Report on mitigation measures

Adopted solutions and recommendations to overcome environmental concerns

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Authors: A. Manzella[1] (coordinator), F. Bianchi[1], M., Bonini[1], S. Botteghi[1], E. Bustaffa[1], L. Cori[1], C. Del Ventisette[1], M.S. Giamberini1, F. Gorini[1], M. Lelli[1], D. Montanari[1], F. Minichilli[1], G. Montegrossi[1], D. Scrocca[1], C. Chiarabba[1], P. Lattanzi[1], E. Pandeli[1], J. Maury[2], C. Maurel[2], A. Ragnarsson[3], S. Hauksdottir[3], A.A. Oladottir[3], G. Manfrida[4], D. Fiaschi[4], M.L. Parisi[4], L. Tosti[4], V. Harcouet-Menou[5], S. Bos[5], M. Luchini[6], A. Lenzi[6], S. Montomoli[6], M. Paci[6], R. Taccone[6], F. Batini[7], C. Bosia[8], N, Cuenot[8], V. Maurer[8], G. Ravier[8], P. Dumas[9], O. Gök[10], N. Aksoy[10], A. Nador[11]

Authors' affiliation: [1]CNR, [2]BRGM, [3]ISOR, [4]CSGI, [5]VITO, [6]Enel GP, Rete Geotermica[7], [8]ES-Géothermie, [9]EGEC,[10]DEU, [11]MBFSZ

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Extended abstract

This report focuses on the monitoring and mitigation measures that are adopted, or have been tested and are under development, to reduce the probability of adverse effects and circumvent their consequences to the environment determined by the human activities during a geothermal project development. The impacts and risks related to health and safety of those working in geothermal facilities are not included in this analysis, since they are strictly regulated and prescribed by the health and safety management programs of geothermal projects.
The environmental impacts and the associated potential risks considered of relevance for the geothermal project development refer to various impacting phenomena.

- Effects associated to surface operations:
  - ⇒ Energy and water consumption and emissions to the environment
  - ⇒ Waste production from surface operations
  - ⇒ Surface disturbance, including vibration, noise, visual, land occupation and dust
  - ⇒ Leaks due to surface installations and operations
- Effects associated to emission of underground material to the surface:
  - ⇒ Liquid/solid effusions and waste
  - ⇒ Degassing
  - ⇒ Radioactivity
  - ⇒ Blowout
- Effects associated to geomechanical changes:
  - ⇒ Ground surface deformation
  - ⇒ Seismicity
- Effects associated to underground physical and chemical modifications
  - ⇒ Pressure and flow change
  - ⇒ Interconnection of aquifers and disturbance of non-targeted aquifers
  - ⇒ Thermal changes

For each potential disturbing phenomenon, after a brief synopsis, the report describes the monitoring techniques and the technologies used for limiting its occurrence and the potential damage. The disturbing phenomena are all treated at the same level with no classification related to their probability of occurrence or gravity. The "worst case scenario" described in this report is intended as a broad base and a virtual reference case for the overview of mitigation technologies and for monitoring and mitigation planning, and is, however, far from representing a real case, as some impacts and risks are accidental or restricted to very defined geological condition or technologies.

Since the report details the remote sensing data that are used for monitoring, a brief overview of these data, their analysis and repositories available in Europe is provided in Appendix.

This report complements the Deliverable D2.1 of the GEOENVI Project “Report on Environmental concerns. Overall state of the art on deep geothermal environmental data”, which analyses in more detail the origin and consequences of the potential risks and impacts of geothermal development.

Introduction

In the past several years, some geothermal technologies have been found or suspected to cause health or environmental damage, drawing heightened public attention. Understanding the potential for producing damages and for limiting their occurrence and consequences is desirable for public authorities, industry, and the public at large. The purpose of this report is to provide accurate and current information about the current best practices and available technologies to avoid, whenever, possible, or otherwise minimise the unavoidable effects to the environment produced by geothermal development.

Mitigation is an integral regulatory procedure in all international interpretations of environmental impact assessment (EIA). Following the European Environmental Impact Assessment Directive, "*Mitigation measures* provide for a system to reduce, avoid or offset the potential adverse environmental consequences of development activities. Their objective is to maximise project benefits and minimise undesirable impacts. Such mitigation measures can be in the form of preventive, corrective or compensatory measures. Prevention means that the potential impact is prevented or reduced before it occurs. Corrective measures reduce the impact to a level which is acceptable. If preventive or corrective measures fail, then compensatory measures are applied. They will compensate for the unavoidable impact." (from https://ec.europa.eu/environment/legal/law/2/module_3_10.htm. The EU directives on EIA are the 85/337/EEC and its later amendments, the last one being the Directive 2014/52/EU, as reported in https://ec.europa.eu/environment/eia/eia-legalcontext.htm).

In this document we will focus on *preventive and corrective mitigation measures* for minimizing environmental consequences of geothermal development. They are, respectively, related to two main strategies:

- Avoidance, by considering potential effects in an early stage of the project design processes and avoiding them using alternatives;
- Reduction, which is the common strategy to deal with unavoidable effects. The measure can focus on reducing the effect itself and/or the exposure to the effect. The measures to reduce the effects include their monitoring, and their control so that acceptable standards are not exceeded (e.g. noise attenuation). When effects occur over an extensive, often unidentified area, the mitigation may reduce the exposure by installing filters between the effect's source and location of potential receptors (e.g. noise barriers).

Mitigation is practiced within or in the surrounding of the site of development. It affects the development, its construction and operation, and, in specific cases, its products and processes.
All phases of a geothermal project (synthetically represented in Figure 1) can potentially have an environmental implication, which requires to be accounted.

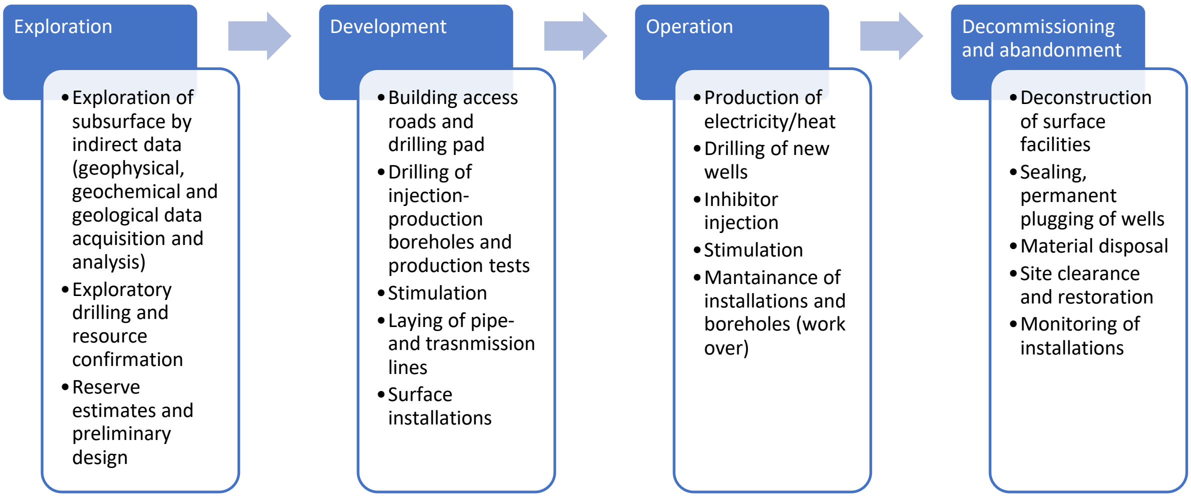

Figure 1: Phases of a geothermal project

The environmental footprint of geothermal start-up and exploration - excluding exploratory wells - is very minor. In the other phases of a geothermal project, the main activities affecting the environment can be roughly synthetized as:

- Site preparation including construction of access roads and drilling pads;
- Well site and reservoir development including drilling, testing and stimulation (hydraulic, thermal and chemical enhancement of wells connection with the reservoir);
- Plant and facilities' installation, including laying of pipelines, power unit and electric grid connection, installation of equipment, and plant commissioning;
- Plant operation and management;
- Decommissioning and abandonment of facilities.

The environmental effects from geothermal development have been categorized in various ways in literature. In this report, and in general for the GEOENVI project, they have been categorized based on safeguard subjects, i.e., endpoint indicators, emphasizing environmental burdens.
In the following chapters, we briefly review the range of environmental burdens associated to the different phenomena, and then describe the tools that are used to mitigate their potential

threats. *Measures related to the safety procedures for people working in geothermal facilities are strictly regulated by European and national laws, and prescribed by the health and safety management program of geothermal projects. Therefore, the specific procedures established to minimize the risks of injuries to workers are not mentioned here.*

The *benefits* that the geothermal development brings in itself, first of all by producing energy from a renewable source, *are not taken into account here*. The "worst case scenario" described in this report is intended as a broad base and a virtual reference case for the overview of mitigation technologies and monitoring and mitigation planning. It is, however, far from representing a real case; some of the described adverse environmental effects are important only at some locations, depending on local geological conditions, land uses in the vicinity of the plants and technological constraint, while some are very common and mitigation measures are recurrent practice, and it is also common to apply measures to prevent accidents.

Each chapter includes a section dedicated to monitoring, which is used to check that anticipated effects are 'as predicted'. Monitored data are necessary for proving that geothermal operations and, where applicable, mitigation measures have produced effects to 'less than significant' level, i.e. compliant with environmental standards, and for facilitating any project design or operational changes that are needed. When unforeseen problems occur, they can require corrective action to keep them within acceptable levels, thereby changing the adopted mitigation measures. Components within the broad definition of environmental monitoring include: planning the collection of environmental data to meet specific objectives and environmental information needs; designing monitoring systems and studies; selecting sampling sites; collecting and handling samples; conducting laboratory analysis; reporting and storing data; assuring the quality of the data; analysing and interpreting data and making it available for use in decision making (Hunt, 2000).

For further details about the origin and consequences of the potential risks and impacts of geothermal development refer to Deliverable D2.1 of the GEOENVI Project "Report on Environmental concerns. Overall state of the art on deep geothermal environmental data".

Bibliography

Hunt, T., 2000. Five lectures of environmental effects of geothermal utilization. Reports 2000, 1, UNU Geothermal Training Programme, Iceland. Available at: https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2000-01.pdf

Part I – Effects associated to surface operations

1. ENERGY AND WATER CONSUMPTION AND EMISSIONS TO THE ENVIRONMENT

Synopsis

During surface operations, energy consumption results from the use of engines, and emissions in the atmosphere are caused by the fuels that they burn: vehicular traffic for everyday business, machines used during the plant operation or decommissioning phases, and in particular those associated to the drilling phase for drill pad construction, for operating the drill bit, for road making. Water is consumed in the drilling phase, to produce the mud and, to a minor extent, the cement. During the plant operation, small amounts of water are consumed to minimize scaling. Water is also required by those power plants using the wet (water) cooling towers.

The use of engines and water is inevitable, and these adverse effects, which are not specific to geothermal operations and can be encountered in many diverse industries, are very minor (Bayer et al., 2013; Tomasini-Montenegro et al., 2017).

This chapter concerns only chronic emissions related to surface operations. The potential emissions of geothermal gases are dealt with in Chapter 6 “Degassing”, and accidental emissions due to blowouts are described in Chapter 8 “Blowout”.

Monitoring

Energy use and losses and water consumption are recorded by operators and used to compute the periodical sustainability balance.

Prevention & Mitigation

Measures to reduce the effects on human health and environment should be taken since the design of the plant. Although it is not possible to reduce the effect indirectly generated by the making of construction material, it is possible to contain energy and water use as well as emissions to the atmosphere.

The consumption of energy related to surface operations is usually contained within the life cycle of a geothermal plant and is limited in time during the development phase of a project. Also, emissions from fossil-fuelled engines, which is regulated by European Directives, is strictly controlled and monitored over the sites. Use of local electricity generation to power engines during construction and operation of the power plant is common practice, but alternative power supply (e.g. fed with locally produced renewable electricity such as wind, photovoltaic, hydro) during drilling phase improves the environmental performances of the geothermal system. Electrical grid connection, wherever possible, represents alternative solutions (Lacirignola and Blanc, 2013).

A common way to successfully reduce the amount of water to be used during drilling is the recirculation of drilling mud (described in detail in Chapter 5 “Liquid/solid effusions and waste”), and the quick plugging of mud losses zones. The freshwater consumption is reduced by using meteoric water collected and stored in containers, as in Italy, for the preparation of mud and cement slurry during drilling phase. Discharged geothermal fluids or low-quality water are used to support cooling and/or as make-up fluid (Bayer et al., 2013). In some project, surface water, e.g. canal water, is used for drilling purposes, after checking its quality to avoid the risk of polluting drinking water aquifers (i.e. by the presence of some bacteria).

Bibliography

Bayer, P., Rybach, L., Blum, P., Brauchler, R., 2013. Review on life cycle environmental effects of geothermal power generation. Renewable & Sustainable Energy Review 26, 446-463.

Lacirignola, M., Blanc, I., 2013. Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment. Renew. Energy 50, 901–914.

Tomasini-Montenegro, C., Santoyo-Castelazo, E., Gujba, H., Romero, R.J., Santoyo, E., 2017. Life cycle assessment of geothermal power generation technologies: An updated review. Appl. Therm. Eng. 114, 1119–1136.

2. WASTE PRODUCTION FROM SURFACE OPERATIONS

Synopsis

Geothermal plants produce both liquid and solid waste, resulting from the construction, operation and maintenance of the plant, as well as urban waste from the personnel. The nature of waste is very diverse, it ranges from household waste (paper, garbage, etc.), plastics from packaging, fuel and lubricant used for engines, steel, copper and scrap metals or hazardous waste from pipes, filters and other tools disposed from sites, chemical waste, unused material for building or road construction and waste-water, excavated earth and rocks resulting from the plant construction, waste timber, rubbery materials, filters and materials contaminated with lubricating oil.

The adverse environmental effects of surface waste production, which can be encountered in any other industrial activities, are regulated by a European Directive and national legislation. Waste being evacuated and recycled or treated, the direct consequences on humans, ecosystems and the atmosphere are almost inexistent. Research and innovation efforts are also improving applicability and use of recycled/secondary materials/waste in geothermal plants, favouring the integration of geothermal into the circular economy.

Only waste produced by surface operations are treated in this chapter. See Chapter 5 "Liquid and solid effusions on surface" for waste of material from underground, such as drilling mud, cuttings, geothermal fluid waste.

Monitoring

Following European and national regulations, as for any industrial facility that produces waste, the plant operator has to keep an official log of waste production and periodically report to the regulating authority the amount of hazardous and non-hazardous waste produced. Waste deposits inside the facility are regularly inspected and characterised, to check for proper management and for the regular functioning of containment basins.

Geothermal operators also apply a very detailed health, safety and environment (HSE) program related to waste during the entire life of the project, for example according to ISO certification 14001.

Prevention & Mitigation

The main measure adopted to minimize the waste amount from geothermal plants is achieved by careful design to minimise the waste and treatment of unavoidable waste during the operations.

According to European Directives, waste producers have the responsibility of their own waste from production to recycling/disposal, and must ensure that the contractor for cleaning and waste disposal is certified and able to do the job.

To ensure hygiene and cleanliness of the site, waste is collected and temporarily stored in proper tanks, basins and areas, segregated from other materials and equipment. Selective collection is mandatory in several countries of Europe for industrial working sites. The storage units are labelled in accordance and placed over containment basins or slabs before being frequently disposed from the site to avoid leakage and contamination of soil. Depending on waste type (e.g. packaging, rubber, lubricant oil, chemicals, scrap metal, timber), the site contractor will manage waste recycling or disposal toward the appropriate treatment plant to limit the impact on the environment and on humans. Waste-water is either collected or connected to sewage to avoid dumping into natural environment. Waste (inert, wood, metal, cartons, plastic, etc.) is placed in appropriate containers and/or bins. Hazardous waste (such as oils and batteries) is stored in segregated and labelled containers. There is a specific storage area at the plants, and licensed waste management plants and carriers are appointed. Depending on waste type (solid, chemicals, scrap metal etc.), the coordinator of site will manage waste distribution toward the appropriate dumping sites.

3. SURFACE DISTURBANCE: LAND OCCUPATION, VISUAL, NOISE, VIBRATION, DUST, SMELL

Synopsis

The development of a geothermal field inevitably involves the presence of structures and components that produce surface disturbances. They are generally encountered during plant construction and equipment installation, drilling and testing phases and also during operation.

Surface disturbances include effects on landscape (deforestation; deviation of rivers; visible industrial infrastructures, roads, derrick and vapour plumes), land occupation (construction of roads and plants, drill pad and other infrastructures on site, etc.), or disturbances associated to increase in road traffic and dust production. The effect on landscape is a key factor especially in areas that are of touristic and cultural interest or in residential sites. Land use, which is limited with respect to other energy sectors, refers to the drilling pads (often temporary) and well-heads, plant facilities, the pipelines for the transport of the fluid and the transmission lines of the electric current.

The nuisances might also come from noise and vibration generated by a variety of activities. Drilling activities, passage of trucks and other vehicles during the different stages of the geothermal project, engines and pumps during the plant operations may be sources of vibration, which is, however, hardly perceived at few tens of meters from the source. Noise is produced from the three main sections of a geothermal production system: production and reinjection wells, pipelines to plant and geothermal plants themselves. In production and reinjection wells, noise is produced during the initial setup and construction of drilling site due to truck traffic, by drilling operations and by well tests after drilling. Noise diminishes with distance (by about 6 dB every time the distance is doubled), although lower frequencies (e.g. noise from drill rigs) are attenuated less than higher frequencies (e.g. steam discharge noises); wind may also influence the transmission of the acoustic noise.

