Isotopes in geothermal energy exploration

by E. Barbier, M. Fanelli, and R. Gonfiantini*

To many readers of the IAEA Bulletin, which is usually devoted to the problems of nuclear energy, the publication of this article on geothermal energy might appear rather curious. What contribution can isotope techniques make to the development and exploitation of this form of energy, which represents only a very minor fraction of the energy currently produced in the world? This article will try briefly to illustrate how geothermal energy arises and the role of isotope investigations in geothermal exploration, just one part of the vast range of isotope applications in hydrology, in geochemistry, and in geology.

The future of geothermal energy presents questions which are not easy to answer. It is certain that up to now only the more easily accessible geothermal fields have been exploited and also that in the near future it can become important for the industrial and social development of many regions in developing countries. However, the particular attraction of geothermal energy is that its ultimate source is practically infinite: the heat of the Earth's interior. The challenge therefore is how to exploit even only the distant periphery of such an immense reservoir of abundant energy.

Heat from the depths of the Earth

Since the 18th Century, measurements in mines have shown that temperature increases with depth: in other words, that there is a continuous heat-flow from the Earth's interior to the surface. The average temperature gradient is 3°C per 100 m depth.

From the surface to the centre, the Earth is made up broadly of three layers: the crust, the mantle, and the metallic core. The crust, mainly composed of granites above and basalts beneath, has a thickness of about 35 km under the continents; the crust is only 5 km thick under the oceans, and consists mainly of basaltic rocks. The crust floats on top of the denser and more plastic materials of peridotitic type which constitute the mantle which has a thickness of 2900 km. The crust is split into six main plates which move relative to each other.

Along the so-called mid-oceanic spreading ridges, the mantle materials ascend to the Earth's surface, determining the growth of the adjacent plates. These plates therefore move away from each other at a rate ranging between 2 and 20 cm per year. In geological terms, this is an enormous speed. To compensate for this growth there are other zones, called subduction zones, where one plate plunges below the adjacent plate into the mantle. These zones often correspond to oceanic trenches, bordered by island arches or by mountain ridges along the continent edges. Mid-oceanic spreading ridges and subduction zones tend to be the areas where the internal heat of the Earth reaches the surface, and where most volcanoes and most of the world's geothermal fields are located.

The geothermal fields

Geothermal fields are areas where the temperature of the groundwater is well above normal values and where the water can be exploited for various purposes, such as space heating and power production (above 150°C). The heat sources are magmatic intrusions at depths of 7 to 15 km or, where the Earth's crust is thinner, the mantle itself. The heat is transferred to sub-surface regions firstly by conduction and then by groundwater convection. Impermeable rocks cover the permeable formations containing the hot water (called the geothermal reservoir), preventing or limiting the heat losses and maintaining the hot fluid under pressure. If boreholes are sunk to the geothermal reservoir, the hot fluid can be extracted and exploited.

When the conditions are particularly favourable, superheated dry steam can be produced with a temperature often exceeding 250°C. This can be conveyed directly to turbines to move alternators and produce electricity. Such geothermal electricity is the cheapest of all the ways of producing electrical power. Examples

