

ENVIRONMENTAL IMPACTS OF LOW ENTHALPY DIRECT USES. THE GEOTHERMAL DISTRICT HEATING CASE

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INTRODUCTION

Reclamation of low grade geothermal heat deposits is most often achieved by extracting the heat stored in tepid and hot water sources, within the 10°C to 100°C temperature range, either straightforwardly or via heat exchangers.

It addresses a wide spectrum of so-called direct uses, from balneological/medicinal/recreational, agricultural, industrial process heat, space heating, heat pump, and, last but not least, district heating utilisations.

In most instances, geothermal heat is mined from an exhaustible source, which arises the problematic of reservoir life and sustainable reservoir development and management.

The foregoing portray an overall context which is resource specific, site specific and process specific.

The forthcoming will focus on the geothermal district heating segment, deemed illustrative of a key development issue, as it challenges the most severe environmental constraints and regulatory frameworks, prevailing in sensitive, densely populated (sub)urban environments.

In so doing it is assumed:

- (i) that a Mining Law exists, categorising low enthalpy fluids as a mineral resource, thus subject to the Mining Code, and to awarding exploration/exploitation concessions/leases by an ad-hoc State Mining Authority, according to the scheme depicted in Fig. 1 (Ungemach and Ventre, 1997);
- (ii) that disposal of geothermal (liquid, gaseous, solid) waste complies with the Environmental Law and regulatory framework in force, with respect to toxic and, environmentally sensitive, gas abatement, solid filtering, heat depleted brine processing and (re)injection, safety, noise and clean air tolerance thresholds;
- (iii) that the previous formatting encompasses the whole of the well exploratory/development, drilling/completion/exploitation, and abandonment sequence.

The foregoing are illustrated by the Paris Basin district heating commissioning/exploitation/monitoring/abandonment protocols, which benefit from a twenty five year backup experience and thirty four heating grids operating to date.

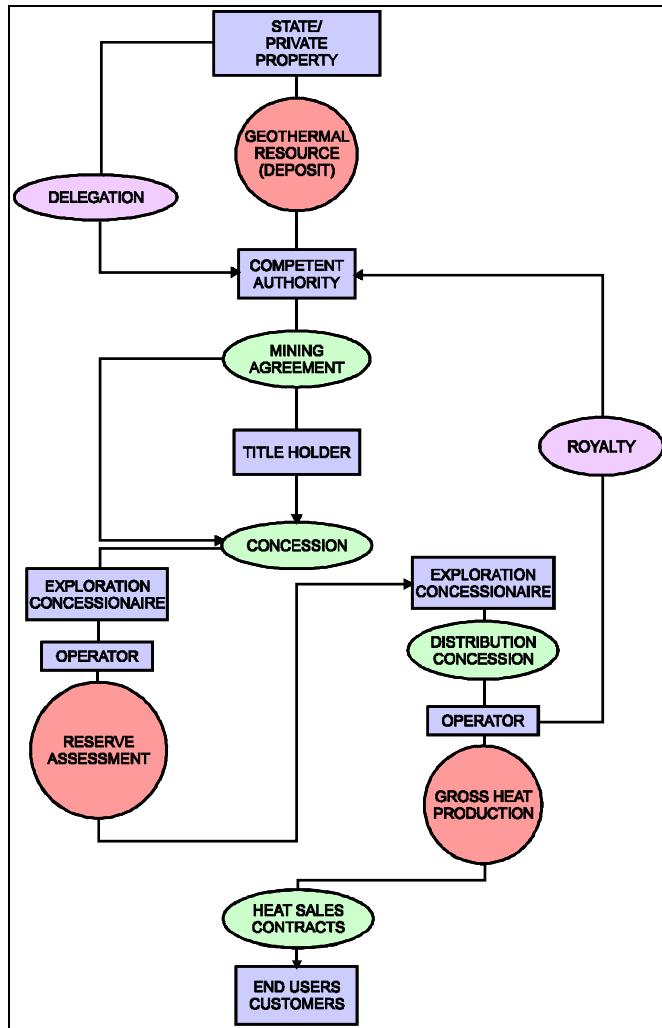


Figure 1: From resource to end users.
A typical geothermal district heating regulatory framework
 (Ungemach and Ventre, 1997)

BACKGROUND

Legal and Institutional

The French legal background, regulating geothermal undertakings, consists of two decrees (Ungemach, 2001). **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 concessionable 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) stands below 150°C.

The exploration permit is granted on the basis of a prefectoral (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 (re)injected, 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 to 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 mines policing ; it enables to declare 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 stipulates 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 protocol discussed later. Quarterly/yearly monitoring reports, workover service records/reports and casing inspection logs are released to the Competent Mining Authority, which files 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 practiced by the industry.

Reservoir Setting

The Paris Basin area belongs to a large intracratonic sedimentary basin, stable and poorly tectonised, whose present shape dates back to late Jurassic age (see areal extent in Fig. 2a)

Among the four main lithostratigraphic units exhibiting aquifer properties, depicted in the Fig. 2b cross section, the Mid-Jurassic (Dogger) carbonate rocks were identified as the most promising development target (Rojas, 1989; Ungemach et al, 2004).

The Dogger limestone and dolomite are typical of a warm sea sedimentary context, associated with thick oolithic layers (barrier reef facies). The oolithic limestone displays by far the most reliable reservoir properties as shown by the present geothermal development status. Reservoir depths and formation temperatures range from 1,400 to 2,000 m and 56 to 80°C respectively.

