海外情報

Low Enthalpy Geothermal Fields, with Reference to Geothermal Energy in France*

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Abstract Geothermal resource are classified according to geological, geochemical and temperature criteria. Methods used for inventory of the hot water reservoirs are described and exploitation techniques are summarized. The importance of a good adequation between resource and surface need in installed power as well as temperature level is shown. Determination of the lifetime of exploitation plants allow a better planning of the future geothermal development. The economy of the projects is shown on the basis of various systems: Dogger of the Paris region, shallower reservoir of the Loire valley and unsalty reservoirs of Aquitain Basin.

Several of the plants presently exploited in France or under project are described. The present geothermal energy policy in France is discussed and various hypothesis of future geothermal development are described.

1. Classification of Geothermal Resources

1.1. Geological Classification

1.1.1. Aquifers in large sedimentary basins

These are thermal water found in porous strata of large artesian basins of platform areas. Aquifers are of very large dimensions, over several hundred km^2. The distance between the exploited areas and recharge areas is very large (hundreds of km). Aquifers are separated from one another by permeable layer. Head values are above the earth surface. Salt content of waters increases, as a general rule, with depth: ex: Parisian Basin (fig. 1).

Fig. 1 Section of the major deep aquifers of the Paris Basin
(1) Tertiary, (2) Upper Cretacious, (3) Lower Cretacious, (4) Upper Jurassic, (5) Middle Jurassic, (6) Lias, (7) Trias, (8) basement.
From top to bottom these aquifers are: Albian sands, Lusitanien limestones, Dagger limestones, Rhetian sandstones, Triassic vosgian sandstones.

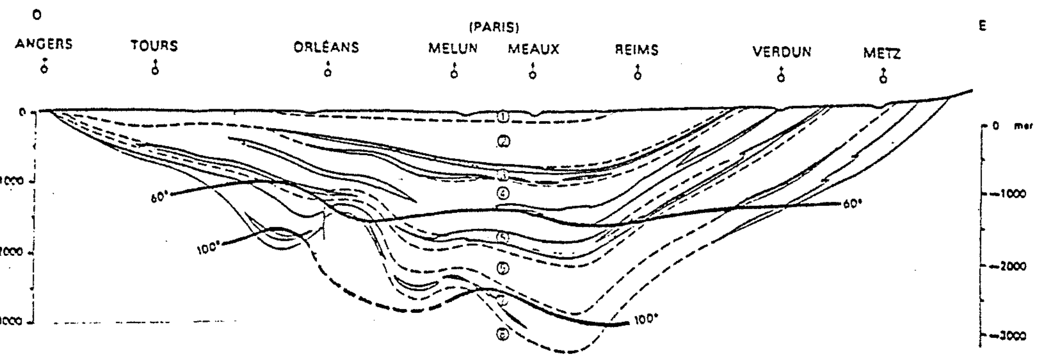

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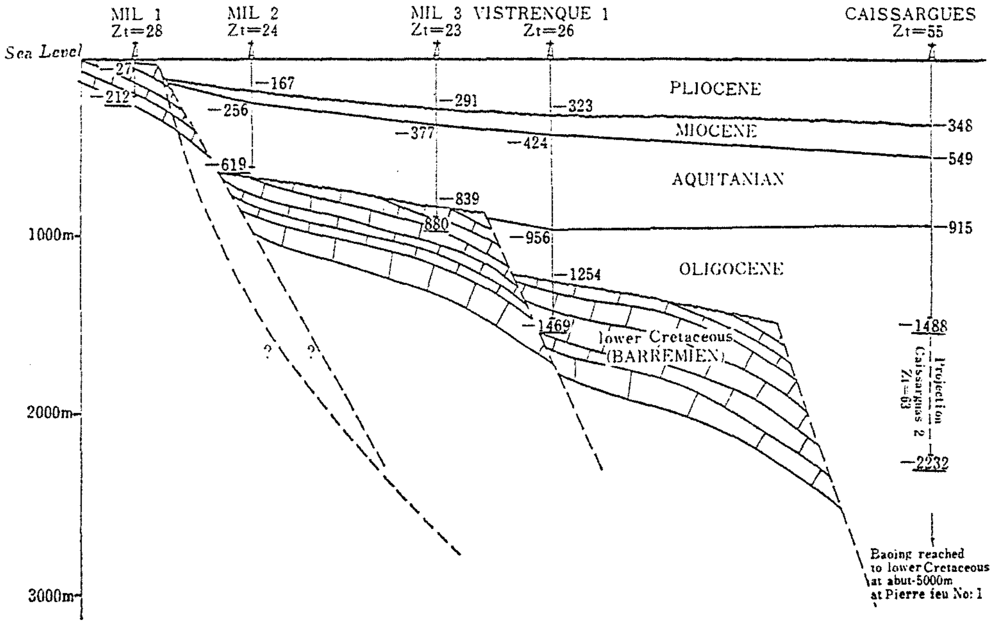
Fig. 2 Selection of the Cretacious (Barremien) geothermal aquifers in the Nimes region



1.1.2. Aquifers in tectonic basins

Smaller basins resulting from extentional (normal faulting, graben) or compressionnal tectonics (folding) contain comparatively smaller aquifers. Distance to areas of recharge are frequently small and these areas are frequently elevated producing excess heads above the earth surface. Outpouring of thermal waters are frequent in the outlying parts of the basin. Tectonic disturbances divide beds into blocks which have no hydraulic connection (fig. 2).

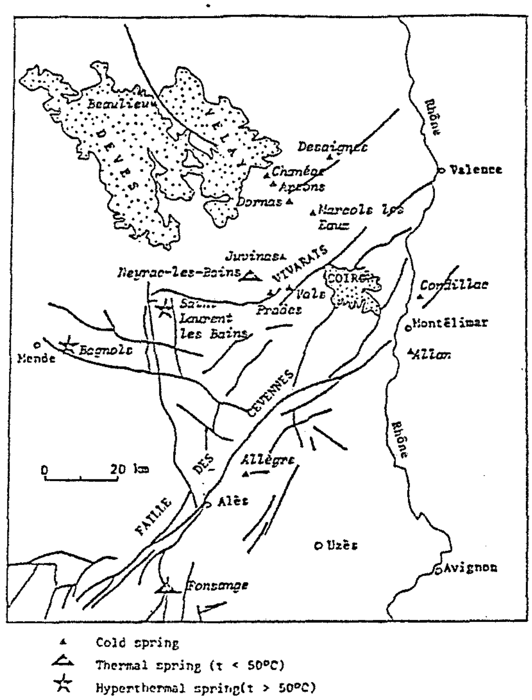
Ex. (grabens): Limagne, Bresse, Rhine Valley, Rhone Valley.