In the rare case of strong degassing from the wells and plants or of liquid and solid effusions, smell might also be triggered *(the other effects of gas effusions are described in Chapter 6 “Degassing” and Chapter 8 “Blowout”)*.

The development and operation of a geothermal field inevitably involves the presence of structures and components. The corresponding disturbances at surface, which have variable duration, are inherent to all geothermal projects and, more broadly, to all industrial activities. Being considered in the EIA, they must be taken into account early on by project owners, from design and conception phases, to prevent unnecessary and unwanted adverse effects.

Monitoring

Prior to any operation, baseline data collection is carried out to predict and evaluate adverse environmental effects, including surface disturbance. The objective of this enquiry is to observe the existing environment and estimate the changes that might occur as a result of a geothermal plant development.

Monitoring of vibration and noise

Vibration monitoring is performed with seismic sensors located around the explored area, or surrounding drilling sites, to ensure that the vibration does not exceed the safety standard.

Noise is recorded at chosen receptors, whose location is defined during monitoring planning, and with instruments capable of recording the reference frequencies. Monitoring requires:

- acoustic characterization of the pre-operation situation, based on the data deriving from campaigns to measure the noise level of the concerned area and taking into account its acoustic classification;
- control of noise pollution during work and post-work.

The measures, beside to giving indications on the respect of the limits of the law in the drilling phase, during construction of sites and facilities, including the traffic and handling of materials and of operation of the plant, also provide information about:

- the actual distances of acoustic impact;
- the perception of the disturbance associated with certain levels of measured noise;
- the evolution of the noise over time in relation to the other sources present and, therefore, to its actual relevance with respect to the background noise of the environment interested.

To estimate peak noise disturbances generated from drilling machines, a noise rose is created (Figure 2). This rose translates the noise generated in the vicinity of the drill pad in a context that is however not representative of the site but only of the drilling machine. Indeed, it does not account for topography, urban constraints, etc. Nevertheless, it provides a view of the noise level generated directly near the site. The example given in Figure 2 shows an estimated noise of 65 dB (A) near the drill pad, an amount comparable to the one generated in a large business office.

Depending on the building found in the different (red or green) zone of the rose, specific mitigation measures are adopted to lower the disturbance on dwellings.

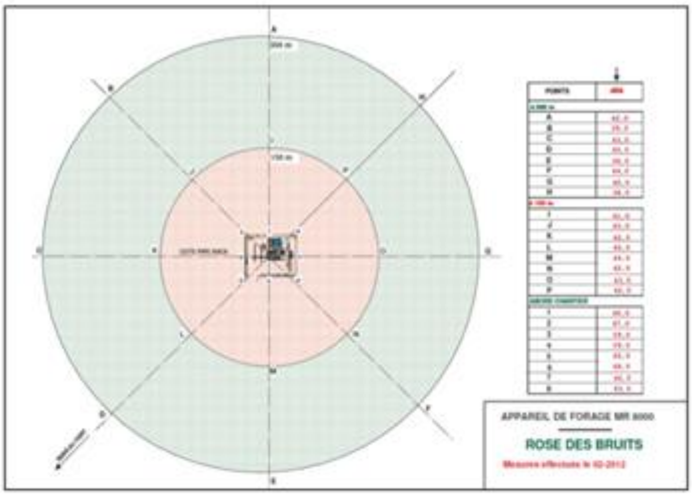

Figure 2: Noise rose of drill pad from a geothermal drilling site in France (BRGM)

Monitoring of the ecosystems

Before geothermal development, an environmental review may be required to categorize potential effects upon plants and animals, for example, by an inventory of vegetation and species in a biological study area beyond the perimeter of the project wellfield and plant, noting of habitat requirements and suitability. Biodiversity monitoring around the geothermal power plants (up to 500 m distance) is required in the Italian geothermal plants since 2000. The monitoring involves the soil, the trees and the surface waters, and focus particularly on epiphytic lichens that are very sensitive to environmental variations.

Monitoring of smell

The assessment of the odour annoyance is quite difficult for several reasons: i) because odour perception is subjective; ii) because of the causal relationship between odour events and odour sources and iii) because of the complex interaction of odorant gases in a mixture (depending on the concentration of individual odorants, on interaction effects, and on individual-specific factors of the exposed subject) (Blanes-Vidal et al., 2009, 2012). Moreover, it is very difficult to distinguish the smell caused by natural emissions (soil degassing, natural manifestations) from the smell caused by geothermal plants, when the interested areas are the same.

A common methodology for odour emission assessment is dynamic olfactometry (electronic noses) that measures odour concentrations, but it does not discriminate each odour-active compound and the relative contribution to the overall odour concentration. Moreover, due to high temporal variability of odour emissions, the air samples collected for olfactometric analysis could not be representative of real annoyance perceived by citizens because they are often collected only after citizen alerts and complaints.

These limits are overcome by modern systems, such as the one developed to quantify the olfactory impact near an oil treatment plant, which comprises a weather station and an innovative odour monitoring and sampling system based on population reports (Di Gilio et al., 2018). By integrating real time quantitative indications of the pollution events determined by the industrial source and the reports of the population, the system provides a level of impact on the urban settlement.

Prevention & Mitigation

Careful siting and project design, where sensitive resources are identified, decreases significantly the cost and extent of surface disturbance in the preparation and operational phases of geothermal development. Specific technologies are described below.

During the last phase of the reclamation and abandonment, it is expected that power plant removal, well plugging, capping and reclamation, and site and access road re-grading facilitate natural restoration.

Visual effects, landscape and land occupation

Visual disturbances are most pronounced during the drilling and site construction, for instance when tall drill rigs are onsite. Landscape planning reduces adverse visual effects of geothermal plants. Facilities, such as buildings and pipelines used during the operation are painted to blend in with the neighbouring environment, and pipes are buried where possible (outside forest zone for example) (Figure 3). High fences are installed during the construction work and through drilling phases to minimise visual effects.

The best solution to avoid the effects produced by constructing of the roads for drilling sites and power plants is to choose the existing roads, and performing some modifications (e.g. enlargements and strengthening). This is also an economical good solution to reduce permanent effects. The visual and geological problems related to road constructions and civil works require carefully planning to minimize the adverse effects and, in particular, to avoid accelerated erosion and landslide risks, e.g. by reducing the number of steeply-sloping exposed banks or planting fast-growing trees which bind the soil.

Figure 3: Examples from Italy. Left: Bagnore 3 power plant in Italy, planted trees to reduce visibility of infrastructures. Right: trench for pipeline. Photo: Enel Green Power.

Pipes close to the existing roads produce a minor effect. Linear pipelines have less adverse visual effect, and the more expensive bellows-type expansion compensators help to build the straight tracts. In some areas, however, the network of pipelines crisscrossing the countryside and the power-plant cooling towers have become an integral part of the panorama and are indeed a famous tourist attraction, like in Italy and Iceland (Figure 4).

Figure 4: Pipes and natural manifestation in the geothermal area of Tuscany, Italy. Photo: Enel Green Power.

As it regards the reduction of the visual impact and the land use of the drillings, many companies all over the world utilize the same drilling site for several deviated wells and it is also desirable that the drilling sites are as close as possible to the power plant. The choice of drilling rig, e.g. the hydraulic telescopic rigs instead of the traditional mast-type ones, may help in reducing the height of the rig and the pad's occupied land. It is also to consider the reduction of the light brightness of the site during the night, choosing the type, direction and location of lamps to guarantee the safety, but projecting less light outside the plant or drilling sites, or by temporary screens around the drilling sites. To reduce the visual impact of the wellheads (the so-called "Christmas trees") they are masked through a cover (e.g. small buildings) with a suitable design with respect to the natural surroundings, that also allows a better maintenance and provides security of the structure (Figure 5).

Figure 5: Left: a wellhead in Italy. Right: Enclosed wellhead (left) at Hellisheidi power plant in Iceland, connected to a muffler (right). Photo: A. Manzella (left), Mannvit, 2013 (right).

The cooling towers of the power plants have been one of the most visible elements in geothermal development, due to their height and the release of white clouds of water vapour. The forced-type cooling towers in the new flash plants reduce significantly these effects, and steam plumes are absent with dry-cooling towers and total re-injection of fluids.

Nowadays, geothermal power plants are temporary constructions, mostly prefabricated, and can be moved in other places within the geothermal field after the end of development of the sites, which is environmentally restored and masked (e.g. through a replanting program).

Since geothermal plants must be located at the site where the resource is assessed, the best technological and architectural solutions are adopted in order to optimize their integration in the local environment.

In volcanic and magmatic areas, geothermal development may also compete with natural manifestation (hot or steaming ground, hot springs and pools, mud pools, fumaroles, geysers and deposits of sinter, sulphur or other minerals). Care is usually taken to preserve these natural geothermal features when they also serve as tourist attractions or competitive economics, or cultural uses. The best mitigation option, in this case, is to create new features of high touristic value, as is the case of Blue Lagoon, in Iceland. Power plants are designed with care to their integration into the surrounding landscape, as in some Italian areas, or are partially hidden by vegetation (usually outside the facility to ease its maintenance) (Figure 6).

Figure 6: Example of landscape planning in Italy. Left: Bagnore4 power plant, designed for an improved blending in the scenery. Right: planted trees and bushes, and tourist tracks around the geothermal power plant. Photo: Enel Green Power.

Noise

Unwanted noise can be a nuisance or a health concern, and its monitoring and control is required by European Directives. Public health codes in European countries regulate the threshold of noise level to be respected within the neighbourhood of the project. Any activity that is forecasted as noisy must be authorized, and provide a specific noise impact assessment, with an estimation of sound levels during its realization and after the works have been completed (post-work situation). Monitoring, as defined in the previous section, is required and enforced. In order to meet requirement in term of environmental protection and human health, precautionary measures are adopted to guarantee safe noise level around the geothermal plant and during drilling operation, i.e. within the limits fixed by authorities. The level of allowed noise is regulated according to the local area and its acoustic level, and different levels are usually set for night-time and day-time and for Sundays and public holidays. An element of fundamental importance is the concept of differential limit, which indicates that the difference between noise produced from a given source and the residual noise (background) must not exceed a certain threshold. The limit values are strictly required for permanent installations, such as geothermal power plants. Authorizations for temporary activities, such as drilling, that overcome the noise limits are requested, usually from local authorities, and mitigation measures are taken for remediation.

For unavoidable noises, major mitigation measures to reduce their adverse effects on population and ecosystems may be synthetized as follows (Webb et al., 1984):

- use of muffled or sound absorption panels around motors, drill pads, vents and pumps;
- use the hydraulic rigs that produce less noise respect to the traditional mast-type ones;
- perform good design and layout of facilities and locate noisy engines in soundproof buildings or choose optimal implantation of engines as far as possible from dwellings;

- restrict noisy activities to day-time (e.g. casing installation, waste disposal, etc.), unless required by safety constrains;
- select site location, when possible, distant from sensitive receptors (i.e. population, human activities, natural parks, ecologically sensitive zone, etc.) and where visual impact is minimum (tall tree around, etc.);
- use electrically driven instead of diesel engines in drilling operations;
- monitor noise and sound emergences continuously during work by authorized inspection body;
- communicate and perform prevention work with population on the project and adopt compensatory measures if needed.

A noise impact study is carried out for the selection of low noise emission equipment, and for proper positioning of the equipment on the power plant's platform.

When the plant is in operation, substantial noise reduction is obtained by the thermal insulation of turbine and the soundproof cages around the turbines and alternators in power production plants, or by soundproof wall (Figure 7). The use of carpets, wood for construction, and soundproofing fan motors, have sensibly reduced the noise of geothermal plants in Italy, so that the geothermal power plants' performance is compliant with the most restrictive noise emission levels (Manzella et al., 2018).

Figure 7: Noise wall at the Insheim geothermal plant, Germany

Special rigs and equipment (low power rigs) are used to work in urban environment and electric power engines reduce the surface effects. Sound barriers, sound shields on engines, and low noise equipment for well testing reduce the external noise during the drilling and well testing phases of the geothermal project. Depending on the building found in the different red or green zone of the rose in Figure 2, specific mitigation measures are adopted to lower the disturbance on dwellings.

Vibration

During seismic data acquisition in exploratory surveys, vibroseismic trucks and related working forces are kept at the minimum possible number, in particular in urban areas, to avoid disturbances while guaranteeing to image the subsoil and the success of the exploration target. This measure is required by law in some country. In France, for instance, prior to the seismic survey itself, a study of the generated vibrations is mandatory to evaluate their impact on constructions, especially in urban areas (Richard et al., 2016). This study has to cover a large frequency and peak-force range. Furthermore, during a recent 3D seismic survey in Northern Alsace, France (Richard et al., 2020), real-time vibration measurements were performed on buildings during acquisition, allowing the operators to immediately stop the vibrotruck, if the measured vibration exceeded a defined threshold, in order to avoid damages. Vibration measurements are taken at the buildings nearest to the vibrotrucks and exceedance limit of vibrations is applied by local regulation (e.g. in Germany, Belgium) to prevent damage to buildings/installations. The nuisance of vibration caused by drilling activities, well development (stimulation) and production in most cases is prevented by careful siting. Mitigation measures of unavoidable vibration, if present, are those of induced microseismic activity, described in Chapter 10 dedicated to “Seismicity”.

Road traffic and dust production

To prevent dust dispersion in the air, trucks displacing soil from the site for the plant installation are covered and cleaned before leaving the working site. Roads are also cleaned up after the passage of trucks. The work sites and roads are sprayed with water during dry weather to reduce dust production from engines and truck circulating in the zone and to prevent its formation. Contractors also ensure that work does not impede the road traffic. Any roadway modification is signalled and work site access is indicated with specific panels.

In the siting of a geothermal plant, one could also look at the vicinity of rivers and large channels allowing the transport of materials over water as a mitigation measure.

Disturbance of ecosystems

While any disruption of land that results from geothermal development has the potential to disturb habitat, geothermal plants, like any type of industrial plant, must comply with a host of regulations that protect the areas set for development. An environmental study before the project development allow to define the background level and to establish the amount of impact. Many disturbances are unavoidable effects, which are mitigated by proper planning and restoration of areas. A special care is addressed to the birds and invertebrates (often linked to the vegetation). In the case of pipelines, their thermal insulation prevents thermal losses in the surroundings that could interact with the biodiversity associations. Particular care is taken when the geothermal development areas include woods, meadowland or environment with natural foliage. Starting from the preparation of the drilling sites up to the operation and decommissioning of the production plant, the industrial development produces unavoidably some damages in the natural landscape due to the preparation of roads, well pads, pipe routes, separator stations, holding ponds, the power house and its associated facilities. So, when the construction of the plant is completed, an appropriate replanting program of native trees and vegetation restores the original natural appearance and improve the repopulation of local flora and fauna.

Smell

Since it happens only in case of smelly gas emissions, mitigation measures are those related to degassing, and are described in Chapter 6.

Bibliography

Blanes-Vidal, V., Hansen, M.N., Adamsen, A.P.S., Feilberg, A., Petersen, S.O., Jensen, B.B., 2009. Characterization of odor released during handling of swine slurry: Part I. Relationship between odorants and perceived odor concentrations. Atmospheric Environment, 43 (18), 2997–3005.

Blanes-Vidal, V. Suh, H., Nadimi, E.S., Løfstrøm, P., Ellermann, T., Andersen, H.V., Schwartz, J., 2012. Residential exposure to outdoor air pollution from livestock operations and perceived annoyance among citizens. Environment International, 40, 44–50.

Di Gilio, A., Palmisani, J., de Gennaro, G., 2018. An Innovative Methodological Approach for Monitoring and Chemical Characterization of Odors around Industrial Sites. Advances in Meteorology, 2018, 1–8.

Manzella, A., R. Bonciani, Allansdottir, A., Botteghi, S., Donato, A., Giamberini, S., Lenzi, A., Paci, M., Pellizzone, A., Scrocca, D., 2018. Environmental and social aspects of geothermal energy in Italy. Geothermics, 72, 232-248

Mannvit, H., 2013. Environmental study on geothermal power. Geoelec WP4 D4.2.

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

Richard, A., Maurer, V., Toubiana, H., Carrière, X., Genter, A., 2020. How to upscale geothermal energy from deep fractured basement in the Upper Rhine Graben? The impact of a new 3D seismic dataset. Proceedings of the World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020.

Webb, J.W., Eddlemon, G.K., Reed, A.W., 1984. Retrospective examination of geothermal environmental assessments. Oak Ridge Natl. Libr.

4. LEAKS DUE TO SURFACE INSTALLATIONS AND OPERATIONS

Synopsis

Leak due to surface installation is a typical risk of any operation of civil engineering and industrial activity, and consists of an accidental escape of fluids from tanks temporary storing waste or from a hole or crack in the surface pipe circuits. The peculiarity of geothermal operation is the characteristics of the fluids encountered, since geothermal fluids can be highly mineralized, and of the produced material (cuttings, additives) (Gombert et al., 2017). A special case is the leak from the circuit of secondary fluids of binary geothermal plants, in case these fluids have a toxic composition or may be explosive.

Temporary storage of waste and circulation of fluids are unavoidable in the geothermal surface operation, and EIA enforces proper management to prevent and mitigate environmental adverse effects due to leaks.

Other accidental discharges at surface of fluids and solids beside leaks from tanks and pipes and a more detailed description of geothermal brine composition are described in Chapter 5 "Liquid and solid effusions on surface".

