40 years of Dogger aquifer management in Ile-de-France, Paris basin, France

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Abstract

The geothermal development of the Paris basin started in the early seventies. Since then, the main target has been the Dogger aquifer. Nearly all operations are using the “doublet” technology consisting of a closed loop with one production well and one injection well. This technology allows the full reinjection of the cooled geothermal brine thus mitigating impacts on both surface environment and hydraulic head in the exploited aquifer.

The main objective of low enthalpy geothermal exploitation is the production of hot water with continuous and large flow rates. The sustainability of the flow rate with an acceptable drawdown can not be obtained without a good knowledge of the long range transmissivity and the hydraulic continuity of the reservoir. Out of the 57 doublet systems, 34 are still active and, following the revival of geothermal energy, new projects are now considered. The exploitation history of these operations, along with the data from various oil exploration wells has provided a better geological characterization of the Dogger aquifer and its behavior.

Though none of the running doublet has ever shown any energy decline yet, the natural heat flux does not allow the renewable exploitation of the resource. Consequently the compilation of this knowledge along with exploitation data is of vital importance to enable a sustainable management of the geothermal resource. This management will rely on both regional and local modeling integrating those data.

Context

Historical context

Since the early seventies, the geothermal development of the French sedimentary basins represents a useful case study. It was favored by three main technical and economical factors (Menjoz, 1990) :

- It exists a productive hot reservoir at reasonable depth (the so called “Dogger aquifer”, a middle Jurassic formation).
- There is an important potential heat market at the surface, with densely populated areas, suitable for this energy production at low temperature level.
- Incentive public policies favored the development of new energy concepts.

In 2009 it will be 40 years since the first geothermal doublet targeting the Dogger aquifer was drilled in the Paris basin. This historical operation is still active today and provides space heating for 5000 housings. Nevertheless, geothermal energy has not experienced a steady growth since then, but its up and downs rather reflected the French technical and historical context.

Nearly all operations targeting the Dogger aquifer were planned and completed in the aftermath of the 1973 and 1979 oil crisis, when incentive policies supported energy saving practices and the development of alternative sources of energy. Then, the 1986 drop in fossil energy prices impeded new operations and initiated a period of withdrawal marked by very little activity. Public support was geared essentially towards the Soultz-sous-Forêts Deep Geothermal Energy Program and in the Paris basin the drilling activities reduced to the replacement of damaged wells or the development of existing facilities (Laplaige *et al.*, 2005).

There has been a boost in geothermal activity since 1998 following the Kyoto Agreement, and the decision taken in France to resume an active policy for energy management and the development of renewable energies. By the same time, just over half of the existing heat networks in the Paris region (17 out of 29) have been equipped with gas cogeneration plants, essentially for economic reasons, by virtue of a particularly attractive rate of purchase of electricity offered by EDF (French Electricity Board). The average rate of geothermal energy coverage for the group of 29 networks is at approximately 60%, and up to 72% for the plants without cogeneration (Laplaige *et al.*, 2005).

Present state

Current policy

The public policy for the revival of the geothermal energy in the Paris basin is based on subvention and insurance measures. After consideration by the French Environment and Energy Management Agency (ADEME) every project can be subsidized up to 30% of the total investment. Then, two types of insurances can cover the financial risk.

In the designing process, the main geothermal parameters, temperature and flow rates, are estimated based on the available geological models. As a detailed reservoir scale model of the whole Paris basin is still lacking, short term risk insurance is used to secure profitability from local geological uncertainties. The insurance subscription depends on acceptance of the technical and financial file by the so called Geothermal Committee and payment of 1.5% of the covered cost. The balance of the fund is partly ensured by public funds (state and ADEME).

Once the doublet is in working order, its economical exploitation is considered feasible, based on proven temperature and flow rate measures. Yet, its long term behavior still remains unknown. The brine chemistry effects on wells and reservoir can induce severe corrosion damage, scaling, or permeability plugging. Geological heterogeneities can lead to an early thermal breakthrough and make the operation lifetime much shorter than expected. To mitigate the financial consequences of these risks, a long term risk insurance integrating depreciation has been set up. Conditions of subscription are enforcement of rules of good technical practice and respect of the regulation, payment of 3.2 % of the covered costs for the first 15 years and, finally, payment of an annual 11.43 k€ contribution for the following 10 years. As for the short term risk insurance, the balance of the fund is partly ensured by public funds (state and ADEME).

Finally, reduced VAT rate applies for company operating heat network supplied by more than 60% of “clean” energy sources including geothermy.

