestations of an intense geothermal activity. The reservoir rock, the Waiora Formation is a permeable pumice breccia, 500 to

1,000 meters thick, which is covered by a relatively impermeable cap-rock (the Huka Falls formation), composed of siltstones, pumiceous sandstones and diatomites (70 to 170 meters thick). Below the pumice breccia, one finds the Wairakei ignimbrite formation, a relatively impermeable sequence of dense ignimbrite sheets, at least 600 meters thick. Indirect evidence points to the presence of a sedimentary greywacke basement, 4,000 meters below the surface. The steam is channeled into the reservoir by several major faults (see fig. 3).

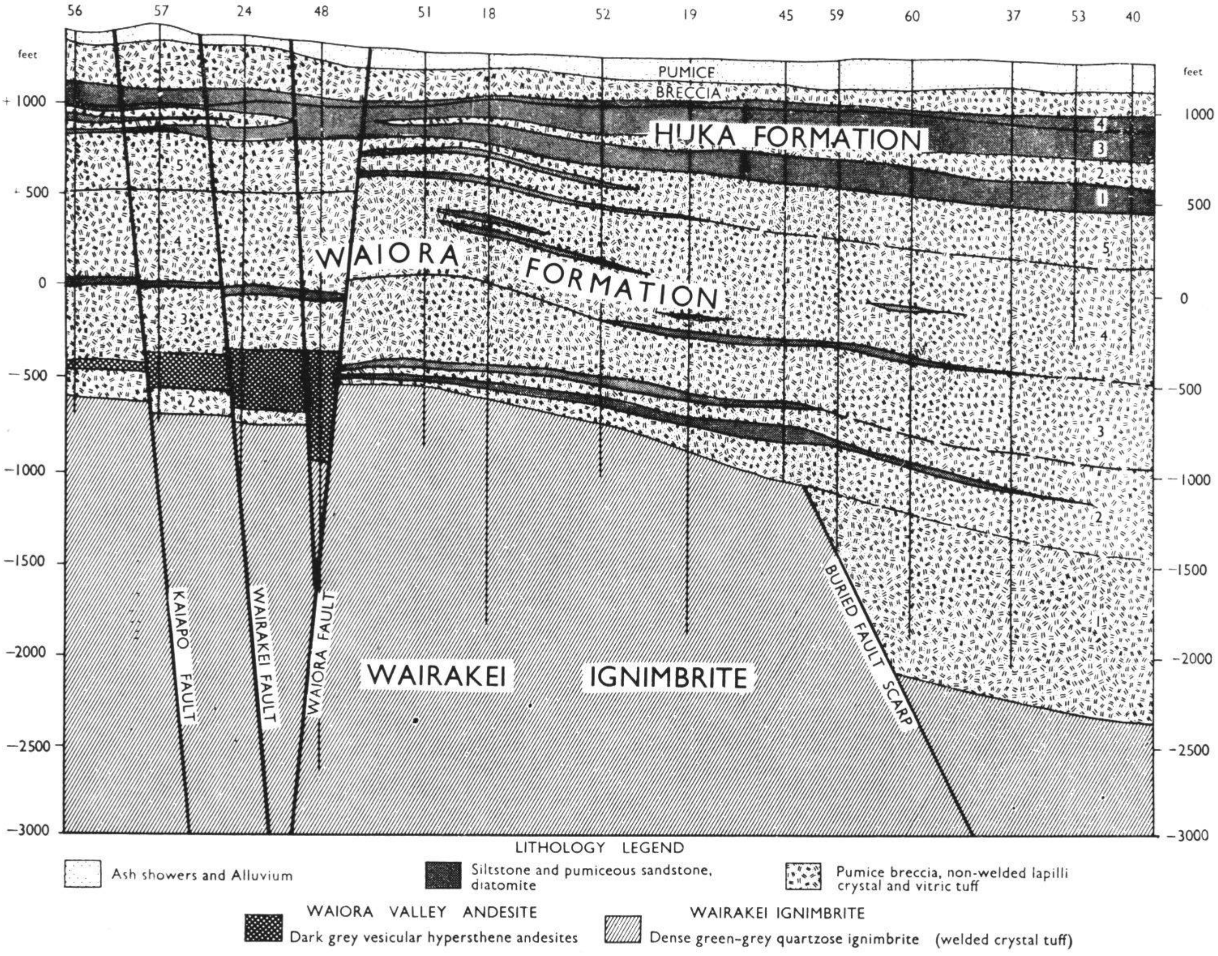

Fig. 3: Cross-section of the Wairakei geothermal field, from borehole 40 to 56 (Grindley, 1964).

The Wairakei field is of Middle Pleistocene age (500,000 years). Magmatic origin has been proposed for the steam. The heat source in areas of such intense volcanic activity may well be provided by buried lava masses which have not cooled completely.

Kizildere, Turkey.

