geothermal energy

residential space heating

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ABSTRACT

The purpose of this study, which was carried out under the auspices of the DGRST, was to determine the best way to use geothermal hot water for residential space heating. It quickly became apparent that the type of heating apparatus used in the housing units was most important and that heat pumps could be a valuable asset, making it possible to extract even more geothermal heat and thus substantially improve the cost benefit of the systems.

Many factors play a significant role in this problem. Therefore, after a first stage devoted to analyzing the problem through a manual method which proved quite useful, the systematic consideration of all important aspects led us to use a computer to optimize solutions and process a large number of cases. The software used for this general study can also be used to work out particular cases: it is now available to any interested party through DGRST. This program makes it possible to

- take climatic conditions into account in a very detailed manner, including temperatures as well as insolation. 864 cases corresponding to 36 typical days divided into 24 hours each were chosen to represent the heating season. They make it possible to define the heating needs of any type of housing unit.
- simulate and analyze the behavior in practice of a geothermal heating system when heat is extracted from the well by a simple heat exchanger. This simulation makes it possible to evaluate the respective qualities of various types of heating apparatus which can be used in homes. It also makes it possible to define the best control systems for the central system and substations and to assess quite accurately the presence of terminal controls, such as radiators with thermostatically controlled valves.
- determine to what extent the addition of a heat pump makes it possible to improve the cost benefit of geothermal heating. When its average characteristics and heating use conditions (price, coefficient of performance, length of utilization, electrical rates, etc.) are taken into account, the heat pump should not be scaled for maximum heating power. Consequently, the program considers several possible sizes, with different installation schemes, and selects for each case the value which corresponds to the lowest cost of heating.

EDF/ELISE/INFRATEL/PARICA

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Fig. 1. Evaluation of geothermal resources that might be used for heating (as of 31 December 1975).

Old massifs

Proven resources

Probable resources

Possible resources

Aquifers for which the total data available are:

- reservoir properties (lithology, depth, thickness, porosity, permeability),
- physical and chemical properties of the fluid

Aquifers for which available data are insufficient. Plausible assumptions of parameter values can be made, although with risk of error.

Resources located in zones where there are probably formations that can make up reservoirs but whose precise localization is difficult and properties are not well known.

1. introduction

Among the improvements in heating installations which have been proposed over the past few years, those which call upon new energy sources hold a special place. Although few in number, those methods which use solar radiation or heat from the atmosphere or from surface or subterranean water are particularly interesting because of the reduction in air pollution as well as the savings in fossil fuels.

Several viable and inexpensive heating methods which have thus been brought to light have favored the development of certain techniques of heat exchange and transfer using these "new energies" and the development of corresponding equipment.

The recent fear of shortages of combustible fossil fuels has pointed up the necessity of extending the use of our total available resources in our own country, which must, over the next 10 years, furnish a not inconsiderable share of the energy we consume.

Heat from within the earth itself, or geothermal energy, is of some interest in the light of this situation. Available geothermal resources in France have been inventoried by the Bureau of Geological and Mineral Research. The map in figure 1 shows the extent of reservoirs in which the temperature exceeds 50° C. Temperatures are even higher in a large part of the Aquitaine and Paris Basins, in Bresse, in Limagne and in Alsace. In the latter two regions temperatures are often over 100° C. A number of geothermal heating installations are working or under construction, notably in the Paris Region where the installations on line in 1976 will allow annual savings estimated at the equivalent of 10,000 tons of oil, which would heat 10,000 homes, factories, and greenhouses. A number of other projects are being studied in Aquitaine, Alsace and Limagne.

The chemical characteristics and operation of geothermal reservoirs determine a precise configuration for a geothermal "generator" (figure 2). The brine gives up

heat through an exchanger in a secondary loop (heating network) from which branch off the auxiliary heating unit and thermodynamic transfer installations. Cooled water is then reinjected into a reservoir at a suitable distance from the production well.

The relatively high initial capital cost of these heating systems and the relatively low heat level of the extracted energy require numerous precautions. The cost-effectiveness of the installation depends on the amount of usable heat extracted annually and thus on the relative size of the system compared with maximum needs. The way in which the heat is distributed, the kind of controls and the characteristics of the building itself (insulation, inertia) are also very important.

Research should therefore be conducted to define the optimal conditions for using geothermal energy and determine the principal precautions needed; this was the thrust of the request for proposals put out by the General Task Force for Scientific and Technical Research (DRGST) for residential heating. Under these auspices a study was carried out by three groups working together:

- the PARICA office of research, under the direction of M. Jean Oliver
 - the Electricity-Insulation Company (ELISE), in collaboration with research office INFRATEL and under the directions of M. Michel Villaume
 - the Study and Research Directorate of Electricite de France (Chatou) under the direction of M. Aureille.
- This report includes the contributions of the various contractors and is organized as follows:
- description of the manual method of approach to problems of using geothermal energy (PARICA)
 - study of space heating systems (INFRATEL)
 - use of heat pumps (EDF)
 - presentation of computational tools used and the principal results obtained (EDF and INFRATEL)
 - conclusions.

2. manual approach method for problems of using geothermal energy (PARICA)

aims, means, obstacles

The object of the computational method proposed here is to make the best use of low temperature (50–80°C) geothermal energy resources for residential space heating. This method attempts to be realistic, and since it depends only on classic, even elementary thermodynamic principles, it can be easily applied. The results obtained are exact but at the same time depend on initial hypotheses which are essentially of an economic nature.

The three aims of this chapter are:

- furnish a general idea of useful areas of application
- call attention to difficulties to be foreseen and errors to avoid
- help thermodynamicists to carry out the necessary research peculiar to each case without taking too much time.

What is a study of Geothermal Heating?

