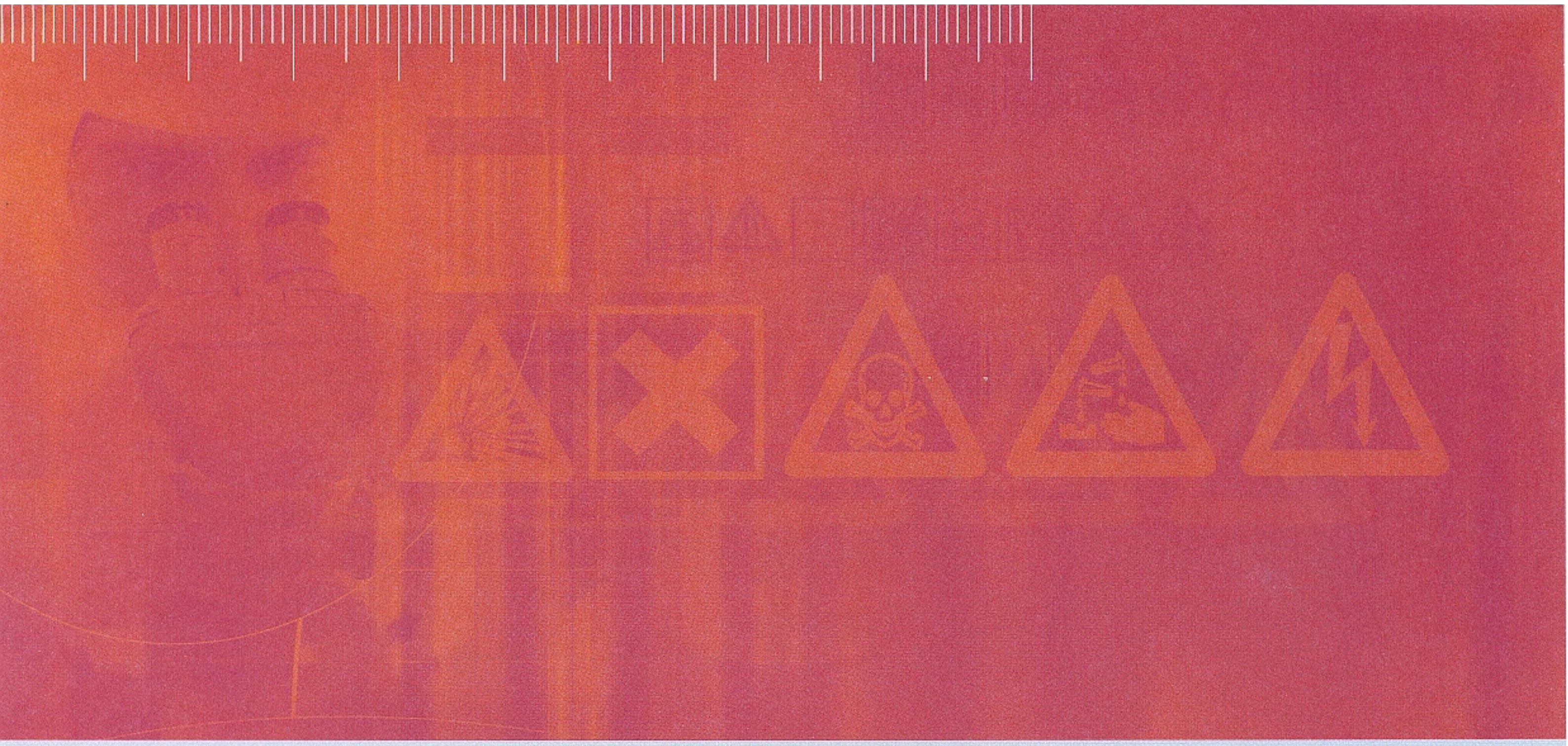

STUDY REPORT 31/05/2018

DRS-18-171541-05971A

State of knowledge about the risks, impacts and potential inconveniences associated with deep geothermal

INERIS

maîtriser le risque
pour un développement durable

State of knowledge about the risks, impacts and potential inconveniences associated with deep geothermal energy

Ground and Underground Risks Division

THANKS

We would like to express our sincere gratitude to Mrs. Judith SAUSSE, professor in the geoengineering department, GEORESSOURCES laboratory, in MINES NANCY, for her thorough review of this report, her thoughtful advice and constructive remarks which significantly helped to improve it.

FOREWORD

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SUMMARY

Deep geothermal is a renewable and non-intermittent source of energy that can contribute to the global transition towards a lower emission of carbon and less greenhouse emitting energy mix. Only a small share of the world's geothermal potential is being exploited today and many countries, including France, have included in their objectives an accelerated development in this area for the coming decades.

Like any industrial activity, deep geothermal drilling is accompanied with potential inconveniences and possible risks for people and the environment, which must be clearly identified and controlled in order to make this industry fully compatible with the expectations and the needs of the citizens, especially those living near such facilities. In past years, some concerns have been expressed by local authorities regarding the development of deep geothermal projects, particularly in the field of high temperature, based on the risks associated with such underground operations.

This report is intended as a scientific and objective contribution to this matter. It aims to present, in a factual and practical manner, the current knowledge about the risks, impacts and potential inconveniences associated with deep geothermal. In addition to the scientific literature, it is based on the feedback from incidents or accidents already recorded in this field. It also capitalizes on INERIS's expertise in the field of risks related to other sectors, such as oil and gas wells, to provide a larger perspective of deep geothermal technologies.

The main findings from this study are provided in the synthesis chapter at the end of the document. The reader will specifically find a global and comparative analysis of all risks, impacts or potential inconveniences linked to this sector.

Given the large amount of work published in the field of deep geothermal energy, whether in the fields of research or engineering, the authors do not claim to have exhausted this subject. They have tried to cover the available sources of information in a way that gives the benevolent reader what they consider to be a relatively comprehensive overview of the main safety and environmental issues, associated with this industry.

KEYWORDS

Geothermal, Hazard, Risk, Impact, Inconvenience, Acceptability, Drilling, Wells, Seismicity

REGION

France, Europe, World

TABLE OF CONTENTS

1. INTRODUCTION

The Paris Agreement on Climate, adopted by 195 countries on December 12, 2015, reaffirmed the international will to combat climate change by reducing greenhouse gas emissions. One of the levers to achieve this objective is to increase the renewable energy share in the global energy supply.

France is at the forefront of this initiative, in particular through the guidelines adopted in Act for Energy Transition and a Green Growth , which plans to increase the renewable energies share in the total energy consumption of the country to 32%[1] by 2030[2].

Geothermal energy, which uses thermal energy from the subsoil to generate heat or electricity, is a technology that can contribute to this goal. It is indeed a renewable energy source [3] with a very low carbon footprint which has the advantage over wind or solar energy of not being intermittent.

Nowadays, geothermal energy still accounts for a small share (0.9%) of the renewable energy generation in France, far behind hydraulic (20%), wind (8%) or solar (3. 4%) (Figure 1).

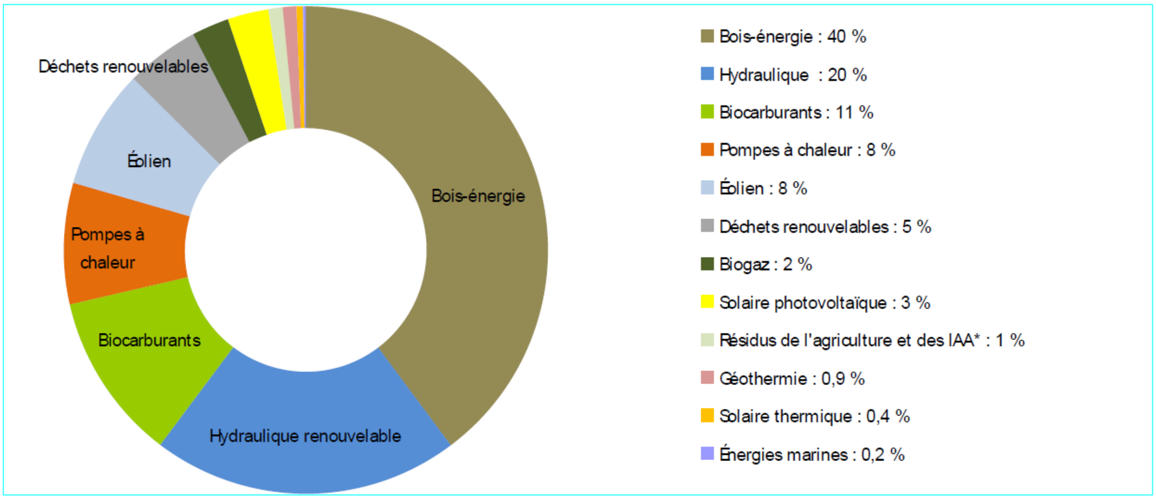

Figure 1. Primary production of renewable energy by sector in 2015 (DGEC, 2016)

However, its potential benefit for the climate, its largely unexploited potential[4] (including in France), the strong public support policies this sector benefits and the expected technological and cost-saving improvements still expected in this area, suggests that the development of geothermal energy will accelerate in the coming years. France's target is doubling its geothermal energy production capacity by 2023 (Table 1.).

[1] This share is now 14.9%, or 22.7 Mtep (source: DGEC, 2016)
[2] 38% of total heat consumption and 40% of the electricity generation.
[3] Provided that the power captured remains less than the capacity of the reservoir to recharge the heat.
[4] it is estimated that less than 6% of the world's geothermal potential is now used for electricity generation. (PPE, 2016)

Table 1. Situation and prospects in the geothermal market of France (sources: AFPG, 2016; EPP, 2016, Bertani, 2015)

Situation and perspectives of the sectors of geothermal energy			Today		2023		2030	
			Production (GWh)	Installed capacity (MW)	Production (GWh)	Installed capacity (MW)	Production (GWh)	Installed capacity (MW)
Géothermal	Geoth. Heat sectors	Very Low Energy (Heat pumps)	3686[1]	2280[1]	5593[1]	3335[1]	7488[1]	4440[1]
		Low energy (District heating)	1244[1]	377[1]	4128[1]	790[1]	6454[1]	1250[1]
		High energy (district heating, industry usage)	0[1]	0[1]	45[1]	104[1]	70[1]	160[1]
		TOTAL Heat sector	4930	2657	9766	4229	14012	5850
	Geoth. Electricity sector		115[3]	17[1]	-	53[2]	-	150[1]
	TOTAL Geothermal		5045	2674	-	4282		6000
Total renewables	Total renewable Heat		145350[2]	-	220932[2]	-		-
	Total renewable Electricity		93000[2]	41000[2]	150000[2]	78000[2]	216000[2]	-

Sources : [1] AFPG, 2016 [2] PPE, 2016 [3] Bertani, 2016

Geothermal energy is structured in three main branches:

- one which captures heat at low temperature in the first hundreds of meters of the sub-soil and the use of which (mainly for heating of individual and collective buildings) requires the addition of a heat pump; this is referred to as <u>geothermal heat pump;</u>
- the two others which exploit deeper horizons, namely:
  - <u>geothermal energy for direct use to heat production</u>, which captures medium-temperature heat contained in deep aquifers and specifically uses it to supply collective heating networks (district heating);
  - <u>geothermal energy for electricity production,</u> which captures very hot water or vapors circulating in volcanic zones or in deep fractured environments (rift basins, back-arc basins, see Genter et al., 2003), in order to generate electricity.

If the first branch uses a variety of techniques (ground loops, geothermal piles, vertical geothermal probes, drilling in shallow aquifers), the other two, which we will refer to as "<u>deep geothermal</u>", are based on the same principle of production: drilling of deep wells (one to several kilometers), similar to those found in the petroleum industry, by which hot water or vapors are extracted, valorized at the surface (as heat or electricity) and, in most cases, reinjected underground by a second well, in accordance with the "geothermal doublet" principle.

Although deep geothermal energy, as a renewable energy source, has a favorable overall image, it sometimes faces acceptability problems locally. The concerns raised by this technology are linked to a combination of factors of technical (induced seismicity, potential water pollution, noise, inconvenience, use of land, etc.), economic (benefits not necessarily perceived by the residents) or ideological (opposition to any form of exploitation underground resources) nature (Chavot, 2016). Recent incidents in the Rhine graben (Basel, Landau, Staufen, etc.), even though they were the result of actions contrary to the professional good practices (see, for example, Hervé, 2009, Goyénèche et al., 2015) also contributed to tarnish the image of deep geothermal energy.

To try to provide an objective and documented view on these issues, in this report INERIS intends to outline the current state of knowledge about the main risks, impacts or potential inconveniences associated with deep geothermal energy.

This state of knowledge is primarily based on feedback from incidents or accidents that have occurred in this field over the past few decades. It is also based on a review of the scientific and technical literature on the risks or impacts associated with the construction or operation of a geothermal site. Lastly, it relies on INERIS expertise in the field of risks related to oil drilling (Lahaie, 2015a, Lahaie, 2015b, Lafortune, 2016), which are very similar to deep geothermal drilling.

It is clearly specified that this report only discusses the risks or impacts related to deep geothermal energy. Impacts of surface geothermal energy (geothermal heat pump) have already been documented in detail (for example, Bezelgues-Courtade et al., 2012) and, therefore, are not discussed here. On the other hand, the experience gained during some surface geothermal projects could be used, when applicable to deep geothermal energy.

This report begins with a reminder of some definitions and elements of context in deep geothermal energy (chapter 1). In chapter 2 is given a generic description of a geothermal site and the risk analysis approach used in this study is presented. Chapter 3 contains an analysis of the feedback from accidents around the world in the field of deep geothermal energy. The following chapters (chapters 4 to 7) describe the main feared events, their possible causes, their potential consequences and their corresponding prevention and mitigation barriers. The report ends with a summary (chapter 8), which includes a comparative analysis of all the risks, impacts and inconveniences associated with deep geothermal energy.

The terminology used hereafter is assembled in APPENDIX 1.

2. GENERAL INFORMATION, DEFINITIONS AND PRESENTATION OF THE RISK ANALYSIS PROCESS

2.1 CLASSIFICATION OF GEOTHERMAL ENERGY

To properly introduce the situation of deep geothermalenergy, we must first address the different classifications of geothermal energy. There are several of them, which definition criteria are specified in Table 1:

A. a classification based on the recoverable energy potential[5]: very low energy[6] (<30°C), low energy (between 30°C and 90°C), medium energy (between 90°C and 150°C) or high energy (>150°C);

B. a legal classification: activities not subject to the mining code, subject to the mining code under the low-temperature geothermal regime known as "of minimal importance" (GMI), subject to the mining code under the low-temperature geothermal regime or subject to the mining code under the high-temperature geothermal regime (see details in APPENDIX 2);

C. a classification according to the types of geothermal heat valorization: heat production by using a geothermal heat pump, heat production by direct use of geothermal heat, electricity production.

It can be noticed that the domains delimited by each of these classifications coincide, although with some discrepancies. Thus, for example:

- geothermal energy assisted by a heat pump is not limited to very low energy geothermal but also encroaches the domain of low energy; certain geothermal heat networks may indeed require the addition of a heat pump up to temperatures of around 50 ° C;
- the production of electricity by geothermal energy does not only concern the high energy domain; this production is technically possible starting from temperatures of around 120° . (or even less), that is to say in the field of medium geothermal energy.

The deep geothermal energy, discussed in this report, is based on the third of the above classifications, that is, by the types of valorization. Thus, we will designate as "deep geothermal" the field that covers both geothermal energy used directly for the production of heat and the one intended for the production of electricity. This field is represented by the red box in Table 1.

[5] Essentially associated with the temperature of the heat transfer fluid at the site of capture.

[6] Sometimes the term "enthalpy" will be used

Table 1. Geothermal classifications (the field of "deep geothermal" is framed in red)

<table>
<tr><th>Classification based on recoverable energy potential</th><th>Criteria of definition</th><th>Legal classification</th><th>Criteria of definition</th><th>Classification according to the types of valorization</th><th>Production techniques[5]</th><th>Range of depths[5]</th><th>Range of temperatures of geothermal outflow</th><th>Range of power of an installation</th><th>Main applications</th></tr>
<tr><td rowspan="4">Very Low Energy[1]
(VLE)</td><td rowspan="4">T° < 30°</td><td>Not subject
to Mining Code</td><td>depth < 10 m</td><td rowspan="5">Heat or cold production with the assistance of a heat pump[3]</td><td>Geothermal loops
Geothermal piles</td><td>0 to 10 m</td><td>10° < T < 15°</td><td rowspan="2">10 to 100 kW$_{th}$
(1 à 20 housings)</td><td rowspan="5">* Heating (residential, collective or tertiary)
* Sanitary hot water
* Temperature regulation of housings
* Industrial, agricultural or leisure applications swimming pools, greenhouses, etc.)</td></tr>
<tr><td rowspan="3">Mining Code
"GMI" regime</td><td rowspan="3">10 m < depth < 200 m
P < 500 kW
Excl. red zones
T < 30° + reinjection + Limited outflow</td><td>Vertical geothermal probes</td><td>10 to 200 m</td><td>15° < T < 20°</td></tr>
<tr><td rowspan="3">Well drilling in shallow aquifers</td><td rowspan="3">10 to 1000 m</td><td rowspan="3">15° < T < 50°</td><td rowspan="3">100 à 1000 kW$_{th}$
(20 à 300 housings)</td></tr>
<tr></tr>
<tr><td rowspan="2">Low Energy[1]
(LE)</td><td rowspan="2">30° < T° < 90°</td><td rowspan="4">Mining Code
Low T° regime</td><td rowspan="4">30° < T° < 150°
or
T < 30° and not respecting GMI criteria</td></tr>
<tr><td rowspan="3">Heat production by direct use of geothermal heat</td><td rowspan="2">Well drilling in deep aquifers</td><td rowspan="2">1 to 3 km</td><td rowspan="2">50° < T < 120°</td><td rowspan="2">1 à 20 MW$_{th}$
(300 à 1000 housings)</td><td rowspan="2">* Collective district heating (heat networks)</td></tr>
<tr><td rowspan="2">Medium Energy[1]
(ME)</td><td rowspan="2">90° < T° < 150°</td></tr>
<tr><td rowspan="2">Well drilling in deep fractured zones
(rift systems)</td><td rowspan="2">2 to 5 km</td><td rowspan="2">120° < T < 200°</td><td rowspan="2">2 à 30 MW$_e$</td><td>* Industriel application (high T° drying)</td></tr>
<tr><td rowspan="2">High Energie[1]
(HE)</td><td rowspan="2">T° > 150°</td><td rowspan="2">Mining Code
High T° regime</td><td rowspan="2">T° > 150°</td><td rowspan="2">Electricity production</td><td>* Electricity production or cogeneration[4]</td></tr>
<tr><td>Well drilling in active volcanic zones</td><td>300 m to 2 km</td><td>180° < T < 350°</td><td>5 à 120 MW$_e$</td><td>* Electricity production or cogeneration[4]</td></tr>
</table>

[1] "Energy" ou "Enthalpy" [2] Low temperature geothermal regime know as "of minimal importance" [3] PAC = Heat pump 4 Cogeneration = electricity + heat production 5 In the french context

2.2 THE SITUATION OF DEEP GEOTHERMAL IN FRANCE AND WORLDWIDE

2.2.1 GEOTHERMAL ENERGY FOR DIRECT USE TO HEAT PRODUCTION

2.2.1.1 Principles

Geothermal energy for direct use to heat production consists of extracting heat from hot water in deep aquifers and using it directly (i.e. without the assistance of a heat pump) to feed collective heating networks (district heating) or for industrial, agricultural or leisure use. The temperature required to directly supply a heating network (without the aid of a heat pump) is between 50 and 90°C, depending on the type of heat utilization at the surface. In regions with a normal geothermal gradient, i.e. between 2 and 4°C/100 m,[7] it is necessary to go down to depths between 1,000 and 2,500 m to find water in this temperature range.

For the resource to be exploitable, the host aquifer must have adequate properties as well (permeability, porosity, thickness, etc.) to allow a sufficient and sustainable outflow (generally between 100 and 300 m^3/h). In France, these types of conditions are found mainly in the two large sedimentary basins (Paris basin and Aquitaine basin).

The method of operation is based on the drilling a well (production well) by which the hot water is extracted[8]. Once at the surface, this water passes through a heat exchanger, where it yields its calories to a heat transfer fluid, which then transports it to the network's users.

Most often[9], the cooled geothermal water is reinjected into the original aquifer through a second well (injection well). This principle, called "geothermal doublet", is illustrated in Figure 2. It has two major interests:

- to find a final destination for water which is in general highly mineralized and therefore unfit for consumption, and avoid any impact of this water on the environment;
- to maintain the pressure in the source aquifer and thus contribute to preserving the resource.

The first advantage of this type of geothermal energy is that it can be used in regions where the geothermal gradient is normal, as is the case in the Paris basin, because it essentially depends on the depth. Another advantage is that deep geothermal reservoirs can be reached with greater certainty because of the continuity of the geological formations which host them, which limits the so-called "geological" risk, i.e. the risk for the operator not to reach an economically viable geothermal resource.

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[7] The average geothermal gradient is 3.3°C/100 m in mainland France.

[8] In general, geothermal water is maintained under pressure in the entire primary circuit (i.e. from production well to reinjection well), in order to limit the problems with precipitation, turbulent flow or corrosion which could be caused by the evaporation of part of the water.

[9] The rare cases in France where water is not re-injected into the subsoil but into the sea (e.g. in the Bouillante plant in Guadeloupe) or in surface waters (for example for some wells in Aquitaine) are strictly regulated and justified by the small difference in the chemical composition between the extracted geothermal water and the receiving environment.

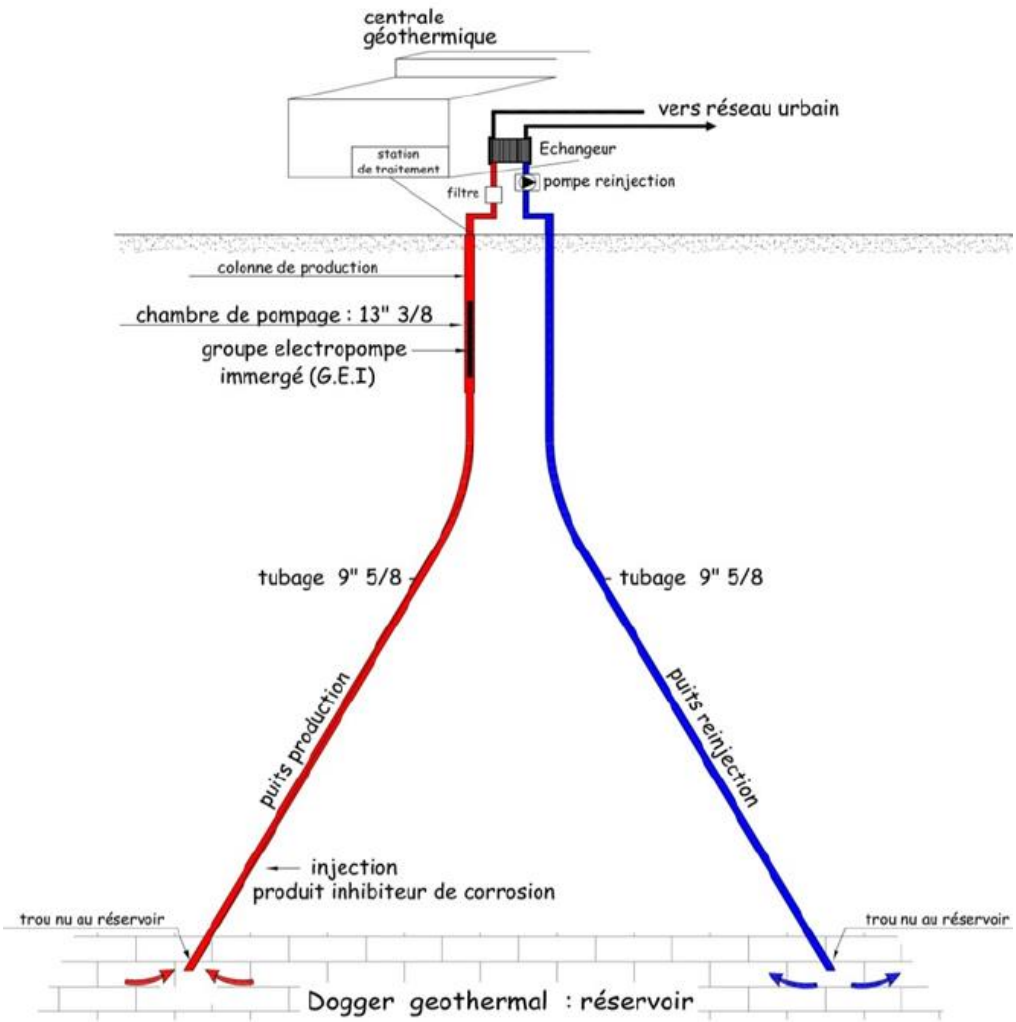

Figure 2. Schematic diagram of the Dogger geothermal doublet in the Paris basin (source: CFG services)

2.2.1.2 Worldwide situation

Globally, the total capacity of heat production by geothermal energy is estimated at 70 GW and the annual production is about 163 TWh (Lund & Boyd, 2015). 71% of this capacity, and 55% of the produced energy is supplied by heat pumps. Thus, geothermal energy for direct use represents 29% of the capacity (approx. 20 GW) and 45% of the energy produced (approx. 73 TWh/year), spread between appox. 1,100 installations (assuming that the average capacity of an installation is approx. 18 MW_{th}, EGEC, 2015).

Combined, these two branches (geothermal heat pumps and direct use) are experiencing significant growth worldwide (around 10% per year). According to the IEA (International Energy Agency), heat production from geothermal sources could reach 1,600 TWh by 2050, which would cover 3.9% of the total heat demand. The leading countries in terms of production are China, the United States, Sweden, Turkey, Iceland and Japan, but in per capita terms on the forefront are the Nordic countries (Iceland, Sweden, Finland, Norway), as well as New Zealand (Lund & Boyd, 2015).

In regards with geothermal energy for direct use, the main global applications are heating of swimming pools (45% of the geothermal heat consumed), collective district heating (34%), greenhouses (10%), aquaculture (4.5%) and industrial uses (4%) (Lund & Boyd, 2015).

In Europe, heating networks for collective heating are the main direct use of geothermal energy. Europe now has 257 geothermal heat networks, with a total installed capacity of 4.7 GW_{th} and annual production of approximately 4.3 TWh (EGEC, 2015). The leading countries in this field are Iceland (46% of european capacity), Turkey (18%), France (8%), Hungary (6%) and Germany (5.5%). Iceland stands out above all by the power of its installations (70 MW_{th} on average, ten times more than the average installation in France).

2.2.1.3 The situation in France

In the early 1980s, following the second oil crisis, France started an extensive program to develop geothermal heat networks (see Figure 3). The decline in oil prices and the technical problems, now resolved, which were subsequently encountered in the wells (corrosion, deposits), hampered the construction of new projects in the period 1990-2000. Since 2007, the sector is revitalizing, under the impetus of favorable renewable energies public policies. Between 2015 and 2016, eight new urban heat networks powered by geothermal energy were created in Île-de-France.

These installations bring the number of geothermal heat networks, now installed in France, to 52, representing a total capacity of 377 MW_{th} and heating 210,000 homes (450,000 people). France ranks third in Europe in terms of capacity and number one in terms of number of networks.

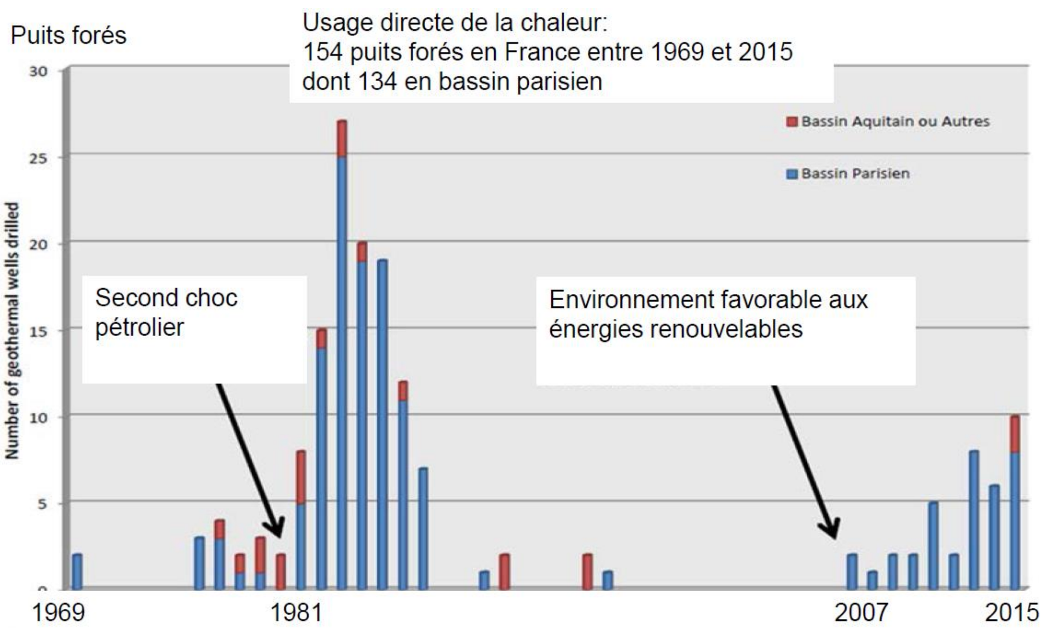

Figure 3. Wells drilled in France for direct use of geothermal heat (source: CFG Services)

In France, the main resources are in the two large sedimentary basins, namely the Paris and Aquitaine basins (see Figure 4). The first is by far the most exploited (82% of the installations) because it benefits from a combination of favorable geology (stacked aquifer formations up to more than 3 km deep) and a high population density. The geothermal doublets mainly exploit the Dogger aquifer at depths between 1,500 and 2,000 m. The temperature at the catchment output varies between 55 °C and 85 °C.

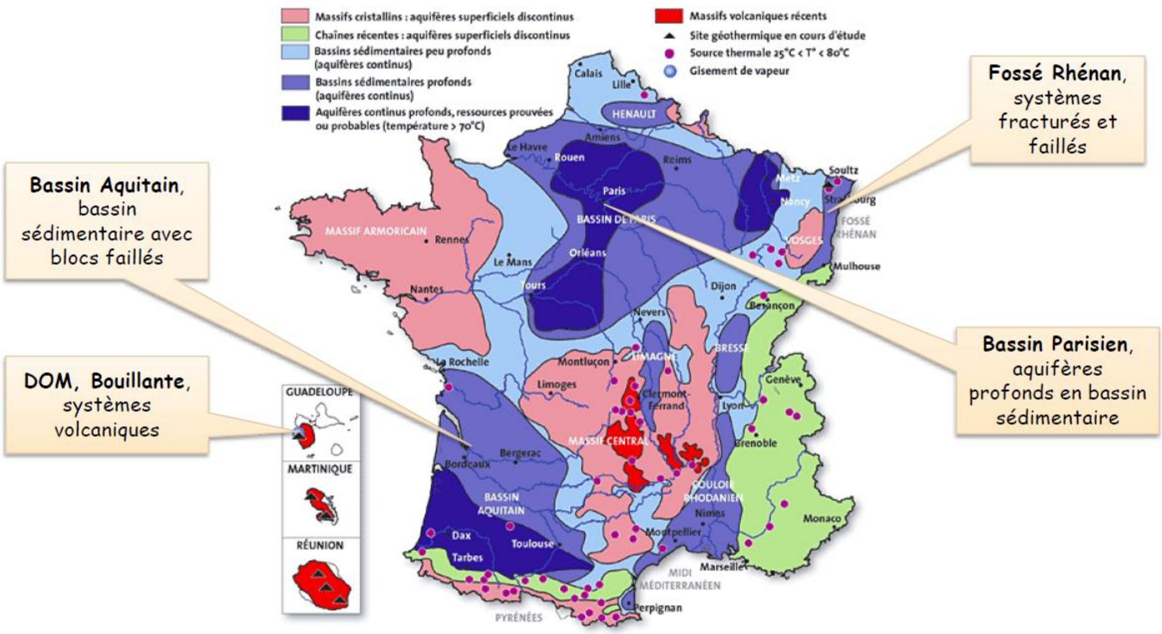

Figure 4. Favorable areas for the direct use of geothermal heat in France (source: BRGM)

France is aiming to double its capacity of geothermal heating networks by 2023 (see Table 1.). It should be noted that due to the saturation of geothermal doublets at the Dogger in certain areas of the Paris basin, the possibility of exploiting the deeper Triassic aquifer (around 2500 m depth) is currently being studied.

2.2.2 GEOTHERMAL ENERGY FOR ELECTRICITY PRODUCTION

2.2.2.1 Principles

Geothermal energy for electricity production (or geothermal power generation) is developing today around three main concepts:

- "volcanic" geothermal energy, by far the oldest and most widespread in the world, which exploits the heat contained in very hot fluids (between 150 and 400°C) circulating in the fault systems of zones with active or recent volcanic activity. The fluids are extracted in the form of steam or, more generally, in the form of a steam-liquid mixture. After separation, the steam is sent to a turbine ("flash" technology) to generate electricity. Some of this steam is then released into the atmosphere (after having been purified of its toxic gases), while the rest is condensed in liquid form and then reinjected into the subsoil or sometimes released in the sea. This the case of the geothermal power station in Bouillante in Guadeloupe (see Figure 5).

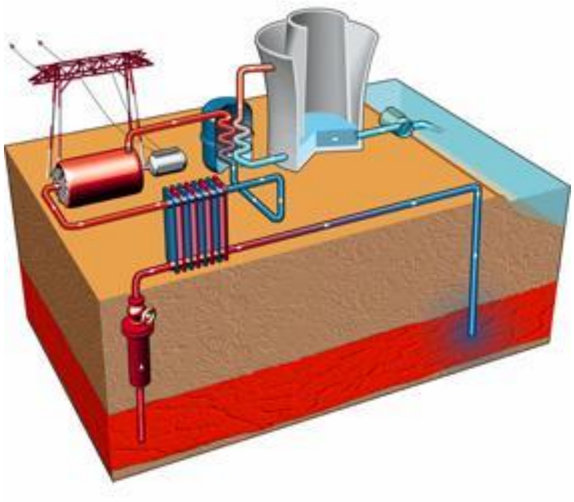

Figure 5. Principle of operation of a geothermal power station (http://www.geothermie-perspectives.fr/)

- Geothermal energy HDR (« *Hot Dry Rock*»), consists of creating a network of artificial fractures in a hard rock by injecting pressurized water (hydraulic fracturing) at greater depth (between 2 and 5 km). After circulating in the network of fractures and heating up in contact with the rock, the water is theoretically recovered by a production well. This concept, applied in particular in the United States (Los Alamos), has a number of disadvantages: difficulty in recovering a sufficient portion of the injected water, seismicity induced by hydraulic fracturing. Although it was tested in Soultz-sous-Forêts (France), this concept has not been implemented in France and will not be studied in the remained of this report;
- The EGS geothermal energy ("*Enhanced geothermal Systems* ") is still emerging, the process consists of using hot waters (generally between 120 and 200°C) which circulate in deep, naturally fractured zones (between 2 and 5 km depth) typical for large rift basins: this for example is the case of the Rhenan graben. The geothermal fluid is kept in liquid form in the production well and then passes through a heat exchanger where it yields its calories to a secondary fluid whose boiling point is lower than the one of water. This triggers the evaporation of the secondary fluid which is then sent to a turbine to produce electricity. The primary fluid, cooled to around 80°C, is either reinjected directly into the subsoil or used for another type of valorization (e.g., to feed a heating network). This is referred to as "cogeneration". Unlike the HDR method, EGS[10] does not require fracturing of the rock, which is already naturally fractured. On the other hand, in order to properly connect the wells to this network of natural fractures, it is necessary to use techniques known as "stimulation" (hydraulic, chemical and/or thermal), as is the case in other fields that produce underground resources through wells (oil and gas production, drinking water production, etc.).

[10] Beware, there is some confusion existing in the literature, where the term "EGS" is sometimes used to refer to geothermal systems which fall under the concept of HDR.

2.2.2.2 Worldwide situation

Globally, geothermal power generation today has a capacity of 13.3 GW_e (PIPAME, 2016) with annual production of approx. 75 TWh_e. This capacity is distributed over approximately 600 installations (Bertani, 2015), i.e. an average of 22 MW_e per installation.