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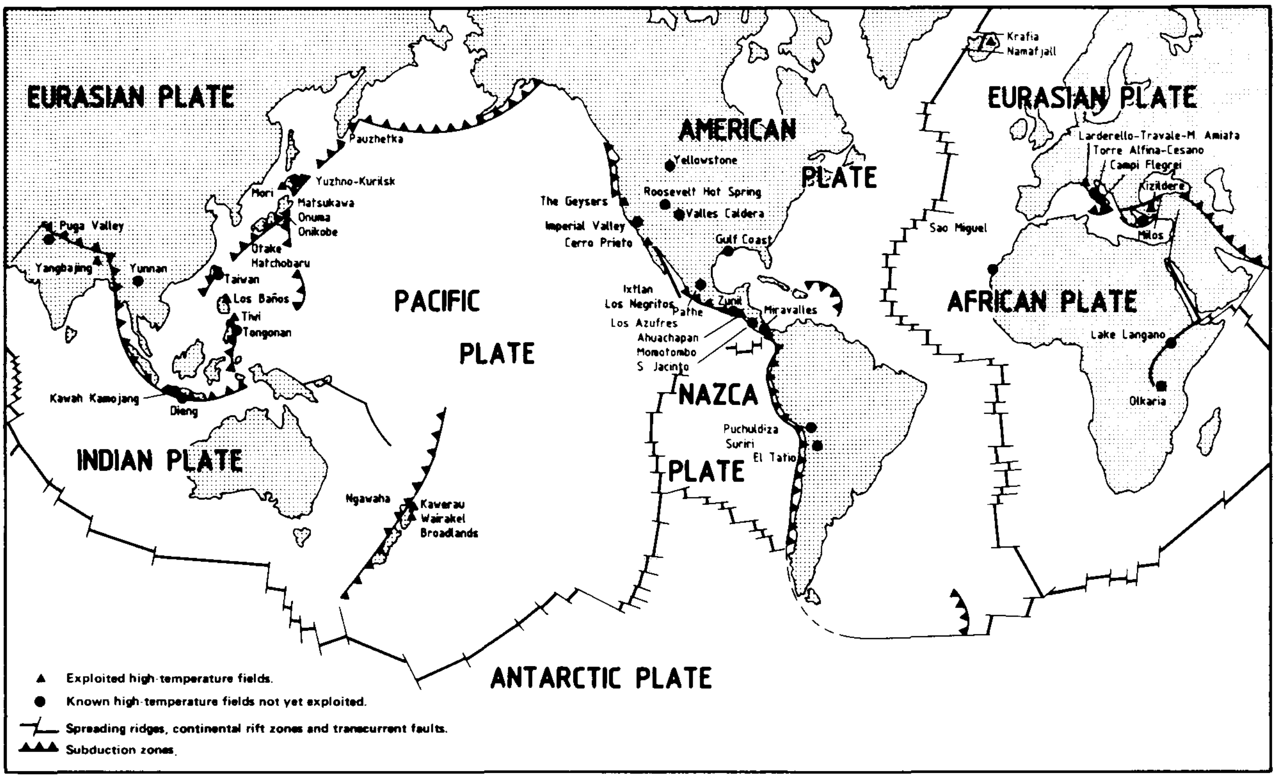
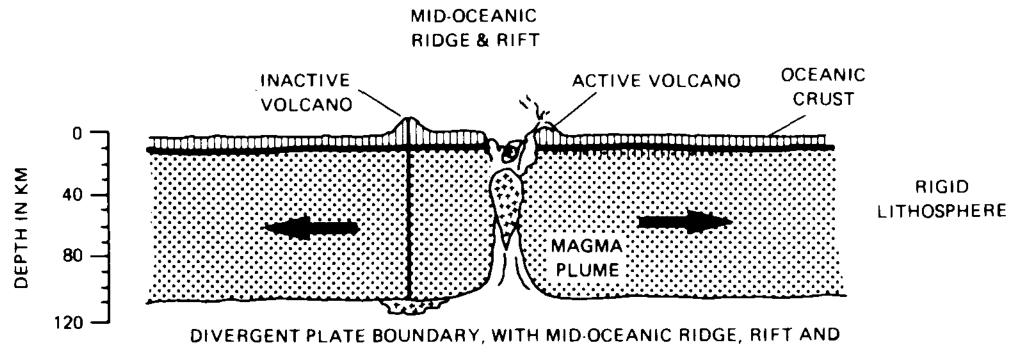
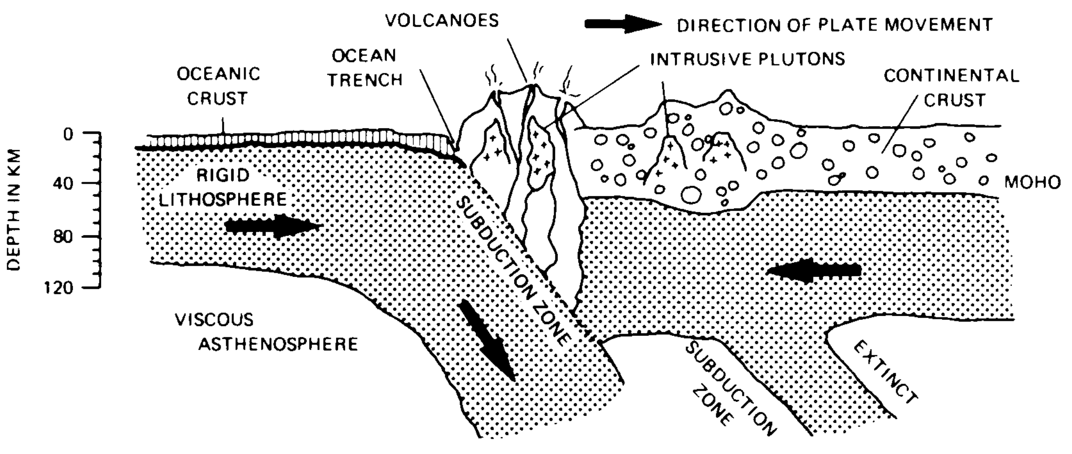