Any study of geothermal heating can be summed up in two words: "optimization" and "cost benefit."

- Optimization, when possible, of heating systems, especially with regard to heat emission at the residential level.
- Optimization of the exchanger (flow rate and size)
- Examination of the financial cost benefit of a well, plus exchanger system.

Estimation of Consumption

The principal difficulty is in the estimate of consumption. Standard methods are inapplicable here, because the share of each energy source (geothermal energy, heat pump, backup unit) varies as a function of the energy power needed and the temperature of the return water, i.e. conditions external to this problem.

The problem can, however, be easily and precisely resolved in each case by means of a simple manual method which is described below.

Temperatures

Important difficulties are encountered when the well temperature is too low with respect to that of the return flow from the heating system. The return flow temperature always plays an essential role. The well temperature, and thus the network flow, at constant energy, are very important when one is using a heat pump, but not as important as the wellhead temperature.

In order to derive any benefit with a standard heating network, the well temperature must approximately be at least equal to the maximum temperature of return flow.

Size of Heating Network

The size of the heating network to be supplied is another obstacle. For example, if the network has a peak power of 5 kilotherms* an hour, the investment in resource and reinjection wells cannot be amortized, even if the system furnishes all the heat necessary.

Base Data

There are other difficulties which should not be overlooked, for example an excessively high interest rate or too infrequent use of the systems, but the risks pointed out above are the most important. This is why results which follow refer to

- well temperature
- maximum value of return water temperature and consequently to types of interior systems used for residential heating.
- maximum power needed by the heating network

Other Factors

There are some other very important factors:

- well flow, difficult to predict even if the geologists have some idea of it in advance.
- the purity of the water from the well, which could eventually dispense with the need for a reinjection well.
- other rather numerous factors.

There are factors peculiar to each geothermal project; therefore this study will be limited to the case of a double well system from which the flow production and reinjection is 100 m³/h.

Energy Cost Benefit

Energy cost-effectiveness is expressed by a ratio established by public authorities:

"ratio of the capital cost (in geothermal energy) to the number of equivalent tons of petroleum saved annually."

This ratio is of concern to the entire Nation, but it also is of concern indirectly to the project manager, as it will play a role in the calculation of financial assistance which may eventually be granted.

*1 therm = 1 million small calories

consumption calculation method

Different Operating Regimes (Figure 3)

In a geothermal heating system there are generally several operating regimes.

First, in mild seasons, when the outside temperature is, for example, over 12° C, the exchanger alone is enough to furnish all the heating energy needed. On the other hand, at -7° C, the output of the exchanger generally becomes very low and sometimes zero. In fact, in mid-winter, when peak power is called upon, the heating units in the homes are hottest and the return flow is consequently at its maximum temperature, consequently allowing the extraction of the smallest quantity of geothermal heat.

For economic reasons, the heat pump, when it is present, must not be sized for peak power. It comes in progressively up to its nominal power (point N) in relation to needs, tops out, and decreases to a lower level if the temperature of the condensor increases. Thus the backup system (conventional fuel-fired boiler) is generally not used in mild weather but supplies most of the heat in cold weather. There are therefore up to four or more regimes.

Principle of the Method

The manual method which has been developed consists of

- determining the different operating regimes which can exist.
- computing the temperatures of transitions between the regimes.
- seeking, for each regime, the value of the weighted average temperature and determining the contribution from the different energy sources.
- summing the partial balances to obtain the total consumptions for each source—geothermal energy, heat pump, backup system.

Transition Temperature

One first establishes the monotonic curve which shows heating needs as a function of the outdoor temperature and thus the degree-days for the region under study. This curve is limited to the space heating period; the furnishing of potable hot water, if there is any, should be treated separately for the summer period.

One first looks for the transition temperatures, either by trial or, preferably, algebraically. For example, the temperature of the transition between the "exchanger only" regime and the "exchanger plus auxiliary" regime is that for which the contribution of the exchanger is exactly equal to heating needs and is computed by writing that these two values, expressed by the same variable, are equal. The exterior temperature is the most convenient variable.

Establishment of Partial Balances

For each operating regime, one computes the weighted average temperature. To do this, one determines the number of degree days included between the transition temperatures (the part of the area under the monotonic curve limited by the two transition temperatures) and the number of days corresponding to that interval (abscissa). The relationship of these two quantities is equal to the value of the degree days, which gives the weighted average exterior temperature.

The calculation is exact as long as the variations in size remain linear as a function of the chose variable; in other cases it is sufficiently close if one takes certain common-sense precautions.

Total Balance

The sum of partial balances gives the distribution of energy consumed during the heating season. It then becomes easy to establish the calculation of optimization and cost benefits by adopting a realistic figure as a value for supplemental energy, and by calculating the exact consumption of electricity (wells, special circulation pumps, heat pump compressors, etc.), this can be calculated by applying the "green" rate of EDF but can be estimated fairly correctly after a certain number of operations.

exchangers: performance, optimization, cost effectiveness

Choosing an Installation Scheme

When a heat pump is not included and geothermal heat is extracted by simple exchange, there are no serious problems in choosing an installation scheme, and in the case of several exchangers, one can install them either sequentially or in parallel, depending on the technology peculiar to the manufacturer. In the case of the eventual use of a bypass, there are several possible cases (fig. 2). When the flow through the heating network is less than or very close to (+15%) well flow, one must use the total flow to feed the exchanger, so that the use of a bypass could have only a harmful effect. On the other hand, when the flow of the network is much larger than that of the well, one can consider using a bypass to optimize the fraction of the flow admitted into the exchanger.

