Good practice guidelines on deep geothermal drilling and exploitation from experience in the Paris Basin (Dogger and Albian aquifers)

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ABSTRACT

This paper presents the development of a good practices guide and recommendations regarding deep geothermal projects in the Paris Basin from the experience gained from the drilling and operation in the Dogger limestone and the Albian-Neocomian sands aquifers.

1. INTRODUCTION

With the relaunch of deep geothermal projects in the Paris Basin since 2007, new techniques in drilling, well architectures, materials and reservoir development have been performed compared to the first wells drilled between the 70's and the 80's. In this context, it is important to gather the lessons learned in order to secure the upcoming drilling operations. Since 2014, BRGM has produced a good practice guide on behalf of the French Technical Committee on Deep Geothermal Energy (which brings together French public and private organisations involved in the development of deep geothermal energy). This research work has consisted in detailed technical analysis of drilling reports, which resulted in the production of synthetic documents or "fact sheets" summarising the main best practices related to the construction of geothermal wells targeting mainly three deep aquifers in the Paris sedimentary Basin. The aquifers are the Albian and Neocomian sands (around 700-850 m bsl, with five doublets and one single well drilled since 2012 and one doublet in 1989), and the Dogger limestone reservoir (around 1700 m bsl, which was targeted by 180 wells since the 1970s - 67 wells since 2007 - and has, in 2021, 46 doublets or triplets operating).

In addition, BRGM with the support of ADEME and geothermal operators, has produced in 2020 a thorough feedback specific of geothermal operations in the Albian and Neocomian silico-clastic reservoirs in the Paris Basin and in other comparable formations in Europe. The French operations are indeed currently facing injectivity deteriorations, which compromises future geothermal development in those type of aquifers. Following the analysis of information collected for the concerned operations (i.e. well completion data, production and injection tests, flow rate logging and exploitation chronicles), recommendations regarding the different phases of the project were formulated. They concern the well design, testing and development, operations, monitoring and propose remediation solutions.

2. LESSONS LEARNED FROM DEEP GEOTHERMAL DRILLING IN THE PARIS BASIN

Over the last 15 years, the number of geothermal operations has gradually increased in the Ile-de-France region, allowing the accumulation of a significant amount of information and experience, sometimes positive and worthy of being leveraged as best practices and sometimes negative, either immediately or in the medium term, and for which fact sheets were elaborated and propose possibilities for correction or improvement as well as recommendations. The idea is not to make deep geothermal well construction principles mandatory or normative but rather to provide a reminder of the main best practices to be applied. Finally, the aim is to provide, wherever possible, indicators to appraise or assess the quality of the work carried out.

Table 2 lists all the new operations carried out between 2007 and 2020, which, whenever possible, have given rise to lessons learned as presented in the guide. Those operations represent 73 boreholes, including 61 targeting the Dogger aquifer, 8 in the Albian aquifer, 2 in the Neocomian aquifer of the Paris Basin and 2 targeting the Cretaceous of the Aquitaine Basin (see Figure 1).

The guide (Hamm et al, 2019, updated on 2021) includes 22 fact sheets divided into 9 categories: Reminders of best practices and surface area, Drilling, Casings, Cementing, Deviation, Completion, Logs, Development and testing, Operation (see Table 1). The complete version of the guide and each individual fact sheet can be consulted and downloaded from the geothermal energy prospects website https://www.geothermies.fr/english-content#documents.

Table 1: Fact sheets including lessons learned from 2015 to 2020

Theme	Fact sheet n°	Specification sheet topic
Best practices and surface area	10	Reminder of main procedures and best practices
Drilling	21	Well architecture
	22	Restricted annular spaces
	23	Drilling and completion fluids
	24	New well architectures
Casings	33	Use of composite material casings
	34	Casing centering
Cementing	41	Possible cementing methods in cases of fracturing risk
	42	Assessment of the wait on cement to dry (WOC)
	43	Abandonment of drilling
	44	Qualitative criteria for analysis of cementing inspection logs (sonic and ultrasonic methods)
Deviations	51	Parameters of the deviations and description of the means used to achieve them
	52	Quality of deviations
Completion	61	Completion of sandy aquifers
Loggings	72	Sonic and ultrasonic cementing inspection tools
	73	Inspection of casings by diameter tools
	74	Logs applicable to the characterization of deep geothermal reservoirs
Development and testing	81	Determining the quality of development operations at the end of drilling
	82	Low-enthalpy geothermal energy formation testing
Operation	90	Operating conditions of the Dogger geothermal facilities
	91	Corrosion-deposit inhibiting treatments of steels
	92	Filtering of geothermal surface water

2.1 Reminder of best practices and surface constraint

Sheet n°10 provides a reminder of the main procedures and best practices applicable to deep geothermal work. It is supplemented by detailed technical memos when required by specific topics and to which reference is made whenever necessary.

