

Deliverable D3.1: A comprehensive report on risk assessment and workflow for soft stimulations

WP3: Risk Governance

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A comprehensive report on risk assessment and workflow for soft stimulations

Deliverable 3.1



Fig. 1 Chemical stimulation operation at Rittershoffen geothermal site (France). ©és

Authors

Abigaëlle Peterschmitt (ESG), Régis Hehn (ESG), Cléo Bosia (ESG), Nicolas Cuenot (ESG), Astu Sam Pratiwi (ESG) and Albert Genter (ESG)

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Abstract

The report “Risk assessment and workflow for soft stimulations” corresponds to the Deliverable 3.1 of the EU DESTRESS project. This public report is done on the framework of the WP3 dealing with Risk Governance. The objective of the dedicated task WP3.1 is to carry out a generic risk assessment related to geothermal well soft stimulations with chemical treatments. Therefore an environmental risk assessment has been achieved in interaction with several DESTRESS WPs.

Every human activity imposes irreversible risks that may affect its own future. Several aspects can characterize the unfortunate event and potential impacts that it can have on the surroundings of the activity. These risks have to be taken into account to anticipate rather than to remedy. As a whole, deep geothermal energy is responsible for the impacts of its operations on the environment, life, and workers on the geothermal platform. Soft stimulation by chemical treatments of geothermal reservoirs is not an exception in terms of risk and has to be assessed, whether in urban or rural areas.

This comprehensive report proposes workflows and a road map for geothermal operators and raises questions upon operational activities, particularly during the reservoir development phases by chemical soft stimulation. Several methods, usually used by specialized company for risk assessment studies, are exposed and their applicability for soft stimulation is discussed. A special focus has been done on the establishment of the context in which the reservoir stimulation is applied, and its importance in terms of technical and regulatory issues.

A road map has been specifically designed for assessing risks in the framework of a chemical stimulation. It proposes tools and a reflective path on the impacts of this operation, particularly on a human, safety and environmental issues aspect. Various risk assessment methods have been combined to design a simple and easily applicable path. This qualitative study requires an expert team and a facilitator who should be available in an operating geothermal company during stimulation phases.

Finally, a case study of risk assessment for a chemical stimulation is presented, introducing a semi-urban geothermal site in the frame of the French regulations. This generic application of this environmental risk assessment deals with potential risks in an area with water-bearing zones. Thus, it has been applied to the on-going Illkirch-Graffenstaden geothermal project located close to Strasbourg urban area where the Rhine aquifer is quite thick.

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1 Introduction

1.1 Purpose of the document

This public report entitled “*Risk assessment and workflow for soft stimulations*” corresponds to the Deliverable 3.1 of the Eu Destress project. This comprehensive report is done on the framework of the WP3 dealing with **Risk Governance** and involved exclusively engineers and scientists from ESG (France).

The main goals of **Destress** is to carried out soft stimulations in various geological contexts in Europe for increasing reservoir transmissivity, maintaining productivity and injectivity of the geothermal system and minimizing the level of environmental impact. The term “Soft stimulation” has been defined in the Destress consortium (2016) as follows: “Soft Stimulation is a collective term for geothermal reservoir stimulation techniques that aim to achieve enhanced reservoir performance while minimizing environmental impacts including induced seismicity. Soft stimulation includes techniques such as cyclic/fatigue stimulation, multi-stage stimulation, chemical stimulation and thermal stimulation.” (DESTRESS, 2016)

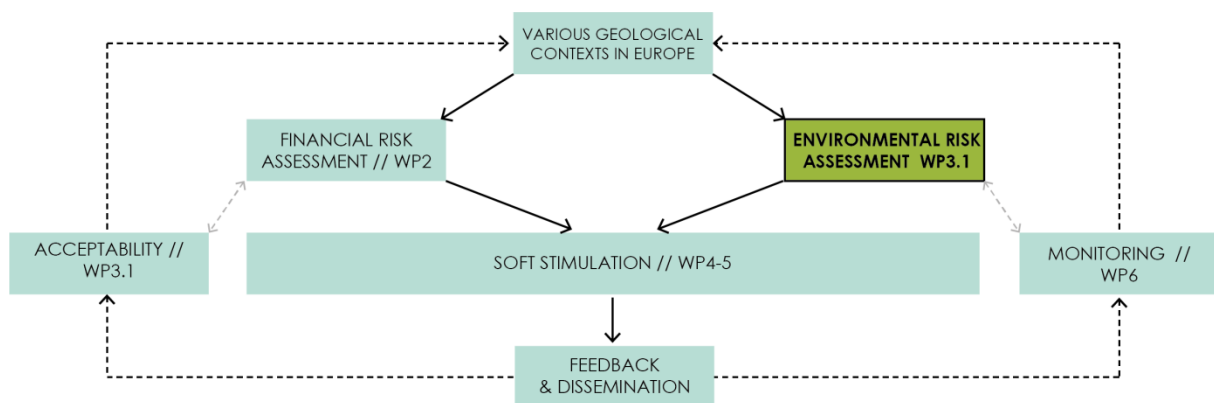


Fig. 2 The position of the environmental risk assessment within DESTRESS Project

The objective of the task WP3.1 will be to carry out a generic risk assessment related to soft stimulations with chemical treatments. Therefore an environmental risk assessment has been achieved in the framework of the risk governance part of Destress in interaction with several WPs (Fig. 2). For example, this environmental risk assessment has been conducted in parallel of financial risk analysis (Reith et al., 2017; 2018) and the others WPs (Fig. 2).