Map showing the location of most of the identified geothermal fields. These are located along the spreading ridges and the continental rifts, and particularly along the subduction zones.

Schematic representation of a mid-oceanic spreading ridge and a subduction zone. (Geoth. Energy Mag. Feb. 1976)



DIVERGENT PLATE BOUNDARY, WITH MID-OCEANIC RIDGE, RIFT AND VOLCANOES (EXAMPLE, MID-ATLANTIC RIDGE)



CONVERGENT PLATE BOUNDARY, AND SUBDUCTION ZONE WITH OCEAN TRENCH, VOLCANOES AND INTRUSIVE PLUTONS (EXAMPLE, PERU-CHILE TRENCH) are the fields of Larderello and Monte Amiata (Italy), The Geysers (California, USA), and Matsukawa (Japan).

Less favourable, but still economically suitable for power production, are those geothermal fields delivering mixtures of steam and hot water. In these cases, the water has to be separated from the steam before this goes to the turbines. Examples of such fields are Wairakei (New Zealand), Cerro Prieto (Mexico), and other geothermal fields in Japan, in the Philippines, and elsewhere. The hot water generally carries large amounts of dissolved salts, which may give rise to problems of corrosion and of incrustations.

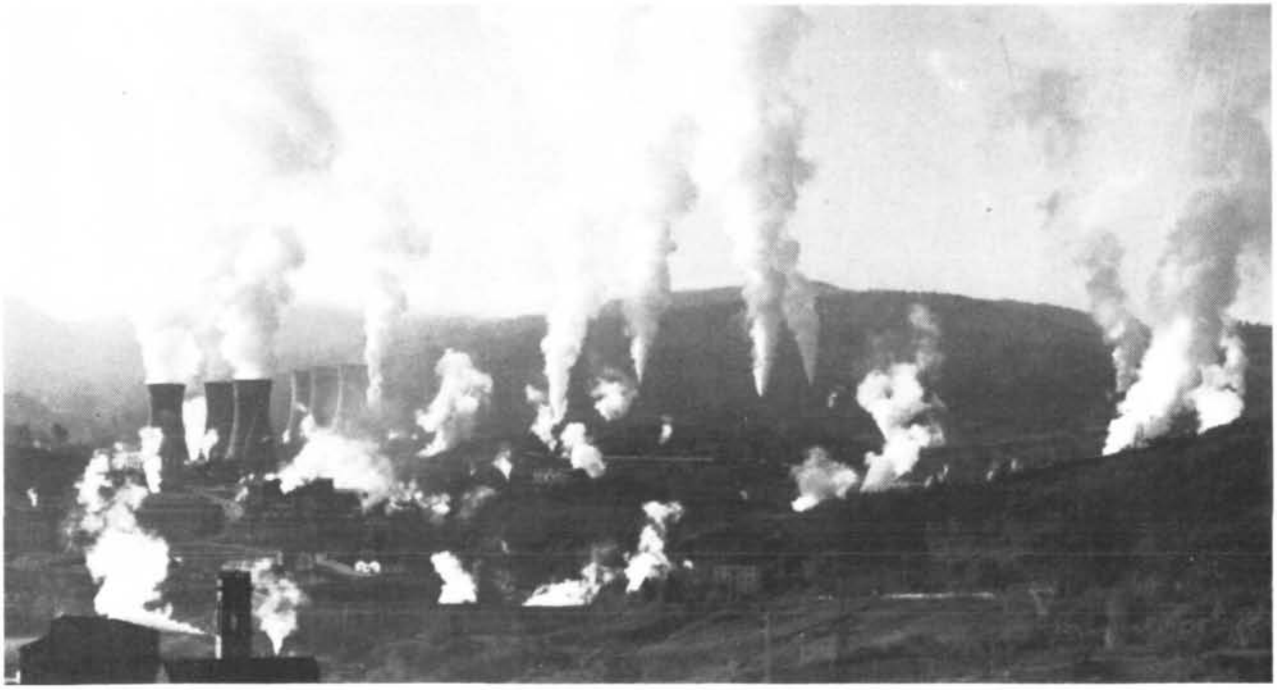
When the temperature of the hot groundwater is only 50 to 100°C, the water is mainly used for space heating (apartment blocks, greenhouses, etc.), as in the People's Rep. of China, France, Hungary, Iceland, the USSR, and in many other countries. A further use is for medicinal and bathing springs.