The reminders of the main procedures relate to:

- surface constraints (drilling platform and wellhead access);
- drilling tools (diameter, type, IADC code);
- casings (characteristics of casings and threads, storage, handling, inspection and screwing);
- drilling fluids (manufacturing, parameter checks and fluid treatment);
- loggings (delayed, instantaneous, mud-logging, production);
- wellheads;
- completion schedule;
- checking of work (completion method, technical checks, IADC daily reports).

2.2 Geothermal drilling

The geometry and structure of deep geothermal drilling differ significantly from the ones most commonly found in the oil industry. Sheet n°21 defines the specific constraints determining the structure of geothermal boreholes and provides recommendations to improve the final quality of the wells: well architecture, overlap between casings, positioning of diverting valves (DV), maximum allowable flow rate during operation.

Sheet n°22 summarises the specificities caused by the restricted annular spaces in the architecture of new or rehabilitated geothermal boreholes. It mainly provides a reminder of the importance of the sealing integrity (vertical and horizontal) of these annular spaces, regarding cementing quality and protection of casings. In this context, recommendations are given regarding the minimum permissible annular space and standoff. The sheet also provides the precautions to be taken to ensure proper quality cementing in a restricted annular space and which relate to the geometry of the drilled hole, the efficiency of the centering and the quality of the slurry placed in the annular space (filling and bonding).

Sheet n°23 on “Drilling and completion fluids” provides lessons learned on the use of drilling and completion fluids in deep geothermal drilling in the Paris Basin. Its primary purpose is to provide an understanding of the fundamental role played by mud in drilling operations. The types of mud used in each drilling phase are described together with the main difficulties that may be encountered (drilled hole geometry, partial or total fluid losses, jamming of the drill string due to differential pressure, bacterial proliferation, bubbling and destabilisation of clays). A few qualitative recommendations are made, with particular emphasis on the precautions to be taken in the specific circumstances related to cementing operations, logging phase and reservoir drilling.

Finally, sheet n°24 on “New well architectures” presents and discuss some new or innovative architectures that have been proposed for tapping geothermal resources in the Paris Basin. The architectures discussed are:

- the sub-horizontal drain (example of the Cachan works in the Dogger aquifer);
- the concept of anti-corrosion wells (example of the works at Melun l'Almont and Bonneuil-sur-Marne);
- the oversizing of production liners (case of Bobigny-Drancy doublets).

In each case, the specificities, advantages and disadvantages of these unusual architectures are analysed and discussed.

2.3 Geothermal casings

Sheet n°33 on “Composite material” describes the rare lessons learned from operations using glass fiber casings (Villeneuve-La-Garenne, Courneuve-Sud, Melun l'Almont) and more recently, in 2015, Chevilly-Larue and L'Hay-les-Roses where glass fibre re-lined liners were installed. Similar operations or projects for new wells made of composite materials are also being considered. The purpose of this memo is to give an overview of the advantages, disadvantages and constraints involved in the use of this type of material (corrosion resistance, mechanical aspects, ageing of composite casings, constraints regarding use and work, cementing, removable casings).

The efficient centering of casings is one of the aspects that determine the cementing quality of the casings concerned. The general quality and durability of wells is directly related to proper cementing. Unlike oil drilling, geothermal wells use technical casings as production liners in which corrosive fluids flow at high flow rates. The quality of the cement lining protecting the outer surface of these casings is therefore particularly crucial. The fact sheet 24 on “casing centering” provides a reminder of the rules proposed by the oil industry regarding the centering of liners and determines the recommendations best suited to the specific conditions of geothermal energy.

2.4 Geothermal cementing

Sheet n°41 describes the two main cementing methods that can be used to avoid the risk of hydraulic fracturing (multi-stage cementing or cementing with light slurry or mixed cementing of light and heavy slurry in a single stage), with their reciprocal advantages and disadvantages.