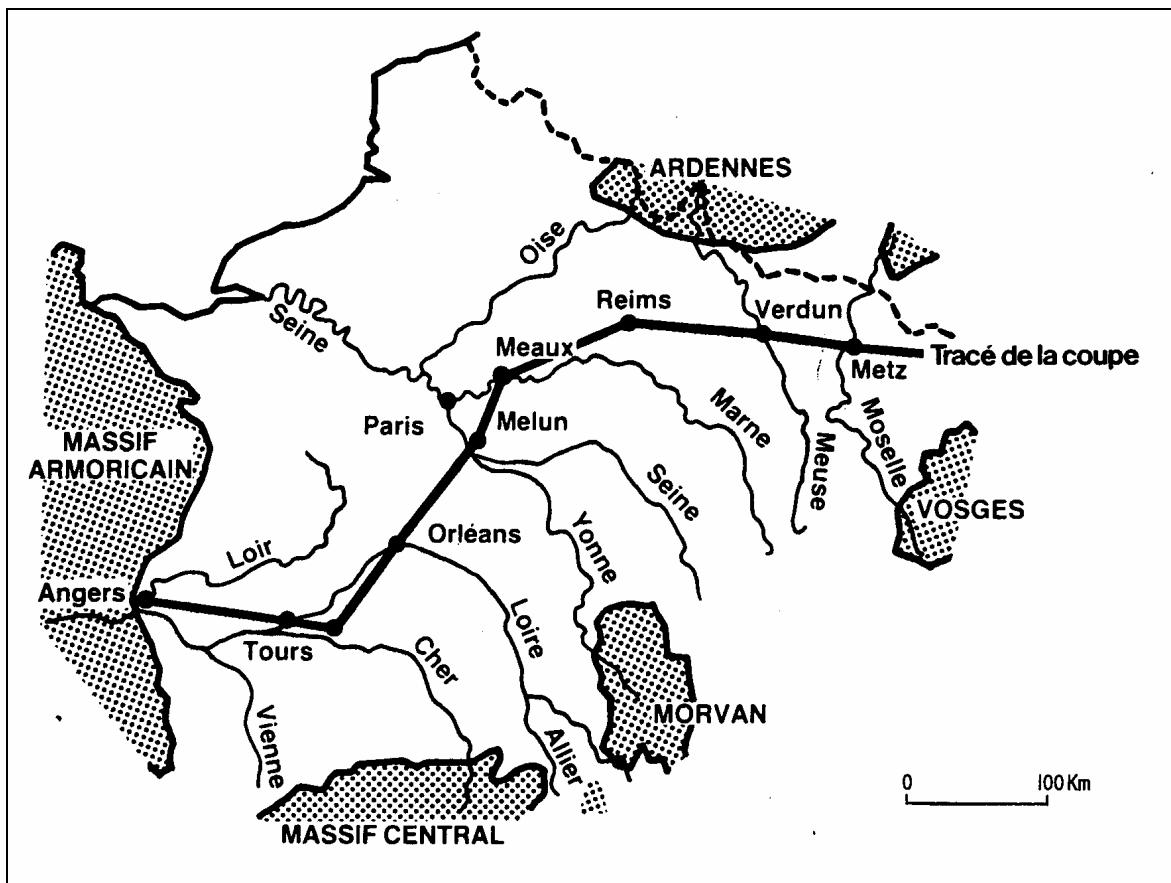


Figure 2a: Paris Basin areal extent (Rojas, 1989; Ungemach et al, 2004)

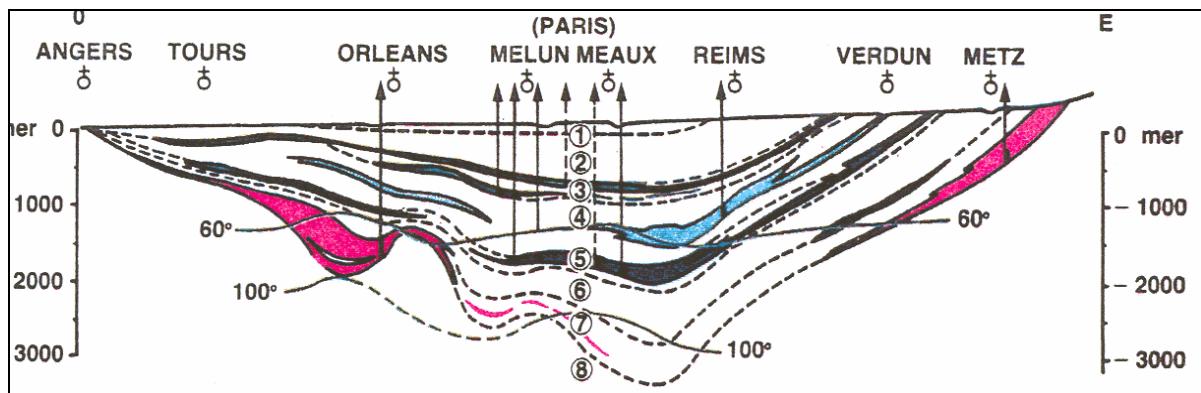
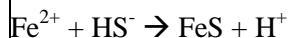
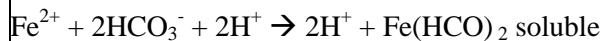
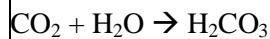


Figure 2b: Cross sectional view of the main deep aquifer horizons (Rojas, 1989; Ungemach et al, 2004)

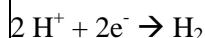
The reservoir fluid, a hot (60 to 80°C), slightly acid (pH=6), saline brine with a CO₂ and H₂S enriched solution gas phase, exhibits severe corrosion and scaling tendencies. The corrosion mechanism in the CO₂/H₂S aqueous system, and subsequent forming, under soluble or crystallised (scale) states, of iron sulphides and carbonates is outlined in the fig. 3 sketch and related chemical reactions.

The presence of sulphates favours the development of sulphate reducing bacteria producing H₂S. This hostile, thermochemically sensitive, environment requires adequate monitoring protocols and downhole chemical inhibition strategies (Ungemach, 1997).

Chemical reaction:



Corrosion induced and native



for pH = 6

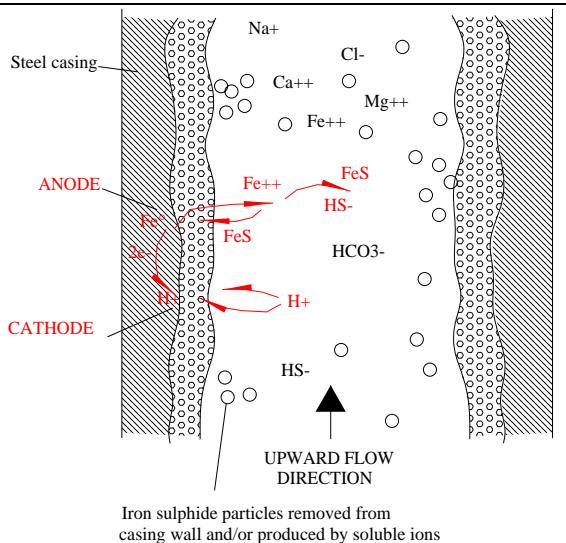


Figure 3: Iron dissolution and sulphide precipitation process in presence of aqueous H₂S and CO₂ (Ungemach, 1997)

Development Status

The locations of the geothermal district heating sites are shown in Fig. 4. They consist of thirty four (as of year 2003) well doublets, supplying heat (as heating proper and sanitary hot water, SHW), via heat exchangers and a distribution grid, to end users.