This geothermal field in the Büyük Menderes (Meander) Valley, North-West of the town of Denizli, in Southwestern Anatolia. It was discovered in 1968 in a Miocene-Pliocene sedimentary series transgressive over a crystalline basement of Precambrian to early Palezoic age (see table II). The field is located in an uplifted fault block on the northern flank of the Büyük Menderes graben.

The hypothetical heat source may be one or more magma chambers connected with a cooling batholith of late Alpine age. The regional association between geothermal activity and cinnabar mineralization in Southwestern Anatolia should be mentioned.

Table II. Stratigraphy of the Kizildere geothermal field (Ten Dam and Erentöz, 1971, slightly simplified)

Age	Rock types	Significance for geothermal field
Pliocene 500 meters	Clays, marles, limestones sandstones, conglomerates	
Upper and Middle Miocene 400–600 meters	Argillaceous and marly argillaceous sediments	First cap-rock
Lower Miocene 400 meters	Fractured limestones	First reservoir
	Marls, sandstones, conglomerates	Second cap-rock
Crystalline basement	Fractured schists, marbles and gneisses	Second reservoir

The Geysers, U.S.A.

The Geysers geothermal field, Northern California, is rapidly becoming the largest geothermal field of the world. A buried heat zone gives rise to numerous surface manifestations such as hot springs, steam vents, hydrothermally altered rocks and silicified areas. This hydrothermal activity also appears to originate the mercury ores which have been mined in the area (White, 1967; Macmillan, 1970). The heat source is probably a buried igneous mass of Pleistocene age North-East of Geysers. Cobb Mountain, a Pleistocene rhyo-dacitic plug, about 5 kilometers from the producing zone, is the nearest youthful igneous body exposed at surface (Koenig, 1971).

The reservoir is composed of highly fractured greywackes, shales and ophiolites (basalts and serpentinites) of the Franciscan formation, Jurassic to Cretaceous in age. The absence of a primary cap-rock led to the elaboration and first successful application of the secondary self-sealing cap-rock theory.

It is interesting to note that in their quest for diversified energy sources, oil companies are taking a considerable interest in the Geysers field. Union Oil, Signal Oil and Gas and Occidental Oil have geothermal leases in the area. However, Union Oil is the most active company, through its partnership with the Thermal Power Company (Barton, 1971). It does the exploratory and developmental drilling and acts as operating agent. The steam produced by the Thermal Power Company is sold for power generation to the Pacific Gas and Electricity Company, which in turn supplies power to Northern California.

Salton Sea, U.S.A.

In 1957, a wildcat test for oil was drilled at Salton Sea, in the Imperial Valley, Southern California. The well was drilled to over 1,600 meters, and produced brine at a temperature of 340 ° C, the highest temperature recorded in a geothermal field. Subsequently 12 additional borehols were drilled (White, 1968; Koenig, 1971).

The reservoir at Salton Sea consists of highly permeable sands and silts of Pliocene age lying at depths greater than 1,000 meters. They are capped by relatively impermeable clay and silt beds of Pleistocene and Holocene age. Within the geothermal field, five buried domes of pumiceous rhyolite and obsidian of late Pleistocene age have been recognized.

The Salton Sea brine field produces a fluid containing approximately a total of 200,000 to 260,000 ppm dissolved solids, mostly chlorides of sodium, calcium, potassium, lithium and cesium. However, heavy metals are also remarkably high. The contents in ppm are: Fe: 2,000; Mn: 1,400; Zn: 500; Pb: 90; As: 12; Cu: 6; Cd: 2; Ag: 1. It has been calculated that the reservoir contains 5 cubic kilometers of interstitial brine. Hence the total tonnage of contained metals is very large. If all the constituents of the brine could be recovered and purified to commercial grade, admittedly a rather academic possibility, their market value (for 1968) would exceed 5 billion dollars. The lithium and cesium tonnage contained in the brine, for instance probably exceeds known world reserves. In terms of steam, one estimate states that 250,000 kW could be generated from the field as presently defined. For a 250MW plant, annual production of potassium chloride alone would exceed 4 million tons. However problems abound: disposal of bittern into surface and ground waters is prohibited, solar evaporation requires very expensive land holding and the extreme corrosivity and scaling characteristics of the brine require specially constructed pipes, valves, separators and turbines.

Considerable speculation about the genesis of this field's extremely high brine content has taken place. According to one theory, the heated aquifer intersected and dissolved a pre-existing evaporite series. A more extreme view postulates that the actual formation of a hydrothermal ore deposit is being witnessed. In many ways, the Salton Sea geothermal field is rather unique, for the time being, but analogies have been drawn to the hot brines deposits in the Red Sea (DEGENS and ROSS, 1969; TOOMS, 1970).

5. Exploration Methods

Each particular exploration venture has to be planned and carried out taking into account numerous specific geological, technical and financial factors. Thus, the actual number of steps composing an integrated program may vary greatly. Since it is not possible to define an ideal sequence of operations, the order in which different stages are described in this article may differ from that observed in actual practice.