One of the most important qualitative factors for casing cementing is the wait on cement to dry (WOC). This is particularly true in deep geothermal energy field where the casings are used both to maintain the well and to extract the fluid. Sheet n°42 provides a reminder of the rules most generally applied in the oil industry and ways to adjust these rules to the specific conditions of geothermal energy. The importance of allowing a drying waiting time appropriate to the slurry used is pointed out. The rules defining the "effective" waiting time are defined. A calculation of the minimum or global times (conservative values) to be observed is provided on the basis of the available data on the mechanical strength of the slurry used.

Sheet n°44 determines qualitative criteria for analysing sonic logs (CBL-VDL) and ultrasonic logs (USIT, URS, CAST, IBC, etc.) used for the inspection of casing cements. These criteria are based on the analysis of the transit time of the CBL log which determines the logs quality, the analysis of the quality of the cement bonding, based on the CBL log, using the so-called Bond Index (BI) method proposed by Schlumberger, the quality of the cement placed in the annular space using the impedance values when the corresponding ultrasonic logs (USIT, URS, CAST, etc.) are available. The vertical isolation integrity of the annular space will depend on the filling and channelling levels. The sheet provides a ranking (CBL and USIT indices) in order to obtain quantified, less suggestive and more homogeneous interpretations of cementing quality, and to allow comparative analysis between wells.

Sheet n°43 summarises the procedures and rules for abandonment of geothermal wells and provides recommendations for some specific cases. It also describes the role of cement plugs and the ageing processes of casings and cements.

2.4 Geothermal deviation

Sheet n°51 summarises the information that must appear in deviation programmes together with the different possible formats for such provision (geographical coordinates, definition of targets, deviation calculation parameter, means used, and inclination measurements in the reservoir).

As a supplement, sheet n°52 provides a reminder of the factors governing the quality of deviation operations and the inspections methods that can be used to assess them. Criteria for the deviation qualitative analysis are provided (Dog-Leg Severity value or DLS value and Tortuosity Index or TI). Quantitative indicators are provided, along with recommendations for defining the geometry of targets under the specific conditions of deep geothermal wells.

2.5 Geothermal completion

Sandy and sandstone aquifers (Albian, Neocomian and Triassic) require specific completion. The equipment used should be adjusted to the reservoir's operating conditions in order to achieve the required pumping rate while maintaining effective filtering and a minimum pressure drop level. In addition to proper follow-up of procedures, a qualitative and suitable choice of the completion material, strainer slot and granulometry of the gravel pack is essential. Sheet n°51 provides a reminder of the basic principles to be applied in this regard (completion structure, anchor positioning, dielectric connection, filtering characteristics, entering velocity in the screen).

2.6 Geothermal logging

Sonic measurements are used to assess the quality of the cement bonding to the borehole casing walls. While the CBL-VDL (Cement Bond Log - Variable Density Log) is a simple and efficient tool, it is important to be aware of its limitations. It may prove to be inaccurate or unsuitable for use in highly deviated wells, on large diameter casings or with low density cements. Ultrasonic measurements have been developed and finalised in an attempt to compensate for the inherent limitations of sonic measurements and to improve, supplement and facilitate their interpretation. The data collected with ultrasonic tools allow better discrimination and interpretation of the discontinuities that may appear in a cemented annular space, with a resolution much higher than the sole axial measurement provided by a CBL log. In some cases, including the analysis of light slurry, they are even the only means available to try to identify and understand the quality of cements. Sheet n°72 provides a reminder of the way these tools work, their limits and the conditions allowing correct interpretation of cementing quality.

As a supplement, sheet n°73 describes the various logging tools available in geothermal industry to monitor the production and injection borehole casings, and thus enable monitoring of their changes during operation (mechanical tools, ultrasonic tools and electromagnetic tools). As the vast majority of deep geothermal boreholes are build using steel casings, the tools developed for the needs of the oil industry are adjusted to the geothermal domain. Recent developments also make it possible to troubleshoot specific well architectures, in particular those made of composite material casings (like ultrasonic tools). In addition, an analysis method is provided to quantify the damage of a steel casing, based on data from inspection logs.

Sheet n°74 describes the measures applicable to the characterisation of deep geothermal reservoirs. This reservoir characterisation phase, carried out after drilling, is crucial for exploration, knowledge and optimal operation of the reservoir. The memo first discusses the logs used for the geological characterisation of reservoirs and then the logs used for the hydrogeological characterisation. A summary table of the available logs is provided at the end of the sheet, with the measurement principle associated, the type of information obtained, and the disadvantages and advantages of each method.