The majority of the production sites are located in volcanic contexts, i.e. on the edge of tectonic plates or in rift zones: the Pacific "fire ring", the Caribbean and Mediterranean arches, the African rift (Figure 6). The top producing countries are the United States (26% of the world's installed capacity, mainly in the West), the Philippines (14%), Indonesia (10%), Mexico (7.5%) and New Zealand (7.5%). Followed by Italy, Iceland, Japan, Kenya and Turkey. Overall, about twenty countries worldwide produce geothermal electricity (Bertani, 2015).

In the United States, the main production sites are in California, where is located the Geysers site, which alone has a production capacity of 1,500 MW_e. Other major installations worldwide include the Lardarello power station in Italy, Krafla in Iceland, Olkaria in Kenya and Amatitlan in Guatemala.

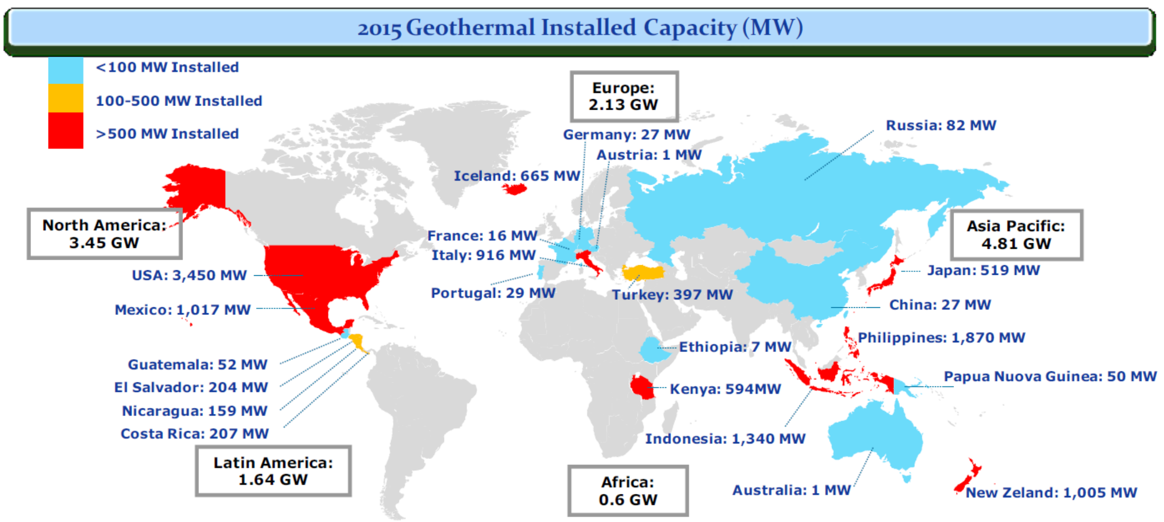

Figure 6. Installed capacities in the field of geothermal power generation (Bertani, 2015)

In Europe, there are 88 operational installations, totaling an installed capacity of 2,285 MW_e (EGEC, 2015). These facilities are mainly located in Italy, Iceland and Turkey. 32 other facilities are under construction and another 176 are in project.

Geothermal generation of electricity is currently growing at a rate of about 10% per year (Bertani, 2015, DGEC, 2016). According to the International Energy Agency (IEA), this production is expected to be multiplied by 20 by 2050 to reach 1,400 TWh, or about 3.5% of the world's total electricity production (PIPAME, 2016). Like the heat sector, the electricity sector of geothermal energy is therefore an important resource of tomorrow.

2.2.2.3 The situation in France

Today, France has two geothermal power plants:

- the Bouillante plant in Guadeloupe, volcanic type, which has been operational since 1984. The plant now delivers 15 MW_e;

- the Soultz-sous-Forêts power plant in the Bas-Rhin, the cradle of European research in the field of EGS technology, which, having been operated as a pilot site for nearly 30 years, entered the industrial phase in 2016. It now delivers an electrical capacity of 2.1 MW_e;

These two plants produce about 115 GWh/year (see Table 1.), which places France at twentieth place in the world and fifth in Europe in the field of geothermal power generation.

Another example is the inauguration of the Rittershoffen (Bas-Rhin) power plant in 2016, which is an application of EGS for the production of industrial heat rather than electricity. Like Soultz-sous-forêt, this station with 24 MW_{th} energy capacity uses the hot water (near 165 °C) found in the deep fractured reservoirs of the Rhenan rift. Even if the heat produced there is not used for electricity, this plant plays a role as a showcase for the development of the EGS sector in France.

France announced its geothermal power generation objectives which are to achieve a production capacity of 150 MW_e by 2030 (see Table *1.*). These ambitious objectives are especially based on the expectation of a large deployment of EGS technology in mainland France. Thus, many projects are in study phase (or in development phase) in Alsace, but also in The Massif Central (Limagne), the Rhone corridor or in the foot of the Pyrenees (Béarn) (see Figure 7). Volcanic geothermal energy should also be developed, notably through the project to expand the Bouillante power plant (whose shares were recently opened to the American company Ormat) and through other projects in the French overseas territories department (DROM), notably in Martinique and in Reunion.

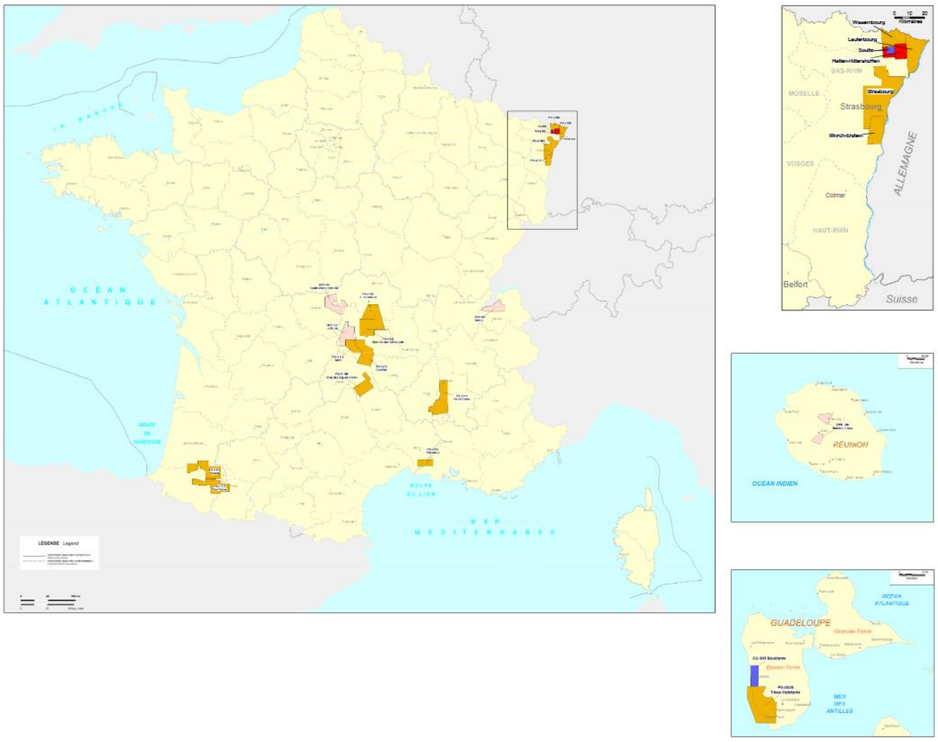

Figure 7. Mapping of the mining titles in France for high temperature geothermal energy (DGEC, 2015).

Legend: in orange, the allocated research permits in the first period; in red, the allocated research permits in the second period; in pink, the allocated research permits in the third period; in beige, the pending applications for research permits; in violet, the current production concessions.

2.3 Brief description of a deep geothermal site

The main purpose of this report is to specify the potential Risks, Impacts or Inconveniences (RII) associated with deep geothermal activities. It is useful to recall the main stages in the life of a geothermal site (the RII are different, according to the phase) and to describe the structures and installations present at the surface during each of these phases.

2.3.1 Phases of a site's lifecycle

Whatever the field of deep geothermal energy (for heat or electricity production), the project development involves two main phases[11] (exploration and production) and within these phases, two secondary phases (resource assessment and abandonment):

- the exploration and resource assessment phases: This involves drilling a first well down to the targeted geological formation, i.e. the one hosting a potential geothermal resource, and carrying out a series of flow tests to characterize this resource, especially the outflow and temperature of the fluid collected at the

[11] In addition to the preliminary geological, technical and economic studies and the possible prospection (geophysical) phases.

surface. If this resource is considered economically viable, a second well is drilled (in the case of a doublet) in which a series of flow tests (production and/or injection) is also carried out. At the end of this phase, which lasts between 4 and 12 months depending on the depth and complexity of the wells, a decision is made on whether or not to the geothermal doublet is put in production;

- the production and abandonment phases: The aim is to build the necessary installations for the operation of the site and to put them in production for a period of at least 30 years, duration generally required for the investment in a deep geothermal installation to be profitable. During production, control and maintenance operations may be carried out on the wells or on the surface installations. At the end of the production phase, the facilities are dismantled, the wells are plugged and the site is rehabilitated: the concession, granted to the operator, is then renounced to the State.

The regulatory framework in which these operations take place is noted in APPENDIX 2.

2.3.2 WELLS

The drilling techniques and the geothermal well architectures are very similar to the ones used for oil wells. The precise description of these is beyond the scope of this report: the reader may refer, for example, to the INERIS report "Context and fundamental aspects of drilling and production of hydrocarbon wells" (Lahaie, 2015b) for more details.

However, the following differences between oil and geothermal wells are noteworthy:

- geothermal wells do not have a completion, i.e. geothermal water is produced directly through the casings. The latter are thus more exposed to corrosion and, in high-temperature contexts, to strong thermal variations, which can lead to expansion/contraction of the steel tubulars. The absence of a control annulus[12] also makes it more difficult to monitor possible leaks (for example by corrosion or rupture of the casing);
- consequently, the casings are systematically cemented over their entire height; this enables to reinforce the sealing between the well and underground formations, to limit external corrosion of the casings and to ensure good mechanical strength of the well with regard to thermal variations (in high temperature environments);
- the diameters of the casings are more important, the production casing often being in diameter 9"$^{5/8}$ (245 mm) for geothermal wells, while it is generally in diameter 7" (178 mm) or even 4 "1/2 (114 mm) for oil wells, allowing for a higher production (or injection) rate, which is necessary for a geothermal well, to be economically viable; moreover, the thickness of the casing is more important than in the petroleum sector, in order to take into account the faster rate of thickness reduction due to corrosion;

[12] In the case of hydrocarbon or gas underground storage wells, the presence of an annular space between the completion and the casing, called the "control annulus", makes it possible to monitor the pressure at the wellhead and thus to detect possible leaks.

- temperatures may be high (180°C in the case of Alsacian EGS, 250°C in the case of volcanic geothermal energy in the West Indies); the cements and drilling equipments must therefore be adapted to such environments;
- the pressures are generally lower than in the petroleum field, since the geothermal reservoirs are generally less pressurized. In order to be able to produce at a sufficient flow rate, the wells are more often equipped with an immersed electro pump placed in the well a few hundred meters below the surface;
- the wells are generally "inclined", i.e. not vertical over their entire length, due to the geothermal doublet principle (see Figure 2); the inclinations are usually between 30 and 45° but can reach 60° or more in the more recent designs (horizontal drilling); even though these technologies are generally well controlled, drilling difficulties (friction of the tools during their descent or ascent, lack of centering of the casings, lack of annular cementing on the upper side of the borehole, etc.) are more frequent there than in vertical drilling;
- injection wells are at least as numerous (sometimes more) as the production wells, because well injectivity is often lower (or more prone to decrease over time) than their productivity.

2.3.3 Surface installations

The type of installations present on the surface and their footprint depend on the phase of life considered.

During drilling and flow tests, all the installations necessary for a conventional deep borehole drilling site (see examples in Figure 21) are found on the surface: drilling rig, motors, drilling rods and casings storage areas, mud tanks, temporary storage pool for the geothermal fluid in the flow test phase, etc.

In the production phase, some installations are specific to geothermal energy (see examples in Figure 22): pipelines connecting the two wells (primary circuit), pumps, heat exchanger, secondary loop, possibly turbine in case of electricity generation.

2.4 Presentation of the risk analysis process

In the rest of this report, we use the following definitions:

- "Risks" means the potential impacts on the health or safety of people (internal or external to the site) resulting from the activities carried out at the geothermal site; a distinction will be made between accidental risks (linked to an unforeseen event) and chronic risks (linked to the site's current activities);
- “Impacts” mean damage to property (buildings, infrastructure, etc.), to human activities (transportation, etc.) or the environment (fauna, flora, water, soil, climate, etc.) resulting from the activities carried out on the geothermal site; accidental impacts and chronic impacts will also be distinguished;
- “Inconveniences" means the inconvenience caused to people as a result of routine (non-accidental) activities carried out at the geothermal site.

This report will focus only on the potential harm to people or the environment; technical or economic risks for the operator will not be addressed, in particular:

- the "geological" risk, i.e. the risk for the developer not to reach an economically exploitable geothermal resource;
- the risk of loss of productivity or injectivity of the wells or geothermal resource alteration over time.

Similarly, risks related to one-time operations (well interventions, well plugging operations) will not be addressed.

The accidental risks or impacts will be represented, in most cases, in the form of a simplified accident sequence (Figure 8), which consists of:

- a critical event, conventionally defined in the center of the accident sequence;
- an initiating mechanism, located upstream of the critical event and constituting its cause;
- a dangerous (or potentially impacting) phenomenon, that is, a phenomenon resulting from the critical event and likely to harm people ("dangerous" phenomenon), property or the environment ("impacting" phenomenon);

It will be called "accident" an accidental sequence that develops fully until reaching vulnerable targets (people, goods, or environment). In the other cases, accidental sequences will be referred to as "incident".

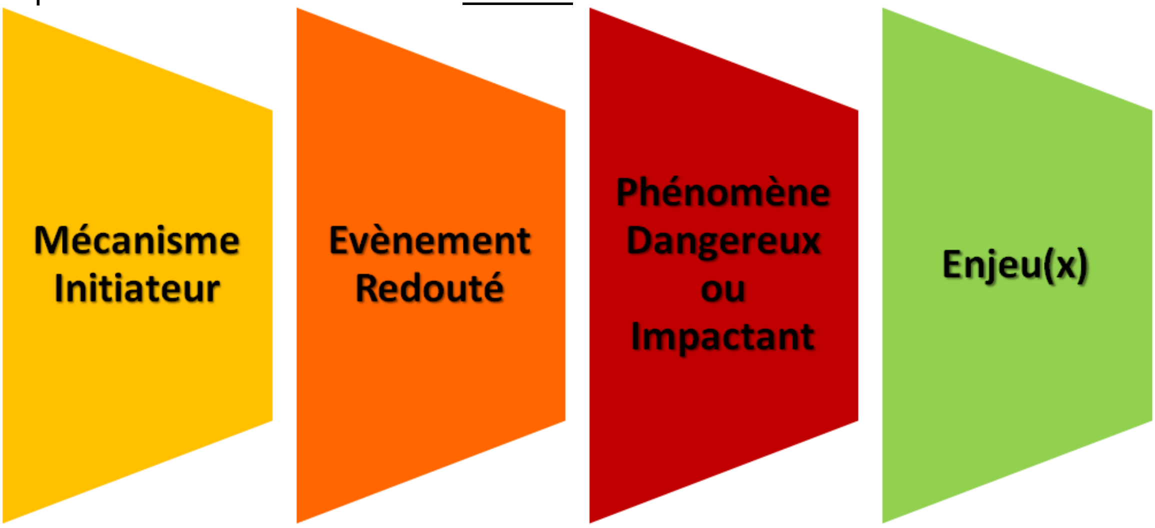

Figure 8. Simplified representation of an accident sequence

Any risk analysis first consist in examining the feedback of previous accidents and incidents in the concerned field. For this reason, Chapter 3 provides an update on the recorded accidentology in the deep geothermal energy sector.

Chapter 4 then reviews some chronic risks and impacts and discusses their relevance to deep geothermal activities.

Chapters 5 to 7 examine the relevance of the most frequently mentioned accidental risks or impacts in the field of deep geothermal energy, grouped into three broad categories:

- accidental releases of fluids on the surface (Chapter 5);
- possible pollutions of the underground environment (Chapter 6);
- possible risks of ground movements or damaging seismic activity (Chapter 7);

For each of them, the following will be systematically presented:

1. the concerned critical event;
2. its main possible initiating mechanisms;
3. the subsequent dangerous or impacting phenomena likely to ensue and the potential effects and consequences on people, property or the environment.

A partial conclusion will end each of these chapters and a general summary of the potential risks, impacts and inconveniences associated with deep geothermal energy will be provided at the end of the report (Chapter 8).

It should be noted that the purpose of this report is not to provide an exhaustive and universal inventory of the risks associated with deep geothermal energy; indeed, it is important that a specific risk analysis be carried out for each site and that specific prevention and mitigation measures be defined accordingly. Instead, this report aims to provide generic insights into the more important risks or the one which are most frequently reported in the sector of deep geothermal energy.

3. FEEDBACK FROM ACCIDENTS AND INCIDENTS

3.1 CREATION OF A DATABASE

To our knowledge, there is no specific database of geothermal incidents or accidents. Information about these events is provided, sometimes in summary form, in general reports on geothermal energy or in press articles. For the most important of them, some specific reports, which give a more precise description and analysis, can be found. In general, information on accidents or incidents related to geothermal energy is scattered and very uneven.

To best inventory themthe following approach has been followed:

- identify the accidents/incidents listed in the general reports on geothermal energy or in the press;
- search for more specific reports on these accidents;
- analyze each accident and gather the main corresponding information in a database presented in tabular format in APPENDIX 3.

This database includes 35 accidents or incidents which are summarized in Table *2*. To simplify the wording, the term "accident" is used to refer to an incident or an accident.

Only accidents with sufficient information have been recorded. Most of these are accidents which occurred in the field of deep geothermal energy. There are also some accidents related to superficial geothermal energy, which feedback has been deemed applicable to deep geothermal energy.

Since this database is not exhaustive, it will be difficult to draw quantitative lessons on deep geothermal accidentology in particular to make comparisons with other industrial sectors. The lessons learned will therefore be essentially qualitative.

3.2 ANALYSIS OF THE DATABASE

The main lessons that can be learned from the analysis of the 35 recorded accidents/incidents are summarized below, taking into account the fact that there is a bias linked to the origin of available sources (mostly european):

- 51% of cases have occurred in Europe, in the following countries: France (7 cases), Germany (6 cases), Switzerland (2 cases), Iceland (2 cases) and Italy (1 case); this finding is not indicative of degraded security in Europe but is the result of the bias associated with the preponderant use of European information sources;

- 89% of the recorded cases correspond specifically to deep geothermal operations and 11% to superficial geothermal cases, selected as relevant for the deep geothermal field.

Table 2. Summary of the collected accidental events

Reference	Event day	Activity	Country	Place	Critical events	Impacting or dangerous phenomena	Number of deaths	Number of injuries
Agua Shuca	10/13/1990	Deep geothermal energy	Salvador	South West of Ahuachapan	Blowout	Explosion Projection	25	35
Ahuachapan 1	summer 1994	Deep geothermal energy	Salvador	Ahuachapan	Surface leak	Toxic or eco-toxic discharge	several	several
Ahuachapan 2	year 1994	Deep geothermal energy	Salvador	Ahuachapan	x	x	several	several
Bâle	12/08/2006	Deep geothermal energy	Swiss	Bâle	Earthquake	Felt seismic shocks	x	x
Berlin 1	1993-1994	Deep geothermal energy	Salvador	Usulutan	Surface leak	Gaseous emissions	x	x
Berlin 2	09/16/2003	Deep geothermal energy	Salvador	Usulutan	Earthquake	Felt seismic shocks	x	x
Biliran	06/23/2014	Deep geothermal energy	Philippines	Biliran	Massive surface outgassing	Gaseous emissions	x	8
Bouillante	02/04/2010	Deep geothermal energy	France	Bouillante, Guadeloupe	-	Landslides Subsidence	x	x
Coulommiers	year 1996	Deep geothermal energy	France	Coulommiers	Underground leak	Eco-toxic discharge	x	x
Geysers	1980-2010	Deep geothermal energy	USA	Californie, 120 km north of San Francisco	Earthquake	Felt seismic shocks	x	x
Habanero	november 2012	Deep geothermal energy	Australia	Cooper Bassin	Earthquake	Felt seismic shocks	x	x
Hengill	10/15/2011	Deep geothermal energy	Iceland	Hengill, south west of Iceland	Earthquake	Felt seismic shocks	x	x
Hilsprich	from 2006	Superficial geothermal energy	France	Lorraine	Uncontrolled dissolution	Subsidence	x	x
Innamincka	04/24/2009	Deep geothermal energy	Australia	Innamincka	Surface leak	Toxic discharge Projection	x	x
Insheim	april 2010	Deep geothermal energy	Germany	Bavière	Earthquake	Felt seismic shocks	x	x
Japon	year 1998	Deep geothermal energy	Japan	-	Surface leak	Toxic discharge	1	x
Kircheim	year 2007	Superficial geothermal energy	France	Alsace	Water intrusions in anhydrite formation	Uplift	x	x
Landau 1	08/15/2009	Deep geothermal energy	Germany	Landau	Earthquake	Felt seismic shocks	x	x
Landau 2	03/13/2014	Deep geothermal energy	Germany	Landau	-	Uplift	x	x
Lardarello	year 1985	Deep geothermal energy	Italy	Lardarello	Underground leak	Eco-toxic discharge	x	x
Lochwiller	2008-2013	Superficial geothermal energy	France	Alsace	Water intrusions in anhydrite formation	Uplift	x	x
Margamukti	05/07/2015	Deep geothermal energy	Indonesia	Pangalengan west of Java	-	-	x	x
Meaux	year 2013	Deep geothermal energy	France	Meaux	-	x	x	x
Neustadt-Glewe	year 1998	Deep geothermal energy	Germany	Neustadt-Glewe	x	x	x	x
Puna 1	08/07/2014	Deep geothermal energy	Hawaii	Honolulu	Surface leak	Toxic discharge	x	x
Puna 2	06/15/1991	Deep geothermal energy	Hawaii	Honolulu	Blowout	Toxic discharge	x	1
Rotokawa	01/01/2010	Deep geothermal energy	New Zealand	Rotokawa	Earthquake	Felt seismic shocks	x	x
Saint Gall	07/20/2013	Deep geothermal energy	Swiss	Saint Gall	Earthquake	Felt seismic shocks	x	x
Salton Sea	1981-2012	Deep geothermal energy	USA	Californie	Earthquake	Felt seismic shocks	x	x
Soultz-sous-Forêts	year 2003	Deep geothermal energy	France	Alsace	Earthquake	Felt seismic shocks	x	x
Staufen	11/01/2007	Superficial geothermal energy	Germany	Staufen	Water intrusions in anhydrite formation	Uplift	x	x
Svartsengi	1976-1999	Deep geothermal energy	Iceland	Svartsengi	Excessive depletion of the geothermal reservoir	Subsidence	x	x
Unterhaching	-	Deep geothermal energy	Germany	Bavière	Earthquake	Felt seismic shocks	x	x
Warakei	1950-1997	Deep geothermal energy	New Zealand	Warakei	Excessive depletion of the geothermal reservoir	Subsidence	x	x
Zunil 1	01/05/1991	Deep geothermal energy	Guatemala	South West of Guatemala, 8 km at south of Quetzaltenango	Surface leak	Explosion Projection	23	yes

3.2.1 LESSONS LEARNED IN TERMS OF RISKS FOR PEOPLE

14% of the recorded accidents resulted in the death of one or more people. Of the total number of accidents, there were 49 deaths and 44 injuries, although in some accidents the exact number of victims was not specified.

This percentage of fatal accidents may seem impressive at first sight, but it should be kept in mind that first, published and well-documented accidents are generally the most serious ones and second, 98% of these deaths are the result of two particularly serious accidents that occurred in the 1990s, in specific contexts, which could are hardly applicable in France:

- the deadliest accident was the one in Agua Shuca in El Salvador in 1990, which resulted in 25 deaths and 35 injuries (Escobar et al., 1992, Goff & Goff 1997); its exact cause could not be defined but the critical event that has occurred is a massive eruption (blowout) due to an uncontrolled rise in the reservoir's pressure; note that such a scenario is highly unlikely in the French context (especially outside the volcanic zones) and is more likely to be controlled because of the systematic use of a blowout preventer or BOP[13] on the wellhead (see Chapter 5.1.1);
- the Zunil 1 drilling accident in Guatemala was also very deadly with 23 fatalities in 1991 (Goff & Goff, 1997; Flynn et al., 1991); it is a large landslide (unknown whether it was induced or not by the geothermal drilling operation) that caused the rupture of casing, causing a massive projection of hot geothermal fluid to the surroundings; this accident is poorly documented and it is not certain that the majority of the victims, who were buried by the landslide, were impacted by the *blowout*.

Apart from these two accidents, that occurred in very specific contexts and which information available on is not very precise, the only victims recorded in the 33 remaining accidents where caused by emissions of H_2S :

- the only death was recorded in 1998 in Japan; it occurred during a maintenance operation and resulted from an emission of H_2S, which accumulated in a confined space (surface facility);
- one injury was caused by emission of H_2S from a well blowout in Puna 2 (Hawaii) in 1991; eight other people were affected by H_2S emissions during a production flow test in Biliran (Philippines) in 2014; they are the only serious accidents recorded in the last decade.

It is also worth noting the cases of two other accidents referenced as Ahuachapan 1 and 2, which occurred in El Salvador in 1994, again in a very particular context. At this site, the geothermal fluid could not be reinjected on site so a 82 km long open canal was built between the geothermal power station and the ocean. A leak then appeared on this canal which contained toxic and very hot water: it is the accident Ahuachapan 1 which does not seem to have caused victims. However, several people approached the canal, which did not have a protective barrier, they fell in the

[13] the BOP or “well blowout preventer" is a safety device installed on the wellhead, which enables to close the well in the event of uncontrolled inflow of fluid.

waterand were burned: it is the accident Ahuachapan 2. It should be noted that this second accident could not occur today in Europe, given that the transport of geothermal fluid is now carried out by pipeline. As for the first accident, the risk of leakage would also be considerably lower in the case of a pipeline transport, although this scenario remains plausible.

Therefore, excluding the very specific accidents in Agua Shuca, Zunil 1 and Ahuachapan 2, which occurred in circumstances not applicable to the french context, our survey records one death and nine injured in almost three decades of feedback, out of about 1,700 geothermal plants currently in operation (see § 2.2.1.2 and 2.2.2.2).

The overall impression is that deep geothermal energy benefits from a rather weak accidentology. It must be kept in mind, however, that this survey is only partial, since it is based mainly on western sources and information found in the public domain. Therefore, we encourage the geothermal industry, via its representative structures at national and international level, to carry on the work initiated here by INERIS and to conduct a systematic survey of the incidents and accidents occurring in the field of deep geothermal energy, in order to consolidate a quantitative analysis which could only be initiated in the frame of this report.

3.2.2 LESSONS IN TERMS OF THE SAFETY EVOLUTION IN TIME

The distribution of victims is not uniform over time. Actually, accidents that occurred before the year 2000 account for 91% of the victims recorded in our database (Figure 9).

Moreover, the seriousness of the events seems to have diminished over time: indeed, no deaths are recorded after 2000 and only 18% of the injured.

This decrease in the number of victims and the seriousness of their injuries over time is even more significant that in the meantime, the number of geothermal installations has been growing worldwide: the installed capacity has increased 6 times since 1995 in the direct heat sector (Bertani, 2015) and increased 3 times since 1985 in the electrical sector (Bertani, 2015).

The decrease in the number of victims observed over time can therefore be considered as an indication of an improvement in safety practices and in feedback analysis of the first accidents in the deep geothermal. It should be noted that a similar improvement is observed in the exploration and production of hydrocarbons (Lahaie, 2015a).

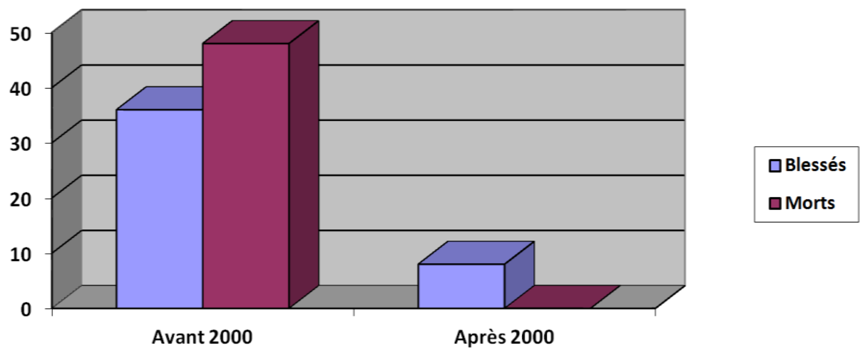

Figure 9. Number of victims before and after 2000

3.2.3 LESSONS LEARNED IN TERMS OF ACCIDENT TYPOLOGY

The critical events that are most often observed are induced seismicity (34% of cases), surface or underground leaks (23%), water intrusions in swelling formations (anhydrite) (9%), cases of excessive depletion of geothermal reservoirs or well blowout (6% each), massive surface outgassing or cases of uncontrolled dissolution of evaporite formations (3% each) (Figure 10). It should also be noted that, in 17% of cases, the type of accidental event is not known.

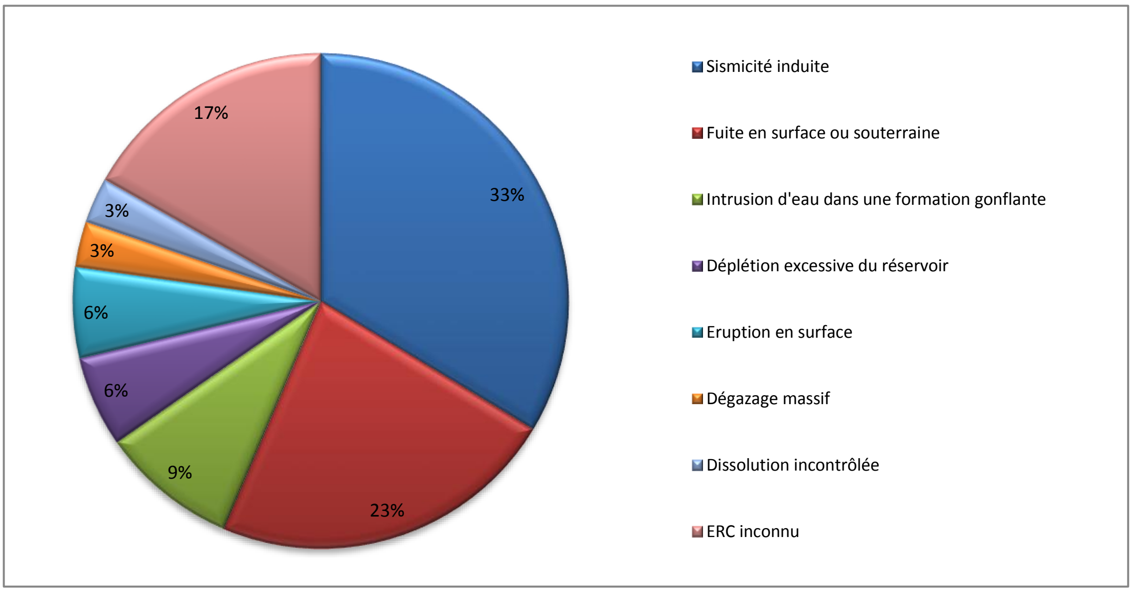

Figure 10. type and proportion of main critical events in deep geothermal accidentology.

The dangerous or impacting phenomena that most often result from these accidental events are felt seismic movements (in 34% of the cases), landslides, (uplift or subsidence) (23%), toxic or eco-toxic discharges (20%), gaseous emissions (6%) or explosions/projections (also 6%) (Figure 11). In 11% of the cases, the dangerous or impacting phenomenon is not specified or does not exist.

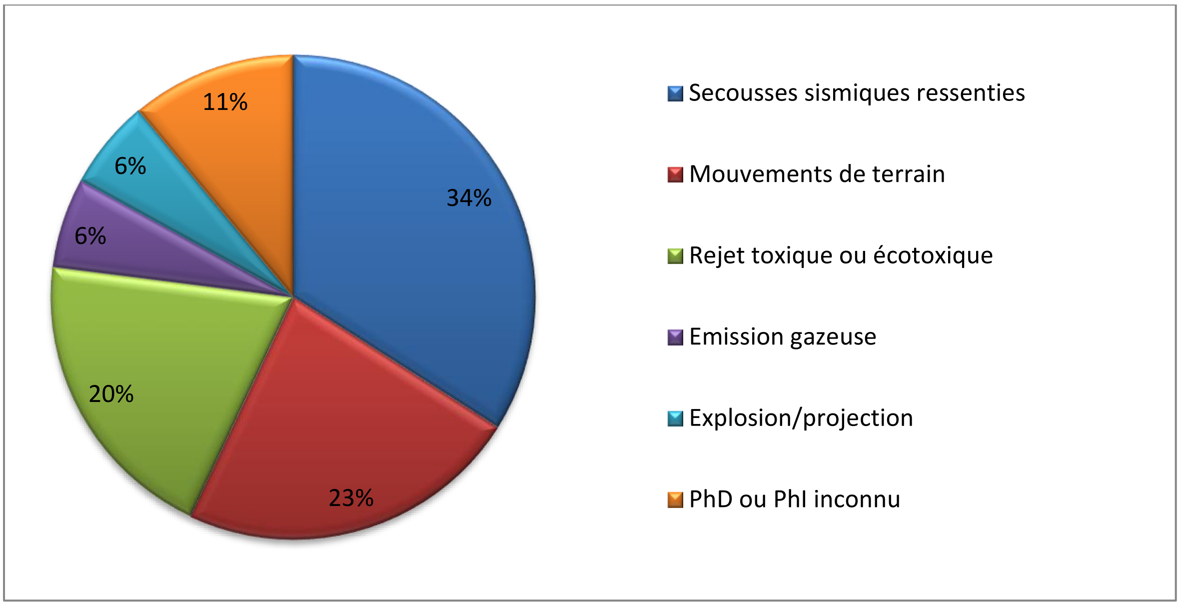

Figure 11. Type and proportion of dangerous or impacting phenomena in deep geothermal accidentology

In three unusual accidents, a landslide caused a rupture of the well casing, leading to a surface leak. These accidents reflect the importance of appropriately choosing the site of implantation of the wells with regard to natural risks, in particular landslides.

When the accident leads to uplift or subsidence and geothermal drilling is located in urbanized areas (which is usually the case), the consequences on housings and infrastructures can be significant. For example, accidents in Baden-Württemberg in Germany (Staufen, Landau 2...) or in the Grand Est region in France[14] (Lochwiller, Kirchheim, Hilsprich), whose origin is generally the same, namely a water intrusion in sensitive formations leading to their collapse by dissolution (salt, gypsum) or their swelling (anhydrite, clay) (Catoire et al., 2017). This type of intrusion may result from a lack of knowledge of the geology of the site, poor cementing of the wells, absence of control of water inflows and/or excessive depletion of the reservoir due to a lack of reinjection (or partial reinjection) of the geothermal fluid underground. Even if these accidents have occurred in the field of surface geothermal energy, they reveal geological phenomena (dissolution or swelling of water-sensitive formations) which must be considered in the design and drilling of all wells, whether superficial or deep.

[14] It should be noted that these accidents occurred in the field of superficial geothermal energy, known as “of minimal importance". Their occurrence led to an important update of French regulations in this area (Decree 2015-15 of January 8, 2015). Thus, due to their position in relation to the regulatory zoning established since 2015 (MEDDE, 2015), now these types of works would require the opinion of an approved expert or even an authorization under the mining code. Therefore, the occurrence of such accidents is much less likely today, when the drilling operations comply with this regulation.