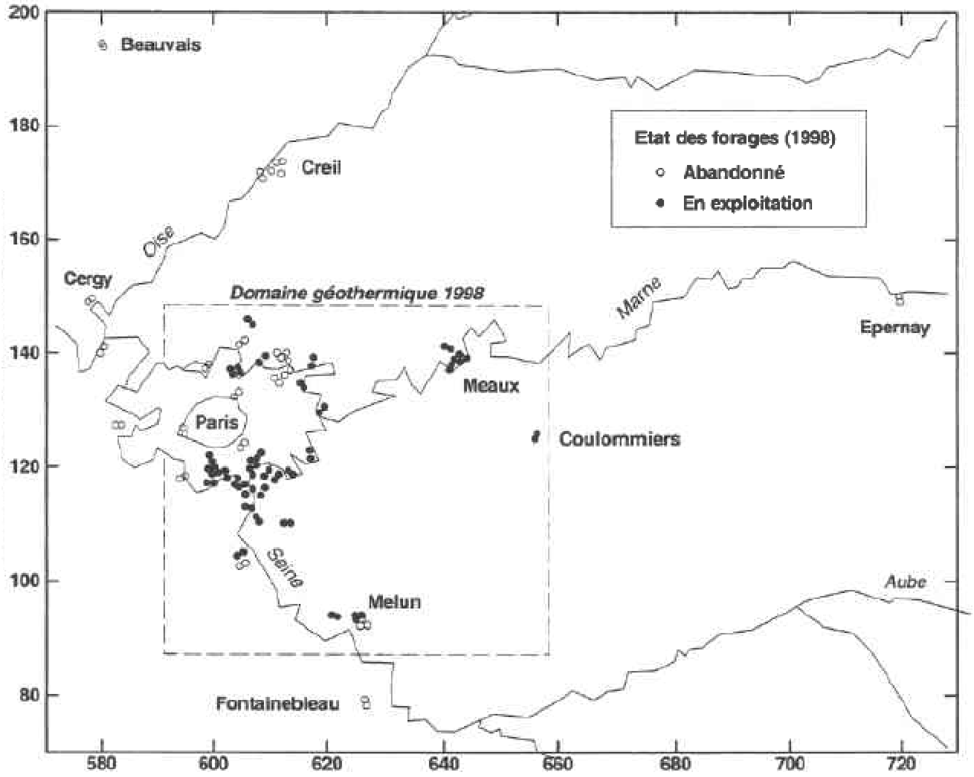

Figure 1: Geothermal wells location in the Paris basin (**Ignatiadis *et al.*, 1998**)

Operating plants

Out of the 57 doublets that were drilled in the Paris basin, 34 are still active. There are 29 geothermal production plants exploiting the Dogger aquifer for district heating. Each plant operates with double or triple wells systems ("doublet" or "triplet"). Only 27 plants show brine temperature higher than 65°C but no energy decline has ever been reported (*cf.* table 1).

37 wells were abandoned mainly for technical (corrosion or scaling) or economical reasons (low profitability of geothermal operations compared with fossil energies). The vast majority of abandoned operations lie in the North West Part of the basin which is the area where the geothermal fluid presents the lowest temperature (*cf.* figure 5).

Figure 2: Well head temperature for geothermal plants in the Ile de France region

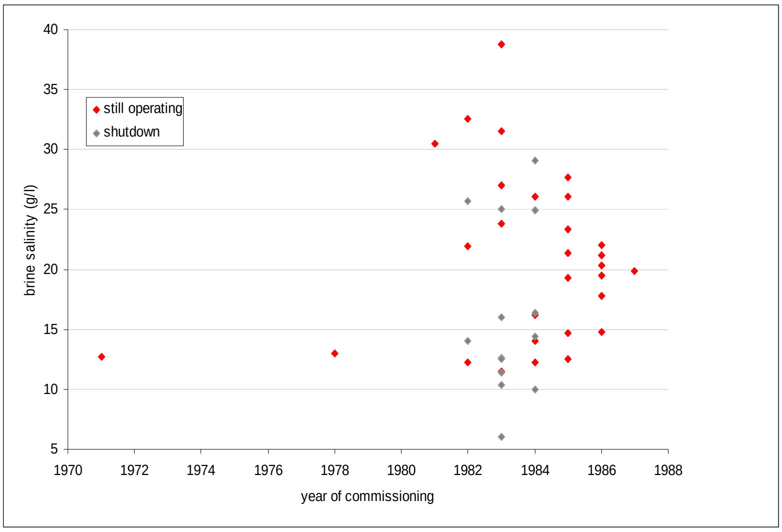

Figure 3: Brine salinity for geothermal plants in the Ile de France region

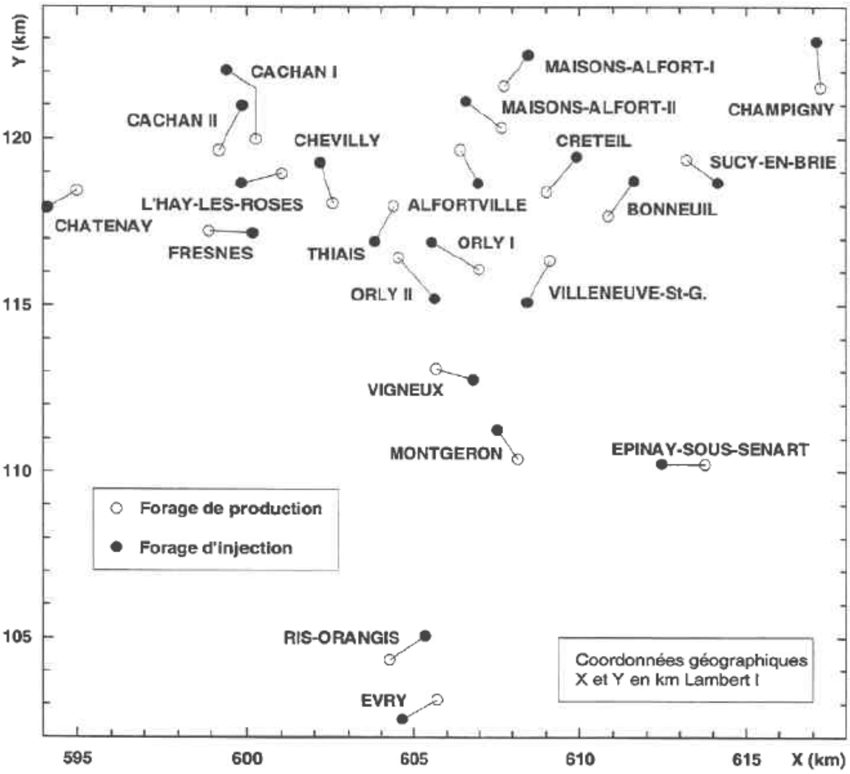

Figure 4: Geothermal wells location in the Val de Marne area (Ignatiadis *et al.*, 1998)

As of today, operations can be gathered in four main groups (cf. figure 1):

- the historical Melun sector,
- the Meaux –Coulommiers sector where all doublets were drilled until 1987,
- the North-East part of the Paris suburbs (Seine Saint-Denis),
- the South-East part of the Paris suburbs (Val de Marne).