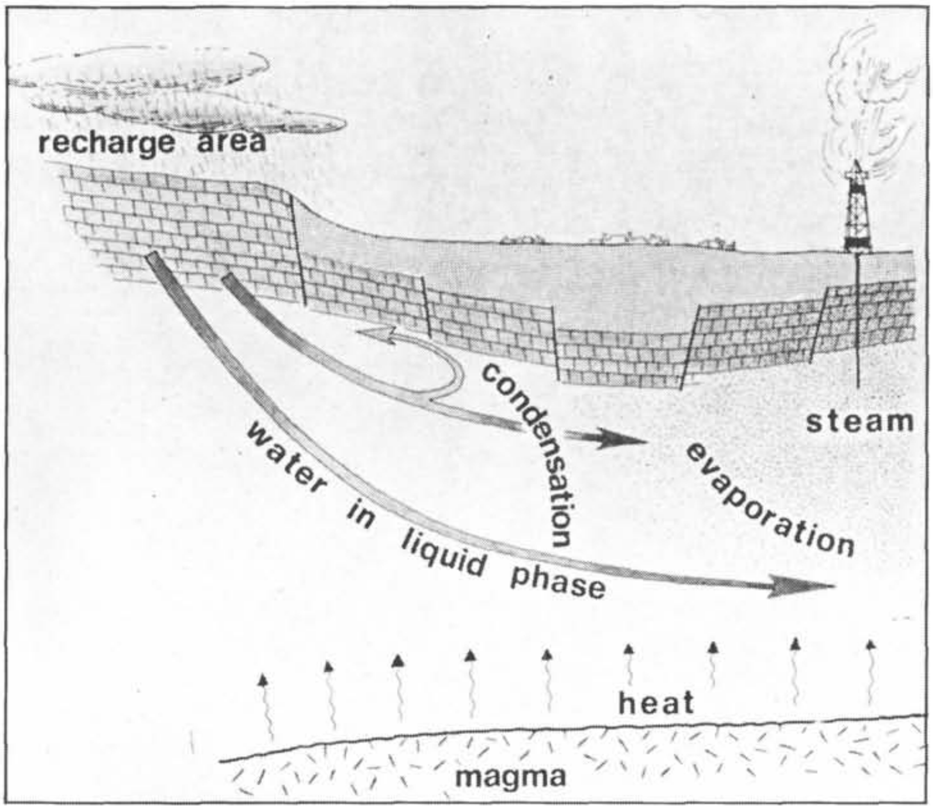
The geothermal plants so far in operation in the world have a total installed power of only about 2700 MWe (see Table), corresponding for example to about 2% of the world capacity of nuclear power stations. To this power capacity however, one should add the non-electrical uses of geothermal energy. In addition, there are a number of already identified geothermal fields which will be exploited in the 1980s. They are in the following countries: Chile, Greece, Guatemala, India, Nicaragua, and the West Indies (France). Geothermal exploration is being carried out in many other countries, and promising results have been obtained especially in Argentina, Bolivia, Bulgaria, Colombia, Costa Rica, Djibouti, Ecuador, Ethiopia, Iran, Israel, Peru, Poland, Spain (Canary Islands), Thailand. In many developing countries geothermal power production may in future meet an appreciable fraction of their energy needs.

