DESTRESS

Demonstration of Soft Stimulation Treatments of Geothermal Reservoirs

FINAL REPORT 2020

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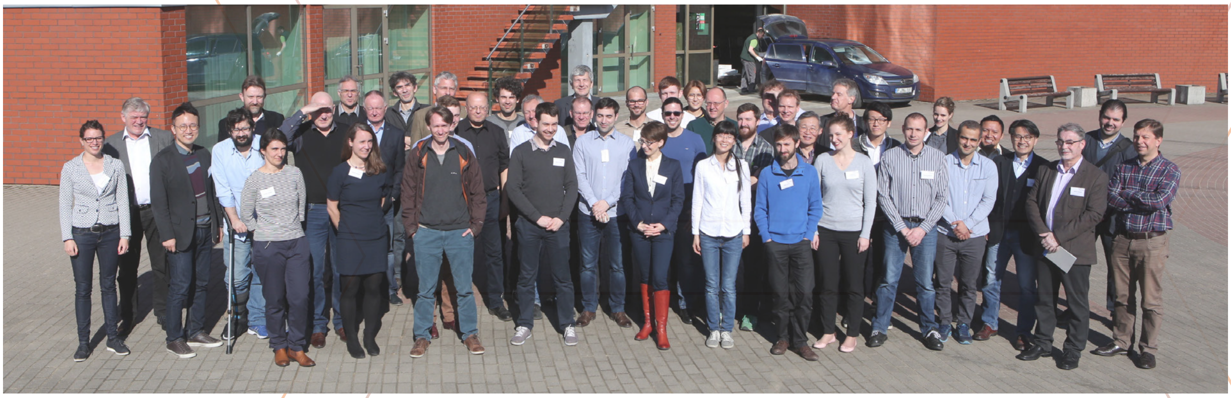
Content



Introduction

Soft stimulation is feasible, but various local conditions have to be considered

The DESTRESS project, funded by the European Commission's Horizon 2020 programme, aimed to demonstrate soft stimulation treatments of geothermal reservoirs, expand knowledge and provide solutions for the economical, sustainable and environmentally responsible exploitation of underground heat.

Geothermal heat offers a renewable source for heat and energy production. However, to exploit its potential, geothermal stimulation treatments need to be optimised for many sites while minimising negative impacts on the environment. This demands a holistic approach considering technological, economic, environmental and societal aspects – as applied within the framework of DESTRESS.

Several geothermal demonstration sites formed the core of DESTRESS and guided the main project activities. Different stimulation techniques applying hydraulic and chemical treatments were modelled, tested and/or demonstrated at sites representing magmatic, volcanic and sedimentary rocks in Soultz-sous-Forêts (France), Rittershoffen (France), Pohang (South Korea), Geldinganes (Iceland), Mezőberény (Hungary) and Bedretto (Switzerland). Other sites such as Haute-Sorne (Switzerland), Klaipeda (Lithuania), Trias Westland or Middenmeer (The Netherlands) were considered in the course of the project but had to be abandoned for various reasons.

The work conducted within DESTRESS focused on engineering geothermal reservoirs, i.e. stimulation treatment in order to enable economic use of the local geothermal system. The aim of the project was to enhance the productivity of geothermal facilities while ensuring their sustainability and respecting environmental concerns, leading to an approach defined as 'soft stimulation'. DESTRESS tested soft stimulation operations in Soultz-sous-Forêts (France), Pohang (South Korea) and Geldinganes (Iceland). For this purpose, special chemical or hydraulic stimulation was performed to minimise the potential for negative impacts. At some sites, cyclic stimulation and zonal well isolations were also applied.

Before starting any treatment, a solid and comprehensive risk assessment was conducted, taking account of environmental, technical, societal and economic aspects. To enhance the success of a stimulation, the societal as well as the geological context have to be taken into account, together with the data gained through test runs, pre-drilling measurements and close monitoring of any activity.

Dense seismic monitoring of a geothermal site is an unquestionable necessity, making it easier to observe the relevant processes in the underground in real time. Accordingly, DESTRESS also tested and further developed conventional as well as adaptive traffic light systems based on operational decisions.

Two additional demonstrations are still in preparation, a combined thermal-chemical treatment at the site in Mezőberény (Hungary) and a multi-stage stimulation in Bedretto (Switzerland) to further examine and prove the soft stimulation approach.

Currently, much of the knowledge and data on how to best stimulate the underground and run a geothermal project is not openly available. This fact is a challenging precondition for calibrating technical or economic models needed to plan and safely operate a geothermal project. The project succeeded in delivering good practice for treatments which may be useful in designing future regulatory frameworks for geothermal stimulation.

About DESTRESS

DESTRESS demonstrates methods used in enhanced geothermal systems (EGSs). The aim is to expand knowledge and to provide solutions for a more economical, sustainable and environmentally responsible exploitation of underground heat. EGSs allow the enormous untapped potential of geothermal energy to be put to widespread use. DESTRESS will improve the understanding of technological, business and societal opportunities and risks related to geothermal energy. Existing and new project sites have been chosen to demonstrate the DESTRESS concept.

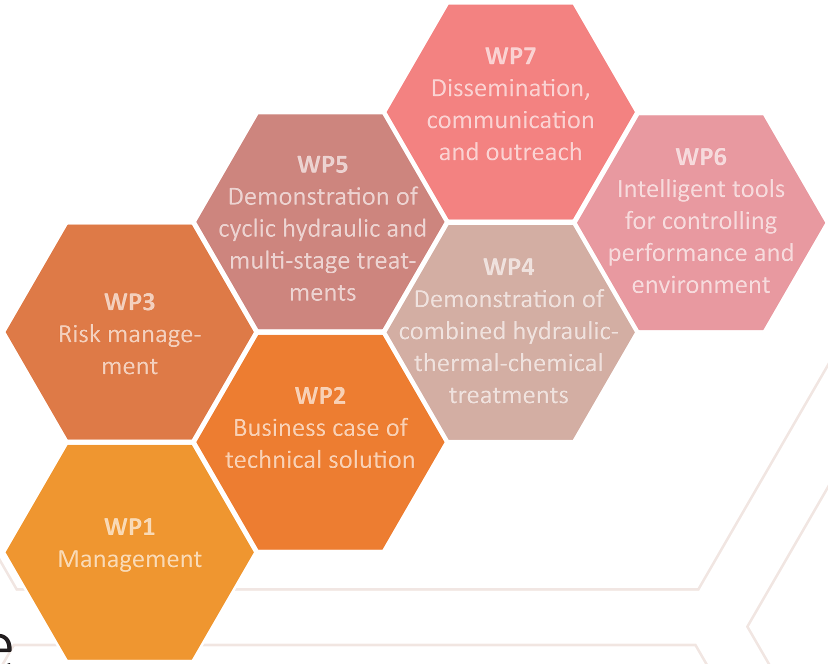
Acronym	DESTRESS
Title	Demonstration of soft stimulation treatments of geothermal reservoirs
Call	H2020-LCE-2015-2
Topic	Low Carbon Energy, LCE-03-2015: Demonstration of renewable electricity and heating/cooling technologies (IA)
Grant Agreement Number	No 691728
Duration	63 months, 01 March 2016 - 31 May 2021
Estimated Project Costs	€25,072,511.25
EU Contribution	€10,713,408.63
Project Lead	GFZ German Research Centre for Geosciences
Partners	17 European and East Asian research institutions, universities and industry representatives (large energy suppliers and SMEs)

Project Partners

DESTRESS brings together an international consortium comprising 17 partner institutions from six countries in Europe as well as South Korea. It includes major research entities that are active in geothermal research worldwide such as GFZ in Germany, ETH Zurich in Switzerland, TNO in the Netherlands and KICT in South Korea as well as universities with specialist expertise such as the University of Glasgow in the UK, TU Delft in the Netherlands, the University of Strasbourg in France and Seoul National University in South Korea.

In addition, the consortium includes geothermal industry companies that deploy or operate geothermal sites, produce geothermal electricity and provide heat in Europe and South Korea, namely EnBW and GTN in Germany, ESG in France, GES in Switzerland, GEOTERMA in Lithuania and NEXGEO in South Korea.

- Helmholtz Zentrum Potsdam (GFZ), Germany
- Energie Baden-Württemberg (EnBW), Germany
- És-Géothermie (ESG), France
- The University of Glasgow (UoG), United Kingdom
- Geo-Energie Suisse AG (GES), Switzerland
- TNO, The Netherlands
- Eidgenössische Technische Hochschule Zürich (ETH), Switzerland
- Geothermie Neubrandenburg GmbH (GTN), Germany
- Université de Strasbourg, France
- Delft University of Technology (TU Delft), The Netherlands
- NexGeo Incorporated, Korea
- Seoul National University (SNU), Korea
- Korea Institute of Civil Engineering and Building Technology (KICT), Korea
- ECW Geomanagement BV (ECW), The Netherlands
- Trias Westland B.V., The Netherlands
- Korea Institute of Geoscience and Mineral Resources (KIGAM), Korea
- Utrecht University, The Netherlands



Work Package Summaries

Achievements, Results and Challenges

DESTRESS aimed to demonstrate an enhanced geothermal system (EGS) development approach taking site-specific geological requirements into account. The DESTRESS concept was applied at several sites in order to demonstrate the concept in a variety of geological environments that are representative of large parts of Europe. In general, a soft stimulation approach was adopted; in other words, a stimulation treatment with a minimised environmental hazard. All processes included in the DESTRESS approach were designed to be transferable to other sites so that the concepts could become the basis for a standardised procedure in the development of EGS projects.

The concepts were based on experiences in previous projects, on developments in other fields, mainly the oil and gas sector, and on scientific progress made on topics such as fluid-rock interaction, enabling the application of a soft stimulation approach, more accurate determination of the stress field and the analysis of induced seismicity.

The following detailed summaries of all the scientific work packages set out the main results achieved and the challenges faced over the last four years.