Ex. (folded zones): South Aquitain Basin, Alps, Jura.

1.1.3. Geothermal waters in fissured crystalline massifs (metamorphic or granitic)

Areas of rejuvenated basement, faulted by young tectonics are characterized by thermal waters confined in faults and fractures. The water temperature varies but may reach 90 to 100°C. Ways of filtration through the systems of fissures are very complex and have frequently no connection with one another. Recharge areas are very difficult to locate, as well as the boundaries

Fig. 3 Thermal springs in southern Massif Central



of fissure zones containing thermal waters. Water may ascend from considerable depth along highly developed system of fissures, and thermal water may hence be tapped by shallow wells (fig. 3).

Ex.: Chaudes-Aigues, Aix, Bourbon Lancy.

1.1.4. Geothermal systems in volcanic massifs

Volcanic massifs display particular features in that they are built of highly permeable rocks (blocky and scoriaceous surface of flows, fractured flows, pyroclasts) with some intercalations of impermeable layers. These strata, generally dipping away from the center are also affected by faults of tectonic and valcano-tectonic origin. Geothermal surface indices are generally located along these faults and producting layers may be found either by tapping faults or aquifers connected with them.

Ex. Monts Dore, Antilles, Reunion.

1.2. Geochemical Classification

Salt content in the water has a direct incidence on exploitation characteristics:

1.2.1. Fresh water (up to 1 g/*l*)

Can be exploited by single wells, with no reinjection. Water may be used not only for its heat content, but also for other economic uses: agricultural, human consumption, industrial or therapeutical. In case such aplications are not found or possible, reinjection is recommended for recharge of the aquifer.

1.2.2. Brackish water (1 to 10 g/*l*)

Generally obliges reinjection. Water may however be used for some therapeutic or other uses.

1.2.3. Saline water (10–35 g/*l*)

Rends reinjection obligatory, with use of

Table 1 The required temperature of geothermal fluids

Fluid	°C	Application	
Saturated steam	200		
	190		
	180	Evaporation of highly concentrated solutions Refrigeration by ammonia absorption Digestion in paper pulp, kraft	Conventional power production
	170	Heavy water via hydrogen sulphide process Drying of diatomaceous earth	
	160	Drying of fish meal Drying of timber	
	150	Alumina via Bayer's process	
	140	Drying farm products at high rates Canning of food	
	130	Evaporation in sugar refining Extraction of salts by evaporation and crystallization	
Water ↑	120	Fresh water by distillation Most multiple effect evaporations, concentration of saline solution	
↓	110	Drying and curing of light aggregate cement slabs	
	100	Drying of organic materials, seaweeds, grass, vegetables, etc. Washing and drying of wool	
	90	Drying of stock fish Intense de-icing operations	
	80	Space heating Greenhouses by space heating	
	70	Refrigeration (lower temperature limit)	
	60	Animal husbandry Greenhouses by combined space and hotbed heating	
	50	Mushroom growing Balneological baths	
	40	Soil warming	
	30	Swimming pools biodegradation fermentations Warm water for year-around mining in cold climates De-icing	
	20	Hatching of fish, Fish farming	

titanium heat exchangers and protection or treatment of the wells.

1.2.4. Brines (over 35 g/*l*)

Rends economic exploitation of geothermal water problematic or hazardous. Particular precautions have to be taken to avoid or limit corrosion. Economic feasability of such exploitations is not proven.

1.3. Temperature Classification

Temperature of water has a determinant effect upon its geothermal use (Table I).

Fig. 4 Charge curve of a geothermal heating plant with peak load covered by traditional fuel heating

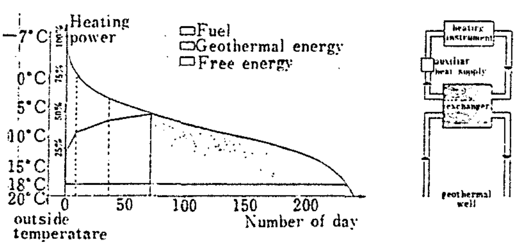
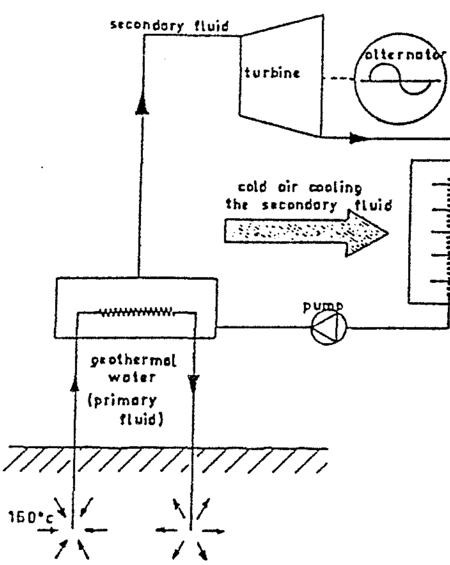


Fig. 5 Generation of electricity from geothermal water



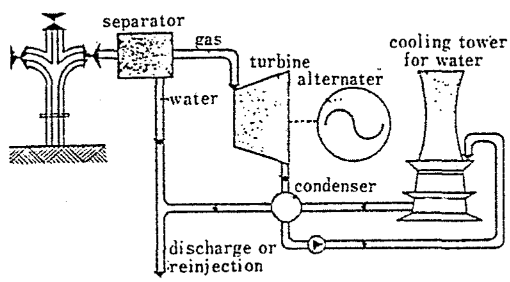
1.3.1. Between 80 and 150°C

Hot water can be economically converted into electricity by using a binary, highly volatile fluid: freon, ammoniac or isobutane. Although still rarely applied, this kind of exploitation can be developed in Alsace, Limagne and Massif Central.