Acidizing treatments could cause damage through the use of hazardous substances, during transportation, injection or disposal as well as in the borehole. Thus, they could impact on human health and cause environmental issues as well as affecting geothermal borehole integrity.

1.2 Scope of the document

This comprehensive report summarizes the work done about environmental risks induced by chemical treatments during soft stimulation. This comprehensive report contains:

- the methodology applied for achieving this environmental risk assessment,
- a focus on risks related to chemicals or chemical stimulation,

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Demonstration of soft stimulation treatments of geothermal reservoirs

- a series of workflows and roadmaps for risk assessment and risk treatment of chemical treatments,
- a generic application of this environmental risks assessment dealing with potential risks in an urban area with water-bearing zones. Thus, it has been applied to the on-going Illkirch geothermal project close to Strasbourg (France) which is located close to a city where the Rhine aquifer is quick thick.

1.3 Related documents

This is the first deliverable of the WP3 and there will be other deliverables associated with. A first milestone (MS6) dealing with the implementation of the communication plans of the DESTRESS Eu project has been produced in the framework of the WP3 (Genter & Peterschmitt, 2017). It aims to structure external but also internal communication of stakeholders from deep geothermal projects enhancing reservoir permeability by soft stimulation, and also in case of crisis due to unexpected event such as induced seismicity or accidental pollution.

2 Risk Assessment Methodology

2.1 Risk assessment definition

According to the definition of the International Risk Governance Council (IRGC, 2008), risk assessment is part of the global framework of risk governance. This important stage of the assessment process is part of the generation of knowledge that will help the management process on the decision on and implementation of actions. Taken in a larger context, the “major task of risk assessment is to identify and explore, preferably in quantitative terms, the types, intensities and likelihood of the consequences related to a risk” (IRGC, 2008).

Following the IRGC (2008) recommendations, the first step of the assessment process consists in establishing the context. It is described as the framing stage and its objective is to determine the limits of the study and the parts of the procedure which will be investigated. Once the frame of the study determined, the risk assessment will take into account the perception (risks, socio-economic) and the non-technical aspects. Then the risk appraisal stage is implemented, focusing on the risk assessment itself and the concern assessment, which correspond to the risk and socio-economic perceptions and their impacts (IRGC, 2008). Once the risk assessment is completed, a management phase is implemented in the aim of proposing reduction measures, in accordance to the risk studies, legal regulations, financial and human resources (IRGC, 2008).

Among the useful tools for the understanding of a concrete set up of a risk assessment procedure, the ISO 31000 ‘Risk management – principles and guidelines’ and ISO 31010 ‘Risk management – risk assessment techniques’ are the most appropriate. Those norms could be applied to develop risk assessment for a project, a process or in the case of the present work, for the chemical stimulation operations. The description of the risk assessment process in the ISO 31000 norm is slightly different from the one in the IRGC (2008) but not inconsistent. For the present study, the definition and methodologies exposed in the ISO norms will be applied.

According to the ISO norms, the risk assessment is described as three stages: Risk identification, risk analysis and risk evaluation (Fig. 3).

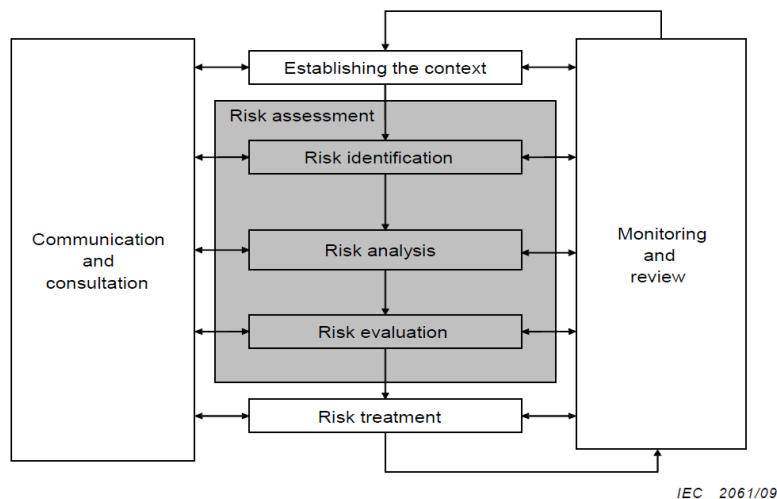


Fig. 3 Contribution of risk assessment to the risk management process (ISO 31000)

Risk identification corresponds to the process of finding, recognizing and recording risks (Fig. 3, ISO 31000 & ISO 31010). The objective of risk identification is to identify the potential causes and sources of the risk or event that could have an impact (positive or negative) upon the expected result. Risk identification methods are various and can include evidence based methods, inductive reasoning techniques or systematic team approaches.