Work Package
2

Business Case – Key Performance Indicator-Based Analysis

Lead Participant: EnBW

Key Points

- Integrating uncertainty information is beneficial for decision-makers.
- Identifying risk mitigation measures helps project developers and authorities.
- Publishing data from operational power plants enables further development of other techno-economic models.

Achievements and Results

Within the framework of WP2, the impact of soft stimulation on the techno-economic performance as well as on the public acceptance of a geothermal project was analysed. Conducting a techno-economic evaluation of soft stimulation allows operators of geothermal sites to evaluate the pros and cons of their planned implementation. For this purpose, a dedicated approach is needed as common cost accounting in business case calculations is insufficient to reflect the characteristics of geothermal energy production. The reason is that key technical data can vary widely and are often poorly described in early project phases. Therefore, experiences from the exploration and production sector within the oil and gas industry are applied by developing and using a Monte Carlo-based cost calculation model.

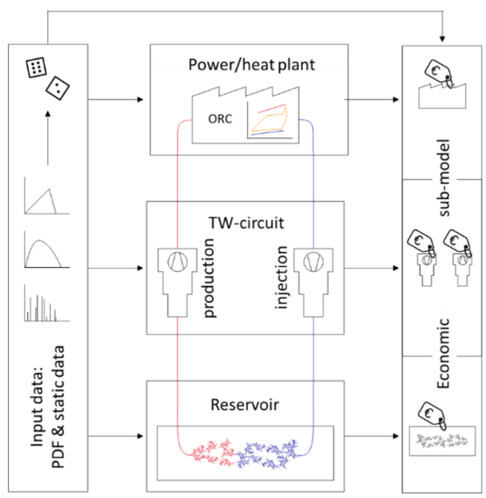


Figure 1: Model overview of the integrated geothermal energy model

The resulting integrated geothermal energy techno-economic model (see Figure 1) includes the results published in Reith, Hehn, Mergner & Kölbel (2017) and presents new development steps in techno-economic modelling. It offers decisive advantages over existing models such as EURONAUT by Heidinger (2010), GEOPHIRES by Beckers et al. (2014) or the model developed by Beckers and McCabe (2018). Additionally, it features considerable improvements compared to the integrated geothermal energy techno-economic model presented in Welter (2018). In contrast to the Organic Rankine Cycle that was calculated by Walter (2018) with a heuristic optimisation approach, the integrated geothermal energy techno-economic model of the DESTRESS project optimises the power plant with the Monte Carlo method, thereby significantly improving the technical modelling.

This newly developed DESTRESS approach is based on the model presented in Collings et al. (2016) and enlarges the solution space and thereby improves the quality of optimisation. In addition to the modelling approach, the DESTRESS techno-economic evaluation considers uncertainty in general as well as uncertainties of risk factors. Uncertainty is an inherent part of every project evaluation and concerns all life cycle steps such as exploration, appraisal, development or operation, and decommissioning. In the early phase of project development, there is considerable uncertainty surrounding the framework conditions (e.g. local geological, geophysical, geochemical, techno-economic properties, legal regimes), while during the implementation phase, risk factors such as public acceptance, induced seismicity or political instability can affect the project. Therefore, the Decision Analysis approach derived from the oil and gas business is used to integrate uncertainty into the techno-economic evaluation. The quantitative risk analysis (QRA) approach has proven to be the foundation of sound decision-making under uncertainty (Abrahamsson, 2002). Therefore, a semi-quantitative approach is used to identify and prioritise risk factors. To this end, a risk assessment workshop was held in Karlsruhe (Germany) with experts from multiple project partners from all over Europe.

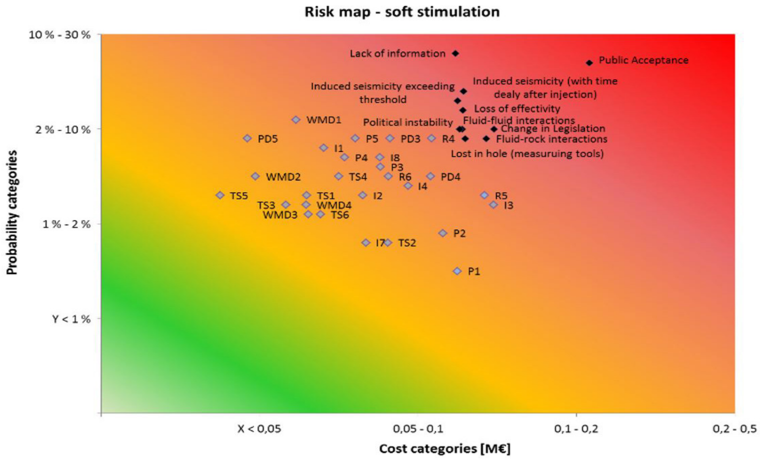


Figure 2: Risk map – soft stimulation

As a result of the workshop, 37 risk factors for future project development were identified and prioritised using a tool called a heat map (see Figure 2). A risk map is a popular tool for the prioritisation of risk factors as it enables an easy visualisation of results (Brünger, 2011). The risk map (Figure 2) shows the general classification of the identified risk factors according to expert judgement. Experts from industry and science jointly concluded that soft stimulation is already a controllable measure (i.e. pressure, flow rate, fluid volume, fluid type and injection scheme can be controlled during operations) for enhancing geothermal energy provision. Public acceptance, lack of information and induced seismicity were evaluated as being the most relevant risk factors. Together with these, the ten most important risk factors out of 37 prioritised by the experts were implemented in the DESTRESS techno-economic model. Due to the modular structure of the mod- el, additional risk factors can be easily integrated. One should not forget that risk perception depends on the actual situation. According to the experts at the risk analysis workshop, it is not only the role of a stakeholder that is important: the local, technical framework conditions (e.g. geological, geophysical, geochemical) also influence risk perception. Additionally, the results of a techno-economic evaluation are always subject to biases as they are based on the knowledge and experience of different experts, which are limited.

Finally, analyses of the costs of geothermal power plants were performed, taking into account the uncertainty caused by stimulation techniques. Experience and data from the DESTRESS stimulation sites were used in the cost analysis, but similar conditions are expected to apply to other geothermal developments around the world. In the cost analysis, the economics derived from Soultz-sous-Forêts and Rittershoffen were used; no operational expenditure (OPEX) data for the other treated sites Pohang and Geldinganes were available. It is important to note that the cost breakdown is specific to the requirement at the sites and to the given task. At the Pohang EGS site in South Korea, multiple hydraulic stimulation treatments were performed in 2016 and 2017 in the deep wells PX-1 and PX-2. No hydraulic connection was achieved between the two wells by these treatments, and the hydraulic performance of the individual wells remained uneconomical. There was no rig cost because the rig was provided by the site owner and waste disposal costs were low due to bleed-off according to the traffic light system (TLS).

A cyclic hydraulic stimulation concept was developed, targeting multiple stages with a view to boosting the productivity of well RV-43. This stimulation concept was based on a site assessment focusing on previous stimulations in the area, stress field and structural geology. The site is not yet included in a power or heat production concept. Therefore, the economics of operation could not be evaluated. Rig costs included the transport and setting of temporal liner. There were no waste management costs due to disposal in the sea nearby, the only chemical costs were for water, and packer costs were included in the stimulation treatment costs.

In the injection well (GPK-4) at Soultz-sous-Forêts, chemical stimulation was intended to increase the performance of the well. Due to concerns about the well integrity, the stimulation fluid needed to be

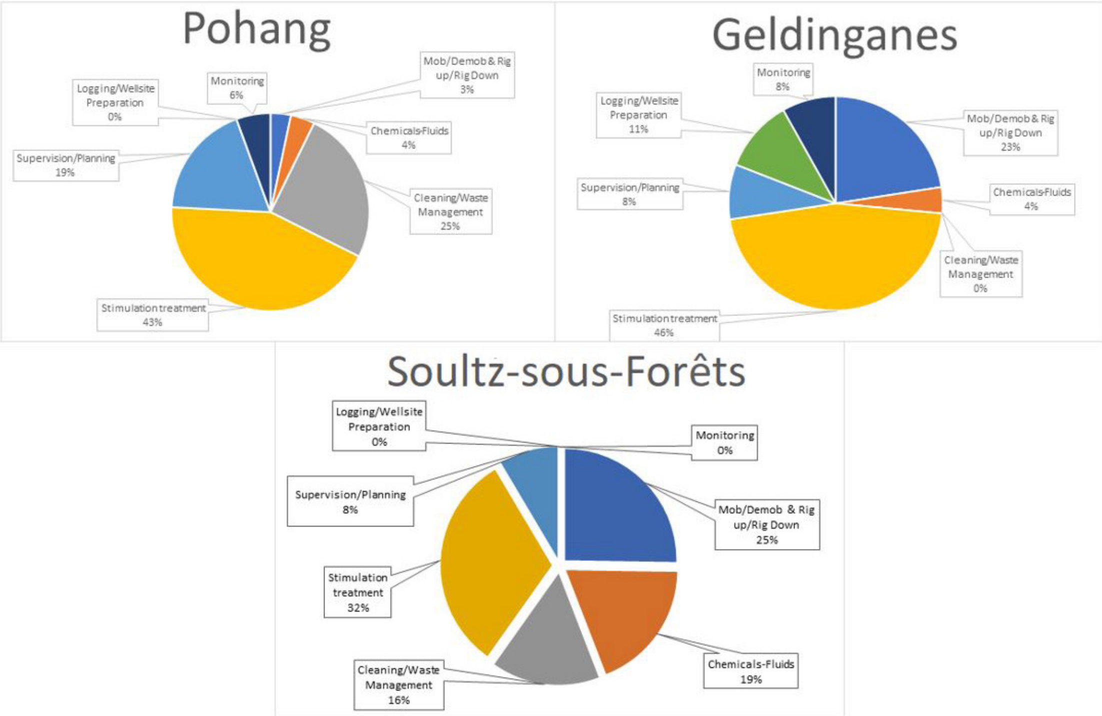


Figure 3: Stimulation investment costs at Pohang, Geldinganes and Soultz-sous-Forêts

injected downhole below a depth of 4,700 m. To perform the injection, a coiled tubing rig was mobilised. To prevent an upward flow of acid within the annulus between the coiled tubing and the casing, geothermal fluid was injected at the same flow rate from the wellhead as stimulation fluid was injected through the coiled tubing. A packer system could not be used instead. The treatment was finished late, which meant that the economics of operation could not be evaluated. There was no rig but there were coiled tubing equipment costs for this site; monitoring was done with already installed equipment. Logging costs exist but could not be provided. Figure 3 shows the stimulation investment cost categories as percentages of total investment costs for the sites in Pohang, Geldinganes and Soultz-sous-Forêts.