1.3.2. Over 150°C

Steam can be used directly (dry steam) or after separation of hot water in a turbine to produce electricity. Although it is not known yet in France, such a geothermal plant is presently developing at Bouillante (Antilles).

Fig. 6 Geothermal plant with steam/hot water separation



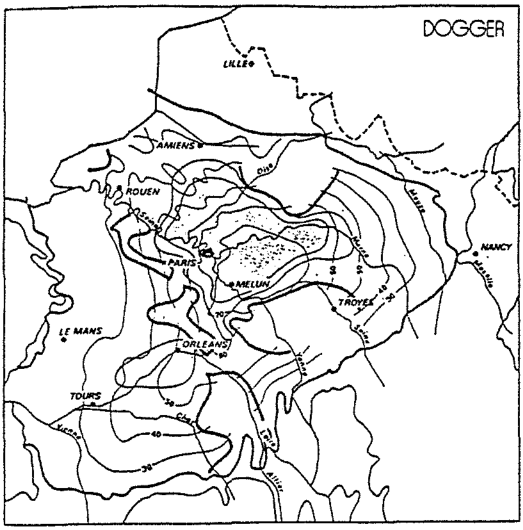
2. Inventory of Hot Water Reservoirs

The knowledge of hot water reservoirs is based on the collection of various data: general geological data on structure, origin, lithology of the area, temperature gradients and heat flow data, and hydrogeological data obtained from drilling logs and tests interpretations.

2.1. Geological Data

Geological synthesis allow to precise the origin of the formations, the evolution of the area with time, the lithologic variations within the formations. The use of geophysical data, and in particular of deep seismic sounding, is particularly valuable. This allows to draw isopach maps for the top and bottom of the reservoirs and to precise major discontnuities, etc...

Fig. 7 Transmissivity and temperature for the "Dogger" of the Paris Basin



Geological limits of the Dogger
Boundaries of the main aquifer
High
Medium zone of relative productivity
Low
Isothermal curves (℃)

2.2. Temperature Gradients and Heat Flow

These can be obtained from previous data, obtained on mud, on bottom hole temperature measurements or on test waters fluids measurements. In some cases, wells

Table 2 Determination of reservoir characteristics: Scheme of the method

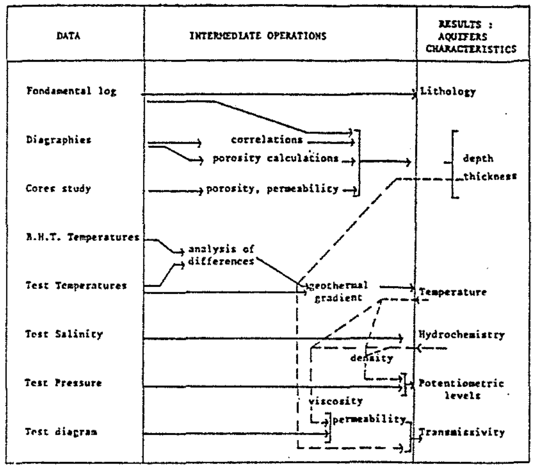
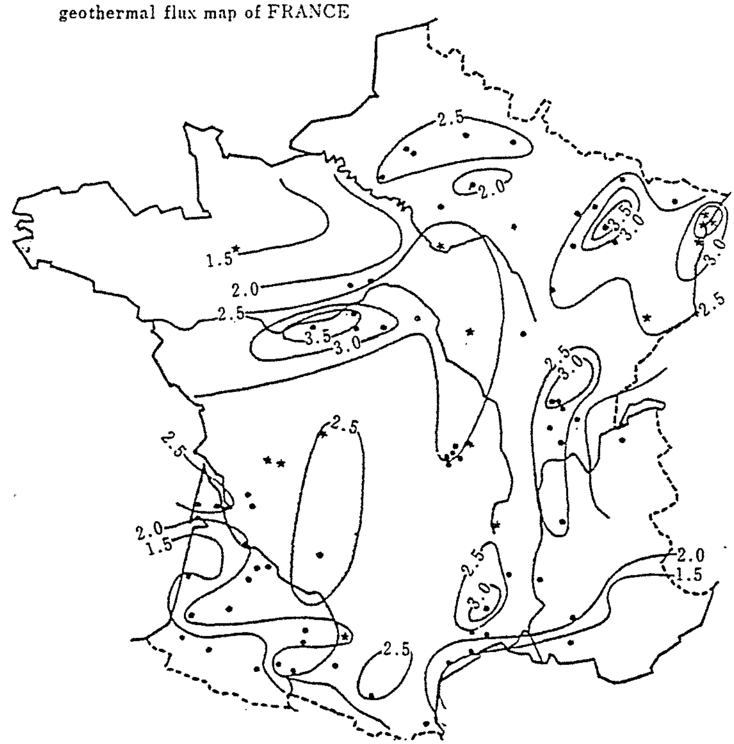


Fig. 8 Heat flow map of France from BRGM and INAG data available in Dec. 1977



1.5 Isoflux curve expressed in Heat Flow Unit (HFU)*
• Flux value deternuned by B.R.G.M.
··· Flux value determined by I.N.A G
(* or 10Kcal/km²/sec)

are still accessible for new measurements, allowing more precise data to be collected either on bottom hole or at the surface on producing wells. From such data, temperature gradients maps, and heat flow maps are computed.

Different gradient values or heat flow values are frequently obtained in the same hole, so that isothermal maps at given depths or at the reservoir top and bottom are preferred.

2.3. Hydrochemistry

Salinity is determined from tests analysis. Tests are generally limited to the top of the aquifer so that the actual salinity of the water is generally higher. The same is valid for gas content in the fluid, which is generally higher in tests than in the whole aquifer thickness.

2.4. Potentiometric Surface

The static level of the aquifer is calculated from bottom pressure data measured during tests.

$P=d\cdot g\cdot H$ where P is the static pressure, H is the height of the water column and d is the density of the water, which varies with salinity and temperature. Incertitude of the data arise from the precision of the registration (±40 m in petroleum data) and from lack of stabilisation of the values.