Risk analysis aims at understanding the risk: causes, sources of risk, their consequences and the probability of occurrence (Fig. 3, ISO 31000 & ISO 31010). Another objective is also to determine the influence of factors on the risks previously identified. For this, many factors such as control assessment criteria, consequence analysis, likelihood and probability estimation, uncertainties and sensitivities have to be taken into account for the risk analysis. Risk analysis methods can be qualitative, semi-quantitative or quantitative, or also be combined for complex situations.

Risk evaluation involves comparing estimated levels of risk with criteria defined when the context was established, in order to determine the significance of the level and type of risk (Fig. 3, ISO 31000 & ISO 31010). The risk evaluation uses the understanding of risk obtained during risk analysis to make decisions about future actions. These decisions could be, for example, treatments, prioritization of risks treatments, or establishment of emergency plans. Risk treatments could include prevention and mitigation measures. However, in this document we use *mitigation* or *treatment* to reflect either prevention or mitigation measure.

Risk identification, analysis and evaluation (in this order) are important paths of the risk assessment and are essential for decision taking.

2.2 Risk assessment survey

For the present study on risk assessment methods, some results of Lohne et al. (2016) have been chosen. In this document, realized for the Geowell H2020 project, the authors have investigated methods used for risk identification, analysis and evaluation by geothermal and oil and gas companies to perform risk assessment in geothermal wells. On the basis of the analysis of Lohne et al. (2016), four of the most used techniques have been selected for each step of risk assessment.

It appears that brainstorming, checklist, scenario analysis and environmental risk assessment are the most used methods for the identification of risks (Fig. 4). The HAZOP method, the scenario analysis, root cause analysis, and environmental risk assessment are the most used ones for the analysis of risks (Fig. 4). Last, but not least, the SWIFT method, the root cause analysis, the Monte-Carlo

simulation and the environmental risk assessment are the four most used for risk evaluation (Fig. 4). It is important to highlight that a few of them can be used at different stages of the study. In particular the environmental risk assessment method, which appears to be the most complete and transversal one. Furthermore, it is important to note that all the methods selected except the Monte-Carlo simulation method are qualitative ones and cannot provide quantitative outputs.

According to the ISO 31010, which analyses the applicability of the different tools for risk assessment, every selected method in this study is applicable for each of the preconized steps of the process.

In order to identify the most appropriate or complementary techniques for each phase of the risk assessment for a soft stimulation procedure, the entries, results, methodology and resources of each selected tool have been compared. Thus, a detailed analysis of the different selected methods is presented in the next section.

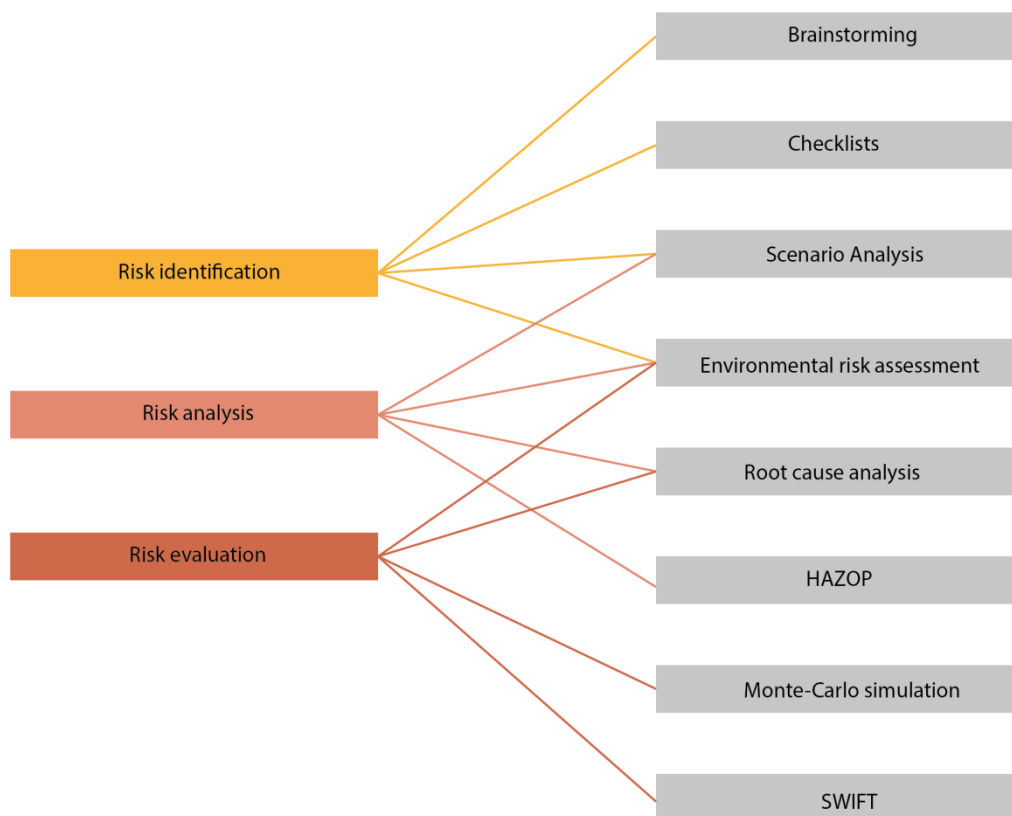


Fig. 4 Methods correlated to the risk assessment process

2.3 Risk assessment methods

2.3.1 Brainstorming

Brainstorming is a risk identification method that can be set up quite easily, as the only entry needed is a professional expert team (Fig. 5). A facilitator is in charge of preparing thinking prompts and triggers and helps to set participants off on a new track when the discussion comes to a dead end. The objective of a brainstorming session is to gather ideas as much as possible. At the stage of risk identification, the outputs of the brainstorming method could be a list of risks, but also of potential dangerous situations (Fig. 5).