Flow Optimization

The part of the flow admitted into the exchanger is optimized by comparing on a broad scale the investment costs and the amount of useful heat extracted from the heat exchanger. All else being equal, the price of the exchanger has a tendency to diminish when the secondary flow increases, through the improvement in the log mean temperature differences. But, from another point of view, the costs of plumbing, pumps, and electricity used to run the system increases.

The optimum falls generally in the neighborhood of 110 to 125 percent of the primary well flow.

*A special rate applied to demands from 5,000 to 30,000 volts.

Optimization of Heat Exchanger Size (Fig. 5 and 6)

It is known that the price of an exchanger is not a direct function of its nominal power but that it depends especially on its exchange capacity, expressed sometimes as "KS," which varies little for the same apparatus, at constant flows and at small differences in temperature. This capacity is the quotient of the nominal power over the log mean temperature difference.

Optimization will be accomplished by taking three of four values of KS and calculating for each case the cost of amortizing the exchanger, the amount of heat extracted in the course of one heating season and the corresponding pumping costs. The curve of the economic benefits of the heating project as a function of KS presents a peak which characterizes the optimum KS.

In the adjoining figure (fig. 5), KS is replaced by ΔT , ΔT referring to the difference in temperature between exit of well flow and entrance of the return flow from the network. The latter has a minimum value, i.e., 25° C for radiator heat and 22° C for floor heaters.

The optimized exchangers (fig. 6) show a few differences by type of system. With a 90/70° C network (radiators), the deviation at the well exit should be on the order of 2° C. With a 55/40° C (floor heater), the optimum deviation is a little higher.

Other Characteristics

Heat exchangers should come as close as possible to the perfect "counter-current." If the water is corrosive, the primary loop should be made of titanium or have a specially designed lining.

Return on geothermal heating relative to standard heating with fuel oil (solution without heat pump)

Fig. 7. Radiator, 90/70°C (without sanitary hot water).

Fig. 8. Floor heater 55/40°C (without sanitary hot water).

Fig. 9. Mixed system, 60/30°C (with sanitary hot water).

Cost Benefit (Figs. 7, 8, 9)

The feasibility of a geothermal operation is tied to its financial cost benefit. This can be calculated simply by difference with a standard operation. One will study the costs corresponding to the investments peculiar to geothermal energy (including all equipment: plumbing, heat insulation, controls, civil engineering, plus all the costs associated with drilling and related expenditures) and deduce the savings compared to a standard installation and calculate the corresponding amortization. On the other hand, one will estimate the savings in combustible fuels and deduct the costs of supplementary electricity.

The joined curves, which characterize the eventual cost benefit of the combination "well + exchanger," without using heat pumps, are established as a function of the well temperature, type of installation, and peak power needs, with fixed interest rate of 10.8%.

The cross-hatched zones show **certain** lack of cost benefit, but cost benefit should be verified in the other cases (influence of planning and related use factors).

The furnishing of sanitary hot water always introduces a positive element, especially when the heating system is not very favorable to using geothermal energy, but the heating system should be the subject of special study (control at substations).

The influence of interest rates applied to investments is extremely important. The curve (fig. 10) shown as an example effectively demonstrates this.

Fig. 10. Effect of interest rate on cost effectiveness of a geothermal heater.

heat pumps: plans, optimization, cost-effectiveness

One should not undertake to study use of a heat pump in a geothermal heating system until the optimization and cost-benefit analysis of the well + exchanger combination has been completed. This study would then be marginally useful by definition, and its results should be compared with those obtained with an optimized exchanger alone, even if the exchanger must be modified for the needs of the heat pump.

Plans

The heat pump is used to extract more heat by chilling the geothermal water reinjected into the reservoir, and for that it is possible to visualize numerous connection plans.

The easiest is that in which the water coming out of the well passes successively through the primary exchanger, then the heat pump evaporator. However, the manufacturers of heat pumps warn against running corrosive water through their components (fig. 11). One can either provide an auxiliary loop (fig. 12) or use the water from the network simultaneously in the evaporator and in the condenser of the heat pump (fig. 13).

In all cases (and there are others) the secondary exchanger and the condensor can be mounted in parallel or sequentially, the criteria being the temperature at the condensor exit, which must remain as low as possible in order not to reduce the value of the coefficient of performance of the heat pump.

In the three schemes there is a certain loss of energy but the average coefficients of performance differ little where the best sequential or parallel choice has been made.

Optimization and Cost Benefit

The marginal value of the heat pump takes the following into account:

- the amortization of investments related to the heat pump (including all costs that it entails, especially controls, civil engineering, transformer, etc.).
- the added cost of annual consumption of electricity by the compressor and the circulation pumps.
- the annual supplemental fuel savings with regard to receipts. The optimization process is the same as for the exchanger.

Three of four hypotheses for power level make it possible to trace a cost-effectiveness curve where the maximum defines the optimal power level of the heat pump.

In order for the heat pump to be acceptable, the cost-effectiveness must be clearly positive, as load factors always play a negative role.

Importance of the Coefficient of Performance

It is quite evident that the coefficient of performance (COP) is of paramount importance and that its value must be increased by all means, especially by reducing the temperature difference between the evaporator and condensor. In fact, it turns out that in this respect the heat pump benefits from favorable conditions.

If one assumes a parallel installation with a deviation of 2°C at the exit of the exchanger, one will have, for example

- evaporator inlet $100\text{ m}^3/\text{h}$ at 47°C
 - condensor inlet $135\text{ m}^3/\text{h}$ at 45°C
- and the COP will be 5.5 if the refrigerating power is on the order of 2000 megacalories an hour and still higher for lower power levels.

One could further considerably improve the overall COP by dividing up the work of the heat pump and by using two or three stage machines. In the preceding example the overall COP of three heat pumps in sequence would be on the order of 7.6. It is further evident that the yield at partial load would be clearly improved.