2.5. Transmissivity

Transmissivity is the product of permeability of the aquifer by the thickness of the producing horizons. It is the fundamental parametre in determining production caracteristics. Transmissivity is calculated from pressure test diagrams. It is written $k\cdot h$ (k permeability, h height of the producing layer), in darcy-metre.

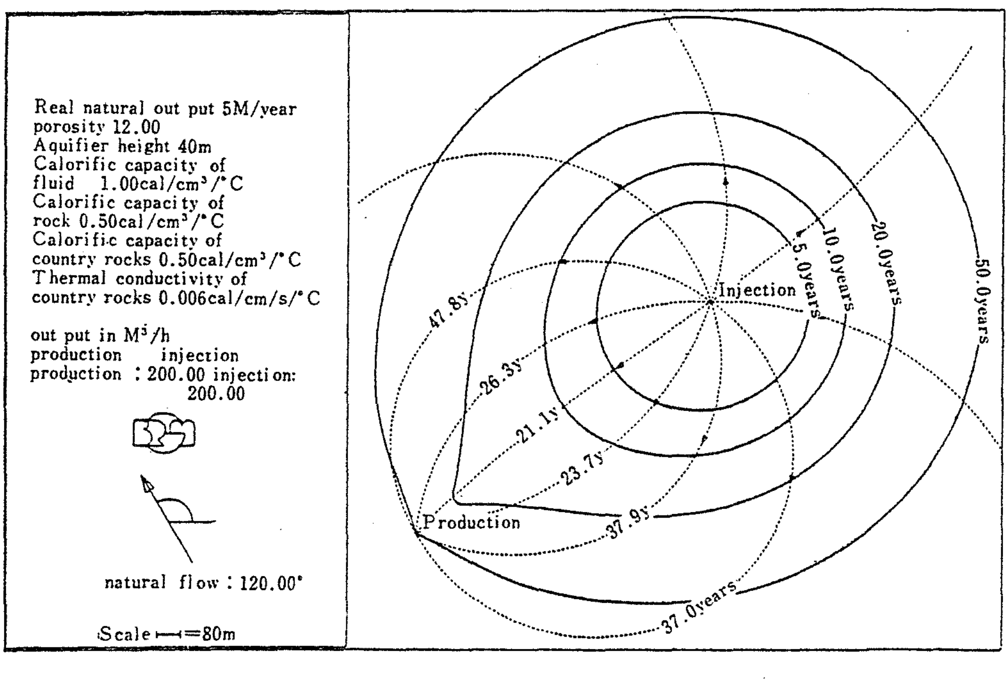
Permeability may also be obtained from logging or cores studies, but these give only indicative data.

Table 2 gives the framework of the methodology used to determine the parametres useful for geothermal production from previous drilling data.

3. Exploitation Techniques

The determination of reservoir parameters allows to calculate heat production capacity with time. This calculation is necessary to determine the characteristics

Fig. 9 Mathematical modelling of doublet lifetime



of the geothermal exploitation.

Chemical composition of water from the reservoire determines wether reinjection is necessary or not. Reinjection -even if not obligatory-has the advantage of maintaining the production pressure. Without reinjection, it is difficult to establish precisely the life-time of an exploitation, especially if other exploitations are developed near by in the same aquifer. In Hungary after several years of exploitation, pressure decreases in several sites. For this reason, we recommend reinjection and exploitation by "doublet".

3.1. Doublet Characteristics

Various criteria may be used to calculate the distance between wells in an exploited geothermal field. Rather than pressure interferences, which may be used advantageously in exploiting sedimentary aquifer, determination of distance between wells is based on calculation of cooling of the aquifer with time, due to reinjection of cold water. Mathematical models have been developped to calculate the lifetime of doublets (fig.9).

This models allow to precise the optimal location of wells in urban areas where only few possible sites are available.

3.2. Drilling Techniques

Drilling techniques do not differ fundamentally from petroleum techniques. More attention should however be paid on insulation of casing, protection of upper aquifers and corrosion problems. Drilling of the reservoir needs special care and clear water drilling is generally preferred.

Diametres are calculated from assumed reservoir characteristics and production requested from surface need. Generally, even for artesian wells, pumps have to be placed in the well, and this has to be planned before drilling as a large diametre is needed to locate the pump. Depth of the pump is calculated from reservoir characteristics (well

