Towards a comprehensive environmental monitoring of a geothermal power plant in the Rhine graben

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ABSTRACT

The purpose of this paper is to present the main environmental monitoring performed during operational phases of a geothermal power plant in the Upper Rhine graben and their associated cost. Five kinds of impacts are identified and monitored from large to local scale influence: induced seismicity and surface deformation, surface water and shallow groundwater resources protection, neighbourhood disturbance, such as vibrations or noise emissions, and evolution of the natural radioactivity resulting from the scaling. To ensure the acceptability of geothermal projects in the Rhine graben, it is strongly required to measure and to apply procedures to minimize those different physico-chemical impacts on the environment and neighbourhood.

1. INTRODUCTION

During their life cycle, deep geothermal projects can induce small disturbances for the local environment and for residents, as can be generated by any industrial power generation project. With operational experience gathered thanks to the three main geothermal projects located in the Upper Rhine Graben in Northern Alsace, France (Soultz-sous-Forêts, Rittershoffen and more recently Illkirch-Graffenstaden), the Electricity of Strasbourg Company (ES) has acquired a strong scientific and technical expertise in order to minimize the impact of geothermal project on both environment and neighbourhood quality of life. Five kinds of impacts are identified and monitored from large to local scale influence:

- Ground motion monitoring, a seismic network is deployed in order to monitor the induced seismic activity before drilling operations and during the operational phase of the geothermal plant. On the top of that, one geodetic station dedicated to the monitoring of surface deformations (subsidence, uplift) is installed on the geothermal platform and is composed of one telemetered GNSS (Global Navigation Satellite System) receiver. Additionally, one corner reflector can also be installed on the geothermal platform in order to measure surface deformations through satellite radar interferometry (InSAR technique). Hence, the monitoring network is designed to monitor a large scale of frequencies, allowing detecting different types of ground motion, from micro-seismic events to slow surface motions;
- Shallow groundwater resources protection, implying regular casing inspection, groundwater's piezometric level and quality monitoring;
- Surface water protection preventing geothermal brine leakage in the environment with corrosion monitoring, regular pipe inspection, surface water management;
- Neighbourhood disturbance, such as noise impact around the geothermal power plant, and possible gas emission;
- Evolution of the natural radioactivity resulting from the scaling formed in the casing and in the surface equipments by the geothermal fluid which naturally circulates in a fractured granite containing radionuclides and, if necessary, radiation protection procedures for public and workers.

2. REVIEW OF THE DIFFERENT ENVIRONMENTAL MONITORING

2.1 Ground motion monitoring

All in place or future deep geothermal projects located in the Rhine graben are designed to exploit faulted zones at depths of 2 500 m to 5 000 m (Genter et al. 2015). Some of these projects may be located in urban areas. In particular one of the main concerns of the surrounding population is the increase of micro-seismic activity and the eventual occurrence of damages on buildings due to surface deformation that may be induced by the geothermal activities (Lagache et al. 2013). Therefore, since acceptability issues have more and more often been rising, a strategy has been set up by designing pluri-parametric geophysical ground motion monitoring networks to control deep geothermal projects in the Rhine graben. The objective of such networks is to detect various types of ground motions, characterized either by high-frequency micro-seismic events, slow displacements, or from deep to surface deformation (Schmittbuhl et al. 2014). This ground motion networks will include a seismic network composed of a strong-motion sensor, at least four short-period sensors and a broad-band sensor installed in parallel with a geodetic station including one telemetered GNSS receiver and two corner reflectors for remote sensing survey of the surface displacements (radar interferometry). Such kind of survey was already efficient in the Upper Rhine Valley related to the unexpected uplift of the Landau power plant (Heimlich et al. 2015).

This strategy was applied to the new deep geothermal project led by Electricity of Strasbourg, which is planned to exploit a fractured/faulted zone at around 2 700 m depth in the southern part of the city of Strasbourg, in the town of Illkirch-Graffenstaden (Maurer et al. 2016). In order to accurately follow both the time space evolution of the micro-seismicity nearby the geothermal operations and the surface deformation, a permanent ground motion monitoring network has been deployed, combining seismological and geodetic measurements. The seismological telemetered network in Illkirch-Graffenstaden is composed of five telemetered short-period surface velocimeters, one downhole broad-band velocimeter buried in a 5 m deep well, and one strong-motion sensor located above the wells trajectories.