When the accident leads to perceptible seismic movements, material damage is often minor, but the psychological and media impact can be very strong, particularly as a result of concerns about possible stronger future movements. Thus, the cases of St. Gallen or Basel, in Switzerland, which occurred in the middle of urban areas, led to the temporary or permanent stop of the corresponding geothermal projects. These accidents show that the occurrence of a perceptible induced seismicity[15] is predominant when the geothermal exploitation is carried out in a bedrock (rather than in a sedimentary basin), in deep, faulty and tectonically active formations. However, there are solutions to limit and control this risk, in particular to moderate the injection pressure, to set up a seismic monitoring network in order to monitor the generated seismic activity and to anticipate the occurrence of a possible perceptible earthquake, to inform the local population from the beginning of the project, etc. (see § 7.1 for further details)

In general, it can be noted that the types of accidents observed in the context of deep geothermal energy are not specific to this field but are present in any exploitation of underground resources involving the drilling of deep boreholes : surface gas emissions, leaks linked to well's sealing defects, induced seismicity, geomechanical disturbances linked to poor insulation of evaporite formations, etc.

However, the context of deep geothermal energy provides conditions that are more favorable to certain types of accidents (or inconveniences) and less favorable to others. Thus, the risks of well blowout accidents or surface gas emissions are considered to be less likely in deep geothermal energy than in the case of petroleum exploitation, for example, because reservoirs are generally less pressurized and it is less frequent to encounter formations containing hydrocarbons or toxic gases (except in volcanic environments).

On the other hand, high-temperature geothermal energy, especially in tectonically active areas, seems to provide conditions more favorable to the occurrence of induced seismicity than low-temperature geothermal or conventional oil extraction. It may also be considered that the direct contact of geothermal water with the well casings makes more likely the casings to be damaged the by corrosion in geothermal wells than in the oil wells. Preventive measures against corrosion have been developed accordingly exist: doubling of the casings in front of sensitive aquifers, additional thickness of casings, injection of corrosion inhibitors, periodic control of corrosion by caliper or sonic logging tools, etc.

We will come back in details to these risks, as well as to their prevention or reduction measures, in chapters 4 to 7 of the report.

3.3 ANALYSIS OF SPECIFIC ACCIDENTS

We have undertaken a description of a few accidents in the context of deep geothermal energy[16] (see below), followed by a more detailed analysis, in the form of fact sheets, of six cases that are particularly informative and representative of the

[15] Corresponding approximately to a magnitude of the order of 2 (see definition of "induced seismicity" in the glossary in APPENDIX 1)

[16] Or in other fields (oil production, superficial geothermal) relevant for deep geothermal.

main risks (see APPENDIX 4): Basel (Switzerland), St. Gall (Switzerland), Coulommiers (France), Puna 2 (Hawaii, USA) and Staufen (Germany).

3.3.1 EARTHQUAKES INDUCED BY HYDRAULIC STIMULATION

The production of microseismic events is a direct and expected consequence of hydraulic stimulation operations, where a substantial volume of water is injected under pressure into natural rock fractures, and sometimes of chemical or thermal stimulation operations. What is accidental, however, is the occurrence of perceptive seismic movements experienced by the population.

In deep geothermal drilling, induced earthquakes are mainly produced during the formation testing phase, where hydraulic or chemical stimulation operations made be carried out, but they can also occur during the operational phase.

3.3.1.1 Soultz-sous-Forêts (Bas-Rhin, France)

The Soultz-sous-Forêts site is located 50 km north of Strasbourg. Since 1987, four wells have been drilled down to the naturally fractured granite where a brackish geothermal fluid circulates[17]: three wells of more than 5,000 m depth and one of 3,600 m. For more than 20 years, this international development and research site has been the most advanced in the world in the field of deep geothermal energy. Since 2008, the site has been converted into an industrial electric power plant with a capacity of 2.1 MW_e.

During the formation testing phases, each stimulation generated several thousand seismic events with magnitudes ranging from -2.0 to 2.9 (Cuenot & Genter, 2013). The vast majority of them were microseisms (see definition in APPENDIX 1): out of a total of nearly 45,000 events generated by the stimulation of GPK2, GPK3 and GPK4 wells from 2000 to 2005, only 9 have reached magnitude 2, which is the approximate magnitude whereevents start to be felt by the population (ESG, 2015).

The location ofhypocentres shows their close relationship with geothermal drilling (Figure 12a). It is likely that there is also a structural control of seismicity by fractures and faults, as shown by the anisotropy of the events cloud visible on the plan view (Figure 12b).

[17] http://labex-geothermie.unistra.fr/article200.html

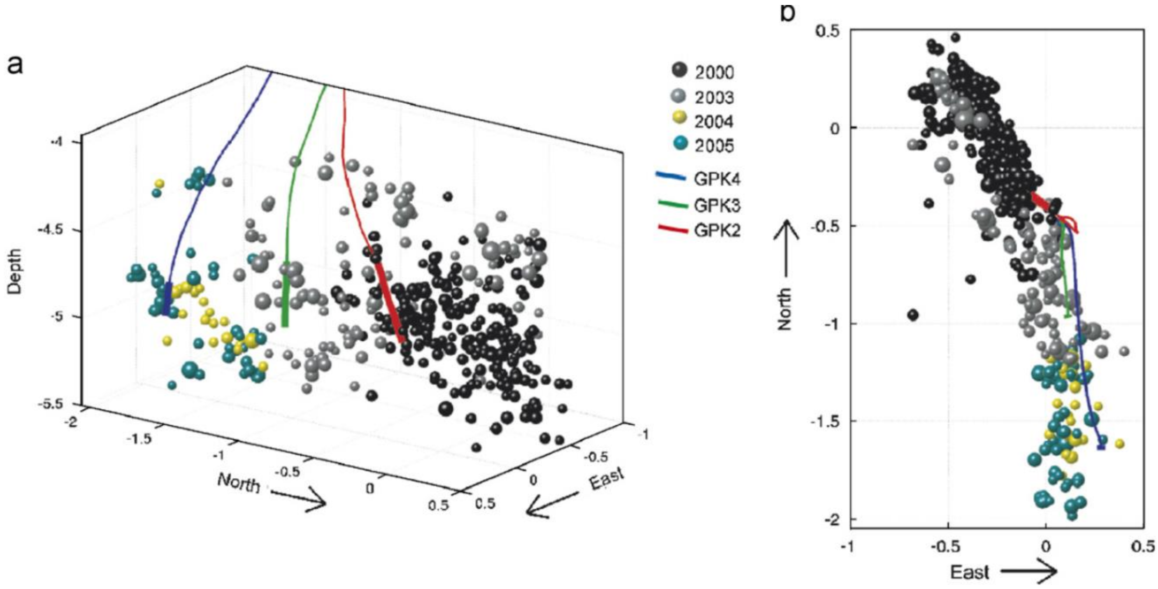

Figure 12. Microseismic clouds recorded during the various hydraulic stimulations carried out at Soultz-sous-Forêts (Charléty et al., 2007)

After the stimulation tests, flow tests were carried out prior to commissioning the plant but in conditions very close to those prevailing during production (ESG, 2015):

- in 2005, a first flow test lasted 6 months, between the production wells GPK2 and GPK4 and the injection drilling GPK3; it generated about 600 microseisms and 2 seismic events experienced by the population, reaching a maximum magnitude of 2.3;
- in 2008 and 2009, three new flow tests were carried out with the existing operational pumps; the seismic activity remained very moderate with a total of approximately 443 events, none of which were experienced, the maximum magnitude being only 1.7;
- in 2010, another water circulation test in operational conditions was carried out for 11 months using a single injection well in which an overpressure in the order of 50 bar (ESG[18]) was applied; this test generated 400 microseisms and 4 events with a magnitude greater than 2 (Cuenot, 2012);
- in 2011, a last water circulation test was done using two injection wells with an overpressure of about 20 bar ; this resulted in only 5 events in 6 months, none of which was felt.

This example shows that taking into account the information obtained during the tests can reduce the number of earthquakes felt by the population.

[18] http://www.es-geothermie.fr/documentation/faq

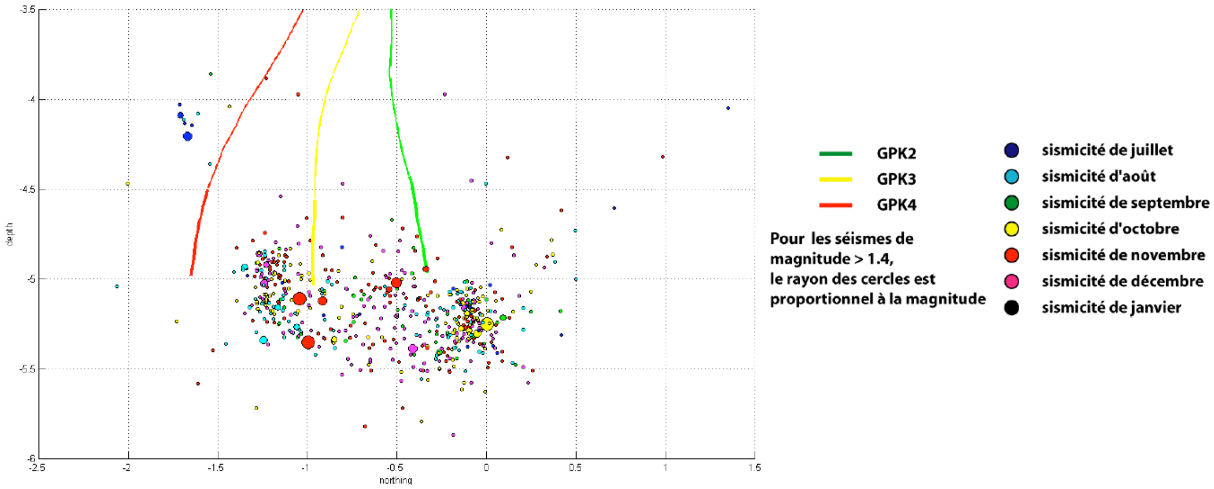

Figure 13. Microseismic activity recorded during the water circulation test of 2005 in Soultz-sous-Forêts (ESG, 2015)

3.3.1.2 Basel (Switzerland)

In 2006, the geothermal project "Deep Heat Mining" in Basel (Switzerland) was the first attempt to construct an EGS system in the country (Géo-Energie. Suisse, 2014). The first well was drilling in the heart of the city and reached about 5,000 m in depth. The subsequent hydraulic stimulation operations resulted in numerous microseisms and at least three seismic events were noticed by the public. These operations were temporarily suspended but at this time an earthquake of magnitude 3.4 occurred, which is exceptionally strong for a geothermal operation (Doherr, 2012). This earthquake caused slight damage to some buildings (cracking or falling plaster) but above all many complaints were filed by the public. It must be remembered that Basel suffered two devastating natural earthquakes in 1348 and 1356, the latter of them destroyed the city and left a mark in the history.

After these events, the operation was abandoned, as well as the corresponding plant project (see details in the fact sheet in APPENDIX 4).

3.3.1.3 Landau and Insheim (Germany)

In the testing phase, the EGS operations in Landau (2009) and Insheim (2010) resulted in earthquakes of magnitude reaching 2.7 and 2.4 respectively, which were felt by the population (Groos et al, 2013) (Figure 14).

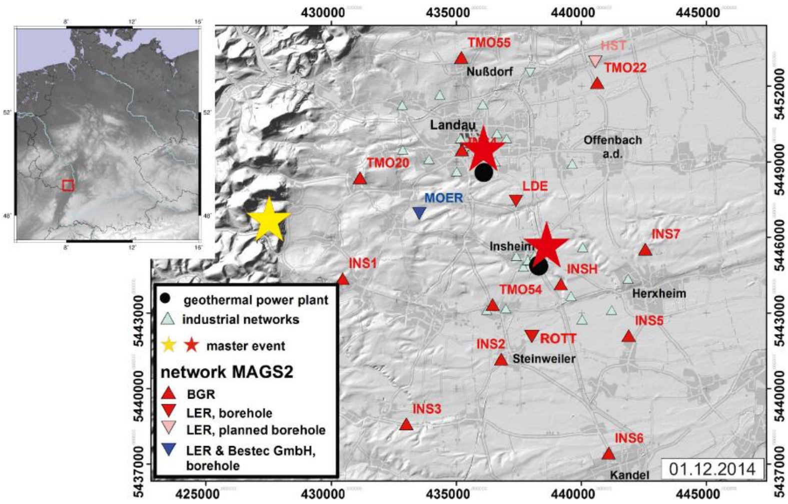

Figure 14. Earthquakes induced by the geothermal operations in Landau and Insheim in Germany (Brüste et al., 2015)

Legend: ● geothermal station, ▲ industry, ▼ seismic monitoring network, ★ earthquake (in red, earthquakes of geothermal nature, in yellow, due to carrier explosions)

3.3.1.4 Cooper Basin (Australia)

On this site, the stimulation tests carried out in 2003, 2005 and 2012 generated a total of more than 45,000 seismic events, the magnitude of which peaked at 3.7 (Baish & Vörös, 2010). The location of these events was initially centered on the injection well and then migrated outwards when the duration of the stimulation increased: it moved about 1 km over a period of 45 days. The authors showed that, like in Soultz-sous-Fôrets, the spatial distribution of induced earthquakes was initially controlled by two-dimensional structures that could correspond to pre-existing faults.

Still inn Cooper Basin, the Habanero geothermal field was the subject of a major hydraulic stimulation campaign in November of 2012, with the aim of improving the connectivity of the deep EGS reservoir (Humphreys, 2014). The campaign lasted 3 weeks during which 34,000 m^3 of water were injected at a depth of 4,077 m at the Habanero fault. A total of 27,000 seismic events were recorded, of which 20,000 could be located on a surface of 4 km^2, with local magnitudes ranging from -1.6 to 3.0. Figure 15 shows that the cloud of events extends mainly on a subhorizontal surface probably corresponding to a fault plane.

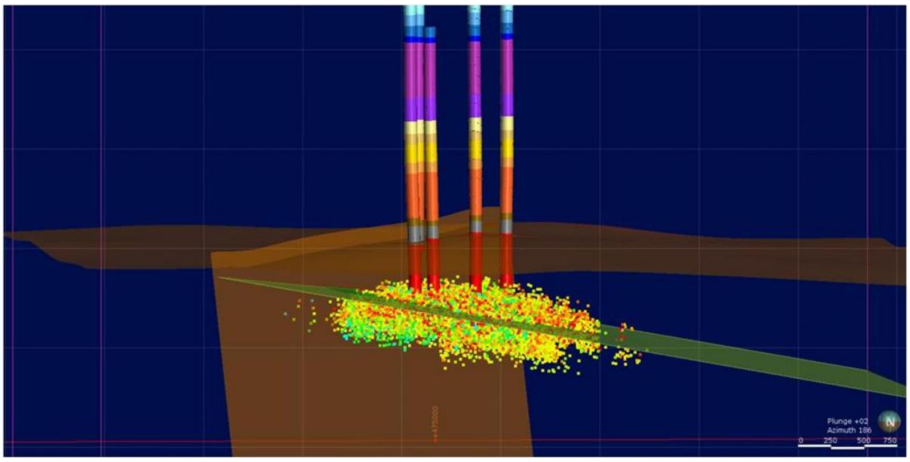

Figure 15. Location of earthquake hypocentres during hydraulic stimulation of Habanero 4 well at Cooper Basin, Australia (Humphreys, 2014)

Legend: the vertical tubes are the geothermal wells (Habanero 4 being the further left one) with the intersected geological formations and the green plan, that of the Habanero fault.

3.3.1.5 Wairakei (New Zealand)

Maréchal et al. (2008) reported that 90 microseisms of magnitude 1 to 2 (three of which were felt) occurred on the Wairakei field during high pressure injection. Seismic events began within 24 hours after the injection at an overpressure of 44-55 bar.

3.3.1.6 The Geysers and Salton Sea (California, USA)

Salton Sea is one of the largest geothermal sites in the United States. The geothermal fluid, which is very hot, is pumped about 2 km deep at a rate of 10 Mm^3/month and produces surface steam. Approximately 81% of this steam is condensed and reinjected into the reservoir, with the remainder being lost in the atmosphere. Therefore, there is a chronic geothermal fluid deficit since the start of operations in 1982. At the same time, there has been an upsurge in earthquakes number (McGuire et al., 2015). From 1981 to 2012, more than 10,000 earthquakes and microseisms with a magnitude greater than 1.75 were recorded. This "seismic background noise" can be modeled by a linear combination of injection and extraction rates (Brodsky & Lajoie, 2013): the seismicity of recent years is in fact correlated with the net volume of fluid lost between extraction and injection.

At the Geysers, the study of the seismic events induced by geothermal operations between 2008 and 2009, shows that several mechanisms can operate at different scales (Martinez-Garzon et al., 2015): predominant thermoelastic[19] mechanisms, induced by the thermal contrast of the injected fluid in the near-field of the reinjection well (see chapter7.1.2.2) as well[20] as poroelastic mechanisms which, during periods of high reinjection, induce an increase in the pore pressure at greater distance.

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[19] In other words, it is relative to the elasticity of a body and its expansion under heat.

[20] In other words, it is relative to the elasticity of fluid containing porous material

3.3.2 GROUND MOVEMENTS RELATED TO INTRUSIONS OF GROUNDWATER INTO SENSITIVE FORMATIONS

3.3.2.1 Uplifting of the surface due to the swelling of an evaporite formation

This is the main mechanism of ground surface uplift in recent accidents, observed in superficial geothermal environments. This mechanism is the result of the swelling of a water-sensitive, shallow formation, following an accidental intrusion of non-geothermal water. This is notably the case for anhydrite ($CaSO_4$) layers which can hydrate in gypsum ($CaSO_4$, $2H_2O$) in contact with water unsaturated in sulphates, resulting in an increase in the volume of the rock matrix of around 60% (Weber, 2011).

In France, this type of phenomenon occured recently in the village of Lochwiller in the Bas-Rhin (Boissavy & Garroustet, 2013, Antoine, M., 2013, Miguet, 2014, Ercket, G., 2015). In this case, a 140 m deep geothermal borehole intended for individual housing heating was drilled. The swelling of an anhydrite layer resulted notably from poor recognition of the local geology, poor cementing of the borehole and the difficulty of controlling the artesian water outflow originating from 60 m depth.

A similar phenomenon occurred in Kirchheim (Bas-Rhin, France), approximately ten kilometers in distance of Lochwiller (Miguet, 2014, Catoire et al., 2017). The swelling of the anhydrite layer was caused by water infiltration in a borehole made in 2007: the lesser importance of this water inflow would explain the lesser damage which, for the moment, is only affecting one apartment building.

In Baden-Württemberg (Germany), six comparable sites were impacted by this phenomenon (Catoire et al., 2017). The most known is the one in Staufen-im-Brisgau, where a superficial geothermal drilling went through an anhydrite layer in the fall of 2007 (see details in the fact sheet in APPENDIX 40). This operation induced a swelling of the surface of the ground which impacted hundreds of buildings (Weber, 2011; Libération, 2013).

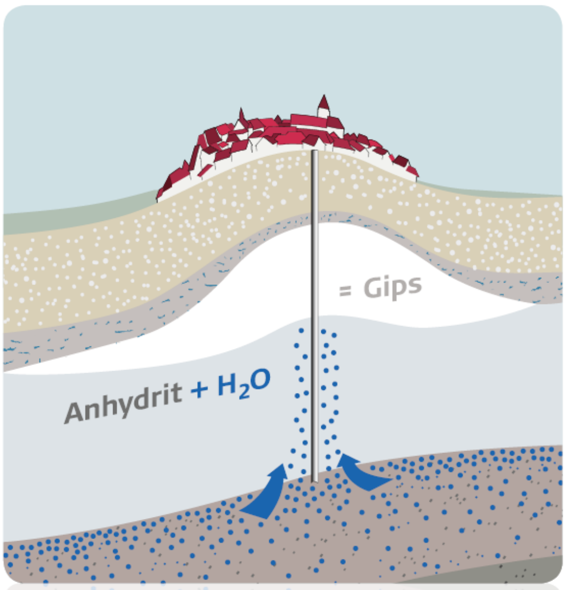

Figure 16. Schematic of the swelling of the anhydrite (anhydrit) during its transformation into gypsum (gips) shortly after the drilling operation in Staufen-im-Brisgau, Germany (Weber, 2011)

3.3.2.2 <u>Subsidence or collapse associated with the dissolution of a saline formation</u>

There is a case of ground subsidence due to the dissolution of a saline formation in the context of superficial geothermal but no known case of ground collapse.

The ground subsidence occurred in Hilsprich (Moselle, France), about one year after the drilling of two superficial geothermal boreholes with depths of 95 and 99m (Barras, 2015; Carton, 2015; Bezelgues-Courtade et al., 2012; Catoire et al., 2017). As a result of the difficulties encountered during the drilling operations, the wells could not be properly cemented, which caused the connection between the surface water aquifer and a 20 m thick salt layer located at a depth of about 100 meters. Due to the pressure difference between the fresh water aquifer and a deeper salty water horizon, a fresh water percolation occurred and resulted in the dissolution of the salt which resulted in surface sinking (Figure 18). A sinking basin of more than 1 km long was formed with a vertical amplitude reaching 90 cm in the center, causing damage on about fifteen houses and on the road network up to 450 m around the site.

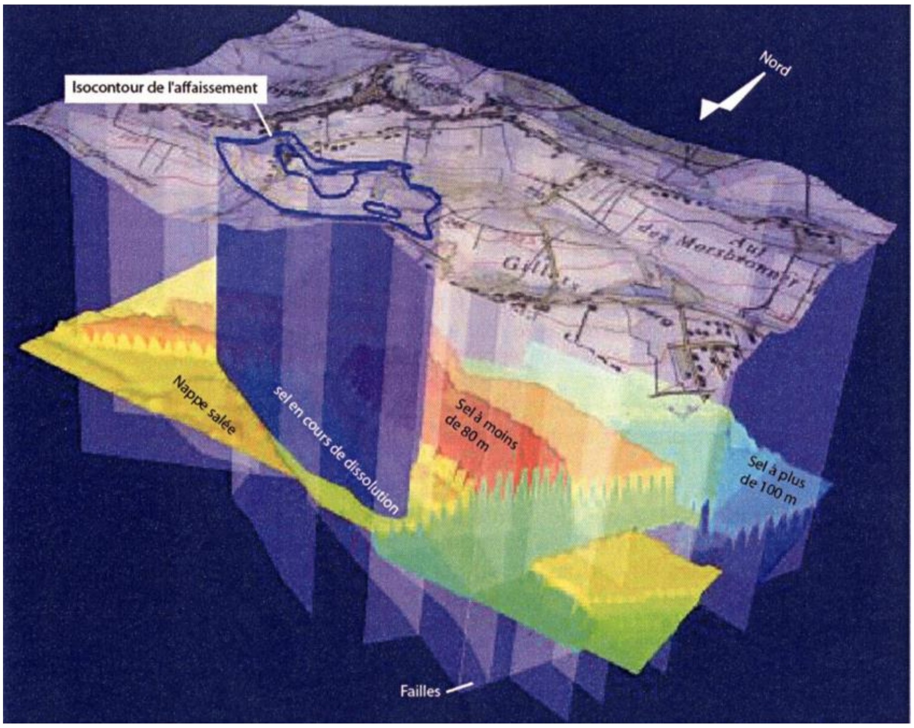

Figure 17. 3D schematic representation of the salt roof and of the collapse zone (blue curves) at Hilsprich (Carton, 2015)

Although there has never been any ground collapse recorded in the field of geothermal energy, this type of event is possible in any type of context where a well is drilled through evaporites, as demonstrates by the example in the oil context of Haoud Berkaoui in Algeria (Morisseau, 2000). At this site, an oil production well was abandoned without casing or plugging (Figure 18). This well brought into communication a deep overpressured aquifer with an overlying salt layer, of which it was separated by an impermeable layer. The salt was dissolved, which led to the formation of a large underground cavity and then an observable collapse at the surface, about 300 m wide and 75 m deep.

A similar accident was observed at Wink Sink (United States, Texas) following the corrosion of a non-cemented oil well (Baumgardner et al., 1982, KS Johnson, 1987 and 2001).

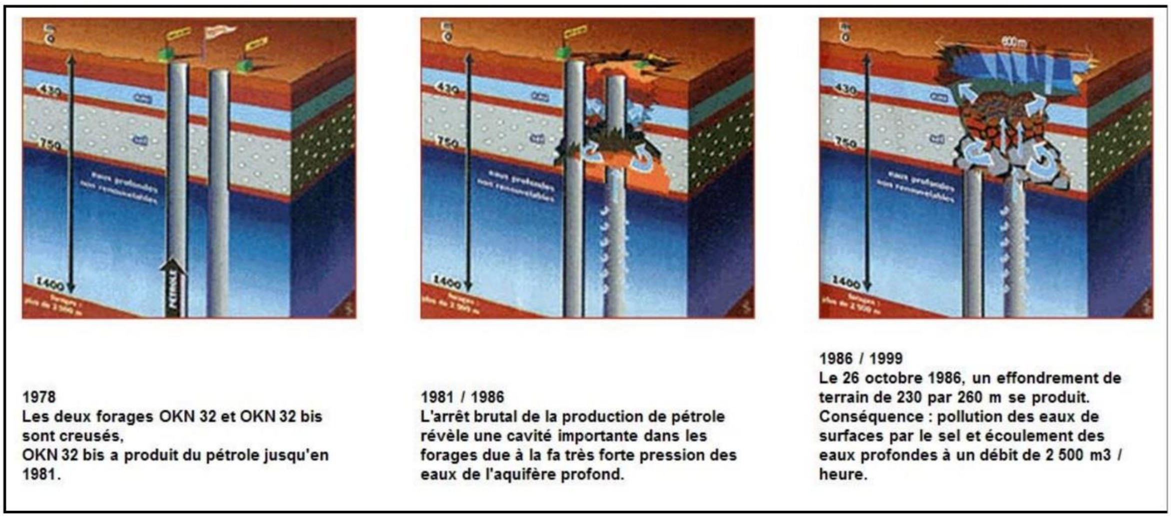

Figure 18. of the collapse of Haoud Berkaoui, Algeria (according to http://www.h2o.net/magazine/urgences/catastrophes)

3.3.3 Intrusion of geothermal fluid into a freshwater aquifer

3.3.3.1 Coulommiers (Seine-et-Marne)

In 1996, in Coulommiers, a leak in a deep geothermal well led to an accidental intrusion of geothermal fluid into superficial freshwater aquifers. It was a fluid from the Dogger reservoir, located about at depth of 2,000 m. This leak occurred in a re-injection well and was detected after an abnormal pressure drop was observed at the head of this well between October 1995 (pressure 10 bar) and July 1996 (pressure of 1.2 bar). Logs revealed two perforations in the casing, located about 50 m and 440 m deep, respectively in front of the Champigny limestones (Tertiary) and of a chalk horizon. These two formations each contain a freshwater aquifer, locally exploited for the supply of drinking water. These perforations probably appeared in October 1995: the leak, which was initially low, probably reached its maximum flow rate (i.e. 70% of the produced 135 m^3/h) in April 1996, leading to a total leakage volume of 660,000 m^3. Due to the low hydrodynamic characteristics of the chalk located here at depth, it was assumed that most of the plume of geothermal fluid flowed out into the Champigny limestones. It was hot water (50 to 85 °), moderately acidic (pH 6.1 to 6.5) but mainly loaded with salts (6 to 35 g/L), dissolved gases (H_2S, CO_2), sulfides and sulfate-reducing bacteria. However, the monitoring of the city's drinking water catchments, located in this same aquifer, did not show any significant indication of water pollution by geothermal fluid. More details about this event are provided in the fact sheet in APPENDIX 4.

3.3.3.2 Belcova (Turkey)

At this geothermal site, located in Belcova, Turkey, the extracted fluid is not re-injected into the geothermal reservoir, located 1 km deep, but in an overlying superficial aquifer, only 150 m deep (Aksoy et al. 2009): it is an alluvial aquifer, used for drinking water and irrigation (Figure 19).

The production well was drilled within a fault naturally draining a mixture of thermal waters and cold waters, coming from different depths. The start of production of this geothermal well has disrupted the existing hydrodynamic equilibrium by accelerating the circulation of the geothermal fluid between the deep reservoir and the surface alluvial aquifer. This has resulted in pollution of this aquifer by hot water (the temperature of the water has reached 22 ° C to 42 ° C in some places) and by various chemical elements of geothermal origin including arsenic, antimony and boron.

Note that this case is mentioned for the record, but it can not be transposed to France, where there is no similar context of operation.

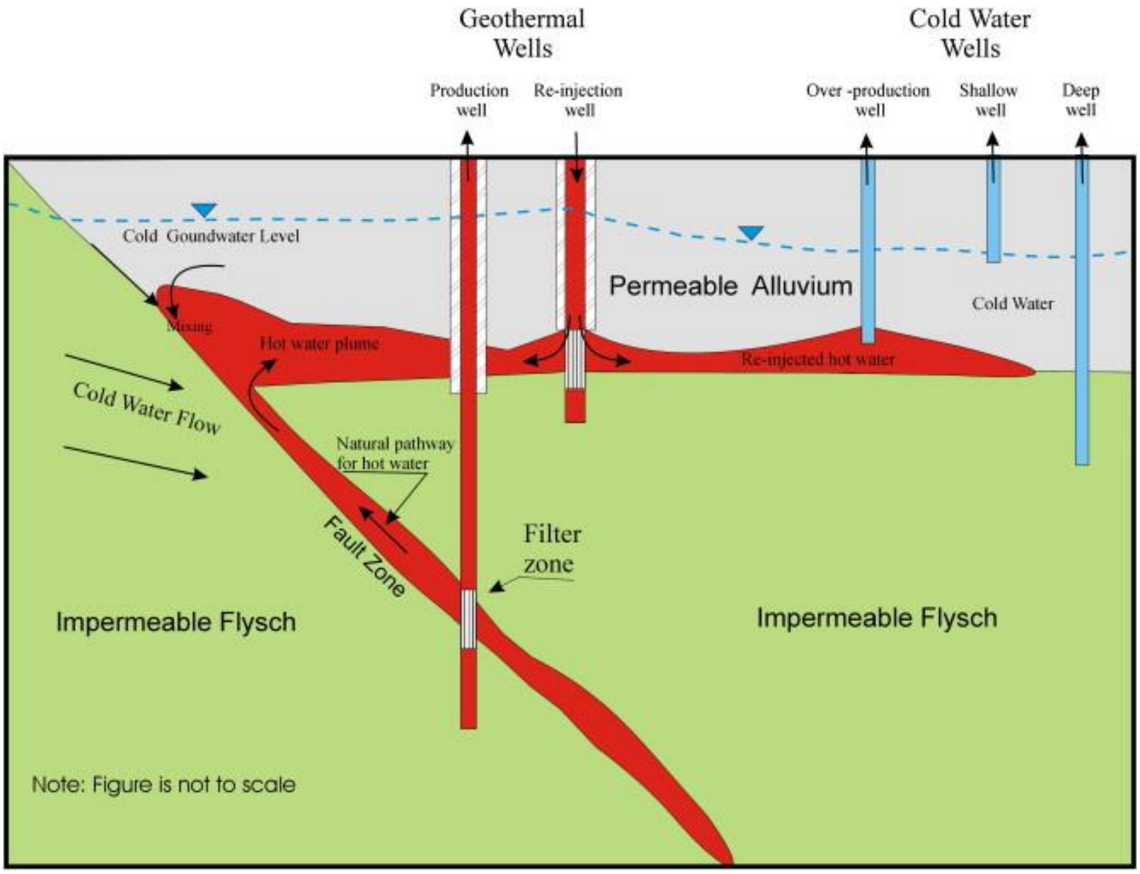

Figure 19. Schematic representation of the path of the geothermal fluid from the deep reservoir (Flysch) to the superficial alluvial aquifer in Balcova, Turkey (Aksoy et al., 2009)

4. CHRONIC IMPACTS AND POTENTIAL INCONVENIENCES RELATED TO DEEP GEOTHERMAL ENERGY

4.1 GENERAL

The lifecycle phases during which a deep geothermal site causes the most inconveniences and potential chronic impacts are the drilling and formation testing phases. In practice, these phases are limited in time: they have a cumulative duration of approximately a few months to one year, whereas the lifetime of a geothermal installation is several decades.

Most of these potential impacts and potential inconveniences are not specific to geothermal drilling and are attributes to any drilling site, whether for drinking water supply or for hydrocarbon recovery. However, we review them hereafter by emphasizing the aspects which most related to deep geothermal energy.

It should be noted that these impacts and inconveniences must be evaluated before the start of the project in the impact assessment (defined in Article R. 122-3 of the French Environmental Code). This study must also present the measures envisaged by the operator to limit them to the best possible extent.

In the villages of Soultz-sous-Forêts and Kutzenhausen (Bas-Rhin, France), located near the Soultz-sous-Forêts geothermal power station, a survey was carried out in the summer of 2012, covering 203 people (Cuenot & Genter, 2013). The perceived most important impacts related to the plant are noise and induced seismicity, followed by pollution and landscape impact (Figure 20).

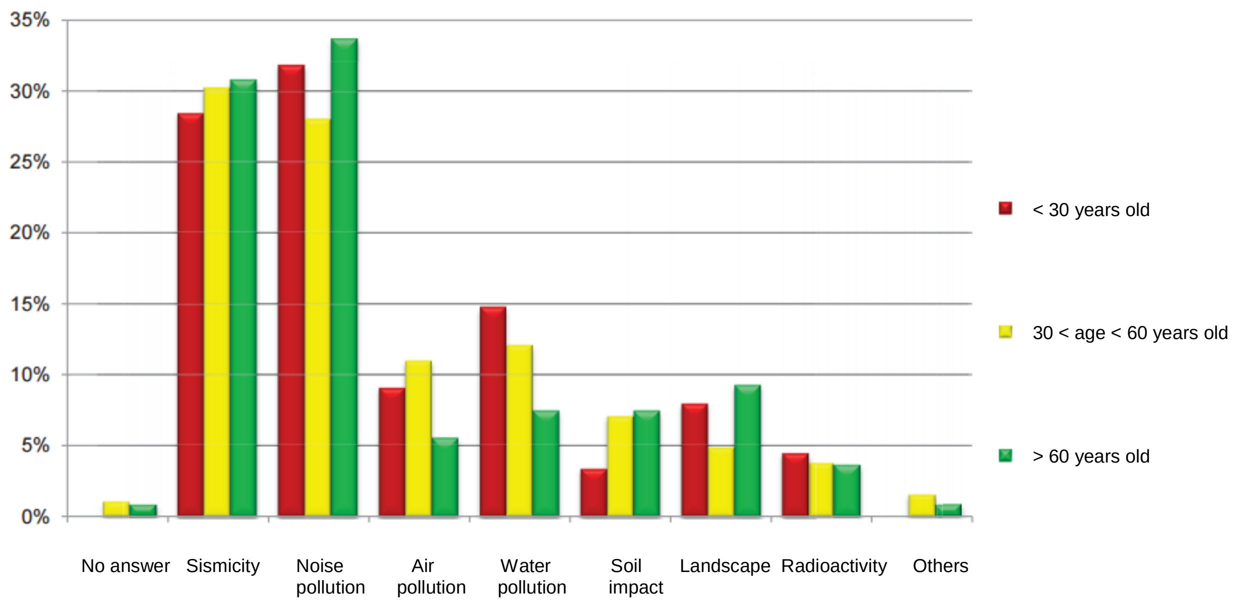

Figure 20. Results of the neighborhood survey carried out in 2012 around the Soultz-sous-Forêts geothermal power station (Cuenot & Genter, 2013)

4.2 LANDSCAPE IMPACT AND LAND USE

4.2.1 IN THE DRILLING AND TESTING PHASE

During the drilling and testing phase, the landscape impact of a deep geothermal site is limited to a temporary disruption caused by the presence of a drilling machine (equipped with an imposing mast) and a fenced lot (Figure 21). The size of their dimensions is 30 to 50 m for the mast height and 4,000 to 8,000 m² for the area of the site. The overall duration of a drilling project of a geothermal doublet is in the order of 6 months to 1 year.

a) in Germany (Meier & Zingg, 2014)

b) in South Africa (DRET, 2011)

Figure 21. Examples of deep geothermal sites

4.2.2 IN THE PRODUCTION PHASE

Once the geothermal resource is proven, the production phase begins, which will induce a definitive landscape impact and a freezing of the soil during the lifetime of the power plant, which is between 20 and 40 years. It should be remembered, however, that the landscape impacts must have been taken into account at the project's stage of feasibility. These impacts are mainly due to the buildings which will house energy production equipment and, in the case of electricity production, cooling installations (condensers). The conventional dimensions of a geothermal power station building are about thirty meters on each side and about ten meters high. A few examples are given in Figure 22. The final footprint will therefore depend on the type of geothermal installation: a district heating system requires much less space than a combined heating and power unit combined with air-cooled condensers (Agemar and al., 2014).

