INSIGHT INTO GEOTHERMAL RESERVOIR MANAGEMENT

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SUMMARY

Geothermal District Heating in the Paris Basin. Milestones. Present Status. Future Prospects

The first attempt to exploit the hot waters hosted in the Dogger carbonate formations of mid-Jurassic age dates back to year 1962, at Carrières-sur-Seine West of Paris. The well, despite its high productivity, was abandoned due to a highly mineralized brine incompatible with the disposal of the waste water in the natural medium (a surface stream). This led, in 1969, Sthal, a private joint venture (Cgc, now Vivendi, operator, and Laurent-Bouillet) to commission the first field application of the geothermal doublet concept of heat mining combining a production well and an injection well pumping the heat depleted brine into the source reservoir.

The doublet (two deviated, 7" cased, wells) produced in self-flowing mode was put on line in 1971 on the henceforth Melun l'Almont emblematic site, South of Paris, to supply heat and sanitary hot water to the local social dwelling compound. It enabled incidentally to design new, titane alloyed, plate heat exchangers able to cope with a corrosive geothermal fluid, a slightly acid (pH = 6), saline (30 g/l eq NaCl) and hot (74°C) brine. The system has been operating satisfactorily since start up, the doublet moving in the meantime towards a triplet array including two injector and one new, innovative, production well combining steel casings and freely suspended, non cemented, fiberglass liners. Noteworthy is that this pionner achievement was completed independently from any energy crisis nor public subsidies whatsoever. Regarded at the time as a technological, fairly exotic, curiosity, it has been extended since then to the whole Paris Basin geothermal district heating schemes.

The energy price crisis following the 1970's oil shocks led the French authorities to promote, among other alternative energy sources, low grade geothermal heat as base load to district heating grids and other space heating systems. This has been concluded by the development, in the sole Paris Basin, of fifty five geothermal doublets of which thirty four are still operating to date (see figure 1 and table 1).

This is indeed an outstanding, almost unique of its kind, accomplishment comparable to the heating of the City of Reykjavik in Iceland, which belongs however to a significantly differenciated geological (volcanic rocks, high source temperatures), technical (no reinjection) and socio-economic (insularity) context.

It has undoubtedly benefited from the conjunction of three main driving factors (i) the evidence of a dependable geothermal reservoir (Dogger limestones) of regional extent, identified thanks to former hydrocarbon exploration drilling[(1)] , (ii) a strong, voluntarist, commitment of the State in favour of alternative energy sources and ad-hoc accompanying measures (mining risk coverage, mutual insurance -sinking- funds against exploitation hazards, financial support to district heating grids and miscellaneous incentives), and (iii) last but not least, the location above the geothermal resource of large social dwelling buildings, eligible to district heating, numerous throughout the Paris suburbs.

This stated, the geothermal venture did not avoid contagion from infantile diseases inherent to the implementation of new technologies as evidenced by various symptoms, mainly:

- structural: lack of expertise from operators (chiefly of the public sector) in managing industrial installations and energy processes with a strong mining impact,
- technical: insufficient mastering in operating heating grids, under a retrofitted scheme combining several base load, back-up/relief energy sources and fuels, repeated failures of submersible pump sets and, above all, devastating corrosion of casings, well heads and equipments by the geothermal fluid,
- administrative and managerial: imprecise definition of the duties and obligations of concerned intervening parties (operators, engineering bureaus, heating companies,

consultants) and of relevant exploitation/service contracts, inefficient marketing and negotiation of heat sales and subscription contracts,

- economic and financial: severe competition from conventional fossil fuels (heavy fuel oil, natural gas) penalizing heat sales and revenues, persistent low energy prices in the aftermath of the second oil shock, adding to a debt nearing 85 % of total investment costs in a capital intensive (5 to 8 Meuros), low equity, high interest rate (12 to 16 %) environment ; this clearly placed most geothermal operators in a typically third world situation.

With time and experience, structural and technical problems could be overcome in many respects by systematic monitoring of the geothermal fluid and primary production/injection loop, periodic logging inspection of well casings, innovating workover and chemical inhibition processes aimed at restoring well performance and preventing corrosion/scaling damage, the latter supported by the State through relevant R & D programmes and funding.

In the early 1990's, the so-called "Brosse Mission" made it possible to mitigate the debt charge, which was renegociated via a spreading out of annuity repayments and interest rate reductions. Tax deductions were applied to geothermal operators, regarded therefore as energy producers, the most significant one addressing the VAT (set a 5.5 % instead of the former 18.6 % rate). Simultaneously, improved administrative and financial management of geothermal district heating grids could be noticed among most operators.

The revival of a technology, at a time endangered to such a point that its abandonment has been seriously envisaged, could be achieved at the expense of the shut in/cementing of 22 doublets, i.e. ca 40 % of the initial load and of a subsequent loss in heat supplies summarized in the following figures:

	1986 (target)	2000 (actual)
• number of operating doublets	54	34
• installed capacities (MWt)	360	227
• yearly heat supplies (heating + SHW) (GWht/yr)	2,000	1,240
• yearly fossil fuel savings (toe's)	135,000	225,000

The situation, although stabilized, remains precarious on purely economic grounds. As a matter of fact, falling energy price trends ultimately condemn geothermal district heating with the exception of ten to twelve, presently profitable, doublets.

The challenge is clear. To remain competitive, the geothermal MWht selling price must stand at ca 200 FRF (30 €), i.e. no more than 10 % above the natural gas (LCI, lower calorific index) price according to the B2S (distribution) tariff offered to industrial users. Consequently, gas cogeneration appeared to many geothermal operators, while negociating renewal of past heat subscription contracts, as the only viable issue securing the survival of their grids and installations. Hence, as of late 2000, twelve combined gas cogeneration plants and geothermal district heating grids were operating, a figure likely to match the twenty mark at the November 2001 deadline.

Gas cogeneration provides stable earnings from sales to the utility (Electricité de France, Edf) of the whole generated power at a high contractual purchasing price, guaranteed over twelve years, elsewhere indexed on natural gas prices, i.e. at minimum financial risk. Cogeneration supplies cheap heat as an electricity by product recovered via the cooling of the generating units (gas engines or turbines). Maximization of power revenues causes cogeneration to be operated as base (constant) load over the 151 calendar day contractual period (from 1st November to 31st March) at the detriment of geothermal heat whose contribution during winter drops by 40 %, if not more, when no extension of the existing grid is commissioned in the meantime (only three sites, out of twelve, to date).

Environmental, clean air, concerns and limitation of greenhouse gas (mainly CO2) emissions could turn geothermal district heating into an asset favouring its everlastingness if not its (re)development. Such a statement however ought to be mitigated in consideration of recent government measures and those likely to be decided with respect to energy and environmental fiscal matters which presently lack consistency.

First, the VAT applicable to heating grids subscription contracts has been reset at the 20.6 % rate against the former 5.5 % rate, the latter still in force for gas and power subscriptions as well as for maintenance/ repair works in collective buildings and individual residences. This indeed penalizes geothermal heating grids vis-à-vis building fossil fuel fired boilers or gas/electricity individual heating as exemplified by the following costs (heating service charges/maintenance costs amounting to 3,500 FRF/530 € all taxes included) applicable in 1999 (Finance Law 2000, in force as of September 1999):

	FRF (VAT free)	FRF (VAT included)
• building heating, geothermal grid	2,920	3,462
• building heating, gas fired boilers	2,920	3,399
• individual gas heating	2,945	3,320
• individual electric heating	2,920	3,414

Second, the modification of the professional tax penalizes heating grids operated under lease/concession contracts (non deductible infrastructure rental costs).

Thus the fiscal prejudice amounts, for a heating grid serving 5,000 dwellings, to ca 450,000 FRF/ 68,600 E (VAT free). It represents a serious handicap, especially while negociating heat subscription contracts with, often shortsighted, ownership representatives and other building managers. It clearly defeats the district heating route previously promoted by the State.

The State issued White Book introduces in its ecotax project (the so-called TGAP, general tax on polluting activities) a damaging discrimination aimed at exempting individual users (families) in the name of the principle that ecologic taxation cannot apply to them! In fact, available energy consumption statistics, summarized hereafter:

		Fuels (Mtoe's/yr)	Electricity (TWh/yr)
• domestic uses (families):	residential	34	119
• transports		24	58
• corporates, transports		25	8
• tertiary sector		10	91
• industry		26	131
• agriculture		18	30

highlight instead the dominant share from individual consumers and speak for a uniformized ecology taxation unless delibirately contradicting its meaning.

Summing up, the outlook for geothermal district heating seems presently limited to the operation of the thirty or so doublets on line and to the implementation of gas cogeneration units on two thirds of the existing grids, restricting geothermal heat supplies to ca 1,000 GWht/yr [(2)].

Privatization of geothermal doublets/heating grids, widely initiated in the past years under the form of acquisitions, concessions, leases and public service delegations should address in the short run over fifteen installations equally shared between the three leading heating/energy groups: Dalkia/Edf/Vivendi, Elyo/Suez Lyonnaise des eaux and Cofatec/Coriance/Gaz de France. Only could the Public and an established State policy, as was the case in the mid 1970's/early 1980's, reverse these adverse trends and reactivate geothermal heating which, everything considered, has proven its technological and entrepreneurial maturity [(3)].

Last but not least, the impact among the Public of recent climatic disasters attributed to global warming and of high oil prices could initiate the necessary stimulus. In this perspective, the taxation of CO2 atmospheric emissions, once scheduled by the Government, at a rate ranging from 200 FRF/30 € (2001) to 500 FRF/76 € (2010) per ton of carbon, is obviously primordial.

Table 1: Paris Basin geothermal district heating doublets. Well summary sheet

Site		Start up date	Owner/Mining title	Status	Heating operator	Doublet type	Depth (m) V	Depth (m) D	Diameters P	Diameters I	Production Mode	Production Flowrate (m^3/h)	Remarks
1		2	3	4	5	6	7	8	9	10	11	12	12
Melun l'Almont		1971	Sthal/Dalkia	ES	Dalkia	2D	1 700	1 775	7"	7"	A	120	1 well (I) cemented, 1 well (P) fiberglass
Creil I	Doublet 1	1974	OpHlm Creil	AB	Dalkia	2V	1 740	1 740	13"3/8 x 7"	7"	LSP	150	
	Doublet 2	1974	OpHlm Creil	AB	Dalkia	2V	1 720	1 720	13"3/8 x 7"	7"	A	120	
Villeneuve la Garenne		1976	Total/CFP	AB	Géoconfort	2D	1 630	1 750	13"3/8 x 7"	7"	A	55	7" fiberglass casings
Le Mée sur Seine		1978	Idex/Strec	ES	Cgcu/Strec	2V	1 710	1 710	10"3/4 x 7"	7"	A	130	gas cogeneration
Coulommiers		1981	Dalkia	ES	Dalkia	1V 1D	1 980	2 310	13"3/8 X 7"	7"	EPI	200	
Aulnay Rose des Vents		1982	SA Hlm Logement Français	AB	Dalkia	1V 1D	1 680	2 113	13"3/8 x 7"	7"	EPI	150	
Montgeron		1982	Dalkia	ES	Dalkia	2D	1 620	1 750	10"3/4 x 7"	5"1/2	EPI	150	injector reconditioned (5"3/4)
La Courneuve sud		1982	Syndicat mixte	ES	Dalkia	1V 1D	1 650	2 050	13"3/8 x 9"5/8 x 7"	7"	EPI	180	
Cergy Pontoise		1982	EPA	AB	Soccp	2V	1 560	1 560	13"3/8 x 7"	7"	EPI	150	
Melleray		1982	Gie Béoval/Cfg-Brgm	AB	Cgc	2V			13"3/8 x 7"	7"	EPI	150	non concerned (Trias aquifer)
Meaux Collinet		1982	Energie meaux Coriance/Gdf	ES	Emex	1V 1D	1 795	2 095	10"3/4 x 7"	7"	EPI	240	gas cogeneration
Beauvais		1982	Opac 60	AB	Riex	1V 1D	1 165	1 390	13"3/8 x 7"	7"	EPI	80	
Clichy sous Bois		1982	Dalkia	ES	Dalkia	1V 1D	1 730	2 110	10"3/4 x 7"	7"	A	90	gas cogeneration
La Courneuve nord		1983	Syndicat mixte	ES	Dalkia	2D	1 640	1 980	13"3/8 x 7"	7"	EPI	190	
Epernay		1983	Ville	AB	Enerchauf	1V 1D	1 575	1 940	13"/8 x 7"	7"	EPI	110	
La Celle Saint-Cloud		1983	Gie Cogecel	AB	Cgc	1V 1D	1 430	1 880	13"3/8 x 7"	7"	EPI	150	
Evry		1983	Siare/Dalkia	AB	Dalkia	1V 1D	1 600	1 710	13"3/8 x 7"	7"	EPI	170	
Meaux Hôpital		1983	Energie Meaux Coriance/Gdf	ES	Emex	2D	1 760	1 910	10"3/4 x 7"	7"	EPI	240	gas cogeneration
Sevran		1983	Seapfa	AB	Dalkia	2D	1 700	1 990	13"3/8 x 7"	7"	EPI	200	
Meaux Beauval	Doublet 1	1983	Energie Meaux Coriance/Gdf	ES	Emex	2D	1 790	2 040	13"3/8 x 7"	7"	EPI	230	self flowing+cogeneration commissioned
	Doublet 2	1983	Energie Meaux Coriance/Gdf	ES	Emex	2D	1 780	2 220	10"3/4 x 7"	7"	A	120	self flowing+cogeneration commissioned
Ris Orangis		1983	SA Hlm Essonne Habitat	ES	Dalkia	2D	1 590	1 800	13"3/8 x 7"	7"	EPI	200	gas cogeneration commissioned
Creil II		1983	OpHlm Creil	AB	Elyo	2D	1 490	1 800	13"3/8 x 7"	7"	EPI	160	
Le Blanc-Mesnil		1983	Seapfa	ES	Sulzer	2D	1 675	1 900	10"3/4 x 7"	7"	EPI	220	
Fontainebleau		1983	Syndicat mixte	AB	Cgec/Elyo	1V 1D	1 770	2 200	13"3/8 x 7"	7"	EPI	120	
Achères		1983	Sa Hlm Foyer pour Tous	AB	Elyo	2V	1 500	1 500	13"3/8 x 7"	7"	EPI	200	
Ivry sur Seine		1983	Cpcu	AB	Cpcu	2D	1 490	1 700	13"3/7 x 7"	7"	A	130	
Vaux le Pénil		1983	Géopénil	AB	Dalkia	2D	1 700	1 880	13"3/8 x 7"	7"	A	140	
Orly Gazier		1 984	Opac 94	ES	Dalkia	2D	1 630	2 050	10"3/4 x 7"	7"	A	120	
Paris Porte de Saint-Cloud		1984	Géoparis	AB	Cpcu	2D	1 435	1 600	13"3/8 x 7"	7"	EPI	170	
Châtenay-Malabry		1984	Syndicat mixte	AB	Elyo	2D	1 640	1 960	13"3/8 x 7"	9"5/8	EPI	150	
Garges les Gonesses		1984	Ville	AB	Elyo	2D	1 650	1 820	13"3/8 x 7"	7"	EPI	200	
Tremblay en France		1984	Seapfa	ES	Elyo	2D	1 715	1 950	13"3/8 x 9"5/8 x 7"	7"	EPI	270	
Aulnay Gros Saule		1984	Ville	AB	Elyo	2D	1 680	1 950	13"3/8 x 7"	7"	EPI	220	gas cogeneration
Cachan	Doublet 1	1984	Socachal	ES	Dalkia	2D	1 600	2 200	10"3/4 x 7"	7"	EPI	170	gas cogeneration projected
	Doublet 2	1984	Socachal	ES	Dalkia	2D	1 660	2 000	13"3/8 x 7"	7"	EPI	180	gas cogeneration projected
Epinay sous Sénart		1984	Semgep	ES	Dalkia	2D	1 635	1 835	11"3/4 x 9"5/8	9"5/8	EPI	250	
Bondy		1984	Syndicat mixte	AB	Missenard Quint	2D	1 700	1 835	13"3/8 x 7"	7"	EPI	230	
Sucy en Brie		1984	Sogesub/Elyo	ES	Elyo	2D	1 730	1 890	10"3/4 x 7"	7"	EPI	200	