Monitoring

Pipes and tanks are inspected periodically (e.g. by acoustic emission testing, as in the Bavaria plants), according to a program whose purpose is to check tank conditions and the thickness of the pipes at representative and specific points. Welds and sensitive metallic equipment are often controlled by gamma radiography to detect any potential invisible defect. Evolution of corrosion and scaling is monitored to prevent the risk of a leak. In France, following feedback over geothermal operations (producing in the Dogger limestone of the Paris basin) and the widespread use of anti-corrosion treatments, the concession license imposes to monitor the use of anti-corrosion products and their efficiency over the installation (e.g. to measure the kinetic of corrosion, the frequency of well and exchanger cleaning, the presence of deposit).

Prevention & Mitigation

Some simple and common measures, i.e. by dimensioning the tanks big enough to avoid overflow and positioning tanks over concrete slab to avoid direct contact with soil, prevent related risks.

To avoid a leak due to corrosion, the material of the pipes and tanks is chosen from the conception and design phases to account for stored fluid composition and requirement. Corrosion resistant alloys, corrosion resistant coating and anti-corrosion treatment applied to the pipes (Finster et al., 2015), as well as passive or active electrodes are corrosion protection technologies, and research is on-going for cost-effective materials and solutions. It is common practice to avoid steel for underground storage tanks, to avoid the risk of galvanic currents. If corrosive elements are present in a fluid, they are treated using reducing agents.

Chemicals are stored in segregated areas with containment basins, in areas where there is no risk of flooding and where spillage, if any, can be contained quickly and limited to small areas (Dickson and Fanelli, 2003). Neutralization products able to hold chemical propagation are stored nearby these chemicals.

The secondary fluid used in binary plants is chosen also in view of its environmental friendliness, ozone depletion potential (ODP) and global warming potential (GWP), to prevent and mitigate the damage in case of leak.

Training programs for workers are also essential to reduce the risk of leakage when transporting or manipulating fluids and pipes at surface.

Bibliography

Dickson, M.H., Fanelli, F., 2003. Geothermal energy. Utilization and technology, UNESCO Pub.

Finster, M., Clark, C., Schroeder, J., Martino, L., 2015. Geothermal produced fluids: Characteristics, treatment technologies, and management options. Renewable and Sustainable Energy Reviews, 50, 952–966.

Gombert, P., Lahaie, F., Cherkaoui, A., 2017. Etat des connaissances sur les risques, impacts et nuisances potentiels liés à la géothermie profonde. Ineris, DRS-16-157477-00515A.

Part II – Effects associated to emission of underground material to the surface

5. LIQUID AND SOLID EFFUSIONS ON SURFACE

Synopsis

As for other industrial operation, the geothermal development involves the risk of spills, flow of fluids from broken tools, or discharge of waste material, and the prevention of these risks is considered in the EIA and the diverse regulations for the protection of the environment. Geothermal power plants produce at surface both liquid and solid underground materials, resulting from drilling wells and the construction, operation and maintenance of the plant, which may accidentally effuse in the environment. The main fluids produced at surface during drilling are drilling mud and other drilling fluid additives like cement slurry, diesel and lubricant, cleaning fluid waste and geothermal brine. The main solid materials produced during drilling are cuttings, excavated earth and rocks. During plant operation the risk of effusion regards the geothermal brine, possibly enriched by chemicals for preventing scaling and corrosion, and thus increasing the risk of pollution if liquids are dispersed at the surface. If the geothermal fluids are not totally reinjected, they become a waste that should be decontaminated before discharge. The abatement and gas treatment create a waste effluent (either liquid or a solid waste) that need to be disposed of.

Prevention for the escape of fluids from pipes and tanks is described in Chapter 4 "Leaks due to surface installations and operations". Accidental effusions related to blowout are treated in Chapter 8 "Blowout", and prevention of underground effusions due to flow of fluids from wells is described in Chapter 12 "Interconnection of aquifers and disturbance of non-targeted aquifers".

Monitoring

Monitoring includes sampling and analysis for target contaminants as a part of exploration or operation permit conditions. The frequency of monitoring reflects both the demands from the permit as well as the character of the development, the geothermal system and the discharge. Monitoring the effect of liquid and solid waste includes groundwater monitoring where chemical and thermal pollution is of the main concern. For liquid discharges, the determinations include suspended solids, pH, temperature, content in hydrocarbon material. Monitoring of surface waste-water is conducted at each intermittent as well as continuous discharge points. These include wellheads, vents, and separators, cooling towers and spent liquid drains.

Control of site condition as regards the safety conditions of pools, waste ponds, slurry etc. is required by regulation in all countries, and is part of the EIA. Waste monitoring consists of a frequent periodical chemical and chemical-physical characterization and visual control of the tanks and other services, in order to identify any accidental losses. Each check must be noted on a worksite register, available to the Mining Authority.

Prevention & Mitigation

Prevention and mitigation of the environmental effects of solid and liquid waste are generally addressed by clear regulations and enforcement, and developers are required to collect and dispose of any material produced from drilling. This involves drill cuttings as well as any fluid that has been used for the drilling or the geothermal fluid that is brought to the surface through the well.

During all phases of geothermal development, drilling and testing of wells as well as power plant operation, any short-term and/or emergency liquid releases are accommodated in a special holding tank or a holding pond (Figure 8).

Figure 8: Drillrig Sleipnir from Iceland drilling during drilling of well WW-3 at Laudat Dominica in 2012. The photo shows a 1300 m^3 "sump" system in the foreground. Photo: Sigurður S. Jónsson, ÍSOR.

As a result, all waste from drilling activities, mud, and cuttings, is stored in what are known as "sumps" for disposal. Sumps provide secure storage for drilling mud and cuttings. They are typically lined with impervious materials to prevent leaching or may be equipped with containment basins. The tank or pond are designed to accommodate an amount (e.g. 50%) in excess of a 60 hours accumulation of geothermal fluid at expected mean capacity of the production, to avoid overflow.

Non-polluting drilling fluid additives and mud recycling minimize adverse effects to environment. To be reused and recycled, the drilling mud must be conveyed correctly, first in waterproofed sedimentation tanks, to separate the coarse debris, then in vibrating screens and/or filter presses. After removing the coarse portion, the mud is re-circulated into the drilling circuit. When the mud is no longer reusable, it is treated and disposed: after the separation of the cuttings, the sludge is dehydrated in a filter press. Tanks and ponds are emptied periodically: water is sent to a waste-water treatment plant, while the solid phase is sent to landfill sites (in some countries, e.g. Italy, landfill is forbidden) or disposed. The brine extracted during the drilling is reinjected back into the underground, or dehydrated (e.g. the mud) and sent to landfills or disposed. Geothermal fluids are reinjected in most cases; otherwise they become part of the liquid waste, and are decontaminated and then discharged.

For mitigating the risk of chemical pollution due to scaling or corrosion inhibitors, the chemical inhibitors are chosen with great care considering the environment. The geothermal fluids that have been in contact with oxygen are treated with biocides and/or oxygen scavengers before being reinjected, to prevent biological impacts in the underground.

A well-designed water management system also reduces the adverse environmental effects. For example, the separated collection of rainwater, geothermal fluid and waste-water of the plant and proper management helps in using some rainwater for reinjection, and treat non-process waste-water of the plant (e.g. from toilets) in a septic tank (Ravier et al., 2016).

Bibliography

Ravier, G., Baujard, C., Dalmais, E., Maurer, V., Cuenot, N., 2016. Towards a comprehensive environmental monitoring of a geothermal power plant in the Rhine graben. Proc. European Geothermal Congress, Strasbourg, France, 19-24 Sept 2016.

6. DEGASSING

Synopsis

The phenomenon of release of gases in the atmosphere, called degassing, may occur during the geothermal development if the geothermal fluids produced at the surface have a gas content. Geothermal fluids have a variable composition and gas concentration, depending on the geological formation of the reservoir, fluid temperature and depth. Water, which is the main constituent of geothermal fluids, in high temperature geothermal systems is produced at surface at temperature well above 100 °C, and, if released in the atmosphere, is in gaseous conditions (water vapour in superheated conditions, usually called steam). High temperature geothermal fluids in volcanic and magmatic areas and, in a few cases, warm geothermal fluids from sedimentary basins (e.g. Pannonian Basin), may also contain non-condensable gases (NCG), i.e. gases that do not condense at the same pressure and temperature conditions as water vapour but remain in the gas phase. The clear majority of the NCGs (95-99%) is typically CO_2 but other gases such as H_2S, CH_4 and N_2 can be present as well. If mitigation measures are not adopted, during geothermal utilization in case of flash and dry steam technologies, the NCG fraction is released to the atmosphere.

In flash and dry steam plants the NCG are released with the water vapour at the downstream of the condenser and at the outlet of the cooling towers, which are usually wet (water) cooling systems. During the life cycle of a geothermal power plant, temporary degassing may also occur during the production tests in the well drilling phase, and during the geothermal plant maintenance operation and plant shut-down due to extraordinary events. After well abandonment, degassing might also occur in case the well has not been correctly sealed.

The effect of degassing to the environment depends on the gas amount, the toxicity and the environmental background condition. Geothermal gases have a natural origin, very different from those obtained by industrial combustion or other anthropic processes. However, European and national regulations enforce rules to guarantee the quality of air. Differently from the chemicals that are diluted or dispersed in the geothermal brine, that are more easily reinjected in the underground, mitigation of degassing require specific treatments, which are often applied also in the case of emission factors below the reference emission thresholds defined for human health and environmental safety.

If present in geothermal gases, some harmful elements and compounds, e.g. mercury (Hg) and ammonia (NH_3), as well as traces of arsenic (As) or antimony (Sb), may be stripped by gases emitted at plants, included in aerosol particles (drift) emitted from cooling towers in power production plants, and then be deposited on soil and washed out by rain. NO_x, SO_2 and primary particulate matter (PM) are not directly emitted by geothermal plants, but secondary PM may form from the oxidation of H_2S and NH_3.

Potential emission and dispersion of geothermal fluids in liquid form are treated in Chapter 5 "Liquid and solid effusions on surface", and emission of gases from engines used in surface operation are treated in Chapter 1 "Energy and water consumption and emissions".

***Monitoring and prevention measures are used only in the cases involving geothermal gas emissions*.**

Monitoring

Monitoring the phenomena is accomplished at three main levels: emissions control at the power plant, air quality monitoring in the surrounding environment, and changes in natural gas/temperature emission from the soil.

Air quality in areas of geothermal development (irrespectively of whether they are volcanic) depends on the geothermal fluid content, as it is related both to geothermal plants and to natural manifestations (in the form of natural soil degassing, fumaroles, geysers, mud pools). Baseline air quality monitoring (including dispersion models) and soil degassing is performed in the area of interest at the earliest moment, ideally before geothermal field development, to assess the background quality level and differentiate between natural environmental conditions and the effects related to geothermal development. The accumulation chamber method is the most common way to monitor the amount of gases released from the soils. It has mostly been used to measure CO_2 and, in some cases, also CH_4 and H_2S, in geothermal and volcanic systems (Peiffer et al., 2018). Other methods like snowmelt tracks and TIR (thermal infrared imagery) are also used and compared to obtain data that are reliable for monitoring changes in surface temperature and gas emission (Óladóttir, 2012; Óladóttir and Friðriksson, 2015). Such monitoring allows to identify the background level before production, and to verify the soil degassing evolution and its potential connection with geothermal production. Another method to measure gas fluxes is the Eddy Covariance method (see Appendix 1), a remote data technology used to continuously measure heat, water and CO_2 fluxes in many natural contexts and cities. Remote data methods (TIR, Eddy Covariance) require skilled personnel for data acquisition and interpretation and provide a coverage over wide areas, whereas accumulation chambers are cheaper and easy to handle but they provide only punctual spatial and temporal data.

Monitoring of gases is carried out to record the amount of released gases from the geothermal plants and at various location of geothermal installation, e.g. close to the condenser and at the cooling towers, or at the degassing tanks. Drift composition is monitored at its source, i.e. the cooling towers. Monitoring with different weather condition provides input to dispersion modelling and enables to predict gas dispersion for different air temperature and pressure and wind velocity and direction. Monitoring is done periodically, or as continuous recording if a permanent network of sensors is installed. Monitoring plans include the definition of the unit in charge of the measurements (operator, authorised control unit), the frequency of the sampling, the elements and sampling protocols, and data management.

Monitoring is necessary for establishing whether degassing due to geothermal field development overcomes the Emission Limit Values and air quality standards. In the absence of regulatory standards, reference values established by international organizations or other authorities in this field can be taken as good practice by national and regional authorities. E.g., Tuscany Region in Italy, for regulatory purposes, makes use of values from main international references for air quality standards, as those shown in Table 1 (Tuscany Region, 2010 and ARPAT, 2018a).

Table 1. Concentration thresholds related to air quality standards from main international references

Parameter	*Concentration*	*Reference*
Hydrogen Sulphide (H_2S)	150 µg/m^3 daily average	(1)
	100 µg/m^3 for 1-14 days (average over the period)	(2)
	20 µg/m^3 up to 90 days (average over the period)	(2)
Arsenic (As)	6 ng/m^3 yearly average	Target value from EC directive 2008/50/CE and D. Lgs. 155/2010
Mercury (Hg)	0.2 µg/m^3	(3) December 2007. Reference year 2001
Boron (B)	20 µg/m^3 daily average	Confidence interval 100 with respect to TLV-TWA of 2 mg/m^3 reported in (4) (inorganic boron)
	10 µg/m^3 > for 1-14 days (average over the period)	(3)
Ammonia (NH_3)	170 µg/m^3 daily average	Confidence interval 100 with respect to TLV-TWA of 17 mg/m^3 reported in (4) (ammonia)
	70 µg/m^3> for 1-14 days (average over the period)	(3)
Antimony (Sb)	5 µg/m^3 daily average	Confidence interval 100 with respect to TLV-TWA of 0.5 mg/m^3 reported in (4) (Antimony)

TLV-TWA = Time Weighted Average.

Ref: (1) WHO, 2000; (2) WHO – IPCS; (3) MRL Minimal Risk Level (ATSDR); (4) ACGIH, 2006.

A number of studies were devoted to the use of vegetation (mainly lichens and mosses, but also tree leaves and barks) as bio-monitors of contaminants (typically, mercury and hydrogen sulphide) released from geothermal plants in Italy (e.g., Bargagli et al., 2003; Loppi et al., 2006; Lattanzi et al., 2019; and references therein). Despite the use of these biological substrates has its inherent limitations and pitfalls, the results of various studies suggest that bio-monitors provide consistent indications on the long-term dispersion of contaminants such as heavy metals, boron and H_2S in the environment. Such indications may result useful for studying the long-term effects on the ecosystems.

Prevention & Mitigation

Preventive measures for degassing consist in the adoption of technologies able to avoid the release of gases in the atmosphere.

Accidental emissions during the drilling phase are prevented adopting blowout preventers and expansion vessels, as describe in the Chapter 8 dedicated to “Blowout”. During plant operation, technologies able to guarantee complete reinjection of the resource (liquid + NCG) represent the most efficient prevention measure to avoid emissions to the atmospheric environment. In binary power plants and district heating systems in low temperature geothermal systems, it is often possible to keep NCGs in water as dissolved phase, by using downhole pumps (ESP-Electrical Submersible Pump or LSP- Line Shaft Pumps) and keeping pressure at above flash point pressure. In this case the plants produce geothermal water without emitting NCG. High NCG content and high temperature can limit pump usage, but up to a certain value this problem is solved by using a gas compressor to increase pressure above dissolving pressure of NCG. For instance, degassing from geothermal plants in the Rhine graben is very low and controlled; most of the geothermal binary plants in this area (with the exception of Bruchsal plant which uses a ‘’gas bridge’’ technology) uses a closed pressurized geothermal loop, over the gas bubble point of the brine at around 20 bar, to keep all the gases (mainly CO_2) dissolved in the geothermal brine which is then reinjected (Mergner et al., 2013). In some cases, very high temperatures and a high NCGs concentration of geothermal fluids, some peculiar geological and physical condition of the reinjection reservoir, or a combination of these conditions, prevent total reinjection by commercial technologies. There is an active research, both in Europe and abroad, to solve the various technical issues and to develop innovative technologies for total gas recovery and reinjection of geothermal fluids that maintain acceptable energy production costs. For example, capture process and subsurface mineral storage of H_2S and CO_2 is currently practiced at prototype development level in some areas of Iceland (Matter et al., 2016, Gunnarsson et al., 2018).

In power plants where total reinjection is beyond actual commercial technology, various corrective technologies are in place to minimise degassing. New designs are being explored for dry steam, flash steam and binary systems to reduce degassing from plants in the Italian geothermal fields characterised by fluids with very high concentration of NCGs (Manente et al., 2019a, 2019b). The degassing from wet cooling towers is reduced using a combination of flash and binary technologies, hence reducing the thermal power exchanged in the cooling tower, and with hybrid cooling towers. Although still tailor-made to adapt them to the different conditions of geothermal sites, these combined technologies are improving with time and are progressively used to revamp flash plants.

The main mitigation measure at commercial level to minimise degassing of NCG is the adoption of abatement systems, and various methodologies have been effectively tested and used around the world to abate H_2S (Rodriguez et al., 2014), mercury and ammonia. E.g., in Italy emission levels are strictly regulated, and H_2S abatement using the «AMIS» technology (Italian acronym for Abatement of Mercury and Hydrogen Sulphide) and ammonia abatement are around 90-99% and above 75%, respectively (Manzella et al., 2018). AMIS abatement systems also reduce the emissions of mercury, with an efficiency that runs from 92% to 99% and resulting in measured Hg concentrations in air never exceeding the limits reported in Table 1 (ARPAT 2018b). Beside establishing the Emission Limit Values, local regulations in Italy require a periodic maintenance of abatement systems and define the maximum ratio between the number of non-operational hours of abatement systems with respect to the hours of power plant in operation and between the hours of free emission during plant shut down with respect to the hours of plant operation.