Geothermal power plants in the world

Country	Installed power in 1982 (MWe)
China, People's Republic of	4
El Salvador	95
Iceland	41
Indonesia	30
Italy	440
Japan	174.5
Kenya	30
Mexico	180
New Zealand	202
Philippines	570
Portugal (Azores Is.)	3
Turkey	0.5
USA	936
USSR	11
Total	2717

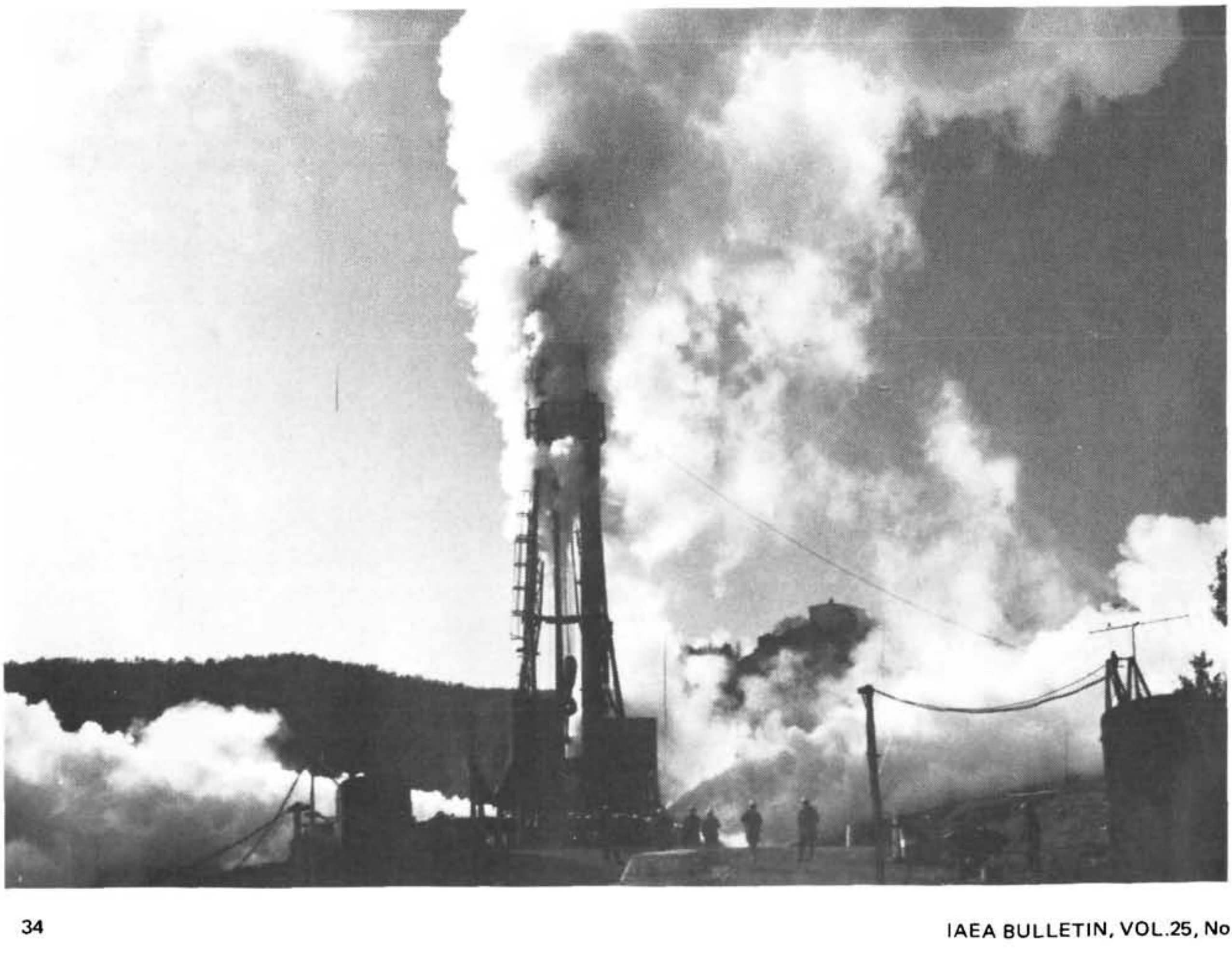
View of the Larderello geothermal field in Tuscany, Italy, as it appears from the village of Montecerboli. The landscape is characterized by the cooling towers of the geothermal power plants and by the steam plumes of wells discharging into the atmosphere. The name of the village derives from *Mons Cerberi*, in Latin "the mountain of Cerberus", the three-headed watch-dog of Hell. And to the first inhabitants of the zone, Hell probably did not appear too far away. Most of the hot sulphurous springs and fumaroles disappeared when intensive exploitation of the geothermal fields started.