Fig. 10A Creil's production well

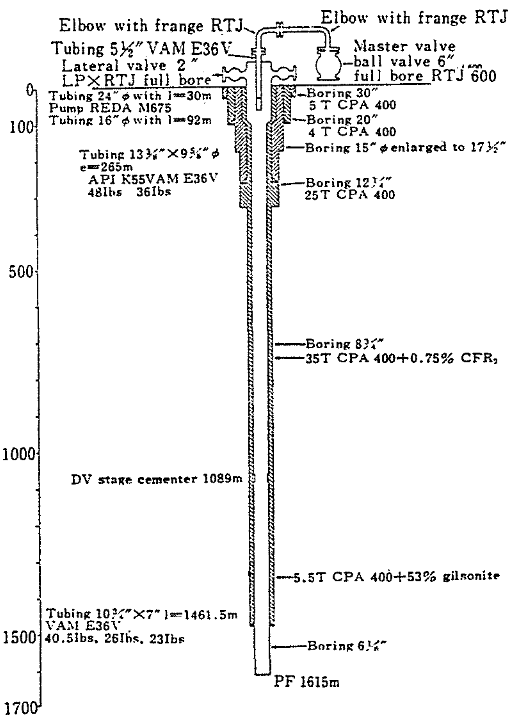


Fig. 10B Creil's injection well

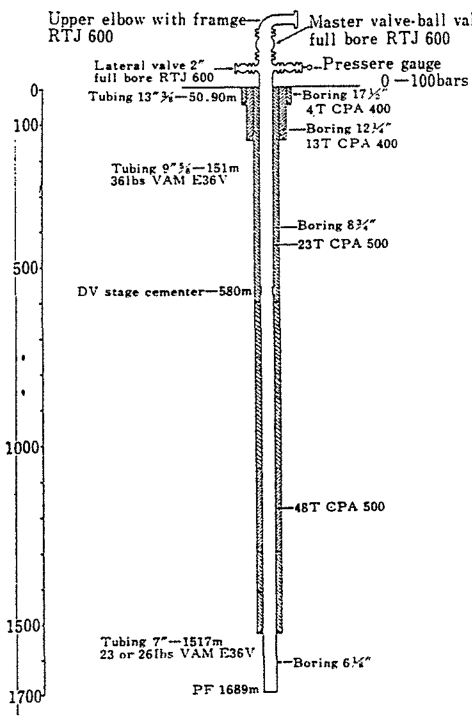
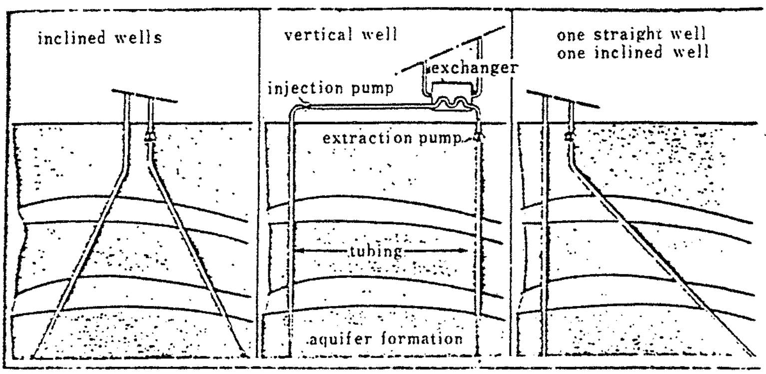


Fig. 11 Various possible schemes of production and injection drillings



head pressure) and production requested. Pumps are also needed for reinjection; their characteristics can also be calculated in advance, but as a surface pump can be used, which does not modify the drilling collumn, it is recommended to wait for reinjection drilling results to be obtained before pumps are determined (fig. 10A, 10B).

Reservoir can be reached either by vertical or deviated drilling (fig. 11).

Although this last technique is more expensive, it has several advantages:

1. Reservoir producing section is longer
2. One drilling site is enough, which is an advantage in urbanized areas, and reduces displacement of rig during drilling
3. Surface pipes are limited to minimum, which simplifies exploitation and environmental impact problems
4. Cost is not always higher, if all parametres are taken into account.

Table 3 Compared economic balance for 3 Geothermal projects (1978)
A: Dogger of the Paris Basin,
B: Orleans region,
C: Aquitain Basin

A

Number of appartments to be heated 2500
Annual need of energy 35000 Kthermie
(≒14Kth/appartment)
Energy supplied by geothermal source (75% conv.) 25000 Kth
Geothermal source exploited by double channels with 1800 m depth
Output (by pumping) 200m³/h
Temperature 65°C
Installation cost (doublet, exchanger, pipings) 10 MF (10^7 F) =4000 F/appartment
Geothermal heating compared with classical heating (with heavy fuel No. 2)

	Geothermal	Classic
Combustibles (60 F/Kth)	0.540 MF	2.100 MF
Electric power for boring 250 KW for 150 days 100 KW for 80 days	0.160	—
Maintenance (pumpes + boring)	0.100	
	0.800 MF	2.100 MF
Refund to government per year	1.975 MF	
(Refund is supposed to continue during 20 years)		
Total	1.975 MF	2.100 MF

Bconomy realized by geothermal heating 6%

B

Number of appartments to be heated 600
Annual energy need 8400 Kth
Geothermal energy supply 6500 Kth
Geothermal source
doublet with 1100 m boring
Output 50 m³/h
Temperature 55 °C (gradient 4.5 °C/100 m)
Installations cost: 3 MF (5000 F/appartment)
Geothermal heating compared with municipal heating

	Geothermal	classic
Combustible	0.171 MF	0.756 MF
Electric power for boring	0.060 MF	
Maintenance (pumps+boring)	0.070 MF	
	0.301 MF	0.756 MF
Annual refund to Government	0.352 MF	
	0.653 MF	0.756 MF

Economy realized by geothermal heating 13.6%

C

Number of appartments to be heated 1500 appartments

Annual energy need 21000 Kth

Geothermal energy supply (coverage 75%) 15500 Kth

Geothermal source exploited by simple well of 1800 m depth

output 150 m³/h

temperature 65°C

Geothermal installation expenses (boring, exchanger, pipings)

5.5 MF (4000 F/appartment)

Geothermal heating compared with classical heating with fuel No. 2

	Geothermal	Classical
Combustible with 60 F/Kth	0.330 MF	1.260 MF
Electric power for boring	0.080	
Maintenance (pump+boring)	0.070	
	0.480 MF	1.260 MF
Annual refund to government (supposed to refund during 20 years)	0.646 MF	
	1.126 MF	1.260 MF

Economy realized by geothermal source 10.6%

3.3. Drilling Cost

Once the reservoir chosen as objective and the production characteristics are determined, the stratigraphic column is established on the basis of provisional geological section. This allows to calculate the drilling cost, which, together with pumps and heat exchangers, dimensions will allow to calculate the cost of production of geothermal water or heat. Table 3 provides some characteristic costs for geothermal drilling in France at various depth. Reinjection has of course an important effect on the cost of production, as it almost doubles the prices. Economic feasibility of geothermal project does not depend only on production cost but equally on thermal needs at the surface.

3.4. Geothermal Plant Design

Once well position is determined, geothermal plants design is fairly simple: insulated pipes connect the production well to the heating station. Heat exchanger allows to transfer the heat to the primary circuit of district heating. Its characteristics are determined from geochemistry of the water, pressure in the circuit (metal to be used) and performance of the heat exchanger (dimension).

Connection to additional heat production centres or heat pumps are determined case by case, depending on preexisting systems, climatic factors or economic criteria.