In addition, a geodetic station dedicated to the monitoring of surface deformations and its time evolution will be installed on the geothermal platform. It will be composed of one GNSS (Global Navigation Satellite System) receiver and two corner reflectors allowing radar interferometry studies from the data acquired by the Sentinel-1 satellite. Geodetic analyses of high enthalpy geothermal fields have already been performed with such methods (Massonnet et al. 1997; Carnec and Fabriol 1999). It has have been shown that vertical and horizontal displacements have been caused by geothermal exploitation (Nishijima et al. 2005; Glowacka et al. 2010).

Hence, the monitoring network has been designed to monitor a large scale of frequencies, allowing detecting various types of ground motion, from micro-seismic events to slow motions, at depth and at surface. As a matter of fact, instrument response of the short-period sensors (1-100 Hz) are adapted to the microseismic monitoring and will allow to detect any rise of a seismic activity potentially induced by geothermal operations.

Before the deployment of permanent monitoring stations, a study has been conducted on the theoretical network geometry in order to maximize the accuracy of events localizations with six stations. To select the final sites (see Figure 1), tests have been performed to evaluate the level of the background noise at several locations. These tests allowed firstly selecting the final sites for deploying the permanent network, and secondly to evaluate the magnitude of completeness of the seismic network (Maurer et al., 2016).

Slow aseismic displacements (Cornet, 2016; Schmittbuhl et al. 2015) which are generally characterized by low-frequency content signals will be recorded by the broad-band sensor, whose instrument response curve "plateau" goes down to 120s. At the same time this sensor can be used to detect and locate micro-seismic events. With a sampling frequency of 30s, the GNSS instrument is able to measure in real time very slight surface deformations (less than a millimetre) whereas the radar interferometry method can provide even more precision but over a larger time period, depending on the Sentinel-1 satellite cycle. Hence, this ground motion network will cover a large frequency range, going from the hundredth of a second to the decade.

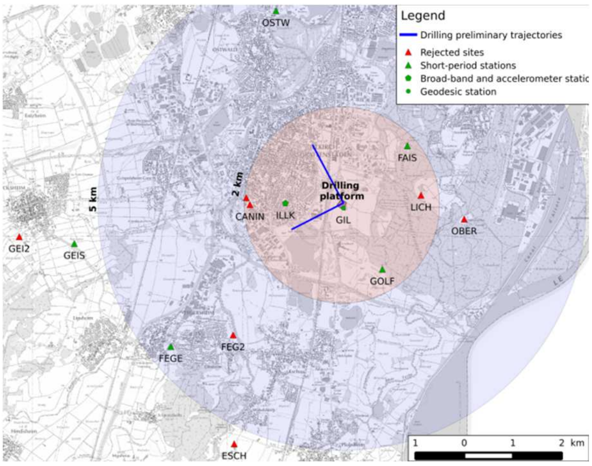

Figure 1 : Location of the tested and selected sites for the seismic network and location of the future geodetic station in the Illkirch area

2.2 Underground water protection

The shallow ground water aquifer of the Upper Rhine Valley is a regional aquifer and its protection is a serious issue for industrial projects from Basel to Mainz. In terms of volume, with 35 000 millions of m^3, it is one of the biggest fresh water resource in Europe. Indeed, the Rhine aquifer covers almost the entire Upper Rhine Valley and can show a thickness several hundreds of meters. It is extremely important for the regional economic development and the drinking water supply. This shallow ground water resource is exploited for 3 main purposes: agriculture, drink water supply and heating and cooling needs of buildings.

However, this groundwater resource is very vulnerable. One third of its surface is already undrinkable without any treatment. Survey quality of the Rhine groundwater and its protection is leaded by a European trans-border program (ICPR, http://www.iksr.org).

The deep geothermal project in Illkirch is very representative of the extensive use of this groundwater resource. The groundwater table is around 2.5 m under the ground on the drilling site. The thickness of the aquifer is estimated to be almost 100 m. The transmissivity is very high (up to 2.10^{-1} m^2/s) and the natural flow direction is the same as the Rhine river (northward). A private well, used by local farmers, is located 50 m from the drilling site. Several tertiary buildings located a few hundred meters to the north of the drilling site use the ground water for heating and cooling needs (the nearest pumping well is located around 200 m north from the drilling site). Last but not least, an important pumping site for drink water supply of the city of Strasbourg is located 5 km north/north-east of the drilling site. In order to make sure that the two deep wells planned in the framework of the Illkirch geothermal project have no impact on this important ground water resource, several actions have been decided.