Difficulties and Solutions

Integrating uncertainty into the DESTRESS techno-economic model posed some challenges. The complexity of assessing the risk factors in soft stimulation was quite high and therefore the whole risk assessment process needed to be simplified. Risks are characterised by their probability distribution and their impact. Defining the data points needed for creating the probability density function for each risk proved to be demanding because of the limited data available from operational sites. In order to solve this issue, a comprehensive risk assessment workshop with different experts and a survey were conducted. Through expert election, a binominal distribution of worst-case impacts for each risk factor was created. Moreover, based on the experiences of the experts, the standard deviation of a normal distribution was applied via a target value search to determine the probability distribution and consequences of each risk factor's worst-case impact.

To improve the robustness of the risk factor assessments, acquisition of relevant data to best describe probability distributions should be explored further. In the future, additional data from real projects should be taken into account to enhance the validity of techno-economic evaluations of geothermal projects. In particular, parameters with a significant impact on the results of the technical modelling, such as heat losses, should be determined more precisely. Within the DESTRESS project, as a first step, the data from the demonstration site in Soultz-sous-Forêts, France, were used to verify the techno-economic model. Additional modelling with more real data would, however, be beneficial.

Deliverables Business Case

- D2.1 Risk and time/readiness maps of all relevant key factors
- D2.2 Key performance indicator analyses based on Monte Carlo simulation
- D2.3 Practitioner's guidelines concerning synergies and standardisation needs
- D2.4 Publications/conferences about key performance indicator-based cost analysis, synergies and standardisation needs in geothermal industry

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Risk Management Workflows for Deep Geothermal Energy

Lead Participant: ESG

Key Points

- No environmental risk analysis means no stimulation operations.
- Operators and institutions must consider the project environment through the eyes of the local population.
- New developments of deep geothermal projects must be framed by appropriate regulatory frameworks.

Achievements and Results

In the framework of WP3, different approaches for managing the risks in deep geothermal projects were examined. In particular, risks related to soft stimulations applying both chemical and hydraulic treatments, as well as risks relevant for sustainable operations like continuous reinjections (Maurer et al., 2020), were analysed. The first approach included a series of risk assessments and workflows that were developed for both soft chemical stimulation (Peterschmitt et al., 2018) and hydraulic stimulation (Grigoli et al., 2017). Such a methodology aimed to provide operators with a reliable decision tool to estimate environmental risks such as induced seismicity in consequence of reservoir operations. Thus, an adaptative traffic light system (ATLS), considering different data from real-time induced seismicity and geomechanical modelling, was developed and tested (e.g. Pohang) with real and synthetic datasets (Grigoli et al., 2018; Mignan et al., 2019).

The second approach comprised several social science studies in various countries, applying different methodologies such as surveys, focus groups, participant observation and media analyses (e.g. Chavot et al., 2018; Ejderyan et al., 2020).

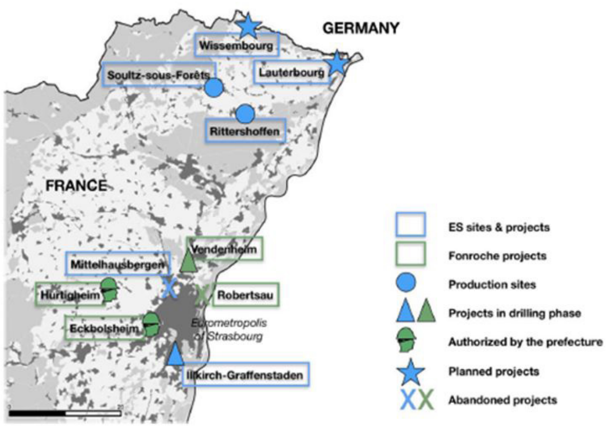

Figure 1: Map of the projects carried out in the Upper Rhine Graben as part of the social studies (Chavot et al., 2019)

Most of these studies were conducted in areas where geothermal stimulations had already been performed in the past or were embedded within the framework of DESTRESS or are planned: in France (Figure 1: Soultz-sous-Forêts, Rittershoffen, northern Alsace, Strasbourg area), in Switzerland (Basel, Geneva, Haute-Sorne, St. Gallen) and in South Korea (national survey on perception of the Pohang earthquake).

The results indicate that the perception of stimulated geothermal energy projects is influenced by a variety of factors, the main ones being:

- cultural factors (e.g. rural/urban, innovative region, tradition of mining activities, social identity);
- political factors (interrelations between institutional politics and geothermal projects);
- informational factors (how project developers engage with the public).

In addition, media analyses were conducted in France, Switzerland and the UK (Chavot et al., 2019; Ejderyan et al., 2019; Willems et al., 2020) and showed that the way the media reports about geothermal energy frames the way geothermal energy will be discussed in the public sphere. In parallel, a state of the art of the regulatory frameworks in various European countries was outlined (Chavot et al., 2019). It shows that developing an appropriate regulatory framework, mainly for induced seismicity, is still necessary as concerns about induced seismicity remain significant. However, the public's response to a project depends not only on risk perception but also on the other factors as highlighted by the case studies. Project developers must take these factors into account in order to embed their projects locally.

Finally, as part of a third approach, risk management was also studied by investigating the risk related to stimulation and sustainable exploitation of geothermal resources by using non-standard monitoring techniques. Sensors were deployed in the field to investigate the vulnerability of the neighbouring buildings during geothermal exploitation (Soultz, Rittershoffen). A set of 500 buildings was surveyed in an area of around 130 km² (Megalooikonomou et al., 2018; Pittore et al., 2018).

The study comprised fieldwork around the operational power plant of Soultz-sous-Forêts and the geothermal plant of Rittershoffen as well as experimental work and numerical modelling activities on coda wave interferometry (CWI) reproducing the mechanical and acoustic behaviour of a typical reservoir rock (Azzola et al., 2018a, b). An induced seismicity study of a fractured granite reservoir related to thermo-hydro-mechanical-chemical (THMC) stimulation and long-term exploitation of a geothermal plant in northern Alsace was also carried out (Maurer et al., 2020).

Difficulties and Solutions

Standard procedures for the risk assessment of soft stimulation at operational sites were poorly developed. Generally, it was challenging to access relevant information about real incidents. Thus, risk management mainly focused on how to build an effective risk screening approach. In order to improve applied expertise, significant efforts had been invested in enhancing best practices for reservoir stimulation under the umbrella of the existing regulatory framework. These workflows for chemical treatments and ATLS were implemented and applied to specific stimulations during the project (e.g. Pohang and Geldinganes). Additionally, as private companies own most geothermal plants, it is difficult to convince them to stimulate their geothermal wells.

First, health and safety in employment (HSE) rules for conducting a soft chemical treatment must be seriously investigated based on a risk analysis. Second, it is necessary to demonstrate to the site owner and the local mining authorities that standards and best practices for HSE, taking into account environmental protection, are considered during operations.

Then, after an in-depth environmental risk analysis, a long process of discussions and contracts between the various stakeholders (operator, site owner, mining authorities, scientists) allows these issues to be resolved (see deliverable D.3.1). Moreover, it proved more difficult than expected to obtain concrete feedback about potential structural damage generated by EGS geothermal plants from insurers due to a lack of knowledge about geothermal energy. Consequently, it was decided to start educating insurance sector representatives about EGS technology and deep geothermal energy by creating a set of guidelines entitled 'Geothermal for dummies'. However, the lack of interest from insurance companies suggested that this is not a significant issue for their business.

The creation of guidelines for governments and regulatory authorities (see deliverable D3.5 Rational guidance to governments and regulatory authorities) showed that the legislative framework is relatively heterogeneous in Europe, and good practices have to be adapted to each country.

Deliverables for Risk Management Workflows for Deep Geothermal Energy

- D3.1 A comprehensive report on risk assessment and workflow for soft stimulations
- D3.2 Workflows for seismic risk assessment for soft stimulations, based on high quality datasets
- D3.3 A risk governance strategy report
- D.3.4 An ad-hoc risk monitoring strategy report including specific recommendations for industrial geothermal projects and insurance companies
- D.3.5 Rational guidance to governments and regulatory authorities
- D3.6 Guidance to insurers
- D3.7 Academic publications and conference participations on risk monitoring and social acceptance

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Work Package

4

Demonstration of Combined Hydraulic-Thermal-Chemical Treatments in Sandstones, Carbonate Rocks and Granite

Lead Participant: UoG

Key Points

- Extensive experimental work at the lab scale
- Reservoir simulation software established and applied
- Concepts for combined hydraulic-thermal or chemical treatments in sedimentary rocks developed
- Concepts for risk assessment and management applied for a treatment at an operating site
- Extended operational experience with chemical stimulation in granitic rocks

Achievements and Results

WP4 focused on experimental work and numerical simulation at different geothermal sites to optimise the design of stimulations and to evaluate outcomes. The aim was to quantify the improvement in well performance (injectivity or productivity) resulting from a stimulation, to provide data on costs of stimulations, and to facilitate business decisions taking into account the economic effectiveness of stimulations. To this end, WP4 was part of an integrated workflow with activities closely linked to tasks in WP2 Business Case and WP6 Intelligent Tools for Controlling Performance and Environment.

This work package focused on two types of sites:

- Sites that were under development at the time of inclusion in DESTRESS (i.e. Rittershoffen and Trias Westland)
- Pre-existing sites or wells that had underperformed (i.e. Klaipeda, Mezőberény, and Soultz-sous-Forêts GPK-4).