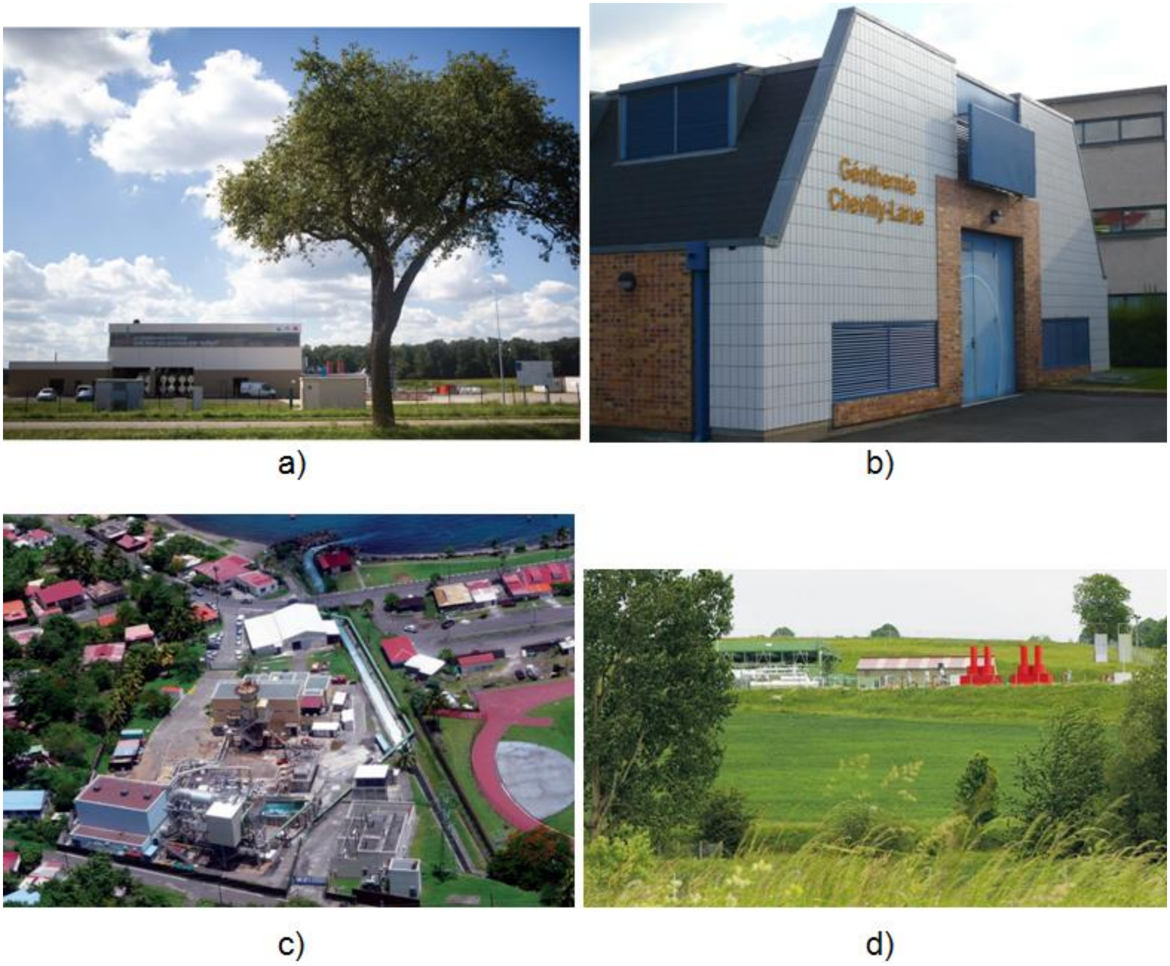

Figure 22. Examples of landscape integration of some geothermal french plants

Legend:
(a) Rittershoffen station, Bas-Rhin, 24 MW_{th} (Leibel, 2016)
b) Chevilly-Larue station, 20 MW_{th}, *Val-de-Marne (http://reseaux-chaleur.cerema.fr/ centrale-geothermique-chevilly-larue-94)*
c) Bouillante station, Guadeloupe, 15 MW_e (www.geothermie-perspectives.fr/)
d) Soultz-sous-Forêts station, Bas-Rhin, 2 MW_e *station (www.geothermie-perspectives.fr/)*

4.3 NOISE AND VIBRATIONS

4.3.1 IN THE DRILLING AND TESTING PHASE

Noise is one of the inconveniences considered by the populations as one of the most important ones related to geothermal energy. The noise and the associated vibrations are mainly produced during the drilling, testing and construction phases of the installations (Webb et al., 1984).

These inconveniences are likely to occur over the entire duration of the deep geothermal site construction, which is about 2 years (about 6 months to 1 year to drill and test, and about 1 year to construct the surface station). During the drilling phase, the work site operates continuously, that is 24 hours a day and 7 days a week: although it is generally moderate and acceptable, the noise level may end up appearing throbbing, especially during quiet periods (night, non-working days).

This noise is mainly due to the operation of the drilling rig, the traffic of vehicles (especially supply trucks) and certain operations (cementation, hydraulic stimulation, venting...).

A specificity of geothermal sites, compared to hydrocarbon extaction sites for example, is that they are generally located in urban areas. To mitigate the effects on residents, noise walls are usually installed (see Figure 21). Drilling companies are also increasingly using drilling rigs specially designed to work in urban environments: the drilling drawworks are replaced by silent hydraulic cylinders, the drill rods are manipulated by an automatic arm, the thermic engines are replaced by electric motors, etc. In addition, the noisiest operations can be planned so as to avoid quiet times and the local residents may be informed ot these operations beforehand.

The noise emitted by the drilling equipments is mainly in the low frequencies (Meier & Zingg, 2014) and therefore exceeds the vibration range. During the digging of the second geothermal well at Rittershoffen (France), Maurer et al. (2016) measured vibrations in the 2-20 Hz range, but failed to distinguish the vibrations induced by these operations from those generated by the environment.

4.3.2 In the production phase

The noise pollution during the production phase of a geothermal power station is lower compared to the drilling and testing phase. On the other hand, it can be continuously produced for 20 to 40 years.

The main sources of noise emission are related to geothermal electricity plants and are due to the fans of the cooling installation, the turbine, the feeding and injection pumps (Meier & Zingg, 2014). By choosing appropriate equipment on the market (silent air coolers) and by means of protective measures (soundproof building), these emissions can be fully maintained within the limits of the regulatory requirements.

With the aim of constructing an EGS-type geothermal power plant in Avenches (Switzerland), the town council visited the german sites of Landau and Insheim, which are located in urban and industrial areas (Buache, 2013): they found that, given the ambient background noise, these two plants did not generate any perceptible or annoying noise inconvenience.

This is not the case on the Milos site (Greece), where noise is perceived by the population as the third factor of discomfort (Mendrinos & Karytsas, 2006). Similarly, on the site of Bouillante (Guadeloupe), some residents complain of noise and vibration (UVED, 2011). In these two cases, mitigation solutions have been proposed: insulation of the installations, reduction of turbine speed, adjustment of operational hours, noise barriers, etc.

Concerning vibrations, measurements were carried out at the ECOGI plant in Ritterschoffen (Richard et al., 2016). The authors found that the particle velocities induced by the operation of the plant were not important enough to be perceived by humans in the plant’s surrounding environment.

4.4 INCONVENIENCES LINKED TO THE INCREASE IN ROAD TRAFFIC

The increase in road traffic linked to a geothermal site mainly concerns the drilling and testing phase, in particular the phase of installation or deinstallation of the site. For illustration, on the site of Ritterschoffen, 70 trucks followed one another for 9 days during the installation (ECOGI, 2012).

The resulting inconvenience is noise, vibration, dust and an increased risk of traffic accidents in the vicinity of the site. However, these inconveniences are usual on a civil engineering site and have nothing specific to geothermal energy.

Once the site is installed, traffic drops to an average of 5 to 10 trucks per day. Traffic can be during the day or the night, but is reduced to a minimum during the night.

4.5 POTENTIAL IMPACT ON ECOSYSTEMS

Like any industrial project, a geothermal site, particularly during the initial construction phase, can have an impact on the fauna and flora: disturbance of animals (especially during the breeding season), damage to sensitive plant species, etc. It should be noted that geothermal power stations are often installed in already urbanized areas, which limits the additional impacts linked to the plant.

The impacts mentioned in the literature are few. At the Milos site in Greece, Mendrinos & Karytsas (2006) reported an incidence of venting on the local flora (several burnt cedars).

At certain sites, the geothermal fluid is not re-injected underground but is released into the sea (this is the case, for example, at the Bouillante site in Guadeloupe), which may raise the question of the impact of this release on the marine ecosystems (Maréchal et al., 2008). In the case of Bouillante, studies have shown that this impact is negligible, in particular because there are already many submarine geothermal sources coming from the same reservoir (ADEME-BRGM, 2004).

In France, apart from the case of Bouillante, the geothermal fluid is always reinjected underground, usually in its source aquifer (doublet principle), thus avoiding any impact of this on ecosystems.

4.6 POTENTIAL IMPACT ON THE WATER RESOURCES

4.6.1 QUANTITATIVE IMPACT

In the drilling phase, the fresh water requirements are the same as for any other drilling and are mainly involved in the preparation of the mud (drilling fluid). It is estimated that about 1 m^3 of water is required per m^3 of drilling mud and that about 5 times more mud is required than the total volume drilled (Clark et al., 2011). This represents several dozens of cubic meters of water per linear kilometer drilled.

In the stimulation phase, however, much more water is needed. The required volume can range from a few thousand cubic meters to tens of thousands of cubic meters for an EGS site, for example (Clark et al., 2011). Note that part of this volume is theoretically recovered by pumping after the stimulation phase.

In the operating phase, the main water requirement concerns the secondary cooling circuit, in the case of a water heat exchanger, which operates in a closed loop.

The freshwater required for all of these operations is usually taken from shallow aquifers, streams or water bodies. The impact of these draws depends on the local context and has to be assessed on a case-by-case basis as part of the impact assessment.

Note that the aquifers exploited for their geothermal resource do not generally contain drinkable or drinkable water. On the other hand, the geothermal water collected there is generally reinjected into the same aquifer. Therefore, even if these aquifers were to constitute a potable or drinkable water resource, the geothermal operation would not have a quantitative impact on this resource.

4.6.2 Qualitative impact

In the drilling phase, the only qualitative impact of the geothermal project on the water resources, apart from an accidental discharge (see Chapters 5 and 6), could come from the use of unsuitable drilling mud.

Indeed, in poorly consolidated and highly permeable soils, the drilling fluid can infiltrate into the soil during the advancement. This phenomenon, called "mud circulation loss ", is easily detectable and generally quickly treated by the driller. Nevertheless, it is sometimes inevitable that a certain volume of mud will spread in the environment of the well.

Therefore, when drilling surface formations and any deeper sensitive aquifers, it is required that this drilling be carried out with a drilling fluid whose composition has no possible impact on these aquifers. It is also an obligation included in the prefectural decrees regulating the work, not only in geothermal energy, but for all drilling work in France. Usually, it is a simple water-based mud mixed with bentonite (bentonite sludge).

In the test phase, chemical stimulation operations use different types of acids (hydrochloric acid, hydrofluoric acid, potassium chloride, ammonium chloride) and sometimes anticorrosive additives and precipitation inhibitors (Hirschberg et al., 2015). However, these substances generally do not migrate far from the well because they react quickly with the present minerals. Thus, at the Soultz-sous-Forêts site, 15 tons of dilute hydrochloric acid were injected between 2003 and 2005 during chemical stimulation operations: according to Maréchal et al. (2008), this would have dissolved the carbonated fillings only a few meters around the wells, (approx. 0.5 to 3.5 m). These acidification operations, which aim to establish a good hydraulic connection between the well and the reservoir formation, are not specific to geothermal wells and are common whatever the application of the well, including water supply wells.

4.7 Emissions of gases, aerosols and odors

In this section are discussed chronic emissions of gases and aerosols , and not accidental emissions which will be discussed in Chapter 5.1. Such emissions can occur during the drilling phases (engine emissions from the various machines present on the site), tests (degassing of the geothermal fluid extracted before its reinjection) and production (mainly in cases where the geothermal fluid is not reinjected underground).

Indeed, the geothermal fluid is either a water potentially charged with gas of deep origin, or water steam capable of conveying the same type of gas. Several authors have analyzed the gases emitted with geothermal water steam (Mendrinos & Karytsas, 2006, Marchand et al., 2015). These are non-condensable gases, the most frequently mentioned being CO_2, CH_4, H_2S, CO, N_2, NH_3 and H_2, as well as traces of Ar, He, HF, SO_2 and aerosols (Table 3). However, the concentration of these emissions can be reduced by sending these gases to cooling towers where they are diluted in a large air stream.

There is generally no mentioning about the need to treat these emissions, except in the case of H_2S. In addition to its toxicity, this gas has a nauseating odor, already reported in its natural state on several geothermal sites: Milos in Greece (Mendrinos and Karytsas, 2006), Bouillante in Guadeloupe (UVED, 2011), Larderello in Italy (Bottai & Cigni, 1985), Olkaria in Kenya (Chauvet, 2014). In the United States, Kagel et al. (2007) report that 99.9% of H_2S is now captured in the geothermal plants and converted to sulfur: H_2S emissions from geothermal energy have been decreased from 860 kg/h to 90 kg/h in a few years, while the same period, the production was multiplied by four.

Table 3. Main non-condensable gases present in the geothermal steam of high temperature deposits

Reference	CO_2	CH_4	H_2S	H_2	N_2	CO	NH_3
Fedeli et al. (2016)			+				+
UCS (2016)	+	+	+				+
Webb et al. (1984)	+	+	+		+	+	+
Marchand et al. (2015)	+	+					
Mendrinos & Karytsas (2006)	++		+				
Clark et al. (2011)	++	+		+	++		
Kagel et al. (2007)		++	+				
Bottai & Cigni (1985)	78 to 94%	1 to 12%	2 to 7%	0 to 2%	1%		
Herzberger et al. (2010)	30 to 90%	5 to 10%			5 to 30%		

Legend: + gas present, ++ abundant gas

Note that Webb et al. (1984) also mention the presence of SO_2, which does not exist in geothermal steam, but results from the oxidation of H_2S when it is emitted into the atmosphere.

For aerosols, they can be found in the plumes emitted by certain geothermal steam capture sites, at a rate of about 1 kg/MWh produced (Kagel et al., 2007) or in the emissions of certain cooling towers, under the form of boron, mercury and arsenic salts (Webb et al., 1984).

4.8 EMISSIONS OF GREENHOUSE GASES

The carbon impact of deep geothermal energy is much lower than that of fossil fuels (Mendrinos & Karytsas, 2006; Berrizbeitia, 2014). By compiling data from eight geothermal projects in Switzerland, the United States and Germany, Hirschberg et al. (2015) have estimated that total greenhouse gas emissions during the lifecycle of a project calculated via the Life Cycle Assessment (LCA), ranged from 17 to 60 g/kWh for CO_2. This value is somewhat higher than other sources of renewable energy, but is much lower than that of fossil fuels or even nuclear power (Table 4).

*Table 4. Carbon emissions from the main sources of energy according to their LCA (according to ADEME, 2010 except * Hirschberg et al., 2015)*

Energy source	Emissions (gCO_2/kWh)
Wind power	9-10
Hydroelectric	10-13
Solar thermal	13
Biomass	14-41
Geothermal *	17-60 *
Nuclear	66
Natural gas	443
Oil	664-778
Coal	960-1050

The main greenhouse gas emissions are linked to the drilling phase because it is generally necessary to use heat engines to drill, transport equipment, install the installations and so on.

It has been shown above that the operation of geothermal resources can also bring to the surface some deep gases, some of which have a greenhouse effect (CO_2, H_2S, CH_4, NH_3): this is mainly the case of high-temperature stations using geothermal steam. For example, at the Bouillante (Guadeloupe) site, a LCA shows that approximately 90% of greenhouse gas emissions occur during the production phase (Marchand et al., 2015). Their order of magnitude varies from 38 to 47 gCO_{2eq}/kWh depending on the considered case.

4.9 RADIOACTIVITY

Deep geothermal operations do not in themselves generate radioactivity, but they lead to bringing to surface two types of radioactive materials originating from the deep levels:

- drill cuttings: these are limited volumes of material (about 20 m^3 per drilled kilometer) produced during a relatively short phase. It is recommended that the radioactivity of these excavated materials be systematically measured during their recovery and treated as necessary (Hirschberg et al., 2015);

- the geothermal fluid, produced in greater quantity and during long period of time; this fluid can transport radon and radium, which can generate radioactive radiation through the pipeline within which it circulates (primary circuit) (Kreuter, 2011, Berrizbeitia, 2014, Hirschberg et al., 2015).

Radium can also be incorporated by precipitation into deposits in the surface pipes (Eggeling et al., 2013). These are mainly deposits of sulfates (barium, strontium) but generally not carbonates. In Bruchsal (Germany), where this type of deposits is predominantly carbonated, the specific activity is[21] approximately 100 Bq/kg. In Soultz-sous-Forêts (Bas-Rhin, France) the precipitation of other elements is observed, such as polymetallic sulphides, in the cold part of the station, at the level of filters and exchangers (Cuenot & Genter, 2013), and also the transport of granite particles in the suspension. The geothermal fluid has a total specific activity of the order of 170 to 180 Bq/kg (Larochelambert, 2013). In this site, radioactivity induced on humans is monitored by the ASN[22] which mentions a radioactive dose flow rate[23] of 11 µSv/h. Although it is low, this value could lead to long-term external irradiation: radiation protection measures have been put in place for employees and workers.

4.10 CONCLUSION

The inconveniences or impacts of chronic nature, generated by a deep geothermal installation are not, for the most part, specific to geothermal energy.

Concerning the impact on the landscape, it is most important at the time of wells drilling and testing, during which a site is installed on an area of approximately 4,000 to 8,000 m^2, with a derrick usually visible from far away. However, this phase is relatively short (6 months to 1 year). In the production phase, a geothermal power station takes the form of an industrial site of rather modest size, comprising one to a few buildings, which can be integrated relatively easily into a landscape, especially when this landscape is urban or industrialized.

As with any civil engineering project, geothermal drilling generates noise and additional truck traffic, which can be felt as a source of inconvenience by the population, particularly in residential areas. However, these inconveniences are limited to a period of a few months to a maximum of one year. Moreover, there are many ways of limiting these inconveniences as much as possible (anti-noise walls,

[21] The specific (or massic) activity is the number of disintegrations per time and mass units, expressed in Becquerel per kilogram (Bq/kg) or per liter (Bq/L). In France, most soils have uranium-238 activity between a few Bq/kg and a few hundred Bq/kg, with an average around 40 Bq/kg (dry soil). In some granitic soils, however, one can reach 1,000 Bq/kg of dry soil. For water, uranium-238 activities range from 0.01 to 0.1 Bq/L for surface water and up to 1.5 Bq/L for groundwater (http://www.irsn.fr/FR/Larecherche/publications-documentation/fiches-radionucleides/environnement/Pages/Uranium-naturel-environnement.aspx#.WCsVbrLhBhE).

[22] Nuclear Safety Authority, an organization which, on behalf of the State, controls nuclear safety and radiation protection in France (www.asn.fr).

[23] the Sievert (Sv) makes it possible to account for the biological effect of an absorbed dose, produced on a living organism. The average natural radioactivity in France is in the order of 2.4 mSv/year, equivalent to 0.27 µSv/h. For comparison, a single ray-scan emits around 10 µSv.

less noisy drilling rigs, planning noisiest operations outside quiet times, etc.). In the production phase, the noise generated by a geothermal power plant remains generally moderate, and not perceptible, notably due to the construction of noise-cancelling buildings. However, on certain sites,especially in geothermal electric power plants, noise inconvenience may remain.

Like any industrial project, the drilling and construction of a geothermal power station can also have an impact on local fauna and flora. It is the responsibility of the operator to evaluate it in their impact assessment. It should be noted, however, that geothermal sites are often located in already urbanized or industrialized areas, which generally limits the additional impacts associated with the plant.

Water resources are generally not impacted quantitatively by drilling or by operating a geothermal power station. The most water consuming phases are hydraulic stimulation operations, which may require several tens of thousands cubic meters of water. Again, it is up to the operator to assess the impact of these withdrawals in the specific context of the site. From a qualitative point of view, except in the case of accidental discharges, geothermal well drilling, testing and operation have no reason to lead to a degradation of the quality of aquifers or surface waters.

Outside from an accidental context, which will be discussed in the following chapters, the main emissions of gas linked to a geothermal operation are due to degassing of the geothermal fluid. Such degassing takes place, for example, during formation tests, where geothermal fluid is pumped and stored in a temporary basin on the surface. These tests take place over a limited period, ranging from a few days to a few weeks. For high-temperature volcanic sites, however, these emissions can be extended over the entire production phase. In all cases, these emissions must be analyzed and their impact on the air quality assessed in the specific context of each site.

Concerning the carbon footprint, deep geothermal energy benefits from a highly positive balance: the total CO_2 emissions calculated over the lifetime of a geothermal project vary between 17 and 60 g/kWh produced, i.e. one to two orders of magnitude less than oil or coal.

Finally, as far as radioactivity is concerned, the geothermal fluid can cause radon and radium to rise to the surface, which are able to generate radioactive radiation through the equipment and pipelines that transport this fluid (primary circuit). This is not a risk for the residents but for the workers, who must be subject to radiation protection and monitoring measures, in accordance with the rules in force in all extractive industries.

5. ACCIDENTAL FLUID RELEASES AT THE SURFACE

5.1 WELL BLOWOUTS

5.1.1 CRITICAL EVENT

A blowout is an uncontrolled outflow of fluid from a well. This fluid may be gaseous or liquid. If the release point is at the wellhead, it is called "surface blowout". If it is located along the well underground, it is called "underground blowout". Only the first case is discussed here, the second being discussed in chapter 6.2.

In general, the risk of blowout in deep geothermal is lower than in other activities relying on the drilling deep wells, for example in oil and gas. One reason for this is that it is less frequent, during a deep geothermal drilling, to cross horizons containing gaseous hydrocarbons or other pressurized gases than in the case of oil drilling (where the goal is precisely to reach horizons producing oil or gas). In most contexts in France, whether in the Paris basin or in the Alsacian rift, geothermal reservoirs are not much pressurized, which limits the risk of eruption.

However, this risk cannot be ruled out, as we have seen in the chapter on accidentology (§ 3), through the case of St. Gall (Switzerland) or of gas blowouts that occurred in volcanic contexts, leading sometimes to serious accidents: Agua Shuca (El Salvador) in 1990, Zunil 1 (Guatemala) in 1991, Puna 2 (Hawaii) in 1991. It should be noted, however, that these blowouts occurred at a time when well blowout preventer stacks (BOP) were not required for shallow geothermal operations (for example, less than 2,500 m in the United States: Webb et al., 1984). Today, these devices are used systematically, especially in France.

5.1.2 INITIATING MECHANISMS AND SCENARIOS

5.1.2.1 In the drilling phase

During the drilling phase, a blowout can only result from the succession of two undesirable events:

- on the one hand, an inflow of fluid under pressure within the well (“kick”), in spite of the counter-pressure exerted by the mud column; such an inflow may be related, for example, to insufficient mud density, too fast drill string maneuvering (swabbing), drilling through unanticipated overpressured formations, mud circulation loss or defective cementing (Lahaie, 2015b; Galin, 2000; Hervé, 2009; Faessler, 2014; Bauer et al., 2015);
- on the other hand, a loss of integrity of the well safety enveloppe (constituted on the borehole walls by the cemented casings and at the wellhead by the BOP), preventing the kick to be properly controlled and evacuated from the platform in a safe manner.

We can recall here the case of the geothermal drilling in St. Gall (Switzerland) where gas composed of 95% of methane suddenly invaded the well (Moeck et al., 2015). The injection of heavy mud carried out to control the kick led to the seismic event felt by the population (see sheet in APPENDIX 4).

5.1.2.2 In the testing phase

In the flow testing phase, the notion of "blowout" is less obvious since the well is deliberately put into production, that is to say, with controlled inflow. In this phase, a fluid outlet with an abnormally high flow rate or through an undesired path could be considered as a well release or a "blowout". This type of event could result from an abnormally high pressure of the geothermal fluid and/or a loss of integrity of the well envelope (Kagel et al., 2007; Hervé, 2009; Rouquet, 2010; Ecorem, 2011; Cuenot, 2012; Reith et al., 2013).

5.1.2.3 In the production phase

In the production phase, a blowout could theoretically result from a loss of containment at the wellhead (Christmas tree), which would lead to an uncontrolled release of geothermal fluid. No accidents of this type have been reported in the accidentology.

5.1.3 Effects and potential consequences

The potential effects of surface blowout are highly dependent on the pressure, temperature and nature of the released fluid (Bottai & Cigni, 1985; Mendrinos & Karytsas, 2006; Marchand et al., 2015):

- setting on fire[24] or explosion of gas (CH_4, CO, H_2S, H_2);
- projection of geothermal fluid, rock or mud (hydrocarbons, all gases including water steam);
- poisoning (CO_2, H_2S, CO) or asphyxia (all gases except O_2);
- burning (hydrocarbons, all gases including water steam);
- emission of greenhouse gases (CO_2, CH_4, NO_X).

5.2 Leaking or overfilling of a surface tank

5.2.1 Critical event

These include leaks that may occur in the storage tanks for geothermal fluid, drilling fluid, hydrocarbons (fuels, oils) or various additives present on the drilling site, or during the transfers on site of such products for disposal or supply.

It should be noted that such a risk is inherent in any drilling site, whatever its purpose.

5.2.2 Initiating mechanisms and scenarios

The mechanism that initiates a leak or an overflow can be of two types:

- internal, such as leakage of a storage capacity (storage tank, tarpaulin, cistern);

[24] in the 1980s, at the time of the deep drilling operations of more than 3,000 m at the site of Larderello (Italy), the high temperature and the concomitant presence of flammable gases and oxygen at depth led to fear risk of spontaneous setting on fire, which has never happened (Bottai & Cigni, 1985).

- external, such as an exceptional flooding or rain, which would lead, for example, to the overflow of semi-buried tanks intended to temporarily store the extracted geothermal fluid during the tests.

5.2.3 Effects and potential consequences

The consequences of such an event can be pollution of the soil, subsoil, aquifers and/or the hydrographic network (Hervé, 2009; Bézèlgues-Courtade et al., 2012; Cuenot, 2012).

Note that although this type of event is frequently reported in the fields of civil engineering or Classified Installations, we have not found any in the literature related to geothermal energy.

5.3 Leak on the primary or the secondary circuit

5.3.1 Critical event

A leak on the primary or secondary circuit is likely to spread the fluid that circulates inside in the environment.

In the drilling and test phases, it may be the drilling fluid, geothermal fluid or a stimulation fluid (water possibly loaded with additives, including acids).

In the operating phase, the problem will concern the geothermal fluid, in the primary circuit, or the heat transfer fluid, in the secondary circuit. There are a variety of heat transfer fluids, depending on the type of process used by the geothermal station (Hirschberg et al., 2015).

5.3.2 Initiating mechanisms and scenarios

With regard to the primary circuit, the mechanisms that could lead to geothermal fluid leak on the surface are corrosion or defects affecting the pipeline that transport this fluid. This risk is cited by several authors but, to our knowledge, there were no such accidents reported in the literature (Galin, 2000; Kagel et al., 2007; Hervé, 2009; Rouquet, 2010; UCUSA, 2012; Holm, 2012; Ecogi, 2012; Cuenot, 2012; Reith et al., 2013; Bauer et al., 2015; Hirschberg et al., 2015).

With regard to the secondary circuit, although a risk of leakage cannot be totally excluded, for example as a result of corrosion or pipe breakage, it is *a priori* smaller than for the primary circuit, because the fluid circulating therein is less hot and less aggressive. The main risk of accidental spillage of this fluid is mostly in the phases of transport, transfer and storage of this fluid.

5.3.3 Effects and potential consequences

In the event of a leak on the primary or secondary circuits, the main risks are:

- the spillage of fluid at the surface with contamination or pollution of the surrounding environment: pollution of soil, runoff towards surface water, infiltration into the groundwater, gaseous emission into the atmosphere;

- direct intrusion into an aquifer if the leak is underground[25];
- possibly fire (in the case of certain heat transfer fluids).

The consequences of such a leak can be:

- on humans, burning (see the Ahuachapan 2 accident in El Salvador in Chapter 3.2), odor emissions, intoxication or even irradiation in specific cases of substances containing natural radioactivity (geothermal fluid);
- on the environment, contamination or pollution of soil (see Ahuachapan 1 accident in El Salvador, Chapter 3.2), of a river, the sea, the atmosphere or the irradiation of the fauna and the flora.

In the case of the primary circuit, it is a hot and mineralized geothermal fluid with the most common chemical composition as follows (Hirschberg et al., 2015):

- strong mineralization (brine), in particular chloride, bicarbonate and sulfate of sodium, calcium and potassium, as well as in silica;
- dissolved trace elements, in particular heavy metals; Hirschberg et al. (2015) mentiones, for example, the presence of arsenic, barium, antimony, boron, lithium, rubidium and naturally occurring radioactive substances such as ^{238}U, ^{232}Th, ^{40}K and ^{226}Ra;
- dissolved gases (see Chapter 4.7).

In the case of the secondary circuit, these are heat transfer fluids, the most frequent of which are n-pentane, isobutane, iso-pentane, benzene, toluene, n-butane, ammonia, carbon dioxide and 1,1,1,2-tetrafluoroethane[26]. Some of these substances are potentially flammable or explosive, others are toxic or ecotoxic.

5.4 EMISSION OF EXCESSIVE VOLUME OF DISSOLVED GAS

5.4.1 CRITICAL EVENT

This involves the risk induced by a large (unexpected) degassing of the geothermal fluid, which may have consequences in confined spaces (intoxication, asphyxiation). This may occur during the test phase, when the geothermal fluid is brought up directly to the surface, or in the production phase, if there is a leak on the primary circuit (case already covered in chapter 5.3).

Such an event may also occur after the abandonment of the site ("post-abandonment" phase), in the event of a bad plugging of the wells, either due to a defective design or setting of the cement plugs, or to a degradation of the plugs over time. This type of event has been reported many times in the case of old hydrocarbon wells (Bachu & Watson, 2009) or in the field of CO_2 geological storage (Gombert & Thoraval, 2010; Farret, 2013).

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[25] For Hirschberg et al. (2015), the most frequent impact of geothermal installations would be the contamination of freshwater aquifers through accidental intrusions of geothermal fluid.

[26] fluid generally known under the trade name "R134a".

5.4.2 Initiating mechanisms and scenarios

The initiating mechanisms of such event are the bringing up of a geothermal fluid, abnormally rich in dissolved gas and/or the existence of a leak or a significant depressurization, possibly aggravated by the presence of a confined environment (Kage et al. 1998; Kagel et al., 2007; Hervé, 2009; Rouquet, 2010; UCSUSA, 2012; Holm, 2012; Ecogi, 2012; Cuenot, 2012; Reith et al., 2013).

During drilling, testing and production phases, the main risk management measures are to install gas detectors to prevent personnel from an abnormal reelase of gas or an abnormally low oxygen content.

In the post-abandonment phase, it will be necessary to have rigorous procedures for the settlement of the plugs, to plug the wells with good quality cement (cement resistant to the geothermal fluid) and possibly, for a defined period, to monitor the absence of gas leaks at the surface.

5.4.3 Effects and potential consequences

Despite the richness of certain geothermal fluids in dissolved gases, the literature does not mention incidents or accidents caused by a large degassing during drilling or testing phases. This can be explained by the fact that during these phases, degassing takes place in the open air. Therefore, the consequences are negligible, with the exception of a possible local and temporary contamination of the atmosphere in certain gases (CO_2, CO, H_2S, NO_X…).

On the other hand, in the production phase, a degassing after a leak in the primary circuit, for example, can occur in a confined environment and thus cause greater risks for the personnel (intoxication, asphyxiation) or even property damage (fire, explosion). The accidentology chapter mentions an accident in Japan due to H_2S intoxication of a worker who entered the oil separation room of a geothermal installation to remove the used oil (Kage et al. al., 1998).

5.5 Conclusion

The construction or operation of a deep geothermal site involves a number of risks of gaseous emissions or effluents of fluids on the surface which need to be managed. These risks can be of various kinds.

The risk of well blowout, even if it is less prevalent in the geothermal than in the hydrocarbon field, nevertheless must be taken into consideration. Indeed, a well, whatever its nature, can pass through overpressure formations, possibly containing gas. The example of the St. Gall incident in 2013 shows that a gas kick must always be considered and it is always difficult to control. Several cases of blowouts in geothermal environments in volcanic zones have been reported, leading some to serious accidents: Agua Shuca (El Salvador) in 1990, Zunil 1 (Guatemala) in 1991, Puna 2 (Hawaii) in 1991. This finding calls for deep geothermal wells to be carried out under the same safety conditions, with regard to the risk of gas kick, as in hydrocarbon wells (BOP at the wellhead, presence of gas detectors, training of the personnel on well control procedures, etc.). It should be noted that this is already the case in France today.

Like any drilling site, a geothermal site also involves the risk of leaks or overflow of reservoirs at the surface. The management of these risks, which concerns all industrial activities involving the storage of fluids at the surface, is conventional and does not present any difficulties specific to geothermal energy.

Leaks can also occur on equipment and pipelines that make up the primary circuit (the one that transports the geothermal fluid) or the secondary circuit. Here again, geothermal energy does not have any specificities compared with other industrial domains involving the transportation of fluids at the surface. It should be noted that the primary circuit is more exposed to this type of leakage (because the transported geothermal fluid is more aggressive) and therefore requires more strict monitoring.

Finally, the risk of a gaseous emission linked to an accidental degassing of the geothermal fluid (for example following a leak of such fluid) is a risk to be considered, in particular when this degassing occurs in a confined environment. Risks to personnel (intoxication, asphyxiation) may follow, as happened in Japan in 1998, when a worker entered in an oil separation room of a geothermal installation.

6. POTENTIAL CONTAMINATION OF THE UNDERGROUND ENVIRONMENT

6.1 COMMUNICATION OF SEVERAL AQUIFERS

6.1.1 CRITICAL EVENT

When drilling a deep well, whether or not for a geothermal purpose, it is common to intersect the following types of aquifers:

- one or more surface freshwater aquifer(s), generally exploited for the supply of drinking water: examples include the Lutetian limestones of Ile-de-France, the Paris Basin chalk, the plio-quaternary sands in the Rhine rift, numerous alluvial formations, etc.;
- one or more deep freshwater aquifer(s), sometimes recognized as a heritage reserve and, therefore, to protect against contamination: this is the case for the Albian and the Neocomian aquifers in the Paris Basin[27], the deep aquifers of the Aquitaine basin[28], the deep karsts in the Drome[29];
- one or more deep aquifer(s) hosting more or less mineralized and hot water, at least one of which represents the targeted geothermal resource: the best known are the Dogger and the Triassic aquifers in the Paris basin, as well as the deep basement aquifers in the Massif Central or the Rhine rift.

These various aquifers are separated by impermeable or semi-permeable formations and can thus contain masses of water of different qualities and pressures. The critical event which is dealt with here involves the accidental communication of several aquifers present in the overburden through the well. It should be noted that the risk of communication of the geothermal reservoir with an overlying aquifer is the subject of a specific event called "intrusion of geothermal fluid into an aquifer", which will be dealt with later (Chapter 6.2).

In the case of aquifers containing drinking water, legislation prohibits any communication with other aquifers[30]. In any case, even where a drinking water or heritage aquifer is not threatened, it is not advisable to put several distinct aquifers in communication, since they are often subjected to different pressures, which may induce a flow between them and a mixing of waters of different qualities.

This type of event concerns in theory all the lifecycle phases of a well; but it is mainly during the operational and post-abandonment phases, because of their duration, that possible communications between aquifers may have the largest impact.