Some Results

For a two-well system having a flow of $100\text{ m}^3/\text{h}$ connected by optimized exchangers to a heating network feeding radiators ($90/70^{\circ}\text{C}$), the optimization of the heat pump shows that its nominal peak should be placed well below the peak power of the heater (fig. 14).

Under these conditions, the marginal cost benefit of the heat pumps is quite remarkable (fig. 15). The curves shown and research in progress show that this marginal cost benefit varies essentially inversely with the quality of previously existing equipment. On the other hand, the cost benefit of the heat pump will often be mediocre if the system is already giving good results with simple heat exchangers.

Fig. 14. Determination of optimum power of the heat pump.

Fig. 15. Marginal cost-effectiveness of the heat pump (radiators $90/70^{\circ}\text{C}$ or more)

The overall cost benefit of the "network with radiators + well + exchangers with or without heat pump" system is shown in fig. 16.

As for the energy cost-benefit ratio, the addition of the heat pump is again a determining factor, citing again the radiator example.

Fig. 16. Return on geothermal heat relative to a standard heater using fuel oil.

Fig. 17. Energy cost effectiveness.

3. study of space heating systems (INFRATEL)

Systems which use geothermal energy for residential space heating are made up primarily of

- production equipment which includes the heat exchanger at the well-head, the backup heating system and finally the heat pumps
- the heating network with substations
- the interior unit

This system is analogous to a high fidelity audio system where each element has its importance and where overall performance is equal or inferior to that of the weakest element.

The Types Considered

Different interior heating units can be divided into 3

large categories:

a. Standard systems which could function at low temperature, for example

- radiators or convectors supplied with water at 90° C maximum
- radiators or convectors supplied with water at 70° C maximum
- floor heaters supplied with water at 55° C maximum
- floor heaters supplied with water at 40° C maximum

When these heaters are supplied with low temperature water, one must increase their radiating surface. Moreover, one must take note that at this time floor heaters alone are incompatible in new construction.

b. mixed apartment heating systems, functioning exclusively with hot water or with electric backup. These systems correspond to "standard systems," for example

- hot water radiator or convector
- water/air exchanger (counterflow type) and floor heater or radiator, etc.

These can be mounted sequentially or in parallel. In any case, analysis shows that the sequential systems are more interesting.

c. Low temperature discharge systems specially designed for geothermal energy, which are the subject of a patent application (no. 75 35929) and are in the technical development stage.

It is certain that geothermal energy utilization is quite sensitive to the choice of interior heating unit and that the cost benefit of the system is dependent on complete utilization of the thermal energy which does not occur in traditional heating. A good system should therefore have a discharge water temperature as low as possible, which implies that:

- the temperature of the return water should not be higher than that of the water coming out of the home heating units;
- any system which limits the flow through the heating units will be favorable to geothermal energy if the temperature of the return water is decreased;
- any system specially designed to obtain a low return water temperature will improve the cost benefit.

In any case, the numerous simulations of heating system operation which have been tried show.

- performance which varies greatly according to the system.
- the necessity of conceiving a heating system specially adapted to geothermal energy, starting with existing or new systems. This solution is manifestly feasible when geothermal energy is being planned for new construction but generally cannot be applied to existing housing.

Controls

Controls play a very important role in geothermal heating systems. They should be based on variation in flow rate, apart from any mixing that would increase the temperature of return water.

Controls occur at several points:

- control of water temperature as it enters the heating system, as a function of the outside temperature, in order to extract the most geothermal heat and to limit losses without making the network oversized.
- control of water temperature feeding the home heating units (precontrol at the substations) as a function of exterior temperature and ultimately of insolation.
- control of heating unit based on variation in flow (2-way valves), which is generally preferable to discharge equipment (3-way valves) maintaining a constant flow.

For hybrid systems which consist of a basic heating system and a supplemental or back-up system, the size of the base system is sensitive, and furthermore, controls play a particularly important role, not only in terms of cost benefit but also in terms of comfort, by limiting overheating.

Cost Benefit and Optimization of Systems

To study cost benefit one must compare the extra

capital investment (ΔI_{geo}) needed to use geothermal energy with the annual energy gain (Q_{geo}).

ΔI_{geo} includes the costs entailed by

- adapting interior equipment, substations, networks,
- well drilling and ancillary equipment,
- the main station (heat exchanger, auxiliary boiler, and sometimes one or more heat pumps).

Cost benefit is thus expressed by the following formula:

$$\Delta I_{geo} < A \cdot p \cdot Q_{geo}$$

where A is the coefficient of actualization and p the unit price of energy.

Some badly adapted or controlled systems cause an energy loss which is reflected by additional consumption of supplemental energy; therefore, to study cost benefit it is essential to consider only geothermal energy usable for space heating and hot water, thus excluding systems where geothermal energy utilization is pushed at the price of a significant use of backup energy.

In the discussion below Q_{geo} represents **usable geothermal energy** which is less than or equal to the geothermal energy extracted from the well.

The quantity Q_{geo} is then computed starting with theoretical needs, i.e., the quantity of heat (Q) which is necessary and sufficient to heat the buildings.

In brief, C represents supplemental energy

$$Q_{geo} = Q - C$$

If one were to overlook the heating losses in some heating units, the energy extracted from the well would be confused with the real savings in energy. This becomes especially serious when one is using geothermal energy because in some cases the backup energy can increase to considerable proportions and even represent the entire amount of wasted energy. In fact, any system producing excessive consumption weakens the real performance and cost benefit.