2.6 Geothermal development and testing

The proper performance of development operations is one of the fundamental factors that determine the quality and success of the implementation of geothermal installations. This is particularly true in the case of clastic (sandy) aquifers where the filtering quality directly affects production capacity and costs. Sheet n°81 provides the development procedures and the means that can be used to assess the results and quality of development operations. The term "development" used covers operations ranging from the supplying of water to the well but also the start-up of production and hydraulic or chemical stimulation.

Formation testing, or "long term testing", are implemented after development operations characterised by "step testing". They are a final step to drilling operation in order to determine the local characteristics of the geothermal reservoir. The conditions under which this testing is carried out, the acquisition of data and the final interpretation of the tests are essential assessment factors, which should be remembered in order to understand the operation of the reservoir and its changes. Sheet n°82 determines a common framework for carrying out tests in order to harmonise practices in the field of low-enthalpy geothermal operations and enrich the databases shared by the industry in a relevant way.

2.8. Geothermal operation

In addition to the standards and applicable regulations in the operating permits, compliance with the operating conditions of wells and the nominal characteristics of the associated equipment should ensure the longevity of geothermal facilities. The physical and chemical restrictions related to the use of the geothermal fluid mainly apply to wells, pumping equipment, pipes and valves and heat exchangers. Sheet n° 91 only deals with the operating conditions of the producer and injector wells and is based primarily on the lessons learned from the Dogger operations in the Paris Basin. It provides information and recommendations regarding the operating constraints related to the operating flow rate, the temperature of the reinjected fluid, the bubble point pressure , the risks of corrosion-deposits and the pumping equipment's. It also provides recommendations for triplet-related operations.

Corrosion-deposit phenomena represent a major risk (technical, environmental and financial) for geothermal operations against which it is essential to take precautions. The materials used for the design of wells and surface facilities are mostly steels (API K55 unalloyed carbon steel for well casings, 316 L stainless steel or duplex steel for equipment). The use of noble metals (titanium, nickel-based alloys) is reserved for sensitive equipment (heat exchangers, pumps, instrumentation, process tubes, etc.). Corrosion can generate holes in well casings that can cause interconnection between aquifers, especially between high salinity aquifers such as the Dogger and shallower aquifers used for drinking water (e.g. Albian). Hole repairs involve costly well rehabilitation operations (relining of casings) and increased electrical pumping costs due to pressure drops caused by the reduction in the diameter of new casings. In addition, deposits accumulate on casing walls, thereby narrowing the fluid passage and increasing pressure losses in casings, which can decrease the flow rate, increase pumping and/or injection energy, or increase the drawdown and/or injection pressure. Particles from corrosion-deposition processes can clog filters and/or heat exchangers on the surface, requiring costly dismantling and cleaning operations. These deposits can also accumulate in the open end of the reinjection well, but can also cause clogging of the nearby injector well. Well and/or open-end cleaning operations with a drilling rig can have a significant financial impact on operations and are always associated with technical risks, as is any work in a well. Sheet n°91 addresses the type of corrosion phenomena and the main influencing parameters, the types of deposits, the treatment system, the types of corrosion inhibitors used in geothermal energy in the Dogger, the lessons learned from new operations carried out since 2007 and the resulting recommendations.

The choice of an optimal filtering solution contributes decisively to limiting disturbances and improving the availability of surface geothermal facilities, thereby significantly increasing productivity. In some hydrogeological contexts (e.g. sandy and/or unconsolidated aquifers such as the Albian, Neocomian, Triassic), geothermal water filtering is required to reduce the risk of physical clogging of the reinjection borehole and the aquifer near the injection works. The choice of filter technology will affect operator cleaning frequency and duration and the pumping power consumption caused by hydraulic pressure drops. Malfunctions generally occur when particles and debris are as large as the operating clearances of moving parts (in the case of dewatering pumps, re-injection pumps and valves) or when their size causes clogging (in the case of plate heat exchangers and small diameter tappings in surface pipes). Sheet n°92 provides a reminder of filter selection and performance indicator definition criteria, the type and origins of solid particles and debris found in the geothermal fluid, existing filtering devices and the development of new generations of filters. It also describes the advantages and disadvantages of devices.