5.1. *Geological reconnaissance*

Normal mapping of rock types, and interpretation of their stratigraphic succession, structure and genesis is of paramount importance. In addition, special attention should be devoted to the surficial nature and distribution of hydrothermal alteration zones.

Meteorological information, such as mean annual rainfall and temperatures, as well as their seasonal variations, must be carefully recorded.

The hydrogeological picture of the region under investigation should be well understood. For this purpose the depth of the water table, its nature, rate of recharge and the complete hydrological balance should be investigated.

Finally a complete inventory of all geothermal surface manifestations (hot springs, and rivers, fumeroles, geysers, etc.) should be established. Waters from these manifestations should be sampled and analyzed, since they may provide useful information about the nature of the concealed surface fluids. Surface temperature measurements will also yield valuable data for the preliminary assessment of a potential geothermal field.

5.2. *Airborne remote sensing*

The infrared sensor, which is used in this method, detects surface temperature anomaly by virtue of the fact that any terrestrial body at a given temperature above the absolute zero emits an energy in the form of characteristic radiations in the microwave region of the electromagnetic spectrum. Thus, regions showing surface geothermal activity give an anomalously high response as compared to the normal background. A few examples are given below to illustrate some successful and unsuccessful applications.

Airborne surveys carried out in New Zealand indicate for instance that the discharge area of hydrothermal systems can be mapped effectively by infrared images of emissive radiation in the 4.5–5.5 micron band. It is claimed that such measurements are much less time-consuming than those using conventional ground-temperature recording methods (HOCHSTEIN and DICKINSON, 1971).

In Iceland, aerial surveys carried out with an airborne scanner system, registering the same band, outlined the surface thermal pattern of geological structures controlling the upflow of hot water. Amplitude-slicing techniques applied to magnetically taped airborne-scanner data permitted an estimate of the natural heat output on the basis of the size of area and specific radiance. Costs for such a survey, not including mobilization-demobilization charges are indicated at $ 1.75 per line-kilometer for 1969, based on a 1450 line kilometers survey (PALMASON *et al.*, 1971).

In California, a previously unknown thermal area, Heise Springs, was located by remote sensing techniques using the 8–14 micron band (HODDER, 1971).

However, it must be understood that this method is not always successful. For instance, in Martinique and Guadeloupe (French Antilles), well known thermal areas were not registered in an airborne infrared survey, probably because of heavy vegetation effects and their small surface (CORMY *et al.*, 1971).

5.3. *Subsurface temperature and conductivity*

Surface information is never sufficient to fully understand the nature of a geothermal field and to assess its economic significance. Necessary additional information can be obtained by drilling exploratory holes of a shallow to intermediate depth, and by temperature and conductivity measurements in these holes.

There is no set rule at what depth a borehole is to be considered of shallow or of intermediate depth. However, in practice shallow holes range in depth between 1 and 50 meters, while holes of an intermediate depth are generally drilled down to 200 meters.

Deep holes are commonly drilled in order to establish the depth of the steam-producing horizon for subsequent production. Recording of relevant physical parameters of the reservoir fluid is of course still of great importance even in a producing field.

Temperature measurements in drill holes are carried out with specially designed thermometers. A wide selection of types in use and their precision are described in the literature (YUHARA, 1971; DEDKOWA *et al.*, 1971). Measurement are taken after a stabilization period of 20 to 30 days.

Average thermal conductivity is measured from core samples in the laboratory, and, less commonly, in situ using heated needle probes.

Subsurface temperature, geothermal gradient and conductivity data can be used to calculate the heat flow, and to draw isothermic, geothermal gradient and heat flow subsurface maps. Maps of this kind are interpreted and used to spot the emplacement of deep exploration holes necessary to intersect the steam-producing zone (CALAMAI *et al.*, 1970).

5.4. *Geochemistry*

Thermal springs are frequent surface manifestations of otherwise concealed geothermal fields. Sample collection and measurements of temperature and discharge rate are simple, fast and low-cost operations. Quantitative determinations of dissolved constituents can be carried out in a normally equiped chemical laboratory. A careful examination of the analytical data obtained yields useful qualitative information on subsurface temperature ranges of geothermal fluids (see table III). Hence, water geochemistry is widely applied in geothermal exploration (WHITE, 1971; TONANI, 1971).

Table III: The main geochemical indicators of subsurface temperatures in wet-steam systems (WHITE, 1971, simplified).

Water geochemistry	Subsurface temperature
SiO_2 content	increases with temperature
Na/K and Na/Ca ratio	decreases with temperature
Mg content and Mg/Ca ratio	increases with temperature
$Cl/HCO_3 + CO_3$ ratio	increases with temperature

No reliable geochemical indicators for subsurface temperatures of dry-steam systems have yet been established.