These four sectors show a relative homogeneity in terms of the geothermal fluid properties and the reservoir characteristics. The Val de Marne sector has the highest density of wells (*cf.* figure 4) and physical parameters make that the conditions for low enthalpy geothermal exploitation are optimal: relatively high fluid temperature (compared to regional average), low initial sulfide concentrations and proximity of neighboring doublet thus maximizing the exploitation of the resource. This density of exploitation is also one of the main challenges for the future in terms of resource management and definition of new operations.

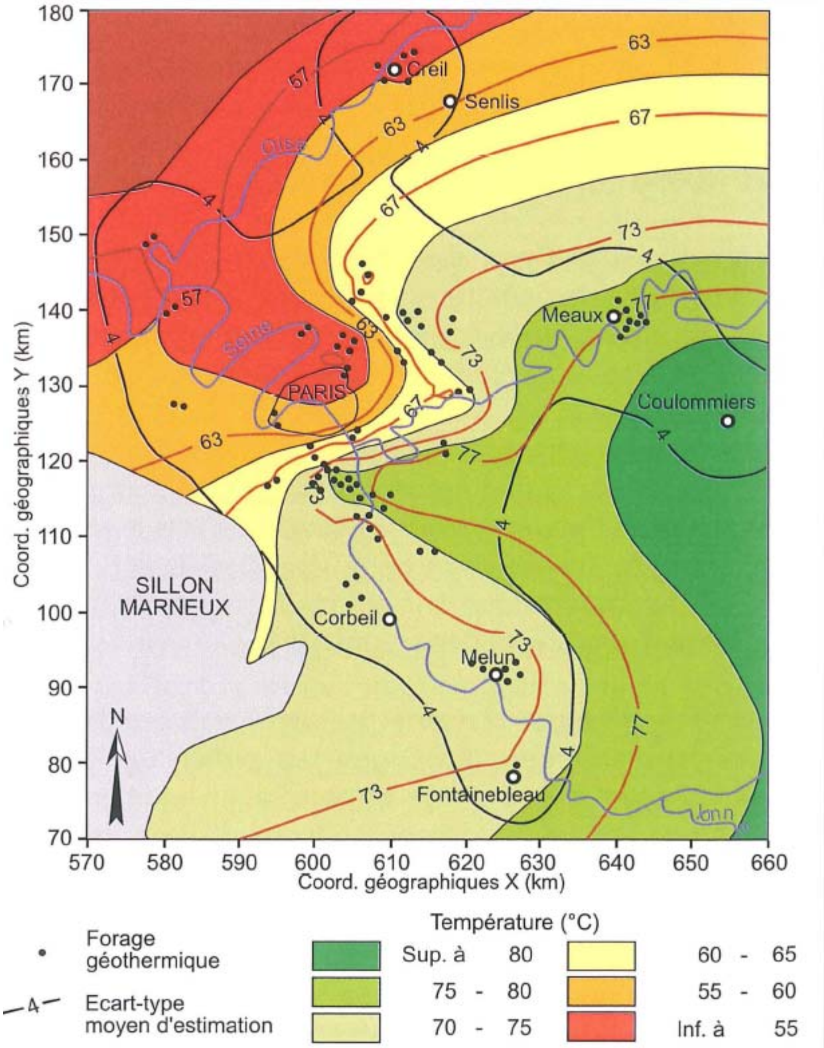

Figure 5: Temperature map of the Dogger aquifer (Rojas.J. *et al.*, 1989; Vathaire *et al.*, 2006)