Site	Start up date	Owner/Mining title	Status	Heating operator	Doublet type	Depth (m)		Diameters		Production		Remarks
						V	D	P	I	Mode	Flowrate (m^3/h)	
1	2	3	4	5	6	7	8	9	10	11	12	12
Maisons-Alfort I	1985	Semgema	ES	Dalkia	2D	1 610	1 850	13"3/8 x 9"5/8	9"5/8	EPI	290	
Vigneux sur Seine	1985	Idex	ES	Idex	1V 1D	1 605	2 170	10"3/4 x 9"5/8	7"	EPI	240	gas cogeneration
Créteil Mont-Mesly	1985	Dalkia	ES	Dalkia	2D	1 660	1 850	10"3/4 x 9"5/8	9"5/8	EPI	275	public servicd delegation
Villiers le Bel/Gonesse	1985	Syndicat intercommunal	ES	Elyo	2D	1 590	1 965	10"3/4 x 7"	9"5/8	EPI	240	
Chevilly Larue	1985	Syndicat intercommunal	ES	Elyo	2D	1 650	1 950	13"3/8 x 9"5/8	9"5/8	EPI	250	gas cogeneration
L'Hay les Roses	1985	Syndicat intercommunal	ES	Elyo	2D	1 630	1 875	13"3/8 x 9"5/8	7"	EPI	250	gas cogeneration
Champigny sur Marne	1985	Ville	ES	Elyo	2D	1 650	2 010	13"3/8 x 9"5/8 x 7"	9"5/8	EPI	250	gas cogeneration projected
Thiais	1986	Elyo	ES	Elyo	2D	1 625	1 784	13"3/8 x 9"5/8	9"5/8	EPI	230	
Chelles	1986	Chelles chaleurCoriance/Gdf	ES	Emex	2D	1 690	2 000	9"5/8	7"	A	210	gas cogeneration commissioned
Orly le Nouvelet	1986	Opac 94	ES	Dalkia	2D	1 625	1 860	13"3/8 x10"3/4x9"5/8	9"5/8 x 7"	TBI	240	
Bonneuil sur Marne	1986	Setbo	ES	Dalkia	2D	1 660	2 000	10"3/4 x 9"5/8 x 7"	9"5/8	EPI	280	
Maisons-Alfort II	1986	Semgema	ES	Dalkia	2D	1 620	1 835	11" x 9"5/8	13"3/8 x 9"5/8	EPI	240	gas cogeneration
Fresnes	1986	Sofrechal/Coriance/Gdf	ES	Elyo/Cofatech	2D	1 615	1 835	10"3/4 x 9"5/8	9"5/8	EPI	240	gas cogeneration
Alfortville	1986	Syndicat mixte	ES	Soccram	2D	1 625	2 035	13"3/8 x 9"5/8	9"5/8	EPI	250	
Villeneuve Saint-Georges	1987	Dalkia	ES	Dalkia	2D	1 620	1 845	10"3/4 x 9"5/8	10"3/4 x 9"5/8	A	350	gas cogeneration
Paris La Villette	-	OpHlm	AB	-	2D	1640	1850	13"3/8 x 7"	7"			never put on line

Key
P production well
I injector well
AB abandoned (cemented)
ES operating
2D two deviated wells
2V two vertical wells
1V 1D one vertical and one deviated wells
A self flowing (artesian) production
LSP enclosed lineshaft pump
EPI electrosubmersible pump
TBI hydraulic turbine driven pump

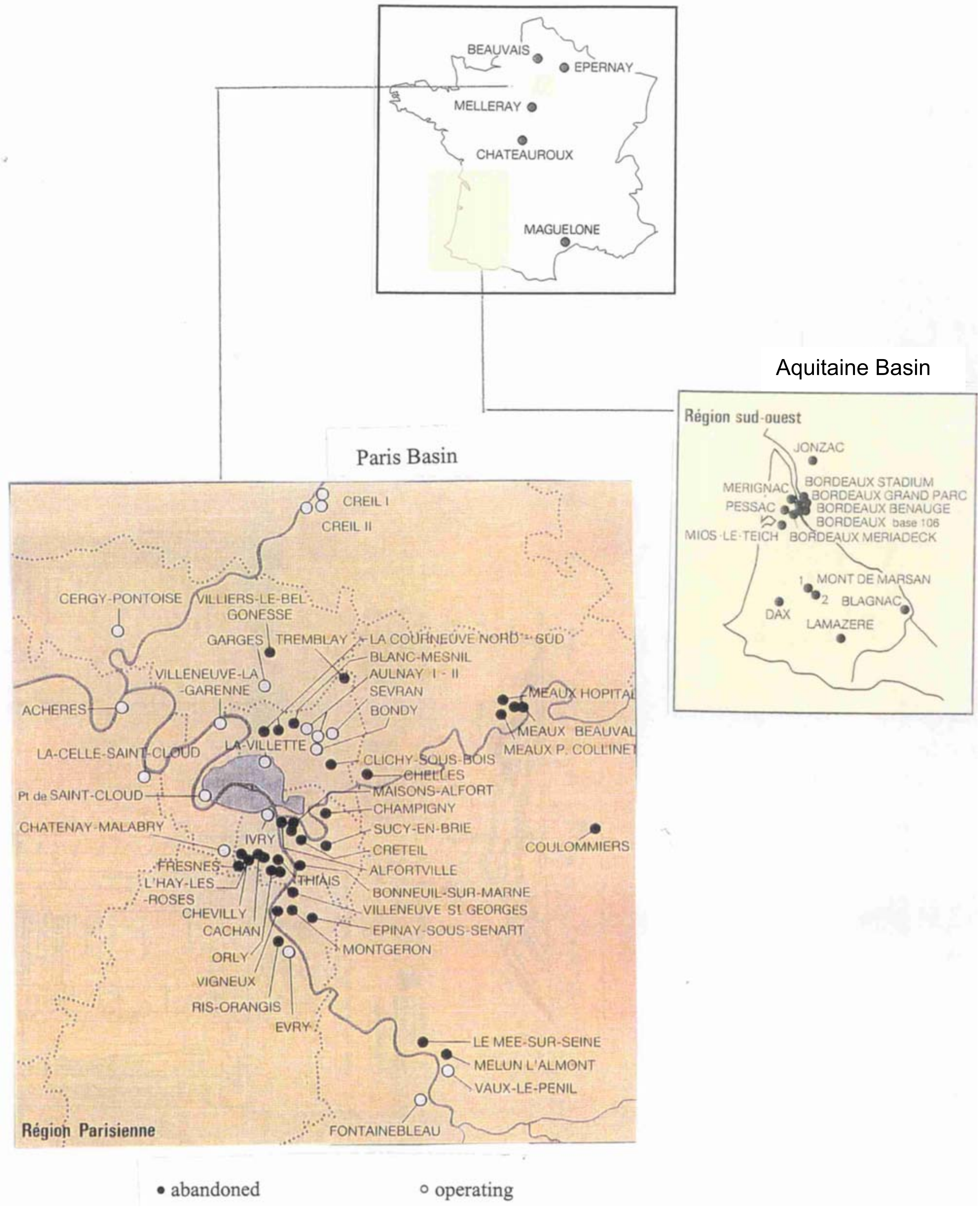


Figure 1: Location of French geothermal sites

1. MILESTONES

The Paris Basin geothermal development milestones are highlighted in the table 2 historical sequence, in which six main steps ought to be distinguished and briefly commented on, namely:

Pre oil shock. 1960's. It addresses the first, abandoned, attempt to tap the Dogger geothermal aquifer followed, in 1969, by the successful completion of the first geothermal district heating doublet at the emblematic Melun l'Amont site.

Post first oil shock. 1973-78. Completion of four geothermal district heating doublets, three (Creil and Le Mée-sur-Seine) combining vertical production/injection wells and one (Villeneuve-la-Garenne) deviated production/injection wells fiberglass (7") cased. Three doublets (Creil and Villeneuve-la-Garenne) were equipped with electrosubmersible pump (ESP) sets, the fourth (Le Mée-sur-Seine) being produced in self-flowing mode. Simultaneously the legal framework was enforced by the State via a relevant geothermal act classifying geothermal fluids as a mineral resource subject to the mining code and to exploration/exploitation leases and concessions.

Post second oil shock. 1979-1986. This period achieves the Paris Basin geothermal development stream materialized by the completion of fifty one well doublets of which one (La Villette) will never be exploited and a second (Melleray) exploiting the Triassic sandstones underlying the Dogger carbonate reservoir. The legal/regulatory/lobbying framework was finalized by the creation of the Comité géothermie, SAF Environnement, Afme/Ademe, Géochaleur and Agémo. The Triassic target, once contemplated West of Paris, was abandoned further to negative testing (resulting mainly from poorly completed wells) and exploitation cencentrated exclusively on the dependable Dogger reservoir. The success ratio was high as only two doublets (Fontainebleau and Fresnes) met the (semi) failure criteria set forth by the Comité géothermie, responsible for supporting geothermal ventures deemed feasible and thus for eligible to the geoological risk allocation and related subsidies. First well damages and production pump (ESPs and lineshaft pumps - LSPs) failure were experienced in the mid 1980's.

Early exploitation phase. Late 1980's. Most doublets undergone severe exploitation problems as a consequence of (initially overlooked) hostile thermochemistry and subsequent corrosion/scaling damage, pump failures (lower than one year average lifetimes), hesitant management, poor heating practice (mainly regulation and monitoring) and, above all, critical financial losses aggravated by oil depleted prices. Implementation of conventional well workovers and of first chemical inhibition trials.

Technological/managerial maturation and debt renegociation. 1990-97. In 1990 the State committed Brosse Mission led most geothermal operators to renegociate their debt (loans mostly contracted with State owned banks) via a moratory inclunding a three year grace period, extended annuity redemptions and lower interest rates. Expert advice was also provided regarding heating exploitation concession and contracts. Simultaneously concerned governmental departments and agencies (Energy and Raw Materials Directorate, Industry and Research Directorate, Afme/Ademe) refueled the SAF mutual exploitation insurance (long term) fund and promoted specific R, D & D actions aimed at designing and implementing novel well workover/restoration/stimulation and thermochemical preventing techniques. The latter proved rewarding in upgrading restoration of casing status and related well productive/injective capacities and limiting corrosion/scaling damage at attractive cost to performance ratios. Doublets facing irreparable physical and/or financial damage, or in several instances managerial laxism, ceased commercial exploitation and wells were cemented in compliance with petroleum/geothermal well abandonment regulations.

Table 2: Paris Basin geothermal development. Milestones

1962	Drilling of Carrières-sur-Seine, Dogger targeted, geothermal well.
1965	Modelling of the doublet concept of heat mining.
1969	Completion of the Melun-l'Almont geothermal district heating doublet (two deviated, steel cased, wells).
1973	* First oil shock.
1974	Completion of the Creil doublets (four vertical wells).
1976	Completion of the Villeneuve-la-Garenne doublet (two deviated, fiberglass cased, wells).
1977	Enforcement of the Geothermal Act (mining law).
1978	Completion of the Mée-sur-Seine doublet (two deviated wells).
1979	* Second oil shock.
1980	Creation of the Comité Géothermie, SAF Géothermie (now SAF Environnement), long term fund (partial coverage of the exploitation risk) and of Géochaleur (geothermal district heating, semi-public, lobby).
1981	Completion of the Coulommiers doublet (one vertical, one deviated wells).
1982	Creation of AFME (French agency for energy control, now ADEME) and of the short term fund (coverage of the mining risk). Completion of eight doublets. Trias well tests at Achères and Cergy.
1983	Completion of fifteen doublets.
1984	Completion of eleven doublets.
1985	Completion of eight doublets. Creation of AGEMO (Association of geothermal district heating operators). Experience of poor early downhole pump performances.
1986	Completion of eight doublets. First evidence of well, corrosion/scaling induced, damage.
1987/88	Workovers initiated for restoration, via mechanical scale removal, of damaged plugged wells. Early downhole chemical inhibition attempts.
1989	Completion of the Melun-l'Almont new, steel cased, injection well. Abandonment (wells cementing) of the La Celle-Saint-Cloud doublet.
1990	Brosse mission. Debt renegociation. State promoted R, D & D programmes. Implementation of novel well clean up/restoration/workover and downhole chemical inhibition technologies.
1991	Abandonment (well cementing) of four doublets. State supported rehabilitation/prevention campaign of ten doublets.
1992	Abandonment (well cementing) of three doublets. State supported rehabilitation/prevention campaign of four doublets.
1993	Implementation of the geothermal workover waste processing line. State supported rehabilitation/prevention campaign of seven doublets. Abandonment (well cementing) of four doublets.
1994	State supported rehabilitation/prevention campaign of three doublets. Abandonment (well cementing) of three doublets.
1995	Drilling/completion of a new geothermal production well (combined steel casing/fiberglass lining) at Melun-l'Almont. First implementation of the triplet well concept. Abandonment (well cementing) of three doublets.
1996/97	Abandonment (well cementing) of two doublets. State supported rehabilitation/prevention of two doublets.
1998/99	Implementation of gas cogeneration (gas driven engines/turbines) on eight geothermal district heating grids. Abandonment (well cementing) of two doublets.
2000	Renewal -ten year duration- of the SAF Environment contract. * Third oil shock ?

Still the economics remained fragile as a result of depleted oil prices and a highly competitive energy market dominated by heavy fuel and, at a greater extent, natural gas contenders.

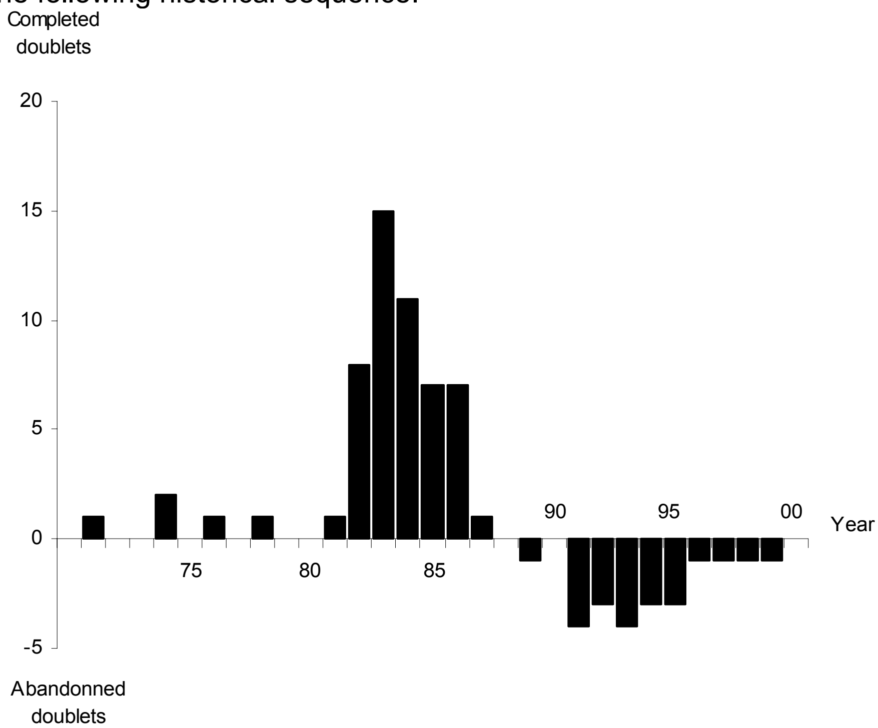
New challenges. Starting 1998. Geothermal district heating in the Paris Basin demonstrates a mature -belowground and surface- technology, clearly assessed exploitation and mining risks, controlled operation/ maintenance/workover costs, experienced management, socially accepted environmental benefits, seconded by instrumental expertise and services. Of the fifty four completed doublets, thirty four, i.e. 60 %, a reasonable score indeed, of the initial load, remain on line as of mid 2000, with a reliably targeted ten year life expectation, the duration of the recently extended SAF Environment mutual insurance contracts. However the fierce competition prevailing while negociating heating contract renewals prompted many geothermal operators to award cogeneration (combined cycle) contracts or leases to the dominant heatig groups (Vivendi, Suez-Lyonnaise des eaux, Gaz de France) in the wake of (partial) power deregulation and incentives in favour of gas cogeneration initiated in France in the mid 1990's. This policy conformed to a survival rationale allowing to keep most geothermal district heating grids alive, at the expense in most instances (no grid extension) of decreasing supplies of geothermal heat no longer utilized as base load during the contractual one hundred and fifty one day (1st November to 31st March) winter heating period allocated to cogenerated heat. The spectacular rise in oil prices noticed since late 1999, peaking at ca 32 US $/bbl, likely to be followed by natural gas tariffs, alongside greater sensitivity of the public to global warming damage, and taxation envisioned by the State of greenhouse gas emissions (estimated at 40 E/ton of carbon starting rate) could radically change the former bleak outlook. Instead of surviving, geothermal district heating could be given a second chance and momentum.