Due to various difficulties during the implementation of the DESTRESS project (described below), only one chemical treatment has been conducted at Soultz-sous- Forêts so far. A combined thermal-chemical stimulation is planned at the site in Mezőberény in early 2021.

When DESTRESS was proposed, the Rittershoffen project to provide geothermal industrial process heat was nearing completion, and the Soultz-sous-Forêts project was in transition from a research centre to a commercial project to generate electricity using geothermal heat. Both plants were commissioned in early 2016 and have been continuously operating since then. At Rittershoffen, the natural permeability of the fractured reservoir rocks, at the contact between sandstone and underlying granite, proved to be so high that no stimulation was required in the production well. Only the stimulation data of the injection well were analysed in depth as part of DESTRESS (Baujard et al., 2017). At Soultz-sous-Forêts, by contrast, the three 5,000-m boreholes were hydraulically and chemically stimulated after drilling.

In the framework of DESTRESS, it was decided to chemically stimulate an existing injection well (GPK-4) to improve its injectivity index and thus the general hydraulic performance of the operating geothermal plant. The full work programme included several steps:

- Pre-stimulation logging programme to check the well integrity (casing, cementation) and to identify preferential zones to be stimulated
- Continuous monitoring of the geothermal fluid, evolution of injectivity index and induced seismicity
- Lab tests and modelling of effects and efficiency chemicals on granite samples
- International tendering process for the performance of the stimulation
- Risk assessment of the operation, based on the methodology developed in the framework of WP3
- On-site performance of the stimulation and subsequent monitoring of its efficiency

After a long and rather difficult tendering process, the stimulation was successfully completed within one week in late December 2019. The main challenge was to perform the stimulation in the conditions of a fully operating plant, meaning that the stimulation operations should have little or no impact on power production. In that respect, the stimulation was a success, as the power plant was not shut down during the operation, and no health, safety and environment issues were reported.

Figure 1: Soultz-sous-Forêts site after rig-up of the stimulation equipment (source: ÉS-Géothermie)

Therefore, it can be concluded that the treatment itself was a mature operation. None of the assessed risks occurred, and the operation was performed without any safety and environmental incident. The low radioactive contamination of the CT equipment by injection scaling in GPK-4 9''5/8 casing was unexpected and is viewed as one of the more important pieces of technical and environmental feedback of the operation to be considered in future projects. However, so far, no significant impact of the chemical stimulation of GPK-4 has been observed, either on hydraulic or seismic and chemical data. Many reasons could explain the poor efficiency of the acid job. Two hydraulic and three chemical stimulations were performed in GPK-4 after the drilling operations, and those past operations had probably already improved the near-wellbore permeability of the well. The recent chemical stimulation only had a limited effect on the near-well zones already stimulated. However, subsequent monitoring tentatively indicated a modest improvement in the injection performance of well GPK-4, by around 5%.

Accordingly, the near-wellbore targeted by the chemical stimulation may not be the limiting parameter of GPK-4 injectivity. The low reservoir permeability could explain the poor efficiency of the chemical treatment, as the radius of acid reaction is too small to enhance far-field reservoir permeability. On the other hand, it cannot be excluded that a positive effect of the acid treatment may be compensated by other effects such as fracture collapse, fine transport or precipitations at the wrong locations. More information is therefore required before positive decisions are reached about the treatment. Laboratory investigations are helpful but not sufficient to clear in advance the performance of the treatment. Additional logging (PLT, casing integrity log) is required to determine which potential flow zones would have been impacted by the stimulation. Standard injection and/or production tests are also needed to determine the skin effect of the well and so the near-wellbore permeability. If the skin effect is high, the chemical treatment is more likely to be effective. But it should be kept in mind that, practically speaking, such tests and logs are difficult to implement and acquire if the well is used for power plant operation.

Figure 2: Deployment of coiled tubing in the well at the Soultz-sous-Forêts site (source: ÉS-Géothermie)

DESTRESS was not able to perform the stimulation at Klaipeda. However, significant work was carried out as part of WP4 to try to understand the underperformance of the site, including analysis of core samples from the Klaipeda wells and other nearby deep boreholes. That knowledge was incorporated into the stimulation concept for the new site located in Mezőberény, which provided a new opportunity to investigate injectivity decline further. Various analyses and experiments were conducted, focusing on physical, chemical and biological processes and their interaction (e.g. Brehme et al., 2019; Brehme et al., 2020). The goal is to have a functioning injection well at the end of the project. For that, good knowledge about the borehole is needed. The stimulation cannot therefore be implemented without the prior execution of borehole measurements needed to fine-tune the concept for the chemical and thermal stimulation to follow. The first stage is both cleaning the well and conducting logging. The stimulation will be done at a later stage, based on these data.

Difficulties and Solutions

Conducting the planned treatments at these sites was subject to numerous challenges, including a lack of public acceptance, long permitting and tendering processes, and financial difficulties faced by industrial partners, which led to them halting operational works and leaving the site.

As for the long tendering processes, the process of inviting tenders from service companies for the chemical stimulation at Soultz-sous-Forêts took two rounds. Both failed because no satisfactory tender was received for a variety of reasons. The stimulation was therefore delayed. After the change of administrative leads, a new call for tenders for stimulation at Soultz-sous-Forêts started in Germany and consultation with service companies finally began. As for the financial difficulties of the operators, it was realised in summer 2017, after intense analysis of geological data within DESTRESS, that the Klaipeda geothermal project was in serious financial difficulties, due to being uncompetitive as a source of heat relative to a nearby energy-from-waste plant. Its operator therefore had to withdraw as a DESTRESS partner. Exploiting geothermal energy is usually linked to economic interests and restrictions. In consequence, operators can only afford interventions that have a great potential to pay off in the future. The intention was to perform a combined hydraulic, thermal and chemical stimulation at the Trias Westland site in the

Netherlands. For reasons of public acceptance, the developer decided just to consider a chemical stimulation, which would only go ahead if the reservoir rocks proved to have a certain natural permeability. This condition was set because, if the natural permeability were too low, the circulation through the reservoir would be insufficient. Chemical stimulation is mainly suitable for resolving near-wellbore issues rather than increasing the permeability of an entire reservoir. Furthermore, if the natural permeability were above the high end of the range, stimulation would not have been worth the added downtime and the risk of other unforeseen technical issues. After the first well at Trias Westland had been drilled in late 2017 and early 2018, the tests of rock properties revealed a very low permeability, below the minimum threshold required. The operators therefore decided to abandon the Triassic reservoir and to reconfigure the project, using the Lower Cretaceous sandstone at a depth of around 2.5 km as the reservoir. As no well stimulation was to be carried out, this site was also withdrawn from DESTRESS. After a few months, it turned out that the originally designated back-up site at Middenmeer in the Netherlands was no longer available due to excessive financial risks, so a search began for another replacement site, which further delayed the project.

In autumn 2017, the search for a replacement for Klaipeda identified a site at Mezőberény (Hungary). Extensive work had to take place to understand the site geology in detail and determine the rock properties using the core from nearby boreholes. No logging or stimulations of the well had yet been carried out to provide additional information. Consequently, the project had to be extended to facilitate geological interpretation of the Mezőberény site, to obtain data including well logs and core samples, and to learn more about the well before planning and executing the demonstration. A similar problem to that faced by the chemical stimulation at Soultz-sous-Forêts occurred when inviting tenders for the Mezőberény chemical stimulation in Germany. After a long and time-consuming public procurement process, in which the first tender process to find a service company willing and able to conduct the a priori well operation according to European safety standards proved unsuccessful, additional problems arose. These included difficulties communicating with local companies and problems with the licences required for the borehole measurement, especially a licence needed for a radioactive source for borehole logging for inspection of borehole conditions, which had to be applied for in Hungary. Not having a company with the correct and valid licence thus caused another delay. This problem was resolved but it took more time than expected. Finally, after cleaning and logging services, a service company responsible for the stimulation will perform the residual operations.

Deliverables for Demonstration of Combined Hydraulic-Thermal-Chemical Treatments in Sandstones, Carbonate Rocks and Granite

- D4.1 Detailed report on thermal, hydraulic and chemical parameters before and after the stimulation treatment (available soon)
- D4.2 Geomechanical characteristics of low-permeability sandstones in potential geothermal reservoirs
- D4.3 Detailed report on reservoir performance in terms of sustainability (every 12 months)
- D4.4 Input data on business plan

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Work Package 5

Demonstration of Cyclic Hydraulic and Multi-Stage Treatments

Lead Participant: GES

Key Points

- Demonstration of soft stimulation in Pohang (South Korea) and Geldinganes (Iceland)
- Application of conventional and advanced seismic traffic light systems
- Mitigation measures by application of cyclic soft stimulation and zonal isolation of well intervals

Achievements and Results

WP5 aimed to demonstrate cyclic and multi-stage hydraulic soft stimulation in geothermal hard rock reservoirs in order to establish sustainable operation with minimised seismic risk.

After validation at laboratory scale, the cyclic soft stimulation concept was demonstrated for the first time in August 2017 in a field-scale experiment at the Pohang enhanced geothermal system (EGS) site in South Korea, with an injected volume of less than 2,000 m^3. With a maximum moment magnitude of 1.9, seismicity stayed below the target threshold during the treatment. In October 2019, a second field-scale demonstration experiment was performed in the abandoned well RV-43 on the Geldinganes peninsula in Reykjavik (Iceland), with an injection volume of more than 20,000 m^3. Zonal isolation by inflatable packers in open hole and casing was successfully applied. The injectivity of the well was pressure-dependent and could be increased by a factor of up to three. Related maximum seismic moment magnitude during stimulation was 0.05 and hence could not be felt by the public. For the first time, an adaptive seismic traffic light system was applied during this experiment.

After laboratory tests of different packer systems at the beginning of the project, the multi-stage stimulation concept will be tested in the Bedretto Underground Laboratory, Switzerland.

Demonstration field experiment at Pohang

Large-magnitude fluid-injection induced seismic events are a potential risk for geothermal energy developments worldwide. One potential risk mitigation measure is the application of cyclic injection schemes. After validation at small (laboratory) and meso (mine) scale, the concept has now been applied for the first time at field scale at the Pohang EGS site in South Korea.