Geothermal plant	year of commissioning	shutdown	wellhead temperature (°C)	average flow rate (m3/h)	brine salinity (g/l)	additional energy source	geothermal contribution to heat supply (%)
Melun (L'Almont)	1971		71	220	12.7	cg gz	63
Villeneuve-la-Garenne	1976	1994	57	50			
Le Mee-sur-Seine	1978		72	200	13	gz df	34
Montgeron	1982		72.5	220	12.2	gz	77
La Courneuve (Sud)	1982		56	180	21.9	cg gz	32
Cergy-Pontoise - Ville Nouvelle	1982	1991	57	200	14		
Coulommiers	1981		85	240	30.5	cg gz	95
Meaux (Collinet)	1982		79	250	32.6	cg gz df	35
Evry - Ville Nouvelle	1983	1999	72	175	10.4		
Aulnay-sous-Bois 1	1982	1994	71	220	25.7		
Clichy-sous-Bois	1985		71	200	19.3	cg gz	33
Orly 1	1984		76	240	12.2	hf df gz	65
Paris 16eme (Porte de Saint Cloud)	1984	1989	62	200	14.4		
Fontainebleau (Ecole des Mines)	1983	1991	74	130	6		
Meaux (Beauval)	1983		78	600	38.8	cg gz df	35
Meaux (Hopital)	1983		75	250	31.5	cg gz	44
Acheres	1983	1989	55	200	12.6		
La Celle Saint-Cloud	1983	1989	62	170	11.4		
Ris-Orangis	1983		72	225	11.5	cg gz df	42
Blanc-Mesnil (Nord)	1983		67.5	250	27	gz df	62
La Courneuve (Nord)	1983		58	200	23.8	gz	64
Sevran	1983	1990	69	275	25		
Vaux-le-Penil	1983	1998	72	140	12.5		
Chatenay-Malabry	1984	1997	67	175	10		
Ivry-sur-Seine	1983	1994	63.8	120	16		
Garges-les-Gonesse	1984	1994	67.7	250	29.1		
Epinay-sous-Senart	1984		75.2	250	14	gz	72
Aulnay-sous-Bois 2	1984	1994	70.5	275	24.9		
Bondy	1984	1989	64	250	16.4		
Tremblay-en-France	1984		74	275	26.1	gz	90
Cachan	1984		70	340	16.2	gz hf	78
Sucy-en-Brie	1984		78	140	24.9		100
Vigneux sur Seine	1985		71.9	300	12.5	gz df	66
Champigny-sur-Marne	1985		78.2	280	27.7	cg gz	71
Chevilly-Larue / L'Hay-les-Roses	1985		75	600	14.7	cg gz	55
Creteil	1985		78.9	300	23.3	cg df	37
Maisons-Alfort 1	1985		73	300	21.4	cg gz df	67
Villiers-le-Bel	1985		67	290	26.1	cg hf	39
Chelles	1986		69	280	21.2	cg gz hf	42
Alfortville	1986		74	260	19.5	gz	74
Bonneuil-sur-Marne	1986		79.3	300	22	gz	66
Fresnes	1986		71.7	200		cg gz df	50
Maisons-Alfort 2	1986		74	260	20.3	cg gz df	35
Orly 2	1986		76.8	250	14.8	hf df gz	65
Thiais	1986		76	250	17.8	gz	87
Villeneuve Saint Georges	1987		76	350	19.9	cg gz df	61
Paris 19eme (La Villette)	1990	1990					

Table 1: Geothermal plants in the Ile de France region

Today, all operating geothermal plants in the Paris basin are located in the Ile de France region. cg, gz, df and hf stand respectively for cogeneration, gas, diesel fuel and heavy fuel oil. Data come from Vathaire *et al.*(2006) and Huchon(2008)

The future

A public technical center is being created to provide both authorities and stakeholders with a pragmatic technical independent support. The other missions of this center will be to gather all information, studies, and data related to geothermal operations and grant them public access. It should coordinate best specialists, project management and knowledge diffusion. It will conduct specific studies about the development of geothermal district heating and related technical issues. The center activity is currently restricted to the Paris basin (specifically the Ile de France region) and it focuses on three tasks:

- state of the art of geothermal operations with the analysis of all existing options: technical (drilling, equipment), call for tender engineering, insurances…
- scientific works around drillings to define drilling techniques best practices and the appropriate material to be used,
- Dogger aquifer management.

There are new operations that are effectively launched, ten of which could be commissioned before 2010.

Technical aspects

Owing to the short period over which they were carried out, all deep geothermal facilities in the Paris basin share some common points (Ignatiadis *et al.*, 1998).

All works were undertaken without any specific preliminary geothermal exploration phase. All the available knowledge came from general geological synthesis. Consequently the modeling work used to design the doublets was based on crude assumptions concerning the homogeneity of petrophysical parameters.

Detailed reservoir characterization of the Dogger aquifer was only made possible with the growing number of close geothermal drilling operations and the progress of data acquisition tools. Furthermore, the fact that there were few servicing societies greatly helped the diffusion of knowledge and technological advances.

The Dogger aquifer

The Paris Basin area belongs to a large intracratonic sedimentary basin, stable and poorly tectonised, whose present shape dates back to late Jurassic age. Among the four main litostratigraphic units exhibiting aquifer properties, the Mid-Jurassic (Dogger) carbonate rocks were identified as the most promising development target (Ungemach *et al.*, 2005, concerning geology cf. also Gaumet, 1997).

The reservoir formation stretches over 15000 km^2, covering a large part of the Paris region and lies between 1500 and 2000 m depth. Downhole temperatures are between 55°C and 85°C and the water salinities range between 6.4 g/l and 35 g/l. Productive layers are found in deposits of Bathonian age. The limestones have very variable hydrological properties, both vertically, as shown by the existence of a number of different productive levels, and laterally, as shown by the fact that the productive levels cannot be individually correlated. To assume a relative lateral continuity, productive levels were grouped into three distinctive *facies* units: the so-called Comblanchian, Oolitic and Cyclical units (from top to bottom). Among these, the oolitic unit is by far the best producer.

Investigations showed a direct relation between the existence of porosity and the sedimentary environment, in particular the environments in which sandy sediments with matrix porosity were deposited (oolitic limestones). These reservoirs have evolved differently during diagenesis. Thus the void network in the Cyclical unit was reduced by the deposition of cement and by compaction, whereas the sandy *facies* in the Oolitic and Comblanchian units have partly preserved their original porosity. Fracturing and dissolution even improved it in places.

By the end of the 70s the routine acquisition of well logs, especially flowmeter logs, revealed the high vertical and lateral variability of the aquifer. There can be from 3 to 20 individual productive layers in the formation, the cumulative thickness of which only represents 10% of the total aquifer thickness: the net total productive thickness is of the order of 20 m on average. On average, ten to fifteen levels present particularly high permeability (2-20 Darcy).

Accurate identification of the true productive thickness remains essential in designing the geothermal operation and setting the distance between the doublet wells: this distance controls the time of the thermal breakthrough, hence the overall lifetime of the operation (Menjoz, 1990). Then, the high lateral heterogeneity is the biggest obstacle to build a detailed 3D reservoir model. Consequently, until now, most of the modeling efforts focused on the impact of the vertical stratification and the thermal effects of the formations surrounding the reservoir.