6.1.2 INITIATING MECHANISMS AND SCENARIOS

The communication of different aquifers is the result of a lack of longitudinal sealing of the well. This may be related primarily to (Galin, 2000; Vernoux et al., 2002; Kaya

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[27] http://www.driee.ile-de-france.developpement-durable.gouv.fr/l-aquifere-multicouche-de-l-albien-neocomien-a2009.html

[28] http://www.gesteau.eaufrance.fr/sites/default/files/SAGE05003-EtatLieux.pdf

[29] http://sierm.eaurmc.fr/sdage/documents/guide-tech-3.pdf

[30] see Article 10 of the amended Order of September 11, 2003 (NOR: DEVE0320170A)

et al., 2011; Ecorem, 2011; Bezelgues-Courtade et al., 2012; Reith et al., 2013; Bauer et al., 2015):

- in the operating phase, to a defective annular cementing (important micro-annular between the casing and the cement, or channelling over an important height), which may be linked to an inadequate cementing program, a defect in the settlement of the cement, or aging of the cement over time;
- in the post-abandonment phase, to a defective annular cementing (see preceding point) and/or to a leak of one or more cement plugs, linked to a poor design or setllement thereof, or degradation of these over time.

6.1.3 Effects and potential consequences

A potential consequence of the communication of aquifers is contamination or pollution of the receptive aquifer.

This flow can also induce phenomena at the level of intermediate geological formations, such as dissolution (limestones, salt, gypsum) or swelling (anhydrite), due to the introduction of a fluid in physicochemical imbalance with certain rocks. Accidents illustrating these types of phenomena have been described in § 3.3.2.

In the Paris Basin, deep wells for geothermal purposes sometimes intersect the superficial Tertiary aquifers and systematically the aquifers of the Senonian chalk, and also those of the Albian and the Neocomian. There is therefore a risk of putting these different aquifers in communication, because the main factor favoring the migration of fluids is the difference in pressure between them, whether natural or induced (pumping or injection into one of the aquifers).

This risk management requires good design, installation and cementation of the casings and, at the time of abandonment, good design and placement of the cement plugs.

6.2 Intrusion of fluid into an aquifer

6.2.1 Critical event

It has been previously seen that it is frequent that drilling of deep well intersects one or more separate aquifers, whether in the context of geothermal energy or not. The accidental event dealt with here concerns the intrusion of fluid (test fluid, geothermal fluid or, exceptionally, gas from kick) into one of these aquifers, used or potentially usable for the production of drinking water, irrigation, industrial needs, superficial geothermal, storage of natural gas or CO_2, etc. These sensitive aquifers are usually superficial aquifers (commonly located in the first hundred meters of depth) but they can also be relatively deep, up to 500 m or even 1,000 m locally, especially in the Paris and Aquitaine basins.

6.2.2 Initiating mechanisms and scenarios

The intrusion of fluid into a sensitive aquifer can occur during all phases of a geothermal installation and result from the following mechanisms:

- during the drilling phase[31], an underground blowout of gas coming from an underlying formation, following a bad kick control; it should be noted that this scenario, which may happen only in very exceptional circumstances, is well known in the field of hydrocarbons but has never been reported in deep geothermal energy even if several accidental events have shown the possibility of eruptions of gas during drilling in such environments (see § 5.1);
- in the test or production phases, an intrusion of geothermal fluid or stimulation fluid caused by a lateral integrity loss of the well, i.e the rupture or perforation of one or more casings, linked for example:
  - to corrosion (internal or external),
  - to the mechanical stresses due to the anchoring of certain equipment (for example the pump in the pumping chamber),
  - to erosion and tool tripping (during interventions),
  - thermomechanical stresses (for high temperature wells),
  - to material defects of the casing or improper screwing of casing sleeves,
  - to shear stresses related to movements along pre-existing fracture planes (Jung et al., 2010; Dorbath et al., 2009).
- in the post-abandonment phase, an intrusion of geothermal fluid following the combination of a longitudinal (annular cementing or one or more cement plugs) and lateral (one or more casings) integrity loss of the well.

It should be noted that the casings of geothermal well are particularly exposed to the risk of corrosion, especially during production, due to the generally aggressive nature of the geothermal fluid they convey (Galin, 2000). In Ile-de-France, many cases of piercing of the casings due to corrosion (internal and sometimes external) have been observed, particularly during the first years of operation of the geothermal doublets. They did not systematically lead to intrusions of geothermal fluid in the surrounding formations because the pumping operation induces a loss of pressure in the geothermal reservoir host formations[32]. Nevertheless, in certain wells, especially injectors, leaks were observed, as it was the case at Coulommiers in 1996 (see § 3.3.3.1 and sheet in APPENDIX 4).

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[31] The intrusion of a drilling fluid into an aquifer, also known as circulation loss, has been described in the chapter of chronic hazards (§ 4.6.2)

[32] in this context, it is more likely that formation fluids penetrate in the well in the event of a piercing, as it happened in Bulalo (Philippines): thanks to the monitoring of tritium in the water, a surface water inflow in two injection wells was proved on this site (Abrigo et al., 2004).

Corrosion develops more particularly at certain points in the casing, in particular in the surface part of the injector well or at the level of the pumping chamber in the production well. It sometimes develops under deposits, which makes its detection delicate by the caliper tools. Since the first findings of this phenomenon on geothermal wells in France in the late 1980s, a series of measures have been taken to prevent and to follow the effects of corrosion: casing thickening, addition of an inhibitor of corrosion to the geothermal fluid, regular passage of tools to check the inside diameter of the casings (caliper tool) or the thickness of the deposits (electromagnetic scanner), doubling the casing if necessary. In the Paris basin, casing corrosion tests are required every 3 years on the injector wells and every 5 years on the production wells. Nevertheless, corrosion management remains one of the key issues for the safety of deep geothermal wells.

Another specific feature of deep geothermal casings, because they are directly in contact with the geothermal fluid, is that they are particularly exposed to thermomechanical effects, particularly in high-temperature geothermal environments. In this case, the casings can undergo significant temperature variations, especially during the stopping and restarting of pumping. These variations lead to thermal expansion and contraction of casing steels, which may ultimately impair the integrity of the casings and the cement sheath that connects them to the terrains (Galin, 2000; Cuenot, 2012; Reith et al., 2013, Bauer et al., 2015). The casings most affected by these temperature variations are the surface casings of the production wells. Therefore, when designing the well, it is necessary to ensure that the characteristics of the casings and cement characteristics allow them to withstand the mechanical stresses generated by these temperature variations.

6.2.3 Effects and potential consequences

The effects of fluid intrusion into an aquifer depend on the flow, volume, temperature and physicochemical quality of the fluid, and on the quality and temperature of the water contained in the impacted aquifer. The nature of the fluid circulating in the geothermal well is different according to the considered phase of the lifecycle and for the geothermal fluid, depending on the regions, the induced effects will, therefore, be significantly different.

It is beyond the scope of this report to analyze all possible situations. This analysis must be carried out in the impact assessment, depending on the specific environment of each site. In the case of the leak associated with the Coulommiers well (1996), 660,000 m^3 of hot and highly mineralized geothermal fluid from the Dogger aquifer were spread over several months in the freshwater aquifer of the Champigny limestones, collected for the water supply of the city (Vernoux et al., 2012). Despite this large volume, the physico-chemical monitoring of the city's drinking water catchments did not reveal pollution.

6.3 Conclusion

Beyond an accidental spill of surface products (already seen in the previous chapter), contamination of a sensitive aquifer at a deep geothermal site may occur as a result of two types of events.

First, the communication of aquifers of different pressure and quality, following a longitudinal loss of integrity of a well. Such a loss may result from a defective cementing or, in the post-abandonment phase, from defects affecting the cement plugs. This risk is not specific to geothermal energy, but it is a major issue in the safety of deep wells. The proper design, placement and control of annular cementations and cement plugs are among the points that need special attention in any deep well, whether it is geothermal or not.

Contamination of a sensitive aquifer may also occur as a result of lateral leak from a well, associated with the piercing or the rupture of one or more casings. This scenario must be payed particular attention (i) in the case of deep geothermal wells, where the casing is in direct contact with the geothermal fluid and thereby more exposed to corrosion, and (ii) in the case of high temperature geothermal wells because of thermomechanical effects due to temperature variations. Corrosion, in particular, has affected many geothermal wells in the Paris basin and led to certain incidents, notably the one of Coulommiers in 1996.

In order to overcome this problem, a number of measures have been taken which now allow better management of the effects of corrosion: additional thickness of the casings, corrosion inhibitors, regular inspection of the internal diameter of casings or of the thickness of deposits, doubling the well casings if necessary. In the Paris basin, controls of casing corrosion are required on the injector wells every 3 years and on production wells every 5 years.

7. GROUND MOVEMENTS OR NOTICEABLE SEISMIC EVENTS

7.1 INDUCED SEISMICITY

7.1.1 CRITICAL EVENT

Like many anthropogenic activities that induce stress changes underground (hydrocarbon production, underground storage, mines, hydraulic dams, etc.), deep geothermal can cause dynamic relaxation of stresses, likely to generate ("earthquakes") whose waves can be sometimes be felt at the surface.

It is common to distinguish “seismic” events (whose waves are felt by people at the ground surface) and "microseismic” events (whose waves are measurable by sensors but not felt by humans). The limit between the two is usually around a magnitude of 2.

The critical event dealt with in this chapter is not the generation of earthquakes, which are inherent in deep geothermal activities, but the fact that events are felt on the surface (seismic events), which can cause discomfort or even fear in the local population, or damage to buildings.

It is common to distinguish "induced" seismicity, that is directly related to the concerned anthropogenic activitiy (in this case geothermal operations) and "triggered" seismicity, which would have taken place naturally but whose occurrence has been prematurely triggered by this activity. For ease of drafting and unless otherwise stated, the term "induced seismicity" will be used to refer to these two situations.

7.1.2 INITIATING MECHANISMS AND SCENARIOS

In the context of deep geothermal wells, an earthquake can be induced by three types of mechanisms:

- an excessive increase in pore pressure which can either fracture the rock or reduce the shear strength of pre-existing fractures and trigger slips along these fractures;
- an excessive cooling of the rock, which can generate thermomechanical stresses and fracture the rock;
- an excessive reservoir depletion (in the case of an incomplete reinjection of the geothermal fluid), which can generate shear stresses above or below the reservoir.

7.1.2.1 Excessive increase in the pore pressure

An excessive increase in pore pressure can be generated on various occasions in the lifecycle of a well:

- in the drilling phase, in the case of a well kick control; the kick control procedure involves increasing the mud pressure in the well, which can lead, if excessive, to exceed the rock strength and to fracture the rock or to trigger an earthquake on a preexisting fault; this seems to be the mechanism that was at the origin of the earthquake of Saint Gall in 2013 (see sheet in Appendix 4) ;

- in the testing phase:
  - during hydraulic stimulation operations: these operations aim to reopen or reconnect fractures in the near-field of a well in order to improve the productivity of reservoir formations (Lopez & Millot, 2008, Ecorem, 2011, Kaya et al., 2011, BRGM, 2012, Cuenot, 2012, Reith et al., 2013) (Figure 23); an injection of water at too high pressure is likely to lower too much the effective shear strength along pre-existing fault planes and to generate earthquakes (Agemar et al., 2014); an hydraulic stimulation operation can generate several thousand seismic events, the vast majority of which are microseisms. Nevertheless, the examples presented in the chapter on accidentology (Soultz-sous-Forêts, Basel, Landau, Insheim, Cooper Basin, Wairakei) show that felt earthquakes can not be excluded.
  - during chemical stimulation operations: these operations consist of injecting a smaller quantity of water than the hydraulic stimulation but with added chemical agents which will act by dissolving the minerals which clog the fractures. With the exception of "flushing" periods where high injection rates are used to push the fluid into the formation, the applied overpressures are generally lower than for hydraulic stimulation and the induced microsismic activity remains generally moderate, both in terms of the number of earthquakes and the reached magnitudes (ESG, 2015).
- in the production phase, in the event of excessive pressure of reinjection of the geothermal fluid. The relationship between injection pressure/flow rate and seismic events has been observed for decades (Webb et al., 1984). Even if the operational phase tends to generate a lower microsismic activity compared to the stimulation phase, it can also generate felt earthquakes, as was observed in Soultz-sous-Forêts (France) during production tests conducted in 2005 and 2010 (Cuenot, 2012, ESG, 2015) or Landau (Germany) in 2009, where seismic events with magnitude of 2.4 and 2.7 occurred two years after the start of the operation (Agemar et al., 2014); it should be noted that following these events, it has been decided to reduce the circulation flow rate of geothermal fluid.

One difficulty is that the notion of "excessive" pore pressure - or in other words of "maximum overpressure not to be exceeded" in order not to induce a felt earthquake - is not identical in all the sites. Evans et al. (2012) studied 41 sites in Europe where earthquakes induced by deep geothermal activities occurred, and concluded that the sites with the highest seismicity were located in regions where the state of natural stresses was critical ("critically stressed") due to the natural tectonic activity. Therefore, there may be a relationship between induced seismicity and natural seismicity related to the tectonic environment. This hypothesis remains nevertheless discussed in the scientific community[33] (Majer et al., 2007, Giordani, 2009, Ungemach, 2002, Rivas et al., 2005).

[33] https://isterre.fr/recherche/equipes/mecanique-des-failles/theses/theses-en-cours/Julie-Richard

Note that there is sometimes a significant time delay between stimulation and the occurrence of earthquakes. For example, in Basel (Switzerland), felt earthquakes occurred between 0.2 and 56 days after the end of the hydraulic stimulation operations (see § 3.3.1.2 and sheet in Appendix 4). One of the hypotheses that could explain this delay is the diffusion time of the pore pressures from the well to the more distant potentially mobilizable preexisting faults (Bachman et al., 2011). This inertia can complicate the task of sorting between induced earthquakes and natural earthquakes, and to establish a causal relation between changes in the operating parameters (in particular injection flow rate and pressure) and the generated seismic activity.

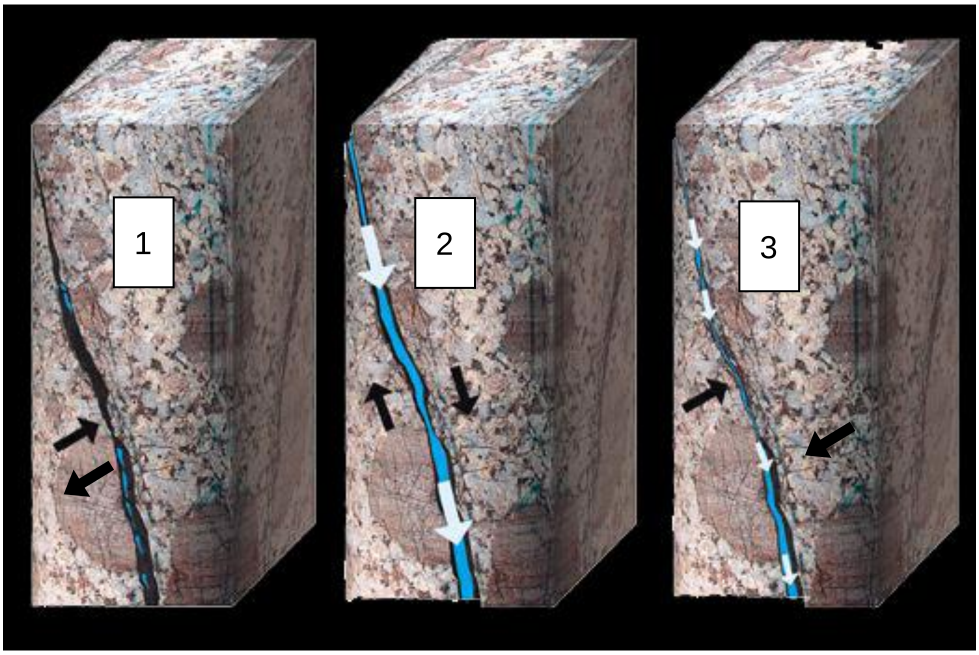

Figure 23. Principle of hydraulic stimulation (ESG, 2015)

Legend:

1) Before the stimulation, the fault plane, corresponding to a surface formed of irregular walls, is more or less clogged by hydrothermal deposits (black filling). On the other hand, the normal stress (black arrows), perpendicular to the fault plane, and the tangential or shearing stress (contained in the fault plane) are balanced: the fault does not move.

2) During stimulation, pressurized water injections (in blue) increase the pore pressure at the fault plane level. This pressure tends to oppose the normal stress which is reduced: the shearing stress then becomes preponderant, generating the sliding of the fault and a (micro)seism. This sliding crushes the clogging deposits and creates permeable channels in the fault plane, helping the circulation of geothermal fluid (white arrows).

3) After stopping the stimulation, the stresses gradually return to their initial state and the fault tends to close, but it has been observed that generally the permeable zones created during the stimulation are preserved even after the stop of the injections: this would be due to the presence of asperities on the fault planes because, since the shearing mechanism is irreversible, the fault walls offer more spaces after the hydraulic stimulation.

7.1.2.2 Excessive cooling of the formation

Excessive cooling of the reservoir rock may also be the cause of induced earthquakes. Such cooling may occur:

- in the test phase, during thermal stimulation operations; in the case of a high temperature reservoir, the thermal stimulation consists in creating a thermal shock by injecting a cold fluid into a very hot rock in order to create or reactivate fractures by using a thermomechanical effect. This mode of stimulation implies significantly smaller water volumes than hydraulic stimulation, which results in fewer seismic events. In Bouillante (Guadeloupe), the thermal stimulation of the BO-4 well mobilized 8,000 m^3 of seawater: the steam extraction rate then increased from 80 to 140 t/h without generating any particular seismic activity in the two months following the operation (Maréchal et al., 2008);
- in the production phase, as a result of the reinjection of cooled geothermal fluid; it is known that the permeability of the reservoir at the injection well decreases with time because the viscosity of the cooled geothermal fluid is higher than that of the hot fluid in place: the injectivity should therefore theoretically decrease with time. This is compensated by the thermal fracturing induced by the injection of cooled geothermal fluid[34] (Lopez & Millot, 2008, Agemar et al., 2014). This can lead to induced earthquakes.

The site of The Geysers (California, USA) is a case study in this matter since the reinjection is done by simple gravity flow of the condensed vapor, without imposing overpressure thanks to the very low pressure of the deep reservoir (NAS, 2013): here the main cause of induced seismicity results from the thermomechanical constraints (Martinez-Garzon et al., 2015; Convertito et al., 2015). These constraints generate a dozen earthquakes per year, one of which has already reached a magnitude of around 3.

7.1.2.3 Excessive reservoir depression

Such a scenario can occur when the geothermal fluid is not reinjected underground or is re-injected into another aquifer than the one in which it was collected. An excessive depletion can then give rise to a poroelastic contraction of the reservoir which may lead to the appearance of shear stresses in the formations above or below the reservoir.

This phenomenon has been well documented on numerous gas reservoirs (eg Lacq in France) or in the field of geothermal at the Salton Sea site in California (see § 3.3.1.6), where it has been observed that the evolution of the seismic activity correlated well with the volume of the lost fluid within the reservoir.

7.1.3 Effects and potential consequences

As we have seen in the chapter on accidentology (§ 3.2.3), earthquakes induced by deep geothermal activities have never had any impact on human life and have very rarely caused property damage at the surface. For example, the Basel earthquake, with a magnitude of 3.4, only resulted in slight damage to the buildings (cracking or falling of plaster).

However, the psychological impact on the inhabitants can be significant, which can have a major impact on the acceptability of the projects, as was recently seen in the

[34] it may also be a question of the increase of the dissolution due to the more aggressive nature of cold water on carbonate mineralizations.

discussions surrounding the EGS geothermal projects in Alsace (France) or as illustrated by the following feedbacks.

Case of Soultz-sous-Forêts (Bas-Rhin, France)

In Soultz-sous-Forêts, the few earthquakes that reached or surpassed magnitude of 2 (maximum 2.9) triggered numerous telephone calls for information and dozens of complaints of alleged damage to homes, complaints that were unsuccessful (Cuenot, 2012). Nevertheless, this experience has led to several decisions:

- at the scientific level, the seismological data has been transmitted to the research structures in order to better understand the induced earthquakes and to identify avenues for better control in the future;
- on the technical side:
  - the chemical stimulations (causing less seismic events) were preferred to the hydraulic stimulations,
  - the injection pressure has been reduced below a certain threshold,
  - the re-injection of water was distributed over several wells (which made it possible to go from 400 micro-earthquakes in 2010 to only 5 in 2011);
- informational steps have been taken (public lectures, distribution of newsletters announcing current operations and possible risk of felt earthquake, etc.).

The survey conducted in 2012 in the concerned municipalities (see Figure 20) showed that 83% of respondents said they did not perceive geothermal exploration as a risky activity (Reith et al., 2013).

Landau case (Germany)

In Landau, it was mainly the lack of prior information that was criticized during the occurrence of two earthquakes of magnitude 2.4 and 2.7 (RETS, 2011). In addition, one of the earthquakes was accompanied by a noise whose intensity could locally reach that of a supersonic bang, which particularly worried the residents (Kulish and Glanz, 2009). The population wished to be warned in advance about the risk of an earthquake. Despite the 200 calls recorded by the police, there was no reported damage to the city's buildings. However, the project finally had to be stopped in 2013 due to the fact that this problem has limited the efficiency of the plant, and that its resolution would have necessitated a too expensive new well (Slavova, 2013).

Case of Basel (Switzerland)

In Basel, an earthquake of magnitude 3.4 had a strong impact on the population, especially since the site was located in the city. The project had to be abandoned and all complainants were compensated without the need for technical expertise, i.e. a total cost of € 9 million (RETS, 2011). It should be noted that sporadic microseisms were detected 3 years later (Giordani, 2009) and that the return time to normal seismic background noise was estimated to be between 20 and 60 years (Bachman et al., 2011).

The case of The Geysers (California, USA),

At The Geysers, minor damage has occasionally been reported, taking the form of cracks on windows, walls or floors. A complaint reception office was then set up:

after analysis and validation, it reimburses the inhabitants for the cost of repairing the damage. This system appears to be satisfactory for all parties although, in six years, the amount spent on these reimbursements was only about € 73,000.

These cases have not only helped to better understand the physical mechanisms involved in triggering induced seismicity, but also to identify the human factors that are the reason of the negative perception of earthquakes and the related fears.

The result is a set of measures which, if not eliminating the risk, enable to better control it and to take into account the concerns of the local residents, in particular:

- to keep the injection pressure below a certain threshold (to be adapted to each site). To achieve this, if necessary, distribute the reinjection between several wells;
- to implement an effective micro-seismic monitoring network to analyze in real-time seismic data and modify the injection parameters accordingly;
- to inform the population and the local authorities about the operations in progress and the possible risks of noticeable earthquakes (Giordani, 2009).

7.2 UPHEAVAL OF THE GROUND SURFACE

7.2.1 CRITICAL EVENT

We are talking here of a risk of upheaval of the ground surface, which could create surface disorders.

The main risk of major upheaval is related to the swelling of a sensitive formation after a water intrusion. This type of event, already described several times in the context of this report (§ 3.3.2.1, § 6, Staufen sheet in Appendix 4), is not specific to geothermal energy and comes to the general problem of zonal isolation of the formations traversed by a well.

Another risk of upheaval is the one linked to poroelastic effects, in the case of excessive injection flow rate or pressure.

7.2.2 INITIATING MECHANISMS AND SCENARIOS

Water intrusion into a sensitive formation can be induced by:

- in the drilling phase, poor characterization of the underground geology and the use of inappropriate drilling mud;
- at all phases, a longitudinal loss of integrity of the well; such loss may result from defective cementing or, in the post-abandonment phase, from defects affecting the cement plugs (see details in § 6.1.2) ;
- in the production phase, a lateral leakage from the well due to the perforation or rupture of one or more casings (see details in § 6.2.2);

Regarding the risk of upheaval due to poroelastic effects, it may be induced in the production phase by an excessively high injection pressure which may create a piezometric dome and a temporary raising of the ground surface around the well (Sanyal et al., 1995; Lopez & Millot, 2008; Kaya et al., 2011; UCSUSA, 2012; Bezelgues-Courtade et al., 2012; Bauer et al., 2015). This occurred in the geothermal field of the Imperial Valley (California, USA) (Sanyal et al., 1995). The ground generally returns to its original level shortly after the injection flow rate and/or pressure have been reduced.

7.2.3 EFFECTS AND POTENTIAL CONSEQUENCES

The magnitude of the upheaval due to the swelling of a sensitive formation depends mainly on the depth, the thickness and the nature of the concerned formation.

In the examples of Lochwiller or Staufen (see sheet in Appendix 4), the impacted anhydrite layer is at a relatively low depth: the effect of the uplift was therefore significant (a few tens of centimeters in places) and the consequent surface disorders important (cracks on buildings, deformation of the roadway, ruptures of the underground networks, etc.).

In the case of the upheavals that occured in Landau (Germany) since 2014, where water intrusion into a sensitive formation (clay) is also suspected (ADIR, 2014, Heimlich et al., 2015), a circular zone of uplift of multi-centimeter amplitude, centered on the geothermal power plant, was measured by radar interferometry.

In the case of Imperial Valley (California), the amplitude of the uplift reached a few inches, about ten centimeters (Sanyal et al., 1995). This created a problem in this vast alluvial plain that is very flat and below sea level. To solve it, it was necessary to redistribute the injection on several wells, spaced between each other.

7.3 SUBSIDENCE OF THE GROUND SURFACE

7.3.1 CRITICAL EVENT

We are talking here about the risk of subsidence of the ground surface induced by geothermal operations. This type of event can occur mainly during the production phase and result from several mechanisms: excessive drawdown of the aquifer, loss of material by entrainment of fine particles, dissolution of an evaporite formation, incomplete or absent reinjection of the geothermal fluid in the reservoir. These mechanisms are not specific to geothermal energy, but relate to all well operations, in particular for hydrocarbon recovery.

7.3.2 INITIATING MECHANISMS AND SCENARIOS

7.3.2.1 Uncontrolled dissolution of an evaporite formation

The drilling of a deep well, whatever its purpose, may lead to intercept evaporite soluble layers (salt, potash, gypsum) of a sometimes significant thickness: it is for example the case of the Tertiary salt deposits of the Mulhouse basin, in the Rhine graben, with thickness from 1,500 to 1,800 m.

In the event of an intrusion of a fluid in chemical imbalance with this formation, we may fear a local dissolution of these evaporites. Such an intrusion may occur as a result of the same mechanisms as those already described in § 7.2.2 for the risk of swelling of a sensitive formation.

This is what happened in Hilsprich (France) where two superficial geothermal boreholes were carried out at less than 100 m depth in 2005. A poor cementing allowed the groundwater to be brought into contact with a 20 m thick salt horizon which underwent dissolution (see 3.3.2.2).

7.3.2.2 Excessive aquifer drawdown

This mechanism is known in hydrogeology, outside the geothermal environment, where it has already generated subsidence at sites where well pumping was conducted at high flow rates within sedimentary formations. It results from the settlement of the particles forming the aquifer reservoir due to a strong drawdown induced by a drop in hydrostatic pressure.

In the geothermal context, it is likely to occur only during the production phase, at the site of the production well (Lopez et Millot, 2008; Kaya et al., 2011; UCSUSA, 2012; Bezelgues-Courtade et al., 2012; Bauer et al., 2015). Such phenomena can also occur as a result of excessive withdrawing, when the pumping rate of the geothermal fluid exceeds the recharge rate (Webb et al., 1984).

This effect tends to fade in the case of deep pumping, but if the deep geothermal reservoir is connected to a more superficial aquifer, the impact could be partially transferred to the latter: there may then be a piezometric lowering of the superficial aquifers and a decrease in the flow of the neighboring sources (Mendrinos & Karytsas, 2006).

This phenomenon occurred on the geothermal field of Brady Hot Springs (Nevada, USA), which has 6 deep wells of 500 to 2,000 m, with a net extraction rate of geothermal fluid of the order of 0.1 m^3/s. A monitoring carried out from 1997 to 2013 by InSAR interferometry revealed a subsidence at a rate of a few centimeters per year on an elliptical surface of about 2 x 5 km whose main axis corresponds to the orientation of the normal fault network (Oppliger et al., 2006). This subsidence originates from the drainage of the surface aquifers towards the deep geothermal reservoir, through permeable zones associated with faults (Ali et al., 2014).

On the other hand, at the Desert Peak site, which is only 7 km away, no such distortion has been observed in spite of a comparable operation context. However, this site does not present any recent faults on the surface, nor thermal springs, and its fault system appears deeper and better isolated from the surface, which reinforces the hypothesis of interactions with the local tectonic environment.

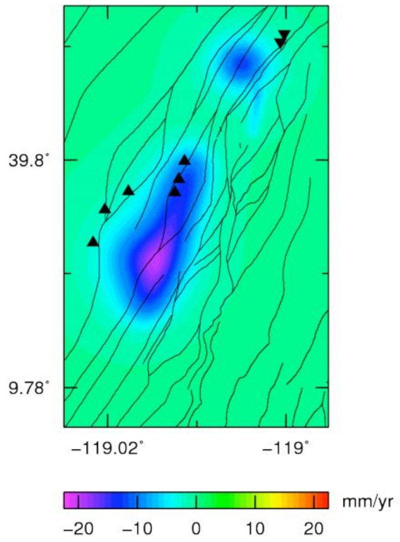

Figure 24. Map of the subsidence area, fault network and production (▼) and injection (▲) wells at the Brady site (Ali et al., 2014)

Legend: the subsidence rate is shown in colors (scale in mm/year)

7.3.2.3 Excessive particle entrainment by suffosion

When the geothermal reservoir contains different sizes of particles, there may be a phenomenon of suffosion (Figure 25): it involves the entrainment of fine particles (clays, silts) through a coarser skeleton (sand, gravel). This is more frequent in sedimentary formations subject to particle size heterogeneity, but it can also occur in hard rock, when fissures are clogged with clay minerals.

This risk is rarely cited in the geothermal context, contrary to its inference, namely the clogging of injection well by fine particles, which is one of the mechanisms causing a loss of injectivity. It would therefore appear that, when this happens, this risk is obscured by the problems of yield loss.

Nevertheless, the establishment of a suffosion was several times suspected in the geothermal domain, notably by Lopez & Millot (2008) in the Dogger of the Paris Basin, by Seibt & Wolfgramm (2008), at the site of Kalipeïda (Lithuania) or by Sanyal et al. (2015), on the Heber or East Mesa sites (California, USA).

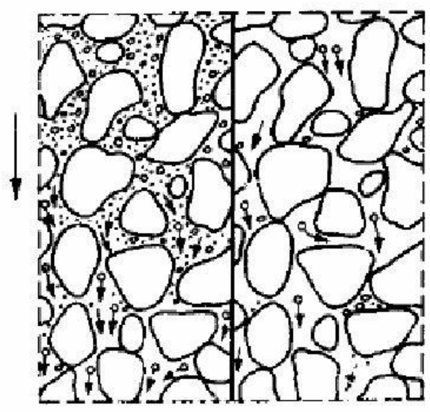

Figure 25. Schematization of the suffosion mechanism (www.uni-weimar.de/)

Legend: on the left, formation before triggering suffosion; on the right, the final result

7.3.2.4 Incomplete or non-existing re-injection

The reduction in pressure induced by the production in a geothermal reservoir can induce a phenomenon of subsidence. This will take on an even greater amplitude as the geothermal fluid is not fully reinjected or is re-injected into another aquifer. It may be an intentional management mode of operation (for example, rejection of the cooled geothermal fluid in the sea or in a river) or the impossibility of reinjecting all the extracted fluid within the formation (Hervé, 2009; Kaya et al., 2011; Cuenot, 2012).

In the extreme case of operation without re-injection of geothermal fluid, frequent in high temperature geothermal deposits, several years of operation can lead to a subsidence of one to several meters in the center of the production area (Mendrinos & Karytsas, 2006). For example, the geothermal fields of Wairakei in New Zealand (Allis, 2000), The Geysers in California (Mossop et al., 1997) or Hatchobaru 2 in Japan (Nishijima et al., 2005).

The case of a subsidence due to an incomplete reinjection occurred in Indonesia, where steam is extracted at a rate of 8 to 13 Mt/year whereas reinjection after condensation only concerns 2 to 2.7 Mt/year (Sofian et al., 2015). This incomplete reinjection can also result from the fact that a small amount of geothermal fluid can evaporate and thus not be returned underground, leading to long-term subsidence (Berrizbeitia, 2014).

7.3.2.5 Modification of underground flows

It should also be pointed out that the extraction of geothermal fluids can lead to a change in the flows between a deep and superficial reservoir, causing the detriment of the latter (ECOREM, 2011). This mechanism may occur, for example, in the vicinity of a fault which acts as a drain between the different aquifers located in these two reservoirs: this would explain the subsidence of the Brady geothermal site (Nevada, USA) (Ali and al., 2014).

7.3.3 EFFECTS AND POTENTIAL CONSEQUENCES

The main effects consist of a lowering (settlement, subsidence, exceptionally collapse) of the ground surface and therefore of the structures or buildings that are present there. This can create disorders to buildings or networks, but also locally disorders to the hydrographic network (creation of ponds, counter-streams, etc.). Note that the nature and extent of the effects on the surface depends on the depth of the source mechanisms.

In the case of the Hilsprich (France) superficial geothermal site, a 1.1 km by 0.3 km subsidence area was detected by radar interferometry[35] with an average deformation rate of 9 cm/year over 3 years (Barras, 2015). These measurements, as well as the leveling, show a subsidence of a vertical amplitude between 0.6 m and 0.9 m over a period of 6 years. Damages appeared in 2006 in about fifteen houses and on the road network, about 450 m around the wells. This community declared a state of "land movements" natural disaster in 2009 (Carton, 2015).

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[35] http://www.brgm.fr/projet/mesure-deformation-sol-sur-commune-hilsprich-interferometrie-radar

In the case of high-temperature geothermal sites of volcanic type, this subsidence can reach one to several meters in the center of the production zone (Mendrinos & Karytsas, 2006). This is the case after several years of operation based on volcanic extraction of large quantities of geothermal fluid without reinjection. To remedy this, it is proposed in the design phase not to plan the installation of buildings, pipelines or other constructions in such a zone, as well as to reinject the entire steam once condensed. It is also necessary to carry out regular topographic monitoring and/or radar interferometry measurements (see Heimlich et al., 2015), with the applicable geophysical investigations (e.g. microgravimetry) to follow up the evolution of the possible zone of subsidence.

In Wairakei, New Zealand, the production without re-injection in the geothermal field from 1950 to 1997 thus created (Allis, 2000):

- a small area of intense subsidence (480 mm/year) over an area of about 1 km²;
- a large medium to high subsidence zone (10 to 100 mm/year) over an area of 30 km².

The maximum subsidence reached 14 m in the center of the subsidence area, which cracked the ground and the linear infrastructures (pipelines, roads, drains...). This phenomenon has been attributed to the slow compaction of lacustrine clay sediments, present at depths of 100 to 200 m.

Other examples of subsidence occurring at high temperature geothermal sites are also cited in the literature (Maréchal et al., 2008):

- 0.15 m at Svartsengi (Iceland) from 1982 to 1987;
- 0.25 m in Kawerau (New Zealand) from 1970 to 1982;
- 0.30 m in Ohaki, New Zealand, from 1968 to 1974;
- 1.70 m in Larderello (Italy), etc.

On the site of The Geysers (California, USA), the largest geothermal complex in the world, the use of high-temperature heat without reinjection has gradually reduced the steam pressure in the reservoir. This resulted in a subsidence of about 5 cm/year between 1973 and 1996, centered at the most active extraction zone during this period (Mossop et al., 1997). In order to maintain this pressure, it has been necessary to re-inject into the reservoir approximately 76,000 m^3 of water per day, the majority of which is waste water.

In Japan, ground surface movements associated with a gravimetric anomaly[36] were found near the geothermal wells of Hatchobaru 2 in 1990 (Nishijima et al., 2005). They affect the injection area and part of the production area and have occurred as soon as the plant started its operation. GPS stations were used to measure subsidence levels of up to 64 mm in amplitude. By modeling, the origin of these movements was located at 750 m depth, at the level of a fault.

[36] In Indonesia, gravimetric measurements were carried out from 2009 to 2011 on a geothermal reservoir in operation where the totality of extracted steam is not reinjected after condensation (Sofian et al., 2015). Negative and positive anomalies appeared, respectively interpreted in terms of loss of mass at the operational wells levels and gain of mass at the injection well level.