Finally, in order to study the influence of different parameters and generalize the results of the calculations, it is

useful to consider the non-dimensional ratio $\frac{Q_{geo}}{Q}$, or:

$$\frac{Q - C}{Q} = E \text{ (geothermal effectiveness)}$$

Geothermal effectiveness has the advantage of considering all the parameters linked at the same time to:

- type of heating unit (radiators, floor heaters, etc.)
- size of heating unit
- use of the system (controls and regard to distribution points)

This magnitude embraces a large number of properties, facilitating the study of systems and cost benefit.

$$1. E = \frac{Q - C}{Q} = 1 - \frac{C}{Q}; \text{ thus } E < 1$$

2. When energy needs increase, effectiveness decreases. One must find out how to obtain the greatest values of E for a given program (number of homes, temperature, and well flow).

3. In making comparisons of energy savings for a given flow and number of housing units among various systems, one need compare efficiencies alone, all wastage being discounted.

4. The product QE represents **usable geothermal energy**. It is very useful for making calculations of the cost benefit of simple exchange geothermal energy systems.

5. Calculations of efficiency for different values of parameters allow the study of the sensitivity of the project to variations in flow, temperatures, controls, size and choice of heating units, etc.

Note

For existing buildings where it is not possible to retrofit the system, one must consider the apparent geothermal effectiveness:

$$E' = \frac{Q'_{\text{geo}}}{Q}$$

where Q' represents the real heating needs for the existing system. Thus, in this case only, Q'_{geo} represents the energy savings realized each year. Proceeding from the

fundamental relationship $E = \frac{Q - C}{Q}$, it is then possible

to study the cost benefit conditions in different ways, all equivalent but some of them allowing easier isolation of the optimum (if there is one).

Cost Benefit: Financial Balance

$$\text{Take } \frac{1}{A} \cdot \Delta I_{\text{geo}} < p \cdot Q_{\text{geo}} = p \cdot Q \cdot E$$

or $m \cdot \Delta I_{\text{geo}} < p \cdot Q \cdot E$ (m is the coefficient of amortization)

Therefore $F1 = p \cdot Q \cdot E - m \cdot \Delta I_{\text{geo}}$ (annual financial savings). Cost-effectiveness is attained when $F1 > 0$.

It is then necessary to draw several curves $F1(N)$ following the values of m (which depends on interest rates and the amortization time of materials).

$F1$ is a function of the number of housing units, N , the characteristics of the heat exchanger, temperature and flow of the well, and in general all the characteristics of the heating system.

Cost Benefit: Energy Cost

The general formula can be expressed as follows:

$$\frac{\Delta I_{\text{geo}}}{A \cdot Q_{\text{geo}}} = P1 < p \text{ or } \frac{\Delta I_{\text{geo}}}{Q \cdot E} < p$$

$P1$ is the cost of all the energy derived from geothermal resources (function of the same variables as $F1$).

Cost Benefit: Annualized Cost of Energy

$$\frac{\Delta I_{\text{geo}}}{A \cdot Q_{\text{geo}}} = A \cdot p \text{ or } \frac{\Delta I_{\text{geo}}}{Q \cdot E} < A \cdot p$$

and one studies:

$$F2 = \frac{\Delta I_{\text{geo}}}{Q_{\text{geo}}} \text{ (extra investment divided by total energy saved annually)}$$

$F2$ depends on the same variables as $F1$.

Accounting

Accounting from the annualized cost $F2$ has the advantage of fixing, by a value of the ordinates, the economic and financial hypotheses independently of the systems and number of housing units.

One can thus place in evidence, for example, an optimum housing program independently of economic conditions, optimum size of the heat exchanger, etc. This is the accounting system which has been adopted. It is therefore easy, using a diagram, to establish the relationship linking the economic hypotheses and the annualized cost.

Determination of Energy Saved or Efficiency

The additional investment is calculated by adding up the various costs; on the other hand it is not easy to determine the energy savings actually achieved, hitherto referred to as usable geothermal energy, without simulating the entire geothermal heating system characterized by quite numerous parameters. Finally, the systematic study of the influence of each parameter forces a generalization of the calculations which has made necessary the use of a dimensionless value, geothermal effectiveness.

Recourse to automatic data processing consequently becomes valuable, if not indispensable:

- to take into account insulation and the various internal positive factors with consequences at two levels:
 - needs are not in proportion to the difference between the inside and outside but depend a great deal on free heat sources which are not uniformly spread through time and space,
 - the action of the controls on well-designed home heating units causes a noticeable reduction in temperature of the discharge water and therefore an increase in the use of geothermal heat which can be useful or not, depending on whether demand is above or below geothermal heat production.
- to simulate the operation of more or less complex systems where the linking of successive controls makes it necessary to do the calculations by successive approximations and where it is necessary to study the behavior of the system on a great number of points of operation in order to determine the flow and temperatures of the network and the exchanger, boiler, heat pump, etc.

The calculations were done with the METEO, BILAN and GEO programs on 864 operational points representing the entire year. These points are characterized by these values:

- outside temperature and its daily pattern
- insolation
- internal positive factors.

The first two were obtained from the analysis of the last 10 years of meteorological data from the Paris-Le Bourget Station in the first study.

4. use of heat pumps (EDF)

Heat transfer making use of thermodynamic machines seems to have a place in geothermal energy. Therefore researchers have been looking closely at the operating conditions and principal characteristics of heat pumps.

Definitions

A heat pump is a refrigerating machine in which heat energy from a warm source is used; this heat being most often transported to a cold source through the expenditure of mechanical energy.

In fact, for the use under consideration, i.e., residential space heating with geothermal water, if one mentions heat pumps, there are two interesting features of the machine. When the problem is diagrammed as in figure 18, it becomes evident that the inclusion of a heat pump allows:

- considerable chilling of the cold source and consequently the extraction of more calories from the geothermal water.
- reheating of the warm water to the heat level required for utilization.

The simplest and most efficient heat pumps considered here are compression heat pumps.