Firstly, a special attention was taken on the completion design of geothermal wells. From the surface to 120 m depth, the two wells are designed with three cemented casings: one 30’’ conductor pipe, one 20’’ intermediate casing and one 13’’3/8 production casing (Figure 2). First drilling section (down to 700 m) will be drilled using a simple bentonite mud using no additives, in order avoid any chemical contamination of the resource if mud losses occur during drilling of the first section of the well.

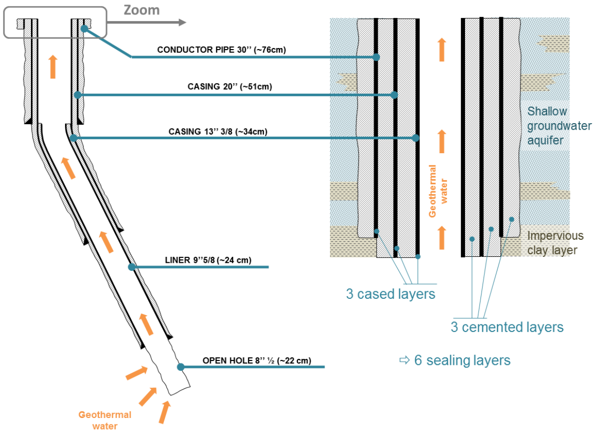

Figure 2 : Schematic technical completion of the Illkirch-Graffenstaden geothermal wells with zoom from the surface to 120 m depth

This casing design ensures a very good ground water protection during the drilling and the operation of the geothermal plant. However, over the 20 or 30 years of operation, these mechanical barriers can be damaged by corrosion. That’s why, in accordance with the local environmental authorities, a program of casing inspection is required during the life-time of the plant. This program, applied in the geothermal operational projects of Soultz-sous-Forêts and Rittershoffen, consists of regular casing inspection through borehole geophysical imagery, every 3 years for the injection well and every 6 years for the production well. Inspection period for injection and production wells are not the same for two reasons. Firstly, a downhole production pump is installed in the production well which complicate the casing inspection: the down-hole pump needs to be removed from the well and this operation requires about one complete week. Secondly, risk of corrosion is higher in the injection well because of the lower temperature, about 60 to 70°C: at this temperature level, sulfate-reducing bacteria can start to develop and contribute to corrosion.

Secondly, a groundwater monitoring network has been designed, in cooperation with a local independent hydrogeologist, in order to be able to guarantee the protection of this aquifer. This monitoring network is composed of 4 piezometers located around the drilling platform.

- One upstream shallow piezometer (8m TVD);
- Two downstream shallow piezometers (8m TVD);
- One downstream deep piezometer (110m TVD).

Prior to the drilling operations, a detailed chemical analysis will be carried out on groundwater samples on the drilling site in order to get a clear initial state of the groundwater quality. The following parameters will be characterized:

- On site physico-chemical measurements: pH, Conductivity, Redox potential and temperature;
- Laboratory geochemical analysis: Main anionic and cationic contents, minerals and metals, pollution indicators and organic components.

During the drilling operations, the same parameters will be followed. On site measurements will be performed in real time and laboratory analyses will be periodic.

2.3 Surface water protection

Management of the surface water protection consists of preventing any leakage of geothermal fluid in the environment. This management is firstly ensured thanks to corrosion monitoring and a geothermal pipes inspection program.

For the corrosion monitoring two methods are possible: tests on metal coupons, this method was used in Soultz-sous-Forêts (Scheiber et al. 2015), or corrosion probes with electrodes, this method is currently tested in Rittershoffen. Additionally to this monitoring, geothermal pipes are inspected periodically according to a program whose purpose is to check the thickness of the pipes at representative and specific points of the plant.