From 7 August to 14 August 2017, a total of 1,756 m^3 of surface water was injected into the Pohang well PX-1 at flow rates between 1 and 10 $l\ s^{-1}$, with a maximum wellhead pressure (WHP) of 22.8 MPa. The injections followed a site-specific cyclic soft stimulation schedule and were subject to a traffic light system. A total of 52 induced seismic events were detected in real-time during and shortly after the injection, the largest measuring Mw 1.9. After that event, a total of 1,771 m^3 of water was produced back from the well over roughly one month. During this time, no larger magnitude seismic event was observed.

The hydraulic data set exhibits pressure-dependent injectivity increase with fracture opening between 15 and 17 MPa WHP, but no significant permanent transmissivity increase was observed. The maximum magnitude of the induced seismicity during the stimulation period was below the target threshold of Mw 2.0, and further knowledge about the stimulated reservoir was gained. Additionally, the technical feasibility of cyclic injection at field scale was evaluated. The major factors that limited the maximum earthquake magnitude are believed to be: limiting the injected net fluid volume, flow back after the occurrence of the largest induced seismic event, using a cyclic injection scheme, the application of a traffic light system, and including a priori information from previous investigations and operations in the treatment design.

Demonstration field experiment at Geldinganes

A second cyclic hydraulic stimulation concept for a target-oriented and safe multi-stage productivity increase of well RV-43 was developed at Geldinganes near Reykjavik (Iceland). This stimulation concept was based on a site assessment with a focus on previous stimulations in the area, existing stress fields and structural geology. Critical for the success of the project was the isolation of new stimulation targets from previously stimulated high-permeability zones. Due to the proximity of the well to the city of Reykjavik, particular emphasis was placed on seismic risk assessment and mitigation (together with WP6).

Figure 1: Drill site during the stimulation of well RV-43 on Geldinganes in Reykjavik, Iceland (photo: Vala Hjörleifsdóttir)

The risk mitigation measures taken include the application of the cyclic soft stimulation concept, multi-stage stimulation, monitoring of the injection volumes and energies, real-time seismic monitoring, a conventional seismic traffic light system and an advanced seismic traffic light system.

The stimulation treatment in the abandoned well RV-43 in Geldinganes was performed in October 2019. Operational work started with reaming/cleaning the well and a subsequent borehole logging. Several borehole measurements (temperature, caliper, gamma-ray, neutron and BHTV) were performed in different sections of the well to set the packers properly, since the proposed stimulation treatment included zonal isolation of reservoir sections followed by a multi-stage stimulation. The borehole conditions imposed some limitations, so a slotted liner was installed to by-pass the sections where the tools got stuck.

The seismic monitoring system was completely installed in August 2019 in cooperation with ISOR, OR, GFZ and ETH Zurich. The traffic light system was set up together with Reykjavik Energy (OR). In parallel, an advanced traffic light system was installed by ETH Zurich and was adjusted with new incoming data from the stimulation stages in near real time. In total, approximately 20,000 m^3 of water was injected at three different intervals, isolated by packers. Only a few seismic events were registered during the stimulation in the deepest part of the well, with a maximum moment magnitude of Mw -0.1.

Difficulties and Solutions

At the Pohang site, the occurrence of a Mw 5.5 earthquake on 15 November 2017 led to an immediate suspension of the project and prevented access to the site. After a year-long study, the international expert commission appointed by the Korean government concluded that the Pohang earthquake was triggered by hydraulic stimulations at PX-2. This is the second well, which had not been used for the DESTRESS injections. The damaging earthquake posed a major challenge to the DESTRESS community and led to various research activities. The findings have been published in several scientific articles. However, many questions remain open and are being further investigated, e.g. the relationship between the injection volume and the maximum magnitude or the operation and use of advanced traffic light systems. Due to the suspension of the Pohang project, an alternative site was required to carry out the stimulation treatments.

The abandoned well RV-43 in Geldinganes near Reykjavik (Iceland) was chosen to test the soft stimulation concepts for the second time and the zonal isolation of well intervals. The challenges posed by the Geldinganes site are related to operational constraints. Since the well was drilled in 1990, the borehole conditions are difficult due to breakouts and cavities at several intervals. These limited access, affected the quality of borehole measurements and made it harder to set the packers at correct intervals.

In consequence of the Pohang earthquake, the Haute-Sorne project (Switzerland) was also halted by the authorities pending further investigation. As an alternative for testing the multi-stage stimulation, the Bedretto Underground Laboratory (Switzerland) was selected, which was a positive outcome after a long search for a suitable fall-back option. Unfortunately, this change of site impacted the project negatively as it slowed project activities and delayed the planned treatment, which is now scheduled for early 2021.

Deliverables for Demonstration of Cyclic Hydraulic and Multi-Stage Treatments

- D5.1 Description of individual completion elements required to segment EGS reservoir section,
- D5.2 Demonstration of reservoir treatment (cyclic stimulation) and long-term performance of energy production
- D5.3 Demonstration of multi-stage reservoir treatment and long-term performance of energy production (pending)
- D5.4 Report on ways and methods to lower the technical, geological and financial risks currently associated with EGS

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Work Package
6

Intelligent Tools Controlling Performance and Environment

Lead Participant: TNO

Key Points

- A reliable conceptual model of the site geology is crucial for the assessment of the technical feasibility and the risks associated with soft stimulations.
- Investments in well tests, pre-drilling measurements and monitoring will significantly enhance the probability of a successful stimulation.
- Adaptive traffic light systems (ATLSs) incorporating fast probabilistic models, data assimilation and monitoring are key to effective and safe stimulations

Achievements and Results

Predictive modelling and on-site monitoring are essential to ensure the success of hydraulic and chemical stimulations of geothermal reservoirs. Predictive models enable the possibilities for reservoir improvement to be assessed and thus can be used to pinpoint the most likely causes of failure. We developed and applied a suite of predictive models for the assessment of the effectiveness and risks of chemical and hydraulic stimulations of geothermal wells. Numerical coupled models were used to improve the understanding of the key physical processes in the hydraulic and chemical stimulations (Candela et al., 2019). We used these models to investigate the driving mechanisms for changes in hydraulic aperture of fractures during the Pohang EGS hydraulic stimulation, and to analyse the relative contribution of hydraulic jacking and shearing to enhance the reservoir permeability. In addition, these models were used to disentangle the driving mechanisms of induced and triggered seismicity at the Pohang EGS site (Grigoli et al., 2017; Hofmann et al., 2018, 2019; Wassing et al., 2019, 2020).

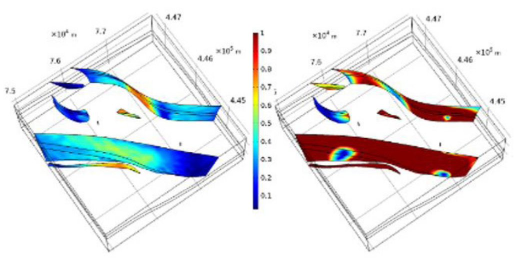

Figure 1: Evolution of SCU (shear capacity utilisation) at the onset (left) and after 30 years (right) of geothermal production. SCU is a measure of fault stability; faults are reactivated at SCU=1.

Coupled numerical models (see Figure 1) can highlight key processes driving permeability increase and seismicity, which can then be captured in fast semi-analytical models. These fast models enable probabilistic assessment of the effectiveness and risks of soft stimulations, accounting for uncertainties in rock properties and subsurface conditions (Fokker et al., 2019, 2020). Fast models were used for seismic risk analysis before the start of and during the hydraulic stimulation at Geldinganes, Iceland.

Coupled flow and fault reactivation models developed in the framework of WP6 combined with financial/economic insights derived from WP2 were used to optimise the geothermal business case, based on closed-loop reservoir management. Well location and production strategies were optimised for a sandstone reservoir reflecting the characteristics of Triassic sandstones in the Netherlands. Dual objective optimisation schemes were implemented to maximise geothermal production whilst keeping the amount of seismicity within predefined bounds (Van Wees et al., 2020).

New techniques and workflows were tested and defined to characterise rocks in terms of chemical composition and flow characteristics. In addition, X-CT analysis was used to determine porosity and presence of clay minerals and carbonate cement blocking pore space within sandstones, as analogues of the Klaipeda sandstone reservoir. SEM (scanning electron microscope) images of sandstone thin sections were analysed to determine mineralogy and accessible surface areas (Ma et al., 2017). These techniques and workflows provided valuable input data to coupled thermo-hydro-chemical models for assessing the effectiveness of chemical stimulations (see Figure 2). Numerical tools were used to extrapolate experimental results on the porosity-permeability relationship, for example.

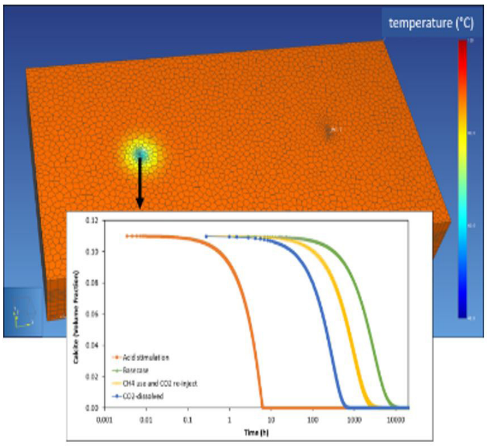

Figure 2: Coupled thermo-hydro-chemical models were used to model the dissolution of calcites and evolution of porosity during acid stimulations.

We sketched best practices for cost-effective technical performance, environmental monitoring and data analysis, with particular emphasis on monitoring of seismicity and subsidence (Grigoli et al., 2018; Henninges et al., 2019; Paap et al., 2020; Raab et al., 2019). For this purpose, we developed and tested real-time monitoring tools for seismicity monitoring, data analysis and risk mitigation, which are integrated into an adaptive traffic light system (ATLS). This ATLS can be used to mitigate seismic risk during soft hydraulic stimulations. Following our best practices, we designed a seismic monitoring network for the Geldinganes EGS site, including a real-time data analysis system, which was tested and evaluated during hydraulic stimulation.