Table 2: Deep geothermal drilling carried out between 2007 and 2020

Geothermal operations	**Aquifer targeted**	**Year of comple-tion**	**Number of wells**	**Underground project manager**	**Boreholes**
Orly 2 Le Nouvelet	Dogger	2007	2	ANTEA Group	GORY-5/GORY-6a
Sucy-en-Brie	Dogger	2008	1	CFG Services	GSUC-3
Paris Nord-Est	Dogger	2009	2	CFG Services	GPNE-1/GPNE-2
Orly ADP	Dogger	2010	2	CFG Services	GADP-1/GADP-2
La Courneuve-Nord	Dogger	2011	1	GPC I&P	GLCN-3
Val-Maubuée	Dogger	2011	2	CFG Services	GVM-1/GVM-2
Coulommiers	Dogger	2011	2	CFG Services	GCO-3/GCO-4
Le Plessis-Robinson	Neocomian	2011	2	G2H Conseil	GLPR-1/GLPR-2
Bonneuil-sur-Marne	Dogger	2012	1	CFG Services	GBL-3
Champigny-sur-Marne	Dogger	2012	1	CFG Services	GCHM-3
Le Mée-sur-Seine	Dogger	2013	2	ANTEA Group	GLMS-3/GLMS-4
Chelles	Dogger	2013	2	CFG Services	GCHE-3/GCHE-4
Meaux Meauval 1	Dogger	2013	1	CFG Services	GMX-10
Meaux Meauval 2	Dogger	2013	1	CFG Services	GMX-11
Neuilly-sur-Marne	Dogger	2013	2	GPC I&P	GNSM-1/GNSM-2
Issy-les-Moulineaux	Albian	2013	2	G2H Conseil	GILM-1/GILM-1
Meaux Hôpital	Dogger	2014	1	CFG Services	GMX-9
Arcueil-Gentilly	Dogger	2014	2	GPC I&P	GAG-1/GAG-2
Fresnes	Dogger	2014	1	CFG Services	GFR-3
Villejuif	Dogger	2014	2	CFG Services	GVIL-1/GVIL-2
Clichy-Batignolles	Albian	2014	2	TERRE	GZCB-1/GZCB-2
Bagneux	Dogger	2014-15	2	CFG Services	GBA-1/GBA-2
Rosny-sous-Bois	Dogger	2015	2	CFG Services	GRNY-1/GRNY-2
Villepinte	Dogger	2015	2	ANTEA Group	GVLP-1/GVLP-2
Bailly-Romainvilliers	Dogger	2015	2	CFG Services	GBR-1/GBR-2

Tremblay-en-France	Dogger	2015	2	CFG Services	GTRE-3/GTRE-4
Ivry-sur-Seine	Dogger	2015	2	CFG Services	GIV-3/GIV-4
Ris-Orangis	Dogger	2015	1	CFG Services	GRO-3
Le Blanc-Mesnil	Dogger	2016	2	CFG Services	GBMN-3/GBMN-4
Grigny II	Dogger	2016-17	3	GPC I&P	GGR1/GGR2/GGR3
Dammarie-Les-Lys	Dogger	2017	2	ANTEA Group	GDAM1/GDAM2
Saclay Moulon	Albian	2017	2	GPC I&P	GMOU1/GMOU2
Saclay Polytechnique	Albian	2017	2	GPC I&P	GEP1/GEP2
Villiers Le-Bel-Gonesse	Dogger	2017	1	GPC I&P	GVLB3
La Courneuve-Nord	Dogger	2017	1	CFG Services	GLCN-4
Cachan 3	Dogger	2017-18	2	GPC I&P	GCAH1/GCAH2
Vigneux-sur-Seine	Dogger	2018	2	ANTEA Group	GVS3/GVS4
Bonneuil-sur-Marne	Dogger	2018	1	GPC I&P	GBL-4
Bordeaux PGE	Cretaceous	2019	2	STORENGY	PGE-1/PGE-2
Bobigny-Drancy	Dogger	2019-20	4	GPC I&P	GBD-1/GBD-2/GBD-3/GBD-4
Champs-sur-Marne	Dogger	2020	2	ANTEA Group	GCSM-1/GCSM-2