General Thoughts on Compression Heat Pumps

Compression heat pumps are made up principally of a compressor, which can be a piston type, as in figure 19, or centrifuge, and exchange surface (condensor and

Fig. 18. Insertion of a heat pump.

evaporator). Their size is relatively small in this case, as the heat transfers at the level of the two sources occur between the working fluid and liquid water (geothermal water, and heating water) which is a dense fluid

Fig. 20

and good conductor. The expansion valve generally causes a simple pressure drop.

By way of defining the characteristic dimensions of a heat pump, it is possible to follow the evolution of the working fluid through a cycle on an operational and enthalpy diagram (figure 20).

Geothermal heat assures the vaporization of the working fluid (1 to 2). The vapor then crosses the compressor, which uses mechanical energy to increase the pressure level and temperature simultaneously (2 to 3). The proper functioning of the compressor demands that aspiration take place in dry vapor (point 2). In the condenser, high-pressure fluid releases condensation heat which is transmitted to its end use (3 to 5). After cooling (5 to 6), the condensed fluid is then released at constant enthalpy (adiabatically and without producing mechanical energy) through an expansion valve (6 to 1), then returns to the evaporator in its original condition (1). It will be noted that the choice of temperatures t_g and t_s which fix the levels of vaporization and condensation also define the compression ratio which is a principal characteristic of the compressor.

Another very important characteristic of heat pumps is the coefficient of performance, defined as the ratio between heat energy P released by the hot source and the mechanical energy W absorbed to carry out this operation.

In the general case of a dithermal heat pump:

$$\text{COP} = \frac{|P|}{|W|} \text{ or here } \text{COP} = \frac{h_3 - h_6}{h_3 - h_2}$$

In the case of a Carnot cycle heat pump one would have

$$\text{COP} = \frac{T_c}{T_c - T_v} = \frac{1}{1 - T_v/T_c}$$

where T_c is the fluid condensation temperature in °K and T_v the fluid vaporization temperature in °K. The efficiency a in relation to the ideal cycle is then given by the ratio between the real coefficient of performance

COP_{real} and the ideal coefficient of performance $\text{COP}_{\text{ideal}}$ in relation to the same change of state temperature:

$$a = \frac{\text{COP}}{\text{COP}_{\text{ideal}}}$$

This efficiency, apparently always less than unity, depends mostly on operating condition of the real heat pump under consideration.

Heat Pumps in Geothermal Heating Systems

To study the advantages of including heat pumps in geothermal heating systems, it is necessary to be well acquainted with their characteristics, especially the coefficient of performance and its variation as a function machine load. If the heat pump must work at 100 percent of its load during the coldest part of winter in order to raise the network water temperature to the maximum, then during the mild seasons the heat level demand by the network is less than the heat pump works at partial load.

We have studied whether equipment adapted specially for geothermal energy can be designed and, whether there are heat pumps on the market which can be converted to this usage. Many contacts have been made with manufacturers of refrigeration and compressor equipment. Based on the data we obtained, an approach to the problem could be made, and for the computer calculations we have taken as base elements the following:

- Either given the curves the coefficients of performance as a function of the load, traced on figures 21 and 22 from the information furnished by some manufacturers of refrigeration equipment.

- or given the variation in efficiency $a = \frac{\text{COP}}{\text{COP}_{\text{ideal}}}$ as a

function of the difference in temperature (curve 23 valid for centrifugal compressor machines and $a = c^e$, valid for certain volumetric machines).

For economic calculations it is necessary to know the cost of heat pumps. It happens that there is a great deal

of variation among the prices given by the manufacturers for each type of heat pump. We have therefore settled on the average curve of the price of the totality of usable power (1 th/h) from heat pumps in a standard case (hot water discharged at 50° C from the condensor) as a function of the nominal power of the equipment (figure 24).

In order to compare various geothermal heating systems with heat pumps, we have computed the price of heat pumps given curve 24 and the following ratio, which accounts for the value of temperature at the condensor

Fig. 23. Variation in $a = \text{COP}/\text{COP idea}$ as a function of ΔT .

level.

$$C(T_c) \text{ in F/th/h} = 0.0125 T_c + 0.375$$

where T_c is the value in °C of the temperature of hot water leaving the condensor.

Although this formula, as well as the average curves given above, is encumbered with a great deal of uncertainty because of the variety of equipment, the curves still allow a good approach to the problem at the level of comparisons among the various heating systems under consideration.

Fig. 24. Cost per unit of power of heat pump (50°C at the condenser outlet).

5. data processing tools used and principal results obtained (EDF and INFRATEL)

Several phases were necessary to work out the computer programs for rapid comparison of the various geothermal heating solutions:

- programming the weather data and determination of heating needs
- putting the geothermal heating system (without heat pump) into the computer
- including heat pumps in the general computer program.

Determination of Heating Needs

The METEO program allows the definition of 864 points representing a year of heating based on statistical data from any weather station. The goal is to obtain a representative, typical year which will show the relationship between insolation and outdoor temperatures.

The BILAN program computes energy needs determined hour by hour for 36 typical days and for typical housing units or other places (tertiary, industry). It takes into account

- construction of housing units or places (makeup and size of walls and glazed areas)
- times when people are home and using household appliances
- room temperatures.

Program With Heat Exchangers Only

The program GEO (fig. 25) simulates combinations such as:

- well and exchanger (at variable or fixed flow)
- auxiliary boiler
- heating network (with bypasses and their controls at variable flow)
- function of heating units placed in the homes, considering variations in performance according to temperature and flow
- function of controls (local and central)
- furnishing of potable hot water (temperature, quantity and production time).

Simulation often calls for making iterative calculations for heat exchangers of all kinds.