A positive aspect of brainstorming is the possibility of finding new risks and original solutions. Nevertheless, limitations could appear if participants lack skills and knowledge (Fig. 5).

Regarding the soft stimulation, due to the lack of verified risks and of statistical data, the brainstorming method is strongly appropriate.

2.3.2 Checklist

The checklist method for risk identification deserves not only the participation of an expert team, but also the formulation/selection of a control checklist, including the typical risks encountered for the analyzed procedure (Fig. 6). The methodology consists in applying the defined checklist on the case study and verifying that all the elements are taken into account. The output of this methodology is a list containing new risks identified during the process and unsatisfactory preventive/mitigation measures along with the associated residual risks. (Fig. 6).

One of the main advantages of this technique is the rapidity and simplicity of its execution. The checklist approach works very well for common and recognized risks, but it could also be an appropriate technique to identify new and unsuspected risks (Fig. 6).

Concerning the soft stimulation analysis, the checklist is a very useful method, as it may significantly reduce the time required for the risk identification procedure. However, this approach should be coupled with a more exhaustive one, in order to include all the specific and rare risks.

2.3.3 Environmental Risk Assessment (ERA)

The ERA approach covers not only the risk identification phase, but also the risk analysis and evaluation. For ERA application, a detailed knowledge of the nature and properties of the hazards is required, together with the vulnerability and exposition of the endangered elements (Fig. 7). The identified risks are characterized following the vulnerability and the exposition to the relative hazard, by taking into account the worst possible scenario. This procedure allows obtaining a quantitative or semi-quantitative evaluation of the risk level for a specific target in a precise context (Fig. 7).

A major strength of the ERA approach is the general comprehensiveness of the analyzed system and the ability to trace a risk from the identification to the existing control/remediation tools (Fig. 7). However, good and detailed data are rarely available for correctly implement the method.

Concerning the application of the ERA approach for the soft stimulation, the lack of experience and knowledge on verified dangers occurred during precedent soft stimulation phases makes it difficult to use ERA for risk identification. However, the approach is strongly relevant to improve the risk analysis and evaluation phases, as it allows a complete and semi-quantitative consideration of the causes and the consequences of the risks.

2.3.4 Scenario Analysis

The scenario analysis is a tool which aims to identify the potential changes that can occur in the future and their cause-factors (Fig. 8). This step, achieved by an expert team through the analysis of existing data and literature, allows focusing on a series of potential scenarios that represent the identified plausible changes. Each of them is explored and evaluated in term of occurrence and probability. The result of the scenario analysis approach is an aware regard on the range of options and risks, but also on the suited actions to modify hazards and consequences (Fig. 8).

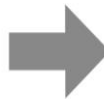
The advantage of the scenario analysis method is to take into account whole range possibilities in the future. However, the lack of data could reduce the efficiency of the method, inducing non-realistic and/or speculative scenarios (Fig. 8).

For the soft stimulation, the application of a scenario analysis could be useful in order to identify and evaluate the potential risks. However, given the lack of data and experienced risks, this approach can be extremely time-consuming, while the produced scenarios might not correspond to significant soft stimulation risks.

BRAINSTORMING

INPUTS

- Team of people with knowledge of the process, system being assessed



PROCESS


- Preparation of reflective elements : prompts and triggers (facilitator)
- Gather as many ideas as possible with the objective of a further analysis



OUTPUTS

- Risk list and control elements including situations, causes and consequences

From ISO/CEI 31010 Risk management - Risk assessment techniques



- + | Imagination is a plus and can bring :
 - new risks
 - original, rapid and easy solutions
- | There could be a risk of :
 - lack of expertise
 - lack of dynamism
 - non-exhaustive list

Fig. 5 An overview of the brainstorming method for risk identification (adapted from ISO/CEI 31010)

CHECKLIST

INPUTS

- Prior information and expertise on the issue




PROCESS

- Definition of the scope of the activity
- A check-list is selected which adequately covers the scope
- The person or team use the check-list steps to go through each element of the process and review each items



OUTPUTS

- List of risks and/or list of inadequate control measures



- + | • Precise, easy to apply, good memo on potential usual problems
- | There could be a risk of :
 - lack of imagination
 - focus on known risks only
 - passivity

From ISO/CEI 31010 Risk management - Risk assessment techniques

Fig. 6 An overview of the checklist method for risk identification (adapted from ISO/CEI 31010)

ENVIRONMENTAL RISK ASSESSMENT

INPUTS

- Good data on the nature and properties of hazards
- Context : vulnerability and exposition