Difficulties and Solutions

When developing our predictive models, we were confronted with a limited amount of data and significant geological uncertainty. Lessons learnt from the Pohang and Klaipeda demonstration sites showed that it is crucial to have a reliable conceptual model of the structural geology of the site, in terms of lithological composition and mineralogy, presence of (sealing) faults, stress regime, background seismicity and operational history of the wells. Moreover, we have to define which particular data, measurements and criteria are generally needed during different stages of a stimulation, from the pre-drilling design phase to the actual stimulation phase, to decide whether or not to continue with stimulation.

Uncertainties in geological data should be quantified and addressed in a probabilistic way, such as performed in case of seismic risk assessment for the hydraulic stimulation in Geldinganes, Iceland. Experiences from projects such as Pohang show that a thorough analysis of all wellbore data is needed, as it can provide valuable information, for example, on the presence of a fault near to or intersecting the injection wells. The well tests performed before the actual stimulation can give valuable insights into the scope for improving permeability, but also valuable information on the presence of sealing faults, for example.

Our experience shows that such information, though recognised in hindsight, can easily be missed. Background seismicity monitoring and seismic monitoring during well injection tests before the actual hydraulic stimulation can give insights into the seismic response of the subsurface but are not common practice yet. Though some standard protocols for well testing exist, standard protocols for testing the seismic response of the subsurface are not yet available. Therefore, setting up such a standard protocol may be very useful. As thermal, hydraulic and chemical stimulations may be crucial for the development of deep geothermal reservoirs, underlying mechanisms of stimulations need to be further understood.

A wide range of modelling tools is available, capturing different aspects of the underlying mechanisms and processes – whereas dominant mechanisms of soft stimulations are not yet fully understood. In due time, with the increasing availability of data and observations, models can be further tested and validated against data. Even then, 'history-matching' our models against the data showed that more than one model or set of input parameters could explain the data. This means that, in addition to field observations, we will need controlled experiments, both small-scale in the laboratory and medium-scale controlled field experiments like the Bedretto Reservoir Project in Switzerland, to learn which mechanisms are most relevant and should be captured in our models.

Finally, predictive models should not be used on a stand-alone basis: fast probabilistic models, data assimilation techniques and cost-effective monitoring strategies need to be further integrated into ATLSs.

Deliverables for Intelligent Tools Controlling Performance and Environment

Best practice workflows and tools for (design of):

- D6.1 soft chemical/acid stimulation
- D6.2 soft hydraulic stimulation
- D6.3 technical performance monitoring and control
- D6.4 environmental performance monitoring and control
- D6.5 optimisation of the business case, based on optimised reservoir management and operation

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Demonstration Sites

Operational Demonstration Sites, Fall-Back Options and Stopped Sites

DESTRESS aimed to demonstrate an EGS development approach, taking site-specific geological requirements into account. The DESTRESS concept was applied at several sites in order to demonstrate the concept in a variety of geological environments that are representative of large parts of Europe. Those geothermal demonstration sites formed the core of DESTRESS and guided the main project activities. In general, a soft stimulation approach was adopted; in other words, a stimulation treatment with minimised environmental hazard. In all cases, risks were managed at each site, with a demonstration of the reduced environmental footprint, and lessons learnt were disseminated to the public. All steps included in the DESTRESS approach were designed to be transferable to other sites so that the concepts could become the basis for a standardised procedure in the development of EGS projects.

The concepts were based on experience in previous projects, on developments in other fields, mainly the oil and gas sector, and on scientific progress made on topics such as fluid-rock interaction, enabling the application of a soft stimulation approach, more accurate determination of the stress field and the analysis of induced seismicity.

On the following pages, we present six DESTRESS demonstration sites: Soultz-sous-Forêts (France), Rittershoffen (France), Pohang (South Korea), Geldinganes (Iceland), Mezőberény (Hungary) and Bedretto (Switzerland). Other sites such as Haute-Sorne (Switzerland), Klaipeda (Lithuania), Trias Westland and Middenmeer (The Netherlands) were considered in the course of the project but had to be abandoned for various reasons. Further information about the DESTRESS demonstration sites can be found on the DESTRESS website.

Geldinganes, Iceland

Geldinganes is a peninsula within the city limits of Reykjavik in Iceland. The exceptional geothermal gradient in this area allows economical heat production for the district heating system of the city of Reykjavik, provided the wells deliver sufficient flow rates. Within the framework of DESTRESS, cyclic injection schemes were applied at multiple stages to increase the productivity of the well. In addition to the existing microseismic monitoring system, the stimulation treatment was monitored closely with an extended network consisting of instruments from three different DESTRESS partners.

In addition to a conventional seismic traffic light system, the advanced traffic light system, developed within the framework of DESTRESS, was applied for the first time in real time at Geldinganes.

More information

Bedretto, Switzerland

In the framework of DESTRESS WP5, the Bedretto demonstration site in Switzerland is the fall-back option replacing Haute-Sorne, Switzerland. It aims to show that the multi-stage stimulation concept is feasible in granitic rocks. The underground laboratory is located in granitic rocks at an approximate depth of 1.1 km below the surface, in the middle of a 5.2-km tunnel connecting the Bedretto Valley in the canton of Ticino with the Furka Tunnel. Its location was chosen because enough crystalline rock volume can be accessed to create a reservoir with similar characteristics to a deep underground environment, except for the temperature, which in Bedretto remains constant at 17 °C.

Between 14 January and 7 February 2020, a DESTRESS-led stimulation treatment was performed in the Bedretto Underground Laboratory. It aimed to assess the feasibility of stimulating fractures in a short borehole section of 10 m to permanently increase their transmissivity. A multi-stage stimulation in Bedretto (Switzerland) to further examine and prove the soft-stimulation approach is still under preparation.

More information

Pohang, South Corea

The site is located in the Heunghae Basin covered by Tertiary sedimentary rocks and quaternary alluvium. Underneath the sedimentary rocks lies a sequence of andesites and crystal tuffs, with a Paleozoic granodiorite basement below 2.4 km. There are two deep boreholes, PX-2 and PX-1. Four medium-depth boreholes (BH-1 to BH-4) and one exploration borehole (EXP-1) exist nearby.

Five hydraulic stimulations were conducted from January 2016 to September 2017. Two months after the fifth hydraulic stimulation, the Mw 5.5 Pohang earthquake occurred on 15 November 2017. After a year-long study, the government-appointed commission concluded that the Mw 5.5 earthquake had been triggered by the hydraulic stimulations. Numerous studies are currently being conducted to ascertain a causal linkage and triggering mechanism, to perform refined seismic analysis and to identify what lessons can be learnt from this unprecedented event and the EGS project. The Pohang EGS project was suspended right after the Mw 5.5 earthquake in 2017 and officially terminated in April 2019. Currently, no geothermal operation is taking place at the site.

DESTRESS stopped its research activities at Pohang in 2018.

More information

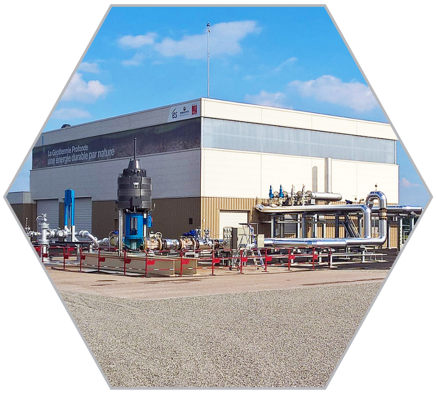
Mezőberény, Hungary

The Mezőberény Geothermal Demonstration Plant is a geothermal heating plant with two wells, belonging to the City of Mezőberény. It is located in the south-east of Hungary in the middle of Békés County. There is a long tradition in Hungary of utilising the geothermal potential of the Pannonian Basin. The main aquifers are karstified Mesozoic rocks and Pannonian sandstones. However, injection into the sandstones has a relatively short history in Hungary.

The Mezőberény geothermal site was constructed in 2011–12, with the aim of harnessing the geothermal potential in the Békés Basin for district heating. The system consists of one production well (B-115) with a depth of 2,003 m, and one reinjection well (K-116) with a depth of 2,001 m. After three weeks of operation, injectivity radically dropped, which led to operation being suspended. In 2017, a mechanical and chemical cleaning campaign was carried out to remove clogging material, but a long-term solution to boost injectivity has not yet been found (Siklósi, 2017).

More information

Rittershoffen, France



Since 2016, the Rittershoffen geothermal heat plant has been producing 25 MWth of heat at high temperature with an availability in excess of 90%. In the framework of DESTRESS, many geoscientific data related to previous thermal, chemical and hydraulic (TCH) stimulations conducted in the first geothermal well GRT-1 were interpreted in detail and published in open access journals. The main findings were that the combined TCH stimulations improved the well injectivity by a factor of four, mainly due to the occurrence of a large, fractured zone located in the granite reservoir. In parallel, non-standard risk monitoring close to the geothermal plant was conducted to evaluate the structural vulnerability of buildings located near the site.

Finally, detailed monitoring of induced seismicity relating to various development phases of the injection well was analysed. The development of the Rittershoffen geothermal reservoir was associated with unfelt seismicity, even though more than 1,300 induced events were reported. Because of the growing geothermal activity in this part of the Upper Rhine Graben, regulations had to evolve to take into account induced seismicity and geodetic monitoring for regulating the exploitation of deep geothermal. Operators of geothermal plants were therefore asked to carry out the required environmental monitoring.

More information

Soultz-sous-Forêts, France

The geothermal power plant of Soultz-sous-Forêts has been producing 1.7 MWe of gross power since 2016. The geothermal fluids discharged from one production well, GPK-2, are simultaneously reinjected into two other deep reinjection wells, GPK-3 and GPK-4, within a deep crystalline fractured reservoir. In the framework of DESTRESS, a soft chemical stimulation methodology, including risk assessment, was defined and applied for enhancing the hydraulic performance of well GPK-4. A chemical treatment was thus designed, using innovative chemicals that can dissolve secondary minerals sealing the natural fractures.