7.4 LANDSLIDE

7.4.1 CRITICAL EVENT

This is the risk of triggering a landslide that could reach a geothermal well or which was generated by a geothermal operation. The chapter on accidentology cites three accidents in which a landslide caused a casing rupture in the well, resulting in surface leak.

It should be noted, however, that this risk is not specific to geothermal energy. It comes from the general choice of the well implantation zone in relation to the natural risks, in this case the risk of land movements.

7.4.2 INITIATING MECHANISMS AND SCENARIOS

Hirschberg et al. (2015) report that landslides have occurred in the past in the vicinity of superficial geothermal sites but their causes have not been clearly established. These authors also point out that many geothermal sites are located in mountainous areas, conducive to landslides.

We should note that it is expected that some shallow geothermal wells could interact with surface discontinuities (faults, sliding surfaces) and cause a land movement.

7.4.3 EFFECTS AND POTENTIAL CONSEQUENCES

The accident that occurred in 1991 on the Zunil 1 well (Guatemala) was very deadly: it resulted from a large landslide which caused the rupture of a geothermal well casing, causing a massive blowout of hot geothermal fluid in the vicinity. A total of 23 people died, the majority of them having been buried by the landslide and not directly impacted by this massive blowout.

It should be noted that in the case where the probability of a landslide occurrence is related to the geomorphology of the site and not to the use made of it, this risk does not disappear when the geothermal well is abandoned.

The location of a well is therefore an important parameter since the external environment can increase the risk of accident. The existence of reliefs must be taken into account when designing a geothermal project.

7.5 CONCLUSION

The production of a deep geothermal site can potentially generate geomechanical disorders at the surface, of various types and origins.

Although this only has caused light damage to buildings, induced seismicity is one of the risks perceived as most important in association with deep geothermal industry. This risk appears mainly during the stimulation operations (particularly hydraulic) but it can continue during the production phase. The link between the probability of occurrence of felt induced earthquakes and the natural seismicity of a region has been widely studied but has not been the subject of a consensus up to date.

From a scientific point of view, the feedback from the events in Soultz-sous-Forêts, Basel or St. Gall has led to a better understanding of the mechanisms involved in triggering induced seismicity, but also the factors that are causing the fears it provokes among the inhabitants. A set of operational measures is set in place which, if not eliminating the risk, enables to control it better and to take into account the concerns of the local residents, in particular:

- to keep the injection pressure below a certain threshold (to be adapted for each site). To achieve this, if necessary, distribute the reinjection between several wells;
- to implement an effective micro-seismic monitoring network to analyze real-time seismic data and modify the injection parameters accordingly;
- to inform the population and the local authorities about the operations in progress and the possible risks of felt earthquakes (Giordani, 2009).

Another source of geomechanical disturbances can come from the contact of an evaporite formation (salt, gypsum, anhydrite) with a fluid which is in chemical imbalance with it (fresh water, geothermal water, etc.). This scenario can occur, both in the production phase and in the post-abandonment phase, in the case of a loss of well seal. The ground surface may be raised in the event of hydration and swelling of this formation, or lowered if it is dissolved. In both cases, significant damage may be caused to buildings, networks or surface infrastructures. Such incidents have occurred recently in the field of superficial geothermal (Lochwiller, Staufen, Kirchheim). However, this risk is not specific to geothermal activities and has more to do with the good insulation of sensitive formations traversed by a well in general, whatever it is its nature.

Upheaval or subsidence of the ground surface may also result from poroelastic effects related to overpressure induced in the geothermal reservoir. This second risk (subsidence linked to a significant reservoir depletion) is particularly present when the geothermal fluid is only partially (or not at all) reinjected into its source aquifer. This situation is not specific to geothermal energy, but it is found particularly in geothermal sites of volcanic type, where partial (or even absent) reinjection is frequent, and where cases of significant subsidence (up to several meters) have been observed in certain production sites. It should be noted, however, that these subsidence areas develop slowly and that their consequences can be anticipated and controlled.

On some geothermal sites in mountainous environments, there is also the occurrence of landslide-type incidents. Again, this risk is not specific to geothermal energy and is due to the more general choice of implantation of deep wells in relation to natural hazards, in this case land movements. Nevertheless, it must be taken into account, even in the case of a deep geothermal well.

8. SUMMARY

Deep geothermal is a renewable and non-intermittent source of energy that can contribute to the global transition towards a lower emission of carbon and less greenhouse emitting energy mix. Only a small part of the world's geothermal potential is now exploited and many countries, including France, have included in their goals an increased development of this activity in the coming decades.

Like any industrial activity, deep geothermal well is accompanied with potential inconveniences and possible risks for people and the environment, which must be clearly identified and managed in order to make this activity fully compatible with the expectations and the needs of the citizens, especially those living near such facilities. In recent years, some concerns have been expressed by local authorities over the development of certain deep geothermal projects, particularly in the field of high temperature, based on the risks and potential inconveniences associated with this industry.

This report is intended as a scientific and objective contribution to this matter. It aims to present, in a factual and documented manner, the current knowledge about the risks, impacts and potential inconveniences associated with deep geothermal. In addition to the scientific literature, it is based on the feedback from incidents or accidents in this field. It also leverages the INERIS's expertise in the field of risks related to other sectors, such as oil and gas wells, to provide a larger perspective of deep geothermal technologies.

The main lessons learned from this work are as follows.

8.1 LESSONS LEARNED FROM ACCIDENTOLOGY

A census of accidents or incidents reported in the field of deep geothermal reported 35 events, of which 32 were deemed relevant to the safety conditions currently in place in this industry. Of these 32 events, one death and nine wounded were recorded in almost three decades of feedback and over about 1,700 geothermal installations operating in the world. Other types of consequences are property damage on the surface (buildings or infrastructures), local pollution or psychological impacts on the inhabitants.

The overall impression that emerges from this assessment is that deep geothermal energy benefits from a rather weak accidentology. It should be noted, however, that this census is only partial, in that it uses only information from the public domain, mainly from Western sources. In order to obtain more definitive quantitative lessons on deep geothermal accidentology, we encourage the industry, through its representative structures at national and international level, to set up a systematic inventory of incidents and accidents occurring in this sector. Beyond the monitoring of safety indicators, such a database would allow a better sharing of accident experience feedback, which would be beneficial both for the safety and for the development and the image of this industry.

On a more qualitative level, more than half of the events recorded were earthquakes (34%) or ground surface movements (23%) related to underground geomechanical disturbances. Other types of events are mainly toxic surface releases or contaminations of underground aquifers. It should be noted that most of these types of accidents are not specific to deep geothermal energy and can appear in any well extraction of subsurface resources (hydrocarbons, drinking water supply, underground gas storage, etc.). On the other hand, the context of geothermal energy offers conditions that are more favorable to certain types of accidents (or inconveniences) and less favorable to others, which we detail below.

8.2 INCONVENIENCES AND POTENTIAL CHRONIC IMPACTS ASSOCIATED WITH DEEP GEOTHERMAL WELLS

The inconveniences or impacts of chronic nature, potentially generated by a deep geothermal installation are not, for the most part, specific to geothermal energy.

Concerning the impact on the landscape, it is most important at the time of wells drilling and testing, during which a site is installed on an area of approximately 4,000 to 8,000 m^2, with a derrick usually visible from far away. This phase is however relatively short (6 months to 1 year). In the production phase, a geothermal power station takes the form of an industrial site of rather modest size, comprising one to a few buildings, which can be integrated relatively easily into a landscape, especially when this landscape is urban or industrialized.

As with any civil engineering project, geothermal well generates noise and additional truck traffic, which can be felt as a source of inconvenience by the population, particularly in residential areas. However, these inconveniences are limited to a period of a few months to a maximum of one year. Moreover, it should be pointed out that there are many ways of limiting these inconveniences as much as possible (anti-noise walls, less noisy drilling rigs, planning noisiest operations outside quiet times, etc.). In the production phase, the noise generated by a geothermal power plant remains generally moderate, and not perceptible, notably due to the construction of noise-cancelling buildings. However, on certain sites, especially in geothermal electric power plants, noise inconvenience may remain.

Like any industrial project, the drilling and construction of a geothermal power station can also have an impact on local fauna and flora. It is the responsibility of the operator to evaluate it in their impact assessment. It should be noted, however, that geothermal sites are often located in already urbanized or industrialized areas, which generally limits the additional impacts associated with the plant.

Water resources are generally not impacted quantitatively by well or by operating a geothermal power station. The most water consuming phases are hydraulic stimulation operations, which may require several tens of thousands cubic meters of water. Again, it is up to the operator to assess the impact of these withdrawals in the specific context of the site. From a qualitative point of view, except in the case of accidental discharges, geothermal well drilling, testing and operation have no reason to lead to a degradation of the quality of aquifers or surface waters.

Outside from an accidental context, the main emissions of gas linked to a geothermal operation are due to the degassing of the geothermal fluid. Such degassing takes place, for example, during formation tests, where geothermal fluid is pumped and stored in a temporary basin on the surface. These tests take place over a limited period, ranging from a few days to a few weeks. For high-temperature volcanic sites, however, these emissions can be extended over the entire production phase. In all cases, these emissions must be analyzed and their impact on the air quality assessed in the specific context of each site.

Concerning the carbon footprint, deep geothermal energy benefits from a highly positive balance: the total CO_2 emissions calculated over the lifetime of a geothermal project vary between 17 and 60 g/kWh produced, i.e. one to two orders of magnitude less than oil or coal.

Finally, as far as radioactivity is concerned, the geothermal fluid can cause radon and radium to rise to the surface, which are able to generate radioactive radiation through the equipment and pipelines that transport this fluid (primary circuit). This is not a risk for the residents but for the workers, who must be subject to radiation protection and monitoring measures, in accordance with the rules in force in all extractive industries.

8.3 Main Accidental Risks

The risk of accidental release of surface fluids

The construction or operation of a deep geothermal site involves a number of risks of gaseous emissions or effluents of fluids on the surface which need to be managed. These risks can be of various kinds.

The risk of well blowout, even if it is less prevalent in the geothermal than in the hydrocarbon field, nevertheless must be taken into consideration. Indeed, a well, whatever its nature, can pass through overpressure formations, possibly containing gas. The example of the St. Gall incident in 2013 shows that a gas kick must always be considered and it is always difficult to control. Several cases of blowouts in geothermal environments in volcanic zones have been reported, leading some to serious accidents: Agua Shuca (El Salvador) in 1990, Zunil 1 (Guatemala) in 1991, Puna 2 (Hawaii) in 1991. This finding calls for deep geothermal wells to be carried out under the same safety conditions, with regard to the risk of gas kick, as in hydrocarbon wells (BOP at the wellhead, presence of gas detectors, training of the personnel on well control procedures, etc.). It should be noted that this is already the case in France today.

Like any well site, a geothermal site also involves the risk of leak or overflow of reservoirs at the surface. The management of these risks, which concerns all industrial activities involving the storage of fluids on the surface, is conventional and does not present any difficulties specific to geothermal energy.

Leaks can also occur on equipment and pipelines that make up the primary circuit (the one that transports the geothermal fluid) or the secondary circuit. Here again, geothermal energy does not have any specificities compared with other industrial domains involving the transportation of fluids at the surface. It should be noted that the primary circuit is more exposed to this type of leakage (because the transported geothermal fluid is more aggressive) and therefore requires more strict monitoring.

Finally, the risk of a gaseous emission linked to an accidental degassing of the geothermal fluid (for example following a leak of such fluid) is a risk to be considered, in particular when this degassing occurs in a confined environment. Risks to personnel (intoxication, asphyxiation) may follow, as happened in Japan in 1998, when a worker entered in an oil separation room of a geothermal installation.

The risk of contamination of sensitive aquifers

Beyond an accidental spill of products on the surface (already discussed above), the contamination of a sensitive aquifer at a deep geothermal site can occur after two types of events.

First, the communication of aquifers of different pressure and quality, following a longitudinal loss of integrity of a well. Such a loss may result from a defective cementing or, in the post-abandonment phase, from defects affecting the cement plugs. This risk is not specific to geothermal energy, but it is a major issue in the safety of deep wells. The proper design, placement and control of annular cementations and cement plugs are among the points that need special attention in any deep well, whether it is geothermal or not.

Contamination of a sensitive aquifer may also occur as a result of a lateral leak from a well, associated with the piercing or the rupture of one or more casings. This scenario must be payed particular attention (i) in the case of deep geothermal wells, where the casing is in direct contact with the geothermal fluid and thereby more exposed to corrosion and, (ii) in the case of high temperature geothermal wells because of thermomechanical effects due to temperature variations. Corrosion, in particular, has affected many geothermal wells in the Paris basin (France) and led to certain incidents, notably the one of Coulommiers in 1996.

In order to overcome this problem, a number of measures have been taken which now allow better management of the effects of corrosion: additional thickness of the casings, corrosion inhibitors, regular inspection of the internal diameter of casings or of the thickness of deposits, doubling the well casings if necessary. In the Paris basin, controls of casing corrosion are required on the injection wells every 3 years and on production wells every 5 years.

The risk of ground movements and noticeable seismic events

The production of a deep geothermal site can potentially generate geomechanical disorders at the surface, of various types and origins.

Although this only has caused light damage to buildings, induced seismicity is one of the risks perceived as most important in association with deep geothermal industry. This risk appears mainly during the stimulation operations (particularly hydraulic) but it can continue during the production phase. The link between the probability of occurrence of felt induced earthquakes and the natural seismicity of a region has been widely studied but has not been the subject of a consensus up to date.

From a scientific point of view, the feedback from the events in Soultz-sous-Forêts, Basel or St. Gall has led to a better understanding of the mechanisms involved in triggering induced seismicity, but also the factors that are causing the fears it provokes among the inhabitants. A set of operational measures is set in place which, if not eliminating the risk, enables to control it better and to take into account the concerns of the local residents, in particular:

- to keep the injection pressure below a certain threshold (to be adapted for each site). To achieve this, if necessary, distribute the reinjection between several wells;

- to implement an effective seismic monitoring network to analyze real-time seismic data and modify the injection parameters accordingly;
- to inform the population and the local authorities about the operations in progress and the possible risks of felt earthquakes.

Another source of geomechanical disturbances can come from the contact of an evaporite formation (salt, gypsum, anhydrite) with a fluid which is in chemical imbalance with it (fresh water, geothermal water, etc.). This scenario can occur, both in the production phase and in the post-abandonment phase, in the case of a loss of well seal. The ground surface may be raised in the event of hydration and swelling of this formation, or lowered if it is dissolved. In both cases, significant damages may be caused to buildings, networks or surface infrastructures. Such incidents have occurred recently in the field of superficial geothermal (Lochwiller, Staufen, Kirchheim). However, this risk is not specific to geothermal activities and has more to do with the good insulation of sensitive formations traversed by a well in general, whatever it is its nature.

Upheaval or subsidence of the ground surface may also result from poroelastic effects related to overpressure induced in the geothermal reservoir. This second risk (subsidence linked to a significant reservoir depletion) is particularly present when the geothermal fluid is only partially (or not at all) reinjected into its source aquifer. This situation is not specific to geothermal energy, but is found particularly in geothermal sites of volcanic type, where partial (or even absent) reinjection is frequent and where cases of significant subsidence (up to several meters) have been observed in certain production sites. It should be noted, however, that these subsidence areas develop slowly and that their consequences can be anticipated and controlled.

On some geothermal sites in mountainous environments, there is also the occurrence of landslide-type incidents. Again, this risk is not specific to geothermal energy and is due to the more general choice of implantation of deep wells in relation to natural hazards, in this case land movements. Nevertheless, it must be taken into account, even in the case of a deep geothermal well.

8.4 COMPARATIVE ANALYSIS OF THE RISKS, IMPACTS AND INCONVENIENCES RELATED TO DEEP GEOTHERMAL ENERGY

All the risks, impacts and inconveniences discussed above have been summarized (see **Erreur ! Source du renvoi introuvable.** and Table7) with a qualitative rating scale to compare them, in terms of their likelihood of occurrence and the severity of the consequences they might have.

This assessment is carried out for each phase of the life cycle of a geothermal site (drilling, testing, production, post-abandonment) and is based on a scale of 4 values, given in Table 5.

It should be noted that this is a generic assessment, which is not intended to replace the specific analysis that has to be carried out in the context of each site.

Table 5. Criteria for assessing risks-impacts and inconveniences related to deep geothermal energy

Probability		Severity	
● [blue]	P0: unlikely and never observed.	■ [blue]	G0: no noticeable discomfort or significant impact on property or the environment
● [green]	P1: unlikely with recent techniques or practices but already observed at least once.	■ [green]	G1: Limited disturbance, low intensity or limited environmental impact[a]
● [yellow]	P2: probable over the lifecycle of the system even with recent techniques or practices.	■ [yellow]	G2: significant discomfort, chronic health impact, non-structural damages to property[b], environmental impact of significant intensity and extent[c]
● [orange]	P3: very likely, can even occur several times during the lifecycle of the system.	■ [orange]	G3: harm to the personal safety, structural damage to property, environmental impact of significant intensity and extent[d]

[a] limited to the extent of the site or to approximately ten meters around
[b] which do not affect the overall integrity of the buildings or infrastructures
[c] approximately few tens to hundreds of meters around the site
[d] beyond several hundred meters around the site

Table6. Inconveniences and potential chronic impacts associated with deep geothermal

<u>Legend</u>: ■ Severity [37] n / a = not applicable

Chronic impacts or inconveniences	**Drilling**	**Testing**	**Production**	**Post-abandonment**
Impact on the landscape and land use	■ [yellow]	■ [yellow]	■ [green]	■ [blue]
Noise	■ [yellow]	■ [yellow]	■ [green]	*n/a*
Road traffic	■ [yellow]	■ [yellow]	■ [green]	*n/a*
Impact on ecosystems	■ [yellow]	■ [yellow]	■ [green] [b]	■ [blue] [a]
Impact on water resources	■ [green]	■ [yellow]	■ [green]	■ [blue]
Emissions of gas and odors	■ [green]	■ [yellow]	■ [green]	■ [blue] [a]
Carbon Impact	■ [green]	■ [green]	■ [blue]	*n/a*
Radioactivity affecting the workers	■ [yellow]	■ [yellow]	■ [yellow]	*n/a*

[a] except in the case of a chronic leak of geothermal fluid due to poor sealing or degradation of the plugging (aging).
[b] except in the case of incomplete reinjection or non-reinjection of the geothermal fluid.

[37] The notion of probability is not relevant to this table since we are here in the chronic field.

Table7. Potential risks and potential impacts associated with deep geothermal energy

Legend: ● Probability ■ Severity n/a = not applicable

Event ↓	**Phase →**	**Drilling**	**Testing**	**Production**	**Post-abandonment**
Risk of accidental gaseous emissions or spillages at the surface					
Well blowout		● (green) ■ (orange)	● (green) ■ (orange)	● (blue) ■ (orange)	*n/a*
Surface leakage/overflow		● (yellow) ■ (green)	● (yellow) ■ (green)	● (blue) ■ (green)	*n/a*
Leak on the 1st or 2nd circuit		*n/a*	*n/a*	● (green) ■ (yellow)	*n/a*
Degassing of geothermal fluid		● (green) ■ (orange)	● (green) ■ (orange)	● (green) ■ (orange)	● (blue) ■ (blue)
Risk of groundwater contamination					
Communication of aquifers		● (green) ■ (yellow)	● (green) ■ (yellow)	● (green) ■ (yellow)	● (green) ■ (yellow)
Well leak into an aquifer		● (green) ■ (green)	● (green) ■ (yellow)	● (yellow) ■ (yellow)	● (green) ■ (yellow)
Risk of ground movements and noticeable seismic events					
Noticeable seismic events		● (green) ■ (yellow)	● (yellow) ■ (yellow)	● (green) ■ (green)	*n/a*
Uplift of the ground surface[a]		● (green) ■ (orange)	● (green) ■ (orange)	● (green) ■ (orange)	● (green) ■ (orange)
Subsidence		● (green) ■ (orange)	● (green) ■ (orange)	● (green) ■ (orange)	● (green) ■ (orange)
Landslide		● (green) ■ (orange)	● (blue) ■ (orange)	● (blue) ■ (orange)	● (blue) ■ (yellow)

[a] In a majoring approach, the probability classes attributed to these risks take into account feedback from superficial geothermal operations, as mentioned in Sections 7.2 and 7.3.

9. BIBLIOGRAPHY

Abrigo MFV, Molling PA, Acu JA, 2004. Determination of recharge and cooling rates using geochemical constraints at the Mak-Ban (Bulalo) geothermal reservoir, Philippines. Geothermics 33: 11-36.

ADEME, 2010. Guide to Emission Factors - Version 6.1 Chapter 2 - Factors associated with direct energy consumption.

ADEME-BRGM, 2004. Geothermal energy. "The challenges of geosciences" Collection, BRGM, December 2004.

ADEME, 2015. Geothermal energy in Ile-de-France. June 2015, 8 p., https://ile-de-france.ademe.fr/sites/default/files/files/Mediatheque/Publications/plaquette-geothermie-juin-2015.pdf

ADIR, 2014. Earthquakes in Robertsau? http://www.adirobertsau.fr/?p=668

AFPG, 2013. Market study of geothermal energy in France. Report of the French Association of Geothermal Professionals (Association Française des Professionnels de la Géothermie), Update 2013.

AFPG, 2016. Geothermal energy in France, market study in 2015, summary. http://www.afpg.asso.fr/wp-content/uploads/2016/12/Depliant_afpg_marche2015_BAT2.pdf

AFPG-SFEG, 2013. Well incident in Lochwiller (Bas-Rhin). Press release, 07/22/2013.

AFNOR, 2014. Water and geothermal well - Construction, monitoring and abandonment of capturing or monitoring of groundwater by well. French Standard (Norme française) NF X 10-999 of August 30, 2014, version of 2014-08-F.

Agemar T, Weber J, Schulz R, 2014. Deep Geothermal Energy Production in Germany. Energies 2014, 7, 4397-4416; doi: 10.3390/en7074397.

Aksoy N, Şimşek C, Gunduz O, 2009. Groundwater contamination in a geothermal field: A case study of Balcova Turkey. Journal of Contaminant Hydrology 103: 13-28.

Ali ST, Davatzes NC, Drakos PS, Feigl KL, Foxall W, Kreemer CW, Mellors RJ, Wang HF, Zemach E, 2014. InSAR measurements and numerical models of deformation at Brady Hot Springs geothermal field (Nevada), 1997-2013. Proc. 39th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202.

Allis RG, 2000. Review of subsidence at Wairakei field, New Zealand. Geothermics, Volume 29, Issues 4–5, 1 August 2000: 455-478.

Allis R, Bromley C, Currie S, 2009. Update on subsidence at the Wairakei - Tauhara geothermal system, New Zealand. Geothermics 38 (2009): 169-180.

Antoine M, 2013. The village whose soil swells. Today in France, 11/20/2013.

Arevalo AS, 1998. Environmental aspects of the geothermal power station in El Salvador. Geothermal training program, Iceland.

ARTE, 2009. Staufen: a city that crumbles. http://www.arte.tv/fr/staufen-une-ville-s-effrite/1755842,CmC=2786544.htm

Bachmann CE, 2011. New approaches to understanding and forecasting induced seismicity.

Bachmann CE, Wiemer S, Wössner J, Hainzl S, 2011. Statistical analysis of the induced Basel 2006 earthquake sequence: introducing a probability-based monitoring approach for Enhanced Geothermal Systems. Geophysical Journal International, 186, 2, 793-807, DOI: 10.1111/j.1365-246X.2011.05068.x.

Bachu, S. & Watson, T.L.. Review of failures for wells used for CO2 and acid gas injection in Alberta, Canada. Energy Proc., pp. 2531-3537, 2009.

Baisch S, Carbon D, Dannwolf U, Delacou B, Devaux M, Dunand F, Jung R, Koller M, Martin C, Sartori M, Secanell R, Voros R, 2009. Deep Heat Mining Basel - Seismic Risk Analysis. SERIANEX Group, November 30th, 2009.

Baisch S, Vörös R, 2010. Reservoir induced seismicity: where, when, why and how strong? Proceedings of the World Geothermal Congress. 2010 Bali, Indonesia, 25-29 April 2010.

Bauer et al., 2015

Baumgardner RW Jr., AD Hoadley, and Goldstein AG, 1982: « Formation of the Wink Sink, a salt dissolution and collapse feature, Winkler County, Texas », Technical Report 114, Report of investigations, Bureau of Economic Geology, Austin, Texas, 1982.

Baumgärtner J, Lerch C, 2013. Geothermal 2.0: The Insheim Geothermal Power Plant. The second generation of geothermal power plants in the Upper Rhine Graben. 3rd European Geothermal Review - Geothermal Energy for Power Production, June 24-26, 2013, Mainz, Germany: 9-10.

Barras AV, 2015. Claims related to geological investigations' geothermal probes. "Journée CFGI" "Small scale geothermal energy", BRGM, May 21 2015, http://www.cfgi-geologie.fr/sites/default/files/seances/20150521/2-CFGI_g-othermie_BRGM_AVBarras_21mai2015.pdf

Berrizbeitia LD, 2014. Environmental impacts of geothermal energy generation and utilization. geothermalcommunities.eu/assets/elearning/8.21.Berrizbeitia.pdf

Bertani R, 2015. Geothermal Power Generation in the World 2010-2014 Update Report, Proc. World Geothermal Congress, Melbourne, Australia, 2015.

Bézèlgues-Courtade S, Durst P et al., 2012. Potential impacts of very low geothermal energy on soil, subsoil and aquifers - Bibliographic summary. Final Report BRGM / RP-59837-EN. February 2012.

Bigot A, Lassoued M, 2011. The various sources of vibrations: the vibrations associated with construction machines. Colloquium: Vibrations in buildings: sources, propagation methods and techniques for their reduction, Paris, 22-23 March 2011.

Bierlein L, 2013. Switzerland: a geothermal well causes an earthquake. http://lci.tf1.fr/science/environnement/suisse-un-forage-geothermique-provoque-un-seisme-8153345.html

Boissavy C, Garroustet E, 2013. Well incident at Lochwiller (Bas-Rhin). Press release, AFPG-SFEG, Paris, 22 July 2013.

Bonijoly D, Rigollet C, Serrano O, 2010. Characterization of the carbonate reservoirs in the Paris basin for the exploitation of hydrocarbons, the storage of CO_2 and geothermal energy. Annual Hydrocarbon Days 2010, Oil & Gas in the future energy mix, Workshop 6: Carbonate reservoirs - Classification and production - major stakes (Brazil, Middle East), Paris, 13-14 October 2010.

Bottai A, Cigni U, 1985. Completion techniques in deep geothermal well. Geothermics, Vol. 14, No. 2/3: 309-314.

Boxall B, 2013. Geothermal plants trigger small quakes near San Andreas fault. articles.latimes.com/2013/jul/11/local/la-me-geothermal-earthquakes-20130712

Brace G, Moureau M, Sevadjian G, 2011. Dictionary Of Well And Wells. English-French, French-English. Editions Technip, 2011.

Breede K, Dzebisashvili K, Liu X, Falcone G, 2013. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geothermal Energy, 2013, doi 10.1186/2195-9706-1-4

Brodsky EE, Lajoie LJ, 2013. Anthropogenic Seismicity and Operational Parameters at the Salton Sea Geothermal Field. Science Mag., 07/29/2013.

Bromley CJ, 2009. Groundwater changes in the Wairakei-Tauhara geothermal system.Geothermics 38: 134-144.

Brown DW, Duchane DV, Heiken G, Hriscu VT, 2012. Mining the Earth's Heat: Hot Dry Rock Geothermal Energy. Springer-Verlag, 658 p., Doi 10.1007 / 978-3-540-68910-2.

BRGM, 2005. Very low and low energy geothermal energy: An energy for sustainable development. The stakes of the Geosciences, Scientific summary sheet, n ° 10, April 2005, 5 p.

BRGM, 2013. Earth, a source of sustainable energy. Geosciences, No. 16, March 2013, 116 p.

Brüstle A, Vasterling M, Richter T, Schmidt B, Wegler U, 2015. Detection and location of induced earthquakes at the Landau and Insheim geothermal reservoirs, SW Germany. 1st Schatzalp Workshop on Induced Seismicity, Davos, Switzerland, 10-13 March 2015.

Buache P, 2013. Avenches. Géothermie de landau et de Insheim en Allemagne. http://www.geo-energie.ch/fr/projekte/Landau-Insheim_Buache_130225.pdf

Catoire S, Guignard P, Jean-Francois M, 2017. How to manage and compensate for the damage caused by geothermal well in the townshsip of Lochwiller (Bas-Rhin). CGEDD Report No. 010788-01, CGE No. 2016/22/CGE/SG, January 2017.

Carton A, 2015. Plan for the prevention of the natural risk of "field movements", Hilsprich Township. Presentation note, 41 p.http://mc.moselle.gouv.fr/data/doc-273/20150505/218187_1.pdf

Charléty J, Cuenot N, Dorbath L, Dorbath C, Haessler H, Frogneux M, 2007. Large earthquakes during hydraulic stimulations at the geothermal site of Soultz-sous-Forêts. International Journal of Rock Mechanics & Mining Sciences 44 (2007): 1091-1105.

Chauvet A, 2014. Kenya: energy to exploit under the hooves of the giraffes. Planet, http://www.20minutes.fr/planete/1493179-20141202-kenya-sous-sabots-girafes-energie-exploiter

Chavot, P. 2016. High-energy projects in urban areas? “Journées de la Géothermie” (Geothermal journal) 2016, Strasbourg.

Chevallier B, 2015. Energy transition for growing green: renewable energies in the French energy mix. Oil & Gas Information, 1836, May/June 2015, 55-58.

Chillou A, Riou M, 2011. Best Practice Case Study: “Geothermal pilot at Soultz-sous-forêt”, Alsace, France". Project RETS (Renewable Energies Transfer System). http://www.rets-project.eu/UserFiles/File/pdf/Best%20practices/ADEC/BP_SOULTZ_EN_v2.pdf

Clark CE, Harto CB, Sullivan JL, Wang MQ (2011). Water use in the development and operation of geothermal power plants. Argonne National Laboratory, Report ANL/EVS/R-10/05, September 2010.

Convertito V, Zollo A, Sharma N, Orefice A, Emolo A, 2015. Earthquake source parameters and scaling relationships at The Geysers geothermal field, California 1st Schatzalp Workshop on Induced Seismicity, Davos, Switzerland, 10-13 March 2015 (poster).

Cordon E, Driscoll JP, 2008. Full life-cycle water requirements for deep geothermal energy developments in South Australia.

Cuenot N, 2012. Environmental impacts and deep geothermal energy at the Soultz-sous-Forêts site. In: Transrhenian seminar "deep geothermics". Strasbourg - Kehl, 24 May 2012, SPPPI, Brief: 4-5.

Cuenot N, 2015. Induced seismicity and monitoring networks of the EGS project in Soultz-sous-Forêts. European Economic Interest Grouping (EEIG) Heat Mining operation.

Cuenot N, Genter A, 2013. The Franco-German deep geothermal project of Soultz-sous-Forêts. Symposium "Energy Sobriety and Efficiency. Necessary conditions for energy transition, 10th edition, Belfort, 28 November 2013.

De Simone S, Carrera J, Vilarrasa V, 2015. On the role of processes interaction in the triggering of post-injection seismicity in Enhanced Geothermal Systems. 1st Schatzalp Workshop on Induced Seismicity, Davos, Switzerland, 10-13 March 2015.

DGEC, 2015. Panorama Energies-Climat. General Directorate for Climate Energy - Ministry of Ecology, Sustainable Development and Energy, 2015 edition.

DGEC, 2016. Panorama Energies-Climat. General Directorate for Energy and Climate - Ministry of Ecology, Sustainable Development and Energy, 2016 edition.

Doherr D, 2012. Geological structure and seismicity of the Upper Rhine region. In: Transrhenian seminar "deep geothermics". Strasbourg - Kehl, 24 May 2012, SPPPI, Brief: 6.

Dorbath L, Cuenot N, Genter A, Frogneux M, 2009. Seismic response of the fractured and faulted granite of Soultz-sous-Forêts (France) to 5 km deep massive water injections. Geophys J Int (2009) 177 (2): 653-675, DOI:

https://doi.org/10.1111/j.1365-246X.2009.04030.x

Dorbath L, Charléty J, 2006. Microseismicity developments during hydraulic stimulations at Soultz-sous-Forêts. ENGINE - Enhanced Geothermal Innovative Network for Europe, Launching Conf., Orleans February 12-15, 2006, France: 57.

DRET, 2011. A guide to leading a sustainable development in mining. Department of Resources, Energy and Tourism, Australian Government, http://www.industry.gov.au/resource/Documents/LPSDP/guideLPSD.pdf

Durand-Delga M, Pandeli E, Bertini G, 2001. The geothermal field in Larderello (Tuscany, Italy): geological situation, industrial uses, role of the Larderel family. Geology Alpine, 2001, t. 77: 9-21.

Durst P, 2014. Risks associated with the presence of non-reported underground works - The importance of experience in small-scale geothermal projects. Oral presentation of May 20, 2014.

Durst P, Ayache B, Saltel M, Abou Akar A, 2011. Decision support for the matter of very low and low geothermal energy in the Aquitaine region. Map of the potential geothermal aquifers. Final report. Report BRGM / RP-59761-EN, March 2011, 175 p.

Eberhart-Phillips D, Oppenheimer DH, 1984. Induced Seismicity in the Geothermal Geothermal Area, California. Journal of Geophysical Research, 89 / B2: 1191-1207.

ECOGI, 2012. Inauguration of the first well of the geothermal station in Rittershoffen. Press kit, ECOGI project.

ECOREM, 2011. Study of the obstacles for deep geothermal energy (low and high energy). Report B01/2165.01.001, General Directorate for Regional Planning, Housing, Heritage and Energy (DGATLP), Department of Energy, Belgium, August 2011.

EGEC (2015). Market report 2015. Preview. European Geothermal Energy Council, 5th Edition, April 2016.

Eggeling L, Genter A, Kölbel T, Münch W, 2013. Impact of natural radionuclides on geothermal exploitation in the Upper Rhine Graben. Geothermics 47 (2013) 80-88.

ENERGY MEAUX, 2013. Geothermal energy in Meaux: a new phase of development. Energy Forum, April 26-27, 2013, Meaux.

ENS-Lyon, 2016. Geothermal energy: the warmth of the Earth. http://acces.ens-lyon.fr/eedd/climat/dossiers/energie_demain/geothermie/geothermie.pdf

Ercket G, 2015. Lochwiller- The case of the cracked houses: Act, and fast. Latest news from Alsace, 07/2/2015.

Escobar Bruno CA, Burgos JA, Ayala MS, 1992. Agua Chuca hydrothermal eruption. Geothermal Resources Council BULLETlN, December 1992: 361-399.

ESG, 2015. Microsismicity induced. geothermal energy, http://www.es-geothermie.fr/var/ezflow_site/storage/original/application/2c412ade5282e243cb81d2e59b41b75f.pdf

Essoyan S, 2002. Blowout shuts geothermal unit in Hawaii. http://articles.latimes.com/1991-06-15/news/mn-503_1_puna-geothermal-venture

Evans KF, Zappone A, Kraft T, Deichmann N, Moia F, 2012. A survey of the induced seismic responses to fluid injection in geothermal and CO2 reservoirs in Europe. Geothermics 41 (2012): 30-54.

Eysteinsson H, 2000. Elevation and gravity changes at geothemal fields on the Reykjanes peninsula, SW Iceland. Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10, 2000.

Fabre J, 2010. Order regarding the technical prescriptions and suspension of activities for the production of electricity from geothermal fluid in the territory of the Bouillante township by the company “Géothermie Bouillante”. AP of 22 February 2010.

Faessler J, 2014. The deep geothermal projects struggle to emerge. http://www.letemps.ch/economie/2014/03/13/realisations-geothermie-profonde-peinent-emerger

Fedeli M, Mannari M, Sansone F, 2016. BAGNORE 4: a benchmark for geothermal power plant environmental compliance. European Geothermal Congress, Strasbourg, Sept. 19-24, 2016.

Flynn T, Goff F, Van Eeckhout E, Goff S, Ballinger J, Suyama J, 1991. Catastropic landslide at Zunil i geothermal field, Guatemala. Geothermal Resources Council Transactions, Vol. 15. October 1991.