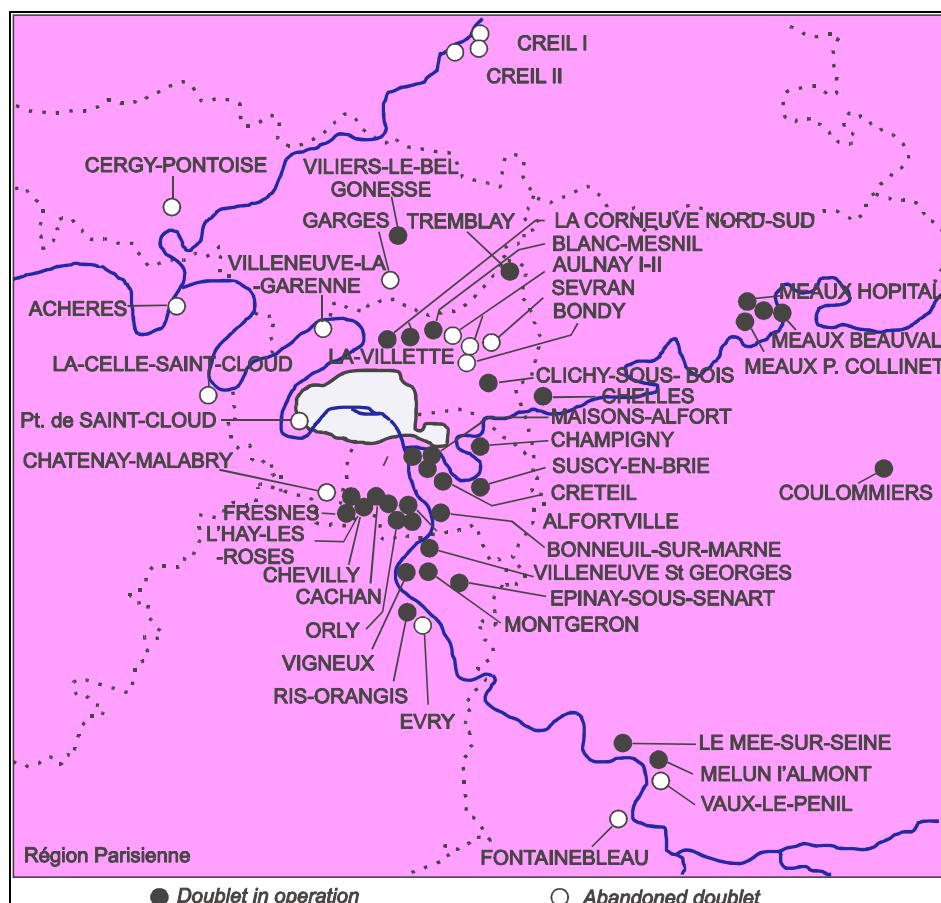


Figure 4: Location of the geothermal district heating sites in the Paris Basin (Ungemach et al, 2004)

Technology Outlook (Ungemach, 1998 and 2001)

The standard geothermal district heating system is based on the well doublet concept, depicted in fig. 5, and on the surface system and governing parameters sketched in fig. 6. It should be noticed that:

- (i) as shown in fig. 5, most well (production/injection) trajectories are deviated from a single drilling pad, with wellhead and top reservoir spacing of 10 and ca. 1,000 m respectively. They are produced via, variable speed drive, electric submersible pump (ESP) sets (see fig. 7);
- (ii) the heat is recovered from the geothermal brine by, corrosion resistant, titanium alloyed plate heat exchangers;
- (iii) geothermal heat is used as base load and therefore combined with backup/relief, fossil fuel fired, boilers unless otherwise dictated by combined gas cogeneration/geothermal systems;
- (iv) district heating complies to retrofitting, which means that geothermal heat supply has to adjust to existing conventional heating devices, most often not designed for low temperature service. This has obvious implications on rejection (injection) temperatures and well deliverabilities.

The principles governing geothermal district heating are summarised in table 1. It should be stressed here, that in no way is the heat supply constant but highly variable instead, as it varies daily and seasonally (in summer only sanitary hot water is produced) with outdoor temperatures. This entails variable discharge/recharge rates and injection temperatures, well deliverabilities and production schedules.

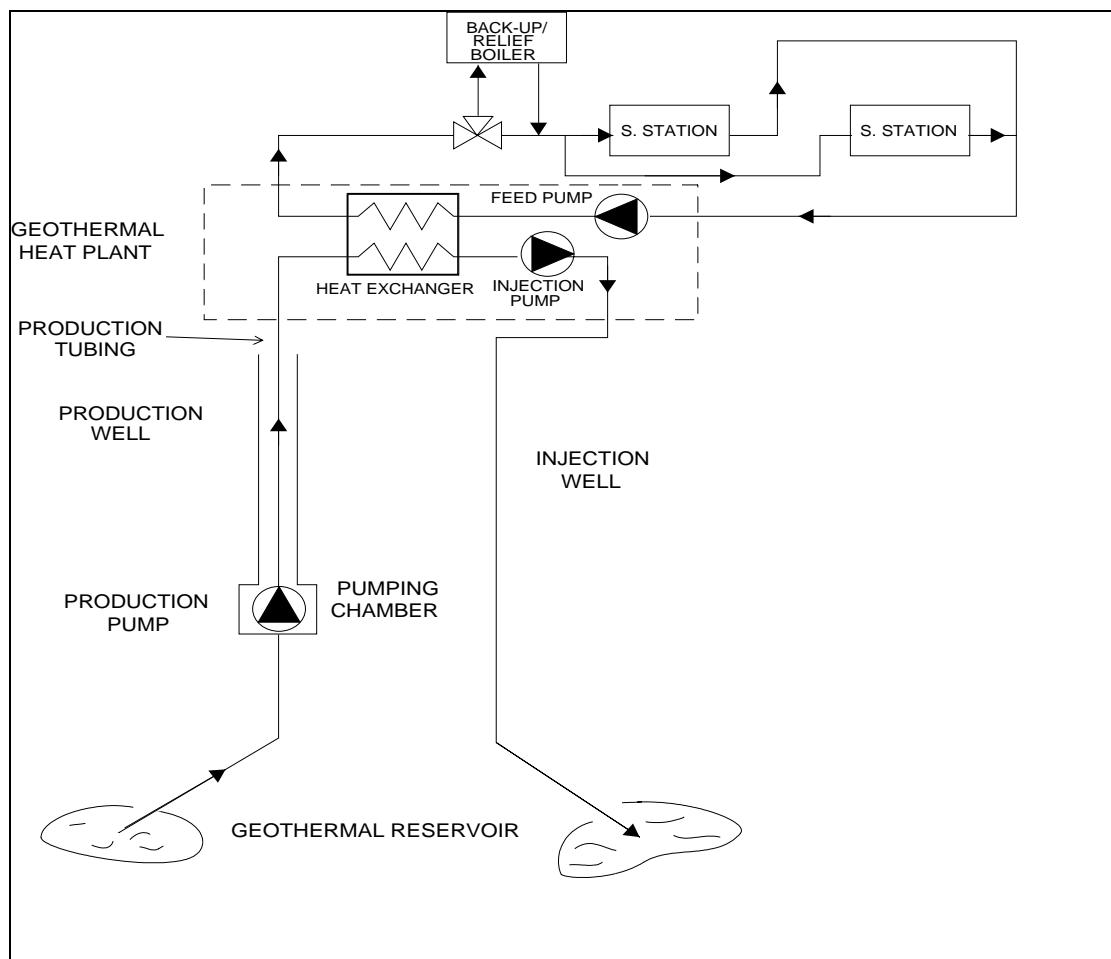


Figure 5: Schematics of a geothermal district heating system (Ungemach, 2001).