To focus the treatment, an innovative methodology was applied whereby the chemicals were injected via coiled tubing at great depth (5 km). Despite the stimulation performed on the GPK-4 well, the impact of the chemical treatment on well injectivity was quite low, and no real hydraulic improvement was observed.

More information

Event Timeline

The history of DESTRESS at a glance

2016	07 March	DESTRESS kick-off and first General Assembly, Utrecht (Netherlands)
	08-09 March	DESTRESS at the Geothermal Meeting of EU-funded projects, Utrecht (Netherlands)
	11 March	Site visit to geothermal power plants, Strasbourg (France)
	21 March	Internal technical workshop for WP3 (Risk Management Workflows), Strasbourg (France)
	11-12 April	Internal workshop on stimulation and monitoring at Pohang, Potsdam (Germany)
	07 June	Inauguration of the Rittershoffen geothermal plant, Strasbourg (France)
	04-08 July	First DESTRESS workshop for international stakeholders, Seoul (South Korea)
	12-13 July	DESTRESS workshop on identification of risks for soft stimulation, Karlsruhe (Germany)
	01 September	Internal progress meeting for all WPs, Potsdam (Germany)
	22 September	DESTRESS at the European Geothermal Congress (EGC) 2016, Strasbourg (France)
	22 September	Kick-off meeting for the Executive and Advisory Board, Strasbourg (France)
	23 September	Site visit to geothermal power plants during EGC 2016, Strasbourg (France)
	10-16 November	Site visits to geothermal plant, Pohang (South Korea)
	23 November	Internal technical workshop for WP4 (Demonstration of Combined Hydraulic-Thermal-Chemical Treatments), Strasbourg (France)
	12 December	Internal technical workshop for WP3 (Risk Management Workflows), Strasbourg (France)
	20 December	Joint technical workshop for WP4 (Demonstration of Combined Hydraulic-Thermal-Chemical Treatments) and WP6 (Intelligent Tools for Controlling Performance and Environment), Utrecht (Netherlands)
2017	26-27 January	Internal technical workshop on social acceptance in geothermal, Strasbourg/ France
	09 February	Internal technical workshop on stimulation at Soultz-sous-Forêts for WP4 (Demonstration of Combined Hydraulic-Thermal-Chemical Treatments), Strasbourg (France)
	15 February	DESTRESS at GeoTHERM 2017, Offenburg (Germany)
	14-17 February	Second induced seismicity workshop, Davos (Switzerland)
	03-06 April	Second DESTRESS General Assembly, Klaipeda (Lithuania)
	04 April	Second meeting of the Executive and Advisory Board, Klaipeda (Lithuania)

2017	05 April	Joint geothermal workshop for DESTRESS and SURE, Klaipeda (Lithuania)
	06 April	Site access programme, Klaipeda (Lithuania)
	Late April	Suspension of operational activities at Klaipeda due to financial problems of the site owner
	22-24 May	DESTRESS at the International Geothermal Congress, Izmir (Turkey)
	15 June	Internal technical workshop for WP5 (Demonstration of Cyclic Hydraulic and Multi-Stage Treatments), Potsdam (Germany)
	19 June	DESTRESS at the H2020 Coordinators' Workshop on Geothermal Energy, Brussels (Belgium)
	07-14 August	First hydraulic soft stimulation of PX1, Pohang (South Korea)
	23 August	Visit to the potential demonstration site in Mezőberény (Hungary) owned by the local authority Mezőberény Város Önkormányzata
	12-14 September	DESTRESS at the German Geothermal Congress, Munich (Germany)
	11-14 October	Joint event by DESTRESS and DEEPEGS during the European Geothermal Workshop in Karlsruhe (Germany), and site access programme, Soultz-sous-Forêts and Rittershoffen (France)
	06 November	Start of drilling at Trias Westland (Netherlands)
	15 November	Site visit for local residents, Strasbourg (France)
	30 November	First DESTRESS review meeting with the European Commission, Rotterdam (Netherlands)
	30 November	Site access programme, Trias Westland (Netherlands)
2018	January	Suspension of operational activities at Pohang after the earthquake
	25 February	Second internal technical workshop for WP6 (Intelligent Tools for Controlling Performance and Environment), Utrecht (Netherlands)
	February	Withdrawal of the Trias Westland site from DESTRESS due to the low probability of a successful stimulation in the well
	14 February	DESTRESS at the Stanford Geothermal Workshop (USA)
	02 March	Second DESTRESS workshop at GeoTHERM, Offenburg (Germany)
	03 April	Third DESTRESS General Assembly, Glasgow (Scotland)
	03-05 April	DESTRESS Mid-term Conference, Glasgow (Scotland)
	May	Inclusion of Mezőberény and Bedretto as new DESTRESS demonstration sites, replacing Trias Westland and Pohang
	11 June	Site visit for engineers and managers of major oil and gas companies, Strasbourg (France)
	18 June	DESTRESS at Geothermal Project Cluster Event, Brussels (Belgium)
	27-28 August	Visit to the potential demonstration site at Geldinganes (Iceland)
	17-19 September	DESTRESS Pohang workshop in Zurich about the Mw 5.5 earthquake and potential connection to Pohang activities
	18 September	Information event about the Bedretto Lab for local residents, Bedretto Valley (Switzerland)
	20 September	Executive Board meeting, Zurich (Switzerland)
	14 October	DESTRESS at the Geothermal Resources Council Annual Meeting, Reno (USA)

2019

18-20 January	Fourth DESTRESS General Assembly, Strasbourg (France)
27 February	Site visit for participants of the European Geothermal PhD Day 2019, Groß Schönebeck (Germany)
March	Inclusion of Geldinganes as a new DESTRESS demonstration site, replacing Pohang
30 April	H2020 Risk Assessment Workshop at GFZ, Potsdam (Germany)
8 May	Internal workshop on cyclic stimulation, Geldinganes (Iceland)
13-14 May	Inauguration of Bedretto Underground Laboratory, Bedretto Valley (Switzerland)
17-18 May	Internal workshop on risks related to stimulation at Mezőberény, Potsdam (Germany)
28 May	DESTRESS at the European Geothermal Congress, The Hague (Netherlands)
June	Site visit for a delegation from the Swiss National Science Foundation (SNSF), Bedretto Valley (Switzerland)
18 June	Site visit for media, Bedretto Valley (Switzerland)
4 July	Hydraulic stimulation of RV-43, Geldinganes (Iceland)
11 Oct - 01 Nov	DESTRESS at Geothermal Cluster Workshop, Brussels (Belgium)
16-23 December	Stimulation of well GPK-4 at Soultz-sous-Forêts (France)

2020

20 January	Site visit for ETH professors, scientists and students, Bedretto Lab (Switzerland)
20-22 January	Final DESTRESS General Assembly, Delft (Netherlands)
29 February	Completion of DESTRESS research activities in WP2 (Business Case), WP3 (Risk Management Workflows), WP6 (Intelligent Tools for Controlling Performance and Environment) and WP7 (Dissemination, Communication and Outreach)
March - October	Planning and execution of soft stimulation at Mezőberény (WP4: Demonstration of Combined Hydraulic-Thermal-Chemical Treatments in Sandstones, Carbonate Rocks and Granite) and multi-stage stimulation at Bedretto (WP5: Demonstration of Cyclic Hydraulic and Multi-Stage Treatments)
March	Start of drilling in Bedretto (Switzerland)
11 September	DESTRESS at Informationsportal Tiefe Geothermie (ITG) webinar, Germany
24-25 November	Public final DESTRESS conference hosted by GFZ, Potsdam (Germany)

To be continued in 2021!

WHAT

WHY

HOW

Best Practice Reports

Decision Analysis | Geochemistry and Hydrochemistry | Risk Assessment | Geothermal Well Construction | Harmonic Pulse Testing as a Monitoring Tool for Enhanced Geothermal Systems | Geothermal Reservoir Characterisation and Well Testing | In-Situ Stress Estimation in Geothermal Reservoirs |Monitoring the Environment Around Geothermal Sites | Induced Seismicity | Hydraulic, Chemical and Thermal Stimulation | Responsible Research and Innovation (RRI)

During the DESTRESS project, a total of 11 best practice reports were released, covering a broad spectrum of topics related to the exploitation of deep geothermal energy. All the reports are peer-reviewed publications and are fully accessible online on the DESTRESS website.

Decision Analysis

Decision analysis (DA) is the discipline comprising the philosophy, theory, methodology and professional practice necessary to address decisions formally. DA includes many procedures, methods and tools for identifying, clearly representing and formally assessing important aspects of a decision. DA helps in systematically comparing decision alternatives, and recommending a course of action following a conditional optimisation of the 'utility' of a well-formed representation of the decision. Ultimately, this formal representation of a decision and its corresponding recommendation is translated into insight for the decision-makers and other stakeholders. Technological innovation, such as in DESTRESS, can add value to a possible course of action (e.g. a specific stimulation technique) by improving its expected utility (e.g. the mean of the net present value distribution) and/or reducing the possible range of bad outcomes.

Author
Christian Bos, TNO

Reviewers
Henk Krijnen[1], Holger Cremer (TNO) and Sören Welter (EnBW)

More information

Geochemistry and Hydrochemistry

Geochemistry is the study of the chemical composition of the materials found in the subsurface of the earth, and of the reactions that they undergo. Hydrochemistry is the study of the chemical composition of natural waters. Many deep geothermal fluids have rather unusual hydrochemical characteristics: they can be highly saline, remarkably reducing or have high contents of dissolved gases (and the composition of these dissolved gases can be very important in many contexts). Also of interest is the composition of waters, acids and other fluids which are injected into the geothermal reservoir for purposes of hydraulic or chemical stimulation.