2. STATUS

2.1 Well record

According to the well summary sheet listed in table 1, fifty six geothermal doublets have been completed during fifteen years (from 1971 to 1986) at vertical depths ranging from 1 165 (Beauvais) to 1,980 m/bgl (Coulommiers) at locations mapped in figure 1. The Melleray doublet, devoted to greenhouse heating, located 140 km South of Paris, addressed the Triassic sandstones and the La Villette doublet has never been exploited so far. The Ivry doublet aimed at preheating the steam fed into the Paris steam heating grid.

As of mid 2000, thirty four doublets remain on line. The completion/abandonment record is displayed in the following historical sequence.



Geothermal district heating doublets have undergone over ninety heavy duty workovers, this figure not including the twenty two abandonment cemeting jobs. The State elsewhere funded, between years 1990 and 1995 (out of the over ninety figures) forty one specific well cleaning/corrosion preventing operations for implementing novel casing jetting techniques and downhole chemical injection lines.

Out of the sixty eight operating to date, thirty damaged (leaky, pierced casings) wells (twenty three production, seven injection) were reconditioned either via casing lining (eighteen producer, seven injector, total twenty five) or casing patches (five producer wells). Reconditioning of production wells dealt, in all cases, with the repair (by lining or patching) of a damaged 13"3/8 pumping chamber and for one well only (Villiers-le-Bel/Gonesse) was added the 7" lining of the underlying 9"5/8 production casing.

2.2 Exploitation update

Relevant figures, from early expectations to reality, are summarized hereunder :

	Target	Achieved	
	(1985)	1990	2000
Operating doublets	55	43	34
Total installed capacity (MWt)	360	260	227
Produced heat (GWht/yr)	2,000	1,455	1,240
Unit capacity (MWt)	6.5	6.0	6.7
Unit yield (MWht/yr)	36,000	33,800	36,200
Artificial lift wells	49	36	27
Self-flowing wells	6	7	7

At the beginning of heating year 1987-88, fifty four doubleets were assumed operational, thus close to the anticipated figure. Actually no more than forty eight were in service, of which one third were undergoing severe exploitation problems resulting in temporary shut in periods attaining in many instances several months.

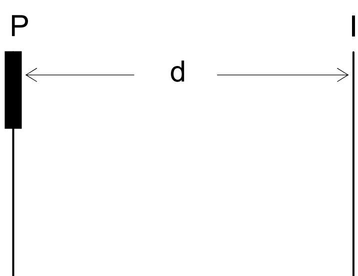
In 1990, forty three doublets were serviced and ca 1,450 MWht delivered to the heating grids, i.e. 25 % below initially projected yields. In year 2000 the annual delivery dropped to 1,230 GWht as a result of lesser operating doublets (thirty four) and start up of ten combined geothermal/gas cogeneration systems. Despite this downward trend, optimization of the most performant doublets, which happen to coincide with the most recently completed (third generation) ones, resulted in unit capacities (6.7 MWt and 36,200 GWht/yr) close to initially anticipated targets. However future implementation of commissioned and projected cogeneration systems is likely to reduce these unit capacities.

3. TECHNOLOGY

3.1 Well completions and doublet designs

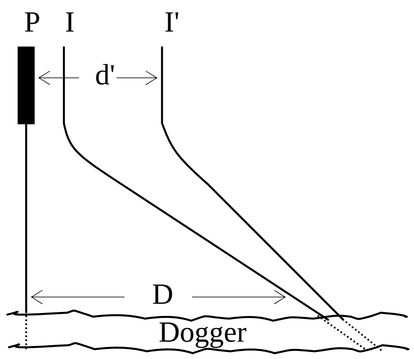
As a matter of fact the geothermal doublet typology followed the patterns sketched in figure 2. This strategy was largely inspired by the views of the National geological survey (Brgm) appointed by the State to launch the geothermal development programme. This strategy prevailed in spite of the early achievements pioneered by designers from the oil industry, on private investment bases, on the Melun l'Almont (1971) and Villeneuve-la-Garenne (1976) sites, the latter adding an innovative fiberglass casing ingredient. Those remained the exception until wide acceptance and generalization (third generation doublet) of this pertinent design in the mid 1980s.

First generation doublets. Two vertical production/injection wells. This configuration has been implemented at Creil (1974), Le Mée-sur-Seine (1978), Cergy (1982) and Achères (1983). The production well includes a 13"3/8 casing, to accomodate a 11" submersible pump, followed by a dual 9"5/8 x 7" casing protection (400 to ca 1,000/1,200 km) of the intermediate Albian/Neocomian fresh water aquifers and a 7" production casing, the target Dogger geothermal reservoir being produced in open hole (6" diameter). The injection well replicates the dual 9"5/8 x 7" casing design with a single 7" injection column, and a 6" open hole reservoir section. A 1,000 to 1,400 m well spacing secures a useful system thermal life of twenty to twenty five years (i.e. until damaging, 3 to 5°C, cooling of the production well occurs).



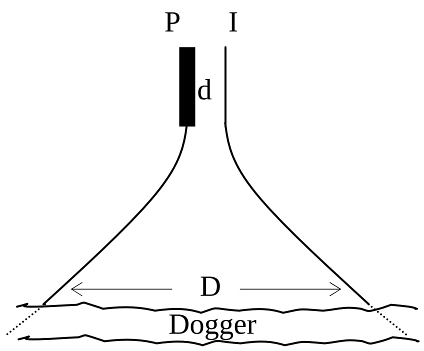
1st generation doublets
2 vertical wells

Diameters
P : 13"3/8 x 7" ou 10"3/4 x 7"
I : 7"
Double 9"5/8 x 7" casing protection
of Albian/Neocomian aquifers



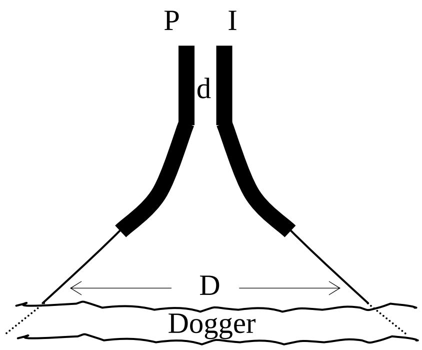
2d generation doublets

1 vertical (P) well, 1 deviated (I, I') drilled from one (I) or two (I') platforms
Diameters
P : 13"3/8 x 7" or 10"3/4 x 7"
I, I' : 7"
Double 9"7/8 x 7" casing protection
of Albian/Neocomian aquifers



3rd generation doublets

2 deviated wells drilled from a single platform
Diameters
(a) P : 13"3/8 x 7" or 10"3/4 x 7"
I : 7"
Double 9"5/8 x 7" casing protection of Albian/Néocomian aquifer
(b) P : 13"3/8 x 9"5/8
I : 9"5/8
No double casing protection of Albian/Néocomian aquifers



4th generation doublets

2 identical wells.
Increased pumping chaber length
Diameters
P : 13"3/8 x 9"5/8
I : 13"3/8 x 9"5/8
No double casing protection of
Albian/Néocomian aquifers

P : production well
I : injection well
D : doublet spacing at top reservoir
d, d' : well head spacing
ζ : pumping chamber

Figure 2: Geothermal doublet typology

Second generation doublets. Vertical production well. Deviated injection well. Casing/open hole diameters and dual casing protection of the intermediate Albian/Neocomian fresh water aquifers identical to those adopted for the first generation doublets. Wells are drilled from a single plateform (eight doublets drilled between 1981 and 1985) with the exception of

Meaux Collinet (1982) and Evry (1983) where the well head spacings (200 to 300 m) enabled to reduce the injection deviation (slant) angle.

Third generation doublets. Two deviated production/injection wells drilled from a single platform. Two designs depending on production/injection casing diameters, either 13"3/8 (exceptionally 10"3/4) x 7" (production) and 7" (injection) including a dual 9"5/8 x 7" cased protection of the Albian/Neocomian fresh water aquifers (twenty two doublets) or a 13"3/8 x 9"5/8 (production) and 9"5/8 (injection) casing string with no dual casing protection of the Albian/Neocomian fresh water aquifers (nine doublets). In this latter design the 9"5/8 production/injection casing is occasionally thicker than in previous completions. Bottom hole (top reservoir impact) spacings are designed in compliance with doublet cooling specifications.

Fourth generation doublets. Two identical production/injection well 13"3/8 x 9"5/8 casing programmes allowing for production/injection replication. The 13"3/8 casing is set at a (deviated) depth of 900 top 1,100 m/bgl, i.e. vis-à-vis the Albian/Neocomian fresh water aquifers whose protection is ensured via an increased steel thickness over the concerned interval.

Casing specifications conform to K55 soft carbon steel grades, compatible with service in the CO_2-H_2O aqueous system, either VAM or Buttress (BTC) threads, 9 to 11.4 mm wall thickness and range 3 lenghts. Deviation (slant angles) vary between 30 to 55° with a build-up gradient of 1°/10 m initiated at depths (KOPs) ranging from 200 to 500 m.

3.2 New well concept

The novel geothermal well design was conceived to reduce corrosion and scaling that had severely affected the integrity and lifetime of Paris Basin geothermal district heating wells. This new generation geothermal well, which represents a material alternative to corrosion, was successfully completed at Melun-l'Almont on March 1995.

Under this new concept, the wells are completed by combining cemented steel casings and fiberglass liners while the annulus is kept free as shown in figure 3a. The casings provide mechanical strength (propping function), while the liners furnish chemical resistance (corrosion and scaling protection). The free annular space allows (i) circulating corrosion/scaling inhibitors and/or biocides, which otherwise would need to be circulated using a downhole chemical injection line, and (ii) removing and, if necessary, replacing the fiberglass liner whenever damaged. It is noteworthy that this design can accomodate a submersible pump set, in which case the upper fiberglass lining is placed under compression, and the lower one is freely suspended under its own weight. Vertical displacement of the fiberglass lining is elsewhere eased by an expansion spool and fiberglass centralizers (not by couplings as often contemplated in other centralizing designs). At Melun, due to exceptional reservoir performance, artificial lift was no longer required and, instead, self-flowing at high production rates prevails, a fact that led to the simplified design depicted in figure 3b.

The well, put on line on late March 1995, demonstrated high productivity, producing about 70°C fluid at a rate of 200 m3/hr at 2.5 bars well head overpressure. It has been connected to two existing wells (one producer and one injector) ; the whole system operates according to the triplet array (two producers, one injector) shown in figure 3c. The well head design, described in figure 3d, achieves the required sealing and fixing (seat/receptacle) functions.

The concept of using wells with steel casings and removable fiberglass liners is seriously considered as an alternative in order to extend the lifetime and improve the reliability of existing installations. The following strategy would be used: a new production well would be drilled and completed, the two existing wells would be reconditioned/lined into injectors, exploitation would resume under a triplet configuration (one producer, two injectors). Total project costs, including workover, are estimated at about 3.5 million €[4]. Another, less innovative but cheaper, alternative would consist of drilling/ completing a large diameter vertical steel cased well securing high self-flowing rates according to the design and cost estimates analyzed in [4].

3.3 Well workover

As far as well heavy duty repair is concerned, two major issues ought to be emphasized in the areas of well clean up and waste processing, respectively:

Well clean up. Conventional restoration techniques used in the past to remove scales and debris from damaged plugged wells addressed standard mechanical removal by rockbits.

Nowadays most damaged geothermal wells are restored by using a combined mechanical/hydraulic system based on a rockbit/sliding nozzle jetter assembly. The system, described in[5], is surface driven and combines drilling, mechanical clean up and hydraulic jetting modes. The tool is, near bit, equipped with lateral sliding nozzles allowing to circulate downhole, either horizontally (jetting mode) or vertically (drilling mode), following the sequence displayed in figure 4. This tool is widely and successfully used for jetting most if not all damaged geothermal wells in the Paris area. Heavy, modern design coiled tubing units, capable of handling 2" diameters and 800 l/mn circulating rates, could be substituted in the future to conventional workover rigs and drill strings provided they prove cost effective.

Chemical cleaning techniques, based on diluted acid plugs spotted and circulated under slow flow conditions, are also contemplated further to recent trials extending to producer wells the soft acidizing stimulation analyzed in § 3.4.

Waste processing line. Possibly is the waste processing line depicted in figure 5 the most valuable achievement noticed in geothermal workover services thus far. The unit[6], which suppresses the mud/refuse pits used in the past, enables to treat the geothermal effluents via a three stage degassing/ filtering/cooling process and to dump into the nearby sewage system a degassed, solid free and cooled liquid. The line meets the following specifications:

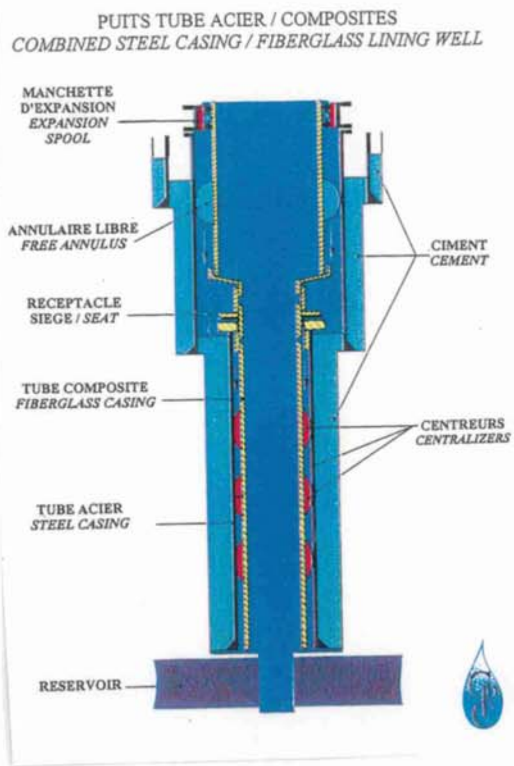
- maximum discharge 250 t/hr,
- gas water ratio up to 0.25 vol/vol,
- particle filtering cut down to 25 µm,
- cooling capacity 45°C depletion (75 to 30°C).

It is ideally suited to the stringent environmental constraints existing in the densely populated and urbanized Paris suburban areas.