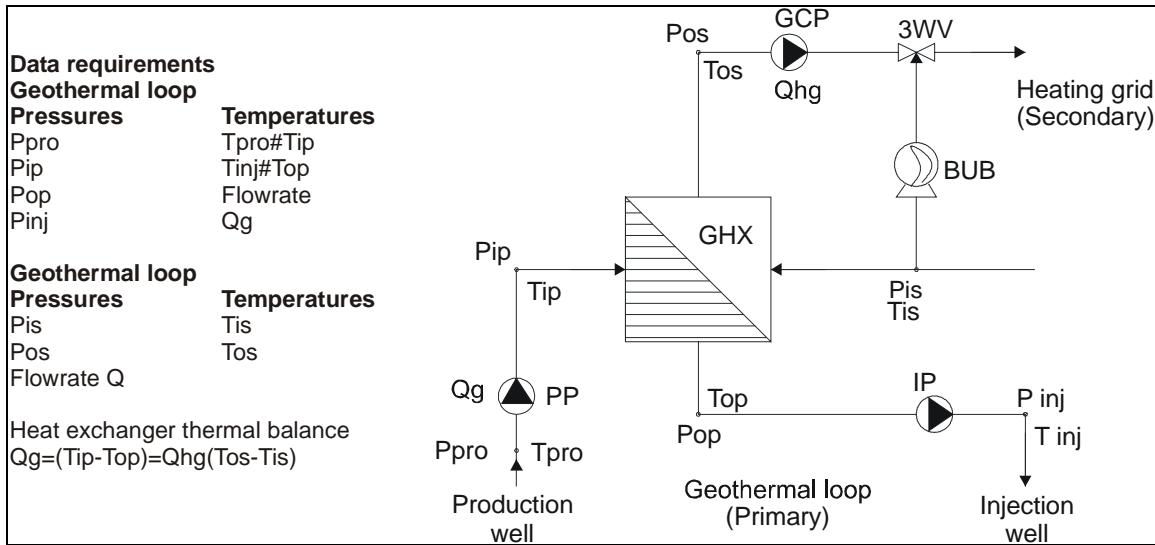


Figure 6: Geothermal district heating parameters (Ungemach, 2001)

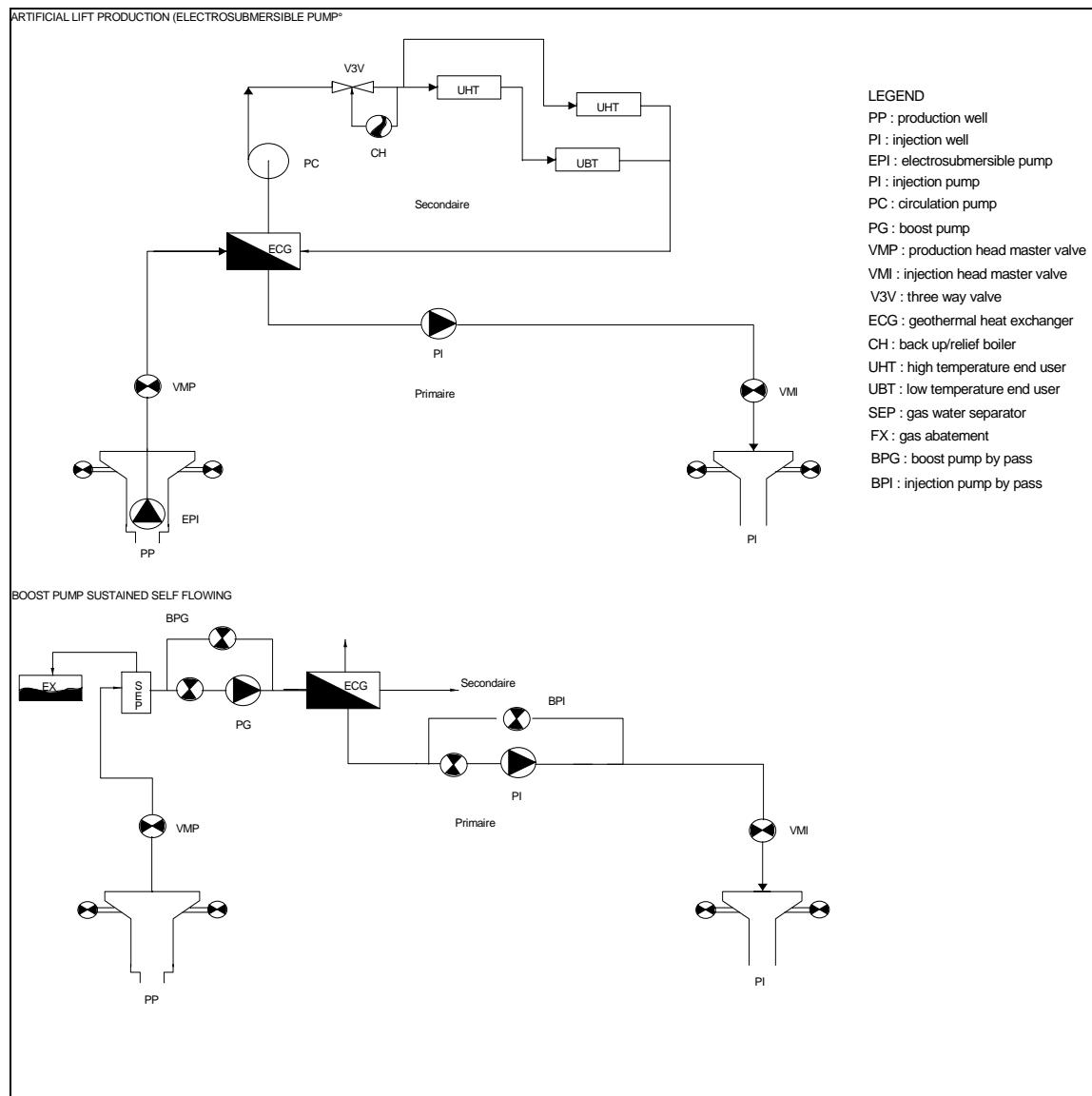


Figure 7: Geothermal well (sustained and self-flowing) production modes (Ungemach, 2001)