Recent experiments in Iceland propose alternative methods to abate H_2S emissions, using redox reaction to obtain H_2 and CO (Syngas), which is then burned and used for producing additional energy. This abatement enhances also the amount of energy produced per unit of gas emission, obtaining an overall better emission factor (Bassani, 2018). Nevertheless, the abatement creates a waste effluent (either liquid or a solid waste), which must be disposed of (see Chapter 5 "Liquid and solid effusions on surface).

In some case, as in Turkey, NCG emissions from geothermal power plants decreased with time as an effect of reinjection of fluids with a lower amount of NCG, which has progressively determined a decrease in the NCG contents of the geothermal reservoir. For example, the NCG flow rate of a geothermal power plant in Germencik-Turkey with a capacity of 47.4 MW, decreased from 55 tons/h to 40 tons/h in six years after commissioning (PLUTO, 2016). In Salavatlı (Aydın-Turkey) the NCG content of the geothermal liquid resource fell from 1.5% to 0.4 after 10 years of production.

Although of natural origin, reduction of CO_2 emission from geothermal plants is an important issue due to the urgency of greenhouse gas emission reduction to minimize the adverse effects of climate change. Beside developing and testing technologies for gas capture and reinjection, at the moment at prototypal level available for low concentration of CO_2, operators are looking for economic ways of reducing emissions from steam condensers through gas treatment. A very large CO_2 stream in the produced fluid at the Kizildere geothermal power plant (Turkey) is used since 1984 for producing industrial grade CO_2 for beverage (Şimşek et al., 2005). The CO_2 discharged from the Dora-I and Dora-II units (Salavatlı-Turkey) is processed in commercial dry-ice and gaseous CO_2 facilities near the plant, and these units have been operating with zero emissions (Aksoy, 2014). Other technologies have been also tested for the use of CO_2 in agriculture, food preparation, algae production (e.g. Bassi et al. 2018).

In the case of low temperature geothermal systems producing a high ratio of mixed thermal water and methane content, the best and most efficient mitigation measure is to separate the free gas content, and then to burn it for local electricity production. Such a good case is known e.g. from Mórahalom in south Hungary, where the thermal waters are characterized by a rather high dissolved gas content (average 520 l/m^3 with 87% CH_4), and for every 2 m^3 of thermal water produced, there is an average of 1 m^3 of methane. Annually this represents about 95,540 m^3 of methane, which was previously released to the atmosphere. Within new development, two small-scale combined heat and power (CHP) engines (4-stroke, in-line 4-cylinder engine) were installed at each of the production well sites, and utilise the separated gas content of the produced fluid, which equals roughly 89,950m^3 CH_4/year (Szanyi et al. 2015)

Regarding the pollution due to the effusion of ammonia and trace elements in the drift, aerosol emissions and soluble pollutants are minimised using drift eliminators, which reduce the drops of condensate and the mass flow of the substances dissolved in the condensate.

Some releases of gases cannot be avoided, e.g. those during production tests for well maintenance or plant shut-down. In these cases, the only possible mitigation measure is the corrective type, by reducing to a minimum the duration of degassing following the strictest maintenance protocol.

Bibliography

ACGIH (American Conference of Governmental Industrial Hygienists), 2006. Guide to Occupational Exposure Values, 168 pp. https://www.acgih.org/forms/store/ProductFormPublic/guide-to-occupational-exposure-values-2006

Agenzia Regionale Protezione Ambientale della Toscana (ARPAT) 2018a. Monitoraggio delle aree geotermiche toscane – concentrazioni di H_2S e Hg nelle aree geotermiche toscane –

Monitoraggi ARPAT e validazione dati ENEL – Report anno 2017 (Regional Environmental Protection Agency of Tuscany – Monitoring of geothermal areas in Tuscany – concentrations of H_2S and Hg in the Tuscany geothermal areas – Monitoring by ARPAT and validation of ENEL data – Report 2017). Available at: http://www.arpat.toscana.it/documentazione/report/report-geotermia/verifiche-autocontrollo-enel/concentrazione-h2s-e-hg-nelle-aree-geotermiche-validazione-dati-enel-anno-2017

Agenzia Regionale Protezione Ambientale della Toscana (ARPAT 2018 b): Monitoraggio delle aree geotermiche toscane – anno 2016 – controllo alle emissioni delle centrali geotermoelettriche (*Regional Environmental Protection Agency of Tuscany – Monitoring of geothermal areas in Tuscany – year 2016 – control of emissions of geothermoelectric power plants)*. Available at: http://www.arpat.toscana.it/documentazione/report/report-geotermia/monitoraggio-delle-aree-geotermiche-toscane-anno-2016

Aksoy, N., 2014. Power generation from geothermal resources in Turkey. Renewable Energy, 68, 595-601.

Bargagli R., Monaci F., Agnorelli C., 2003. Oak leaves as accumulators of airborne elements in an area with geochemical and geothermal anomalies. Environmental Pollution 124, 321–329

Bassani, A., Previtali, D., Pirola, C., Bozzano, G., Nadezhdin, I.S., Goryunov, A.G., Manenti, F., 2018. H_2S in Geothermal Power Plants: from Waste to Additional Resource for Energy and Environment, Chemical Engineering Transactions, 70, 127-132.

Bassi, N., Paci M.; Bardi, A., Torsello, L., Bonciani, D., Vichi, M., Cenerini, M., Biondi, N., Rodolfi, L., Tredici, F., Tredici, M., 2018. Arthrospira platensis cultivation using geothermal CO2 and heat, 5th AlgaEurope Conference 2018.

Gunnarsson, I., Aradóttir, E.S., Oelkers, E.H., Clark, D.E., Arnarson, M.Þ., Sigfússon, B., Snæbjörnsdóttir, S.Ó., Matter, J.M., Stute, M., Júlíusson, B.M., Gíslason, S.R., 2018. The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. Int. J. Greenh. Gas Control. 79, 117–126.

Lattanzi P, Beutel MW, Costagliola P, Fagotti C, Rimondi V (2019). Tracing the impact of geothermal plants in the Monte Amiata area, Tuscany, Italy: evidence from Hg contents in stream sediments and tree barks. Proceedings of EUROPEAN GEOTHERMAL CONGRESS 2019, The Hague, 11-14 June 2019, Paper 217

Loppi, S., Paoli, L., Gaggi, C., 2006. Diversity of epiphytic lichens and Hg contents of *Xanthoria parietina* thalli as monitors of geothermal air pollution in the Mt. Amiata area (central Italy). Journal of Atmospheric Chemistry 53, 93-105.

Manente, G., Lazzaretto. A., Bardi A., Paci, M. 2019a. Geothermal power plant layouts with water absorption and reinjection of H2S and CO2 in fields with a high content of non-condensable gases. Geothermics, 78, 70–84.

Manente, G., Bardi A., Lazzaretto. A., Paci, M. 2019b. Low emission flash-binary and two-phase binary geothermal power plants with water absorption and reinjection of non-condensable gases. Geothermics, 80, 155–169.

Manzella, A., R. Bonciani, Allansdottir, A., Botteghi, S., Donato, A., Giamberini, S., Lenzi, A., Paci, M., Pellizzone, A., Scrocca, D., 2018. Environmental and social aspects of geothermal energy in Italy. Geothermics, 72, 232-248.

Matter, J. M., Stute, M., Snæbjörnsdottir, S. Ó., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., Sigfusson, B., Gunnarsson, I., Sigurdardottir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H. A., Wolff-Boenisch, D., Mesfin, K., de la Reguera Taya, D.F., Hall, J., Dideriksen, K., Broecker, W. S., 2016. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. Science 352 (6291), 1312-1314.

Mergner, H., Kölbel, T., Schlagermann, P., 2013. Geothermal Power Generation - First Operation Experiences and Performance Analysis of the Kalina Plant in Bruchsal, Conference Geothermal Power Generation.

Óladóttir, A, 2012. Application of soil measurements and remote sensing for monitoring changes in geothermal surface activity in the Reykjanes field, Iceland, thesis submitted in partial fulfillment of a Magister Scientiarum degree in Geology, Faculty of Earth Sciences School of Engineering and Natural Sciences University of Iceland Reykjavik, July 2012, 128 pp, https://skemman.is/bitstream/1946/13001/1/LOKAUTGAFA.pdf Accessed on April 14, 2019

Óladóttir, A, Friðriksson, Þ., 2015. The Evolution of CO2 Emissions and Heat Flow through Soil since 2004 in the Utilized Reykjanes Geothermal Area, SW Iceland: Ten Years of Observations on Changes in Geothermal Surface Activity. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015.

Peiffer,l., Carrasco-Núñez,g., Mazot,A., Villanueva-Estrada,R.H., Inguaggiato,C., Romero, R.B., Miller,R.R., Rojas, J.H., 2018. Soil degassing at the Los Humeros geothermal field (Mexico). Journal of Volcanology and Geothermal Research, 356, 163-174.

PLUTO 2016. Assessing the use of CO2 from natural sources for commercial purposes in Turkey. Report for European Bank for Reconstruction and Development (EBRD)
https://temizenerjifinansman.com/Uploads/Editor/files/2016-PLUTO.pdf

Rodríguez, E., Harvey, W.S., Ásbjörnsson, E.J., 2014. Review of H_2S Abatement Methods in Geothermal Plants. Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014.

Şimşek, Ş., Yıldırım, N., Gülgör, A., 2005. Developmental and environmental effects of the Kızıldere geothermal power project, Turkey. Geothermics, 34, 239-256.

Szanyi, J., Medgyes, T., Kóbor, B., Molnár, e: (eds) 2015. Technologies of injection into sandstone reservoirs, best practices, case studies. Geolitera. Hu ISSN 2060-7067

Tuscany Region, 2010. Criteri direttivi per il contenimento delle emissioni in atmosfera delle centrali geotermoelettriche. Prescrizioni da utilizzare nei procedimenti regionali di VIA e di concessione/autorizzazione ex L. 896/1986 e L.R. 39/2006, pp.88 (Allegato A alla DGRT n. 344/2010) (in Italian).

World Health Organisation (WHO), 2000. Air quality quidelines for Europe. 2nd Edition. Open File Report http://www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf

WHO – IPCS, WHO International Programme on Chemical Safety. Open Report Documents (continuously updated) http://www.who.int/ipcs/methods/harmonization/en/

7. RADIOACTIVITY

Synopsis

In the infrequent case of abundant circulation and drilling in natural radioactive rocks, like granite for example, there is a potential for radioactive contamination at surface. The natural radioactivity of geothermal fluid is usually very low and can't be detected above the ambient radioactivity, but cuttings from well drilling and deposits (scale) that develop within casing and surface equipment can be significantly more radioactive (Scheiber et al., 2012). In some, restricted sites, where the radioactivity level appears above the natural level due to peculiar geological conditions and to the accumulation of NORM (Naturally Occurring Radioactive Material) in the surface installations, mitigation measures are required to protect population and environment. As for any planned, existing or emergency exposure situation which involves a risk from exposure to ionizing radiation, geothermal operations dealing with radioactive materials must be compliant to the European regulation and its national applications, which establish thresholds for dynamic and cumulative radioactive doses, and safety standards. These are enforced by the EIA procedure for permission to operate a geothermal plant, which prescribes provisions for management of radioactivity, usually based on the worst-case scenario.

***Monitoring and prevention measures are applied only in those few cases involving radioactive material*.**

Monitoring

Monitoring implies the recording of background condition, possibly before the industrial development, and at the geothermal installations. Exposure is possible during drilling, when managing rocks and fluids, and during operation and maintenance. Radioactivity is checked not only in fluids, but also in the surface installation equipment, since scaling, i.e. precipitation and deposition of minerals due to temperature and pressure drops in the geothermal fluids, may contain radioactive materials (Scheiber et al., 2012).

In order to obtain a clear overview of the potential radioactive emissions due to a geothermal power plant, an initial state of the natural ambient radioactivity is measured before starting any drilling or civil work operations. Then, before the commissioning of the geothermal plant, a clear overview of the level and location of radioactive emissions within the installation is obtained by an inspection. This measurements campaign allows to evaluate the risk related to the drilling and construction activities and establish a reference of the initial ambient radioactivity on the site. Regular inspections are then performed in order to check for the presence of radioactivity and monitor its evolution. These inspections consist in measuring dose rate values at various places of the geothermal site (Cuenot et al., 2013). To monitor the level of radiation in areas were radioactive material is present, radiometers (Figure 9) are used to record the dose rate, i.e. the dose of radiation received per unit of time. In some cases the activity, which is the number of nuclear disintegrations per unit of time expressed in cps (counts per second) is also measured, usually with a contamination detector.

Figure 9: Dose rate measurement performed with a radiometer on a pipe at the Soultz-sous-Forêts power plant (Cuenot et al., 2013).

"Contact" dose rates are also measured at about 1 cm from the equipment to closely identify the places where high dose rate values can exist, that is, where scales can accumulate (filters, pipe bend, heat exchanger outlets…), to define the potentially contaminated equipment.

"Ambient" measurements are recorded at about 50 cm to 1 m from the equipment, and are used to define different zones within the site, depending on the level of measured dose rates (i.e. "public", "monitored" and "controlled" zones) implying specific authorized access, protective and mitigation measures. Data are acquired at the same location with time, to verify the evolution of the radioactive level and any correspondence with fluid flow circulation in the plant, or plant operations.

Monitoring is periodically done also on samples from the filter elements and the scaling as well as the geothermal water in order to determine their radionuclides composition and activity level. The frequency of the deposits and brine monitoring depends on the radioactive emissions detected and the estimated risk for workers and environment.

To complete the monitoring plan, external analysis of radioactive emissions in atmospheric particles should be realized on the closest houses, ideally downwind of the geothermal plant. Regular sampling and radiological analyses of liquid and solid effluents (other than geothermal fluid and scales) can be done in the environment around a geothermal plant.

Prevention & Mitigation

Apart from standard protection measures for personnel working at the site, mitigation measures for human exposure apply only to visitors of the geothermal plants: based on actual knowledge and conservative assumptions, it is not expected that the reference level for the population will be exceeded outside any geothermal installation area. Visitors are allowed only in “public” zones and equipped with radiation protection equipment. The basic principle of radiation protection is the so-called “ALARA” principle: the received dose should be “**A**s **L**ow **A**s **R**easonably **A**chievable» by adopting radiation protection measures to ensure that visitors do not receive a cumulative dose larger than the threshold established by regulation and to guarantee a minimum level of exposure.

Radioactive waste being usually avoided, the potential NORM “residue” including rock material, scaling material from pipes, and also defective plant components, filter material, sludge, and protective clothing, are treated following the radioactive waste management rules, which is regulated differently from one country to the other. Protective clothing and organic filter materials are recycled thermally, and defective plant components are melted down. NORM “residue”, such as rock particles or scaling residues containing long lifetime radionuclides, are disposed for long term storage (Figure 10).

Figure 10: Storage of radioactive residues at the Rittershoffen heat plant (courtesy of ES-G)

Depending on the radionuclide content, only specialized companies can manage these residues. As an example, in France, ANDRA (French National Agency for Nuclear Waste Management) is in charge of collecting all types of radioactive waste, including NORMs. Nevertheless, management of radioactive waste represents significant costs for the operators. The adoption of technological solutions to prevent or reduce scaling is a further mitigation measure for reducing radioactive material at surface (Scheiber et al., 2013; Mouchot et al., 2018). Total reinjection of fluids and prevention for scales (deposits) formation is a way to decrease and, in the best case, to completely avoid the radioactivity related to geothermal fluid production.

Bibliography

Cuenot N., Scheiber J., Moeckes W., Guéry B., Bruzac S., Sontot O., Meneuset P., Orsat J., Vidal J., 2013. Evolution of the natural radioactivity within the Soultz geothermal installation. Proceedings European Geothermal Congress, 2013.

Mouchot J., Genter A., Cuenot N., Scheiber J., Seibel O., Bosia C., Ravier G., 2018. First year of operation from EGS geothermal plants in Alsace, France: Scaling Issues. Proceedings 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, 2018.

Scheiber J., Nitschke F., Seibt A., Genter A., 2012. Geochemical and mineralogical monitoring of the geothermal power plant in Soutz-sous-Forêts (France). Proceedings 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, 2012.

Scheiber J., Seibt A., Birner J., Genter A., Moeckes W., 2013. Application of scaling inhibitor system at the geothermal power plant in Soutz-sous-Forêts: Laboratory and on-site studies. Proceedings European Geothermal Congress, 2013.

8. BLOWOUT

Synopsis

Blow-outs are uncontrolled flows of formation fluid from drilled wells. They are very rare incidents, that may occur from natural causes (e.g. the drilling through an over-pressure zone), or in relation to drilling operation (e.g. if pressure inside the well falls below the saturation pressure and steam is formed) (Holmgren, 2018). In a blowout, fluid is ejected to the surface: firstly, water located above the inflow zone is ejected rapidly out of the well, followed shortly after by steam and water.

Prevention of geothermal blowout is common practice in the geothermal drilling operations, and the level of risk is incomparably lower than for oil and gas industry.

The prevention of blowouts effects occurring underground is treated in Chapter 12 "Interconnection of aquifers and disturbance of non-targeted aquifers". The prevention of geothermal gas emission beside blowout is described in Chapter 6 "Degassing".

Monitoring

Modern drill rigs are equipped with number of sensors to display critical parameters during drilling operations, and well data are continuously checked in order to notice early warning signs of potential blow-outs. It is common practise that the drilling crew is in alert at all times in order to notice early warning signs of potential blowouts. Alert may rise for sudden changes of stand-pipe pressure (increase/drop), temperature and flow (increase/decrease/fluctuation/gas bubbles) of the returning fluid, changes in drilling parameters (e.g. rate of penetration), changes in cutting analysis, inspected by the on-site geologist.