Finally, it is worth noting that the usual gravity driven flow under the assumption of constant density (hydrogeological approach) may be locally perturbed by an additional component, the density driven flow owing to different salinity and temperature gradients (Menjoz et Lambert, 1991).

The doublet technology

All geothermal operations targeting the Dogger aquifer use the “doublet” technology. It consists of a closed loop with one production well and one injection well. As the doublet technology allows the full reinjection of the cooled geothermal brine:

- there are no environmental impact,
- production flow rate is secured,
- exploitation pressures are stabilized (beneficial pressure interferences),
- area impacted by the pressure variation is limited and an exploitation domain can be legally defined by the authorities.

As the natural heat flux does not allow renewable exploitation, the geothermal development of densely populated Parisian suburbs will be faced with the inexorable exhaustion of the Dogger aquifer resource. On the long term, the cold reinjected brines will reach the production well and lead to a temperature drop. Three specific times can be identified to characterize the energy decline at the production well.

The **thermal breakthrough time** is the time after which the first cold particles reach the production well without having any consequences on the temperature of the produced brine because of the mixing processes. This time is rather a theoretical concept linked both to the thermal velocity (1.7 times the Darcy velocity in the reservoir) and the chemical breakthrough time (the true velocity of a chemical tracer being somewhere between 3 and 5 times the thermal velocity).

The **theoretical lifetime** is defined as the time after which measurements can demonstrate a drop in the produced brine temperature (typically 0.2 to 0.5 °C). This time depends a lot on reservoir heterogeneity and the thermal contribution from the reservoir surrounding formations.

Finally, the **practical lifetime** of the doublet will depend on the maximum temperature drop that is economically acceptable. This time is periodically updated taking into account the current situation and technological choices (use of heat pump, increase of the flow-rate, drilling of new wells).

Several doublets have already experienced a chemical breakthrough, *i.e.* particles of the reinjected brine have effectively reached the production well. Nevertheless, none of the operating doublet has reached its theoretical lifetime yet.

Reservoir management

The design phase

The main objective of low enthalpy geothermal exploitation is the production of hot water with continuous and large flow rates, up to 300 m^3/h. The sustainability of the flow rate with an acceptable drawdown can not be obtained without a good knowledge of the long range transmissivity and the hydraulic continuity of the reservoir. The exploitation history of past operations, along with the data from various oil exploration wells has provided a better geological characterization of the Dogger aquifer and its behavior. This knowledge must be integrated in the designing of new operations.

Yet, both for practical reasons because of the high level of uncertainty, the reservoir architecture is dramatically simplified in the designing process. Only one homogeneous productive layer with equivalent thickness and petrophysical properties is considered. Consequently, the doublet system is only defined by two parameters:

- the distance between the wells (measured at the reservoir top or at a depth computed as the weighted averaged of the production levels depths),
- the net total productive thickness which represents typically 10 to 20 % of the total aquifer thickness.

The nominal exploitation flow rates both in term of brine production and energy extraction are considered to be constant. They are defined based on the year averages of the expected energy needs and the expected production flow rate and injection temperature, so that the averaging process smoothes all seasonal variations. Then, simple models are considered to maximize the lifetime of the doublet based on the maximum admissible distance between wells. Experience proved that flowmeter logs were one of the most important information to take into account in every step of the designing and exploitation phases.

In terms of well head pressure forecasts, the thermal exchanges with the formations surrounding the reservoir induce a dependence of the production and injection temperature on the flow rate. As the density of the brine varies with its temperature the thermal state of the well influences the potential artesian pressure. Moreover, as the cold injected water body grows, the pressure work necessary to push it should increase steadily as a consequence of its lower viscosity. Yet, in the carbonate Dogger formation no noticeable increase of the injection pressure has been reported. Indeed, the cold water being more aggressive towards the formation tends to dissolve the calcareous cement of the geological deposits around the injection wells, thus improving its injectivity index (*cf.* infra).

The exploitation phase

Deviations from usual working state are diagnosed upon consideration of the fluctuations of the flow rate and the well-head pressure data. Pressure variations usually reflect reservoir behavior (impact of neighboring doublets, progressive cooling) whereas flow rate variations are usually consequences of head losses in the production well (effects of scaling, corrosion, possible leakage).

Some past incidents

<u>Corrosion and scaling</u>

After the first 4 years of exploitation of the Dogger aquifer important anomalies were reported and were characterized by:

- an increase in stabilized production drawdown,
- an increase of required injection pressure at wellhead,
- an overall progressive drop of the flow rate.

Detailed studies for diagnosis and downhole investigations were imposed by the huge economical consequences of the over-use of electricity for pumps and the reduction of the thermal power distributed to users. A substantial workover program was then realized and this was a powerful opportunity to examine in detail the *in situ* state of a few injection and production wells after several years of continuous exploitation.

As it required the identification of the perturbed areas along the underground system and the quantification of the unexpected phenomena, the diagnosis from surface measurements was not simple. Well logging, especially pressure logging, revealed that the overall decrease of production was the consequence of the deposition of iron sulfides. This process affected three zones of the observed wells.

The most important effect of soft deposits was identified along casings with a thickness reaching one inch in some cases. The hydraulic consequence on pressure losses of such deposits was tremendous, the losses being proportional to the 5^{th} power of the internal well diameter.

In injection wells, deposition could occur at the reservoir level, in front of the productive layers. This phenomenon, much similar to mud cake effects, acted as an additional skin factor on the damaged well and induced a local over-pressure reducing the injectivity index of the well.

Finally, at the bottom of the well, the sedimentation was progressively filling the safety length below the lowest productive layer (*rat-hole*). Consequently the total net pay was being reduced as a growing layer of sediment was blocking the bottom-most productive layers.