**Table 1: Geothermal district heating analysis.
System components and parameters (after Harrison et al)**

| GEOTHERMAL POWER | NETWORK/HEATERS | HEAT DEMAND |
|--|--|---|
| $P_g = M_g (\theta_g - \theta_r)$ $M_g = \rho_w \gamma_w q_g / 3.6$ | $P_n = M_n (\theta_a - \theta_{ref})$ $M_n = NED \times V \times G / (m_{hi} / m_{ho})$ $m_{hi} = (\theta_{hi} - \theta_{nh}) / (\theta_a - \theta_{ref})$ $m_{ho} = (\theta_{ho} - \theta_{nh}) / (\theta_a - \theta_{ref})$ | $P_d = M_d (\theta_a - \theta)$ $M_d = NED \times V \times G / 1,000$ $W_d = 24 \times NDD \times M_d / 1,000$ $NDD = \int_0^{NHD} (\theta_a - \theta) dt$ |

| HEAT EXCHANGE | GEOTHERMAL SUPPLY |
|--|---|
| $P_{hx} = \eta_{hx} P_g = \eta_{hx} M_g [(\theta_g - \theta_{nh}) - M_{ho} (\theta - \theta_{ref})]$ $\eta_{hx} = \{1 - \exp [-N(1 - R)]\} / \{1 - R \exp [-N(1 - R)]\}$ $N = UA / M_g$ $R = M_g / M_n$ | $W_{hx} = \eta_{hx} M_g \{(\theta_g - \theta_{nh}) - m_{ho} \times 24 \int_0^{NHD} [\theta(t) - \theta_{ref}] dt\}$ $GCR = W_{hx} / W_d$ |
| REGULATION CRITERIA | $\theta_{no} = \theta_{ref} + m_{no} (\theta_a - \theta)$ $\theta < \theta^* : \text{maximum geothermal flowrate, back up boilers}$ $\theta^* < \theta < \theta_{ref} : \text{total geothermal supply}$ |

| 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) | γ = specific heat (J/kg·°C) | |
| G = average dwelling heat loss (W/m ² ·°C) | ρ = volumetric mass (kg/m ³) | |
| N = number of heat transfer units | θ = 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 | $V = 185 \text{ m}^3$ | $\theta_{hi}/\theta_{ho} =$ |
| NDD = 2,500 | $\theta_{ref} = -7^\circ\text{C}$ | 90/70°C cast iron radiators |
| NHD = 240 | $\theta_r = 40/50^\circ\text{C}$ | 70/50°C convectors |
| $N = 5$ | $\theta_g = 55/75^\circ\text{C}$ | 50/40°C floor slabs |
| $q_g = 200/350 \text{ m}^3/\text{h}$ | $\theta_a = 17/18^\circ\text{C}$ | |
| $g = 1.05 \text{ W/m}^2\cdot^\circ\text{C}$ | $\theta_{nh} = 20^\circ\text{C}$ | |

ASSESSMENT OF ENVIRONMENTAL IMPACTS AND PREVENTING/REMEDIAL PROCEDURES

These need to be thoroughly investigated at design, implementation and operating stages, and mastered accordingly.

Not only does the process aims at complying with the environmental regulations in force, it contributes to building among the public the image of a mature technology and entrepreneurial management skills, thus securing the geothermal district heating route.

A geothermal heat mining project life addresses three phases, drilling/completion, operation/maintenance and abandonment respectively.

Drilling/completion

The environmental segment of the feasibility survey, submitted to the ad-hoc Mining Authority, will be later disseminated, in the framework of the Public Inquiry, to all concerned parties, and relevant answers given by the operator, within a six month delay, before project commissioning.

The environmental dossier deals with the following, deemed the most sensitive, items:

- **drilling proper**

It has to fit into the site specific constraints, which in the Paris Basin consists of densely urbanised districts, with large social dwelling buildings, city facilities and busy street/road traffic conditions.

In this respect, the areal view of a heavy duty rig force (250 t hook load), operated South of Paris, is displayed in fig. 8, speaks for itself.

Drilling/completion has to cope with stringent noise, safety, ground/underground integrity, waste disposal requirements and prerequisites.

- **noise**

It must not exceed the legal 50 dBA threshold, at a 50 m distance from the rig platform. Hence, sound proof, electrically driven, rigs are mandatory, bearing in mind that the rig operates continuously (three shifts) 24 hrs around the clock.

- **safety**

Qualifications and records of the rig personnel must be disclosed and up-to-date professional certificates (blow out control among others) of the drilling staff (tool pusher, driller and supervisor) and superintendent produced accordingly. Subcontractors and service companies are to be approved by the customer.

A nominated safety manager is to be provided by the drilling contractor.

Toxic gas (H₂S, CO₂) detectors, placed at strategic locations, connected to a central logging unit and to visual and acoustic alarms, are required, together with a set of oxygen masks and bottles for personal protection.

Two emergency exits are accommodated.

Names and phone numbers of contact persons and administrators (managers, hospital, police, fire brigade, Mining Authority, etc.) are displayed in the tool pusher/rig manager's portable cabin.

An emergency repetition exercise is performed, prior to drilling, in presence of a representative of the Mining Authority.

- **ground and underground integrities**

The drilling site is to be restored identical to its initial status, apart from the wellhead contractual designs. Access to well heads conforms to the safety standards practiced by the industry.



**Figure 8: Aerial view of a drilling site in the Paris urban area
(GPC and Sedco-Forex, 1995)**

Protection of the subsoil, in particular of the intermediate fresh water aquifers intersected by the drilling, are secured by (i) properly designed casing programmes, and (ii) utilisation of biodegradable, polymer based, drilling fluids.

Regarding well longevity and subsoil protection concerns, the combined steel propping casing/fibreglass lining well concept, depicted in fig. 9, is becoming a standard design in future Paris Basin undertakings (Ungemach, 1998).

- **waste disposal**

The cuttings and mud refuse pits must comply with the new environmental regulation, which will, sooner or later, restrict the refuse pit to the sole cutting recovery function. As a matter of fact, upgraded solid control should ultimately render the liquid waste pit obsolete, and a liquid/solid/gaseous waste processing line of the type, applied in workover operations, substituted instead (GPC, 1996).

Cuttings and waste cannot be any longer disposed in garbage localities, neither in settling ponds nor spreading fields, but processed and eliminated in abatement/incineration facilities instead.

In order to limit the impact of this cost intensive segment, emphasis is to be placed on “in house” improved mud/drilling fluid formulations and “on the spot” waste processing facilities.