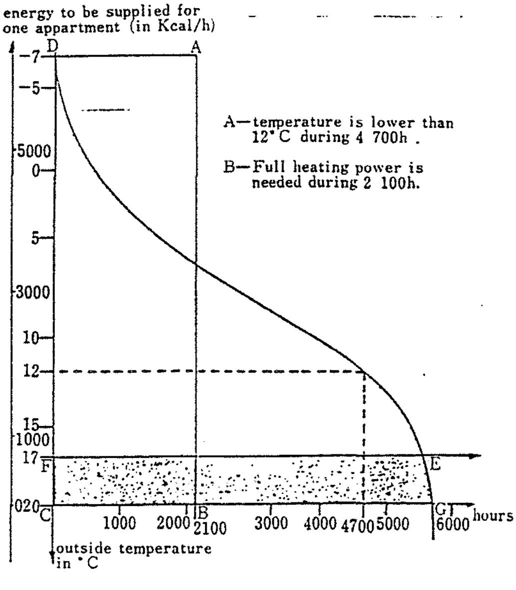
4. Thermal Needs at the Surface

The feasibility of geothermal energy highly depends on characteristics of surface needs, both in power and temperature level. Various cases can be distinguished.

4.1. District Heating

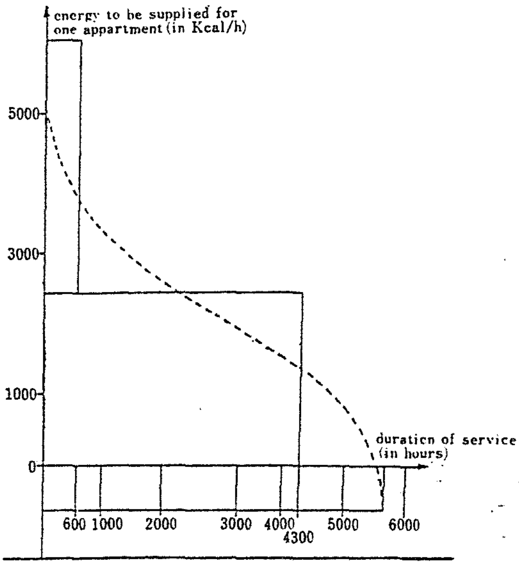
This is the first exploitation techniques developed in France, since 1969 and in Iceland since 1928. Temperature level to be reached in appartments and houses for human comfort is in the ranges +15~22°C, whereas outside geothermal ranges between say −20 and +35°C in Europe. House heating is hence needed and the amount of heat requested along the year can be determined by establishing the "monotone curve" (fig. 12).

Fig. 12 Monotone curve for Paris region
Heating season: Oct. 1~May 31



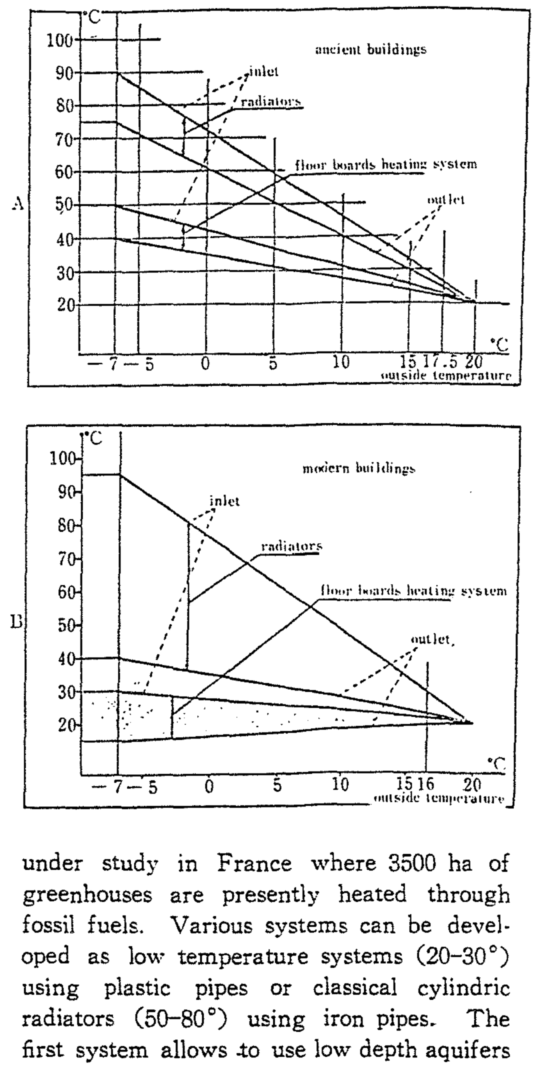
This curve varies with climatic conditions and has to be established for any region where district heating plant is planned. It allows to determine the maximal power requested and the number of days for which heating is requested at a given temperature. In the Paris basin conditions, the economic optimum is found for nearly half the power covered by geothermal (base load), representing 80% of the thermal need) and half the power covered by fossil fuel combustion (peak load, representing 20% of the need) (fig. 13).

Fig. 13 Determinations of optimal covering of thermal need by geothermal and fossil fuel sources (same case as fig. 12)



Installed power per geothermal unit -e.g. number of flats to be heated by a doublet varies with systems of heat dissipation in houses and in particular the entry and return temperatures. The most adapted systems have a low temperature return (20°C). (fig. 14).

Fig. 14. Comparison of ancient radiators and ground floor heating systems and new systems with low return temperature allowing a better heat exhaust from geothermal source



4.2. Agricultural Uses

Hot waters have various agricultural uses: the major are green houses. mushroom culture and pisciculture. Greenhouses geothermal heating is developed in Iceland, Hungary (170 ha of greenhouses), USSR (several units of 10 to 15 ha). Projects are under study in France where 3500 ha of greenhouses are presently heated through fossil fuels. Various systems can be developed as low temperature systems (20–30°) using plastic pipes or classical cylindric radiators (50–80°) using iron pipes. The first system allows to use low depth aquifers whereas the second system necessitates to exploit deep aquifers, which in turn is applicable only for large size agricultural plants. The heat consumption of greenhouses varies from 0. 150 th/m^2/h. For a doublet producing 150 m^3/h of water at 70°, with reinjection at 25 °C, the geothermal power is 6750 th/h, which allows to heat surfaces at 4. 5 to 2 ha. If geothermal energy is used to cover the base load, with conventional heating for peak load, surfaces of 10 to 5 ha have to be considered.