Fonroche, 2014. FAQ Deep Geothermal energy Brochure, 32 pages.

Gadis N, 2014. Hydrogen Sulfide Release at Puna Geothermal.

http://bigislandnow.com/2014/08/07/uncontrolled-hydorgen-sulfide-release-at-puna-geothermal/

Galin R, 2000. Deep Well: another form of post-mining? “Annales des Mines”, May 2000, 41-46.

Gáspár E, Ördögh J, Mácsai I, 2016. Effects of the long-term thermal water utilizations on the aquifer in SE-Hungary. European Geothermal Congress, Strasbourg, Sept. 19-24, 2016.

Gayraud M, 2008. Ancient balneology in Gaule du centre. Academy of Sciences and Letters of Montpellier, Conference N° 4037, Bull. 2008: 491-497.

Genter A, Guillou-Frottier L, Breton JP, Denis L, Dezayes C, Egal E, Feybesse JL, Goyeneche O, Nicol N, Quesnel F, Quinquis JP, Roig JY, Schwartz S, 2004. Typology of the HDH/HFR geothermal systems in Europe. Final report. BRGM / RP-53452-EN, 165 p.

Genter A, Guillou-Frottier L, Feybesse JL, Nicol N, Dezayes C, Schwartz S, 2003. Typology of potential Hot Fractured Rock resources in Europe. Geothermics 32 (2003): 701-710.

Gentier S, 2013. EGS: a generalized geothermal operational method for temperatures from 130 to 180 °C. Geosciences, 2013: 54-63.

Geo-Energie Suisse, 2014. Summary of studies on induced seismicity. Haute-Sorne deep geothermal pilot project. Geo-Energy Report Switzerland, 25 April 2014.

Giardini D, 2009. Geothermal quake risk must be faced. nature 462, 848-849 (17 December 2009), doi: 10.1038 / 462848a; published online 16 december 2009.

Gniese C, Bombach P, Rakoczy J, Hoth N, Schlömann M, Richnow HH, Krüger M, 2014. Relevance of deep-subsurface microbiology for underground gas storage and geothermal energy production. Adv Biochem Eng Biotechnol (2014) 142: 95-121, DOI: 10.1007 / 10_2013_257

Goff SJ, Goff F, 1997. Environmental impacts during geothermal development: some examples from Central America. NEDO Int. Geothermal Symp., Sendai, Japan, March 11-14, 1997.

Gombert P, Thoraval A, 2010. Current knowledge about the risks related to the geological storage of CO_2. Report No. 1: risks in the injection phase. Report INERIS DRS-08-95145-11842B, 03/19/2010.

Goyenèche, O., Bugarel, F., Guttierez, A., Hervé, JY 2015. Feedback on deep geothermal well. Phase 1. Report BRGM / RP-65443-EN, December 2015.

Groos J, Zeiß J, Grund M, Ritter J, 2013. Microseismicity at two geothermal power plants at Landau and Insheim in the Upper Rhine Graben, Germany. EGU General Assembly 2013, April 7-12, 2013, Vienna, Austria.

Halldorsson B, Ólafsson S, Snæbjörnsson JT, Sigurðsson SU, Rupakhety R, Sigbjörnsson R, 2012. On the Effects of Induced Earthquakes due to Fluid Injection at Hellisheidi Geothermal Power Plant, Iceland. 15th World Conference on Earthquake Engineering, September 24 to September 28, 2012.

Häring MO, Schanz U, Ladner F, Dyer BC, 2008. Characterization of the Basel 1 enhanced geothermal system, Geothermics 37 (2008): 469-495.

Heimlich C, Gourmelen N, Masson F, Schmittbuhl J, Kim S, Azzola J, 2015. Uplift around the geothermal power plant of Landau (Germany) as observed by InSAR monitoring. Springler Journal. Geothermal Energy 2015, 3: 2, DOI: 10.1186/s40517-014-0024-y.

Heimlich C, Masson F, Schmittbuhl J, Ferhat G, 2016. Geodetic measurements for geothermal site monitoring at Soultz-sous-Forêts and Rittershoffen deep geothermal sites. European Geothermal Congress, Strasbourg, Sept. 19-24, 2016.

Hervé JY, 2009. Report on the state-of-the-art relating to the design and implementation of geothermal well in Dogger. Final report. BRGM / RP-57245-EN, October 2009.

Herzberger P, Münch W, Kölbel T, Bruchmann U, Schlagermann P, Hötzl H, Wolf L, Rettenmaier D, Steger H, Zorn R, Seibt P, Möllmann GU, Sauter M, Ghergut J, Ptak T, 2010. The Geothermal Power Plant Bruchsal. Proceedings World Geothermal Congress 2010 Bali, Indonesia, 25-29 April 2010.

Hirschberg S, Wiemer S, Burgherr P et al., 2015. Energy from the Earth. Deep Geothermal as a Resource for the Future? Hirschberg S, Wiemer S and Burgherr P eds., Vdf Hochschulverlag 2015.

Holm A, Jennejohn D, Blodgett L, 2012. Geothermal Energy and Greenhouse Gas Emissions. Geothermal Energy Association (GEA), November 2012.

Humphreys B, 2014. Habanero Geothermal Project Field Development Plan. Geodynamics Ltd., Document COM-FN-OT-PLN-01166, October 9, 2014.

Jaud P, Lamethe D, 1985. The geothermal installations in Bouillante. La Houille Blanche, No. 3/4: 347-352.

Jaze-Charvolin MR, 2014. Thermal spas: from abandonment to rebirth. A brief history of thermal spas in France since Antiquity. In Situ [Online], 24 | 2014, http://insitu.revues.org/11123, DOI: 10.4000/insitu.11123.

Johnson KS, 1987: « Development of the Wink Sink in west Texas due to salt dissolution and collapse », In Beck and Wilson, editors, Proc. 2nd Multidisciplinary Conference on Sinkholes, pages 81-92, 1987.

Johnson KS, 2001: « Sinkholes associated with petroleum wells drilled through salt deposits in the USA », In Proc. S.M.R.I. Fall Meeting, Albuquerque, pages 8-17, 2001.

Johnson KS, Collins EW, Seni SJ, 2003. Sinkholes and land subsidence owing to salt dissolution near Wink, West Texas, and other sites in western Texas and New Mexico: in Johnson KS and Neal JT, editors, Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey Circular 109: 183-195.

Jung R, Schindler M, Nami P, Tischner T, 201. et al., 2010. Determination of flow exits in the Soultz well GPK2 by using the brine displacement method. CR Geoscience 342 (2010): 636-643.

Kage S, Ito S, Kishida T, Kudo K, Ikeda N, 1998. A fatal case of hydrogen sulfide poisoning in a geothermal power plant. Journal of Forensic Sciences, July 1998, Vol. 43 Issue: 4: 908-910.

Kagel et al. (2007) A guide to geothermal energy and the environment, Geothermal Energy Association, Washington, DC.

Khon, 2014. Alert issued after uncontrolled emissions reported at Puna Geothermal. http://khon2.com/2014/08/07/alert-issued-after-uncontrolled-emissions-reported-at-puna-geothermal/

Kreuter H, Deep Geothermal Projects in Germany. Status and Future Development. GeoThermal Engineering, Paris, 04.05.2011.

Kulish N, Glanz J, 2009. German geothermal project leads to second thoughts after the earth rumbles. The New York Times Company, Sep. 10, 2009.

Kuperkoch L, 2014. Working towards Highly Accurate Microseismic Event Locations at Insheim Geothermal Site (Pfalz/Germany).1st Bochum Workshop on Geothermal Reservoir Monitoring and Characterization, September 3rd 2014.

Lahaie F, 2015a. The lessons learned from accidents in the exploration and operation of hydrocarbons. Report INERIS DRS-15-149641-02735A, 05/07/2015.

Lahaie F, 2015b. Context and fundamental aspects of well and operation of hydrocarbon wells. Report INERIS DRS-15-149641-01420A, 05/06/2015.

Lafortune S, 2016. Analysis of the risks associated with the conversion of deep structures into geothermal wells. INERIS Report DRS-16-141899-07943A, 10/11/2016.

Larochelambert (De) T, 2013. Deep geothermal energy versus shale gas. http://tdelarochelambert.blog.lemonde.fr/2013/08/07/geothermie-profonde-versus-gaz-de-schiste/

Leibel D, 2016, The keys to success of the Ritterschoffen Geothermal Power Project, “Journées de la Géothermie”, 20-22 September 2016, Strasbourg.

Liberation, 2013. An Alsatian village is afraid of becoming uninhabitable because of a geothermal well. Article published in Libération on July 5, 2013,

Lund JW, Boyd T, 2015. Direct utilization of geothermal energy 2015 worldwide review, Proc. Word Geothermal Congress 2015, Melbourne, Australia, 19-25 APRIL 2015.

Lopez S, Millot R, 2008. Problems with the re-injection of geothermal fluids in a clay-sandstone reservoir: feedback and study of fluids from the Triassic of the Paris Basin. report BRGM / RP-56630-EN.

Majer E, Baria R, Stark M, Smith B, Oates S, Bommer J, Asanuma H, 2007. Induced seismicity associated with Enhanced Geothermal Systems. Geothermics 36 (2007): 185-222.

Marchand M, Blanc I, Marquand A, Beylot A, Bezelgues-Courtade S, Traineau H, 2015. Life Cycle Assessment of High Temperature Geothermal Energy Systems. Edited by Roland Horne and Toni Boyd. World Geothermal Congress 2015, Apr 2015, Melbourne, Australia. Proc. World Geothermal Congress 2015: 11.

Maréchal JC, Lopez S, Petit V, 2008. Bibliographic study on the re-injection of geothermal fluid in a high enthalpy field - Applied in Bouillante. Report BRGM / RP-54861-EN, May 2008.

Martinez-Garzón P, Kwiatek G, Sone H, Bohnhoff M, Dresen G, Hartline C, 2015. Short– term seismicity changes at The Geysers geothermal field with different injection volumes. 1st Schatzalp Workshop on Induced Seismicity, Davos, Switzerland, 10-13 March 2015 (poster).

Mauguit Q, 2013. Geothermal energy makes the earth tremble near the Salton Sea. Futura Planet, 07/15/2013.

Maurer V, Lehujeur M, Richard A, Vergne J, 2016. Ground vibrations caused by geothermal well operations: a case study from the Rittershoffen EGS project (Alsace, France). European Geothermal Congress, Strasbourg, Sept. 19-24, 2016.

Mazoyer A, 1999. Man and volcanism in Tuscany: geothermal energy. In: Bull. Assoc. Geogr. Franç., 76st year, 1999-4: 341-347; doi: 10.3406/bagf.1999.2126.

McMahon A, Baisch S, 2013. Case study of the seismicity associated with the stimulation of the enhanced geothermal systemS at Habanero, Australia. Proc. Australian Geothermal Energy Conf. 2013 Brisbane, Australia, 14-15 Nov. 2013.

McGuire JJ, Lohman RB, Catchings RD, Rymer MJ, Goldman MR, 2015. Relationships among seismic velocity, metamorphism, and seismic and aseismic fault slip in the Salton Sea Geothermal Field region. Journal of geophysical research, Volume 120, Issue 4, April 2015: 2600-2615.

MEDDE, 2015. A guide to developing a map of small-scale geothermal projects regulatory areas. July 2015, 83 p., http://www.geothermie-perspectives.fr/sites/default/files/guideelaboration_v4.pdf

Mendrinos D, Karytsas C, 2006. The environmental impact of the geothermal industry. From Ledru P. & Genter A. (eds.) 2006, in Proceedings of the Engine Launching Conference, 12-15 February 2006, Orleans, France. ISBN 978-2-7159-0978-6. Orleans, BRGM Editions. Collection Acts / Proceedings. ISSN 1773-6161.

Meier P, Zingg O, 2014. Technical report. Haute-Sorne deep geothermal pilot project. Geo-Energie Switzerland, Version 4, October 15, 2014.

Miguet L, 2014. Geothermal energy: two disastrous Alsatian villages. The Monitor, http://www.lemoniteur.fr/article/geothermie-deux-villages-alsaciens-sinistres-23652043

Milsch H, Seibt A, Spangenberg E, 2009. Long-term Petrophysical Investigations on Geothermal Reservoir Rocks at Simulated InSitu Conditions.Transp Porous Med (2009) 77:59-78, DOI 10.1007/s11242-008-9261-5.

Moeck I, Bloch T, Graf R, Heuberger S, Kuhn P, Naef H, Sonderegger M, Uhlig S, Wolfgramm M, 2015.The St. Gallen Project: Development of fault controlled geothermal systems in urban areas. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015.

Moran MS, 1979. The Impacts of deep geothermal fluid production on shallow ground-water systems. Oak Ridge Nat. Lab., US Dep. of Energy, Nov. 1979.

Morisseau JM, 2000: « Uncontrolled leaching of salt layer in an oil field in Algeria », In Proc. S.M.R.I. Fall Meeting Technical Session, San Antonio, pages 330-333, 2000.

Mossop A, Murray M, Owen S, Segall P, 1997. Subsidence at The Geysers geothermal field: results and simple models. Proc. 22nd Workshop on Geothermal Reservoir Engineering Stanford Univ., California, January 27-29, 1997: 377-382.

SIN, 2013. Induced Seismicity Potential in Energy Technologies. National Academy of Sciences, Washington, USA, ISBN 13: 978-0-309-25367-3.

Nishijima J, Fujimitsu Y, Ehara S, Kouno E, Yamauchi M, 2005. Micro-Gravity Monitoring and Repeated GPS Survey at Hatchobaru Geothermal Field, Kyushu Central, Japan. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005.

Norbeck JH, Horne RN, 2015. Earthquake rupture behavior in EGS settings. 1st Schatzalp Workshop on Induced Seismicity, Davos, Switzerland, 10-13 March 2015 (poster).

Oppliger G, Coolbaugh M, Shevenell L, 2006. Improved Visualization of Satellite Radar InSAR Observed Structural Controls at Producing Geothermal Fields Using Modeled Horizontal Surface Displacements. GRC Transactions 30: 927-930.

PIPAME, 2016. Challenges and prospects in the industrial sectors of the deep-subsoil energy valorization. Final report. Interdepartmental Center for Foresight and Anticipation of Economic Changes, ISSN: 2491-0058.

PPE, 2016. Multi-year Energy Program, Ministry of the Environment, Energy and the Sea, http://www.developpement-durable.gouv.fr/IMG/pdf/PPE-complet-1.pdf.

Radeckas B, Lukosevicius V, 2000. Klaipeda geothermal demonstration project. Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10, 2000: 3547-3550.

Reith S, Kölbel T, Schlagermann P, Pellizzone A, Allansdottir A, 2013. Public acceptance of geothermal electricity production. GEOELEC, deliverable No. 4.4, April 2013.

RETS, 2011. Best Practice Case Study: "Geothermal pilot at Soultz-sous-Forêt, Alsace, France". Information compiled in March 2011 by Marion Désissaire, ADEC, www.adec.fr

Richard A, Maurer V, Lejujeur M, 2016. Induced vibrations during a geothermal project and acceptability, how to avoid divorce? European Geothermal Congress, Strasbourg, Sept. 19-24, 2016.

Richter A, 2015. Tragedy hits geothermal site in Indonesia. Think geoenergy, 15/05/2015. http://www.thinkgeoenergy.com/update-tragedy-hits-geothermal-site-in-indonesia/

Rivas JA, Castellón JA, Maravilla JN, 2005. Seven Years of Reservoir Seismic Monitoring at Berlín Geothermal Field, Usulután, El Salvador. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005.

Robert Z, 2014. Two Icelanders suffer hypoxia at Philippines Geothermal Sites. http://icelandreview.com/news/2014/06/23/two-icelanders-suffer-hypoxia-philippines-geothermal-site

ROMANDIE, 2013. CH / Geothermal St. Gall continues its well in spite of the July earthquake. http://www.romandie.com/news/n/CHGeothermie_St_Gall_poursuit_son_forage_malgre_le_seisme_de_juillet88270820131846.asp

Rouquet, R. 2010. Geothermal energy, a local response to a burning problem, presented to the Council of Europe, March 2010.

Sailhac P, Larnier H, Matthey PD, Schill E, Chambodut A, 2013. Testing geothermal monitoring using MT and SP at Rittershoffen 2nd European Geothermal Workshop, 24-25 Oct. 2013, Strasbourg, 4 p.

Sanyal SK, Granados EE, Menzies AJ, 1995. Injection – related problems encountered in geothermal projects and their mitigation: the United States experience. In: Proceedings world geothermal congress, 1995, 2019-2022.

Seibt P, Kabus F, Hoth P, 2005. The Neustadt-Glewe Geothermal Power Plant – Practical experience in the reinjection of cooled thermal waters into sandstone aquifers. Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005.

Seibt P, Wolfgramm M, 2008. Practical experience in the reinjection of thermal waters into sandstone. Workshop for Decision Makers on Direct Heating Use of Geothermal Resources in Asia, organized by UNU-GTP, TBLRREM and TBGMED, in Tianjin, China, 11-18 May, 2008, 18 p.

Sewell SM, Cumming W, Bardsley CJ, Winick J, Quinao J, Wallis IC, Sherburn S, Bourguignon S, Bannister S, 2015. Interpretation of Microseismicity at the Rotokawa Geothermal Field, 2008 to 2012. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015.

Slavova I, 2013. Geothermal plant may be closed - report. Jun 19, 2013. http://renewables.seenews.com/news/

Sofyan Y, Daud Y, Nishijima J, Fujimitsu Y, Kamah Y, Yani A, Fukuda Y, Taniguchi M, 2015. The first repeated absolute gravity measurement for geothermal monitoring in The Kamojang Geothermal Field, Indonesia, Geothermics, 53, January 2015: 114-124.

SPPPI, 2012. Deep geothermal energy. Summary note of the Transrhenan seminar, Strasbourg, 24 May 2012.

Starkey N, 2014. Pumping water underground could trigger major earthquake, say scientists. The Guardian. https://www.theguardian.com/science/2013/jul/11/fracking-water-injection-major-earthquakes

Stauffacher M, Muggli N, Scolobig A, Moser C, 2015. Framing deep geothermal energy in mass media: the case of Switzerland. Technological Forecasting & Social Change 98 (2015) 60-70.

Stephen T, 2013. Geothermal power facility induces earthquakes, study finds. University of California, Santa Cruz. http://news.ucsc.edu/2013/07/geothermal-earthquakes.html

Strickland E, 2009. Geothermal explosion highlights a downside of a leading alt-energy source. http://blogs.discovermagazine.com/80beats/2009/04/28/geothermal-explosion-highlights-a-downside-of-a-leading-alt-energy-source/#.V_O9kvmLS70

Therin F, 2010. Madness about German geothermal energy. Les Echos, May 17, 2010. http://www.lesechos.fr/17/05/2010/LesEchos/20678-042-ECH_vent-de-folie-sur-la-geothermie-allemande.htm

Tribune De Geneve, 2013. A geothermal well causes a small earthquake. http://www.tdg.ch/suisse/Un-forage-geothermique-provoque-un-petit-seisme/story/22040751

UCS, 2016. Environmental impacts of geothermal energy. Union of Concerned Scientists, 25/02/2016, www.ucsusa.org/

Ungemach P, 2002. Energy development problematics in the Mediteranean. The Aeolian and Aegean islands. The geothermal energy case. Int. Workshop on the possibilities of geothermal development of the Aegean islands region, Milos, 5-8 September 2002.

UVED, 2011. The geothermal station in Bouillante (Guadeloupe). http://unt.unice.fr/uved/bouillante/cours/ii.-etude-de-cas-la-centrale-geothermique-de-bouillante-en-guadeloupe/2.-contexte-economique/2.2.-impact-sur-lenvironnement.html

Vernoux JF, Degouy M, Machard de Grammont H, Galin R, 2002. A bibliographic study on the monitoring of the risks generated by deep well on the underground water bodies in the Seine-Normandy basin. Ref. BRGM / RP-51312-EN.

Webb JW, Eddlemon GK, Reed AW, 1984. Retrospective examination of geothermal environmental assessments. Oak Ridge National laboratory report ORNL/TM-9071.

Weber KF, 2011. Network for a city separated in two halves. Leica Geosystems global magazine: 3-5.

White SP, Creighton AL, Bixley PF, Kissling WM, 2003. Modeling the dewatering and depressurization of the Lihir open pit gold mine. Proc. TOUGH Symposium, Lawrence Berkeley, National Laboratory, Berkeley, California, May 12-14, 2003.

Zang A, Oye V, Jousset P, Deichmann N, Gritto R, McGarr A, Majer E, Bruhn D, 2014. Analysis of induced seismicity in geothermal reservoirs - an overview. Geothermics, Vol. 52, October 2014: 6-21.

10. LIST OF APPENDICES

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APPENDIX 1

TERMINOLOGY USED IN THIS REPORT

Accidental impacts: Impacts related to an unforeseen event;

Accidental risks: risks related to an unforeseen event;

Acidification : injection in the formation of an acid diluted in water to clean the peripheral area of the well.

Anhydrite: evaporite rock formed of anhydrous calcium sulfate capable of hydrating and transforming into gypsum in prolonged contact with water; this hydration can be accompanied by a swelling of about 60% and thereby generate damage at the surface (ground uplift, damage to buildings, etc.).

Blowout: uncontrolled release of effluents (liquid or gaseous) from a well. The release point of the effluents may be located at the wellhead (surface blowout) or along the well (underground blowout).

BOP("Blow Out Preventer") is a set of shutters installed on the wellhead during drilling and whose function is to close the well in case of undesired inflow of formation fluids in the well (kick).

Casing: set of tubes places in a borehole, intended to consolidate the walls and to isolate, after cementing them, the geological formations that require to be isolated.

Chemical stimulation: technique for restoring or improving the natural permeability of the formation around the well by injecting a chemical product, generally acidic (see "acidification"); the injection pressure must be sufficient to allow the penetration of the water into the rock and, if necessary, the reopening of existing natural fractures, without however exceeding the fracturing pressure of the formation.

Chronic Impacts: Impacts related to the routine operations on the site;

Chronic risks: related to routine operations on the site;

Circulation loss: loss of mud in the formation during drilling.

Drilling: action of performing a wellbore.

EGS ("Enhanced Geothermal System"): a geothermal system whose development is based on techniques aiming to increase the permeability of the environment; this can be achieved by various approaches, such as thermal, hydraulic and/or chemical stimulation, or even hydraulic fracturing (which is not practiced in France).

Hydraulic fracturing: creation of new fractures in a deep rock by injection of fluid under pressure (according to http://labex-geothermie.unistra.fr/article205.html).

HDR (Hot Dry Rock), also known as Hot Fractured Rock (HFR): deep geothermal concept consisting of creating an artificial network of fractures in an initially hot and dry low-permeability rock and circulating a fluid in it by injection and withdrawal from the surface (according to http://labex-geothermie.unistra.fr/article205.html).

Hydraulic stimulation: technique for restoring or improving the permeability of a fracture or an existing fracture network by the action of a fluid under pressure (according to http://labex-geothermie.unistra.fr/article205.html); the injection pressure must be sufficient to allow the penetration of the water into the rock and, if necessary, the reopening of existing natural fractures, without, however, exceeding the fracturing pressure of the formation (unlike hydraulic fracturing).

Hypocenter (or focal point): the starting point of a deep seismic rupture; its projection on the surface is the epicenter.

Impacts: proven damage to property (buildings, infrastructure, etc.), to human activities (transport, etc.) or the environment (fauna, flora, water resources, etc.) resulting from the activities carried out at the geothermal site;

Inconveniences: inconvenience to persons resulting from routine (non-accidental) activities carried out on the geothermal site.

Induced seismicity : generation of earthquakes caused by human activity. In the case of a geothermal site, the term "induced seismicity " is used when earthquakes are created at the reservoir level and "triggered seismicity" when it concerns the activation of faults outside of the limits of the reservoir (ECOREM, 2011). In this document, the term "induced seismicity" covers both of these meanings. The threshold of earthquakes noticeability on the surface is around the magnitude of 2. Below this threshold, one speaks of microseisms.

Kick: Unwanted inflow of formation fluids in a well. A non-controlled (or badly controlled) kick may result in a blowout

Microseism: low magnitude earthquake (generally less than 2 or 3), not felt by humans but recorded by instruments (Kagel et al., 2007). See also "induced seismicity".

MW_e, MW_{th}: see Watt.

Risks: threats to the health or safety of persons (internal or external to the site) resulting from activities carried out at the geothermal site;

Suffocation: entrainment of fine particles (sand, clay loam) within a coarse aquifer formation (pebbles, gravels, sand), likely to lead to underground voids and movements at the ground surface.

Treatment: restoration or improvement of the natural permeability of the formation around the well by chemical or hydraulic stimulation.

Watt: unit for power (W), the main multiples of which are kW (10^3 W), MW (10^6 W), GW (10^9 W) and TW (10^{21} W). The “Thermal Watt " (W_{th}) and the "Electric Watt" (W_e) respectively correspond to power produced in thermal form and in electrical form. Since most power plants derive their energy from thermal sources (nuclear power plant, fossil fuel power station, geothermal power station), their thermal power is significantly higher than their electrical power due to losses in energy conversion (yield of around 10% for a geothermal power plant).

Well: cased borehole carried out by well drilling.

APPENDIX 2:

REGULATORY FRAMEWORK FOR A DEEP GEOTHERMAL SITE

Main applicable codes and texts:

Under French law, underground heat is assimilated to a mining substance known as a "geothermal deposit". The activities necessary for the research and exploitation of this substance are thus essentially governed by the mining code (article 112-1) and[38] the texts for its application. These include:

- decree No. 78-498 of March 28, 1978 about titles for geothermal energy research and operation;
- decree 2006-648 of June 2, 2006 about mining titles and underground storage titles.
- decree No. 2006-649 of June 2, 2006 about mining work, underground storage works and the policing of mines and underground storage;
- decree 2011-2019 of December 29, 2011 about the environmental impact studies

It should be noted that some surface installations of a geothermal site may also be subject to the ICPE [39] regulations of the Environment Code.

In addition, power generation facilities are covered by the Energy Code.

Lastly, on a European scale, geothermal activities are governed by Directive 2009/28/EC of 23 April 2009.

Legal classification of geothermal sites

The mining code distinguishes three categories of geothermal deposits (article L112-2 of the mining code and article 3 of decree 78-498):

- high temperature geothermal deposits, that is to say for which the temperature of the heat transfer fluid measured on the surface during the exploration well tests is greater than 150 °C;
- low temperature geothermal deposits, that is to say for which the temperature of the heat transfer fluid measured on the surface during the exploration well tests is less than 150 °C;
- small-scale low-temperature geothermal deposits, the definition criteria of which are specified in Article 3 of Decree 78-498 and summarized in Table 2.1 below.

From these definitions, it is evident that the geothermal sites intended for supplying heat networks systematically belong to the low-temperature regime.

On the other hand, geothermal sites intended for the production of electricity are subject either to the high temperature regime (when the temperature of the fluid leaving the well is> 150 ° C) or to the low temperature regime (when the temperature of the fluid outlet from the well is <150 ° C).

In fact, this threshold of 150 °C was originally defined as the limit below which it is not technically possible to produce electricity. However, it is now known that this

[38] Apart from certain specific installations such as the Canadian wells, thermal geostructures or heat exchangers with a depth of no more than 10m (Article L112-1 of the Mining Code and Article 3 of Decree 78-498)

[39] Installations classified for environmental protection

threshold is no longer applicable to current technologies, which make it possible to produce electricity from lower fluid temperatures (in the order of 120 °C or less). It is expected that this threshold will be reviewed in future regulatory updates.

High T°	**Low T°**	**Small-scale Low T°**	
		Closed geothermal heat exchangers	**Open geothermal heat exchangers**
Fluid T°> 150 °C on the surface	T° of the fluid <150 °C on the surface	Well depth <200 m Maximum thermal power <500 kW	Well depth <200 m Maximum thermal power <500 kW T° of the pumped water <25 °C Pumped water discharged into the same aquifer and difference between withdrawn and reinjected water = 0 Debits pumped or reinjected <at the authorization threshold set out in section 5.1.1.0 of Article R.214-1 of the EC
		Located outside the red zones, where geothermal activities present serious dangers or serious disadvantages, defined in article 22-6 of decree 2006-649	

Table 2.1 - Criteria for defining the three legal regimes for geothermal deposits

Legal stages of the lifecycle of a deep geothermal site

On the legal level, a deep geothermal project involves two main phases, each of which gives rise to the issue of mining title:

- in the research phase, which covers prospecting, operation and testing works. This work is carried out:
  - in the case of a high-temperature deposit: under an exclusive research permit or PER (issued by a ministerial decree);
  - in the case of a low-temperature deposit: within the framework of a research permit (issued by a prefectural decree).
- the operational phase, which covers the works related to operation and the closure of the site. This work is carried out:
  - in the case of a high temperature deposit: as part of a concession (granted by a Conseil d'Etat Decree);
  - in the case of a low-temperature deposit: under an operating permit (issued by a prefectural decree).

The procedures for the granting of these mining rights are described:

- in the case of a high-temperature deposit: in Decree 2006-648[40];
- in the case of a low-temperature deposit: in Decree 78-498[41].

Applications for authorization to begin the work

Within a mining title, the operator may undertake the works if he submits an application for authorization for open mining works (AOTM) in advance to the competent prefect. It concerns a file including (article 6 of Decree 2006-649):

- a descriptive memorandum of the proposed work;
- an impact study;
- a document indicating the planned measures to safeguard the health and safety of workers;
- a document indicating the conditions for stopping work;
- a document indicating the impact of the work on the water resource.

After consulting with the concerned administrative services and public inquiry, the authorization to carry out the work is issued by a prefectural decree. This order in particular specifies the requirements to be met by the operator in the field of public safety and environmental preservation.

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[40] Decree 2006-648 of 2 June 2006 on mining titles and underground storage titles.

[41] Decree 78-498 of March 28, 1978 relating to titles for geothermal energy research and operation, amended by decree 2015-15 of January 8, 2015.

APPENDIX 3

ACCIDENT DATABASE

The accident / incident table contains 32 information fields:

- 1 field for referencing of the event:
  - Identifier
- 5 fields to describe the context of the event:
  - Date
  - Type of activity concerned
  - Country
  - Location
  - Additional information
- 8 fields to describe the circumstances and the nature of the event:
  - Functional unit concerned
  - Phase of operation
  - Critical event (CE)
  - Initiating event (IE) or inoperative barrier
  - Detail of Initiating Event (IE) or inoperative barrier
  - Substances released
  - Corresponding quantity
  - Additional information
- 5 fields to detail the causes of the event:
  - Equipment-related causes
  - External causes
  - Human causes
  - Organizational causes
  - Additional information
- 4 fields to report the phenomenon(s) caused by the event:
  - Dangerous phenomenon (Dph) or impacting phenomenon (Iph) generated
  - Release environment
  - Type of accident involving people (as the case may be)
  - Additional information
- 8 fields dedicated to the consequences of the event:
  - Number of deaths
  - Number of injured
  - Of which seriously injured
  - Other human or socio-economic consequences
  - Corresponding amount (compensation cost in euros, number of destroyed buildings, etc.)
  - Environmental consequences
  - Corresponding quantity (polluted area in m², number of threatened species, etc.)
  - Additional information
- 1 field to indicate the used sources

Some terms in the table cells are explained in the glossary in the APPENDIX 1. Furthermore, to specify two symbols:

- **“-”**: means **unspecified**, that is to say:
  - that available sources do not provide information;
  - that some sources provide information which could not be verified;
- **“x"** means not applicable, i.e. the information requested by the field is inappropriate in view of the accident considered (eg field "released substance" can not be filled in the case of an event of the "induced earthquake" type).