To successfully run a geothermal plant, geothermal engineers need to understand the chemical interactions between fluids, rock minerals and gases during the stimulation and operation of a geothermal system. Consequently, the abrupt temperature changes that the fluids and rocks may undergo have to be taken into account. In particular, hydro- chemists will consider how the compositions of the fluids, minerals and gases change throughout the lifetime of a geothermal site, to understand the chemical processes taking place in the reservoir. This will allow them to evaluate whether these changes are likely to lead to the formation of secondary minerals, permeability decreases, scaling or clogging of the reservoir or wells, or whether they may lead to permeability enhancement. This information must be communicated to the geothermal engineers as clear recommendations for the stimulation or operation of the geothermal system.

Author
David Banks, University of Glasgow

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More information

1 Board member of the European Decision Professionals Network and president of Navincerta

Risk Assessment

Risk assessment for geothermal projects using soft stimulation serves to analyse and evaluate risk within a defined context. Collecting and analysing data depicting the overall risk situation as well as single risk factors of soft stimulation measures (e.g. legislation, accidents, public acceptance) has two advantages for risk management. First, data, training and knowledge gained during a risk assessment help the individuals concerned to take decisions and act proactively in the event of a crisis. Second, knowing about risk and the related uncertainty, with a special focus on soft stimulation, assists decision-makers in the decision-making process. The 'decision analysis' research field incorporates uncertainty caused by different risk factors into the decision-making process and can serve as a valuable tool for decision-makers.

Author
Sören Welter (EnBW)

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Falko Bethmann and
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More information

Geothermal Well Construction

Every project targeting an underground resource involves some excavation. Whether it is looking for water, oil or gas, or harnessing geothermal energy, a well will need to be drilled. Projects in which a hole in the ground is dug and then handed over to others to operate are seldom successful. The well designers have to know what is expected from the wellbore in order to select the most appropriate method of construction. The well will be the location of measurements and of fluid movement (inflow or outflow, placement of a treatment, stimulation or plugging) and the place where tools must be run in and safely retrieved. Because the operations performed at the bottom are the very purpose of drilling, a well is always designed from bottom to top. In other words, what is expected at the bottom and what will be done there determines certain design parameters such as completion technique, stimulation methods, placement issues, selectivity and minimum diameter. To design a well that is fit for purpose, the bottom hole completion technique and any inner well requirements must be determined before the casing strings and hole size diameters can be designed.

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More information

Harmonic Pulse Testing as a Monitoring Tool for Enhanced Geothermal Systems

Author
Peter Fokker, TNO

Reviewer
Günter Zimmermann (GFZ)

Harmonic pulse testing is a technology with similar capabilities to regular well testing. It seeks to determine hydraulic parameters such as transmissivity, wellbore storage, skin and storativity. A train of equally long pulses in injection rate or production rate is applied to the reservoir by switching the rate. The pressure is monitored in the pulser well, or in a nearby observer well. Unlike well testing, pulse testing employs several pulses rather than a single one. It therefore requires more time, but there are two crucial advantages. First, deployment is simple. A regular pump must be switched at set times while rates and pressures are monitored. This can all be done with standard equipment. Second, harmonic pulse tests can be performed while other operations are ongoing, which saves expensive non-productive time. Even more importantly, this facilitates the use of the technique as a monitoring tool during operations. As an example, the effect of stimulation can be assessed in real time by superposing a pulse on top of an injections schedule. This way, the injectivity during different background injection rates can be tracked.

More information

Geothermal Reservoir Characterisation and Well Testing

Authors
Clement Baujard, Albert Genter and Régis Hehn, ÉS-Géothermie

Reviewer
Kerstin Nowak, Geothermie Neubrandenburg GmbH

After drilling a geothermal well into a reservoir, one needs to characterise its properties (lithology, fractures, stress, permeability, porosity, fluid temperature, chemical composition, etc.), and assess the well properties (i.e. determine maximum production or injection flow rate). This knowledge is essential for efficient and fast decisions, e.g. when configuring soft stimulation treatments, as well as for the design of surface facilities. Reservoir characterisation is based on various samples, analyses and measurements aimed at gathering information about the reservoir properties and the fluid flow.

Well testing mainly consists of pumping or injecting tests to estimate the reservoir hydraulic parameters (‘hydraulic characterisation’) and to ascertain what flow rate can be pumped or reinjected from/into the well on a long-term basis. The aim of well testing and reservoir characterisation is to gather information used to determine suitable well stimulation and reservoir development strategies and to design appropriate downhole installations as well as surface facilities. Another objective is to ensure well and reservoir initial conditions that will preserve injectivity (avoid/reduce damage at the injection well and reservoir).

More information

In-Situ Stress Estimation in Geothermal Reservoirs

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Régis Hehn and Clément
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In-situ stress is a set of far-field mechanical forces impacting underground structures. There are four types of in-situ stresses: gravitational, tectonic, residual and terrestrial stresses. The gravitational and tectonic forces produced by the motion of crustal plates are the main sources of in-situ stresses; the others account only for in-situ stresses at shallow depths. Enhanced geothermal systems (EGSs) based on hydraulic stimulation enhance the hydraulic connection of the fracture network in geothermal reservoirs. In consequence, the development of a reservoir depends on successful hydraulic stimulation. Breakdown pressure, the direction in which hydraulic fractures propagate, the injection pressure required to activate stimulation, the reservoir's response to hydraulic stimulation, the evolution of permeability, and the migration of induced seismicity are closely related to the in-situ stress. Furthermore, the in-situ stress affects the stabilities and trajectories of deep boreholes: a high in-situ stress ratio relative to rock strength often makes deep boreholes unstable. Given that EGS geothermal development is accomplished by drilling boreholes that are several kilometres deep, the ability to estimate stresses is limited at these depths, as they are difficult to access. It is therefore desirable to combine the data from various stress measurement methods and follow a set of steps to construct a reliable rock stress model.

More information

Monitoring the Environment around Geothermal Sites

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Reviewer
Peter Meier,
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The environment of a geothermal site includes all elements related to nature such as air, soil, surface and deep water, fauna and flora, people and infrastructure, which may be impacted by geothermal operations. Environmental monitoring is a vital tool for identifying and quantifying the spatio-temporal consequences of geothermal exploitation as well as the causes of the observed impacts.

The requirements for environmental monitoring vary according to the reservoir context, the project design and the operational phase. This means that the monitoring system needs to be adapted depending on the frequency and severity of the observed/expected impacts. Furthermore, it is essential to characterise in advance the initial environmental parameters in order to evaluate the effect of the geothermal exploitation correctly. In general, the ground motion, resources, waste disposal, underground water and surface disturbance should be monitored to minimise environmental impacts.

More information

Induced Seismicity

Authors
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Reviewers
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The term ‘induced seismicity’ generally refers to the seismic activity directly or indirectly caused by industrial operations. In general, any industrial activity that alters the stress state within the Earth’s crust has the potential to induce or trigger earthquakes. Aside from wastewater disposal, the most common operations associated with induced seismicity are underground mining, water reservoir impoundment, oil and gas production (from both conventional and non-conventional resources), geothermal energy exploitation and natural gas storage operations. Induced seismicity monitoring is key to identifying and better understanding the physical processes governing this phenomenon. It also allows potential active faults near industrial sites to be identified and mapped. Such information is essential for risk assessment operations.

To tackle the problem of induced seismicity, a comprehensive risk governance strategy must include suitable monitoring infrastructure, sophisticated data analysis techniques for real-time seismicity characterisation, quantitative risk analysis and transparent decision protocols. All these elements combined will help to evaluate the system response before the occurrence of critical events, allowing a risk mitigation strategy to be implemented in advance.

More information

Hydraulic, Chemical and Thermal Stimulation

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Reviewers
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Stimulation, in general, is a method of enhancing well productivity or injectivity within different types of reservoirs, ranging from sediments like sandstones and limestones to crystalline rocks like granites and basaltic rocks. The choice of hydraulic, thermal or chemical stimulations is based on the type of reservoir and its environment.

Hydraulic stimulation can be described as the injection of fluids at high flow rates into a reservoir to develop new fractures or reactivate and enhance the hydraulic performance of existing fractures. The term chemical stimulation refers to the injection of fluids with chemical additives into the geothermal target formation. It is performed to overcome formation damage in the rock matrix as well as inside existing fractures and fissures, leading to the dissolution of certain minerals and thus increasing the hydraulic pathways in the rock and enhancing the permeability. Horizontal multi-stage hydraulic fracturing is the process by which multiple fractures are created along a horizontal section of the wellbore in a series of consecutive operations. It is a well-established practice in the oil and gas industry and can be seen as a key technology enabling the development of enhanced geothermal systems. For thermal stimulation of a well, cold water is injected below the fracturing pressure over a certain time period. Due to the low temperature of the water compared to the temperature of the rock, the stress in the rock changes, leading to stimulation of natural fracture networks or initiation of new fractures. Thus, the effect of thermal stimulation is very similar to the effect of hydraulic stimulation.

All stimulation designs have in common that they are necessary to increase the productivity (or injectivity) of low-permeability geothermal reservoirs and that fluids are injected into geothermal reservoirs.

More information

Responsible Research and Innovation (RRI)

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Responsible research and innovation is a key issue in the European Union's Horizon 2020 framework programme. In this context, it is defined as an approach that anticipates and assesses potential implications and societal expectations concerning research and innovation, to foster the design of inclusive and sustainable research and innovation. Hence, applying the RRI principle means that research and innovation must be considered not only from a science-centred perspective, or through the prism of economic interests or political considerations, but also from environmental and societal perspectives. In this connection, several aspects of RRI overlap. RRI is inclusive and encourages the involvement of different categories of actors, from scientists, industrialists and politicians to NGOs, associations and educators. It takes seriously the concepts of transparency, open access, ethics, social desirability and sustainable development and gives new dimensions to those terms. RRI requires stakeholders to think more carefully about how to develop a project, and how to facilitate the involvement of local authorities and residents in project development, with all the implications this may have in terms of adapting the communication strategy and project governance. In this context, social science research related to geothermal energy can provide essential insights for the adoption of RRI principles.

More information

Imprint

DESTRESS
Demonstration of Soft Stimulation Treatments of Geothermal Reservoirs

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