It should be stressed that in nature there is a complete range between wet and dry-steam systems, and that a meaningful interpretation of analytical data must take into consideration all the significant parameters of fluids in a given geothermal field.

5.5. *Geophysics*

Electric resistitivity.

Hot water reservoirs can readily be mapped and their thickness estimated because of the anomalous increase in electric conductivity of hot saline waters. Direct and inductive methods have been widely used. The disadvantage of inductive methods is that the procedures used to determine resistivity from field measurements are more complicated than those obtained by the use of direct-current methods (KELLER, 1971; STRANGWAY, 1971).

Gravity.

The existence of an empirical correlation method between high heat-flow areas and gravity highs has been known for some time. A significant increase in density occurs with increasing hydrothermal alteration. Indeed a density difference of 0.3 to 0.4 g per cm^3 has been established between hydrothermally altered and unaltered rocks of the same geological unit. Thus, gravity surveys can be quite successful, provided there is enough quantitative information available to allow the removal of disturbing effects of non relevant structures in the area under study (BANWELL, 1971; HOCHSTEIN and HUNT, 1971; MEIDAV, 1971).

Seismic reflection and refraction.

Seismic reflection sounding has been used in two Japanese geothermal fields. The introduction of a magnetic tape recording system and digital data processing has made it possible to remove from the records undesirable noise and multiple reflection. Thus, interfaces as deep as 2 kilometers have been recognized (Hayakawa, 1971).

In the Broadlands field in New Zealand, seismic refraction profiles were used to construct a contour map of the refractive interface underlying the pumice, tuff-siltstone sequence. Subsequent drilling has shown that two larger structures indicated on this contour map are ryolite domes (Hochstein and Hunt, 1971).

Geothermal ground noise.

Acoustic noise patterns within certain frequency ranges seem likely to provide a further useful and relatively simple method for detecting and mapping certain types of geothermal area (Clacy, 1968; Whiteford, 1971). However, this method has not been applied sufficiently to test its overall effectiveness.

Airborne and surface magnetism.

The major difficulty of magnetic surveys is their correct interpretation. Indeed the number of magnetic anomalies in each given survey is so large, especially in volcanic areas, that most of them, taken alone, seem to mean very little. It has been suggested that the use of magnetic methods is appropriate to complement resistivity surveys. Hence, a distinction may be made between conducting zones due to permeable formations containing hot water and those resulting from the alteration of volcanic rocks into conductive material. It may be assumed that, other things being equal, magnetic susceptibilities will be different according to the cause of the resistivity anomaly (Duprat, 1971).

6. Drilling

6.1. *Methods*

Drilling of wells for steam is carried out with rotary rigs similar to those used in the oil industry, normally of a 1,000 to 2,000 meters capacity, and relatively large hole diameters, with casings of $13^3/_8''$ or $9^5/_8''$ (Giovannoni, 1971). Power supply is generally provided by a Diesel system when distribution centers for electric power are distant, principally during the exploration phase. The use of electricity can become economical when a geothermal power plant is operating in the region (Cigni, 1971).

Cementing of the casing is rendered difficult in geothermal drilling by the high environmental temperatures, ranging from 120 to 200° C, which cause radical physicochemical changes in the cementing materials, thus preventing adequate solidification. Furthermore, failures also arise from the contamination of the cement by the mud which remains between casing and well. To overcome these difficulties, the correct cement must be used, and the work should be carried out in the following sequence (Fabbri and Giovannoni, 1971):

a) The mud is removed from the well by pumping in slurry in a state of turbulence, to avoid canalization and to increase the percentage of mud displaced. During this stage it is indispensable to maintain water cushions between mud and cement.

b) The casings are equipped with centralizers and scratchers of sufficient number and type to assure adequate centralizing of the casing and removal of mud cake from the walls.

c) In addition, it has become rather common practice to move the casing during cementation to improve the distribution of cement in the anulus. This is believed to facilitate the elimination of water pockets which could cause the casing to collapse by formation of steam and expansion at the prevailing high temperatures.

Normal cements give rise to hydration products with low mechanical resistance and consequent retrogression phenomena, which can be eliminated by addition of up to 30 percent silica. However, silica should be added only for zones in which temperatures exceed 110° C. At lower temperatures the silica does not cause the formation of the beneficial high-resistance products, and in fact conditions worsen. Along with silica, chemical additives such as retardants, friction reducers, antifoamants are also used.

High temperature contributes to the degradation of some mud products because it speeds up unfavourable chemical reactions which lead to flocculation. Hence, chromolignosulfate and chromolignine muds are widely used. (FABBRI and VIDALI, 1971). In Japan, for instance, the successful use of neochromite muds has been described, consisting of a mixture of ferrochromolignosulfate and chromite in a 3:1 ratio. The chromite employed is a telnite B treated with a bichromate to reduce the viscosity and resistance of the gel. The chromite has a pH of about 9; it is not a compound of ferric and chrome ions but a chelated lignosulfonic and huminic acid which will not dissociate even in the presence of ions in solution (NAKAJIAMA, 1971).