Production wells were first mechanically clean. Then preventive measures were taken with corrosion inhibitors injected in the production well at the level of the casing shoe in order to protect the whole geothermal loop. Suitable procedures were designed, field proofed and implemented on most doublets operating to date with continuous chemical injection lines, of the AIT (auxiliary injection tubing) coiled tubing type (Ungemach *et al.*, 2005). Though very efficient, this treatment acts on the kinetics of chemical reactions and only slows down the corrosion of the well casing. Concerning this point, much is expected from the development of composite casings.

All these investigations also led to new considerations for the geometrical design of the next wells drilled in the Paris basin. It is worth noting that while small operating problems concerning the overall reliability of the plants occurred randomly over the whole field, the corrosion and scaling problems were related to specific chemical characteristics of the reservoir. As these parameters show geographical variations, it could explain why the doublets in the northeast of the Paris basin have been particularly affected (Menjoz, 1990).

Doublet interferences

By the end of the 80's a general decrease of the artesian pressure of the Dogger reservoir was reported around the geothermal exploitations. Detailed studies showed that these decrease was a temporary consequence of aquifer pressure disequilibrium between some doublets. This disequilibrium was caused by small leakages due to the piercing of some casings. As a result of this study the interferences between doublet have been studied and their sensitivity to the exploitation of neighboring doublet could be quantified (Iris et Viennot, 1988; Viennot, 1989).

Other considerations

The logging operations of the 1986 workover program revealed an increase of the well bore diameter in the reservoir at the injection well (open-hole). This was attributed to the dissolution of the calcareous cement by the aggressive cooled brine. This increase, ranging from 6'' to 20'', led to a skin effect improvement and was beneficial for the injectivity index of the well. It balanced the adverse affect of the higher viscosity of the cold brine.

The increased understanding of operating problems and the need to control them also lead to new design of the geothermal loop and progressive improvements. On a broader scope, the interpretation of anomalies which occurred since the commissioning of the first plants has not shown any noticeable evolution of the reservoir hydraulic parameters. The main evolutions occurred inside the well, be it in the tube part (scaling or corrosion) or in the open-hole part (formation dissolution).

The “Télésuivi” database

In 1986 the ADEME (formerly AFME) conceived and implemented the “Télésuivi” operation which is a remote system that aims at monitoring and collecting all data related to the exploitation of the geothermal plants (Lesueur et Jaudin, 1997). Though there are several missing records, mainly related to the up and downs of the French geothermal activity, the database has grown over the years into a very valuable source of information to model and study the Dogger aquifer at both regional and local scales.

Data collected consist in about a dozen parameters measured every 30 minutes at the well head or along the geothermal loop. The three main parameters reflecting the reservoir behavior are the production flow rate, the production well-head temperature and the injection pressure. Their fluctuations are summarized in time tables that can serve as input to numerical modeling. Other data concern the heat exchanger and can be useful to correct inconsistent parameters or possibly estimate missing data.

Forecasting energy decline

Numerical modeling

As no energy decline has been observed yet, numerical modeling remains the only way to forecast this phenomenon and try to define a sustainable way of managing the Dogger aquifer (see also Ungemach *et al.*, 2007; Ungemach, 2008). The impact of the reservoir vertical stratification, the exploitation parameters, or the viscosity variations were successively studied and compared to the single homogeneous aquifer layer approach.

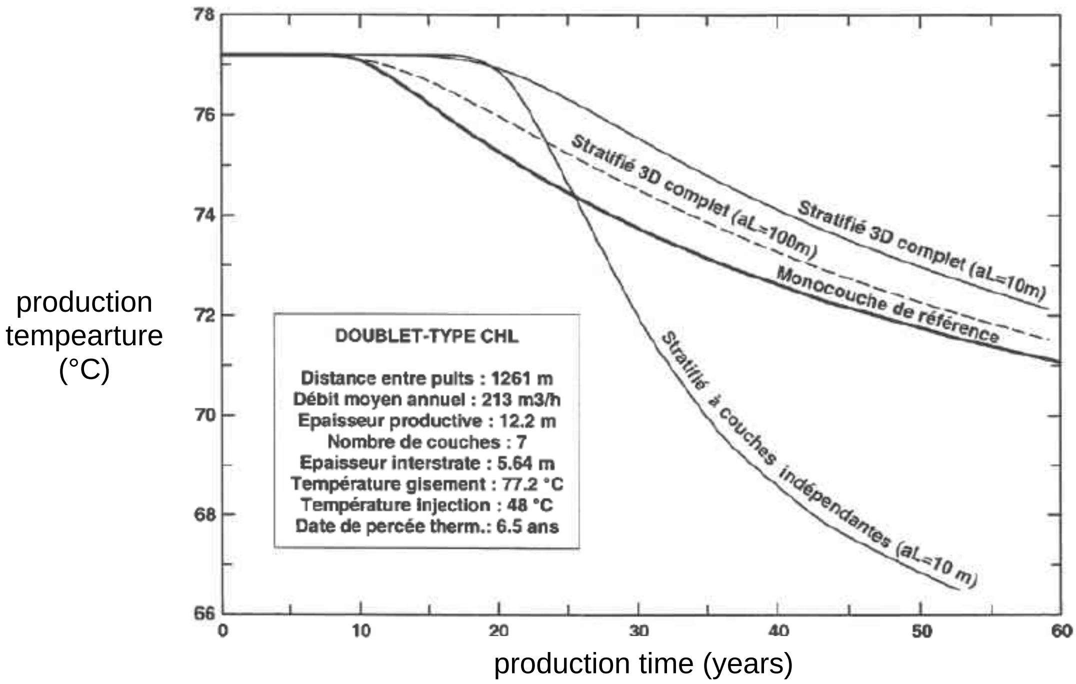

Figure 6: Impact of the reservoir stratification on the production temperature (**Menjoz *et al.*, 1996**)

In terms of geometry, the stratification of the reservoir increases the surface available for heat exchange and has a significant impact on both the thermal breakthrough and the doublet lifetime (*cf.* figure 6). This stratification is very difficult to characterize as it shows very important lateral variations. On a single doublet, productive layers that can be identified on flow-meter logs can hardly be correlated from one well to the other. Consequently, the geometry of the reservoir is characterized by considering the production well and its number of productive layers, their average thickness and the average thickness of the inter-strata.