Geothermal fluid leak in the environment is also prevented with an appropriate water management on the geothermal power plant. Water management was a key point of the Rittershoffen geothermal plant. Collection of rainwater, geothermal fluid and waste water of the plant are separated. Some geothermal fluid can be discharged out of the closed geothermal loop during starting or cleaning phase. This geothermal fluid as well as a mix of water and geothermal fluid is collected by a waterproof system and reinjected in the reservoir. All the rainwater of the power plant is collected in a tank by gravity. When the tank is filled with rainwater, an operator checks the conductivity of the fluid and if the value is below 5 mS/cm, he can open a normally closed valve to empty the spool. The rainwater is first treated with a sand filter and with a scrubber and an oil separator. If the conductivity is higher than 5 mS/cm, the fluid is considered as contaminated by geothermal fluid and is pumped to the geothermal storage basin and then pumped into the injection well. Non-process waste water of the plant (toilets…) is collected separately and treated first by a sceptic tank and then by the scrubber and the oil separator. Figure 3 presents the water management scheme on Rittershoffen plant.

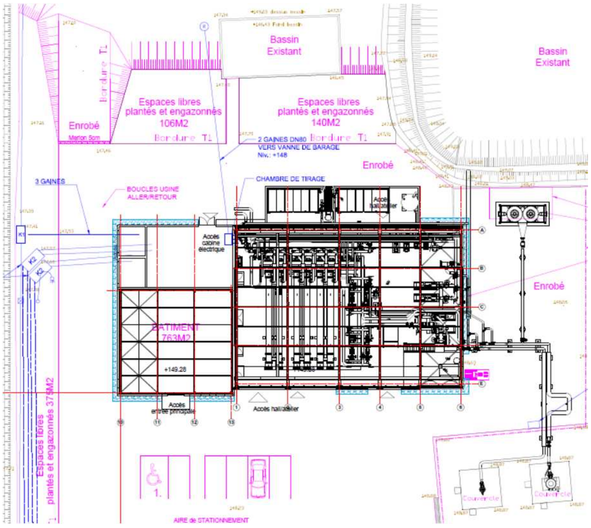

Figure 3 : Draft of the water management scheme in Rittershoffen

3. Neighbourhood disturbance

Noise emissions are probably the main concern for the neighborhood in urban as well as rural area. In France, maximal noise emissions are regulated by law. Installations classified for environmental protection, must be designed, built and operated in order to prevent to be a source of noise, which can be an issue for safety at work and for the neighborhood. Maximal noise emissions at the limit of the installation should not be above 70 dB(A) during the day and 60 dB(A) during the night, excepted if the ambient noise is above these limits. Moreover, installations classified for environmental protection should not increase the ambient noise in surrounded regulated noise area, such as residential area, more than values presented in Table 1.

Table 1 : Acceptable emergence values in regulated area including noise emission of the project

Ambient noise in regulated area, including noise emission of the project	Acceptable emergence values between 7 am and 10 pm, excepted Sundays or public holidays	Acceptable emergence values between 10 pm and 7 am, and on Sundays or public holidays
Between 35 dB(A) and 45 dB(A)	6 dB(A)	4 dB(A)
Above 45 dB(A)	5 dB(A)	3 dB(A)

In the Rhine graben, noise emissions have to be considered from the pre-engineering studies of the geothermal plant. Noisiest equipments of the geothermal plant are generally centrifugal pumps, such as injection pumps (around 87 dB) and production pump in case of line shaft pump (around 91 dB). For electricity generation projects, using binary cycle, noisiest equipments are air condenser (around 70 dB), turbine (around 90 dB), generator (95 dB) and feed pump (around 90 dB). A noise impact study is highly recommended for the selection of low noise emission equipments, such as the air-condenser, but also for proper positioning of the equipments on the power plant's platform. Especially it can give some recommendation for sound insulation (for instance, anti-noise wall around the plant) to respect the noise legislation. Figure 4 presents a simulation with the software CadnaA about noise emissions around the geothermal plant of Rittershoffen. For this project, a special cladding used inside the building was selected to reduce noise emissions.