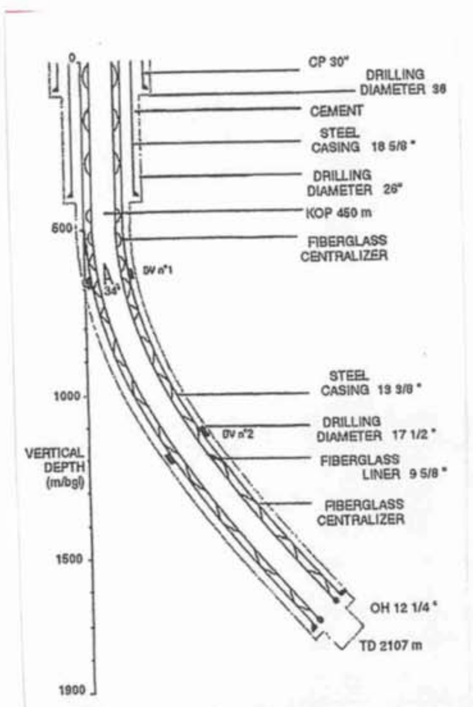
3.4 Well stimulation. Soft acidizing. Coiled tubing

In early Paris Basin operations, it was customary to restore well productive and injective capacities by pumping acid through a light service rig drillstring. The remedial impact did not last long as the consequences rather than the causes of the plugging damage were treated thus far. As a result well stimulation jobs became scarce and seldom attempted, at the occasion mainly of heavy workover operations. The routine procedure was to spot, at top reservoir, 10 to 20 m3 of hydrochloric acid (HCl, 15X), flush an equivalent volume of fresh water, wait for acid reaction and flow back the well through an ad-hoc gas abatement line to neutralize CO_2 and H_2S (reaction by products of HCl with reservoir carbonate rocks and with iron sulphide deposited on the well sandface and, chiefly, casing walls). Results did not always shape that favourably, especially during the extensive workover campaigns of summers 1991 and 1993.

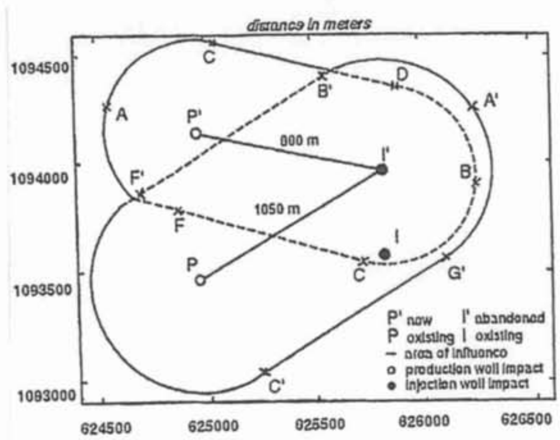
Another matter of concern were injection wells, whose injectiviy indices tended to decrease regularly with time, a fact evidenced by injection well head pressure rises while resuming the heating season. A stimulation technique, known as soft acidizing, has been purposely designed to cope with injector well damage, which relies on continuos injection from surface of strongly diluted HCl solutions mixed with an iron sequestrant additive. The philosophy behind the process is to inject the same acid volume (10 m^3 HCl, 15X) to that normally squeezed into the reservoir via a drillstring during conventional stimulation jobs, at much lower concentrations therefore extending accordingly acid to casing and sandface exposure times. Effectively injection durations currently reach 60 hrs against 1 hr for a conventional acid spotting. The etching process, in the conventional procedure, concerns the reservoir alone whereas soft acidizing addresses both well casing and/or formation damage. The technique has been successfully implemented in the framework of a field test programme, on three purposely selected wells, encompassing the whole damage spectrum : casing and/or near well formation damage. The acidizing process has been reported[7] to significantly upgrade well injectivities, often above nominal figures, and also optimum injection rates. The latter feature is manifest on wells exhibiting prevailing casing friction losses. Cheap implementation of the concept resulted in pay back times (gains in additional heat sales against process operational costs) ranging from eight to twenty four months.



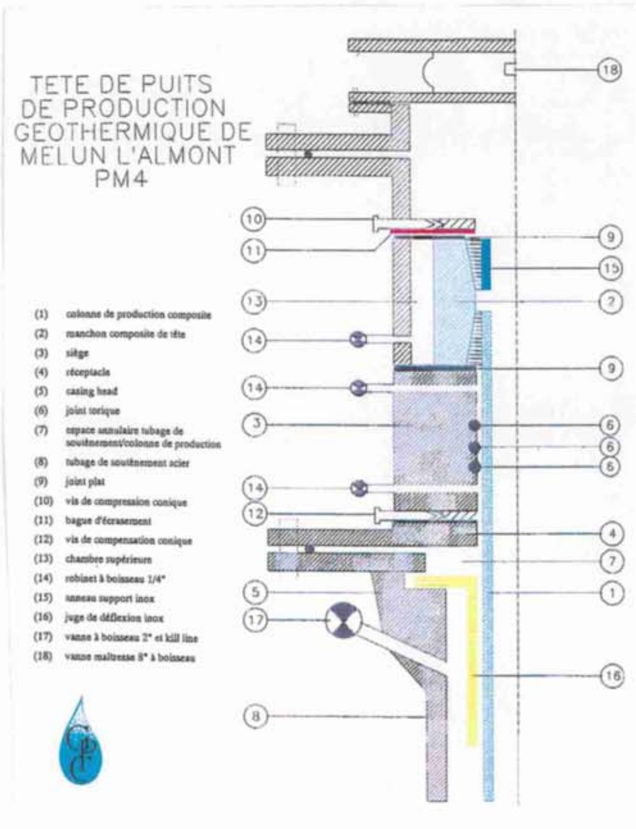
a) anti-corrosion geothermal well concept



b) simplified geothermal production well design



c) triplet exploitation array



d) well head design

Figure 3: New geothermal, anti-corrosion, well design

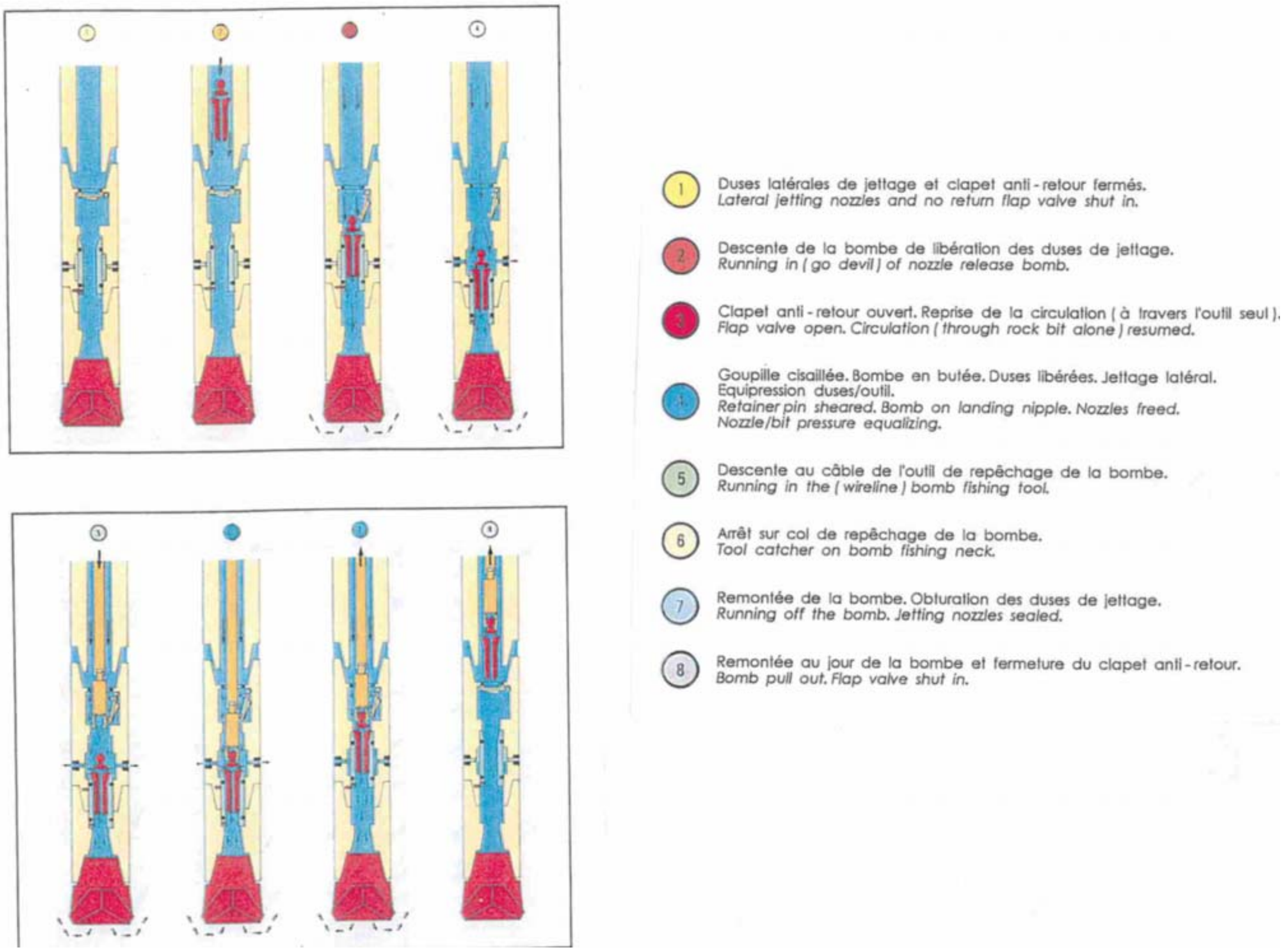


Figure 4: Well clean up. Jetting tool

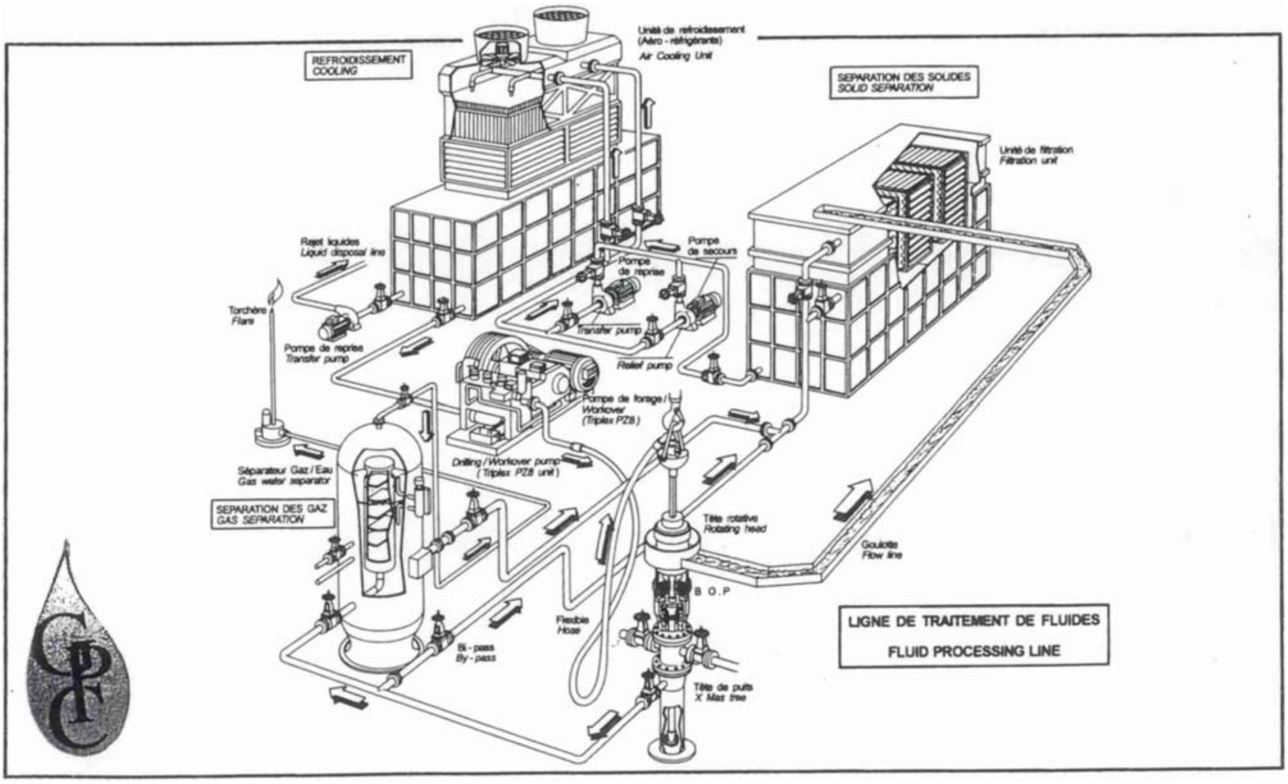


Figure 5: Workover waste fluid processing line

Coiled tubing technology proved more performant than conventional drillstring acidizing, as exemplified by recent acid stimulations completed on four production and two injection wells with a 1"1/4 CTU (coiled tubing unit).

Production well sequence (see field outfit in figures 6a and b):

- open hole control by coiled tubing (CT) short trip,
- CT positioning vis-à-vis first producing layer,
- preflush (5 m^3 fresh water),
- acid spot (20 m^3 HCl 15X) 120 l/mn,
- flush (10 m^3 fresh water),
- spooling of CT to surface,
- awaiting (2 hrs) acid reaction,
- well flow back via waste fluid processing line.

Improved performance by CT is attributed to better spotting (at productive layer and no longer at casing shoe), longer pumping time (3 hrs against 1 hr), weaker flush (10 m^3 against 20 m^3), securing thorough acid attack as whitnessed by the strong (CO_2) post acid kick. Nothing but traces of H_2S are monitored as opposed to the coventional acid backflow. All jobs restored productivites often above expectations.

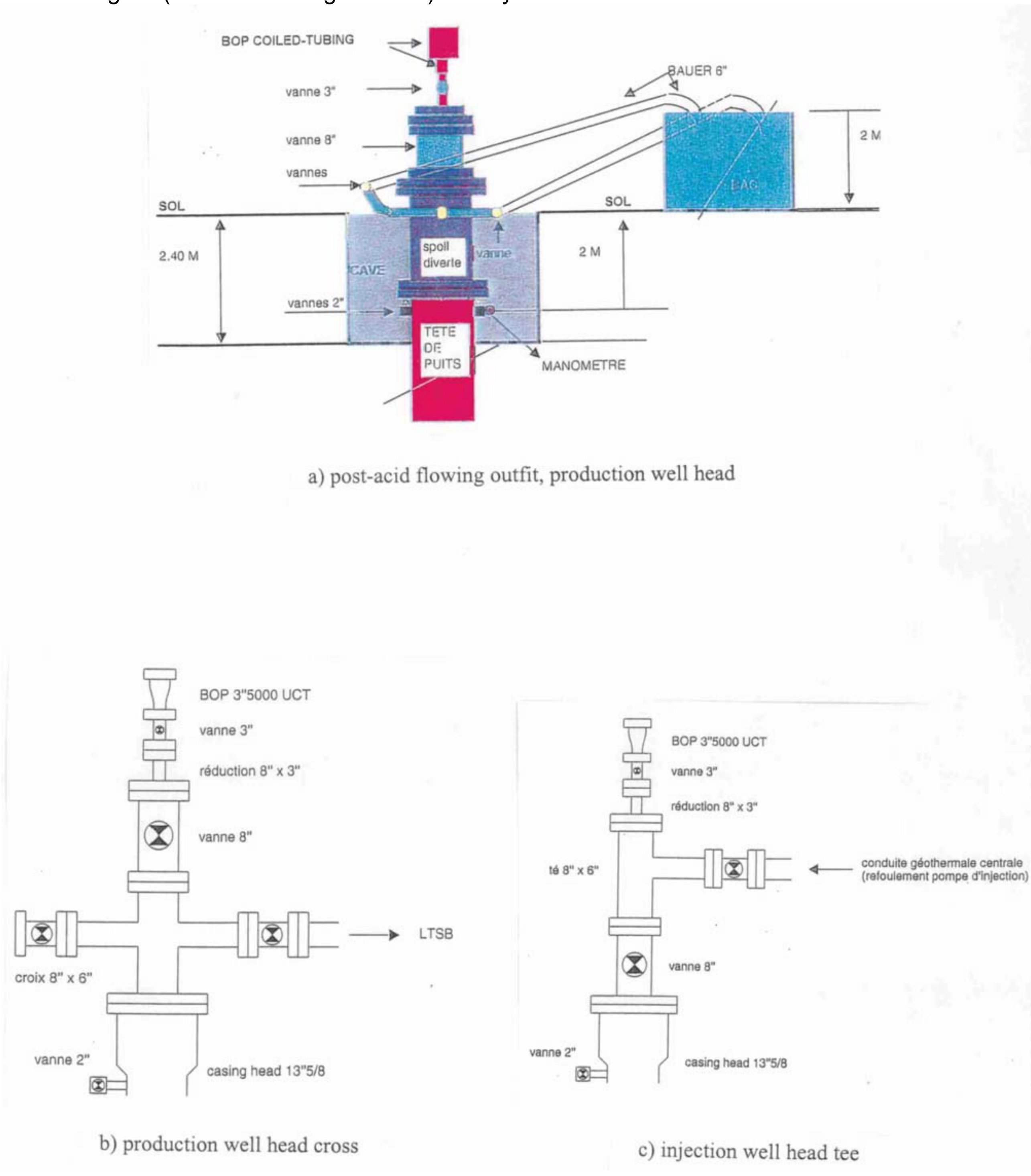
Injection well sequence (see well head arrangement in figure 6c) : the field procedure differs from the one implemented on the production well in that both the casing walls and the reservoir are treated sequentially and that there is no backflow episode. In fact the experimented protocole achieves both the objectives of soft acidizing standard reservoir stimulation. Experimental protocole:

- run 1"1/4 CT downhole (7" casing shoe),
- preflush (1 m^3 fresh water),
- pump 1,200 l of acid (HCL, 15X with iron sequestrant) (bottom well plug spotting),
- spool up CT (22 m/mn), pump acid at 100 l/mn and control equivalent annular water flow back,
- acid flush by pumping 1,400 l of fresh water at 350 m/bgl depth,
- stop CT at 100 m/bgl depth and shut annular back flow valve,
- awaiting for acid reaction 1 hr 30 mn ; acid concentration (ca 4 % i.e. 10 m^3 HCL 15X diluted by 40 m^3, the well capacity, of geothermal water),
- run CT downhole to 7" casing shoe,
- pump acid (10 m3 HCL 15X) into the geothermal reservoir,
- fresh water flush (5 m^3),
- awaiting (2 hrs) for acid reaction,
- reactivate the geothermal loop by circulating the injection pump at 100 m3/hr.