The calculations give energy actually produced by each source as well as the possible losses. It also permits the study of other losses brought about, for example, by the displacement of control points, heating places at 21°, 22° or 23° C or increased ventilation.

The programs automatically verify the consistency of the data and the calculations.

The results obtained are very sensitive to various parameters:

1. Control of the network and substations.

The researchers are trying to obtain the lowest possible return temperature. This implies

- substations which are controlled without allowing a mixture of flows tending to reheat the discharge water.

- variable flow in the heating network.

2. Indoor heating units in the homes.

Efficiency is particularly sensitive to the types of heaters used in the housing units.

3. Losses.

Assuming that losses are uniformly spread, they affect the value N/D , the ratio of the number of homes heated, N , to flow of geothermal water, D . A change of scale directly gives the new value N/D , counting losses.

Fig. 25. GEO simulation of geothermal installations

- Start of computation
- needs: print annual needs subprogram TEDF
- outside temperature: subprogram ZTMI

SYSTEM

simple

mixed parallel

mixed sequential

temperatures and flows depending on system or base

temperatures and flows under SERIE program

auxiliary calculation: temperatures and flows

calculation of energy complementary to geothermal energy

study: flows, mini, maxi calculation of wastage by overheating

control of calculations by general heat balance: automatic verification of compatibility of data and of validity of calculations

ERROR

print partial results: SDUMPI

print subprogram RESULT results

STOP

4. Well flow.

Use of the variable N/D directly influences the well flow.

5. Well temperature.

Value of the efficiency is as a function of the temperature of the geothermal water.

6. Heat exchanger.

The exchanger can function in different ways:

- variable flow to the secondary: total flow of the heating network passes through the heat exchanger.
- variable partial flow to the secondary: by means of a bypass the flow varies from D_1 to D_2 ; consequently, if D is the instantaneous flow which crosses the heat exchanger one will have:

$$D_{\text{mini network}} < D_1 < D < D_2 < D_{\text{maxi network}}$$

- constant flow at the secondary. It can also be obtained through the bypass; this case limits the above (the large flows to the secondary assure best performance of the heat exchanger).

Efficiency Curves

The curves presented below were established on the following hypotheses:

1. New homes, $G = 1.11 \text{ W/M}^3\text{°C}$ average, replacement of fresh air: $200 \text{ m}^3/\text{h}$ floor area: 76 m^2
 2. Potable hot water:
 - preparation temperature: 50°C
 - temperature at exit of sanitary hot water heat exchanger at the substation: 25°C
 - annual consumption counting losses: 4000 kWh/yr per home.
 3. Simple systems (figures 26 and 27)
 - floor heater 55/40 and 35/27 rated respectively PL 55/40 and PL 35/27.
 - hot water radiators, 90/70, rated 90/70 and 70/50.
 - radiators with thermostatic valves rated RDT 90/70 and RDT 70/50.
- a) heating unit with low output temperature controlled in each room (patent pending on system) rated B.T.R.

Fig. 26. Geothermal efficiency of simple systems (solution without heat pump).

Fig. 27. Geothermal efficiency of simple systems (solution without heat pump).

Fig. 28. Effect of well temperature (solution without heat pump).

Fig. 29. Geothermal efficiency of mixed systems with 'sequential' installation (simple exchange)

Fig. 30. Geothermal efficiency of mixed systems with 'sequential' installation (simple exchange)

b) radiators with thermostatic valves and a series of floor heaters.

Remarks: Individual Metering

Decree No. 75/1175, 17 December 1975, requires individual metering for at least a part of the heating charges.

Among the exceptions to this responsibility for individual metering are the systems calling on geothermal energy for at least half their consumption. Thus all investment in geothermal adaptation for which the value would not be higher than the cost of metering can be considered allowable. This value is poorly understood at this time, but one can place it between 1000 francs and 1500

francs per housing unit, perhaps 2,000,000 to 4,500,000 francs for 3,000 housing units. One will notice that the price of metering is thus not negligible compared to the price of wells and various equipment for a geothermal heating system.

The influence of metering is clearly visible on the cost benefit curves for the hybrid system made up of heating floors fed by geothermal energy and electric backup system without doing away with individual metering.

Cost Benefit

The curves given below were based on the following hypotheses (see Figures 31 and 32):

Fig. 31. Economic and energy cost-effectiveness (exchangers only).

determination of $A \cdot p_e$
 A = actualization coefficient
 p_e = unit price of energy

- costs of drilling, pipelines, titanium heat exchanger and its accessories: 6.6 million francs.
- impact of exchangers and home hot water tanks in the substations: 150 francs/housing unit.
- adaptation of indoor systems: depending on the increase in radiating surfaces.

Program With The Addition of Heat Pumps

The addition of heat pumps to geothermal heating systems was performed in two stages:

- first, EDF conceived a computer program considering that heating needs were defined by the load curve in relation to type F4HLM apartments* in the Paris region and starting with the thermal characteristics of the heating units (radiation curve of 90/70 radiators, heating floors, etc.).
- then, in order to respect a certain homogeneity with studies made by the research office INFRATEL, a variation of the computer program was implemented which allowed the direct use of the results obtained by the METEO and BILAN subprograms. In every case, the scenarios considered come to resemble the scenario with heat exchangers only, as when the heat pump is removed.

The program in essence allows one to calculate the cost of usable heat from geothermal energy. It is composed of a principal program which organizes the energy and economic calculations and calls on a number of subprograms with quite interesting possibilities for development and adaptation as well as diversity.

The principal program (fig. 33) contains the following commands:

- read data
- determine the power to be furnished by the heat pump
- thermal calculation taking into account the scenarios

*Municipal low-rent housing.

chosen and the characteristics of the materials used (heat exchangers, heat pumps)

- calculation of the contributions made by the different energy sources: geothermal energy/heat pump/backup system
- calculation of economic balances
- load curve for each case considered.