REFERENCE	CONTEXTE DE L'EVENEMENT					CIRCONSTANCES ET NATURE DE L'EVENEMENT								CAUSES					PHENOMENES GENERES				CONSEQUENCES								SOURCES
Identifiant	Date	Type d'activité	Pays	Lieu	Infos complémentaires	Unité fonctionnelle concernée	Phase d'opération	Evènement redouté	Evénement initiateur (EI) ou barrière inopérante	Détails de l'EI1 ou de la barrière inopérante	Substances relâchées	Quantité	Infos complémentaire	Causes liées aux équipements	Causes externes	Causes humaines	Causes organisationelles	Infos complémentaires	PhD ou PhI	Milieu de rejet	Type d'accident individuel	Infos complémentaires	Nb morts	Nb blessés	Dont graves	Autres conséquences humaines ou socioéconomiques	Qté	Conséquences environnementales	Qté	Infos complémentaires	Sources
Agua Shuca	13/10/1990	Géothermie profonde	Salvador	Sud Ouest de Ahuachapan	Zone géothermale étendue	-	-	Eruption	-	-	Fluide géothermal boue roches	1600 m3	-	-	-	-	-	La cause n'est pas définie de manière exacte : il semble qu'une modification brutale des flux de chaleur de la zone géothermale ait provoqué une montée en pression incontrôlée du réservoir.	Explosion Projection	Sol	x	Cratère de 40 m de diamètre et 5 m de profondeur	25	35	-	bâtiments détruits	x	-	-	-	Escobar Bruno et al., 1992 Goff & Goff, 1997
Ahuachapan 1	été 1994	Géothermie profonde	Salvador	Ahuachapan	-	Circuit primaire	Exploitation	Fuite en surface	-	-	Fluide géothermal	-	Comme la réinjection des eaux était impossible, un canal de rejet des eaux de 82 km a été construit entre la centrale géothermique et l'océan.	-	-	-	-	-	Rejet toxique Rejet écotoxique	Sol Rivière	x	El Rio San Rafael pollué	plusieurs	plusieurs	-	-	-	Pollution importante	-	-	Goff & Goff,1997
Ahuachapan 2	année 1994	Géothermie profonde	Salvador	Ahuachapan	-	Circuit primaire	Exploitation	x	x	x	x	x	La mauvaise protection du canal de rejet a entrainé la chute d'animaux et de personnes dans le canal.	-	-	Erreur de conception	-	-	x	x	Chute accidentelle	Canal non protégé : brûlures, chute mortelle d'animaux, de personnes	plusieurs	plusieurs	-	-	-	-	-	-	Goff & Goff,1997
Bâle	08/12/2006	Géothermie profonde	Suisse	Bâle	Réservoir à 5000 m de profondeur	Réservoir	Stimulation hydraulique	Séisme	Pression de fluide excessive	-	x	x	-	x	x	Erreur de conception	x	Mauvaise connaissance du réservoir ou mauvaise planification des paliers d'injection	Secousses ressenties	x	x	11 000 évènements enregistrés dont 900 au dessus de la magnitude 0,9 et un maximum de 3,3	x	x	x	Dommages aux habitations (fissures) Abandon définitif du projet	9 millions de dollards de dédommagement	x	x	-	Baisch et al., 2009 Bachman, 2011 Giardini, 2009 Haring et al., 2008
Berlin 1	1993-1994	Géothermie profonde	Salvador	Usulutan	7 puits d'injection et 10 puits de production 700 à 2500 m de profondeur 183°C	Puits	Exploitation	Fuite en surface	Rupture de cuvelage	-	Fluide géothermal	-	-	x	Mouvement de terrain	x	x	Zone de glissement de terrain	Emission gaseuse	-	-	-	x	x	x	-	-	-	-	-	Goff & Goff,1997 Arévalo, 1998
Berlin 2	16/09/2003	Géothermie profonde	Salvador	Usulutan	8 puits d'injection et 10 puits de production 700 à 2500 m de profondeur 183°C	Réservoir	Stimulation hydraulique	Séisme	Pression de fluide excessive	-	x	x	Zone d'activité sismique naturelle importante	-	-	Erreur de conception	-	-	Secousses ressenties	x	x	Séisme de magnitude 4,4	x	x	x	-	-	x	x	-	Majer et al., 2007
Biliran	23/06/2014	Géothermie profonde	Philippines	Biliran	-	Puits	Essai de production	Dégazage massif	-	-	Gaz asphyxiant	-	-	-	-	-	-	-	Emission gaseuse	-	-	-	x	8	2	-	-	-	-	-	Robert Z., 2014
Bouillante	04/02/2010	Géothermie profonde	France	Bouillante, Guadeloupe	Puits allant jusqu'à 1400 m	Puits	Exploitation	-	-	-	-	-	-	-	-	-	-	-	Désordres géotechniques Subsidence	x	x	Apparition d'un effondrement (1,5 m de diamètre et 1,5 m de profondeur) Affaissement de 1 à 14 cm	x	x	x	Suspension de la production géothermique par le prefet	-	-	-	-	Fabre J., 2010 Marchand et al., 2015
Coulommiers	année 1996	Géothermie profonde	France	Coulommiers	-	Puits de réinjection	-	Fuite souterraine	Défaut d'étanchéité d'un cuvelage	Perforation par corrosion	Fluide géothermal	660 000 m3	-	-	-	-	-	-	Rejet écotoxique	Aquifère	x	-	x	x	x	-	-	Contammination de 2 aquifères (50 m et 440 m) mais non observée au niveau des captages d'eau potable	-	-	Vernoux et al., 2002
Geysers	1980-2010	Géothermie profonde	Etats-unis	Nord Californie, 120 km au nord de San Francisco	-	Réservoir	Exploitation	Séisme	Refroidissement excessif du réservoir Réinjection partielle	-	x	x	Zone d'activité sismique naturelle importante Modification du champ de contraintes lié à la déplétion et à l'injection d'eau plus froide	-	-	-	-	-	Secousses ressenties	x	x	18 évènements de magnitude supérieur à 3 et un de 4,6 en 1982	x	x	x	-	-	x	x	-	Majer et al., 2007
Habanero	mois de novembre 2012	Géothermie profonde	Australie	Cooper Bassin	Puits d'injection de 4077 m de profondeur	Réservoir	Stimulation hydraulique	Séisme	-	-	x	x	-	-	-	-	-	-	Secousses ressenties	x	x	en 3 semaine de stimulation, 27 000 séismes enregistrés de magnitude comprise entre 1,6 et 3	x	x	x	-	-	x	x	-	Mcmahon & Baisch, 2013
Hengill	15/10/2011	Géothermie profonde	Islande	Hengill, sud ouest de l'islande	-	Réservoir	Exploitation	Séisme	Débit de réinjection excessif	-	x	x	Zone d'activité sismique naturelle importante Le débit de réinjection est de 500 L/s	-	-	-	-	-	Secousses ressenties	x	x	3 séismes de moyenne 3 et le plus élevé 3,8	x	x	x	-	-	x	x	-	Halldorsson et al., 2012
Hilsprich	à partir de 2006	Géothermie superficielle	France	Lorraine	2 sondes géothermiques de 95 m et 99 m de profondeur	Puits	-	Dissolution incontrôlée	Cimentation defectueuse	-	-	-	-	-	-	-	-	-	Subsidence	x	x	-	x	x	x	Quinzaine de maisons fisurées et chaussées dégradées	-	-	-	-	Durst, 2014
Innamincka	24/04/2009	Géothermie profonde	Australie	Innamincka	-	Puits	Essai de production	Fuite en surface	Défaut d'étanchéité d'un cuvelage	Perforation par corrosion	Fluide géothermal	-	Eau+vapeur	Défaut matériel	x	Erreur de conception Erreur de test	x	-	Rejet toxique Projection	Sol	x	-	x	x	x	-	-	-	-	-	Strickland, 2009 University of Queensland, 2013
Insheim	mois d'avril 2010	Géothermie profonde	Allemagne	Bavière	3 puits : 1 de production et 2 d'injection Température de 165°C	Réservoir	Stimulation hydraulique	Séisme	-	-	x	x	-	-	-	-	-	-	Secousses ressenties	x	x	2 séismes de 2,2 et 2,4 de magnitude	x	x	x	-	-	x	x	-	Kuperkoch, 2014 Brustle et al., 2014.
Japon	année 1998	Géothermie profonde	Japon	-	-	Installation de surface	-	Fuite en surface	-	-	H2S	-	Accumulation de gaz dans un local confiné dans lequel un homme est rentré	-	-	-	-	-	Rejet toxique	Local	-	-	1	x	x	-	-	x	x	-	Kage et al., 1998
Kircheim	année 2007	Géothermie superficielle	France	Alsace	6 sondes géothermiques de 100 m	Puits	-	Intrusion d'eau dans une formation d'anhydrite	Cimentation defectueuse	-	-	-	-	-	-	-	-	-	Surrection	x	x	Variation de volume de 60%	x	x	x	1 bâtiment collectif fissuré	-	-	-	-	Durst, 2014 Miguet, 2014

REFERENCE	CONTEXTE DE L'EVENEMENT					CIRCONSTANCES ET NATURE DE L'EVENEMENT								CAUSES					PHENOMENES GENERES				CONSEQUENCES								SOURCES
Identifiant	Date	Type d'activité	Pays	Lieu	Infos complémentaires	Unité fonctionnelle concernée	Phase d'opération	Evènement redouté	Evénement initiateur ou barrière inopérante	Détails de l'EI1 ou de la barrière inopérante	Substances relâchées	Quantité	Infos complémentaire	Causes liées aux équipements	Causes externes	Causes humaines	Causes organisationelles	Infos complémentaires	PhD ou PhI	Milieu de rejet	Type d'accident individuel	Infos complémentaires	Nb morts	Nb blessés	Dont graves	Autres conséquences humaines ou socioéconomiques	Qté	Conséquences environnementales	Qté	Infos complémentaires	Sources
Landau 1	15/08/2009	Géothermie profonde	Allemagne	Landau	-	Réservoir	Exploitation	Séisme	-	-	x	x	-	-	-	-	-	-	Secousses ressenties	x	x	2 séismes importants (magnitude 2,4 et 2,7)	x	x	x	-	-	x	x	-	Brustle et al., 2014 ADIR, 2014 Kulish & Glanz, 2009
Landau 2	13/03/2014	Géothermie profonde	Allemagne	Landau	-	Puits	Exploitation	-	-	-	-	-	L'hypothèse non vérifiée est une intrusion d'eau dans une formation d'argile dûe à une cimentation défectueuse	-	-	-	-	-	Surrection	x	x	-	x	x	x	Fissures dans certaines rues et soulènvement du sol Fissures de 25 à 70 mmm de large 280 bâtiments endommagés	-	-	-	-	ADIR, 2014 Heimlich et al., 2015
Lardarello	année 1985	Géothermie profonde	Italie	Lardarello	Vapeur exploitée entre 200° et 400 °C Réservoir à 2500m de profondeur	Puits	Exploitation	Fuite souterraine	Défaut d'étanchéité d'un cuvelage	Perforation par corrosion	-	-	Perforation au bout de 12 jours d'installation du tubage	Défaillance matérielle	Eaux très agressives	x	x	-	Rejet écotoxique	Sous-Sol	x	-	x	x	x	-	-	-	-	-	Bottai & Cigni, 1985 Durand-Delga et al., 2001
Lochwiller	2008-2013	Géothermie superficielle	France	Alsace	1 sonde géothermique verticale de 140 m de profondeur	Puits	Forage	Intrusion d'eau dans une formation d'anhydrite	Venue d'eau incontrolée	-	x	x	-	x	x	x	Compétence insuffisante du personnel Non respect de la réglementation	-	Surrection	x	x	-	x	x	x	Maisons fissurées, chaussée déformée, atteintes aux réseaux enterrés	-	-	-	-	Boissavy & Garroustet, 2013 Antoine, 2013 Miguet, 2014 Ercket, 2015 Libération, 2013
Margamukti	07/05/2015	Géothermie profonde	Indonésie	Pangalengan ouest de Java	-	-	-	-	Rupture de cuvelage	-	-	-	-	x	Mouvement de terrain	x	x	x	-	-	x	-	x	x	x	-	-	-	-	-	Richter, 2015
Meaux	année 2013	Géothermie profonde	France	Meaux	-	Puits	Exploitation	-	Corrosion importante	-	-	-	-	-	-	-	-	-	x	x	x	-	x	x	x	-	-	-	-	-	Energie Meaux, 2013
Neustadt-Glewe	année 1998	Géothermie profonde	Allemagne	Neustadt-Glewe	Puits de 2200 m de profondeur	Puits	Exploitation	x	Colmatage	Précipitation de fer et de carbonates	x	x	-	Défaillance matérielle	x	x	x	Entrée d'oxygène par une vanne défectueuse en surface	x	x	x	Elimination des colmatants par acidification HCL	x	x	x	-	-	x	x	-	Seibt et al., 2005 Seibt & Wolfgramm, 2008
Puna 1	07/08/2014	Géothermie profonde	Hawaii	Honolulu	-	Puits	Exploitation	Fuite en surface	-	-	H2S	-	-	-	-	-	-	-	Rejet toxique	-	x	-	x	x	x	-	-	-	-	-	Khon, 2014 Gadis, 2014
Puna 2	15/06/1991	Géothermie profonde	Hawaii	Honolulu	Forage à 1060 m	Puits	Forage	Eruption	Venue	Formation en surpression	H2S	-	Durée : 30 heures	x	x	Erreur de conception	Non respect des procédures	-	Rejet toxique	-	-	-	x	1	x	Evacuation des personnes	-	-	-	-	Essoyan, 2002
Rotokawa	01/01/2010	Géothermie profonde	Nouvelle Zélande	Rotokawa	Puits de 500 m à 3000 m de profondeur	Réservoir	Exploitation	Séisme	Refroidissement excessif du réservoir	-	x	x	-	-	-	-	-	-	Secousses ressenties	x	x	-	x	x	x	-	-	x	x	-	Sewell et al., 2015
Saint Gall	20/07/2013	Géothermie profonde	Suisse	Saint Gall	Puits de 4500 m de profondeur	Puits	Forage	Séisme	Pression d'injection excessive	Poids excessif de la colonne de boue ayant fracturé les terrains	x	x	Opération de reprise de contrôle du puits suite à une venue de gaz Injection de 650 m3 d'eau	x	x	Erreur de conception	x	Mauvaise connaissance du réservoir (présence d'une quantité inattendue de gaz)	Secousses ressenties	x	x	Séisme de 3,6 de magnitude	x	x	x	120 plaintes pour dégâts matériels Abandon du projet	-	x	x	-	Hirschberg et al., 2015 Romandie, 2013 Bierlein, 2013 Faesser, 2014 La Tribune de Genève, 2013 20 minutes, 2014 Breede et al., 2013
Salton Sea	1981-2012	Géothermie profonde	Etats-unis	Californie	Puits de 2000 m de profondeur Température de 320°C Vapeur exploitée	Réservoir	Exploitation	Séisme	Réinjection partielle	-	x	x	Zone d'activité sismique naturelle importante Modification du champ de contraintes lié à la déplétion (seulement 81% du fluide géothermal est réinjecté)	-	-	-	-	-	Secousses ressenties	x	x	Séisme le plus important de magnitude 5,1 et 10 000 séismes en tout de magnitude moyenne de 1,75	x	x	x	Crainte d'une réactivation de la faille de San Adreas	-	x	x	-	Boxall, 2013 Mauguit, 2013 Joyce, 2013 Brodsky & Lajoie, 2013 Starkey, 2014 Stephen, 2013
Soultz-sous-Forêts	année 2003	Géothermie profonde	France	Alsace	8 puits entre 1 500 m et 5 000 m de profondeur Eau très minéralisée Température de 201°C à 5 000 m	Réservoir	Stimulation hydraulique	Séisme	-	-	x	x	-	-	-	-	-	-	Secousses ressenties	x	x	Séisme de magnitude 2,9	x	x	x	48 plaintes	-	x	x	la stimulation chimique a été ensuite utilisée car elle est moins génératrice de séisme	Chillou & Riou, 2011 Cuenot, 2015 Spppi, 2012. Cordon & Driscoll, 2008
Staufen	01/11/2007	Géothermie superficielle	Allemagne	Staufen	7 sondes géothermiques à 140 m de profondeur	Puits	Forage	Intrusion d'eau dans une formation d'anhydrite	Cimentation defectueuse	-	x	x	-	x	x	Erreur de conception	Non respect des procédures	Mauvais programme de forage et de cimentation	Surrection	x	x	-	x	x	x	Fissurations de plusieurs maisons	267 bâtiments	-	-	-	Weber, 2011 Arte, 2009 Therin, 2010
Svartsengi	1976-1999	Géothermie profonde	Islande	Svartsengi	-	Réservoir	Exploitation	Déplétion excessive du réservoir	Réinjection partielle	-	x	x	-	-	-	-	-	-	Subsidence	x	x	Abaissement du sol de 23 cm (1 cm/an)	x	x	x	-	-	-	-	-	Eysteinsson, 2000
Unterhaching	-	Géothermie profonde	Allemagne	Bavière	-	Réservoir	Exploitation	Séisme	Refroidissement excessif du réservoir	Injection d'eau froide dans un système de failles	x	x	-	-	-	-	-	-	Secousses ressenties	x	x	-	x	x	x	-	-	x	x	-	Agemar et al., 2014
Warakei	1950 à 1997	Géothermie profonde	Nouvelle Zélande	Warakei	-	Réservoir	Exploitation	Déplétion excessive du réservoir	Réinjection partielle	-	x	x	Couche de sédiments compressibles	-	-	-	-	-	Subsidence	x	x	Sol abaissé de 15 m (20 à 40 cm/an)	x	x	x	-	-	-	-	-	Allis, 1999 Allis et al., 2009 Berrizbeitia, 2014
Zunil 1	05/01/1991	Géothermie profonde	Guatemala	Sud-Ouest du Guatemala, 8 km au sud de Quetzaltenango	puits ZCQ 4 Température de 280°C 1300 m de profondeur	Puits	Exploitation	Fuite en surface	Rupture de cuvelage	-	-	-	-	x	Mouvement de terrain	x	x	glissement de terrain de 800 m de long et de 200 à 300 m de large	Explosion Projection	-	x	cratère de 15 m de diamètre	23	oui	oui	les morts sont le résultat du glissement de terrain	-	-	-	-	Goff & Goff,1997 Flynn et al., 1991

APPENDIX 4

DETAILED ACCIDENT REPORTS

Name of the event: PUNA 2
Date of the event: 06/15/1991
Location: Honolulu, Hawaii
Activity: Deep Geothermal
Phenomenon: Gas emission

SUMMARY

A massive gas blowout, mostly H_2S, occurred during deep well. More than 30 hours were needed to put it under control. Many people have been evacuated.

CONCERNED INSTALLATIONS

This is a well being drilled. Its depth was 1,060 m when the accident occurred.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident

On June 15, 1991, during the well of a well, a gas emission occurred, releasing mostly H_2S. The nearest inhabitants remained confined to their homes, others are evacuated.

Human and social consequences

1 wounded and 75 people confined in their homes.

The blowout lasted one day and two nights generating a plume of toxic gas and a continuous noise of 90 decibels.

Environmental consequences

Unspecified.

Economic consequences

Unspecified.

ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

Origin

The emission of gas is due to an eruption during well, caused by an uncontrolled inflow.

Immediate Causes

A high-pressure gas zone had been located but was reached earlier than expected by the well, resulting in the occurrence.

Two hypotheses are proposed: either the gas zone had not been well localized, or the driller did not properly estimate the progress during the well.

Internal Causes

Unspecified.

ACTION TAKEN

Immediate response and rescue measures

Unspecified.

Securing the site:

Unspecified.

Site clean-up and rehabilitation:

Unspecified.

Legal proceedings

Unspecified.

LESSONS LEARNED

The lessons learned are the following:

- The importance of having the best possible knowledge of the subsoil before well;
- Importance of having a trained team and the necessary equipment (including a well block) to manage any gas inflow, even when unexpected;
- The volcanic environment is conducive to the encounter of formations under strong gas pressure during well.

REFERENCES

Susan Essoyan, 2002. Blowout shuts geothermal unit in Hawaii. http://articles.latimes.com/1991-06-15/news/mn-503_1_puna-geothermal-venture

Name of the event: COULOMMIERS
Date of the event: 1996
Location: Coulommiers, France
Activity: Deep Geothermal
Phenomenon: Spill in aquifers

SUMMARY

In 1996, in Coulommiers, a leak in a deep geothermal well led to an accidental intrusion of geothermal fluid into superficial freshwater aquifers. It was a fluid from the Dogger reservoir, located about at depth of 2,000 m. This leak occurred in a re-injection well during operation and was detected after an abnormal pressure drop was observed at the head of this well between October 1995 (pressure 10 bar) and July 1996 (pressure of 1.2 bar). Logs revealed two perforations in the lining, located about 50 m and 440 m deep, respectively, at location with limestone in Champigny (Tertiary) and with chalk. These two formations each contain a freshwater aquifer, locally captured for the supply of drinking water. These perforations probably appeared in October 1995: the leak, which was initially low, had to reach its maximum flow rate (i.e.70% of the 135 m3 / h produced) in April 1996, which represents a total leakage volume of 660 000 m3. Due to the low hydrodynamic characteristics of the chalk, located here at depth, it has been assumed that most of the plume of geothermal fluid had to flow out into the limestones of Champigny. It was hot water (50 to 85 °), moderately acidic (pH 6.1 to 6.5) but mainly loaded with salts (6 to 35 g/L), dissolved gases (H_2S, CO_2), sulfides and sulfate-reducing bacteria. However, the monitoring of the city's drinking water catchments, located in this same aquifer, did not show on its end any significant indication for the inflow of geothermal fluid.

CONCERNED INSTALLATIONS

It is the reinjection well referenced as GCO2, it is 2,315 m deep.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident

- October 1995: the re-injection pressure of the GCO2 well decreases abnormally.
- January 1996: the pressure of the well, usually greater than 10 bar, is only 2.6 bar.
- early July 1996: well pressure continues to drop to 1.2 bar. A series of logs is launched and confirms the perforation of the well casing at two locations around at a depth of 50 m and 440 m. The leak must have appeared in October 1995.

Human and social consequences

Unspecified.

Environmental consequences

The estimated leakage volume is 660,000 m^3. The geothermal water of the Dogger is renowned for its high mineralization, particularly high salinity. Water quality monitoring is carried out in 6 AEP catchments located downstream of the wells (quantitative analysis of chloride ions, sodium, fluorides, sulfates and conductivity). According to the analyzes, the water from the leak did not reach the drinking water catchments.

Economic consequences

Unspecified.

ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

Origin

It appears that the leak is due to a perforation of the casing.

Immediate Causes

Corrosion would be at stake.

Internal Causes

Unspecified.

ACTION TAKEN

Immediate response and rescue measures

Unspecified.

Securing the site:

Unspecified.

Site clean-up and rehabilitation:

Water monitoring (chemical analysis) was carried out until 1999.

Legal proceedings

Unspecified.

LESSONS LEARNED

The lessons learned are the following:

- Specific vulnerability of deep geothermal well to corrosion, particularly in the environment of well at the Dogger in the Paris basin.
- Increased vulnerability of reinjection wells and the risk of leakage (due to higher pressure than in production wells).
- An abnormal drop in wellhead pressure should be interpreted as a sign of possible leakage and should allow for a rapid logging campaign before the volume of brine poured into the well environment is too high.

REFERENCES

JF Vernoux, M. Degouy, H. Machard de Gramont, R. Galin, 2002. Bibliographic study on the monitoring of the risks generated by deep well on the groundwater reservoirs in the Seine-Normandy basin, report BRGM/RP 51312-EN, 70 pages, 14 figures, 1 table, 2 appendices.

Name of the event: STAUFEN
Date of the event: 11/01/2007
Location: Staufen, Germany
Activity: Surface geothermics
Phenomenon: Upheaval

SUMMARY

Following a surface geothermal well in the city center of Staufen in the fall of 2007, a phenomenon of upheaval occurred, causing damage to 267 buildings in the city. The well would have created an infiltration of water into an anhydrite bank, causing it to swell and thus an uplift of the soil.

CONCERNED INSTALLATIONS

In September 2007, the municipality of Staufen called on an Austrian company to carry out, behind the town hall offices, 7 geothermal probes of 140 meters deep.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident

- **September 2007:** well works begin
- **end of 2007:** cracks appear on the Town hall and on 179 buildings in the historic center.
- **spring of 2008:** cracks continue to increase and soil elevation is measured: this elevation reaches 12.5 mm/month;
- **2011:** the cumulative elevation reaches 40 cm in places; 260 private buildings and 7 municipal buildings are damaged, with cracks up to 10 cm wide.

Human and social consequences

Damage is visible on many houses of the classified historical center of this municipality. The offices of the public authorities were evacuated because of the risk of collapse and many buildings had to be reinforced. The width of some cracks can reach 10 cm. The former fire station used by municipal services was declared unsanitary, after a crack 30 centimeters wide separated the building in two.

Environmental consequences

The ground level has risen in some places up to 40 cm.

Economic consequences

Current estimates of the cost of damage, for buildings only, is between 42 and 50 million Euros.

The municipality provisionally financed part of the repairs from public funds, but if it is established with certainty that the wells are at the origin of the cracks, it intends to pursue remedies from the well company and the engineering firm.

ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

Origin

The uplift of the land was caused by the swelling of an anhydrite bank located under the village of Staufen, which, in contact with water, was transformed into gypsum (see the Figure below). This hydration of the gypsum anhydrite gives rise to a volume increase of 60%, which induced a soil uplift.

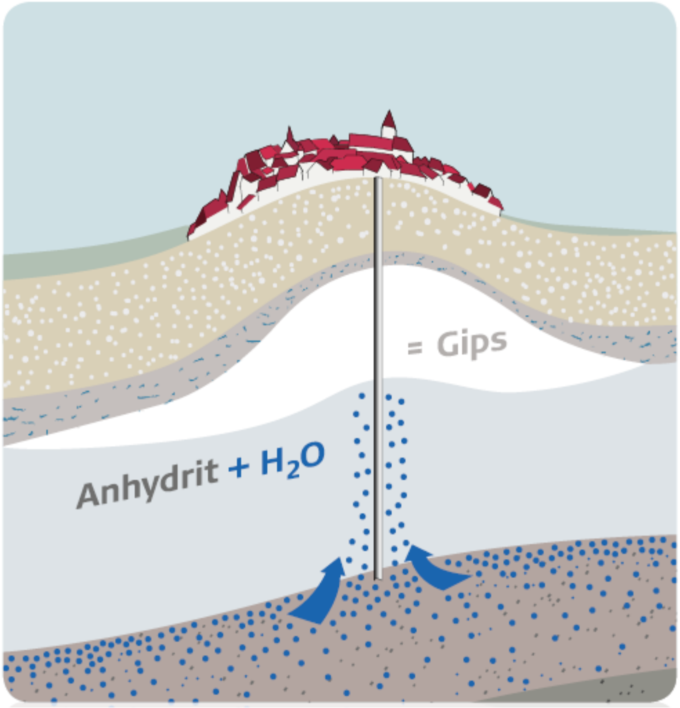


Diagram of the effect of the swelling of the anhydrite (Weber, 2011)

Immediate Causes

Infiltration of water into the formation of anhydrite would be linked to poor cementation of the well. The well company would not have used a cement which is sufficiently resistant to the sulfates, found in the anhydrites formation. On certain sections of the well, the cementing would even be not present.

Internal Causes

Unspecified.

ACTION TAKEN

Immediate response and rescue measures

Unspecified.

Securing the site:

Since March 2011, a second well has been carried out in order to pump the water. The maximum uplifting rate has thus decreased from 12mm per month to about 5.5 mm per month.

Site clean-up and rehabilitation:

Unspecified.

Legal proceedings

The well company and the engineering firm were prosecuted.

LESSONS LEARNED

The lessons learned are the following:

- The importance of having the best possible knowledge of the subsoil before well;
- The importance of good quality of annual cementing of the well;
- Required Qualification of the well company.

REFERENCES

Karl-Friedrich WEBER, 2011. **Network for a city torn in two.** The Leica Geosystems World Magazine, November 2011.

Arte, 2009. **Staufen: a city that crumbles.** http://www.arte.tv/fr/staufen-une-ville-s-effrite/1755842,CmC=2786544.htm

Frederic THERIN, 2010. **Wind of madness in German geothermics.** Les Echos, May 17, 2010. http://www.lesechos.fr/17/05/2010/LesEchos/20678-042-ECH_vent-de-folie-sur-la-geothermie-allemande.htm

Name of the event: SAINT GALL
Date of the event: 20/07/2013
Location: St. Gallen, Northern Switzerland
Activity: Deep geothermal energy (EGS)
Phenomenon: Quakes noticed

SUMMARY

On 20 July 2013, a high-pressure water injection is carried out in a deep geothermal well in order to control a gas inflow. The result is an earthquake of magnitude 3.6. Several damage of minor importance are reported by individuals. This incident led to the temporary abandonment of the project.

CONCERNED INSTALLATIONS

It is a geothermal well 4,500 m deep.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident

- **March 2013:** start of well operations
- **July 17-19, 2013:** during the preparation of the well tests, inflow of gas is detected on July 19, in the evening. In order to control this, 650 m^3 of water is injected under high pressure into the well. Approximately 100 microseisms are recorded in the perimeter of the well.
- July 20, 2013, 5:30 am: an earthquake of magnitude 3.6 is recorded west of the city of St. Gall. The hypocenter is located 4 km deep.

Human and social consequences

120 reports of damage by individuals.

Environmental consequences

Unspecified.

Economic consequences

Significant economic losses related to temporary abandonment of the project.

ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

Origin

The earthquakes were caused by the injection of water under high pressure, carried out in order to counteract a gas inflow.

Immediate Causes

The injection pressure was too high, which probably led to the release of stresses along a pre-existing fault and the generation of a sensed earthquake.

Internal Causes

A lack of knowledge of the deep subsoil (presence of gas) and an inappropriate choice of the position of the well were among the causes that led to the accident.

ACTION TAKEN

Immediate response and rescue measures

Plugging of the wells.

Securing the site:

Unspecified.

Site clean-up and rehabilitation:

Abandonment of the project

Legal proceedings

Unspecified.

LESSONS LEARNED

The lessons learned are the following:

- Importance of having the best possible knowledge of the subsoil before well (formations likely to house gas);
- Importance of having a team trained to control possible gas inflows;
- Importance of prioritizing the risks: in this case, the management of gas inflow was considered a priority, despite the induced risk of seismicity.

REFERENCES

Stefan HIRSCHBERG, Stefan WIEMER, Peter BURGHERR, 2015. **Energy from the Earth – Deep Geothermal as a Resource for the Future?** ISBN 978-3-7281-3654-1.
ROMANDIE, 2013. **CH/Geothermal St. Gall continues its well in spite of the July earthquake.**
http://www.romandie.com/news/n/CHGeothermie_St_Gall_poursuit_son_forage_malgre_le_seisme_de_juillet88270820131846.asp

Louis BIERLEIN, 2013. **Switzerland: a geothermal well causes an earthquake.** http://lci.tf1.fr/science/environnement/suisse-un-forage-geothermique-provoque-un-seisme-8153345.html

Jerome FAESSLER, 2014. The realizations of deep geothermal energy struggle to emerge**.** http://www.letemps.ch/economie/2014/03/13/realisations-geothermie-profonde-peinent-emerger

The Geneva Tribune, 2013. **A geothermal well causes a small earthquake.** http://www.tdg.ch/suisse/Un-forage-geothermique-provoque-un-petit-seisme/story/22040751

20 minutes, 2014. **St Gallen abandons its geothermal energy project** http://www.20min.ch/ro/news/monde/story/14948152

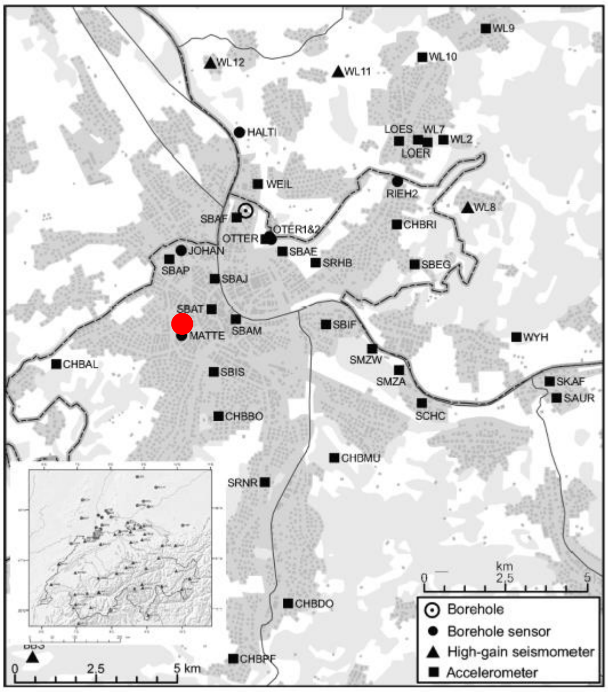
Katrin BREEDE, Khatia DZEBISASHVILI, Xiaolei LIU, Gioia FALCONE, 2013. **A systematic review of enhanced (or engineered) geothermal systems: past, present and future.** Geothermal Energy, **2013.** http://geothermal-energy-journal.springeropen.com/articles/10.1186/2195-9706-1-4

Name of event: BASEL
Date of the event: December 8, 2006
Location: Basel, Switzerland
Activity: Deep Geothermal energy (HDR)
Phenomenon: Quakes noticed

SUMMARY

An earthquake of magnitude 3.4 occurred on December 8, 2006 during the development of a geothermal reservoir 5 km deep underneath the the city of Basel. A hydraulic stimulation operation of the geothermal reservoir was then under way. The earthquake was felt in the city accompanied by a strong detonation. The operator's insurance paid nearly $ 9 million for the damages. After this event, the geothermal development of this area was stopped.

CONCERNED INSTALLATIONS



Location of the injection wells (red dot)

The concerned installations are located in the densely populated city center of Basel (Adjacent figure). The *"Deep Heat Mining"* project in Basel was aiming to become one of the first commercial power stations based on deep heat extraction within crystalline rock, located about 4-5 km deep (EGS technology).

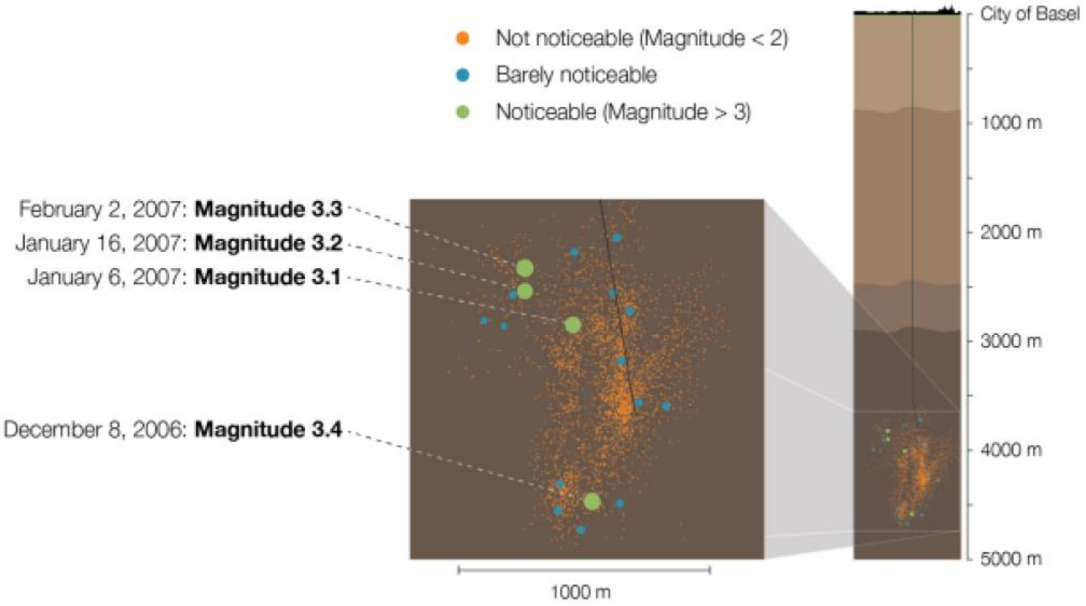
It was intended to improve the permeability of the reservoir by injection of high pressure fluid (hydraulic stimulation) over a period of time of about two weeks. A seismic monitoring system was installed, consisting of six deep probes, drilled at depths between 300 m and 2,700 m, and 30 surface stations.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident

- **12/02/2006**: start of the hydraulic stimulation operation (injection of a volume of water of approximately 11,500 m^3)
- **12/02/2006 to 12/ 07/2006:** the flow rate is increased in increments of 0 to 100 L/min resulting in a wellhead pressure of 110 bar. The flow is then progressively amplified to a maximum of 3,300 L/min resulting in a head pressure of 296 bar.
- **12/08/2006, at around 2h**: after about 16 hours of injection at these maximum flow and pressure values, an earthquake of magnitude 2.6 is recorded at the reservoir.
- **12/08/2006**, **at 4h:** reduction of the injection pressure.
- **12/08/2006**, **at 11h33:** stop of the injection.

- **12/08/2006, around 16h30:** during the preparations for purge of the well, a new earthquake of magnitude 3.4 is felt in the city of Basel.
- **12/08/2006, around 17h30:** initiation of the purge of the well
- **12/12/2006**: the pressure at the bottom of the well regains hydrostatic pressure. As a result, seismic activity decreases slowly.
- **01/06, 01/07 and 2/02/2007:** three other earthquakes occur, with magnitudes above 3 (3.1, 3.2 and 3.3 respectively), whereas no injection operation is in progress.



Seismicity observed after the December 8, 2006 event of magnitude 3.4

Human and social consequences

The damage observed on the structure is qualified light structural damage: fine cracks in the plaster of certain houses. On the other hand, these events were clearly felt by the inhabitants and led to numerous complaints. A risk study conducted by SERIANEX concluded that the risk of seismicity induced was too high in the event of a continuation of the project and that this project had to be abandoned.

Environmental consequences

More than 11,000 microseismic events were recorded during the stimulation operation and in the following weeks. Among these events, 900 with a magnitude greater than 0.9 were located.

Economic consequences

The project was finally abandoned in 2009. The insurance of the consortium which carried out the works (the Geothermal Explorers Ltd or GEL) has settled the total requested amount for damages, 9 million dollars.

ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

Origin

The earthquakes were induced by the injection of water under high pressure into a massive bedrock subjected to strong natural constraints.

Immediate Causes

The flow and the injection pressure were much too high and led to the release of the stresses accumulated on neighboring faults.

Internal Causes

Underestimation of the risk, due in part to lack of feedback. Indeed, Basel was one of the very first industrial implementation projects of the EGS technology after the tests carried out in Soultz-sous-Forêts.

ACTION TAKEN

Immediate response and rescue measures

The established seismic network allowed to follow in real time the evolution of the seismicity.

Securing the site:

Stopping the injection and purging the wells.

Site clean-up and rehabilitation:

No pollution generated.

Repair of cracked dwellings.

Legal proceedings

None. The operator's insurance compensated the victims.

LESSONS LEARNED

The lessons learned are the following:

- The injection of water into deep tectonically active fault structures must be carried out with a limited flow and pressure, the threshold of which must be defined at each site;
- Any EGS type geothermal project must be accompanied by real time microseismic tracking, which must make it possible to stop the operations in the event of detection of abnormal microseismic activity;
- Microseismic activity may continue (or intensify) for several weeks after the stopping of the injection operations;
- Although the seismicity induced by geothermal operations has only created slight material damage to buildings, it has a significant psychological impact on the population;
- EGS projects must be accompanied by guarantee funds, enabling victims to receive prompt and full compensation.

REFERENCES

Stefan BAISCH, David CARBON, Uwe DANNWOLF, Bastien DELACOU, Mylène DEVAUX, François DUNAND, Reinhard JUNG, Martin KOLLER, Christophe MARTIN, Mario SARTORI, Ramon SECANELL, Robert VOROS, 2009. **Deep Heat Mining Basel - Seismic Risk Analysis.** SERIANEX Group, November 30th 2009.

Corinne Elisabeth BACHMANN, 2011. New approaches to understanding and forecasting induced seismicity.

Stefan HIRSCHBERG, Stefan WIEMER, Peter BURGHERR, 2015. **Energy from the Earth – Deep Geothermal as a Resource for the Future?** ISBN 978-3-7281-3654-1.

Domenico Giardini, 2009. **Geothermal quake risks must be faced.** Nature 462, 12/16/2009. http://www.nature.com/nature/journal/v462/n7275/full/462848a.html.

Markus O. HÄRING, Ulrich SCHANZ, Florentin LADNER, Ben C. DYER, 2008. **Characterization of the Basel 1 enhanced geothermal system.** Elsevier, 469-495, 26/07/2008.