Down-hole pressure and temperature are checked to establish if steam is close to be formed within the well in high temperature systems, to avoid that pressure inside the well falls below the saturation pressure.

Prevention & Mitigation

Good drilling practices are the best way to prevent geothermal blowouts (Hyett, 2010; Standards New Zealand, 2015). They include proper project planning, well design, proper training of the staff and correct selection of blow-out prevention (BOP) equipment and standards. The blowout preventer (BOP) (Figure 11) is nowadays a common and essential part of the drill rig equipment. It is located on top of the well and has the purpose to close the well during drilling operations, if the control of the formation fluid is suddenly lost. The control of the rig while it is operational is safe if the personnel in charge of any drilling or workover operations is well trained and competent in blowout prevention and control of geothermal wells.

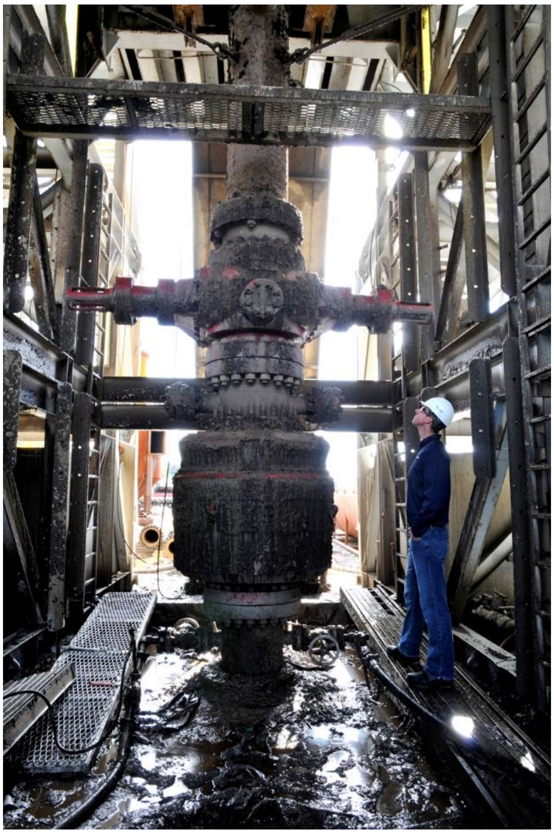

Figure 11: Blowout preventer at rig site at the Geysir geothermal field.

BOPs are checked every shift during drilling and enough amount of killing fluid materials and water are stored on the location (Finger and Blankenship, 2010; The African Union, 2016). Constant and sufficient supply of drilling water and high-density drilling mud guarantee safe drilling practice. If signs of a blowout are imminent, regaining well control is in most cases relatively easy by maintaining a constant bottom-hole pressure. For high temperature underpressurized geothermal reservoirs it is usually enough, in case of water flashing to steam, to raise the pressure sufficient or cool the well, to make the steam bubbles collapse and return to water. The only case that requires special treatment is in the case of high ratio of non-condensable gases in the steam (mostly CO_2), or where the geothermal reservoir is over pressurized. Those kinds of situations are dealt with preventive procedures, for example using high density drilling mud (barite) and different casing strategy (Ásgeirsdóttir et al., 2017). Well planning and casing design is optimised by experienced engineers who consider previous wells and formation aspects such as pore pressure, fracture gradients and proximity of other wells. The spreading of geothermal fluid around the well is prevented by digging pools and channels during the preparation of a drilling pad. When pumping killing fluid into a well, formation fracture pressure should not exceed the one at the casing shoe.

Bibliography

Ásgeirsdóttir, R, S., Sigurgeirsson, M, Á., Guðmundsdóttir, V., Tryggvason, H., Egilsson, Th., Guðjónsdóttir, S, R., Pétursson, F., Ingólfsson, H., Sveinbjörnsson, S., Árnadóttir, S., Stefánsson, H, Ö., Kristinsson, B., Sveinbjörnsson, B, M., 2017. Theistareykir-Well ThG-13. Phase 3: Drilling for a 7" Perforated liner down to 2505 m depth. LV-2017-020.

Finger J. and Blankenship D. 2010. Handbook of Best Practices for Geothermal Drilling. Sandia report, SAND2010-6048, Prepare by: Sandia National Laboratories, USA, printed in Decempber 2010, 84 p.

Holmgren, M., 2018. X-Steam. Properties of water and steam (Steamtables). Add- in for Excel. Available at: http://www.me.ua.edu/me215/f07.woodbury/ExcelStuff/XSteam-v2a.xlsm (Accessed in December 2018)

Hyett, D., 2010. Environmental risk assessment in environmental impact assessment-optional or mandatory? 30th Annual Meeting of the International Association for Impact Assessment 6-11 April 2010, International Conference Centre Geneva - Switzerland (www.iaia.org).

Standards New Zealand, 2015. New Zealand Standard. Code of practice for deep geothermal wells. NZS 2403:2015, 118 p.

The African Union Code of Practice for Geothermal Drilling, 2016. Published by the African Union's Regional Geothermal Coordination Unit, 150 p.

Part III – Effects associated to geomechanical changes

9. GROUND SURFACE DEFORMATION

Synopsis

Geothermal development and operation may cause deformation of the ground surface that subsides (lowers) or uplift, generally in response to pressure and/or temperature changes within the geothermal reservoir. Fluid extraction from the underground can lead to a decrease in both pressure and temperature within the geothermal reservoir, thereby causing subsidence. Conversely, re-injection of geothermal fluids can induce a pressure increase within the geothermal reservoir, resulting in a ground uplift. This latter may be partially counteracted by the rocks and sediments contraction as they cool down due to the temperature decrease.

Monitoring

Many geodetic techniques can be used to monitor ground surface deformation at a geothermal field. Currently, SAR satellite interferometry (InSAR), global navigation satellite systems (GNSS), and levelling are the main techniques used. InSAR provides a good spatial coverage of geothermal fields and their surroundings thanks to different available SAR satellite platforms (Appendix). New generation of satellites acquire images regularly, every 6 days in the case of the Sentinel-1 EU mission, allowing to monitor precisely the evolution of the deformation. InSAR is sensitive to snow and vegetation, which can limit the long-term monitoring of an area. However, it is possible to bypass this limitation by installing corner reflectors at specific points of interest. InSAR measures the deformation along one axis (toward and away from the satellite), which complexifies the interpretation of results and makes it fairly insensitive to deformation along the North direction. A GNSS permanent station provides a continuous monitoring of the deformation in all directions (East, North, Up). Its limitation is that it measures only one specific point and it is expensive to run many of them within a geothermal field. Benchmarks can also be installed throughout the geothermal field and surveyed at regular interval using GNSS, levelling, or total stations. This allows to monitor specific points of interest than cannot be monitored by InSAR or permanent GNSS stations, at the cost of sending a team to the field to do measurements. A combination of all techniques is usually the best way to ensure a detailed monitoring of surface deformation within geothermal fields

Prevention & Mitigation

Monitoring, prediction and control are the three main means to mitigate the effects of ground surface deformation in geothermal fields. By recording spatial changes and the temporal evolution of surface deformations, information regarding subsurface modifications can be inferred. Prediction is based on the numerical modelling of reservoir performance and requires the simulation of the complex interactions between heat and mass transfer processes and the reservoir properties (i.e., permeability and porosity), and of the geotechnical characteristics of rock.

Injection of fluids in the geothermal reservoir proved to be a very effective way to control and mitigate land subsidence in geothermal systems, since in many cases it compensates for mass deficit and pressure decline induced by fluid extraction. Injection of fluids requires special care, predictive measures and experience, to avoid ground inflation for excessive reinjection, as reported in Turkey, or subsidence due to contraction of the hot formations by cold reinjection, as in New Zealand (Kaya et al., 2011; Diaz et al., 2016). Usually the injected fluids are the geothermal brines recovered after heat and power production: the term “reinjection” is used in this case. Reinjection proved effective also for resource sustainability and has become an integral part of all sustainable and environmentally friendly geothermal utilization (Diaz et al., 2016).

In case the prevention by reinjection is not enough and ground deformation appears, the best recovery measure it is to reduce the rate of geothermal fluid extraction or raise the re-injection temperature.

Bibliography

Diaz, A.R., Kaya, E., Zarrouk, S.J., 2016. Reinjection in geothermal fields - A worldwide review update. Renewable and Sustainable Energy Reviews 53, 105–162.

Kaya, E., Zarrouk, S.J., O’Sullivan, M.J., 2011. Reinjection in geothermal fields: A review of worldwide experience. Renewable and Sustainable Energy Reviews 15, 47–68.

10. SEISMICITY

Synopsis

Many geothermal areas are associated with geological structures that are characterized by natural seismicity. Geothermal development tends to modify the characteristics of a reservoir by withdrawing and injecting hot and/or cold fluid into the underground. In particular, circulating water through the geothermal reservoir creates pressure changes that can cause small seismic events. Production and injection rates and pressures, fluid volumes, and injection duration are factors that affect the likelihood and magnitude of an induced seismic event. If the reservoir is fractured (i.e. fluid moves principally within fractures and not within the porous media), the forced fluid circulation can cause induced seismicity by lowering the fracture resistance to slip or by thermal cracking. Some other effects, like perturbations due to drilling, or redistribution of stress due to variations in fluid volume within the reservoir, can also cause induced events. Microseismicity (i.e. seismic events that are detected by seismometers but are not, or are slightly, perceived by population, having magnitude below 2-3, depending on many factors including subject sensibility) is often associated to geothermal development, whereas felt, although minor, seismic events characterised a few geothermal projects. There are some cases of Enhanced Geothermal System (EGS) projects which used high pressure for injecting fluids underground to enhance permeability (hydraulic stimulation) and induced seismic events producing damage and fear.

Monitoring

Seismometers are the common devices for monitoring seismicity, both natural and induced. In some countries it is mandatory to have seismometers installed on a geothermal site. These devices continuously record the motion of the ground (velocity or acceleration, depending on the instrument), so that when an earthquake occurs, its main parameters may be retrieved. The most known parameter is the earthquake magnitude. Peak ground velocity (PGV) or peak ground acceleration (PGA) are sometimes preferred as reference parameters, since they are directly recorded by the seismometer, with respect to magnitude which is a calculated value. Moreover, different definition of magnitude such as local magnitude (ML), commonly referred to as "Richter magnitude", duration magnitude (Md), surface-wave magnitude (Ms), body-wave magnitude (Mb), and moment magnitude (Mw) may generate confusion in the communication with the population. Seismometers are connected to a monitoring centre where automatic detection is carried out. These centres may be managed directly by the operators. However, in some country official observatories are mandated to monitor seismicity and to alert the local authorities in case of problem.

Prevention & Mitigation

Quantifying hazard and risk requires probability assessments, that help establish specific “best practice” protocols for geothermal project development. Five key practices were defined during international research projects and the experience gained in several industrial initiatives. They comprise:

1) detailed geological and seismotectonic studies to identify faults capable of generating damaging earthquakes;
2) technologies that maintain a balance between produced and reinjected fluid and minimize pore pressure changes at depth;
3) local seismic monitoring networks, to be installed and operated before development (e.g. in French Rhine Graben area it is required to monitor natural micro seismicity 6 months before drilling);
4) operational protocols jointly defined by operators and public regulators (e.g., hydraulic stimulation protocols and traffic light systems) to reduce the possibility of a felt seismic event, and to mitigate the effects of an event if one should occur, e.g. by further control or, in some case, suspending activities;
5) transparent and effective communication to achieve informed public acceptance.

The first three points are usually taken into consideration during the EIA required by regulation in most countries and are often mandatory. The analysis of these data is the base of seismic hazard and risk assessments, as defined for EGS projects in USA (Majer et al., 2013) or other anthropic activities (Bommer et al., 2015). In case of hydraulic stimulation, safety protocols are built with the aim of maximizing injection while minimizing induced seismicity, for example imposing by regulation a maximum injection pressure both for hydraulic stimulation and fluid production, as in France where injection pressure is limited to 100 bar, or by progressively decrease the injection flowrates at the end of hydraulic stimulation, since in most of the observed cases the largest seismic event occurred for constant-rate injection in the so-called “shut-in period”. Moreover, the *soft stimulation* concept was developed for geothermal applications, with the same aim of minimizing induced seismicity (Hofmann et al., 2018). Soft stimulations are based on the hydraulic fatigue concept (repetition of injections, and progressive, but limited, damage of rocks). They are optimized to have a high yield with limited pressure and low injected net fluid volume. They also aim to minimize sudden and important variations to the system.

Mitigation strategies aligned with the monitoring system always imply some reactive protocols to be implemented. The common way is based on the application of the *traffic light system (TLS)*. The seismicity is monitored in real time and if an event has a reference parameter (earthquake magnitude, ground acceleration, ground deformation velocity,…) above a given threshold and is connected with variations in the operations at the geothermal site, the latter are checked, reduced or, eventually, stopped. TLSs are not the only solution, but are one of the most common and understandable by the population. Potentially damaging events are less likely to occur when TLS are set conservatively, i.e. with interruption thresholds set lower, and injections interrupted earlier. However, more conservative traffic lights may have a strong and adverse effect on the commercial success rate of the projects. An agreement between the interested subjects, namely the local authority and the operator, usually defines the monitoring protocol and the related technical details, such as number of monitoring stations, data handling and communication with the population, TLS etc..

Another important aspect of mitigation, still in a preliminary stage of development, is the one related to the *pre-assess screening*, to get a sense, early on in the planning stage, of the extent to which seismicity is a concern for a specific project. One important aspect is the implementation of *seismicity pro-active protocols* or *Adaptive Traffic-Light Systems* (ATLS), based on defining the probability of exceedance of some reference seismicity values rather than the later verification of exceedance. Pre-assessment tools for risk governance that take into account both technical and social aspects are also under development. E.g. the *Geothermal Risk of Induced seismicity Diagnosis* (GRID) (Trutnevyte and Weimar, 2017), ranks projects by four categories, ranging from projects with no concern about induced seismicity to ones with a high level of concern. The risk governance measures for induced seismicity are defined for each category, based on hazard and risk assessment, social site characterization, seismic monitoring, insurance, structural retrofitting, traffic light systems, information, and public and stakeholder engagement.

Bibliography

Bommer, J., Crowley, H., Pinho, R., 2015. A risk-mitigation approach to the management of induced seismicity. J. Seismol., 19, 623–646.

Hofmann, H., Zimmermann, G., Zang, A., and Min, K.-B., 2018. Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments, Geothermal Energy, 6 (27), 33 pages.

Majer, E.L., Nelson, J., Robertson-Tait, A., Savy, J., Wong, I., 2013. Best Practices for addressing induced seismicity associated with Enhanced Geothermal Systems (EGS), Lawrence Berkeley National Laboratory. Available at: http://escholarship.org/uc/item/3446g9cf.

Trutnevyte, E. and Wiemer, S., 2017. Tailor-made risk governance for induced seismicity of geothermal energy projects: An application to Switzerland, Geothermics, 65, 295–312.

Part IV - Underground physical and chemical modifications

11. PRESSURE AND FLOW CHANGES

Synopsis

Extraction of fluids during the geothermal plant operation produce underground hydraulic pressure changes. The pressure normally declines most rapidly at the beginning of utilization, then the change is slowed down and the pressure reaches a balance when the production of fluids from the reservoir equals its recharge, natural from open boundaries and/ or from reinjection.

Monitoring

Regular monitoring of pressure, temperature and production in a geothermal well, before and after the beginning of its utilization allows to follow the evolution and to enable good management during long-term utilization. In low temperature systems the water level is often monitored instead of pressure. Besides the well logs, chemical samples are collected regularly and analysed to see the evolution of the fluid's composition with time. Tracer tests, i.e. injection of a chemical compound in one well and retrieval in the surrounding wells, also provide useful information regarding permeability and other hydraulic parameters of the reservoirs.

Pressure and temperature are logged regularly in selected monitoring wells in high temperature geothermal system, preferably production wells which have rested for some weeks and therefore recovered partly the pressure drawdown, as well as exploration wells which are not utilized. Often the temperature and pressure are plotted at selected depths over time to see clearly the changes.

Besides the regular monitoring after utilization of a well starts, there are several types of monitoring and logging performed to increase the knowledge about a well and the geothermal system. To mention some of them, *step tests* are performed at the end of drilling by changing stepwise injection of water into a well and monitoring to see the pressure change, and *production step tests* are performed before start utilizing a well. The series of temperature and pressure logging during the warmup and thermal recovery period of a well after drilling allow to estimate the formation temperature and initial pressure at the well.

Monitoring is utilized in decision making for necessary mitigations if the pressure decline is not acceptable and for modelling the system, its response to utilization in time and forecasting scenarios.

Preventions & Mitigations

The injection of fluids in the reservoir to replace the volume of extracted fluids is the only long-term risk-mitigation measure which helps to avoid the pressure decline in the resource (reservoir depletion) on a large scale, and during long-term operation. The *reinjection*, i.e. the injection of the geothermal fluids extracted during production and available after releasing their heat to the generator or heat exchanger, is the most common procedure, and is used both to restore the original water balance in the underground (sustainable development) and to prevent the environmental effects of the wastewater at surface.

The most clear and known example of the beneficial effects of reinjection after a main pressure decline is from the most productive geothermal field in the world, The Geysers in California, USA, where the excessive production of fluids without proper reinjection produced a steep decline of reservoir's pressure and of resource's productivity in the late 1980's (Figure 12 and 13). Only after a large increase of injection rate of fluids and prolonged injection, the pressure and productivity declines stabilized.