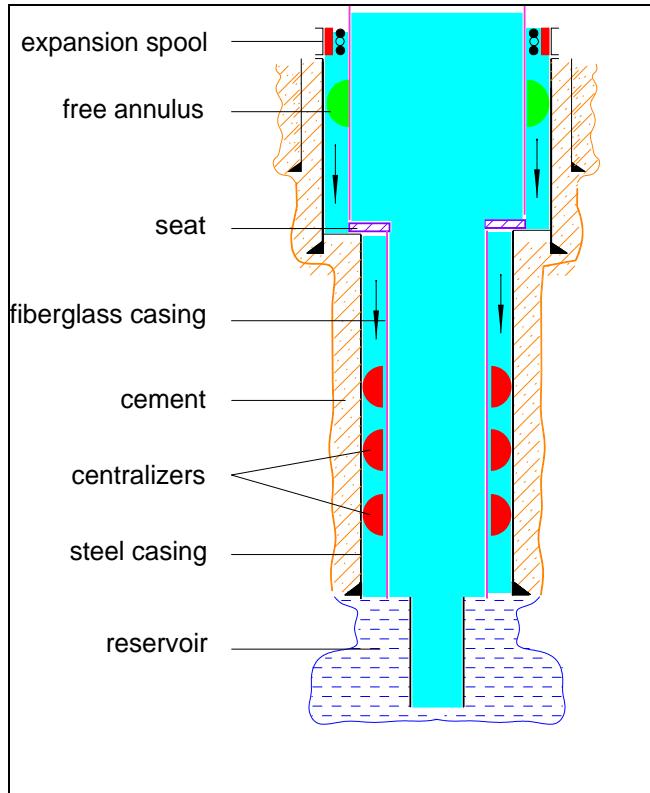


Figure 9: Combined steel casing/fibreglass lining well (WELCOM; Ungemach, 1998)

Operation and maintenance

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 bar 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 leaks 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 (Ungemach, 2001).

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.

- **monitoring and surveillance**

According to the mining and environmental regulation in force and to site specific agreements, geothermal loop monitoring and surveillance comply to the following protocol (Ungemach, 1997 and 2001; GPC, 1998):

- 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,
- 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,
- well deliverabilities :
 - well head pressure/discharge (recharge) curves (step drawdown/rise tests),
- pump and frequency converter characteristics
 - voltage, amperage, frequencies,
 - powers,
 - efficiencies,
 - ESP insulation,
- inhibitor efficiencies :
 - corrosion/scaling indicators control,
 - inhibitor concentrations,
 - filming (sorption/desorption) tests,
- inhibition equipment integrity :
 - metering pump,
 - regulation,
 - downhole chemical injection line,
- well head, valves, spool, filter integrities,
- surface piping (ultrasonic) control,
- 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 inhibitor injection/regulation and corrosion control (coupons, corrosion probes) equipment.

- well heavy duty works and maintenance

During a Paris Basin geothermal well life (20 to 25 years), a number of heavy duty workovers are likely 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 likelihood level of such events is assessed from a risk analysis, based on available well records, makes 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.

The operators are requested, prior to workover, to submit an environmental impact report, whose format is similar to the one required for drilling/completion operations.

A typical field layout of a doublet workover is displayed in fig. 10.

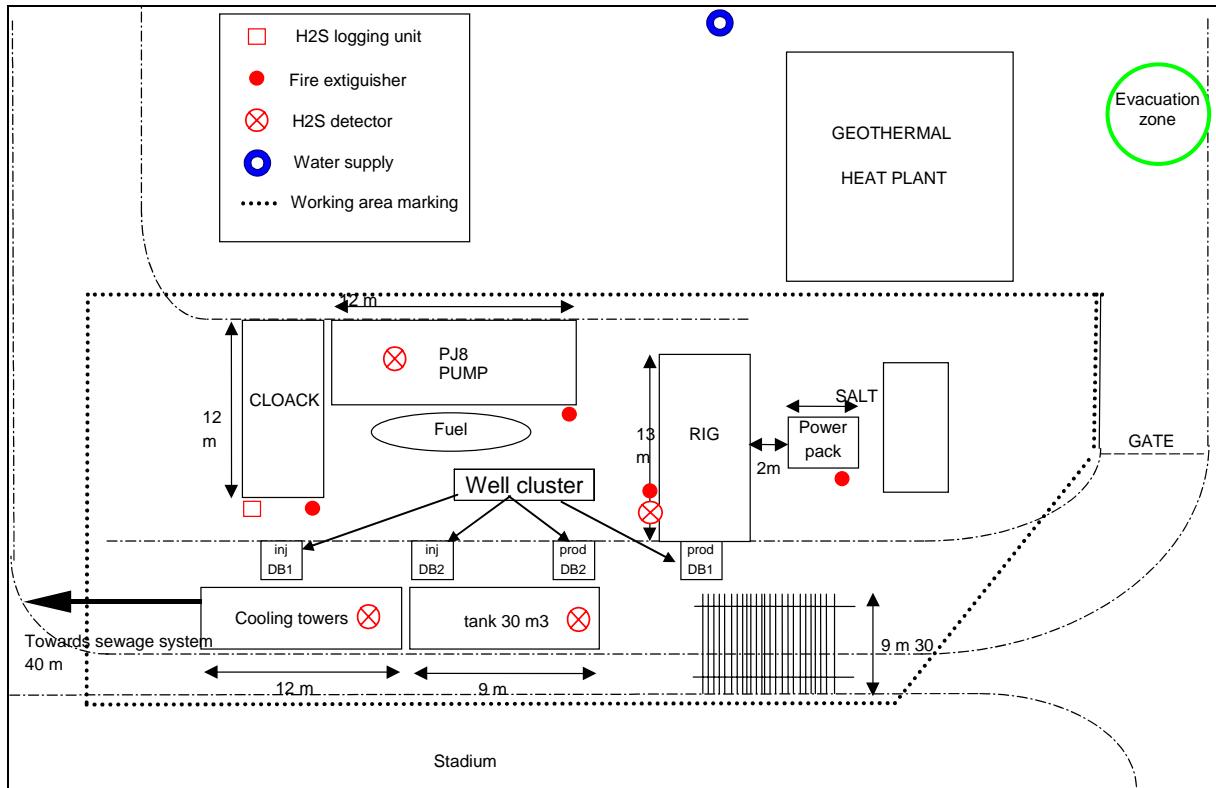


Figure 10: Geothermal workover area (GPC, 2003)

Possibly is the waste processing line depicted in fig. 11 the most valuable achievement noticed in geothermal workover services thus far. The unit, 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 (GPC, 1996):