The capture of steam from wells below the productive casing can be achieved by two methods: open-hole production, or the use of a slotted liner or perforated casing. The choice of method is determined primarily by the productive geological formation, but also by the pressure, the temperature and the continuous yield of fluid. In the Italian and the Californian geothermal fields, the productive permeable strata are formed by rather hard creviced formations of Mesozoic age, so that production can be maintained without a liner. In New Zealand and Japan on the contrary, the steam originates from permeable strata consisting mainly of loose volcanic breccias and soft tuffs, a rock-type in which a soltted liner is required to keep rock fragments out, and to prevent swelling and caving of the walls. (KATAGIRI, 1971; STILLWELL, 1971).

The importance of well surveys to determine the technical state of drilling operations, and to give essential information of productivity must be stressed (see table IV).

Table IV. Measurements in boreholes (Matsuo, 1971)

Investigations in well	Surveying Instrument	Purpose of investigation
Temperature measurement	Point surveys Thermometer check at various depths, showing maximum temperature Multiple and continuous check with Kuster and Thermistor	Study of temperature variations in the well and distribution of the geothermal heat Possible identification of steam or hot water strata
Electric logging	Electric apparatus from the service company	Comparison of formations and supplementary analysis of the terrain by electric inspection
Measurement of internal flux in well	Spinner	Measurement of steam flux
Measurement of inclination	Clinometer of Totco, Tokoto and Murata types	Measurement of the direction and inclination of the well to define its exact location
Measurement of pressure	Amerada type apparatus (Bourdon tube), or Humble type (spring)	Measurement of pressure in the well; possibility of productivity forecast
Check of fluid entering bottom of the rig	Bottom hole sampler	Check of water under pressure into the well
Logging for consistency of cement	Sonic logging	Check of success of the cementation

6.2. *Costs*

Table V. Drilling costs.

Location	Number of bore holes	Depth in meters	Cost per meter (in $)	Reference
Otake, Japan	not available	500 1,000 1,500	106	Hayashida, 1971
Matsukawa, Japan	6	1,200–1,500	172	Nakamura, 1971
Broadlands, New Zealand	9	800–1,000	90–110	Stillwell, 1971
	6	1,500	40– 72	
	1	2,600	50	
Geysers, U.S.A.	not available	1,600–2,600	60–100	Mac Millan, 1971
United Nations, unspecified country	5	1,200	65	Bradbury, 1971

7. Utilization

7.1. *Power production*

The main utilization of geothermal energy is the production of geothermal power. The choice of the best suited plant is conditioned by the physico-chemical properties of the steam, and by the type of power which is to be produced. Two classical types for instance are in use at Larderello: the non condensing type (or cycle 1), in which the steam is returned directly to the atmosphere after passing through the turbine, and the condensing type (or cycle 3), in which the steam is condensed in a cooling tower after passing through the turbines (see fig. 4 and 5).

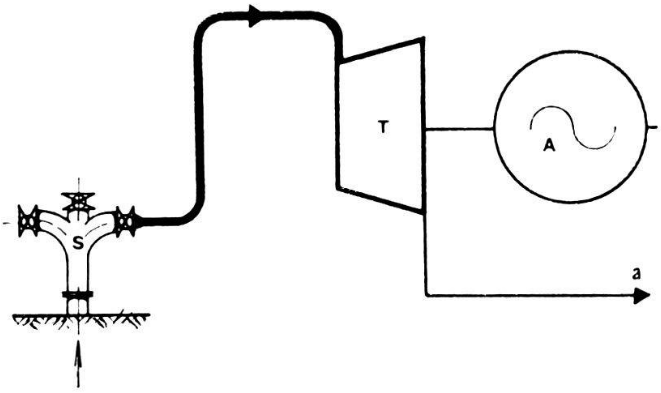

Fig. 4: Non-condensing geothermal plant, Larderello (ENEL, 1970).
S. Well-head; T. Turbine; A. Generator; a) Exhaust to atmosphere.

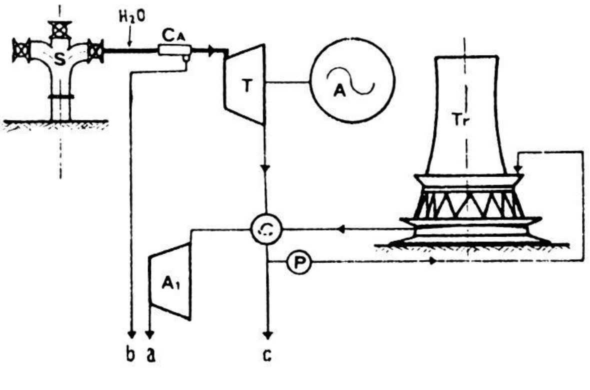

Fig. 5: Condensing geothermal plant, Larderello (ENEL, 1970).
S. Well-head; H_2O. Injection of water for washing steam; CA. Axial separator; T. Turbine; A. Generator; C. Mixing condensor; Tr. Cooling tower; P. Pump; A_1. a) Gas discharge; b) Boron-bearing water discharge; c) Excess water.