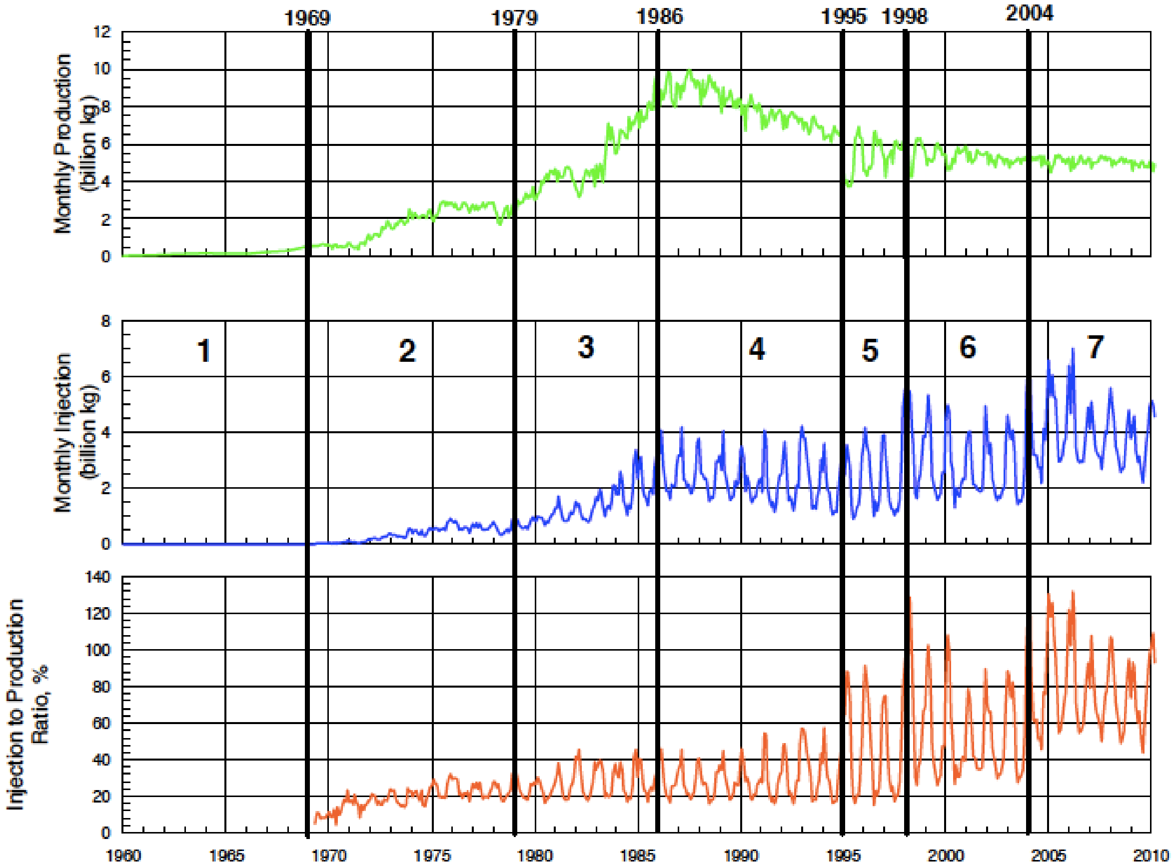

Figure12: The production and injection history of The Geysers geothermal field in California, USA. From Sanyal and Enedy, 2011.

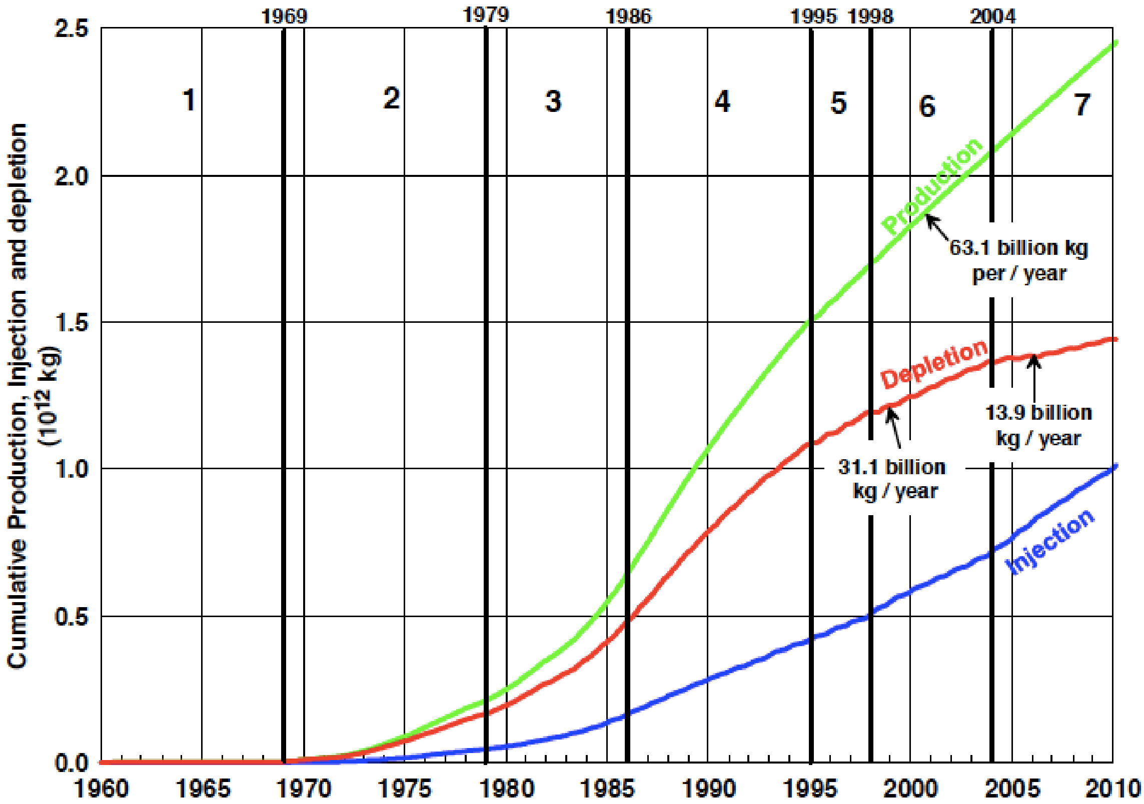

Figure 13: History of cumulative production, injection and depletion data in The Geysers geothermal field in California, USA. From Sanyal and Enedy, 2011.

Underground injection/reinjection is a technical procedure which calls for high-quality well design supported by monitoring data, the completion of the well and its testing and operation, and close observation of the several risks involved. Risks on the reservoir scale are more probable at fractured reservoirs, while risks in the vicinity of the well (i.e. problems near to the well-bore itself) are more frequent at porous reservoirs.

According to Axelsson (2012) reinjection sites are essentially located: (a) Inside the main production reservoir, i.e. in between production wells. Often production/reinjection doublets. (b) Peripheral to the main production reservoir, i.e. on its outskirts but still in direct hydrological connection. (c) Above or below the main reservoir. (d) Outside the main production field. In this case direct hydrological connection to the production reservoir may not exist.

Reinjection requires care to avoid a so-called thermal break through (see Chapter 13 related to “Thermal changes”), and the risk of generating seismicity (see Chapter 10 on “Seismicity”). The hydraulic connection between the production and reinjection well are evaluated by in situ hydrogeological testing, including interference and tracer tests, and hydrogeological modelling. Reinjection of geothermal fluid can also cause changes of permeability in the reservoir, which in turn cause pressure changes. The main cause is the *scaling* in injection wells and the rock formation surrounding them, when the minerals in the cooler reinjected fluid become less soluble and precipitate. Other causes of reduction of permeability are: (a) swelling of clays, silica, or carbonate scaling in the reservoir, (b) biofilm growth, and/or (c) corrosion particles originating from the surface pipelines; (d) clogging caused by the migration of fine particles among larger grains in the reservoir, near the well, or in the screens. Reinjection in porous reservoirs has further challenges, the most common being the damage caused to the formation due to drilling and well activities (and even the injection process itself) which result in a deterioration of the permeability of the rocks.

Successful prevention of reinjection failures requires comprehensive knowledge about the processes involved, and to avoid sudden starts and stops of the flow. To this aim, an accumulation tank is built in the vicinity of the reinjection well to provide an injection flow rate which is as constant as possible.

Wells are completed by under-reaming and gravel pack, an over ground micro-filtering system that removes the suspended solids from the water prior to injection in the well. All wells are shut down periodically, at least once a year, so that their static water level can be measured, and the surface piping system can be cleaned. If the pressure in the production wells increases, the following interventions are carried out:

- filter cleaning with a compressor, hourly water sampling and visual inspections,
- sterilization of the piping system,
- backwashing of the reinjection well with hourly water sampling,
- bottom-hole cleaning of the well, incorporating packer tests,
- layer cleaning involving acid treatment.

Various procedures prevent silica scaling, e.g. with “Hot” injection when the separation water is injected directly from the separator, at temperatures 160-200°C (Axelsson, 2012). In “cold” injection the temperature of the return fluid is below the saturation temperature for silica. Other preventive measures include deposition of silica in ponds or the use of scale inhibitors before injecting the fluid.

Additional mitigations for declining pressure and production from a system include drilling makeup wells and cleaning of wells which are partly clogged by precipitated minerals, both in the case of a production well and reinjection well. Pressure is also recovered letting some wells to rest while others are used, or to rest some parts of the geothermal system.

Bibliography

Axelsson, G., 2012. Role and management of geothermal reinjection. 001226914.

Sanyal, S. K., Enedy, S. L., 2011. Fifty years of power generation at The Geysers geothermal field, California – the lesson learned. Proc. Thirty-Sixth Workshop on Geothermal Reservoir

Engineering, Stanford University, Stanford, California, January 31 - February 2, 2011, SGP-TR-191

12. INTERCONNECTION OF AQUIFERS AND DISTURBANCE OF NON-TARGETED AQUIFERS

Synopsis

With depth varying between a few hundred to thousand meters, geothermal resources are explored, developed and produced through well drilling. To reach the targeted resource, the well is expected to intersect one or several aquifers of different quality and property that are separated by impermeable levels. Without the adoption of proper mitigation measures, during development, in particular drilling, and operation of a geothermal industrial plant, there is a risk of accidental connection of aquifers via the wellbore or disturbance of non-targeted aquifers with fluid intrusion (geothermal fluid, testing fluid, drilling mud, etc.). The phenomena is driven by differential hydraulic pressures between layered aquifers, and can be caused by well barrier and integrity failures due to poor cementation practices, mechanical damage during well development, corrosion and scaling, geo-mechanical disturbances, underground blowout, thermal stress and material failure or degradation, and aging over the life cycle of operations. It can be triggered during the drilling process and through all life stages of a geothermal project, and also result from improper reinjection applications.

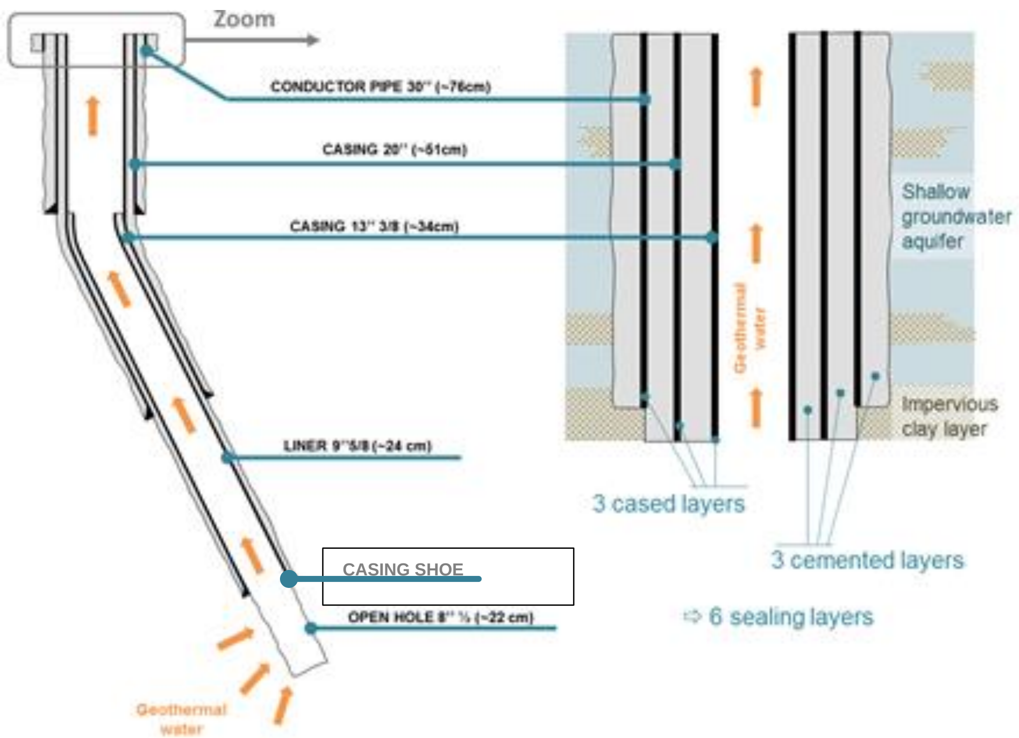

Figure 14: Example of well design of a geothermal well in Ilkirch, France (ESG), from Ravier et al., 2016, where the main terms used in this chapter are shown.

Monitoring

To check casing condition in geothermal wells, and to intervene in case of detection of incurrent or potential damage, various monitoring systems have been implemented in different countries. For example, in France a certain number of measures are being carried out since the late 1980s to identify and monitor the effects of corrosion, thermomechanical and other disturbances on the casing in the wellbore. These measures include adding corrosion inhibitors when reinjecting the geothermal fluid in the reservoir, using thicker tubing, wellbore integrity scans to assess deposit thickness and corrosion evolution. Casing corrosion controls in France are enforced by legislation, and performed every 3 years over injector wells and every 5 to 6 years in production wells.

Flow rate, pressure and water quality are monitored during the operation phase to identify potential leakage. The quality of cementing work during and after drilling is tested through pressure tests and borehole logging (e.g. Cement bound Log (CBL) and Cement Evaluation Tool (CEV)) (Galin, 2000; Vernoux et al., 2002).

The potential interference of the different aquifers is monitored using piezometers, which record water levels and conductivity in real time of the aquifers above the developed geothermal reservoir, and in particular potable aquifers. A correct monitoring plan requires the recording of meteoric conditions, in particular the rainfall and snowfall regimes. A continuous monitoring of piezometric regimes and periodical chemical analyses of waters reveals the hydraulic parameters of the freshwater resource, and establishes the correlation between the aquifers and meteoric inflow, and thus defines if there is any correlation with geothermal fluid production. Water quality controls of intersected aquifers allow to be reactive in case of contamination and take actions to contain pollutant propagation.

Prevention & Mitigation

Different preventive and remedial solutions are implemented in order to mitigate the risk of connection between aquifers and their disturbance. First, optimal well design, and more specifically the choice of materials for isolation from surrounding formation, both when conceiving drilling programs and when setting up the well, and monitoring the work done during cementation and tubing placement, are essential to prevent adverse effects on groundwater aquifers. The monitoring of reservoir behavior, the control of casing and tubing condition, and maintenance operations also contribute to prevent and mitigate aquifer interconnection and contamination.

Corrective solutions implemented to stop or confine the potential leakages can be carried out through direct well operations and work-over using patch or new casing. Injection of anticorrosion inhibitor is also a prevention method done at surface and downhole production wells in many countries, e.g. in Paris Basin and Netherland.

The sealing of the well through the whole life cycle of the well is ensured by appropriate drilling work, and more specifically cementation and casing implementation (cementation&casing in the following). During decommissioning the risk is managed through great care in conception and implementation of plugs; casing and cement need to be selected in accordance with the property of fluids along with thermal and mechanical constraints encountered.

Working with qualified professionals (driller, manufacturer, etc.) and understanding the local geological and hydrogeological context are key elements to succeed in geothermal operation and prevent environmental risks.

Main preventive solution to mitigate the risks

In the shallow few hundred meters the isolation from multilayer casing and cementation (see Figure 14) prevent the risk of aquifer connection and fluid migration. At deeper depth, with fewer casing&cementation, it is the quality of drilling practices that avoid the flaws, and the selection of materials in accordance with the property of fluids along with thermal and mechanical constraints encountered.

The main roles of cementation and casing is to:

- ensure horizontal sealing by preventing chemical aggression and corrosion of the casing;
- ensure vertical sealing in the annulus to avoid contamination and connection between overlapped aquifers or with geothermal fluid and drilling mud;
- seal and fix the casing to the surrounding formation;
- account for mechanical constraints on the casing and tubing (formation pressure, fluid pressure in the production or injection column, axial and vertical dilatation with temperature).

Anticorrosion treatments improve the aging of materials and reduce the risk of leakage due to piercing of casing and tubing. The anticorrosive materials are chosen taking into account the geothermal fluid composition and properties. In Italy, it is prohibited to use chemicals that are not naturally present in the original geothermal fluids.

Water quality controls of intersected aquifers allow to be reactive in case of contamination and take actions to contain pollutant propagation.

Water-based mud, bentonite or biopolymer-based mud are commonly used for geothermal well drilling to limit the potential effects of intrusion of drilling mud in permeable formations crossed along the well or fault zones. Oil-based muds are never used, and are prohibited in European countries, in consideration of their high potential environmental risk. Also, the density and pressure of the mud during the drilling phase is continuously monitored and kept lower than static pressure in intersected formations to prevent drilling mud intrusion.

To avoid the effects of deep blowout, formation fracture pressure is kept below the pressure at the casing shoe (see Figure 14) when pumping fluid into a well.