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

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

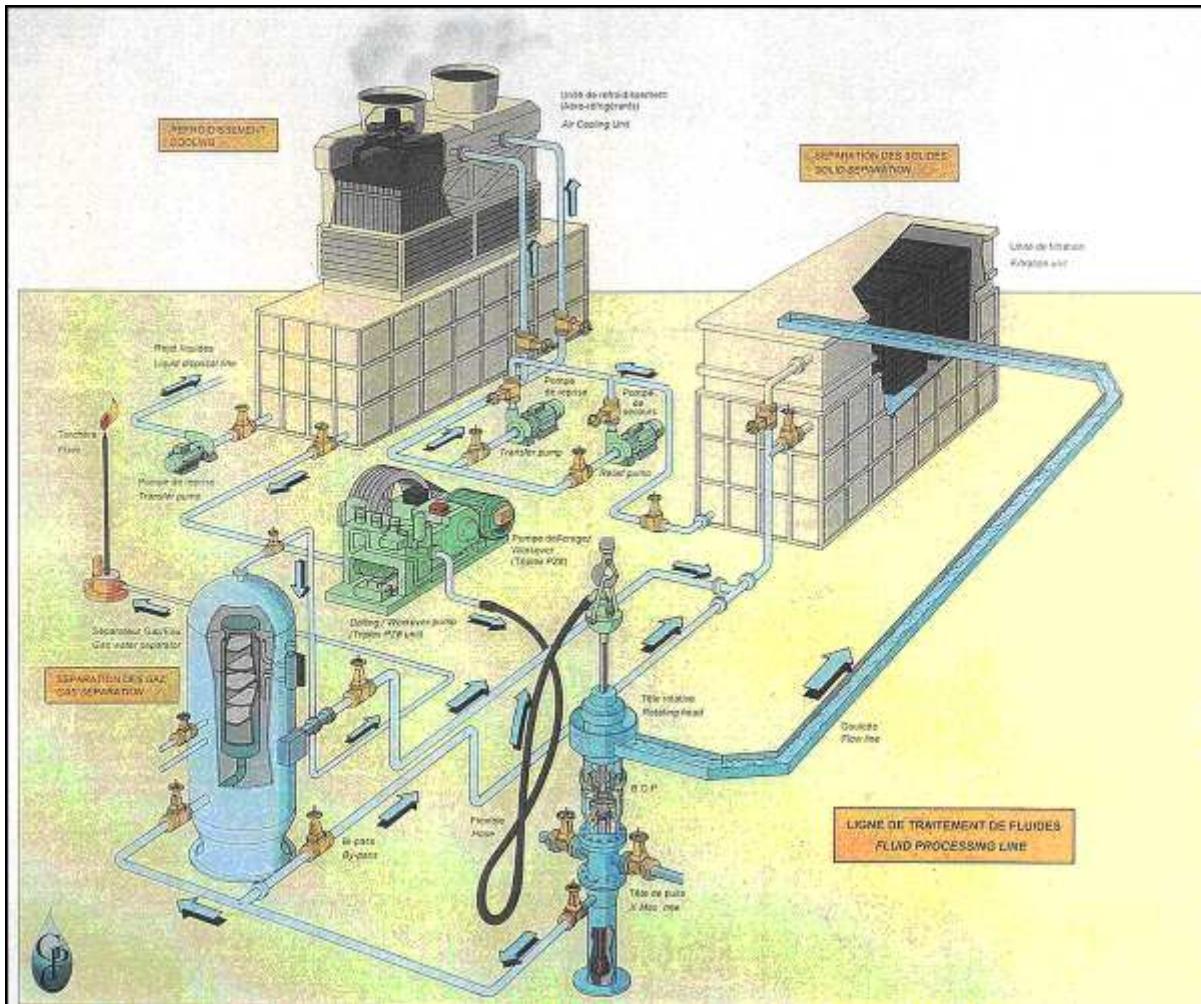


Figure 11: Waste processing line (GPC, 1996)

Since blowouts are unpredictable, geothermal operators initiated an emergency service in order to limit their magnitude. The contract was awarded to a service company, required to design, acquire, maintain and operate a wild well control facility, which should be mobilized in less than six hours. Geothermal operators subscribe to a five year (renewable) contract.

Abandonment

It follows the procedure, summarised hereunder, set by the Mining Authority for both exploration and exploitation, hydrocarbon and geothermal wells (MIR, 2000).

- **exploitation wells**
 - (i) casing clean-up, either by mechanical (rock bits, scrappers) or hydraulic (jetting) means;
 - (ii) assessment of casing status, by log inspection via multifinger calliper, ultrasonic and, whenever required, cement control (CBL-VDL) logging tools;
 - (iii) setting a viscous gel plug at top reservoir and cementing of sensitive casing and annulus intervals, allowing for sufficient overlapping, according to the designs sketched in fig. 12 (plugging principle) and 13 (productive layers isolation). Cementing is performed by conventional inner-string equipment or, better, by a coiled tubing unit, the latter favouring a continuous cement fill up, deemed a more secure abandonment alternative;
 - (iv) erasing of the well head (Xtree) and cave fill-up.

- **exploration wells**

- cementing of the well and annulus in compliance with fig. 12 and 13 designs;
- erasing of the casing head and fill-up the cave.