PROCESS

- Problem formulation and context definition
- identification of all possible sources of harm to the potential targets defined in the scope of the study. It relies on expert knowledge and literature.
- Understand the nature of the hazard and how it interacts with the target
- Exposure analysis (how a hazardous substance or event might reach a susceptible target population and its intensity)
- Risk characterization (estimate the probability of particular consequences when effects from all pathways are combined)



OUTPUTS

- Exposition risk level of a particular target at a particular danger in a specific context (quali/ semi-quali and quantitative analysis)



- + | • Very detailed understanding of the nature of the problem and influencing factors
- Useful tool for improving controls and introduce new ones
- | • Good data often not available
- Potential tricky extrapolation

From ISO/CEI 31010 Risk management - Risk assessment techniques

Fig. 7 An overview of the environmental risk assessment method for risk identification, analysis and evaluation (adapted from ISO/CEI 31010)

SCENARIO ANALYSIS

INPUTS

- Team that has an understanding of the nature of relevant changes and imagination to think into the future without necessarily extrapolating the past
- Data and literature



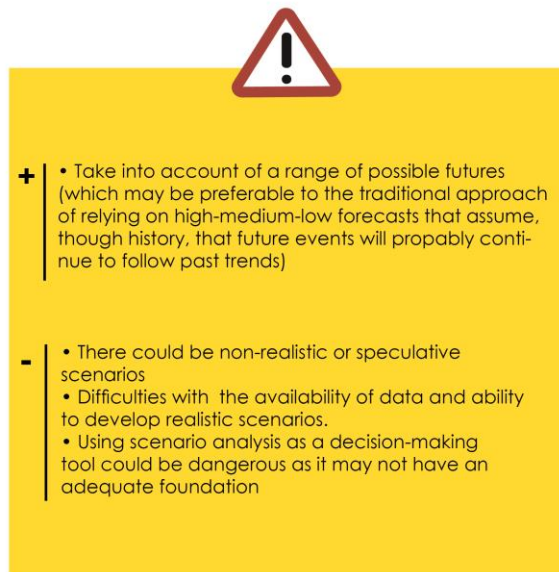
PROCESS

- Define the context of the problem and the issues to be considered
- Identify the nature of changes that might occur (research of the major trends and timing)
- Changes to be considered may include : external changes, decisions that need to be made in the near future, stakeholder needs, changes in the macro environment (e.g. regulatory)
- Factors can be listed and ranked for importance and uncertainty
- Key factors or trends are mapped against each other to show areas where scenarios can be developed
- A series of scenarios is proposed with each one focussing on a plausible change on parameters
- A « story » is written for each scenario
- The scenario can be used to test or evaluate the original issue, taking in account any significant but predictable factors and then explores how successful the activity would be in this new scenario.
- The probability of each scenario have to be evaluated



OUTPUTS

Clearer perception of the range of options and how to modify the chosen course of action as indicators move



From ISO/CEI 31010 Risk management - Risk assessment techniques

Fig. 8 An overview of the scenario analysis method for risk identification and analysis (adapted from ISO/CEI 31010)

2.3.5 HAZOP

The hazard and operability study (HAZOP) is a method for risk analysis and evaluation based on the application of a set of guidewords to different elements of the global context in order to evaluate the possible deviations (Fig. 9). For this purpose, an expert team works with a leader on different sub-systems extrapolated from the main context to identify the potential risks, causes and consequences as a function of the selected guide-words. The final output of this approach is a list of possible deviations, their causes (actions or persons) and the potential remediation measures (Fig. 9).

The strength of the HAZOP method relies on the systematicity of the procedure, allowing an exhaustive analysis of a wide range of procedures and the formulation of the causes and consequences of the identified risks (Fig. 9). However, this approach is very expensive and time-consuming. Additionally, it requires a detailed documentation and abundant specifications on the analyzed procedure.

Similarly to other discussed methods, HAZOP might have a significant potential for the analysis and the evaluation of the risks related to the soft stimulation. However, nowadays, the literature and the existing data available on the accidents occurred during soft stimulation procedure are very scarce and do not allow to implement a high intensity data procedure as the HAZOP.

2.3.6 Root cause analysis

The root causes analysis is an approach based on the study of previous known failures or loss evidences, within the goal to decipher the root causes and to develop the appropriate solutions (Fig. 10). The implementation of the root causes analysis method requires a group of expert and a wide range of data on gathered failures on similar projects. The conclusions mainly consist in a list of the most likely cause of failure and a description of the preventive/mitigation recommendations (Fig. 10).

The root cause analysis allows a precise and structured analysis of the identified risks and of their evaluation. The approach also produces a useful recommendation list to set up. On the other side, the method needs the presence of high knowledgeable experts and the availability of a complete and coherent dataset concerning the recognized failures and losses (Fig. 10).

In the light of the soft stimulation, the application of the root cause analysis may appear useful to fully understand the causes of the risks induced by the stimulation treatments and thus identify the more appropriate remediation measures. However, so far, the feedback on the failures occurred during soft stimulation on geothermal sites is very poor, making it very complicated to correctly implement the root cause analysis approach.