4.3. Industrial Uses

Hot water uses in industry are difficult to establish precisely, as energy consumption is frequently considered in integrated formulae for which hot water need and exact temperature level is difficult to establish. Several examples can however be described.

Geothermal fluids are used for diatomite plants in Iceland, for agroindustries in Hungary, and other industrial uses in USSR. In France, some industries have a very high water consumption, for which geothermal applications should be studied:

—Dairy farms and milk industry requires 1 to 1.5 litres of hot water (30–50°C) per litre of milk;
—salt production requests 50 to 55 litres of hot water (20–60°C) per kg of salt;
—brewing requests 0.4 litres of water (35 to 55°C) per litre of beer produced;
—canning of food requests 4 to 5 litres of water at 30 to 60°C per kg of canned food;
—paper industry requests an average of 0.5 TEP energy per ton of paper produced.

In France, only this represents more than 2 million Tep/year, consumed mainly as hot water and steam.

5. Economy of Low Enthalpy Geothermal Energy

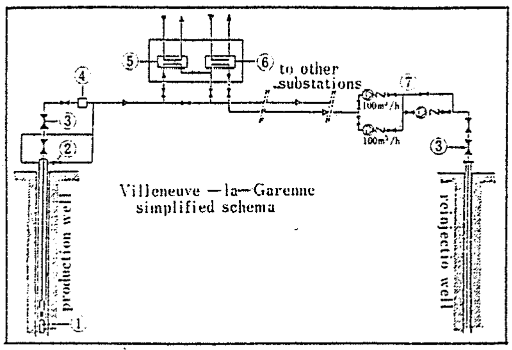
Low enthalpy geothermal energy is characterized by relatively heavy investments but light exploitation costs. The economy of a project has to be established specifically, and varies with charactristics of the resource (temperature, flow rate, and depth, which determine drilling costs representing 80% of the total investment), but also with surface characteristics (installed power, return temperature i.e. heat exhaust from the geothermal resource).

Practically, when resource inventory and surface needs show a possibly good adequation, a feasibility study is carried which establishes the cost of production of geothermal heat and the energetic balance in terms of amount of spared fossil fuel. Comparison between the existing system and geothermal solution allows to conclude on economic feasibility of the project. Examples of economic balances are given in Table 3 for three representative cases: Eastern Paris region exploiting the "Dogger" aquifer, Orleans region where a higher geothermal gradient is found and Aquitain basin where exploitation through single well is possible due to the good quality of geothermal water.

6. Some Examples

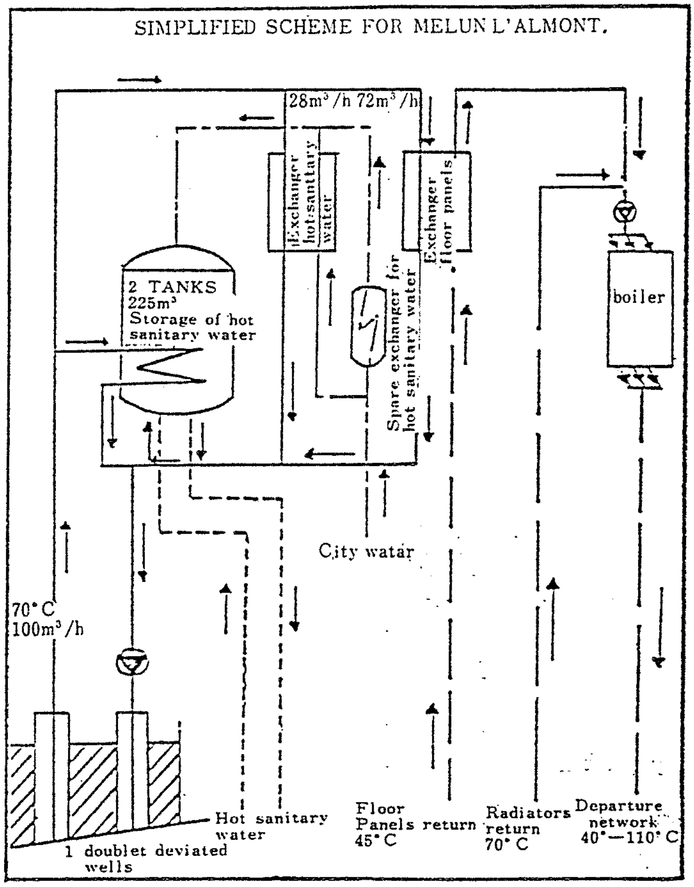
Geothermal energy started in France at industrial level in 1969, when Melun plant (2000 appartments) was built. Since then, 5 projects have been built and 5 other projects are planned.

◎ Villeneuve la Garenne (ヴィルヌーヴラガレンヌ)



—Reservoir tapped by 1 deviated doublet (25° in relation to perpendicular). Total depth of boreholes: 1,800 meters.
—Production tubing made of fiber glass.
—Present rate of flow in winter: 180 m³/h by puumping.
—well head temperature: 58°C.
—Number of dwellings involved: 1,800.
—The geothermal water network is made of fiber glass with heat insulation and is supplied separately by 10 exchangers (5 for heating and 5 for hot water household use) lacated in 5 sub-stations.
—Annual primary energy saving through use of geothermal sources: 2,000 t oil-equivalent.

◎ Melun l'Almont (ムーランラルモン)



—Reservoir tapped by 1 doublet, with deviated wells (deviation: 20° with respect to vertical).

—Total depth reached: 1,800 meters.