The considerable progress in power production (see table VI) raised the total world installed capacity from 385,7 MW in 1960 to 675,6 MW in 1969. In 1975, the planned capacity of 1581,6 MW will be reached, taking into account the rapid development of The Geysers field to 500 MW. One has to bear in mind that the total capacity of this area proven by drilling is of 2,500 MW. Hence, it is certain that for the next decade at least, The Geysers field will become and remain the largest field of the world. Many other exploration projects are nearing the stage at which a final decision on exploitation will be taken in the next few years.

Table VI. World geothermal power production (Facca, 1971).

Country	Field	Installed capacity (MW) 1960	Installed capacity (MW) 1969	Additional capacity planned for 1975 (MW)
El Salvador	Ahuachapan			20
France	La Bouillante (Guadeloupe)			30
Iceland	Namafjall			3
Italy	Larderello	274.7	358.6	
	Monte Amiata	10.5	25.5	
Japan	Matsukawa		20.0	7
	Otake		12.0	50
	Shikabe			180
Mexico	Cerro Prieto	3.5	3.5	150
New Zealand	Wairakei	60.0	160.0	
	Kawerau	10.0	10.0	
Taiwan	Tatun			10
Turkey	Kizildere			30
U.S.A.	The Geysers	27.0	83.0	400
U.S.S.R.	Pauzhetka		3.0	20
	Kunashiry (Kurili)			6
Total		385.7	675.6	906

7.2. *Cost of power*

Cost calculations are difficult and at times even controversial. Numerous factors contributing to the final cost have to be carefully considered: land purchase (or royalties), exploration, drilling, pipeline installation and maintenance, plant cost and maintenance, interest rates, amortization and depreciation, taxation, load factors, etc.

The economic significance of such costs for a given field cannot be evaluated per se, but must be compared with costs of power produced by other conventional methods, such as fuel, natural gas and uranium. A case in point is the Broadlands field, New Zealand. Detailed studies proved that a power plant for an installed capacity of 120 MW could be operated economically. Just before the decision to commission the necessary plant was taken, the Mauri natural gas field was discovered, which could provide a cheaper energy source for power generation. Thus, plans to exploit the Broadlands geothermal field were suspended.

Costs figures are available only for a few geothermal fields (see table VII).

Table VII. Geothermal power generation costs.

Geothermal field	Costs in mills of US $/kWh (1 mill = 0.001 $)	Reference
Namafjall, Iceland	2.5–3.5	RAGNARS et al., 1971
Larderello, Italy	3.2–4.8	FACCA, 1971; Unpublished information
Matsukawa, Japan	4.6	MORI, 1971; FACCA, 1971
Cerro Prieto, Mexico	4.1–4.9	ALONSO *et al.*, 1967
The Geysers, U.S.A.	5.0	MACMILLAN, 1971
Pauzhetka, U.R.S.S.	7.2	ARMSTEAD, 1971

For future projects, the following «rule-of-thumb» has been formulated: In a developed country, the cost of the kWh produced by a dry steam geothermal field is about $^3/_5$ of the cost of the kWh produced by conventional fossil fuels, for a power system of the same capacity. In the case of wet steam, the cost of the kWh produced by a geothermal fields is competitive with the cost of the kWh produced by conventional methods, for a power production of the same capacity (FACCA, 1971).

If this postulate is accepted, the future of power production from geothermal energy appears promising indeed.

7.3. *Other uses*

Varied applications principally in district, agricultural, and industrial heating and cooling have been found for geothermal fluids. Examples of these applications are given by country.

Hungary.

The intensive geothermal exploration of the Hungarian basin led to the discovery of vast quantities of hot water at 85°–90° C at 1,800–2,000 meters depths with an average yield of 80–90 m³ per hour. Of the 80 geothermal wells in operation, the majority are located in the province of Csongrad near the Yugoslav border. An average well heats 1,200 housing units and associated public buildings, swimming pools, etc., and supplies domestic hot water. By mid 1969 about 500,000 m³ of housing units and public buildings were heated by geothermal water. For the town of Szeged, the total heating costs come to US $ 3/Gcal, as compared to US $ 11/Gcal for a comparable coal-fired district heating system.*

The use of geothermal energy for greenhouses and other agricultural applications, such as heating of pigsties, chicken houses and other farm premises and for drying crops is developing rapidly. The heated greenhouse area was of 400,000 m² in 1969, and doubled in 1970.