HAZOP - HAZARD AND OPERABILITY STUDY

INPUTS

- Current information about the system (drawings, specification sheets, flow sheets...)



PROCESS

- Nomination of a person with the necessary responsibility and authority
- Definition of the objectives and scope of the study
- Establishing a set of guidewords for the study
- Defining a team (multidisciplinary w/ technical expertise)
- Collection of required documentation
- Splitting the system, process or procedure into smaller elements to make the review tangible
- Agreeing the design intent of each subsystem. For each item, applying the guidewords one after the other to postulate possible deviations which will have underisable outcomes
- When undesirable outcome is identified, agreeing the cause and consequences in each case and suggesting treatment to prevent them occuring or mitigate the consequences
- Documenting the discussion and agreeing specific actions to treat the risks identified




OUTPUTS

- Minutes of the HAZOP meeting with items for each review point recorded :
- The guide word used, the deviation(s), possible causes, actions to address the identified problems and person responsible for the action

Reference document : IEC 61882, Hazard and operability studies (HAZOP studies) - Application guide)

From ISO/CEI 31010 Risk management - Risk assessment techniques



- +
 - Provide the means to systematically and thoroughly examine a system or procedure
 - Multidisciplinary team
 - Generate solutions and risk treatment actions
 - Applicable to a wide range of procedures
 - Allows explicit consideration of the causes and consequences of human error
 - Written record of the process
- - Can be time-consuming and therefore expensive
 - High level of documentation and procedure specification
 - Focus on finding detailed solutions rather than on challenging fundamental assumptions
 - Discussion can be focused on detail issues
 - Constrained by the design, scope and objectives given to the team
 - Objectivity can be difficult when analysing its own design

Fig. 9 An overview of the HAZOP method for risk analysis and evaluation (adapted from ISO/CEI 31010)

ROOT CAUSE ANALYSIS (RCA)

INPUTS

- All of the gathered failure or loss evidence
- Data of other similar failures
- Group of experts



PROCESS

- Establish the scope and objectives of the study
- Perform a structured analysis to determine the root cause of the gathered data and evidence from the failures and losses
- Develop solutions and make recommendations
- Implement the recommendations
- Verify the success of implemented recommendations

The structured analysis can use various techniques, but one of the easiest to apply could be the «5whys» technique which consist of repeatedly asking 'why?' to peel away layers of cause and sub cause



OUTPUTS

- Results of the simulation or a distribution of the results
- Analysis of the influence of factors on results



- +
 - Involve experts
 - Structured analysis
 - All likely hypotheses are considered
 - Results are documented
 - Recommendations are produced
- - Availability of experts
 - Data or evidence may be not available
 - Could be time consuming
 - Recommendations may not be adequately implemented

From ISO/CEI 31010 Risk management - Risk assessment techniques

Fig. 10 An overview of the RCA method for risk analysis and evaluation (adapted from ISO/CEI 31010)

2.3.7 SWIFT

The SWIFT method, acronym of “Structured What If Technique”, consists in a discussion on the known risks, incident experiences and control measures by analyzing each element through a what-if hypothesis (Fig. 11). This approach requires an expert team, a facilitator, as well as a precise knowledge of the context(s) but also of similar procedures. The main output of the risk evaluation method is a risk-ranked list along with a treatment plan (Fig. 11).

Positive points of the SWIFT approach are the facts that it is widely and quickly applicable and it provides recognition of the system response to deviations (Fig. 11). On the other side, the method requires a careful preparation and a strong experience on similar procedures. Finally, the SWIFT methodology may not reveal complex and/or correlated causes (Fig. 11).

In the perspective of a soft stimulation procedure, the SWIFT approach could certainly be very interesting even if its application may be relatively complicated. First, it is challenging to dispose of an experienced and capable facilitator able to correctly structure the procedure. Furthermore, it is complicated to develop a strong experience to ensure the identification of most of risks and hazard, as almost no accident are recognized for the soft stimulation practice to date.

2.3.8 MONTE-CARLO

The aim of a Monte-Carlo approach is to numerically evaluate the risks, by simulating the system through a model or algorithm running multiple times (Fig. 12). The outputs of the model are then processed statistically in order to provide a distribution of the results and accessorially a sensibility analysis of the different factors. Through the Monte-Carlo approach, it is thus possible to obtain a quantitative analysis of the risks and of the main elements influencing their causes and consequences. To perform such a numerical method, a good model of system and a quantitative database should be available (Fig. 12).

As models are relatively simple to develop and software is financially accessible, the Monte-Carlo simulation method can be easily set-up and adjusted to different contexts (Fig. 12). However, this approach is not appropriate for large and complex system, as well as for high-consequence/low-probability risks.

Even if the Monte Carlo approach is one of the few methods producing a quantitative evaluation of the risks and the influencing factors, its application might be unsuited for soft stimulation risk evaluation. Indeed, soft stimulation often deals with risks presenting strong gravity but low occurrence, which are not easily detected by a numerical approach. In addition, the lack of quantitative and exhaustive database on the risks for soft stimulation procedure is a major problem for the simulation success.