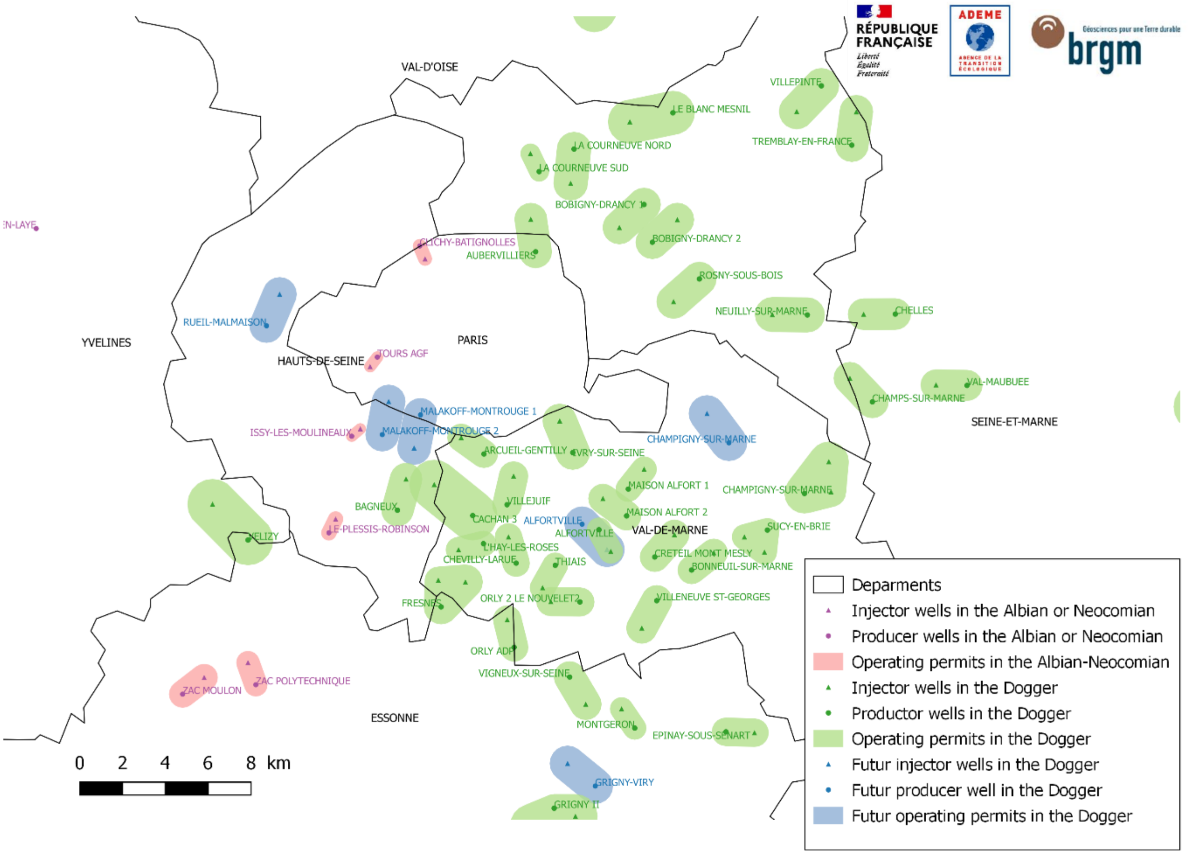

Figure 1: Localisation of the geothermal doublets taping the Albian or Neocomian sands (pink) or the Dogger Limestones (green and blue) in Paris area

3. LESSONS LEARNED FOR THE EXPLOITATION OF UNCONSOLIDATED SANDY FORMATIONS IN PARIS BASIN

The analysis of geothermal operations exploiting the sandy aquifers of the Albian and Neocomian of the Paris Basin confirms that the main cause of the loss of performance of the doublets is linked to the degradation of the injectivity of the injector wells. The more or less rapid clogging of these wells is mostly due to the transfer of fine particles from the producing wells. For all the operations carried out in Ile-de-France (5 in the Albian, 1 in the Neocomian, see Figure 1), injection difficulties were encountered during the initial development and pumping test phases of the works, and continue, or even deteriorate, during the operation of the doublets. Damage to the reservoir, within a radius of the injector well (internal filter cake), can be more significant in some cases where remediation operations (backwashing in particular) seem to have a limited effect.

The recommendations formulated are intended to propose preventive solutions (in particular for new projects) and curative solutions (for existing operations). They aim in particular to:

- limit the entry of fine particles into the production well and their transfer to the reinjection works;
- avoid clogging of the injector structures;
- restore the performance of the doublets.

The recommendations (Maurel et al., 2020) include a reminder of the good practices to be implemented for the realisation of geothermal projects targeting sandy aquifers (clastic formations), from the design phase of the doublets and the realisation of the drilling works (in particular concerning completions), the characterisation of the reservoir, the development of the wells and the pumping tests, up to the operation phase (see Table 3).