Corrective solutions in case of leakage (worst-case scenario)

In case of accidental and proven connection between aquifers, some actions are directly carried out on either the injection or production wells to stop the leakage and mitigate contamination, and wells are repaired.

If the connection occurs through the well casing in the injection column, the injection is immediately stopped, and the well repaired. In the worst-case scenario, the inflow rate inside the non-targeted aquifer will be limited to the artesian flow rate.

If the connection occurs in the production well, the geothermal fluid is extracted at the maximum pressure (flow rate), in order to let the fluid from the untargeted aquifer flow in the well and to avoid the contamination. If the leak is just below the well head, the contamination of shallow formations is prevented by closing the safety valve.

Depending on the severity of the damages, the wells are repaired installing patches on tubing or implementing new casing. Weak cementation is repaired with injection of high-pressure cement.

Specific case of abandoned wells

In case of abandonment, legislation enforces the use of Best Available Technologies to ensure definitive sealing between the well and avoid connection between intersected aquifers. The state of tubing in the well is diagnosed by borehole logging and tests (e.g., calibration tool, acoustic or electromagnetic logging, pressure test or tracing) (Hamm et al., 2017). When weaknesses of cementation are identified, specific repairs avoid risks during the decommissioning (removal of casing, pressurized cement injection, replacement of casing) and abandonment phases.

Multiple plugs are then installed: above permeable levels and sensitive aquifers, between liners and tubing, where diameter reductions occur, and at the top of the well, near the surface (Hamm et al., 2017). Pressure or weight tests of the plugs are carried out to control the quality of the work before ending the decommissioning operations. Illustration of well abandonment in France is given in Figure 15.

Surface operation to remove well head and plug the well should be operated with great care to avoid leakage and generate surface pollution.

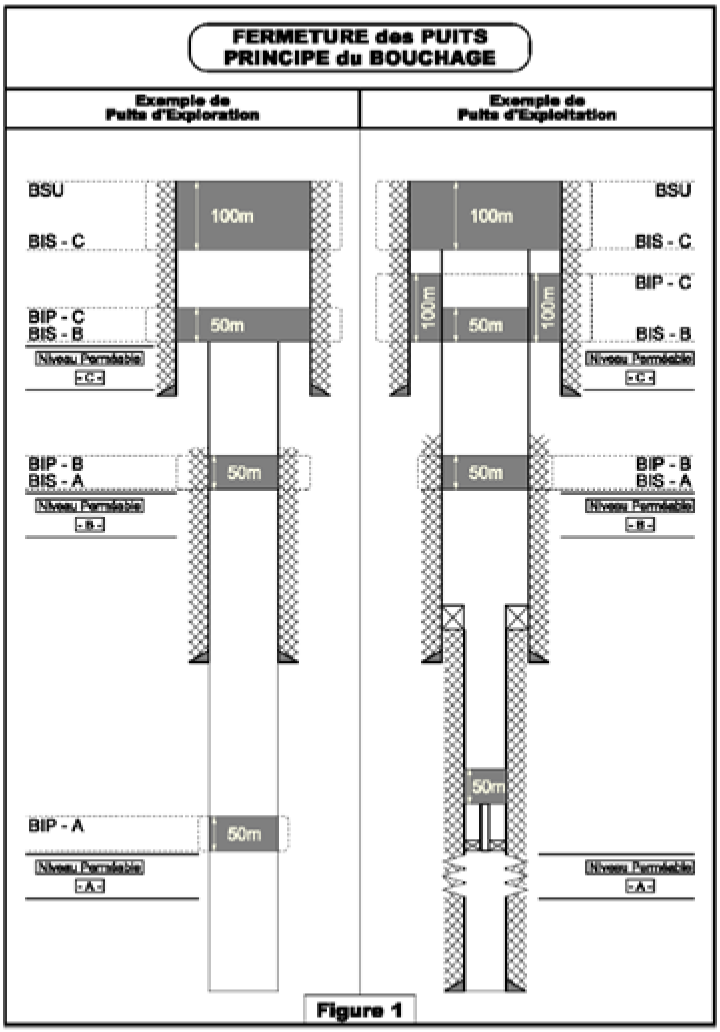

Figure 15: Example of well plugging for abandonment in a case of exploration well (left) and production well (right)

Bibliography

Galin, R., 2000. Les forages profonds: un autre après-mine ? Ann. des Mines.

Hamm, V., Bugarel, F., Giuglaris, E., Goyénèche, O., Guttierez, A., 2017. Guide de « bonnes pratiques » sur les retours d'expérience des forages géothermiques profonds, Rapport final. BRGM/RP-65443-FR.

Ravier, G., Baujard, C., Dalmais, E., Maurer, V., Cuenot, N., 2016. Towards a comprehensive environmental monitoring of a geothermal power plant in the Rhine graben. Proc. European Geothermal Congress, Strasbourg, France, 19-24 Sept 2016.

Smith, D., 1976. Cementing 1976. SPE Monogr. Publ. by Millet Printer, Inc., Dallas, Tex. 4.

Vernoux, J.-F., Degouy, M., Galin, R., 2002. Risques engendrés par les forages profonds sur nappes d'eau souterraine du bassin Seine-Normandie, Rapport final BRGM/RP-51312-.

13. THERMAL CHANGES

Synopsis

Production from geothermal reservoirs and reinjection into the reservoir may cause thermal changes, when production exceeds the natural long-term rate of thermal recharge, resulting in reservoir thermal decline, and due to the difference of inflow and in-situ fluid temperature during reinjection of fluids in the reservoir, since injected fluids can be tens of degrees cooler than reservoir.

Monitoring

Temperature logs in monitoring wells are performed regularly to monitor the temperature in the wells to evaluate thermal changes in the reservoir.

Prevention & Mitigation

Thermal decline due to geothermal fluid extraction and fluid injection can be minimized by keeping production in balance with the natural inflow of water and by careful siting of injection wells.

Results from numerical model simulations have shown that recovery of geothermal areas driven by natural forces (pressure and temperature gradients) begins after production stops (Fridleifsson et al., 2008). Production creates a hydraulic/heat sink in the reservoir, which in turn generates an inflow of fluid/heat after termination of production. The models show that recovery is fast at the beginning and then slows down. Practical replenishment (e.g. 95%) occurs on similar time scale as the lifetime of the geothermal production systems (Axelsson et al., 2005).

Bibliography

Axelsson, G., Stefánsson, V., Björnsson, G., and Liu, J., 2005. Sustainable utilization of geothermal resources for 100-300 years. Proceedings World Geothermal Congress 2005, Antalya, Turkey, April 24-29, 8 pp.

Fridleifsson, I.B., Bertani, R., Huenges E., Lund, J.W., Ragnarsson, A. and Rybach, L., 2008. The possible role and contribution of geothermal energy to the mitigation of climate change. IPCC scoping meeting on renewable energy sources. Proceedings, Lübeck, Germany, 20-25 January, 2008. 59-80.

COMMENTS AND CONCLUSIONS

A very important environmental aspect for prevention and mitigation that was not mentioned in this report is the one related to health. Geothermal development is subject to the EIA Directive, which dictates the obligation to identify, describe and assess the direct and indirect significant effects on population and human health. In the industrial developments subject to EIA, all the environmental stressors must be analysed to define their inherent hazard and the potential risk to specific habitats, living organisms and humans. Also in the case of geothermal development, the potential consequences to humans need to be addressed in the appropriate phases, foreseeing suitable management, monitoring and mitigation. Three main issues must be included when analysing the complex health domain: the health of communities living in the geothermal areas, the health of workers and the risk of accidents in geothermal plants, with all the internal and external safety measures, to be managed by local environmental protection and health agencies. Since the requirements from the European EIA Directive draw specific attention on instruments to monitor health impacts on a permanent basis, the GEOENVI project has reviewed scientific evidence related to the health of communities residing in areas with geothermal development, to identify the main areas of attention, and monitoring and remediation routines to establish effective and efficient instruments to support current management procedures in the specific field. The review underlined the lack of integrated environment-health surveillance system on the health status of communities in geothermal areas, and also its complexity, the heterogeneous and sometimes conflicting results and the difficulty to distinguish the exposure among a variety of confounding factors. A large number of studies is necessary on these aspects.

The mitigation measures described in this report represent the State of the Art of practises and technologies used in geothermal development for reducing adverse effects on the environment. However, environmental effects are not only adverse and the reader is referred to Deliverable D2.1 and Shortall et al., 2015 for a review of benign, together with adverse, effects, which include environmental as well as social (poverty, education and demographic) and economic aspects of geothermal development.
All the environmental effects analysed in this report are well documented and mitigation measures have proven to be effective, so that it is possible to keep geothermal industrial development safe and sound. Research and Innovation on these aspects is proceeding and innovative solutions are improving the environmental friendliness of the geothermal technologies.

For more detailed description of the environmental effects of geothermal development and environmental data, the reader should refer to Deliverable D2.1 of the GEOENVI Project "Report on Environmental concerns. Overall state of the art on deep geothermal environmental data".

Bibliography

Shortall, R., Davidsdottir, B., Axelsson, G., 2015. Renewable and Sustainable Energy Reviews 44, 391–406.

Terms and abbreviations

- **Abandonment (of a well):** well abandonment is the last step of a well lifecycle including well plugging, monitoring of the cement plug and testing of efficiency and well head removal. It shall isolate all permeable and prevent contamination of freshwater aquifers and leakage of any wellbore fluids to the surface.
- **Artesian flow rate**: when an well is drilled in an artesian aquifer, i.e. an aquifer surrounded by layers of impermeable rock and containing groundwater under pressure, the water in the well rises to a height corresponding to the point where hydrostatic equilibrium is reached. If water reaches the ground surface under the natural pressure of the aquifer, its flow is named artesian flow rate.
- **Binary plant**: a geothermal electricity generating plant employing a closed-loop heat exchange system in which the heat of the geothermal fluid (the "primary fluid") is transferred to a lower boiling point fluid (the "secondary" or "working" fluid). The heat causes the second liquid to turn to steam, which is used to drive a generator turbine.
- **Binary system**: a power generation system used in binary plants.
- **Biomonitoring**: in environmental sciences, any technique that uses the observation of living species to detect changes in the environment; it may involve the analytical determination of some specific parameter (e.g., heavy metals in blood) or simply the observation of appearance/disappearance of certain species or associations.
- **BOP**: Blow Out Preventer, device used to seal well to prevent uncontrolled gas or liquid eruption at the surface.
- **Casing shoe**: the bottom of the casing string or a device which is attached to the bottom of the casing string.
- **Casing and casing string**: a pipe inserted in the well to prevent the collapse of the borehole and unstable upper formations from caving in and sticking the drilling equipment.
- **Decommissioning**: removal process performed on surface equipment before well abandonment. It consists in dismantling and processing all surface installations.
- **Dry steam plant**: take high-pressure hot water from deep inside the earth and convert it to steam to drive generator turbines. When the steam cools, it condenses to water and is injected back into the ground to be used again. Most geothermal power plants are flash steam plants.
- **Doublets**: a pair of wells, one for production and the other for injection of fluids from the underground
- **EIA**: Environmental Impact Assessment.

- **Flash steam plant**: use of steam directly from a geothermal reservoir to turn generator turbines. The first geothermal power plant was built in 1904 in Tuscany, Italy, where natural steam erupted from the earth.
- **Galvanic currents**: a direct current which stimulates as the current is suddenly applied or suddenly discontinued.
- **Geomechanical disturbance**: phenomena that modify the physical properties and characteristics of the rock.
- **NCG:** Non-condensable gases.
- **NORM**: Naturally Occurring Radioactive Materials.
- **Reinjection**: underground injection of geothermal fluids, cooled after heat extraction, typically close by the extraction area.
- **Scaling**: accumulation of deposit inside the installation (pipes, heat exchangers…), as well as in wells, formed by thermodynamic or corrosion process of the geothermal fluid.
- **Stimulation**: a treatment performed to restore or enhance the productivity of a well. This treatment can be done by injecting water at a certain pressure (hydraulic stimulation), by thermal shock injecting cold water in hot rocks (thermal stimulation), or by dissolving some deposited minerals (chemical stimulation).
- **Surface operations**: consist in all operations, from the construction phase, to drilling operations and the utilization of the geothermal resource that have an impact at surface (e.g. implantation of the drill pad, maintenance of the cooling tower or well pumps).
- **TLS**: traffic light system used in protocol for seismic.
- **Well testing**: pumping or injection in wells and monitoring of pressure and temperature variation for short (few hours) or long period of time (few days) to provide information on the reservoir and its behavior or information on the fluid composition by sampling water.

APPENDIX

1. Remote data for measuring gas fluxes from the soil

Micrometeorological methods, i.e. Eddy Covariance, measures average flux exchanges over an area (called footprint) whose dimension depends on local meteorological conditions and from the height above the soil surface of the tower, where the sonic anemometer is installed. Eddy covariance is currently widely used to measure heat, water and CO_2 fluxes in many contexts, and in particular, over forests, grasslands, wetlands and tundra, but also cities. Current applications of monitoring of CO_2 emissions from satellite data are a technology still under development. Eddy Covariance provides 24h / 7 days data, but it requires skilled personnel for data acquisition and interpretation.

The applications of the Eddy Covariance method to quantify gas fluxes is widely used by the members of the ICOS research infrastructure (https://www.icos-ri.eu/ where the map of sites and all data are available) or by members of the Fluxnet network (https://fluxnet.fluxdata.org/).

2. Remote reference data for detecting ground elevation and monitoring ground deformation

Introduction

The radar interferometry approach to study surface deformation is based on the phase difference (interferogram) between SAR measurements using two principal methods: (1) Differential Synthetic Aperture Radar (SAR) Interferometry (DInSAR, Gabriel et al. 1989; Massonnet and Feigl 1998; Rosen et al. 2000; Hanssen 2001) and (2) Advanced DInSAR (A-DInSAR) based on multi-interferogram or multi-image algorithms (Ferretti et al., 2001, Bernardino et al., 2002; Werner et al., 2003; Lanari et al., 2004; Wegmuller et al., 2004; Hooper et al., 2008; Ferretti et al., 2011) that permit to follow the temporal evolution of deformation phenomena via the generation of displacement time series. These techniques allow detecting, measuring and monitoring ground deformation over large areas (»104km2) with fine spatial resolution (»102m2) and high accuracy (»1 cm; Gabriel et al., 1989). In the last years, several web-based InSAR processing (Galve et al., 2017) and cloud-based processing (Hogenson et al., 2016) were developed.

One of the first examples on the use of InSAR data for detecting surface deformation associated with geothermal production was applied to the East Mesa field in the Imperial Valley, California (e.g. Massonnet et al., 1997).

Successively, several geothermal fields have been studied using radar interferometry in California (Coso Geothermal field - Fialko and Simons, 2000; Wicks et al., 2001; Imperial Valley - Eneva et al., 2009, 2012; The Geysers - Vasco et al., 2013; Brawley - Wei et al., 2015); Nevada (Dixie Valley - Foxall and Vasco, 2003; Brady - Oppliger et al., 2004, 2006; Shevenell et al., 2012; Ali et al., 2016; San Emidio – Falorni et al., 2011; Eneva et al., 2011), Idaho (Raft river – Ali et al., 2018), Mexico (Cerro Prieto; Carnec and Fabriol, 1999; Sarychikhina et al., 2007; Mexicali Valley – Trugman et al., 2014, Sarychikhina and Glowacka, 2015, Sarychikhina et al., 2015), Ethiopia (Tendaho - Temtime et al., 2018), Iceland (Svartsengi - Jonsson, 2009; Masters, 2011; Reykjanes – Parks et al., in press), Germany (Landau - Heimlich et al., 2015; Staufen im Breisgau – Lubitz et al., 2014).

One of the main purposes of these studies on the geothermal fields under development is to infer the geometry and the behaviour of the reservoir by analysing the surficial deformation (Ali et al., 2016; Failko and Simons, 2000). These studies have assumed an elastic media to model the deformation using a change in volume or based on numerical model (Vasco et al., 2013) and to envisage the relationship between geothermal exploitation and induced seismicity risk (Trugman et al., 2014; Sarychikhina et al., 2015; Wei et al., 2015; Taira et al., 2018).

However, it has been proved that InSAR analysis can also be used during the development phase (Falorni et al., 2011) to get insights into the underground geometries and properties.

Prediction of reservoir behaviour is based on the numerical modelling of reservoir performance and requires the simulation of the complex interactions between heat and mass transfer processes and the reservoir properties (i.e., permeability and porosity), and of the geomechanical characteristics of rock. The types of models and software used to study geothermal land subsidence are well documented in the literature (Pritchett et al., 1976; Lippmann et al., 1977; Miller et al., 1980; Herd, 1985; Bodvarsson et al., 1994; Lawless et al., 2003; Yeh and O'Sullivan, 2007; O'Sullivan, 2010; Asadollahfardi et al., 2014; Koros et al., 2015).

SAR satellite description

Satellite remote sensing offers a systematic view of the Earth, thereby becoming a useful tool to improve our knowledge of the environmental phenomena over large areas with the aim to understand the history of land surface and predict possible hazards. Obviously, for an accurate ground movement analysis, the Earth Observation (EO) data must be integrated with on-site ground-based data.

In the last decades, satellite Synthetic Aperture Radar (SAR) interferometry became a most used technique to evaluating ground deformation on large areas. Synthetic Aperture RADAR (SAR) uses the different locations of the sensor, as it moves along the flight path, to simulate a large antenna from a smaller one. This enables SAR sensors to provide high resolution imagery that does not degrade with distance like traditional RADAR systems with large antennas. SAR satellites use the microwave band and work at different wavelength (i.e. frequency; Figure A1).