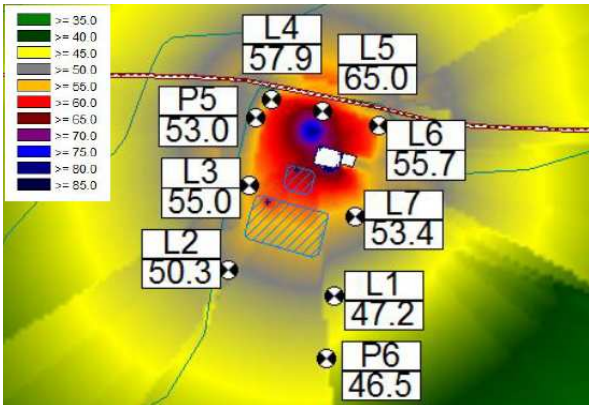

Figure 4 : Simulation of noise emissions around the Rittershoffen geothermal plant

During operation, noise emissions are measured at the limit of the plant and at the nearest neighborhood. These measurements enable to check if the plant respects the noise legislation. If not, additional noise protection has to be considered to reduce noise emissions. However, sometime in rural area, like in Soultz-sous-Forêts, as the local ambient noise is very low because of the very low anthropic activities, it is really difficult to respect the noise limitation.

Gas emission in the atmosphere, especially hydrogen sulfide, can be a concern for the neighborhood for big flash geothermal plant. However, in the Rhine graben, on one hand, the H_2S content is negligible and below the limit detection in the geothermal fluid. On another hand, because of the high salinity of the geothermal brine (Sanjuan et al. 2016) and brine temperature, it is not economic to use flash plant for electricity generation. Most of the geothermal plants in the Rhine graben use a closed pressurized geothermal loop, over the gas bubble point of the brine at around 20 bar, to keep dissolved all the gases (mainly CO_2) in the geothermal brine, excepted the Bruchsal power plant which uses a ''gas bridge''(Mergner et al. 2013). Gas emissions in the atmosphere from geothermal plants in the Rhine graben are consequently very low and very well managed.

4. Evolution of natural radioactivity

The geothermal fluid circulates through a fractured granite which is naturally enriched in some radionuclides (Eggeling et al. 2013) such as Uranium, Thorium and their descendants (mainly Radium 226, Lead 210…). A small fraction of these radionuclides are leached by the fluid and can come up to the surface equipments of geothermal plant facilities. Whereas the natural radioactivity of geothermal fluid is still very low and can't be detected above the ambient radioactivity, scales that develop within casing and surface equipments can be more significantly enriched in radionuclides. As a matter of fact, two main types of scales are concerned in Upper Rhine Graben area (Scheiber et al. 2014):

- Barium and Strontium sulfates (BaSO4, barite and SrSO4, celestite): atoms of ^{226}Ra can substitute to Ba and Sr during scale formation
- Lead sulfide (PbS, galena): atoms of ^{210}Pb can substitute to "stable" Pb

These types of materials, enriched in natural radionuclides, are called "NORM" (Naturally Occurring Radioactive Material). It is important to note that in Upper Rhine Graben, all geothermal facilities reinject the fluid into the reservoir. Thus, the radioactive sources, i.e. the scales, are confined within the closed geothermal loop and don't spread into the environment.

Two different approaches have been set up in order to manage the radioactivity on site (Scheiber et al. 2015). Firstly, efforts have been made in order to identify scale inhibitors that are efficient in the context of Upper Rhine Graben conditions. Secondly, internal procedures have been set up in order to protect public and workers from the radiations, even if they are of low level.

An effective way of managing radioactivity issues on geothermal site is to prevent, or at least reduce, the scale deposition within equipment. Thus, there would be no (or less) accumulation of radioactive material and no (or less) emergence of radioactivity. For this purpose, various experiments have been performed in Soultz-sous-Forêts pilot plant in order to select in laboratory and test in-situ the appropriate inhibitor for barite deposits. An inhibitor, based on phosphoric acid, has been identified which efficiently reduces barite precipitation for Upper Rhine Graben brines (Scheiber et al. 2015). These research efforts are still going on, mainly in order to identify an appropriate inhibitor for galena deposits as well.

However, even if the use of scale inhibitors reduces the growing rate of barite and galena, these scales could still precipitate and lead to the emergence of an induced radioactivity in the geothermal loop equipment. In that case, it is mandatory from the French nuclear safety regulation to set up appropriate procedures to monitor and manage the natural radioactivity on site in order to protect public and workers from the radiations.