3.5 Corrosion/scaling inhibition

The consequences of the hostile thermochemistry of the, Dogger hosted, geothermal fluid, a hot (60 to 80°C), slightly acid (pH = 6), saline brine with a CO_2 and H_2S enriched dissolved gaseous phase, have long been noticed and reported in literature[(8)]. This thermochemically sensitive fluid environment caused severe corrosion of tubulars and equipments and heavy metal (essentially iron) sulphide deposition and other, more or less exotic, crystal species. The corrosion mechanism in the CO_2/H_2S aqueous system and subsequent forming, under soluble or crystallized (scale) states, of iron sulphides or carbonates is outlined in the figure 7 sketch and associated chemical reactions. The corrosion process caused irreparable damage to more than ten doublets in the early development stage (mid to late 1980s) before adequate inhibition procedures be designed, field proofed and implemented on most doublets operating to date.

In order to prevent corrosion/scaling damage or at least to slow down damaging kinetics, continuous chemical injection lines, of the AIT (auxiliary injection tubing) coiled tubing type, have been designed to inhibit the process at its initiation, i.e. at bottom hole[(9)]. Typical AIT designs for low and high temperature service are shown in figure 8a and downhole chemical inhibition configurations in artificial lift production wells illustrated in figure 8b. Characteristics of candidate thermoplastic/elastomer encapsulating materials are listed in table 4. A number of inhibition formulations have been tested in various fluid and production environments, of which the most representative are listed in table 3. In the Paris Basin, commonly used agents belong to the monofunctional (anticorrosion/filming, type CORI1 or CORI2) and bifunctional (anticorrosion-biocide) families. The first type is recommended in the Northern areas which exhibit high dissolved H_2S contents, and the second in the Southern part with lower dissolved H_2S and high microbiological (sulfate reducing bacteria) activity.



a) post-acid flowing outfit, production well head

b) production well head cross

c) injection well head tee

Figure 6: Well stimulation. Coiled tubing acidizing

Chemical reaction:

$CO_2 + H_2O \rightarrow H_2CO_3$

$2H_2CO_3 \rightarrow 2H^+ + 2HCO_3^-$

$Fe^{2+} + 2HCO_3^- + 2H^+ \rightarrow 2H^+ + Fe(HCO)_2$ soluble

$H_2S + H_2O \rightarrow H^+ + HS^- + H_2O$

$Fe \rightarrow Fe^{2+} + 2e^-$

$Fe^{2+} + HS^- \rightarrow FeS + H^+$

Corrosion induced and native

$2\,H^+ + 2e^- \rightarrow H_2$

for pH = 6

$H_2S + H_2O + CO_2 + Fe^{2+}$ (native)

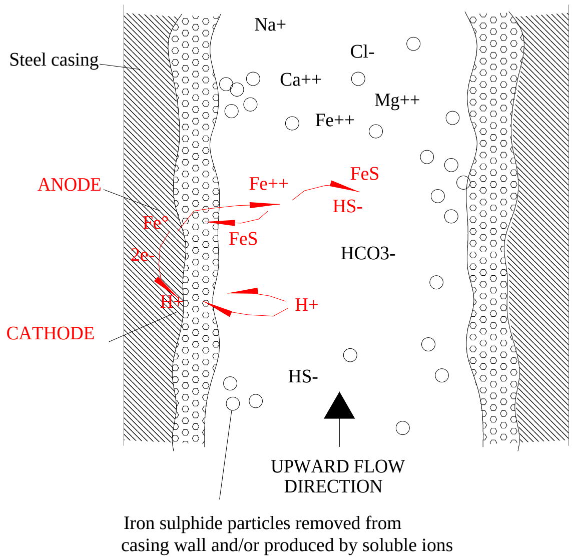


FIGURE 7: Iron dissolution and sulphide precipitation process in presence of aqueous H_2S and CO_2

Table 3: List of selected candidate inhibitor agents

Name	Function				Description
	Antiscale	Dispersant	Anticorrosion	Biocide	
SCI 1	X				Phosphonate non ionic
SCI 2		X			Low molecular weight polyacrylate anionic
SCI 3	X	X			Phosphonate/polyacrylate anionic
CORI 1			X		Cationic surfactants ; non ionic in glycol solutions
CORI 2			X		Fatty amin derivatives in aqueous solutions
BIOC 1				X	Non ionic surfactants and aldehydic derivatives
BIOC 2				X	Cationic surfactants and quaternary ammonia
BIOC 3				X	Superior aldehydes in aqueous solution
SCORI 1	X		X		Sequestering agents and fatty amin derivatives
SCORI 2	X	X	X		Phosphonate, polyacrylate and fatty amin derivatives
CORBIO 1			X	X	Non ionic surfactants and aldehydic derivatives
CORBIO 2			X	X	Fatty amin derivatives and quaternary ammonia
SCB 1		X	X	X	Polyacrylates, fatty amin derivatives, quarternary ammonia

Table 4: Candidate thermoplastic and elastomere material properties

Type de matériau (*) *Material type*	PPC	PA 11	PA 6	EPDM/ PP	PVDF	HALAR	PA 6/PP/ EPDM	PPS	TPFE	TPFA
Temp. de service max. (°C)	105	95	120	140	150	170	120	196	204	260
Max. operating temp. (°F)	*220*	*220*	*250*	*280*	*300*	*340*	*250*	*350*	*400*	*500*
Résistance à la traction (Mpa) *Tensile strength (Mpa)*	25	55	35	28	46	50	43	90	22	28
Elongation (%)	300	300	240	600	80	200	300	10	300	300
Module d'élasticité (Mpa) *Flex modulus (Mpa)*	1 200	1 000	760	347	2 700	1 700	1 980	750	655	625
Dureté *Hardness*	60 D	72 D	40 R	50 D	77 D	75 D	65 D	70 D	60 D	55 D
Absorption d'eau (%) *Water absorption (%)*	< 0,1	2,5	5	2	< 0,1	< 0,1	< 1	2,1	0	< 0,03

(*) PPC : Polypropylene Copolymer; PA 11 : Polyamide 11; PA 6 : Polyamide 6; EPDM : Etylene Propylene Dyene Monomer; HALAR : Chloro Tri Fluoro Ethylene; PVDF : PolyVinyle Dyene Fluoride; TPFE : PolyTetraFluoroEthylene (Teflon); TPFA : PerFluoro Alkoxy (Teflon); PPS : PolyPhenyl Sulphone

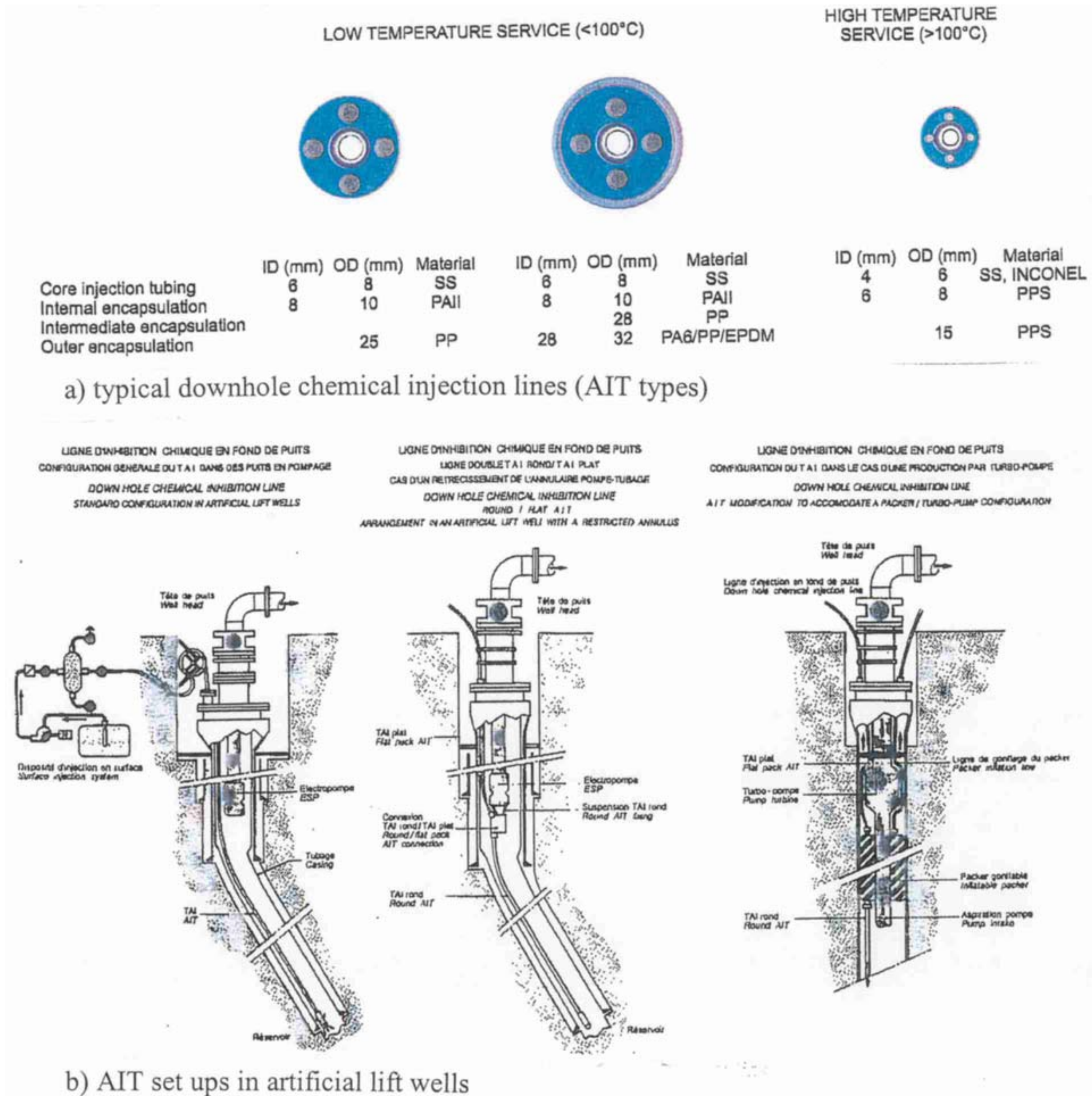


Figure 8: Downhole chemical inhibition. Ait lines

3.6 Heating engineering insight

Operation of Paris Basin geothermal district heating grids conform to a standard engineering rationale, summarized in the table 5 parameter system analysis and in the generic doublet/heating grid modules, namely:

- a geothermal supply module (the so-called geothermal loop): geothermal reservoir, production and injection wells and related equipments (production/injection pumps, electric and hydraulic control devices),
- a demand module: heat load consisting of end users' consumptions, i.e. heaters connected, via substations, to a distribution grid,
- a back up/relief module: fossil fuel fired boilers,
- an interface: geothermal heat exchanger.

The following items deserve a special comment.

Heat loads: retrofitting is the rule. Geothermal heating had to comply with existing buildings and heaters seldom designed for low temperature service. Social dwellings compose the majority of the load, followed by public office buildings, schools, swimming pools and gymnasiums. Supply of domestic sanitary (tap) hot water (SHW) adds in many instances to heating proper. Centralized SHW represents a bonus, with a supply amounting to ca 10 % of heating loads.

Heating devices: forced air convectors are absent. Therefore heat is diffused by conventional cast iron radiators requiring high (90/70°C) inlet/outlet temperatures and floor slabs (50/30°C temperature range), the latter more favourable to geothermal heat. As a result many heating grids are conceived to adjust to those two contrasted heaters by means of high temperature and low temperature networks. High inlet temperature heaters restrict temperature depletion and achievement of low rejection (at injection well head) temperatures which remain close to 40°C and seldom attain 35°C.

Regulation: it is indeed the vital segment of any combined geothermal/boiler heating management as it aims at minimizing the back-up boiler supply, thus upgrading the geothermal coverage ratio. District heating as opposed to industrial or agro-industrial process heat loads is subject to climatic charges and subsequent variable demand. Two temperature thresholds (besides the minimum reference outdoor temperature, set at - 7°C in the Paris Basin, to which is matched the installed heat capacity) are thus defined: the so-called transition (Θ*) and non heating (Θnh) temperatures respectively. Below Θ*, the doublet is circulated at its maximum (nominal) flowrate and the complementary (peak) demand supplied by fossil fuel fired boilers. In the (Θ* - Θnh) temperature range, the whole demand of the (centralized)grid is supplied by geothermal heat. Above Θnh, whenever SHW supply is required, the doublet is operated at its minimum flowrate. Hence the geothermal and grid flowrates are ascribed to variable speed drive achieved by frequency converters. Depending upon local grid/heater characteristics, the transition temperature varies between 5 and 8°C; the non heating temperature is set by law at 17°C. In the (Θ* - Θnh) range, the geothermal flowrate decreases linearly. Practically these simple regulation criteria are managed by an automaton which handles the grid/geothermal loop interface by driving, via pressure/temperature sensors, the frequency converters and the safety (low/high pressure) instructions by closing the motor actuated well head valves. The regulation suite usually conforms to the following sequence: the grid demand is transmitted, in terms of geothermal flowrate, to the injection pump frequency converter which adjusts the pump speed to the requested flowrate ; the injection pump inlet pressure transducer signals to the production pump frequency converter the adequate flowrate instruction ; whenever the production pump outlet pressure exceeds the high pressure (heat exchanger/piping protection) instruction, the geothermal loop is shut down and relief boilers actuated accordingly ; the same criterion applies to the low pressure (injection pumps inlet) instruction (pressure below bubble point).