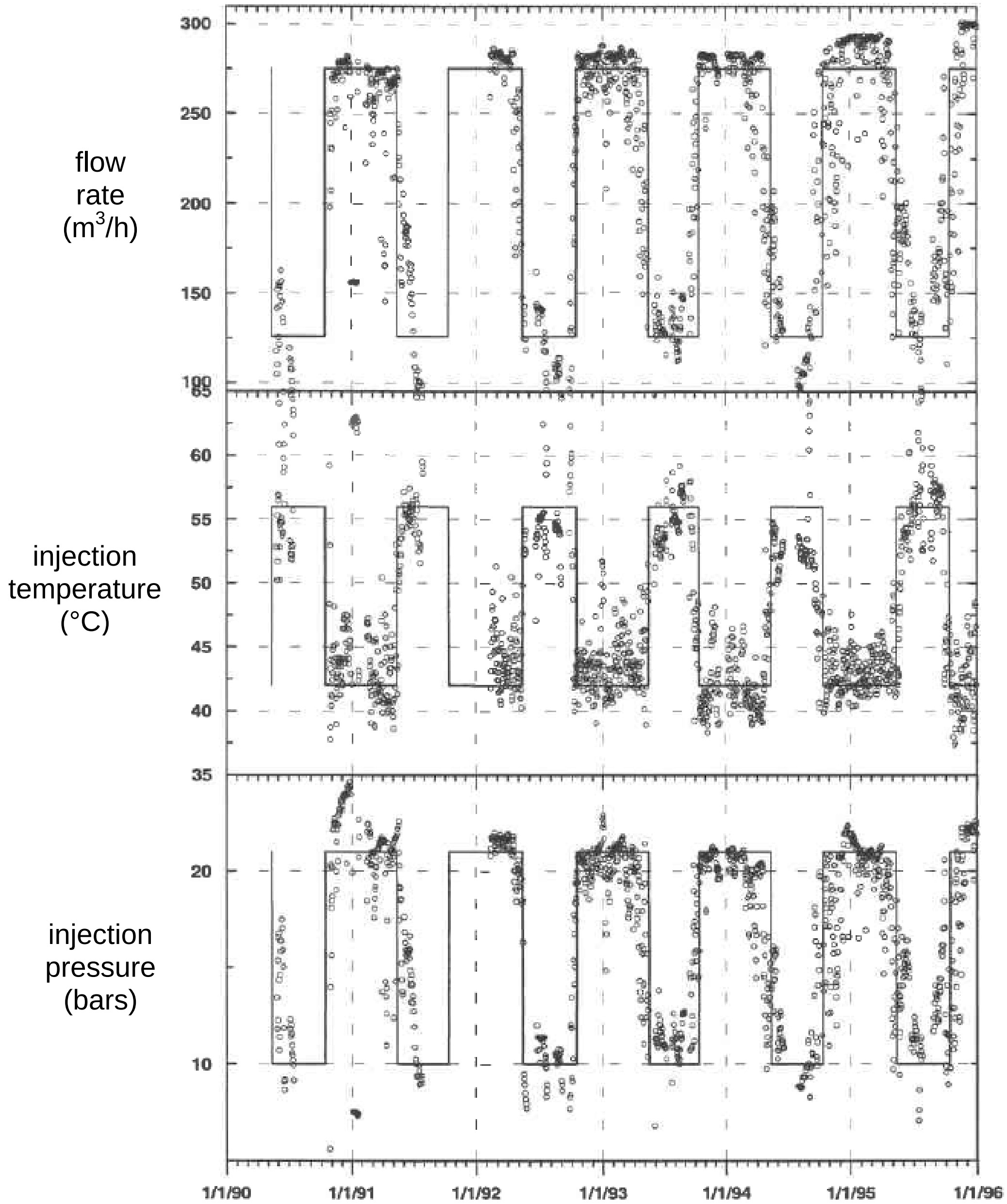

Figure 7: Parameters fluctuations from the "Télésuivi" database and seasonal averages (Ignatiadis *et al.*, 1998)

Updating initial forecasts

The data collected in the "Télésuivi" program can be used to estimate the radius of the reservoir area invaded by the cooled geothermal brine. This estimation relies on well test interpretation techniques adapted to study certain events. For example, abrupt changes in the exploitation flow rate, in spring or autumn, reflecting seasonal transitions can be exploited to derive this radius from the evolution of the injection pressure. Yet, the analysis is made complex because of the interferences caused by the production well.

Servicing shutdowns can also be the opportunity to perform long production tests on the injection well. Nevertheless, the duration of the tests increases with the radius of the cold water body to be estimated. As an example, this duration was between 5 and 7 days for a 12 years long exploitation period and this consequently limits the actual use of such tests.

In terms of management and production forecast, the main drawback of all workover operations has been to constantly modify the transfer functions of the wells thus necessitating additional information to identify the reasons of new anomalies or requiring a new total well test.