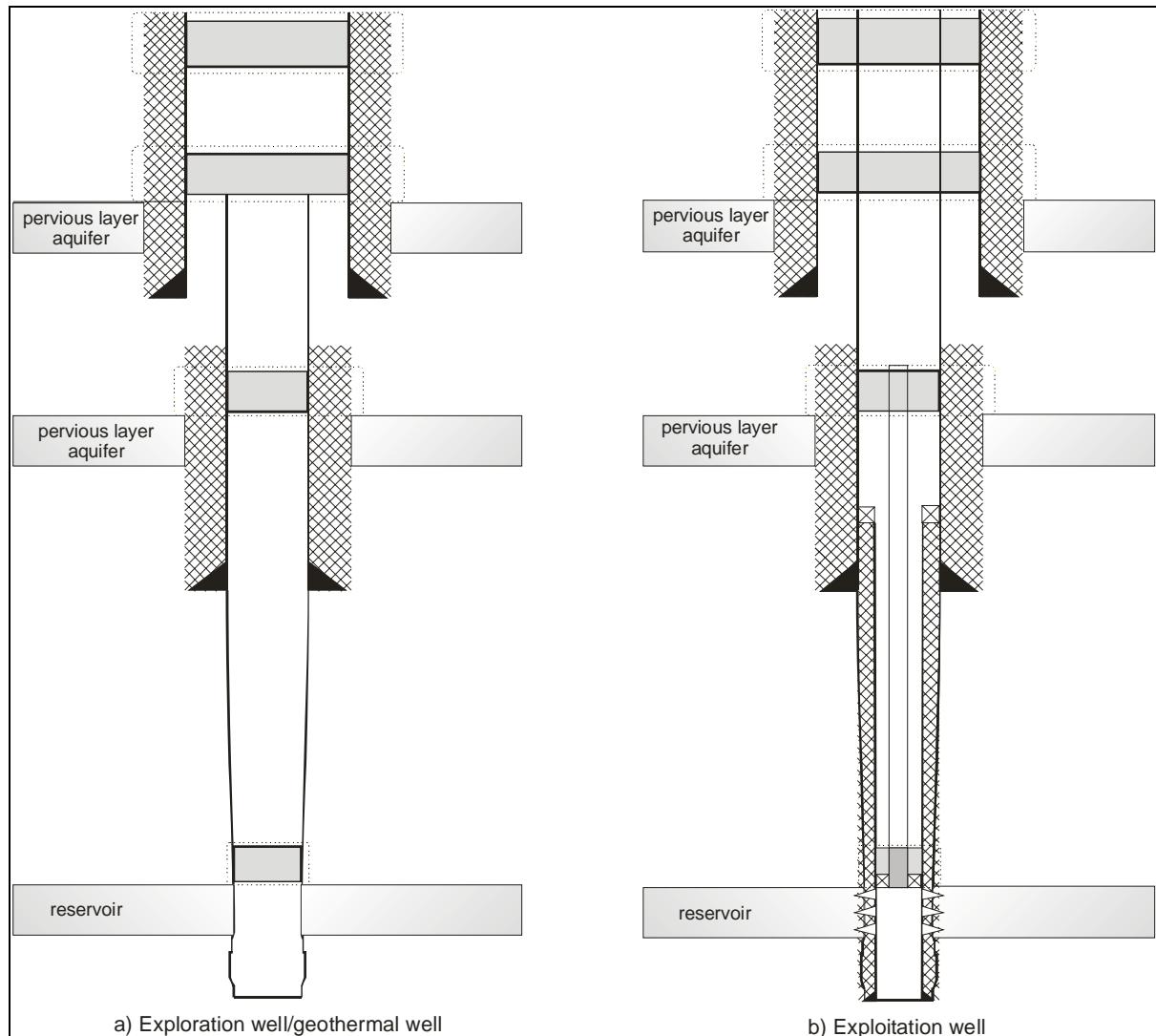
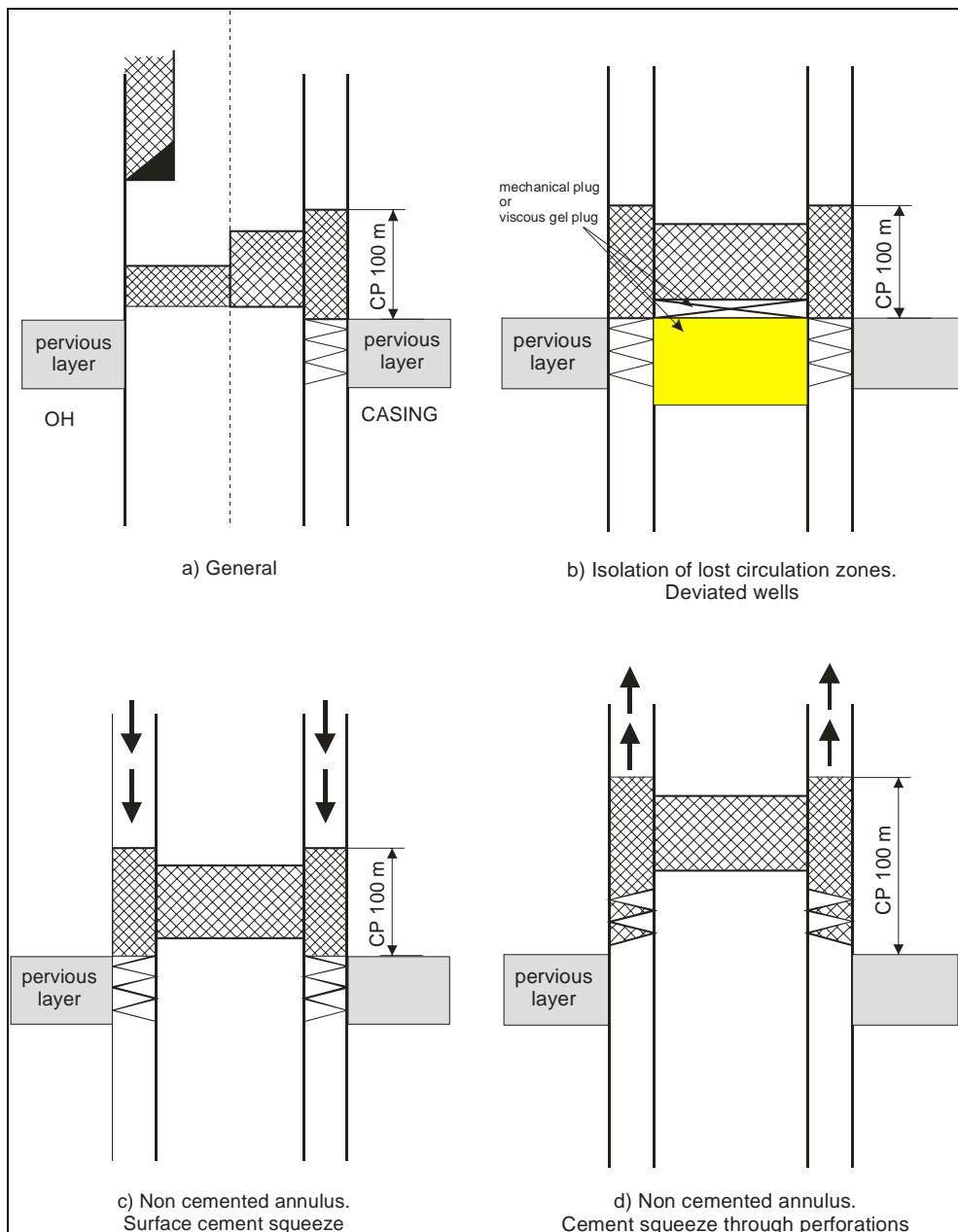


Figure 12: Well abandonment cementing designs (MIR, 2000)



**Figure 13: Well abandonment cementing.
Examples of pervious layer isolation (MIR, 2000)**

CONCLUSION

Geothermal district heating represents, in many respects, the most environmentally constraining segment of the direct use spectrum as it addresses the drilling, (re)completion, operation and maintenance of production/injection wells located in sensitive, densely populated, urban and suburban environments.

As a result, it requires the enforcement of a relevant legal and institutional background i.e. (i) a Mining Law categorising geothermal heat as a mineral, exhaustible, resource, and (ii) a thorough environmental regulatory framework (Rybäck, 2003), encompassing all aspects pertinent to safe and friendly operation of geothermal district heating undertakings, in compliance with clean air, water quality, noise and, last but not least, sustainable reservoir management concerns.

Given these prerequisites, and based on a twenty five year experience gained on the thirty four geothermal district heating doublets operating to date in the Paris Basin, this paper focused on the segments, deemed critical as regards environmental protection and awareness, itemised below:

- well drilling/(re)completion
- well casing integrity and corrosion inhibition
- blowout preventing and control measures
- workover operations
- waste processing and disposal
- monitoring protocols
- well abandonment procedures

Successful achievement of the foregoing contributed to improving the credibility and the image of the geothermal district heating route and to securing future sustainable reservoir development and management issues.

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