3.7 Equipment performances/lifetime record

Components, including wells, equipping the geothermal loop are itemized, and their recorded and projected lifetimes listed, in table 6. This document speaks for itself. It constitutes the relevant data base for the cost estimates, risk assessment and economic evaluation developed in sections 5, 6 and 7.

Production technology, with respect to artificial lift and self-flowing mode, is analyzed, alongside pros and cons of the three experienced submersible pump concepts, in(3).

3.8 Environmental impact

Geothermal exploitation in the Paris Basin can be regarded, from an environmental point of view, as a risk as well as an asset. Hazards relate to the production of overpressured (up to 11 bars well head pressures and over 200 m3/h artesian free flow), hot and saline brines including toxic and flammable solution gases occurring in fresh water aquifer and densely populated urban environments. They are materialized by casing leaks and well head failures leading to (exposed) aquifer contamination and surface blowout damage. Workovers represent another risk source with respect to waste disposal, gas escape and noise. In many instances these risks remain under control and their consequences minimized. Fluid chemistry, well head pressures/ temperatures and well deliverabilities are periodically monitored and casings inspected by wireline logs easing detection of casing leakage/piercing and prompting relevant repair procedures.

Workover technology and practice are adapted to services in a sensitive urban context by means of sound proof (diesel) engines, waste processing units and flexible working schedules (no night shifts), indeed a contrast with the earlier days common, oil and gas inherited, practice. Nevertheless the industry is still awaiting the advent of silent, electrically driven, service rigs and pumps.

Table 5: Geothermal district heating analysis.
System components and parameters (after Harrison et al)

GEOTHERMAL POWER	NETWORK/HEATERS	HEAT DEMAND
$P_g = M_g (\square_g - \square_r)$ $M_g = \square_w \square_w q_g / 3.6$	$P_n = M_n (\square_a - \square_{ref})$ $M_n = NED \times V \times G / (m_{hi} / m_{ho})$ $m_{hi} = (\square_{hi} - \square_{nh}) / (\square_a - \square_{ref})$ $m_{ho} = (\square_{ho} - \square_{nh}) / (\square_a - \square_{ref})$	$P_d = M_d (\square_a - \square)$ $M_d = NED \times V \times G / 1{,}000$ $W_d = 24 \times NDD \times M_d / 1{,}000$ $NDD = \int_0^{NHD} (\theta a - \theta) dt$

HEAT EXCHANGE	GEOTHERMAL SUPPLY
$P_{hx} = \square_{hx} P_g = \square_{hx} M_g [(\square_g - \square_{nh}) - M_{ho} (\square - \square_{ref})]$ $\square_{hx} = \{1 - \exp[- N (1 - R)]\} / \{1 - R \exp[- N (1 - R)]\}$ $N = UA / M_g$ $R = M_g / M_n$	$W_{hx} = \square_{hx} M_g \{(\square_g - \square_{nh}) - m_{ho} \times 24 \int_0^{NHD} [\square(t) - \square_{ref}] dt\}$ $GCR = W_{hx} / W_d$
REGULATION CRITERIA	
$\square_{no} = \square_{ref} + m_{no} (\square_a - \square)$ □□□ : maximum geothermal flowrate, back up $\square\square\square\square\square_{ref}$: total geothermal supply	

NOMENCLATURE	
P = power (kW_t)	U = heat exchanger heat transfer coef. (W/m^2°C)
W = energy (MWh_t /Yr)	A = heat exchanger area (m^2)
M = thermal capacity (kW_t/°C)	R = flow ratio
NED = number of equivalent dwellings	GCR = geothermal coverage ratio
NDD = number of degree days	m = heater characteristic (slope)
NHD = number of heating days	q = flowrate (m^3/h)
V = equivalent dwelling volume (m^3)	□ = specific heat (J/kg°C)
G = average dwelling heat loss (W/m^3°C)	□ = volumetric mass (kg/m^3)
N = number of heat transfer units	□ = temperature (outdoor) (°C)
Subscripts	
g = geothermal	o = outlet
w = fluid (geothermal)	hi = heater inlet
d = demand	ho = heater outlet
n = network	nh = non heating (lowest heater temperature)
h = heater	a = ambient (room)
hx = heat exchanger	ref = minimum reference outdoor
i = inlet	r = rejection (return)

Typical values (Paris area)		
NED = 2,000/4,500	V = 185 m^3	$\square_{hi}/\square_{ho}$ =
NDD = 2,500	$\square_{ref}$ = - 7°C	90/70°C cast iron radiators
NHD = 240	$\square_r$ = 40/50°C	70/50°C convectors
N = 5	$\square_g$ = 55/75°C	50/40°C floor slabs
qg = 200/350 m^3/h	$\square_a$ = 17/18°C	
g = 1.05 W/m^3°C	$\square_{nh}$ = 20°C	

Table 6: Equipment performance. Lifetime record

Item	Lifetime (years)	Remarks
Production well	20-25	subject to reconditioning
Injection well	20-25	subject to reconditioning
Casing heads/spools	15	
Master (ball) valves	5	
Wing (ball) valves	5	
Butterfly valves	3-5	
Valve motorization	6-8	
Fiberglass liners	10-15	projected figure
Fiberglass liner well head	8-10	projected figure
Expansion joints	5-8	optional equipment
Geothermal loop piping : - carbon steel	15-20	
- fiberglass	10-15	often subject to odd initial fitting
Filters, strainers, screens	5-8	higher lifetime when duplicated
Desurgers (hammer preventers)	15-20	
Geothermal loop instrumentation/regulation :		
- pressure, temperature gauges	3-6	require periodical recalibration
- flowmeters	10	electromagnetic types, require periodical recalibration
- pressure/temperature sensors	3-6	require periodical recalibration
- automaton	5	change due to obsolescence
Production pumps : - ESPs	4	safe figure
- LSPs	-	unsufficient record
- HTPs	5-8	could last 10 yrs if no casing inspection required
Production tubing :		
- rubber (I/O) coated carbon steel	8	highly reliable figure
- fiberglass	5	abandoned alternative
Production pump transformer	10	
Water level control line	5	often subject to breakages during pump maneuvers
Injection pump	10	replaced by parts
Surface boost pump	10	replaced by parts ; applicable to self flowing wells
Surface charge pump	5	replaced by parts ; applicable to HTP
Inflatable packer	8	applicable to HTP
Frequency converters	10	replaced by parts : thyristors and control cards
Down hole chemical injection line	5-8	AIT type
Surface metering pump	10	highly reliable figure
Degasser	10	projected figure ; applicable to self flowing wells
Hidden combustion flare	10	projected figure ; applicable to self flowing wells
Geothermal heat exchanger	10	titane alloyed plate type ; replacable by parts (seals and plates)

ESP = Elecrosubmersible pump
LSP = Lineshaft pump
HTB = Hydraulic turbine pump
AIT = Auxiliary injection tubing

Since blowouts are unpredictable, the operators professional association -Agémo- initiated an emergency service in order to limit their magnitude. The contract awarded (after due bidding) to GPC specified to design, acquire, maintain and operate a wild well control facility, which should be mobilized in less than 6 hrs. Twenty geothermal operators subscribed to a five year (renewable) contract whose effectiveness was checked on four blowouts recorded to date.

The progresses registered since the pioneer days of geothermal district heating contributed to upgrade its image among the public. Better social acceptance and growing clean air concerns should therefore turn geothermal district heating into an asset in consideration of saved greenhouse gas emissions. Such savings, with reference to natural gas fuelled heating, amount to ca 120,000 tons of carbon/yr. Would an ad hoc ecotax be passed, the geothermal industry could benefit from an additional income of ca 23 FRF (3.5 E)/MWht on a taxation basis of 250 FRF (38 E)/ton of carbon, i.e. almost 10 % of the present heat selling price.

4. OPERATION/MAINTENANCE REQUIREMENTS

4.1 Power

Net (i.e. at frequency converter inlets) production and injection pump powers monitored on selected doublets, at nominal (winter) circulation flowrates, are listed below.

Name	Flowrate (m3/h)	Production pump (kWe)	Injection pump (kWe)	Total power (kWe)	Production mode
Blanc-Mesnil	210	235	165	400	ESP
Cachan 1	180	220	255	475	ESP
Cachan 2	170	230	155	385	ESP
Chelles	200	65	155	220	self-flowing/boost pump
La Courneuve nord	180	175	125	300	ESP
La Courneuve sud	180	145	100	245	ESP
Créteil	250	230	140	370	ESP
Epinay-sous-Sénart	255	170	140	310	ESP
Fresnes	250	460	160	620	ESP
Maisons-Alfort 1	280	270	155	425	ESP
Maisons-Alfort 2	250	175	120	295	ESP
Le Mée-sur-Seine	130	45	65	110	self-flowing/boost pump
Orly 1	100	no pump	50	50	self-flowing/boost pump
Orly 2	250	315	190	505	HTP
Tremblay	275	230	245	475	ESP
Vigneux-sur-Seine	240	160	380	540	ESP
Villiers le Bel/Gonesse	235	230	75	305	ESP
Villeneuve Saint-Georges	330	220	175	395	ESP

The wide power spectrum, from 50 to 620 kWe, reflects the variety of well designs (see table 1), production modes, nominal flowrates and, last but not least, local reservoir performances. Self-flowing wells exhibit the best record despite 7" cased injector wells. The Orly 2 site evidences the low HTP net efficiency as compared to ESPs. In the Vigneux-sur-Seine case, the injection power is a consequence of a slim (2,000 m 7" cased) injection well and poor injectiviy. The Fresnes high production powers results from poor reservoir performance (10 Dm transmissivity) and low static overpressure (5 bars). At Villiers-le-Bel the reconditioning of the production well (initially 13"3/8 x 9"5/8 cased, further lined 10"3/4 x 7") has caused a two fold increase in power, the injection power remaining low (9"5/8 injection casing).

Requirements of the heating grid ought to be added to the foregoing. Boost pump power ratings range usually between 50 and 100 kWe. In practice pump ratings are set 20 to 25 % above actual figures for safety (declining well productivity/injectivity), longer lifetime and variable speed drive considerations.

The total power consumption (geothermal loop + heating grid) of a doublet equipped with an ESP set varies from 1,500 (Epinay-sous-Sénart) to 3,200 MWhel/yr (Fresnes). Intermediate figures stand at :

- Maisons-Alfort 1 ....2,350 MWhel/yr,
- Maisons-Alfort 2 ....1,850 MWhel/yr,
- Cachan 1 et 2 (interconnected grid) ....4,200 MWhel/yr.

4.2 Monitoring, surveillance, consumables

According to the mining and environmental regulation in force and to site specific agreements, geothermal loop monitoring and surveillance comply to the following protocol:

1. geothermal fluid:
   - hydrochemistry (main anions/cations) and corrosion/scaling indicators: iron and sulphide/mercaptant
   - thermochemistry: bubble point, gas/liquid ratio, dissolved gas phase,
   - microbiology (sulfate reducing bacteria),
   - suspended particle concentrations,
   - coupon monitoring,

2. loop parameters:
   - well head pressures and temperatures,
   - production well head dynamic water level,
   - heat exchanger inlet/outlet temperatures,
   - geothermal and heating grid flowrates,
   - heat exchanger balance check,
3. well deliverabilities:
   - well head pressure/discharge (recharge) curves (step drawdown/rise tests),
4. pump and frequency converter characteristics:
   - voltage, amperage, frequencies,
   - powers,
   - efficiencies,
   - ESP insulation,
5. inhibitor efficiencies :
   - corrosion/scaling indicators control,
   - inhibitor concentrations,
   - filming (sorption/desorption) tests,
6. inhibition equipment integrity :
   - metering pump,
   - regulation,
   - downhole chemical injection line,
7. well head, valves, spool, filter integrities,
8. surface piping (ultrasonic) control,
9. casing status: periodical wireline logging (multifinger caliper tool) inspection of production (3 to 5 year) and injection (3 year) well casings.

Consumables address essentially the supply of chemicals (consumption of 3 to 6 tons/yr) and repair or replacement of parts of the inhbitor injection/regulation and corrosion control (coupons, corrosion probes) equipment.

4.3 Well and equipment heavy duty works and maintenance

During a Paris Basin geothermal well life (20 yr minimum), a number of heavy duty workovers are likelihood to occur, addressing well clean-up (casing jetting), reconditioning (lining/cementing of damaged pumping chambers and injection casings) and stimulation (reservoir acidizing and casing roughness treatment). The likely level of such events is analyzed in section 5 (risk assessment). However presently available well records make it possible to reliably assess the following schedule:

- well clean-up		2 to 3, i.e. 1 every 7 to 10 yr,
- well lining		1 to 2, i.e. 1 every 10 to 20 yr,
- well stimulation (coiled tubing acidizing):	production well	3 to 5, i.e. 1 every 4 to 7 yr,
	injection well:	4 to 6, i.e. 1 every 3 to 5 yr.

Equipments itemized in section 4.7 require periodical repair and/or replacement according to recorded lifetimes. In order to minimize doublet shut in periods and improve geothermal utilization factors (standing currently above 90 %), most operators have passed so-called total warranty and emergency service contracts with concerned suppliers and service companies. This policy is most pertinent with respect to submersible production pumps, master/wing valves and downhole chemical injection lines whose manufacturing/delivery delays often attain 3 to 4 months. For other equipments such as frequency converters and injection/boost pumps, maintenance can be reliably accomodated by the availability of duplicate vital parts most frequently subject to failures (control/regulation cards, power module thyristors, electronic filters, pump shaft packing, seals, joints). In addition, sound management would imply to suscribe a well blowout emergency contract.

5. RISK ASSESSMENT

Paris Basin geothermal district heating projects and accomplishments faced five levels of risks, exploration (mining, geological), exploitation (technical, managerial), economic/financial (market, institutional, managerial), environmental (regulatory, institutional) and social acceptance (image) respectively.

Exploration risk

The mining/geological risk could be minimized thanks to two favourable factors and incentives. First, the existence of a dependable hot water aquifer (Dogger limestones) of regional extent evidenced thanks to previous hydrocarbon exploration/step out/development drilling (see appendix 1), which enabled to reliably assess the geothermal source reservoir prior to development. This resulted later in a 95 % geothermal drilling success ratio according to the success/failure criteria set forth by the ad-hoc geothermal steering committee. Second, the coverage by the State of the geological risk amounting to 80 % of the costs incured by the first, assumed exploratory, drilling.

As a result of the high drilling success ratio, the (so-called short term) provisional fund could be allocated, at a later stage, to the (so-called long term) exploitation mutual insurance budget line.

Table 7: Summary of risk factors

Risk description	*Nature weight*	*Ranking*	*Status*	*Remarks*
Last known casing status	Technical 1	1	Fine	Residual steel thickness >75% nominal WT before treatment
		2	Fair	Residual steel thickness >50% nominal WT before treatment
		3	Bad	Residual steel thickness <50% nominal WT before treatment
Damaging kinetics	Technical 1	1	Low	Corrosion rate <150µm/an before treatment
		2	Medium	Corrosion rate >150µm/an before treatment
		3	High	Corrosion rate >300µm/an before treatment
Chemical inhibition efficiency	Technical 1	1	High	Provisional statement
		2	Low	Provisional statement
Casing lining opportunities	Technical 1	1	Full	No diameter restrictions
		2	Partial	Some diameter restrictions
		3	None	Total diameter restrictions
New well drilling expectation	Technical 1	1	Long term	> 20 yrs
		2	Medium term	> 10 yrs
		3	Short term	< 10 yrs
Other	Non technical 3	1	favorable	
		2	hostile	

Table 8: Recapitulation of provisions (sinking funds) required by heavy duty well workover/repair/ redrilling over 15 years (cost per well/year, 10^3 FRF)

SCENARIO	A	B	C
Risk level		1	
Yearly provision	485	650	820
Risk level		2	
Yearly provision	1329 (1505)	1265 (1450)	1675 (1815)
Risk level		3	
Yearly provision	1455 (1580)	1320 (1395)	1350 (1415)
TOTAL (Weighted average)		1135 (1220)	

Exploitation risks

Those could not be estimated from scratch. A (long term) fund financed by the State was created in the 1980s to cope with the hazards induced by the exploitation of the geothermal fluid. To benefit from this mutual insurance fund, managed by SAF Environment, a yearly subscription amounting to ca 10,000€/doublet is paid by geothermal operators.