It is firstly required to get a clear overview of the level and location of radioactive emissions within the installation. A first inspection is made before the commissioning of the geothermal plant. This gives a reference of the natural ambient radioactivity on the site. Regular inspections are then performed in order to measure the radioactivity and monitor its evolution. These inspections consist in measuring dose rate values at various places of the geothermal site. Dose rate is indeed the reference measurement for radiation protection. Two types of measurements are thus performed (Cuenot et al. 2015):

- Ambient dose rates: these measurements are taken at several locations (~50 sampling points) on the facilities at ~1 m from the equipment. As they are more representative of actual work places, they will be used to define the required radiation protection procedures;
- Contact dose rates: ~300 measurements are performed at ~1 cm from the equipment. They are used to closely identify the places where high dose rate values can exist, that is, where scales can accumulate (filters, pipe bend, heat exchanger outlets…)

Figure 5 presents an example of a full survey performed on the Soultz-sous-Forêts power plant (GPK2 platform) in June 2009, after a few months of circulation. It indicates all measurements points defined on the facilities.

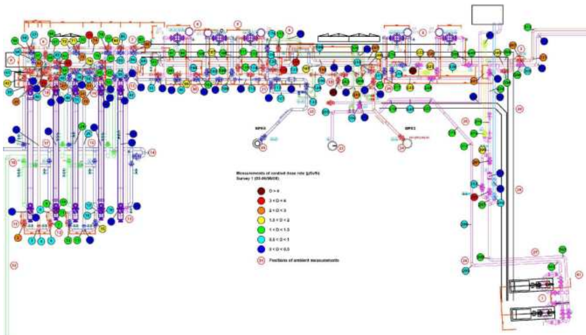

Figure 5: Cartography of dose rates on the Soultz-sous-Forêts power plant (GPK2 platform) from the survey performed in June 2009, coloured circles correspond to the contact measurements points and the colour code is function of the dose rate value. The red circles with a red number indicate the ambient measurement positions (from Cuenot et al. 2013)

On the basis of these inspections, if the emergence of radioactivity induced by the geothermal activity has been detected, different zones can be defined within the site, depending on the level of measured dose rates:

- "Public" zones, where the radioactive dose cumulated over a month is less than 80 µSv/h. In comparison, the average annual dose received by someone in France is 3.7 mSv/year, i.e. around 300 µSv/month (IRSN, http://www.irsn.fr);

- "Monitored" and "controlled" zones where the access is restricted to authorized persons only.

The cumulative dose received by authorized persons is strictly followed through the use of personal dosimeters worn in permanence on site. Dosimeters are analyzed every 3 months to ensure a correct follow up of the received cumulative dose for any worker. In geothermal facilities, as the natural radioactivity level is rather low, as compared to other use of radioactive sources in industry or for medicine, the aim is to keep the cumulative dose received by workers under the public threshold of 1 mSv over 12 consecutive months (two other thresholds exist to classify workers in France: 6 and 20 mSv over 12 consecutive months).

As the radionuclides present in the scales are mainly α- and β-emitters, there is a very little risk of external contamination (mainly due to γ-emissions) but a higher risk of internal contamination in case of inhaling or ingesting radioactive particles. Thus, for specific operations exposing workers to scale residues or dust such as pipe, filter or heat exchanger cleaning, a procedure indicates the way to perform the operation in order to minimize exposure to radioactivity, and the required protection equipment to avoid the contact, ingestion or inhalation of radioactive material. Moreover, an evaluation of the dose that can be received during the operation has to be performed, based on real dose rate measurements. While performing the job, an operational dosimeter should be worn: it indicates in real time the cumulative received dose and allows the worker to react in case of emergence of an inappropriate dose level.

The contaminated waste such as scale debris or disposable suits worn while manipulating radioactive material are sorted by types and stored separately in a specific controlled zone. These wastes are then removed by ANDRA, the French national agency for radioactive waste management, and managed by this public agency afterwards.

All this measures should contribute to limit the emergence of radioactivity on a geothermal site and prevent dispersion of radionuclides in the surrounding environment. They should also provide the conditions for workers and public to access to the geothermal facilities in a safely manner that will keep their received dose under the regulatory threshold of 1 mSv over 12 consecutive months.

3. COST OF THE DIFFERENT MONITORING

Monitoring of the four kinds of environmental issues described previously has a financial impact on capital expenditure (CAPEX) and operating expense (OPEX) of geothermal project in the Rhine Graben. In this chapter, a detail of the costs of the different monitoring is proposed.