For geothermal installations already in operation, the main recommendations are:

- adapting the operating flows to the admissible flows (based on the dimensions of the well, critical speeds and strainer inlet speeds);
- the installation of sufficiently fine surface filtration;
- the implementation of backwashing of the injection wells (if the sizing of the screens allows it).

The purpose of the backwash operation is to encourage the mobilisation of particles from the production well or endogenous particles which have progressively clogged the injection well's screens and the reservoir's pores in the near-well environment. It should be done at a flow rate equivalent to or preferably higher than the operating flow rate (a margin of +10% is generally accepted) and it is essential to avoid sudden variations in pressure (overpressure or underpressure), in particular sudden stops which can destabilise the formations and cause additional clogging. Backwashing can be carried out by air-lift assisted pumping or by simple pumping. Particular care should be taken at the start of air-lift assisted production to avoid oxygenation of the geothermal loop.

The positive effect of backwashing on the performance of the Albian and Neocomian doublets, and more generally on the exploitation of sandy aquifers, remains to be demonstrated, particularly over time. On the other hand, this measure seems to be quick to implement and inexpensive, in terms of the equipment required and the time needed to interrupt operations. It has proved its worth on some doublets in the Albian aquifer, and operational test phases could be continued on the different sites and developed on others to verify the effectiveness of this technique in the long term.

Continued monitoring of hydraulic, physico-chemical, bacteriological and particulate parameters at the level of the operations is also essential for assessing the risk of clogging of the wells.

For future operations, in addition to the recommendations listed before, the main recommendations concern

- the need to define the role of the well (producer or injector), only after development and testing phase and estimates of injectivity and productivity indices (pumping tests, flowmetry);
- the fact of sizing the well screens and gravel pack accordingly so as to be compatible with the injection and production in each well;
- compliance with good practice in terms of the design of wells and the sizing of their components (diameter, casing, completions) according to the characteristics of the formations (grain size) and the operating conditions envisaged, as well as compliance with good practice in terms of development and pumping tests, giving priority to gradual increases in flow;
- the possibility of fitting out the injector structure and the surface installations to facilitate cleaning and backwashing operations.

Table 3: Recommendations and good practices for sandy formations

Phases	Recommandations or good practices	Objectives
Exploration	Acquire new data to increase reservoir knowledge (first exploration well)	Caracterize the reservoir before drilling and choose adapted well design and completion
Design	Respect good practice in well design and dimensionning of well elements (well diameter, casings, completion) depending the formation characteristics	Improve geothermal well quality
Design	Take into account avantages and disavantages of deviated wells (setting up the gravel pack) versus vertical wells	Minimize operational risks of completion during works
Design	Determine the role of the well (producer or injector) after devlopment of wells and testing phase	Maximise the chances of success for reinjection
Design	Use preferably same well architecture between both well (producer and injector)	Maximise the chances of success for reinjection
Design	Dimension and choose well screens and gravel pack compatible with injection and production	Minimize risks of clogging and reservoir destabilization during backwashing operation. Allow reversible flows
Design	Dimension well screens and gravel pack in accordance to grain size and operational conditions	Obtain an efficient filtration for the achieved flowrate. Avoid destalization near well.
Design	Anticipate the possibility of specific equipments at the surface and in the injection well to facilitate cleaning and backwashing	Clean or unclog wells and near-well formations with minimal disruption
Drilling	Realize drilling work with an experimented compagny in deep geothermal drilling	Minimize operational failures and improve wells quality
Drilling	Anticipate the involvment of an experimented engineering compagny for fluid management and reservoir testing	Minimize operational failures and improve wells quality
End of drilling	Check the completion of the work and the placement of the well screens and gravel pack in the well by video inspection log	Ensure the filtration of particles and allow the implementation of well cleaning and development
End of drilling	Acquire additional data at the development boreholes by well loggings, sampling and formation logging prior to well development	Improve geological characterisation of the reservoir, suspended fines, estimate reservoir productivity (at low flow), reservoir temperatures and pressures, nature of fluids on each well
Developpement	Respect good practice in well development and favour long development phases with a gradual increase in flowrate and increasingly long stages	Avoid clogging of the injection well by discharging fines-laden water into the well
Developpement	Characterise the evolution of the mobilised particules load, measure turbidity and its evolution as a function of production flows in the development and test phases	Improve the characterisation of fines (nature, quantity, origin) and adapt flowrates to minimise their production
Developpement/ Exploitation	Discharge pumped water at the surface during development, testing and commissioning of the loop or during well rehabilitation and cleaning operations	Avoid clogging of the injection well by discharging fines-laden water into the well
Developpement	Check the efficiency of the development operations by camera inspection (existing gravel behind screens, limit traces of fines as much as possible) and by turbidity analysis or particle counting of the water at the end of the development	Maximise the chances of successful filtration and characterise the water and its suspended particle content
Developpement	Carry out a flowmeter log at nominal flow rate at the end of the development	Characterise the intervals contributing to the flows and estimate the entrainment velocities at the inlet of the wells under operating conditions
Testing	Applicate good practice in long term formation testing including re-pressurisation times after development phase, pumping/injection and pressurisation times and flow rates achieved	Characterise the hydrodynamic parameters in the vicinity of the well