Schematic representation of a geothermal field.

A steam-producing well at Larderello, Italy, at the moment of blow-out, that is when the drilling reaches the geothermal reservoir. This well was drilled in January 1972, and it produced 326 tonnes/hour of superheated steam at 184°C and 8 atmospheres. The well-discharge tends to decline slowly with time.



In future, it is hoped to extract the heat of the Earth's interior from deeper and deeper formations, including deep hot rocks which are compact and dry. In such a case two wells would be drilled and hydraulically interconnected at depth through a network of artificially created fractures. Cold water would be injected in one well and hot water recovered from the other. Preliminary experiments at 3000 m depth done at Los Alamos, New Mexico, USA have shown the feasibility of such projects. The experiments are continuing in the USA, and others have been undertaken in the UK (Cornwall), to develop and refine the technology.

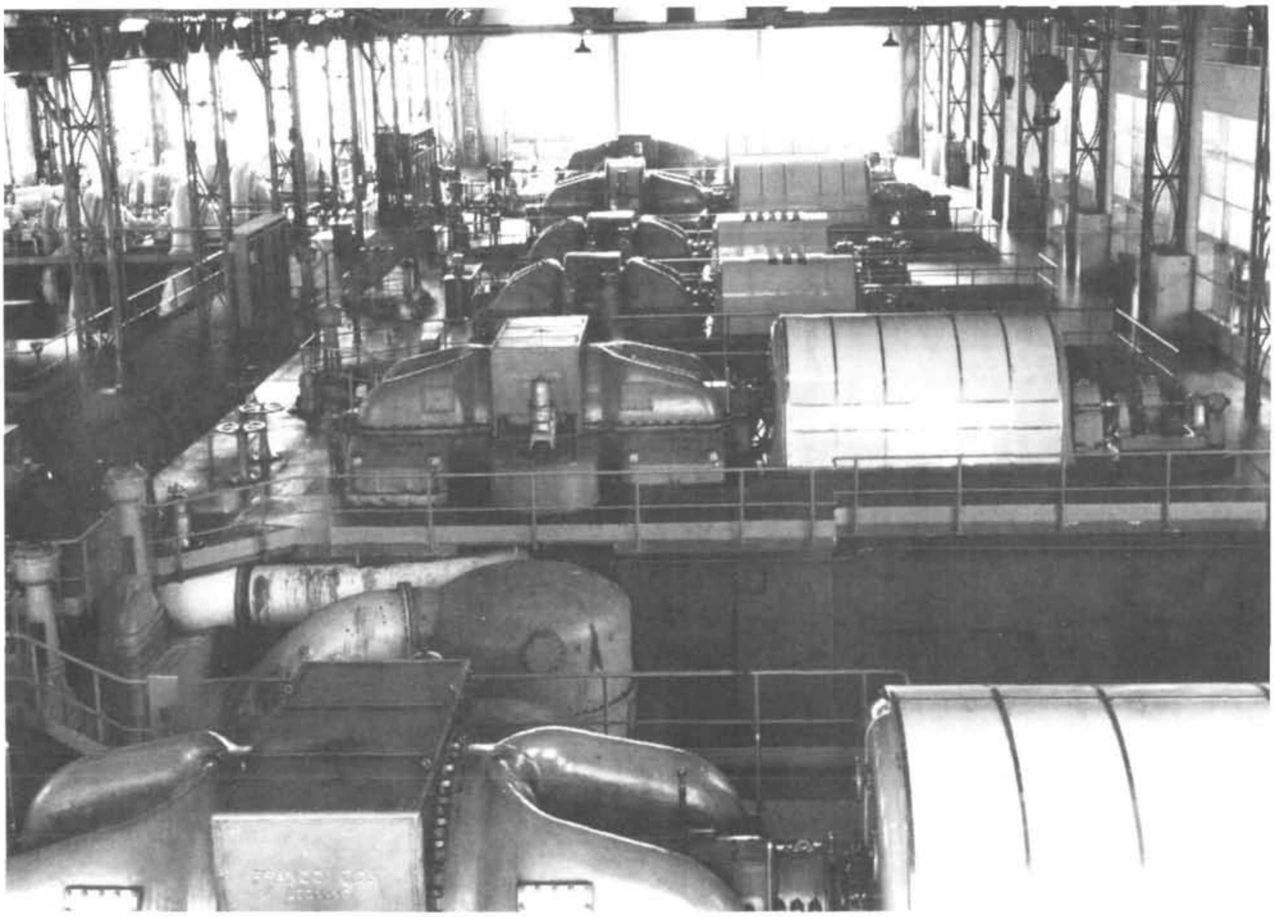
Natural isotopes as a tool in geothermal exploration