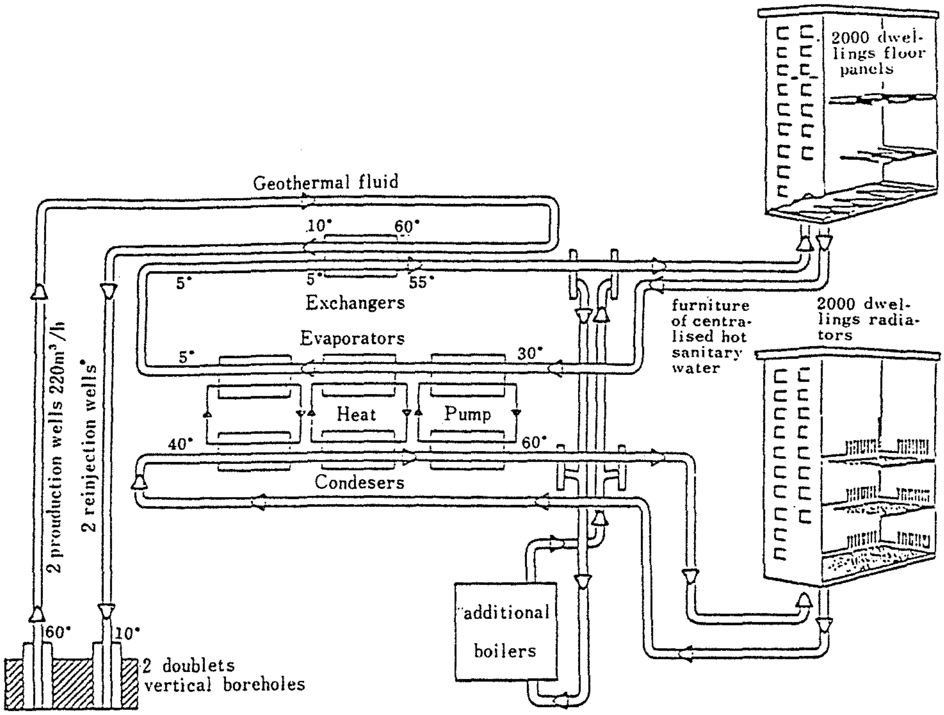
—Flow rate during winter season: 90 m³/h artesian.

—Well head temperature: 70°C.

—Number of dwellings involved: 3,000 heated with radiators and floor panels. Geothermal fluid covers 100% of furniture of heat sanitary water and heating of "floor panels" returns.

—Primary energy savings per year: 1,500 t. oil-equivalent.

◎ Creil (クレイユ)



—Reservoir tapped by 2 doublets (2 reinjection wells, 2 production wells. Total depth of boreholes = 1,650 meters.

—Actual rate of flow during winter: 220 m^3/h (maximum potential rate: $300m^3/h$). ($140m^3/h$ by pumping + $80m^3/h$ artesian).

—Well head temperature: 57°.

—Number of dwellings involved = 4,000~ 2,000 heated by floor panels, 2,000 ba radiators with supply of hot sanitary water.

—100% of hot sanitary water supplied throughout the year from geothermal sources.

—Heating 100% covered by geothermal sources for outside temperatures higher than 11°C.

—Heating 100% covered by geothermal sources + heat pumps for outside temperature between 11°C and 8°C.

—Heating covered by geothermal sources + heat pumps + additional boilers for outside temperatures under 8°C.

—Expected primary energy savings through use of geothermal sources: 4,000−5,000 t oil-equivalent.

◎ Mont-de-Marsan (モン・ド・マルサン)

—Reservoir tapped by a production well (no reinjection). Total borehole depth: 1,850 m.

—Well head temperature = 59°C.

—Pumping rate of flow (with possible modulation): 120 m^3/h and 300 m^3/h.

—The well feeds into a fiber glass network connected as follows:

- In series with the air base of Mont-de-Marsan (conventional plant 85/65° at −5°C, heating + hot sanitary water), and the Résidence Hélène Boucher (384 dwellings heat with floor panels).
- In parallel with St Anne Hospital (heated by a conventional plant with centralised supply of hot sanitary water).

—In a later phase, it is planned to connect

to the network a barracks which is now being renovated.
—Estimated annual primary energy savings: 2,000 to 3,000 t oil-equivalent.

◎ Melun-M'ee Sur Seine (ムーラン・メ・シュール・セーヌ) (建設中)

—I doublet was drilled in late 1977.
—A second doublet is planned.
—Total depth of boreholes: 1,800 m.
—Artesian flow obtained during tests on production well: 187 m^3/h.
—Temperature at well head: 71°C.
—Estimated annual primary energy savings through use of geothermal sources: 9,000 t oil-equivalent.

7. Geothermal Policy in France

Inventory of the geothermal resource of the country, and research for new resources and exploitation techniques are developed in the geological survey (BRGM), geothermal department. Some research is also carried in universities and CNRS. Regional inventory and feasibility studies are carried by BRGM at the request of regional authorities. Local feasibility studies are made for public or private partners by BRGM and other private firms. In 1974, the Ministry of Industry created a geothermal committee which helps geothermal development by limiting the geological and mining risks i.e. by giving a loan, covering up to 80% of the cost of the first drilling and reimbursed by the promoter in case of failure. In the same time, a law precised the legal aspects of geothermal energy, which is considered as a mine i.e. is concessible to public or private companies.

Nearly 20000 appartments are presently heated by gaothermal energy and several plants are under project. The objective of the last five years plan was to spare 1 to 1.5 million of Tep in 1985. This would have meant 25 to 35 doublets per year during 10 years. Although possible, these objectives have not been reached, and a more dynamic policy has to develop. It should allow to face three major handicaps:

1. Information of the citizens and of concerned public or private bodies on geothermal energy
2. Reluctance of the profession presently controlling district heating and hot water distribution for new alternatives
3. Investments for energy production, which have to be paid by the consumer.

If the first two can be solved by simple means, the third necessitates the development of adequate bodies able to invest in energy production and to sell hot water to consumers.

要旨

フランスにおける低エンタルピー地熱地域，特に地熱エネルギーについて

ジャック・ヴァレ (BRGM* 地熱部)

地熱資源を地質学的，地球化学的見地と，熱源の温度の点から分類した。熱水調査に用いられた方法にふれながら，地熱開発技術を略述した。地域における熱エネルギーの需要，地熱源の規模，熱源の温度の要素に従って，調和ある開発方針をたてることが大切である。開発プラントの寿命の正しい推定が，将来の地熱開発の立案に役立つ。

パリ盆地の Dogger (ジュラ紀) 層，ロワール河流域の浅部熱源，アキテーヌ地方の無塩熱源等の場合を例にとって，開発計画の経済バランスを紹介した。現在，フランスで開発されている数プラント，および計画中のプラントの記述をした後，フランスの地熱エネルギー政策と将来の見通しに関する若干の仮説に論及した。

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