It soon became obvious that the, initially overlooked, hostile thermochemistry of the geothermal fluid provoked severe corrosion and scaling damage to casing and equipment integrities resulting in significant production losses. A prospective survey commissioned in 1995 by SAF Environment aimed at assessing the exploitation risks and related restoration costs projected over a fifteen year well life. The results of this exercise, applied to thirty three doublets, are presented in (10). The governing rationale consisted of (i) listing potential and actual, technical and non technical, risks ranked and weighted as shown in table 7, and (ii) classifying risks according to three levels (1 : low, 2 : medium, 3 : high), each subdivided in three scenario colourings (A : pink, B : grey, C : dark) regarding projected workovers deadlines and expenditure. This analysis led to a symmetric distribution, i.e. eleven sampled sites per risk level, each split into three (A), five (B) and three (C) scenario colourings.

The next step applied the workover/repair unit costs to concerned wells, required works and forecasted schedules, thus leading to the synthetic expenditure breakdown summarized in table 8. This evaluation illustrates the paradox between competing (if not conflicting) well heavy duty maintenance strategies, i.e. repeated repair of damaged infrastructures, vs redrilling/recompletion of new wells reflected by scenarios 2 (A, B, C) and 3 (A, B, C). Here the optimum, in terms of investments but not necessarily cash flows, is represented by scenarios 2B and 3B, case 2C displaying definitely the worst profile.

In conclusion, an average provision (fiscally deductible) of 1,22 million FRF (ca 186,000 €/yr) has been recommended to cope with future exploitation hazards resulting in a 12 % increase of initially anticipated OM costs. Loose management remaining the exception, managerial risks can be reliably regarded as minimized in year 2000.

Economic/financial risks

They represent a major uncertainty owing to a somewhat unpredictable, if no chaotic, energy market and pricing context in which geothermal heat must prove competitive. This is indeed a difficult challenge bearing in mind that geothermal district heating grids are structurally, especially under Paris Basin conditions, strongly capital intensive and financially exposed, in case of low equity/high debt ratios a distinctive attribute of Paris Basin loan policies.

At the time, in the wake of the second oil shock, most geothermal district heating doublets were commissioned, oil prices, dollar exchange and inflation rates stood high and accordingly feasibility projections shaped very optimistic, in spite of their fragilized financial planning. A few years later, these trends were totally reversed. This, added to the dramatic technical, financial and managerial problems undergone by most geothermal doublets, endangered grid operation to a stage the abandonment of the geothermal district heating route was envisaged. These difficulties could be overcome at the expense of the shut in of technically irreparable/economically non feasible doublets and rationalizing exploitation technologies and management of the remaining thirty four doublets operated to date.

The economic/financial risks were controlled thanks to debt renegociation, technological/managerial imporvements and stable heat selling prices agreed in long term and users subscription contracts. These contracts, passed in the mid 1980's, expire in the late 1990's/early 2000's. Negociation of these contracts was clouded by depleted, downward trending, deregulated energy prices prevailing in years 1998 and 1999. This situation incited several operators to pass cogeneration contracts and concessions, a compromise deemed satisfactory to remain competitive and secure the survival of the geothermal heating grid regardless from any environmental considerations whatsoever. The pros and cons of the cogeneration issue are discussed further in section 8.

In year 2000, both a sharp increase of oil prices and natural gas tariffs and growing environmental concerns (global warming and related climatic disasters) modify again the energy panorama. Taxation of greenhouse gases becomes a realistic working hypothesis for the future, limiting the uncertainty margin of geothermal heating prices. In this perspective a 250 FRF (38 €)/MWht selling price appears a reasonable threshold safeguarding the economic feasibility of most operating grids.

Environmental risks

Damages caused to the environment by casing leaks, uncontrolled well head blowouts and workover operations have been minimized. Limitation of the environmental risks is to be credited to the periodical (quaterly) doublet monitoring and casing inspection logging imposed by the competent mining/environmental authority (Drire) and blowout control/waste processing equipments currently operated by the industry, discussed previously in section 3.8.

Social acceptance

Geothermal energy, particularly direct uses of low grade heat, has a structural image problem. The product and the recovery (heat exchage) process remain somewhat mysterious or esoteric to the public as opposed to obvious, visible, competing solar, wind and fuel sources. For many years indifference, at the best, was the prevailing attitude. In the early days of geothermal development (the infancy stage), it was regarded as a poorly reliable and costly, occasionally, environmentally hazardous technology. Nowadays mature engineering and management and growing environmental (clean air) concerns have gained wider acceptance by the public of the geothermal district heating alternative. Still, image building efforts need to be persued to popularize the technology.

6. ECONOMY

Total geothermal investment costs amounted in the Paris Basin to ca 3.2 billion FRF (i.e. 500 million €) representing a unit investment cost of ca 9,200 FRF/installed kWt. Investment costs split as follows (million FRF):

	Min.	Max.	Mean
- mining (well) costs	12	18	15
- heat plant/primary surface loop	4	7	5
- grid construction/substation modifications ...	30	90	45

It is a generally accepted fact that, under normal feasibility conditions, total investment costs stand close to 65 million FRF to which the whole geothermal loop (wells, heat plant, surface piping and equipment) contribute to 30 % and the grid proper to 70 % respectively. From 80 % to 90 % of the investment was provided by (public) bank loans and the remaining 10 to 20 % by public subsidies and grants.

Operation and maintenance costs include three main headings, namely energy (electricity and back-up fossil fuels), light maintenance/monitoring and heavy maintenance /equipment warranty and miscellaneous (provision for heavy duty works, overhead) costs.

The grid (primary and secondary networks) is operated permanently by a heating company with an assigned staff of three to five employees. The geothermal segment is monitored periodically and serviced occasionally by a geothermal engineering bureau. A thermal engineering bureau is usually appointed by the geothermal operator to assist the management in controlling grid operation and heat supplies.

Description of the various capital investment and OM cost items relevant to Paris Basin district heating systems may be found in a comprehensive economic review developed in (10).

Revenues address heat sales to end users connected to the grid. These sales include both geothermal and boiler (back-up/relief) generated heat.

Global cash flow streams, selected on sites deemed representative of Paris Basin conditions, are displayed in the table overleaf. It emphasizes the dominant financial share of the debt repayment annuity which often nears 60 % of total expenditure. This, added to back-up/relief boiler costs sensitive to natural gas prices and to the geothermal coverage ratio, exemplifies the structurally fragile economic and financial balance of Paris Basin geothermal operations. Actually, out of thirty four doublets, twelve achieve profitability, twelve breakeven and ten show a deficit. Prices close to 250 FRF (38 €) could hardly compete in the past years with natural gas whose tariffs could afford a near 200 FRF (30 €)/MWht figure. It is worth mentioning however that on several doublets (A, C and D in the afore mentioned list, among others), debt repayments will cease in year 2002.

To overcome these financial problems, two issues can be contemplated, in the short term, combined natural gas cogeneration/geothermal grids and, in the medium term, enforcement of an ecotax applicable to greenhouse gas emissions. The latter would definitely secure a more attractive profit margin for the mutual benefit of geothermal producers and end users. Along this line, a typical example of a Paris Basin prospective balance sheet is given in (10) and several revival scenarios of presently abandoned doublets are analyzed in appendix 4.

Item/doublet	A1 (1)	A2 (1) (2)	B	C	D1 (1)	D2 (1) (2)
Total heat supply (MWht/yr)	58,000	43,500	48,888	51,000	40,000	31,000
- geothermal	39,500	32,500	42,000	41,000	26,000	15,000
- back-up boilers	18,500	11,000	6,000	10,000	14,000	16,000
- geothermal coverage %	68	75	87.5	80	65	48
Heat selling price (FRF/MWht)	251	241	247	258	272	272
Revenues (10^3 FRF/yr)	13,980	10,480	11,860	13,160	10,800	8,430
Expenditure (10^3 FRF/yr)	13,520	10,540	11,570	12,370	9,790	8,850
- debt charge	7,100	6,800	6,900	7,600	4,300	3,200
- power	875	710	1,030	590	560	520
- back-up fuels	3,330	1;980	1,080	1,800	2,520	2,880
- maintenance	1,620	1,470	1,840	1,760	1,810	1,650
- heavy duty workover provision	360	240	400	330	250	250
- overhead	240	240	320	290	350	350
Balance (10^3 FRF/yr)	+ 460	- 60	+ 290	+ 790	+ 1,010	- 420

(1) dual doublet management (2) cogeneration on line in 2000

7. LEGAL, INSTITUTIONAL AND MANAGERIAL MATTERS

The French legal background regulating geothermal operations consists of two decrees. **Decree 77-620 of 16 June 1977** added a new title, "Low temperature geothermal deposits", to the mining code, creating an obligation to obtain an exploration permit before drilling and an exploitation permit before starting up production. **Decree 74-498 of 24 march 1978** defined the legislation concerning "geothermal prospecting and exploitation licences". According to these decrees, geothermal deposits are considered concessible and therefore assimilated to mines. A geothermal resource is categorised as a low enthalpy deposit as long as the temperature measured at the surface during testing (**not** the reservoir temperature) is below 150°C.

The exploration permit is granted on the basis of a prefectural (State regional representation) decision following a public enquiry. The decision fixes the siting of the drilling or determines a perimeter within the wells can be drilled. The exploration is exclusive and delays no longer than three years. A number of documents (technical, economical, administrative, financial, environmental) must be submitted by the applicant in support of the request. The application must also assess instantaneous maximum yields and maximum daily water volumes withdrawn and reinjected, as well as fluid and heat uses. The holder of a prospecting permit has the right to an exploitation lease if requested before expiration of the prospecting permit. An exploitation permit is also compulsory and issued by the Prefect. It grants exclusive exploitation rights by drilling within the authorized perimeter. The application must be backed by pertinent information on heat and water yields and volumes, drilling locations and characteristics and on heat uses. An environmental impact study is required before completion of the project. A simplified procedure is foreseen for operations whose overall cost stands below 1 M€.

In so doing the State acts through a competent authority, Drire, part of the Mining and Energy Directorate of the Ministry of Industry.

These decrees have been complemented by the following texts:

- decree 95-696 of 9 may 1995 concerning the opening of mining works and the mines policing ; it enables to pronounce the shut down of mining works and exploitation,
- water act, law 92-3 of 3 January 1972,
- public health code (articles L20, L738, L737),
- decree 93-743 of 29 March 1993 ; it defines the nomenclature of operations subject to declaration or authorization according to the water act (law 92-3) amended by decrees 94-1227 and 95-706,

which precise the environmental requirements to be fulfilled by geothermal operations as far as water (ground, surface) and air qualities are concerned.

The exploitation permit is awarded over a period of fifteen years renewable after due examination by the authority of an ad-hoc application report and format. Geothermal exploitation, particularly from the well integrity standpoint, is periodically controlled via a monitoring/inspection protocole discussed previously in section 4.8. Quaterly/yearly monitoring reports, workover service records/reports and casing inspection logs are released to the authority, which keeps complete records of the well life. Simultaneously the geothermal operator (owner of the mining title) issues a yearly exploitation report indicating produced geothermal heat, water yields and boiler generated heat. The authority is kept informed of any intervention and workover, the latter subject to the issuing of an appropriately documented environmental impact study. Well abandonment is carried out in compliance with the state of the art cementing procedures set by the authority and agreed by the industry.

Besides this substantial legal and institutional material, the State has been active in promoting relevant supporting policies, agencies and incentives among which ought to be distinguished:

- the geothermal ad-hoc committee for examination of candidate exploration/development projects on the basis of widely documented technico-economical prefeasibility and feasibility surveys cost shared by the committee ; it proved decisive in standardizing the evaluation methodology,
- the coverage (short term fund) of the geological/mining risk by supporting up to 80 % of the first well drilling/completion costs,
- the creation of Géochaleur, a lobbying agency in charge of marketing geothermal district heating projects, fund rising and assisting operators in project design, tendering, completion and start-up,
- the creation of SAF Environement, responsible for the management of a mutual exploitation insurance (long term) fund covering the geothermal exploitation risk ; for a yearly subscription of 60,000 to 70,000 FRF (ca 10,000 €)/doublet and a damage excess allowance of 500,000 FRF (76,000 €), the operator can apply for reimbursement of expenses incurred by a clearly identified exploitation damage,
- the funding of R, D & D actions directed towards curing and preventing the critical corrosion/scaling shortcomings and the design of innovative well restoration, completion and stimulation technologies,
- the initiation of various incentives in the areas of fiscal deductions (VAT, once reduced) and subsidies, the latter as part of the energy savings supporting policy (grants to saved toe's, district heating grids),
- last but not least, the creation of the Brosse mission, which pointed out and solved the critical debt repayment issue, without violating any ethical standards whatsoever, allowing the potentially feasible doublets to survive and operators to upgrade their managerial skills.

The managing policies among a number of geothermal public operators, possibly the less prepared to industrial management, consisted of conceding the exploitation and related risks to large, experienced, heating companies from the private sector. As a result, one half of the existing doublets may be regarded a privatized or in the privatization process as of late 2000.

8. THE COGENERATION ISSUE

Cogeneration appeared recently as a realistic survival alternative to geothermal operators facing severe competition from cheaper fossil fuels, firing conventional boilers, while negociating renewal of end users heating contracts.

Gas cogeneration on geothermal district heating grids raises growing interest for the simple reason that the power required to produce the heat, which remains largely unused (hardly 10 % of the grid capacity), is sold to the utility at a price guaranteed over twelve years and indexed on gas market prices, with tax incentives added as a bonus, indeed a financially and fiscally attractive issue. The interest is mutual. The gas compagny (Gdf) increases its market share and sells significant gas quantities to meet the demand of the grid (currently producing between 30,000 and 50,000 MWht/yr). The grid operator purchases cheap heat produced at marginal cost as a by product of power generation.

Practically candidate (combined cycle) systems consist of natural gas fired engines or turbines driving alternators. Heat is recovered (i) on engines on the cooling circuit and, at a lesser extent, on exhaust gases, and (ii) on turbines via exhaust gases. Heat to power ratios stand around 1.1 (engines) and 1.35 (turbines) respectively. The essentials of gas/geothermal cogenerated system designs are schematized in figure 9a (gas engine) and 9b (gas turbine). The dual cycle (combining a gas and a, superheated, steam turbine) proposed by a Soccram/Danto Roja/Spie Trindel/Gpc joint venture, outlined in figure 9c, is ideally suited to geothermal heating grids. As a matter of fact it takes advantage of low (40 to 50°C) geothermal rejection temperatures, thus offering a freely available cold source eligible to a condensing steam cycle. The design, sketched in figure 9c, increases by 45 % the net power output as compared to the gas turbine alone, at the cost however of an additional boiler needed to superheat the steam (450°C/4 bars) at turbine inlet.

The cogenerator must comply to the following conditions :

- - 50 % minimum (global) energy efficiency,
- - heat to power ratio higher than 0.5,
- - use (self-utilization) of produced heat,
- - conformity certified by the competent authority (Drire).

The contract is passed with the utility (Edf) for a duration of twelve years. The cogenerator suscribes a guaranteed installed power and a plant utilization factor (subject to bonus/malus) of 95 %. Cogeneration extends over a 151 calendar day (from November 1st to March 31st) heating period.