It may be worth while mentioning that in Hungary oil was discovered incidentally through geothermal exploration. In 1966, a geothermal borehole near Szeged led to the development of the country's largest oil and gas field, increasing the total national production capacity by a yearly amount of 7 million barrels, and doubling its natural gas reserves (BOLDIZSAR, 1971).

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* 1 Gcal = 1 cal × 10^9; 1 Tcal = 1 cal × 10^{12}

Iceland.

Total energy production for geothermal househeating has doubled in the last decade. At present over 40% of the total population (200,000) live in houses heated with geothermal water. This percentage is estimated to reach 60–70% in the next decade. The Reykjavik district heating system is by far the most important, with a total power of 235 Gcal/h, a yearly heat production of 1,040 Tcal/year (1968), heating 10.3×10^6 m^3 of buildings. The distribution system consists partly of a single pipe system in which the water is wasted after passing once through the house plants, and partly of a double pipe system where the waste water is collected in return mains and admixed to the high temperature water from the Reykjavik field in order to reduce its temperature to 80° C, which is the distribution temperature.

In the Reykjavik district heating system, the users pay \$ 0.16/m^3 for delivered water. Based on average utilization, this corresponds to \$ 4.00/Gcal as compared to \$ 6.70/Gcal for heating with imported fuel. The geothermal district heating system is saving imports of approximately 200,000 tons of fuel oil per year, a significant quantity for the economy of a small country (EINARSSON, 1971; PALMASON and ZOEGA, 1971).

In 1970, approximately 100,000 m^2 of glass-covered greenhouses were heated by natural steam. About 70% of the area is used for vegetables, mostly tomatoes, cucumbers and lettuce, giving an anual crop of 1,000 tons, as against 30% for various flowers.

Rich deposits of high-grade diatomite were discovered on the bottom of Lake Myvatn, the well known tourist resort in Northeastern Iceland. The Namafjall geothermal field was developed principally to dry the diatomites. These are dredged and dewatered before processing the raw material into diatomite filteraids. The mining company, which produces 24,000 tons/year of diatomite is jointly owned by the Government of Iceland and the Johns Manville Corporation, U.S.A. It exploits the only water-covered diatomite deposits of the world. Steam is used directly to dewater the wet diatomite, and to generate power for a non-condensing power plant, with a capacity of 3 MW. Plans are being studied for the construction of a geothermal district heating system for the mining village, the tourist hotels on the lake, swimming pools, greenhouses, etc. (LINDAL, 1971 a; RAGNARS *et al.*, 1971).

The power cost of this project is quoted at US \$ mills 2½–3½ per kWh. Approximately 7½ tons of steam are used to dry one ton of wet diatomite. Assuming that the plant pays \$ 0.25 per ton of steam, the approximative expenditure for the drying process is \$ 2 per ton. With the local cost of fuel oil, drying costs by conventional heating methods would be on the order of \$ 12 per ton (LINDAL, 1971 a).

Japan.

Several small district heating and greenhouse installations function satisfactorily (MASHIKO *et al.*, 1971).

Sea water is dryed by geothermal steam in one small plant for salt production. It is planned to expand production to 100,000 tons per year. The new plant will use a multistage vacuum distillation, incorporate an ion exchange eletrolytic dialysis unit, and produce salt and fresh water from sea water.

Sulfur extraction from volcanic fumeroles is practiced on an artisanal scale.

Kenya.

In the semi-arid Rift Valley, drinking water for cattle is obtained on a small scale by local farmers from surficial natural steam. The country's geothermal potential can certainly be developed beyond this artisinal utilization. In 1966, the author of this article evaluated the geological and economic data available on Kenya's geothermal fields, and recommended further exploration work. On the basis of these recommendations, a geothermal exploration project was planned by the United Nations. This project went into operation in 1970.

New Zealand.

The town of Rotorua, on Northern Island is heated with natural steam. Contrary to Iceland's procedures, based on an integrated central district heating system, Rotorua is heated by an amazingly high number of 1,000 boreholes. Each borehole is connected to single houses or group of houses and building complexes. The boreholes range between 45 and 430 meters in depth, most of them having a depth of 100 to 150 meters. Strict regulations on ownership of steam, water disposal and H_2S pollution are enforced (BURROWS, 1971; COOKE, 1971).

An interesting project in the same town is the air conditioning of a 100 room tourist hotel, the system being designed for outside temperatures between —4 ° and +30 ° C. The cost of the installation including the borehole is said to be comparable to that of an oilfired system. The operating costs however are only $ 0.12/Gcal as compared to $ 2.40/Gcal for oil in New Zealand (REYNOLDS, 1971).

The Tasman Pulp and Paper Company near Rotorua is probably the largest consumer for process heating in the world (SMITH, 1971).

U.S.A.