SWIFT (STRUCTURED 'WHAT-IF' TECHNIQUE)

INPUTS

- Established external and internal contexts (documents, plans, drawings..)
- Expert pluridisciplinary team
- Facilitator




PROCESS

- The facilitator prepares a suitable prompt list of words or phrases
- The external and internal context of the item, system, change or situation and the scope of the study are discussed and agreed
- The facilitator asks the participants to raise and discuss :
 - Known risks and hazards
 - Previous experience and incidents
 - Known and existing controls and safeguards
 - Regulatory requirements and constraints
- Discussion is facilitated by creating a question using a 'what-if' phrase and a prompt word or subject
- Risks are summarized and controls are considered
- The team validates the descriptions of risks, causes, consequences and expected controls
- The team considers whether the controls are adequate and effective and agree a statement of risk control effectiveness
- Further 'what-if' questions are asked to identify further risks
- The prompt list is used by the facilitator to monitor the discussion and suggest additional issues



OUTPUTS

- A risk register with risk-ranked actions or tasks
- Treatment plan
- Update of the risk control process



- +**
 - Widely and quickly applicable
 - Minimal preparation by the team
 - The major hazards and risks quickly become apparent
 - System oriented and allow to observe the response of the system to deviations
 - Creates a risk register and a risk treatment plan
 - The results of the SWIFT study can be used in a quantitative study
- - An experienced and capable facilitator is needed
 - Careful preparation is needed
 - A strong experience based is needed to be sure that most of risks and hazards are identified
 - May no reveal complex, detailed or correlated causes

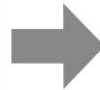
From ISO/CEI 31010 Risk management - Risk assessment techniques

Fig. 11 An overview of the SWIFT method for risk evaluation (adapted from ISO/CEI 31010)

MONTE-CARLO SIMULATION

INPUTS

- A good model of the system and information on the types of inputs, the sources of uncertainty, the required output
- Input data



PROCESS

- A model or algorithm is defined, representing as closely as possible the behaviour of the studied system
- The model is run multiple times using random numbers to produce outputs of the model
- Outputs are processed using conventional statistics to provide : average values, standard deviation, confidence intervals



OUTPUTS

- Results of the simulation or a distribution of the results
- Analysis of the sensitivity of the different parameters on results

Reference document : IEC 61649, Weibull analysis // IEC 62551 Analysis techniques for dependability - Petri net techniques // ISO/IEC Guide 98-3:2008 Uncertainty measurement
From ISO/CEI 31010 Risk management - Risk assessment techniques



- + • Models are relatively simple to develop
- Strongly parametrable
- Models can be easily understood
- Can provide a measure of the accuracy of a result
- Software is available and financially accessible
- • The accuracy of the solutions depends upon the number of performed simulations
- It can be difficult to represent uncertainties in parameters by a valid distribution
- Large and complex systems may be challenging to model
- Not well suited for high-consequence/low probability events

Fig. 12 An overview of the Monte-Carlo simulation method for risk evaluation (adapted from ISO/CEI 31010)

3 Soft stimulation

3.1 Definition

Originally developed in the oil and gas industry, the stimulation technique corresponds to the treatments performed to restore or enhance the productivity of a well (Schlumberger Oilfield glossary). Among the range of treatments applied for well stimulation, the main approaches that can be identified are the hydraulic fracturing, the thermal stimulation and the matrix treatments.

For geothermal reservoirs, different techniques can be required to improve the productivity of the system, depending on its sensitivity on different environmental parameters. In particular, the sustainability of the geothermal system is strongly influenced by the geological, hydrogeological, chemical and thermal conditions. To deal with the various reservoir-specific constraints, several stimulation techniques were adapted from the petroleum sector, including hydraulic, chemical and thermal stimulation treatments (Fig. 13). Based on the existing literature, Brehme et al. (2017 and references therein) summarize those techniques. The hydraulic stimulation aims at opening pre-existing fractures and/or creating new ones. Chemical stimulation acidifies and dissolves rock particles to enlarge fluid flow pathways. Thermal stimulation expands the fractures cooling down the medium.