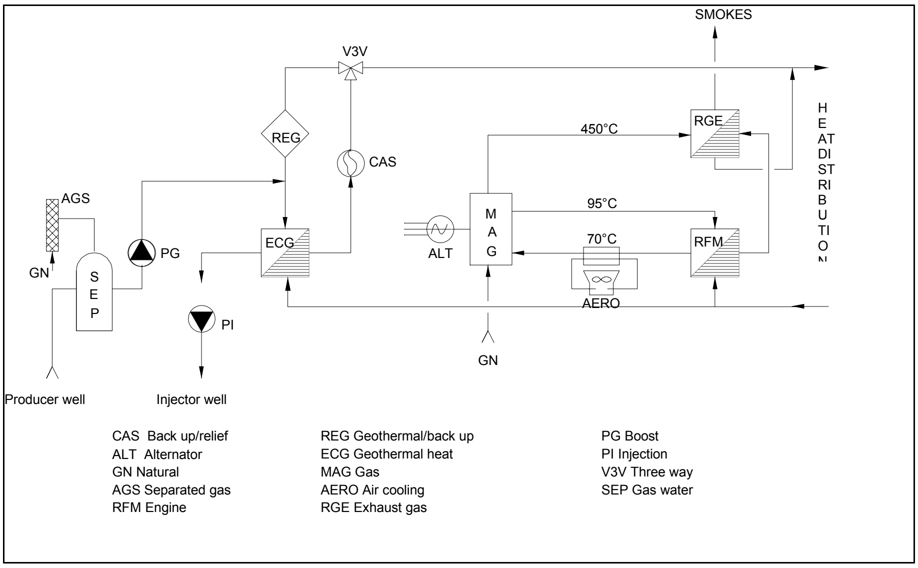
The foregoing have important implications on geothermal production. Power (and heat) is generated constantly, at nominal rating over 151 days (3 624 hours) to maximize electricity sales. Therefore cogenerated and geothermal heat are operated as base and back-up loads respectively during winter heating. This results in a somewhat drastic drop of geothermal heat supplies. Actually, in many instances artificial lift was abandoned and self-flowing production substituted instead, according to the design depicted in figure 10.

On economic grounds, the following figures, borrowed to two typical cogeneration grids, shape quite attractive with discounted pay back times nearing five years.

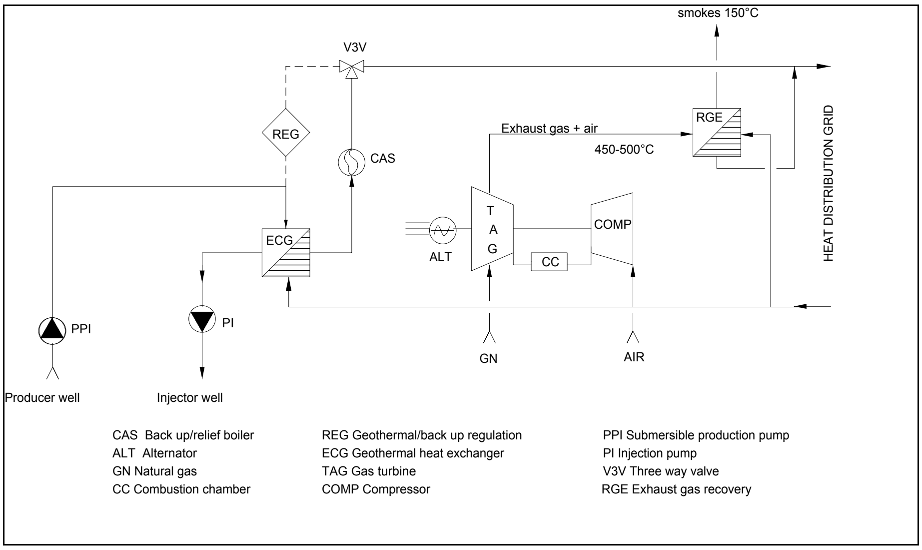
	grid 1	grid 2
Generating unit	gas engine	gas turbine
Power rating (MWe)	4	5.5
Power production (MWhe)	13,100	16,400
Gas consumption (MWht ; HCI)	39,700	57,700
Heat production (MWht)	16,400	21,600
Revenues (10^3 FRF)	10,980	13,470
- power sales	6,600	8,260
- heat sales	4,380	5,210
Expenditures (10^3 FRF)	8,580	11,510
- debt charge	2,040	2,100
- gas costs	5,160	7,160
- maintenance	1,180	1,940
- miscellaneous	200	300
Balance	+ 2,400	+ 1,960

Increases in natural gas prices have a penalizing impact, mitigated though, thanks to the contract passed with the utility, which compensates ca 75 % of gas tariff rises. In the aforementioned examples, a 40 % increase in gas prices would result in additional expenditures amounting to 510 (1) and 730 10^3 FRF (2) respectively.

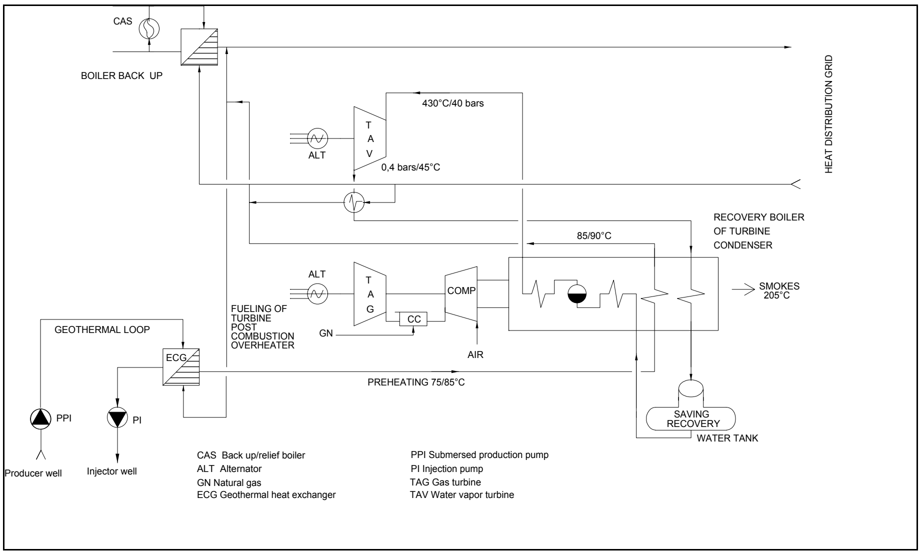
Cogeneration has become a reality on many operating doublets. At the start of the 2000/2001 heating season, twelve cogeneration/geothermal heating grids were on line. Five other doublets are already commissioned and due to operate in 2001. Three to five sites are projected. Summing up, within the next years only ten to twelve doublets should be exploited via the conventional heat exchange/back-up relief boilers heating mode.



a) motor cycle

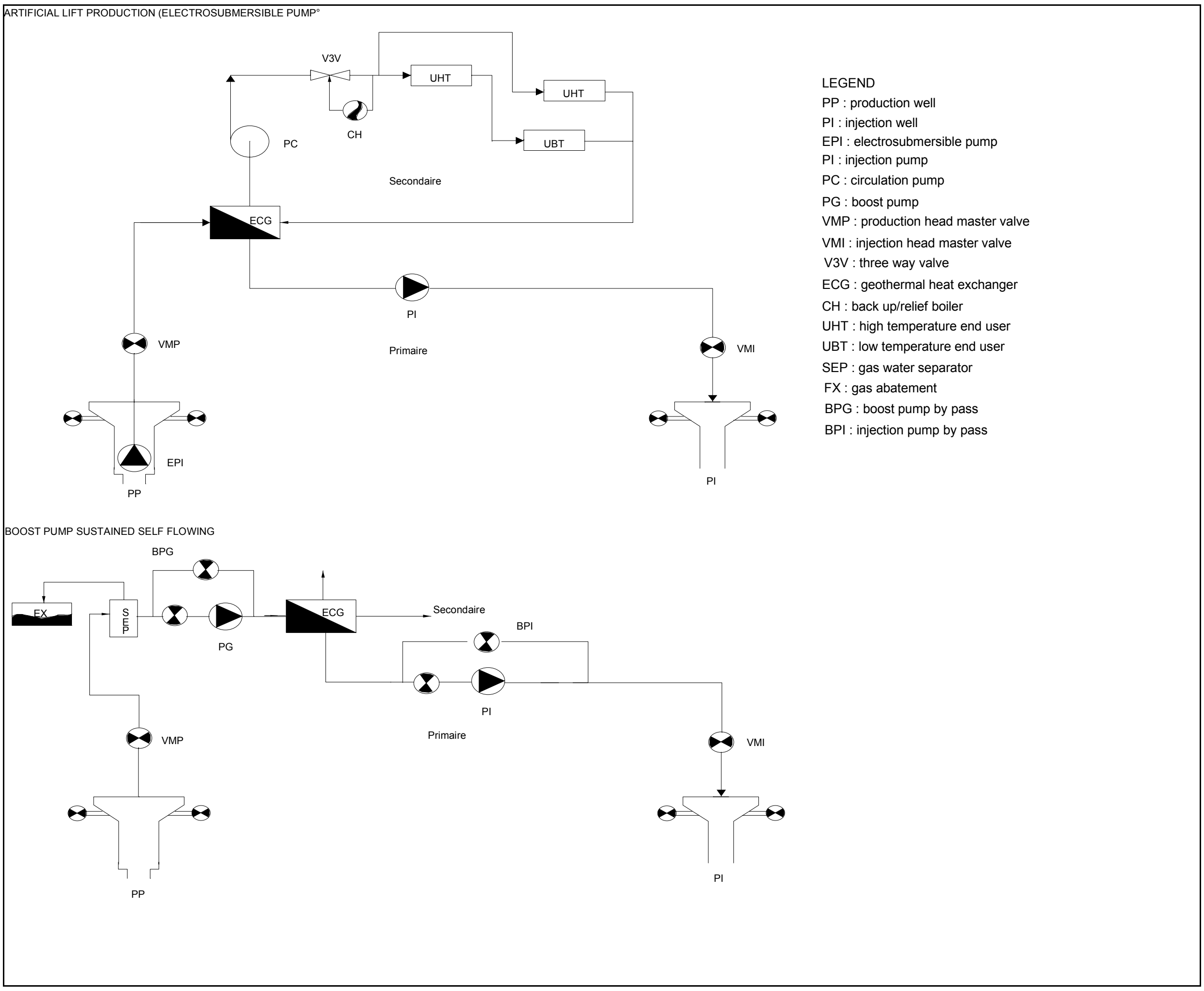


b) turbine cycle

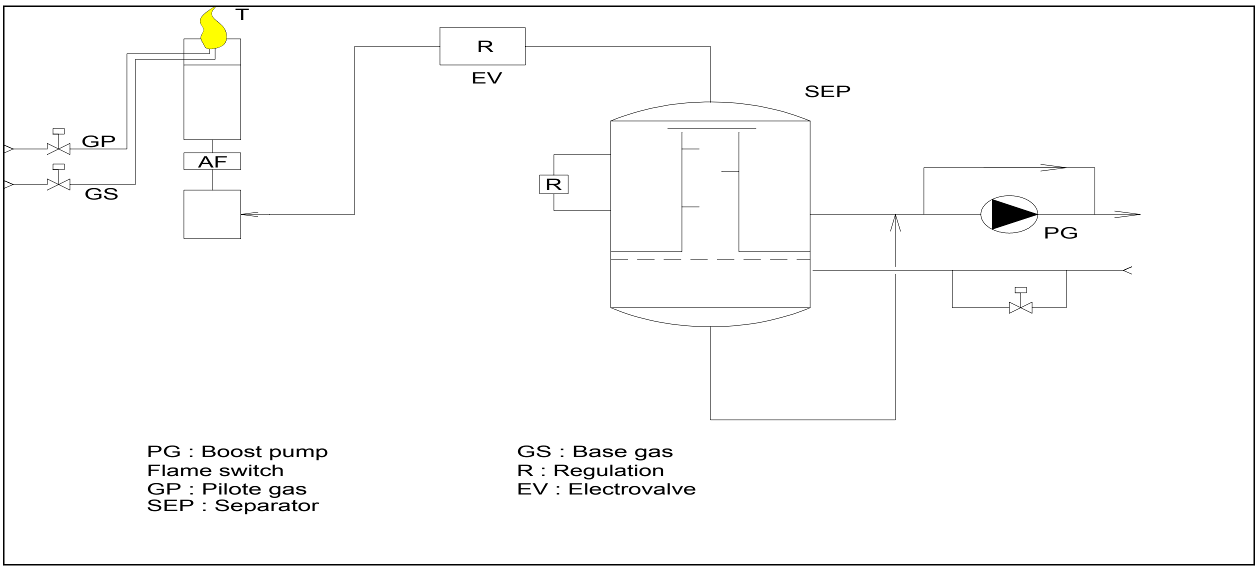


c) dual gas/steam turbine cycle

Figure 9: Gas cogeneration cycles



a) production modes



b) gas separation and abatement (self flowing production below bubble point)

Figure 10: Geothermal production modes and gas abatement

9. CONCLUSIONS

Based on an experience dating back to the mid 1970's, the following conclusions may be drawn as to the past, present and future of geothermal district heating in the Paris Basin.

The geothermal source proved dependable with respect to reservoir extent and performance securing easy well completions and high yields. Drillings achieved a 95 % success ratio and well productive capacities currently attain 250 m3/h - 70°C nominal ratings.

Large social dwelling compounds of the Paris suburban belt favoured the district heating development route as a result of suitable heat loads overlying the heat source.

The doublet concept of heat mining and retrofitting were the governing rationale in exploiting the resource and heating the end users connected to the heating grid downstream of the geothermal heat exchanger.

Developments benefited from a strong involvement of the State, following the first and second oil shocks, in favour of alternative energy sources. Relevant supporting policies addressed the areas of legal/ institutional (mining law), risk coverage (exploration and exploitation sinking funds), financial backing (fiscal incentives, subsidizing), project reviewing/commissioning (ad-hoc committees) and heat marketing.

In the mid 1980's, fifty four doublets were on line and exploitation targets set at 360 MWt (installed capacity) and 2,000 GWht/yr (heat production) respectively. Since then recorded figures did not match expectations. As a matter of fact actual figures, as of year 2000, stand at thirty four operating doublets, 227 MWt installed capacity and 1,200 GWht/yr heat supply. This situation reflects the learning curve phases, infancy, teenage and maturity, inherent to any new technological development, particularly in the mining field.

Paris Basin geothermal development was soon confronted to three major problems, namely :

- technical problems: the thermochemically sensitive geothermal brine caused severe, corrosion/scaling induced, damage to well tubulars and production equipments ; these problems had been clearly overlooked at design/implementation stages,

- financial problems: deemed the most critical, they resulted from a massive debt charge (no equity) aggravated by a, low price, depleted energy market in the aftermath of the second oil shock,

- managerial problems: they related to the lack of experience and expertise of geothermal operators, the large majority belonging to the public/municipal sector, in handling industrial installations including a significant mining segment ; consequently loose monitoring and maintenance policies were the rule.

This bleak outlook could be progressively overcome thanks to innovative, State supported, chemical inhibition and well restoration technologies, debt renegociation and sound management of geothermal heating grids. These sharp progresses were however accompanied by the abandonment of the twenty or so poorly reliable doublets.

So, everything considered, in spite of a fairly hostile, competing, economic environment geothermal district heating scored well. It demonstrated so far its technological and entrepreneurial maturity and gained wider social acceptance.

Still economic viability proves fragile and only could gas cogeneration secure the survival of a number of geothermal district heating grids. Twelve cogeneration systems are operating to date and it is likely this figure will reach the twenty mark in the near future.

Where to go next?

A major question arises on whether the future of geothermal district heating reduces to the sole gas cogeneration survival scenario in which geothermal heat no longer supplies base load.

Recent climatic disasters attributed to global warming and greater sensitivity of the public to environmental, clean air, concerns could challenge this trend and turn low grade geothermal heat into a widely accepted asset. Taxation of greenhouse gas emissions, the so-called ecotax, would in this respect be decisive in giving geothermal heating a new chance.

Prospective developments could, in the short run, address realistically two objectives. First the extension of existing (cogenerated and non cogenerated) geothermal grids to new users. Second the reactivation of abandoned doublets according to a revival, triplet, design combining two injectors (the old wells) and one, new generation, production well.

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