Competition from conventional fuels diminishes the interest of natural steam for district heating. Thus, only the Klamath Falls, Oregon project uses geothermal fluids for this purpose, in a fashion similar to that employed in Rotorua, New Zealand. Approximately 400 buildings are heated by over 350 wells, of an average depth of 150 meters. Each well is cased and perforated, and a U-shaped length of pipe is inserted. The well is then sealed around the pipe, and cool water is circulated down-well in the pipe. There the water is heated by the surrounding hot fluids and is carried by thermosyphon to taps and radiators. The methods employed in this project are of particular interest, because they eliminate scaling and water-table lowering problems (FACCA, 1971).

U.S.S.R.

Several district heating and greenhouse projects have been developed, or will be in operation in the near future (EINARSSON, 1971).

7.4. *Future developments*

A world-wide interest in the existence and the utilization of geothermal energy has developed only after World War II. Hence, there is still an acute need for more basic and applied research in order to understand its nature and origin. The similarity of geothermal and hydrothermal processes, for instance, has not been widely recognized and further studies in this field may be fruitful for the understanding of the genesis of many ore deposits.

Exploration of many fields is not as yet completed, and may significantly change the present utilization pattern of natural steam. The possibility of the existence of completely concealed fields, such as the one discovered in the Hungarian basin, should not be ruled out, but their discovery will require more sophisticated tools and know-how.

Inadequate legislation on ownership and utilization of natural steam still prevails in many countries, and has restricting effect on exploration. In the U.S.A. for instance, legal problems have severely hampered exploration on public lands (KAUFMANN, 1971). Improvements in existing legislation will have a strong impact on the development of geothermal energy.

In the field of power production, the advantages of power plant decentralizations for geothermal fields extending over large areas will be of considerable significance, calling for a more efficient transmission of geothermal fluids. Power plant automation will certainly be considered carefully in future exploitation projects (ARMSTEAD, 1971). Finally, a growing interest is being detected for power generation in the use of secondary fluids, such as freons (PESSINA *et al.*, 1971).

Increased use of natural steam can be anticipated for refrigeration and processing of crops such as sugar, rice and coffee.

Various systems for production of water from geothermal steam in arid countries are being studied (ARMSTEAD, 1967).

The use of geothermal steam for heavy water production is being considered in Iceland. For a 400 ton per year plant, production costs of $ 36.80 per kg D_2O have been calculated, as compared to $ 40.14 for a plant using conventional steam (VALFELLS, 1971).

The production of sodium chloride, potassium chloride, calcium chloride and bromide from the Reykjanes field in Iceland is under study. This field contains geothermal brine which is contamined with seawater. For a yearly production of the order of 300,000 tons per year, the cost of salt may be as low as $ 4 per ton (LINDALL, 1971 b).

Up to now, the major developments in the utilization of geothermal energy have taken place in developed countries, while geothermal fields in many developing countries have been somewaht neglected.* Preliminary United Nations studies in over 30 countries significantly lacking in reserves of conventional fuels, have led to the approval and the execution of 5 geothermal projects. These are financed by the United Nations Development Program and the Governments of Chile, El Salvador, Ethiopia, Kenya and Turkey. The projects in El Salvador and Turkey are at an advanced stage. Results are positive, and plans for electric power production are under way. Harnessing of geothermal energy through international co-operation will certainly be intensified in years to come.

8. Conclusions

Prior to World War II, the significance of geothermal energy was hardly recognized, and was limited more often than not to a vague knowledge of its more spectacular surface manifestations such as the geysers in Iceland and Yellowstone Park or the soffioni in Italy. Since then, many geothermal fields have been investigated in detail and several have been brought into production for the generation of electric power and for numerous other industrial and agricultural applications. A considerable theoretical and practical knowledge of natural steam had to be gained and put to good use in order to achieve such remarkable results in little over two decades. Geologists in many countries deserve considerable credit for this rapid development which was achieved in close cooperation with physicists, chemists and engineers – an outstanding example of a successful interdisciplinary approach towards a new subject.

The costs of harnessing and utilizing geothermal energy are generally low and compete favourably with those of energy produced by conventional fossil fuels. Hence, it may be anticipated that the use of geothermal energy will increase. It may have, in some instances, a significant impact upon the economic development of countries well endowed with natural steam.

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* Currently, geothermal exploration programs of varying importance are carried out in the following countries: Algeria, Colombia, Chili, Dominica, El Salvador, Ethiopia, Guadeloupe (French West Indies), Greece, Iceland, India, Indonesia, Israel, Italy, Japan, Kenya, Mexico, Morocco, New Hebrides, New Zealand, Philippines, Rwanda, St. Lucia, Spain, Taiwan, Tanzania, Turkey, Uganda, U.S.A., U.S.S.R.

Finally, it is also gratifying to notice that some oil companies are already actively participating in a major geothermal venture, and that others are on the verge of entering the field. Considering the increasing need for a diversified supply in energetic raw materials, which has been repeatedly stressed in recent years, the oil industry's involvement is certainly to be welcomed.

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