To perform numerical modeling, exploitation data from the “Télésuivi” base are simplified by averaging the flow rates, temperature and injection pressure (*cf.* figure 7). Seasonal cycles are defined, over which averages are performed (5 months summer/7 months winter). Nevertheless, numerical modeling tends to show that temperature and well-head pressure at the production well are not greatly affected by the seasonal variations because of the important capacitive and dispersive effects of the aquifer.

Present day situation

As of today, no noticeable temperature decline has been reported for any geothermal plant exploiting the Dogger aquifer in the Paris basin. The main reasons explaining the abandonment of 37 geothermal wells were of technical or economical sorts but not because of resource exhaustion. In the context of low prices fossil fuels, corrosion and scaling processes were deadly processes for some low temperature geothermal operations (*cf.* figure 2).

Chemical tracers

In order to forecast the thermal breakthrough, several potential precursors were considered. Numerical modeling showed that production pressure was not a good candidate. The use of artificial chemical tracers at the doublet scale did not seem either to be an interesting option. Restitution times were long and it necessitated very large amounts of tracer. Yet, as chemical variations travel at the real fluid velocity they reach the production well much earlier than the temperature drop (3 to 5 times earlier) and constitute a very good precursor.

A substitute for artificial tracers was consequently sought amongst chemical phenomena which were natural consequences of the geothermal exploitation. Particularly, sulfides producing batteries develop because of the doublet exploitation. Considering that these sulfides (mainly H_2S and HS^-) does not react in the reservoir with other chemical species, the monitoring of their concentrations at the production well was considered to give a good indication of the recycling time of the geothermal brine. Sampling and analyses over more than ten years seem to corroborate this hypothesis (Ignatiadis *et al.*, 1996).

As there are no important chemical exchanges between the surrounding formations and the geothermal reservoir, the study of the chemical tracer breakthrough reflects the hydrodynamic behavior of the doublet exploitation. It can serve as a basis to estimate dispersion effects in an idealized reservoir with adiabatic walls. On a practical point of view, the thermal effects of the surrounding formations are quantitatively important and considerably dampen the thermal dispersion effects.

Main causes of uncertainty

Many causes of uncertainty still subsist about the Dogger aquifer. The major one concerns the deep reservoir petrophysical characteristics and its detailed geological architecture. Though there were several studies of basin scale geology and *facies* distribution (*e.g.* Rojas.J. *et al.*, 1989; Gaumet, 1997), the available data is often too scarce to correctly represent the sedimentary and diagenetic heterogeneity at the doublet scale. Consequently, the horizontal connectivity of the aquifer which is greatly affecting the hydraulic behavior of the doublet remains a major unknown.

Detailed geological modeling might be considered for a few sites where there is additional information coming from oil exploration. Reservoir studies in the context of the geological storage of CO_2 in deep saline aquifers also represent a good opportunity to acquire this missing knowledge.

The thermal properties of the formations surrounding the aquifer also remain largely unknown whereas modeling revealed that they had a crucial impact on the lifetime of the doublet.

Long term management

A long term project devoted to the Dogger aquifer management has just started recently. It is run in cooperation between ADEME and BRGM. The objectives are the setting of a « Dogger observatory » based on the update and support of the former « Télésuivi » database. Modeling activities are integrating data from this base and are focusing on densely populated and exploited areas. The ultimate delivery would be an online database linked with the numerical model so that exploitation data can be integrated in the model and the model can be used to plan new drilling operations.

As Ungemach *et al.* (2005) puts it: «The general modelling philosophy consists of using a calibrated regional model as a thorough reservoir management tool, online with an exploitation database, and then extract multistage subregional/local models whenever required by operators need. »

Alternative options

The main difficulty in identifying the beginning of the energy decline is due to the very small amplitude and the slowness of the parameters evolution compared to background noises due to ordinary exploitation. This stresses the importance of rigorously compiling all exploitation data so as to define reference scenarios. Temporary problems must also be identified (scaling, corrosion, interferences with neighboring doublet…) and filtered out of the data, to be able to reconstruct the evolution of the deep reservoir parameters. Then, when faced with energy decline several options can be considered.

The initial objective that was an important flow rate can become less relevant with modification of the geothermal loop in order to maximize heat extraction form the geothermal brine: addition of a heat pump, replacement of the heat exchanger…

Instead of extending the resource lifetime, new wells can be drilled in order to replace the resource and maximize its spatial exploitation. In that case careful modeling must determine the location of the cold reinjected brine so as to find an optimal location for the new well.

A “doublet” operation may be turned into a “triplet” operation. As it is located to find new resources, the new well is the producer and the two old wells are exploited as injectors. In terms of well location, every case has its specificity depending on neighboring installations, aquifer properties, well diameters… The Melun l’Almont plant used a triplet system for a time before reverting to a classical doublet installation. A new production well has just been drilled on the Sucy-en-Brie plant and it is going to resort also to a triplet system (cf. Ungemach *et al.*, 2007 for the La Courneuve example). At Orly 1, operators preferred to drill a new doublet close to the old one.

Finally, on a very long term, seasonal storage of waste heat in the Dogger aquifer could become a way to smooth energy demand during winter peak production periods and possibly restore the initial resources of the cold injected brines. In the light of the knowledge gained from the geothermal exploitation of the Paris basin, the key points concerning its feasibility are expected to be the high temperature of the stored brine and the cyclical reversal of injection and production wells. The high temperature of the reinjected brine, hotter than the aquifer natural state, may produce undesirable chemical reactions and precipitates.

Concerning the reversal of the production/injection cycles no long-term experience is available on the Dogger aquifer.

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