2.1 Cost of ground motion monitoring

Geophysical monitoring is probably the most expansive of the global geothermal environmental monitoring in the Rhine Graben. As a reminder, on the French side of the Rhine graben, seismological telemetered network of all deep geothermal projects is at least composed of five telemetered short-period surface velocimeters, one downhole broad-band velocimeter, buried in a 5 m deep well, and one strong-motion sensor located above the wells trajectories. CAPEX of short-period surface velocimeters are about 40 k€ each, including site selection, equipment supply, installation of energy supply, telecommunication and commissioning. Downhole broad-band velocimeter is installed on one short-period velocimeter's site. Telecommunication and energy supply are shared by the two sensors. CAPEX for the additional seismic station are about 90 k€, including the 5 m deep well the broad-band sensor and the strong-motion sensor. The geodetic station is installed on the geothermal platform, CAPEX for this station is about 30 k€. A view of seismological stations is given on Figure 6.

Figure 6: View of an isolated permanent station of the seismological monitoring network

OPEX of the geophysical monitoring networks can be split in operational and maintenance expenses. Operational expense is the exploitation and interpretation of the telemetered data. Maintenance expense mainly depends on the energy supply: grid connection or solar energy. Indeed, solar energy supply involves some batteries and these elements require additional maintenance and replacement during all the power plant operation. However, most of the time, the geophysical monitoring network is a mix of grid connected and isolated stations. Annual OPEX for the operational and maintenance expenses and provision for material renewal is about 80 k€/year.

3.2 Cost of groundwater monitoring

CAPEX of ground water monitoring system, composed of 3 shallow piezometers and one deep piezometer, mainly depend on the depth of the last one. For a 100 m deep piezometer, installed for the Illkirch geothermal project, CAPEX are about 100 k€, including hydrogeological study, permitting, drilling and piezometer equipment. Compared to the CAPEX, annual OPEX for the ground water monitoring are quite low, about 10 k€/year and are mainly due to the exploitation and interpretation of the onsite measurements (pH, conductivity, Redox potential and temperature) and the monthly laboratory analyses. Additionally to the ground water monitoring, regular casing and cementation inspections have to be provided to the French mining authorities: every 3 years for the injection well and every 6 years for the production well. Cost of these inspections and interpretation is about 60 k€ every 3 years considering one injection well and 110 k€ every 6 years for a doublet, depending on the used inspection tool and method.

3.3 Cost of surface water protection

Concerning the surface water protection, the most expensive is the management of the rainwater, geothermal fluid and waste water. However, important savings can be done if the discharge circuit of waste water is taken into account at the early stage of the project, that is, from the civil works of the power plant. For example, at the Rittershoffen geothermal plant, CAPEX for the water management were about 50 k€, including sceptic tank, scrubber and oil separator, rain water collection and spool (Figure 7), geothermal spool… CAPEX for the corrosion monitoring are about 10 to 20 k€ and 5 k€ for the pipe inspection program. OPEX of the water management are included in the daily maintenance without any significant increase of cost. Corrosion monitoring can be estimated to 10 k€/year, whereas pipe inspection program can generate important OPEX. Indeed, the geothermal power plant needs to be shut down to inspect all the pipes externally and internally. OPEX for pipe inspection are about 50 k€ every 5 years.

Figure 7: View of rain spool of the Rittershoffen geothermal plant with the transfer pump in case of contamination by geothermal fluid

3.4 Cost of neighbourhood disturbance

Neighborhood disturbance, such as noise emissions, can really be an economic issue for geothermal power plant using binary cycle including an air-cooler. Low speed and low noise emission air-cooler requires larger surface and investment. Extra CAPEX for low noise emission air-cooler can reach 10% of the total CAPEX of the binary cycle. Noise emission study is about 5 k€ and it can recommend some additional noise protection, such as anti-noise walls. Such anti-noise walls were built at the Insheim geothermal power plant (Germany) and can represent extra-CAPEX of 200 k€ (Figure 8). Fortunately, OPEX for noise emissions are not really significant during operation.

Figure 8: View of the anti-noise wall at the Insheim geothermal plant (Baumgärtner et Lerch 2013)

Gas emission is not a real concern for geothermal power plant in the Rhine Graben and doesn’t generate extra-CAPEX or OPEX, excepted if a ‘’gas bridge’’ is preferred to pressurized loop.