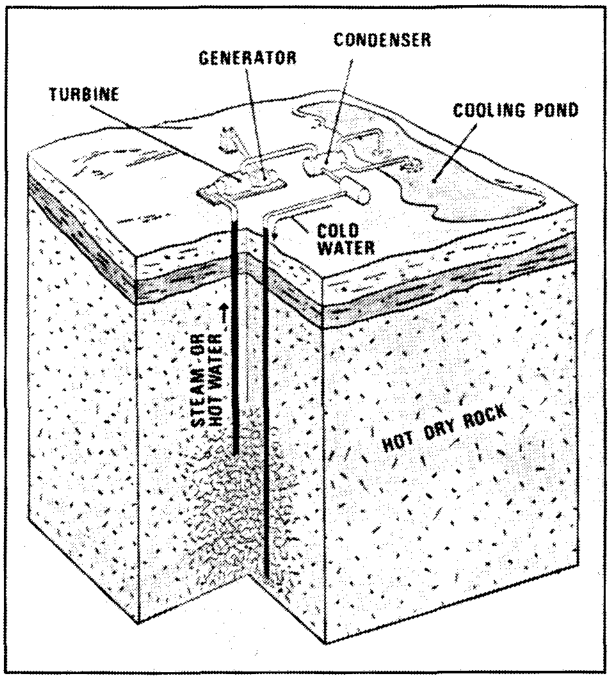
Water is the most abundant component of the geothermal fluid and is also the major energy carrier, since water has a high heat capacity and a high latent heat of vaporization. Other gaseous components accompanying the steam phase of a geothermal fluid are carbon dioxide (0.5 to 5%); hydrogen sulphide, ammonia, nitrogen, methane, hydrogen (up to 2 or 3% altogether); boric acid; and rare gases.

The first contribution that isotope techniques made in the understanding of geothermal fields, was in demonstrating that hot water and steam derive from rainwater infiltrating from the outcrops of the geological formations constituting the geothermal reservoir. Although it nowadays seems rather trivial, this hypothesis was far from being generally accepted about thirty years ago, before deuterium and oxygen-18 content measurements demonstrated it definitely. Before then scientists believed that the geothermal steam was of juvenile origin, that it originated from the Earth's interior and was appearing for the first time on the Earth's surface.