Operations are carried out in the following manner: After having read the data concerning

- primary and secondary flow crossing the exchanger (in all our calculations there were assumed to be 100 m³/hr)
- types of heating units (radiators, heating floors, etc.) used in the homes
- flows and temperatures of the heating network for the 864 points representing the various climatic conditions for an average year.

The program can treat, in the course of the same run through the computer, a significant number of cases differentiated by variations in

- temperature of the geothermal water (40-80° C)
- number of housing units (1000-3000 or more)
- type of heat pump (screw compressor, piston, centrifuge)
- plan (figure 37) for the installation of heating (point where heat is extracted by the evaporator, several possible cases)
- the percentage P (fig. 34) of the peak heating power furnished without using the auxiliary heating unit (several possible values).

For each case, the program

- chooses from among the 864 values of the climatic data a point where the percentage of heating power comes closest to the percentage P.
- determines whether this power can be furnished without calling on the backup heater; if this is not the case, it starts over with a lower percentage.

The point finally retained is taken as the nominal point of the heat pump (point B, fig. 34).

The subprogram ECH thus determines the value of the KS of the exchanger.

Knowing the nominal power of the exchanger and the heat pump for a given case, the program

- calculates the electric, geothermal, and backup shares for each of the 864 points in time.
- determines the division of energy among the different sources.
- divides consumption as a function of hours and months (EDF green schedule).

Knowing the power of the installed equipment (heat pumps, exchanger, backup heater) and the share furnished by the different sources of energy being used, the program determines the economic balance. To do this, it takes into account:

- investment cost: wells (5 million francs), heat pumps (see curves), (0.5 × KS francs), auxiliary heater (30 francs/th/h)
- exploitation cost (consumption of electrical energy and backup energy)
- an amortization rate of 10 percent over 30 years
- deducting the price of return from the heat and the savings implemented with relation to a traditional fuel heating method.

At the end of each run, the results are sorted by the subprogram REPART, then processed by the subpro-

gram RESULT to obtain the annual totals of

- energy provided by geothermal resources
- energy provided by the backup system, as well as by the well pumps and heat pumps, taking into account several possibilities for cancellation during peak hours.

The principal program can also call on the subprogram TRASS which gives the load curve with the share attributable to each energy source for each case.

In the course of the economic calculations intended to judge the benefits of a geothermal heating system with heat pump, the share of the cost of electricity in the use Fig. 33

cost seemed sufficiently important to justify more detailed study optimizing the use of electricity. It appeared in particular that heat pumps, which are very attractive from the point of view of heat transfer, unfortunately add to peak electrical loads. Nevertheless, this problem can usually be eliminated if heat pumps can be used only during off-peak hours.

After performing the various optimizations needed, one

Fig. 35. Cost of a therm of heat as a function of the geothermal water for the three schemes under consideration.

can calculate the savings realized by geothermal energy with or without heat pumps, as a function of

- the number of housing units (5.45 kW per unit)
- geothermal water temperature
- type of heating unit installed in the apartments.

By retaining the optimal values of each series of calculations, it has been possible to trace the curves shown here, giving the price of usable heat as a function of various parameters.

Figure 35 shows that the geothermal water temperature has a deciding influence on the cost of heat but that the choice of scheme also has great importance, especially in the difficult cases where geothermal water has a low temperature.

The curves in Figure 36 give, for geothermal water at 60° C, the cost of heat as a function of the number of housing units and the type of heating apparatus used: radiators (90/700, floor heaters (55/40), and 35/27 floor heaters with forced air systems (BTR system, with low return temperature).

For this last type of system, it is helpful to consider supplemental installation fees. These are hard to calculate, and we have taken them in a branch going from 0 to 40 F/m² per housing unit. Further it should be noted that in this case heat pumps are not a practical solution. Their favorable contribution becomes negligible, even negative.

Figures 38 and 39 show that with a geothermal water

Fig. 36. Cost of a therm of heating as a function of the geothermal water heat for the three circuits considered.

Fig. 37. examples of scheme for heat pump insertion

temperature of less than 80° C, the heat pump plays a quite favorable role in the case of radiators; in any case, it allows one to obtain an even more attractive

price for heat with heating floors when the number of housing units is over 1500.

6. conclusions

The results obtained show that in general geothermal space heating is most cost-effective when the number of housing units involved is large, the temperature of return water from the surfaces of the heat exchanger is low, and the temperature of the geothermal resource is high. The effective use of heat pumps (adequate use time and little consumption during peak hours) makes it possible to extend noticeably the area of cost-effectiveness of geothermal heating. Pumps also make it possible to connect a greater number of homes from a given well. The use of these machines provides an important asset when the initial situation is poor (heating by radiators and low geothermal water temperature). On the other hand, their use and the advantage gained can disappear entirely when the initial situation is already quite satisfactory. Thus, heaters with low return water temperature make it possible to use relatively low-temperature wells under good thermal conditions.

The use of these results should, of course, be adapted to the individual study of each project, which should take into account:

- planning of operations. This is always a negative influence, as much on account of extraneous interests as on account of the deficit usually run up during the first years of use.

- additional factors in use including cost of skilled labor, low maintenance, upkeep of systems and general overhead, especially in the cases where there is a heat pump.

- central and substation controls, which should be brought about by limiting the flow from the network without permitting any mixture which could raise the temperature of the return water. Further, to furnish sanitary hot water one should have the lowest possible distribution temperature, a large storage system, or a system of priorities in order to avoid the consequences of consumption during peak periods.

It is important to remember that the results are extremely sensitive to economic hypotheses relating to costs of geothermal systems themselves, wells, and backup systems.

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