3.5 Cost of natural radioactivity management

CAPEX of radioactivity monitoring are mostly related to the prevention management with the inhibitor injection system (Figure 9). For the Rittershoffen power plant, CAPEX were about 30 k€, including equipment supply, piping and electrical connection.

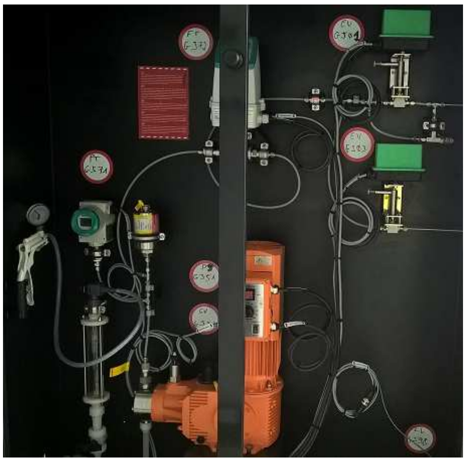

Figure 9: View of the inhibitor injection system on the Rittershoffen power plant

Management of the risk of radioactivity doesn’t represent a big issue in term of investment. It is mainly related to equipment buying (radiometer), personal training and procedure writing. For risk management, CAPEX are approximatively 10 to 20 k€.

Two topics of radioactivity monitoring have to be taken into account in the business plan. Prevention management is related to the adjustment of inhibitor dosage as a function of geothermal production flowrate. For Rittershoffen, with a production of

70 L/s, annual OPEX are about 40 k€. However, these costs should help reducing cleaning operations of the heat exchangers, evaluated at 30 k€/year, and waste disposal. In France, waste contaminated by natural radioactivity are managed by ANDRA and the cost for disposal is about 60-80 €/kg. Concerning the mapping of the natural radioactivity on the facilities, it is planned for Rittershoffen to inspect the geothermal loop every month during the first year of operation. Then, inspection can probably be only once a quarter. OPEX for these inspections are about 2 k€/month including measurements, mapping and analysis of evolution. Safety at work, requiring a radiation protection officer (PCR in French), is about 10 k€/year for procedure writing and exposure management for specific operation.

4. CONCLUSIONS

As explained previously, geothermal projects in the Rhine graben are concerned by five kinds of environmental impacts, from large to local scale influence: induced seismicity and surface deformation, surface water and shallow groundwater resources protection, neighbourhood disturbance, such as vibration or noise emissions, and evolution of the natural radioactivity. To ensure the acceptability of geothermal projects in the Rhine graben, it is strongly required to measure and to apply procedures to minimize those different physico-chemical impacts on the environment and neighbourhood.

All in place or future deep geothermal projects located in the Rhine graben are designed to exploit a faulted zone at depths of 2 500 m to 5 000 m for power or/and heat generation. CAPEX are in between 35 M€ and 50 M€, mainly depending on the drilling depth. Those geothermal projects operate, or are planned to operate, with a brine flowrate between 60 and 80 L/s and a brine temperature between 140°C and 180°C. Annual turnover of those projects is about 4.5 M€ to 7.0 M€, depending on the available geothermal power.

Environmental monitoring represents about 3% to 5% of the total investment and about 5% to 7% of the annual turnover of geothermal projects in the Rhine graben. These CAPEX and OPEX really need to be taken into account in the business plan. Table 2 gives an overview of the different environmental monitoring and their associated CAPEX and OPEX.

Table 2 : Overview of the different environmental monitoring and their associated CAPEX and OPEX

Environmental impact		CAPEX	OPEX
Micro-seismicity and surface deformation	Short-period surface velocimeter Broad-band post-hole velocimeter and strong-motion sensor Geodetic station	40 k€ 90 k€ 30 k€	90 k€/year
Ground water protection	Piezometer monitoring Injection casing inspection Production casing inspection	100 k€ - -	10 k€/year 60 k€/3 year 50 k€/6 years
Surface water protection	Surface water management Corrosion monitoring Pipes inspection	40 k€ 20 k€ 5 k€	- 10 k€/year 50 k€/5 years
Neighborhood disturbance	Noise study Low noise emission aircondenser Anti-noise wall Gas emission managment	5 k€ 10% ORC CAPEX 200 k€ -	- - - -
Management of the radioactivity	Preventing management (inhibitor) Risk management Waste management	30 k€ 10 k€ -	40 k€/year 35 k€/year 60-80 €/kg

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