Isotopic measurements, especially when carried out in parallel with conventional geochemical analyses, provide information on the characteristics of the geothermal fields: for example, on the mixing between waters of different temperatures and origins; on the underground flow patterns of the hot fluids; on the degree of interaction with the reservoir rocks; on the origin of the various fluid components; etc. However, the most important application of isotope techniques in geothermal exploration is probably to estimate the

The interior of a geothermal power station at Larderello, Italy. Larderello, 65 km south-west of Florence, was the first geothermal field exploited in the world. In 1827 Francesco de Larderel, a former officer in Napoleon's army, who had emigrated to Tuscany (he was born in Vienne in the Dauphiné), had the idea of exploiting the geothermal water, evaporating part of it, and extracting the boric acid. The place was later called Larderello in his honour. In 1904 a small turbogenerator produced electricity from the geothermal steam for the first time, and one year later a 20 kW power plant was installed. Power production in the largest known geothermal field of the world, The Geysers in California, USA, started only in 1960, although the first exploration well was drilled in 1921. (Photo ENEL, Italy)





Schematic representation of an artificial geothermal field. The two wells are hydraulically interconnected at depth by means of an artificial network of fractures, created in the originally compact and dry hot rock. Cold water is injected into one of the wells and steam is recovered from the other. A preliminary experiment of this type has been successfully carried out at Los Alamos, New Mexico, USA. The depth was 3000 m and the fractures were produced by injecting water under pressure. A similar experiment is currently being performed at a depth of 4000 m.

deep temperature. This parameter is generally not easily accessible but is essential in assessing the potential of geothermal fields. In particular, the use of isotopes is invaluable during the preliminary geochemical exploration of geothermal fields. When drillings have not yet been made, samples are collected from springs, geysers and mofettes. Isotopes are also important when the boreholes do not reach yet a sufficient depth or are insufficient in number.

Isotopic geothermometers exploit the fact that the isotope distribution between two components in thermodynamic equilibrium depends only on temperature. The most commonly used isotopic geothermometers are those based on hydrogen isotopes in the systems methane/hydrogen gas and water/hydrogen gas; on oxygen isotopes in the system water/dissolved-sulphate; and on carbon isotopes in the system carbon dioxide/ methane.

Also geo*chemical* thermometers have been developed based on the silica content of the hot waters; or on the relative concentrations of sodium, potassium, and calcium; or on the composition of the gas-steam phase. All these geothermometers, including the isotopic ones, are affected to differing extents by processes occurring during the ascent to surface of the geothermal fluids: such as, mixing processes, evaporation losses, interaction with the rocks encountered, partial re-equilibration at lower temperature, and so on. However, the parallel use of as many geothermometers as possible helps in evaluating correction terms and in attaining the right result.

Tritium has been used to identify occurrences of modern water in geothermal fluids. As is known, atmospheric thermonuclear tests have injected large amounts of tritium into the hydrological cycle, especially in the years 1952 to 1962. Therefore, tritium can be used to evaluate mixing of shallow groundwater and to trace the arrival and the flow patterns of modern recharge from the edges of geothermal fields.

Recently, isotopes have been used to follow the fate of reinjected geothermal fluids. This is a new and interesting application which results from the attempts to reduce the environmental impact of the geothermal fluids: instead of releasing them into surface waters after they have been exploited, they are reinjected in the geothermal field and "recycled". Among other things, this may also increase the production of the field.

IAEA activities

The Agency's activities in applying isotope techniques to geothermal exploration are carried out by the Isotope Hydrology Section of the Division of Research and Laboratories. The Section is co-operating in geothermal exploration projects currently being implemented in Costa Rica, India, Mexico, and Thailand. Other projects will be possibly included in a co-ordinated research programme on the application of isotope techniques to hydrology and geothermics in Latin America, financed by the Government of the Federal Republic of Germany and executed by the Agency. The programme is now in its preparatory phase and the field work will probably start towards the end of the year.

The Agency recently (November 1981) organized a consultants' meeting on the application of isotope techniques to geothermics, whose proceedings will be published in a special issue of the journal *Geothermics.*

Finally, mention should be made of the continuing co-operation between the Agency and the Istituto Internazionale per le Ricerche Geotermiche, Pisa, Italy, and with the Department of Scientific and Industrial Research, Petone and Lower Hutt, New Zealand.

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