Testing	Monitor the turbidity of the water produced during the long-term tests and characterise the particle load at several stages of the tests	Ensure the effectiveness of the development of the wells
Testing	Filter water before re-injection during injection trials	Avoid clogging of the injection well by discharging fines-laden water into the well
Testing	Estimate the entrainment velocities at the inlet of the well screens for the measured productive thickness (ideally close to the design flow rate)	Avoid destabilisation of the reservoir formations in the vicinity of the wells and adapt the exploitation rates
Exploitation	Clean the connecting pipes with clean water before commissioning the geothermal loop and discharge to the surface outlet	Remove any fines that may be present and avoid the discharge of fines-laden water into the reinjection well
Exploitation	Adapt the maximum operating flowrates according to the estimated drawdown, critical velocities and screen entry velocities for each well	Limit destabilization and erosive forces in the production well environment and mobilization of suspended fines. Limit drawdown in the production well
Exploitation	Define the initial state for the physico-chemical and bacteriological parameters of the water, the particulate load, the hydrodynamic parameters of the reservoir and characteristics of the connection between the wells and the reservoir	Establish the performance of the well and have a reference to identify possible drifts linked to the progressive clogging of the wells
Exploitation	Monitor the wells and operations (physico-chemical, particle load, bacteriological, hydrodynamic)	Identify potential drifts and impacts of rehabilitation (cleaning, flow reversal) on performance by comparing measurements with the initial state of the wells
Exploitation	Set up backwash or flow reversal phases at the injection wells and adapt the installations in the well and on the surface (electrical cabinet, pump or pistoning, dewatering column, water discharge) to repeat the operations while limiting operating interruptions	Maintain the performance of the doublet by mobilising the fines present at the level of the screens, gravel pack and in the reservoir at the injection well (preventive and corrective)
Exploitation	Set up a surface filtration system that is adapted to the particle size of the fines, the operating rates, the pressures considered, the equipment of the doublet, the hydraulic properties of the reservoir at the injection well and the admissible pressure drops	Filter the production water before reinjection into the injector well to avoid clogging by fines of 10 µm or less in diameter. Limit pressure losses due to filtration

4. CONCLUSIONS

The relaunch of deep geothermal energy since 2007 has provided exhaustive feedbacks of practices on geothermal deep well drilling, mostly over the Paris Basin. It has led to the edition of a "good practice" guide, comprising 22 fact sheets covering 9 areas: drilling, casings, cementing, deviations, completions, logs, development and testing, and well operations. Each area includes one or more sheets addressing specific topics and providing reminders of the rules and procedures to be followed to avoid failures and, whenever possible, providing more quantitative recommendations and indicators. The idea is not to make deep geothermal well construction principles mandatory or normative but rather to provide a reminder of the main best practices to be followed. Finally, the aim is to provide, whenever possible, indicators to appraise or assess the quality of the work carried out.

It should be noted that some rules, procedures and recommendations referred to in these sheets are taken into consideration in the analysis of ADEME's fund application within the Heat Fund and in the analysis by the technical committee for the application of the guarantee fund (short and long-term risks).

The origin of the clogging in the Albian and Neocomian operations seems to be mainly due to the presence of particles coming from the production well and progressively clogging the injection well which can reach sizes smaller than 1 µm. Injection difficulties were encountered during the development and testing phases and continue, or even deteriorate, during the operation of the doublets. Recommendations related to the design of the wells, the execution, the development, the production and injection tests and the operation of the doublets have been formulated, following the analysis of the operations. Recent research works carried out by IFPEN (publication to come) have also identified the potential role of the heat exchanger (hydrodynamic and thermal processes) that could have an impact on particles aggregation. Some operations are now testing the impact of filtering before and after the heat exchanger.

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