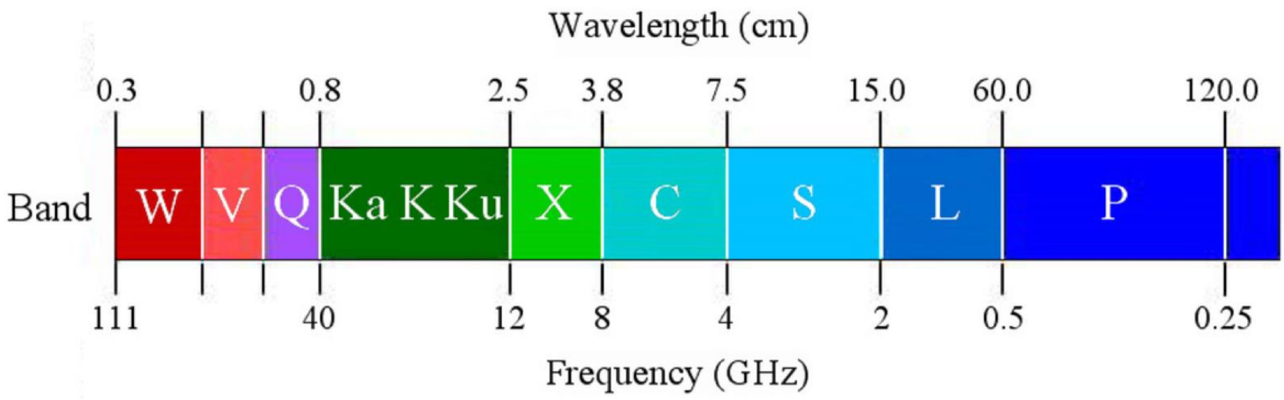

Figure A1. Band designation of microwave spectrum used for SAR (from Ouchi, 2013).

The first spaceborne SAR for Earth observation was put into orbit in 1978 on board the SEASAT satellite (Jordan, 1980). Successively, many SAR satellites were launched by different space agencies (Table A1).

Table A1. Selected spaceborne satellite for EO. SC –ScanSAR; SCN-ScanSAR near; SL – Spotlight; SM –Stripmap; WS -wide swath; HR –high resolution; N – narrow; W – Wide; S – spotlight; UF – Ultra fine; F - Fine

SAR System	Band	Polarization	Revisit time	Resolution			Operativity	Agency/Country
				Azimuth		Range		
SEAT-SAR	L	HH					1978	NASA/USA
ERS-1	L	HH	35	30		30	1991÷2000	ESA/Europe
ALMAZ-1	S	HH		15			1991÷1992	USSR
JERS-1 SAR	L	HH	44	18 (3 looks)		18	1992÷1998	NASDA/Japan
	C	HH	24	F	9	8.9	1995÷2013	CSA/Canada

RADARSAT-1				Standard	28	21-27		
				W	28	23,27,35		
				SC N	50	50		
				SC W	100	100		
ERS-2			35	6		25	1995÷2011	ESA/Europe
ENVISAT-ASAR	C	dual	35	30-1000			2002÷2012	ESA/Europe
ALOS-PALSAR	L	quad	46	Fine 1	10	7-44	2006÷2011	JAXA/Japan
				Fine 2	10	14-88		
				PL	10	24-89		
				SC	100	100		
RADARSAT-2	C	Quad	24	UF	3	3	2007	CSA/Canada
				F	8	8		
				Standard	26	25		
				Wide	26	30		
				SC N	50	50		
				SC W	100	100		
Cosmo-SkyMed (4)	X	Quad	16/8/4	SL	1	1	2007÷	ASI/Italy
				SM	3	3		
				SC	30	100		
TerraSAR-X	X	Quad	11	SL	2	1.5-3.5	2007÷	DLR/Germany

				HR SL	1	1.5-3.5		
				SM	3	3-6		
				SC	16	16		
TanDEM-X	X	Quad	11				2009	DLR/Germany
RISAT-1	C	Quad	25				2012	ISRO/India
HJ-1-C	S	HH-VV	31				2012	CAST/China
Kompsat-5	X	Dual	28	SL	1	1	2013÷	KARI/Korea
				SM	3	3		
				SC	20	20		
Sentinel 1	C	dual	6	WS	20	5	2014÷	ESA/Europe
				SM	5	5		
PAZ	X	Quad	11	SN	3	3	2014÷	Ministry of Defence/Spain
				SC	16	6		
				SL	1	1		
				HR S	<1	<1		
ALOS 2	L	Quad	14	SM	3	3	2014	JAXA/Japan
SAOCOM-1°/b	L		16/8	10		100	2016/2018	CONAE/ASI
RADARSAT costellation	C	Dual					2018	CSA/Canada

The Copernicus program (ex GMES program - Global Monitoring for Environment and Security) provides high frequency datasets of EO data. Copernicus collects data from multiple sources, processes and delivers these data. Regarding satellite SAR data, Copernicus delivers data coming from the Sentinels satellites.

Furthermore, in Italy, the "Ministry of the Environment and Protection of the Territory and the Sea" performed the "Not ordinary plan of remote sensing" through which it makes available almost for free (http://www.pcn.minambiente.it/mattm/servizio-distribuzione-dati-pst/) the PS-InSAR data (derived from the processing of ERS and ENVISAT images) throughout the national territory.

To find data:

- You can get Sentinel-1 data from scihub.esa. It requires only registration (and most likely, non-commercial use). As Sentinel-1 has just become operational, the archive is not very extensive but should grow up quite quickly.
- You can set request data-access proposal at Alaska Satellite Facility. Some data are open access. For ALOS-PALSAR you must be a resident of the United States to receive approval for data access.
- You can get data from UNAVCO SAR data archive.
- Finally, you can get data from earth.esa.int. To access these data, you must submit a project proposal. To preview scenes, use EOLi esa. ENVISAT ASAR the best option.

Bibliography

Ali S.T., Akerley J., Baluyut E.C., Cardiff M., Davatzes N.C., Feigl K.L., Foxall W., Fratta D., Mellors R.J., Spielman P., Wang H.F., Zemach E., 2016. Time-series analysis of surface deformation at Brady Hot Springs geothermal field (Nevada) using interferometric synthetic aperture radar. Geothermics 61 (2016) 114–120, http://dx.doi.org/10.1016/j.geothermics.2016.01.008.

Ali S.T., Reinisch E.C., Moore J., Plummer M., Warren I., Davatzes C., Feigl K.L., 2018. Geodetic measurements and numerical models of transient deformation at Raft River geothermal field, Idaho, USA. Geothermics, 75, 106-111.

Asadollahfardi, G., Ghanbari, A., Esmaeily, P., Hosseini, S.A.A., 2014. Application of the cylindrical model to predict subsidence at ngatamariki geothermal plant, New Zealand. J. Eng. Geol. 8 (1), 1917–1938

Berardino, P.; Fornaro, G.; Lanari, R.; Sansosti, E. A new algorithm for surface deformation monitoring based on Small Baseline Differential SAR interferograms. IEEE Trans. Geosci. Remote Sens. 2002, 40, 2375–2383.

Bodvarsson, G., Lippmann, M., Pruess, K., 1994. Modeling of geothermal systems. GRC Bull. 144–160.

Carnec, C., Fabriol, H., 1999. Monitoring and modeling land subsidence at the CerroPrieto geothermal field, Baja California, Mexico, using SAR interferometry.Geophys. Res. Lett. 26 (9), 1211–1214.

Eneva, M., Adams, D., Falorni, G., Morgan, J., 2012. Surface deformation in Imperial Valley, CA, from satellite radar interferometry. Geother. Resour. Counc. Trans.36, 1339–1344.

Eneva, M., Falorni, G., Adams, D., Allievi, J., Novali, F., 2009. Application of satellite interferometry to the detection of surface deformation in the Salton Sea geothermal field, California. Geother. Resour. Counc. Trans. 33, 315–319.

Eneva, M., Falorni, G., Teplow, W., Morgan, J., Rhodes, G., Adams, D., 2011. Surface deformation at the San Emidio geothermal field, Nevada, from satellite radar interferometry. Geother. Resour. Counc. Trans. 35, 1647–1653.

Falorni G., Morgan J., Eneva M., 2011. Advanced InSAR Techniques for Geothermal Exploration and Production. GRC Transactions, Vol. 35.

Ferretti, A.; Prati, C.; Rocca F. Permanent scatterers in SAR interferometry. IEEE Trans. Geosci. Remote Sens. 2001, 39, 8–20.

Ferretti A., Fumagalli A., Novali F., Prati F., Rocca F., rucci A., 2011. A new algorithm for processing interferometric data-stacks: SqueeSAR. IEEE Transactions on Geoscience and Remote Sensing. 49(9), 3460–3470.

Fialko, Y., Simons, M., 2000. Deformation and seismicity in the Coso geothermalarea, Inyo County, California: Observations and modeling using satellite radarinterferometry. J. Geophys. Res. 105 (B9), 21781–21793.

Foxall, B., Vasco, D., 2003. Inversion of synthetic aperture radar interferograms forsources of production-related subsidence at the Dixie Valley geothermal field.In: Proceedings of the 28th Workshop on Geothermal Reservoir Engineering,Stanford University, CA.

Gabriel, A.K.; Goldstein, R.M.; Zebker, H.A. Mapping small elevation changes over large areas: Differential radar interferometry. J. Geophys. Res. 1989, 94, 9183–9191

Galve JP, Pérez-Peña JV, Azañón JM, Closson D, Caló F, Reyes-Carmona C, Jabaloy A, Ruano P, Mateos RM, Notti D, Herrera G, Béjar- Pizarro M, Monserrat O, Bally P. Evaluation of the SBAS InSAR Service of the European Space Agency's Geohazard Exploitation Platform (GEP). Remote Sensing. 2017; 9(12):1291.

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

Herd, M.A., 1985. Mathematical modelling of subsidence at Wairakei geothermal field. 7th New Zealand Geothermal Workshop, Auckland University 139–146.

Hogenson, K., Arko, S.A., Buechler, B., Hogenson, R., Herrmann, J. and Geiger, A., 2016. Hybrid Pluggable Processing Pipeline (HyP3): A cloud-based infrastructure for generic processing of SAR data. Abstract [IN21B-1740] presented at 2016 AGU Fall Meeting, San Francisco, CA, 12-16 December.

Hooper, A. A., 2008. Multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches. Geophys. Res. Lett., 35, doi:10.1029/2008GL034654

Hunt, T. M, 2000. Five lectures on environmental effects of geothermal utilization. UNU-GTP Iceland, report 1, 109 pp.

Jonsson, S., 2009. Anthropogenic and natural deformation on Reykjanes Peninsula,southwest Iceland, observed using InSAR time-series analysis 1992–2008. EGUGeneral Assembly Conference Abstracts, vol. 11., pp. 5142.

Jordan, R.L., 1980. The Seasat—A synthetic aperture radar system. IEEE J. Ocean. Eng., 5, 154–164.

Koros, W., O'Sullivan, M., Ryan, G., 2015. Comparison of coupled one-dimensional subsidence models. In: World Geothermal Congress. Melbourne, Australia. pp. 1–10.

Lanari, R.; Mora, O.; Manunta, M.; Mallorqui, J.; Berardino, P.; Sansosti, E. A small baseline approach for investigating deformations on full resolution differential SAR interferograms. IEEE Trans. Geosci. Remote Sens. 2004, 42, 1377–1386.

Lawless, J., Okada, W., Terzaghi, S., White, P., Gilbert, C., 2003. Two dimensional subsidence modelling at Wairakei-Tauhara, New Zealand. International Geothermal Conference Reykjavík 88–94.

Massonnet, D.; Feigl, K.L. Radar interferometry and its application to changes in the Earth's surface. Rev. Geophys. 1998, 36, 441–500.

Massonet, D., Holzer, T., and Vadon, H.: Land subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry, Geophys. Res. Lett., 24 (8) (1997), 901-904.

Masters, E., 2011. Interferometric synthetic aperture radar analysis and elastic modeling of deformation at the Svartsengi geothermal field in Iceland, 1992–2010: Investigating the feasibility of evaluating reservoir pressure changes from low earth orbit (Master's thesis). University of Wisconsin,Madison, WI.

Miller, I., Dershowitz, W., Jones, K., Myer, L., Roman, K., Schauer, M., 1980. Simulation of Geothermal subsidence. Report Number: LBL-10794, Golder Associates, Inc. Consulting Mining and Geotechnical Engineers, Kirkland (Seattle), Washington 98033. Prepared for Lawrence Berkeley Laboratory, pp.160.

Oppliger, G., Coolbaugh, M., Foxall, W., 2004. Imaging structure with fluid fluxes atthe Bradys geothermal field with satellite interferometric radar (InSAR): Newinsights into reservoir extent and structural controls. Geother. Resour. Counc.Trans. 28, 37–40.

Oppliger, G., Coolbaugh, M., Shevenell, L., 2006. Improved visualization of satellite eradar InSAR observed structural controls at producing geothermal fields usingmodeled horizontal surface displacements. GRC Trans. 30, 927–930.

O'Sullivan, M.J., 2010. Geothermal fluid dynamics. In: 17th Australasian Fluid Mechanics Conference. Auckland, New Zealand. pp. 10.

Ouchi K., 2013. Recent Trend and Advance of Synthetic Aperture Radar with Selected Topics. Remote Sens. 2013, 5, 716-807; doi:10.3390/rs5020716

Parks M., Sigmundsson F., Sigurðsson, O., Hooper A., Hreinsdóttir, S., Ófeigsson, B., Michalczewska K., In press. Deformation due to geothermal exploitation at Reykjanes, Iceland. Journal of Volcanology and Geothermal Research https://doi.org/10.1016/j.jvolgeores.2018.08.016

Pritchett, J.W., Garg, S.K., Brownell, D.H., 1976. Numerical simulation of production and subsidence at Wairakei, New Zealand. Stanford Geothermal Workshop 310–324.

Rosen, P.A.; Hensley, S.; Joughin, I.R.; Li, F.K.; Madsen, S.N.; Rodriguez, E.; Goldstein, R.M. Synthetic aperture radar interferometry. Proc. IEEE 2000, 88, 333–382.

Sarychikhina, O., Glowacka, E., Mellors, R., 2007. Preliminary results of a surfacedeformation study, using differential InSAR technique at the Cerro Prietogeothermal field, BC, México. Geother. Resour. Counc. Trans. 31, 581–584.

Sarychikhina O. and Glowacka E., 2015. Spatio-temporal evolution of aseismic ground deformation in the Mexicali Valley (Baja California, Mexico) from 1993 to 2010, using differential SAR Interferometry Proc. IAHS, 372, 335–341, 2015 proc-iahs.net/372/335/2015/ doi:10.5194/piahs-372-335-2015.

Sarychikhina O. Glowacka E., Robles B., Nava A., Muzma M. , 2015. Estimation of Seismic and Aseismic Deformation in Mexicali Valley, Baja California, Mexico, in the 2006–2009 Period, Using Precise Leveling, DInSAR, Geotechnical Instruments Data, and Modeling. Pure Appl. Geophys. 172 (2015), 3139–3162

Shevenell, L., Oppliger, G., Coolbaugh, M., Faulds, J., 2012. Bradys (Nevada) InSAR anomaly evaluated with historical well temperature and pressure data. Geother. Resour. Counc. Trans. 36, 1383–1390.

Taira T, Nayak A, Brenguier F, Manga M., 2018. Monitoring reservoir response to earthquakes and fluid extraction, Salton Sea geothermal field, California. Science Advances, 2018 Jan 10;4(1):e1701536. doi: 10.1126/sciadv.1701536

Temtime T., Biggs J., Lewi E., Hamling I., Wright T., Ayele A., 2018. Spatial and temporal patterns of deformation at the Tendaho geothermal prospect, Ethiopia. Journal of Volcanology and Geothermal Research 357 (2018) 56–67

Trugman, D. T., A. A. Borsa, and D. T. Sandwell (2014), Did stresses from the Cerro Prieto Geothermal Field influence the El Mayor-Cucapah rupture sequence?, Geophys. Res. Lett., 41, 8767–8774, doi:10.1002/2014GL061959.

Vasco, D., Rutqvist, J., Ferretti, A., Rucci, A., Bellotti, F., Dobson, P., Oldenburg, C.,Garcia, J., Walters, M., Hartline, C., 2013. Monitoring deformation at the Geysers geothermal field, California using C-band and X-band interferometric synthetic aperture radar. Geophys. Res. Lett., 40, 2567-2572.

Wegmuller, U.; Werner, C.; Strozzi, T.; Wiesmann, A. Monitoring Mining Induced Surface Deformations. In Proceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium, IGARSS '04, Anchorage, AK, USA, 20–24 September 2004; Volume 3, pp. 1933–1935.

Wei S., Avouac JP, Hudnut KW., Donnellan A., Parker JW, Graves RW, Helmberger D., Fielding E., liu Z, Cappa F., Eneva M., 2015. The 2012 Brawley swarm triggered by injection-induced aseismic slip. Earth and Planetary Science Letters 422, 115–125

Werner, C.; Wegmuller, U.; Strozzi, T.; Wiesmann, A. Interferometric Point Target Analysis for Deformation Mapping. In Proceedings of the 2003 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'03, Toulouse, France, 21–25 July 2003; Volume 7, pp. 4362–4364.

Wicks, C.W., Thatcher, W., Monastero, F.C., Hasting, M.A., 2001. Steady state deformation of the Coso Range, east central California, inferred from satellite radar interferometry. J. Geophys. Res. 106 (B7), 13769–13780.

Yeh, A., O'Sullivan, M.J., 2007. Modelling subsidence in geothermal fields. 29th New Zealand Geothermal Workshop 1–9.

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