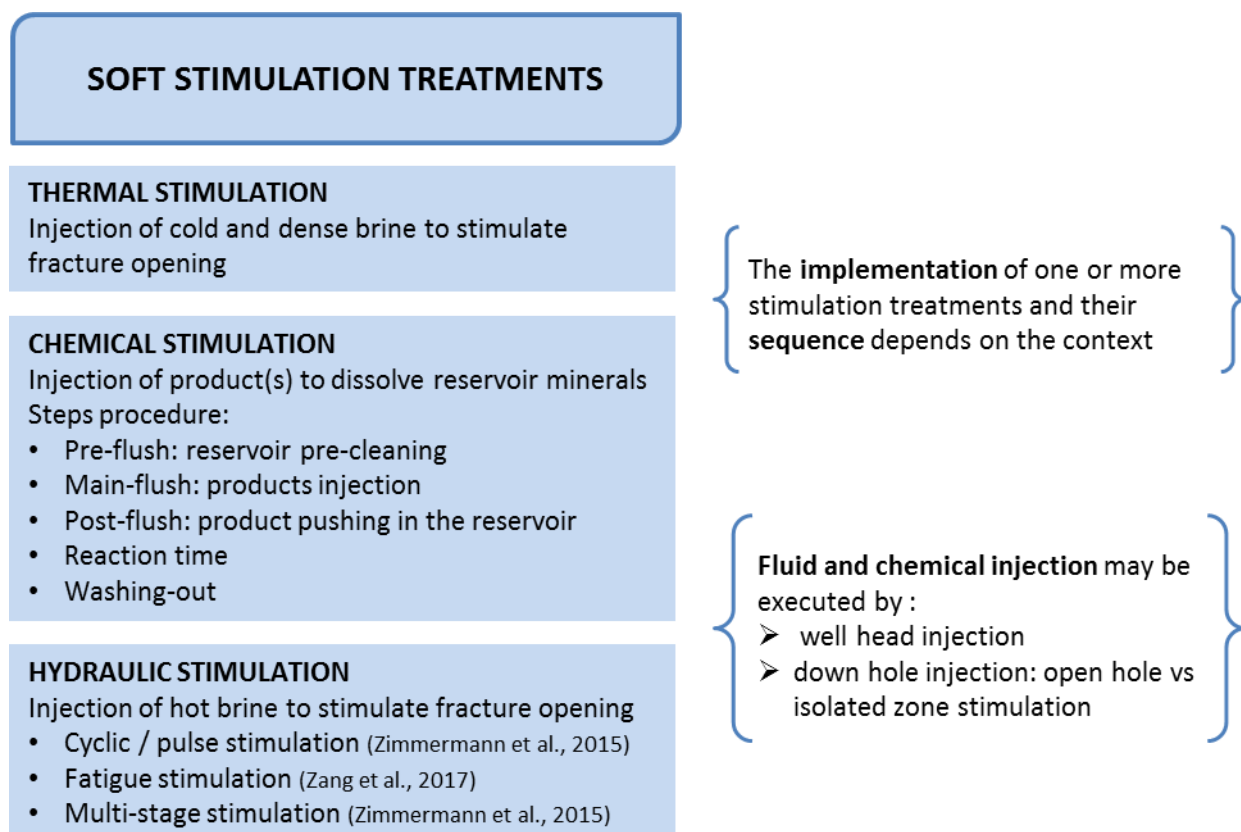


Fig. 13 A short definition of the soft stimulation: thermal, chemical and hydraulic treatments

It is in the framework of the Enhanced Geothermal System (EGS) technology that the concept of “soft stimulation” emerged. This term includes all the techniques that aim to enhance reservoir performance while reducing their environmental consequence (Brehme et al., 2017). In particular, the applied treatments have to minimize the micro-seismicity induced by the hydraulic fracturing. As

the assessment of seismic risks is very challenging, a specific task is dedicated to this subject in the framework of the WP3 of the Destress project, where the hydraulic fracturing technique and the associated risks are detailed.

Chemical stimulation treatments, also known as acidizing treatments, consist in acid or solvent injection into the formation in order to increase the formation permeability (Fig. 13). Two basic types of acidizing operations can be conducted : matrix acidizing and fracture acidizing (Portier et al., 2007; 2009). The latter one aims at creating new fractures by operating at high flow rate and pressure. As this approach does not allow increasing the well performance while minimizing the environmental consequences, it will not be considered in this report. The matrix technique conducted for soft chemical stimulation consists in injecting fluids at below fracturing flow rate and pressure (Portier et al., 2009). As mentioned above, the goal of those operations is to increase formation permeability by dissolving and displacing near-wellbore damage or material deposited in fractures due to precipitation processes that impair or reduce the well performance (Portier et al., 2007; 2009).

Matrix acidizing corresponds to one of the oldest stimulation techniques developed in oil and gas well and today frequently used by the geothermal industry. Initially applied for limestone formations, the procedure was subsequently extended to sandstone reservoir (Smith and Hendrickson, 1965).

Nowadays, a number of different acids, mixtures and additives are used for acidizing treatments, depending on the structural and mineralogical composition of the reservoirs and the intention of the treatment.

HCl is the acid generally selected to carry out the majority of acidizing treatment, in particular for carbonate formations while to dissolve clays and silica in sandstone reservoirs HF is classically used (Fig. 14). Several examples of mineral solubility with HCl and HF are reported in Table 1.

Table 1 Solubility of sandstone, clay and carbonate minerals vis-à-vis of HCl and HF acid (modified from Portier et al., 2007)

Minerals	Solubility	
	HCl	HCl-HF mixture
Quartz	No	Very low
Feldspars	No	Low to moderate
Micas	No	Low to moderate
Kaolinite	No	High
Illite	No	High
Smectite	No	High
Chlorite	Low to moderate	High
Calcite	High	High
Dolomite	High	High

The stimulation of sandstone lithology is classically carried out through a multiple phase stimulation procedure including (Fig. 13):

- a pre-flush, performed with an HCl solution in order dissolve the calcareous material present in the formation;
- a main flush, composed of an HCl-HF mixture, also called regular mud acid (RMA) or other chemical products, which aims to remove damage and phyllo-silica minerals (Fig. 14);
- an overflush, consisting in an HCl-salts solution or freshwater, whose goal is to displace the non-reacted mud acid and the dissolved mineral products far away from the well (Portier et al., 2009).

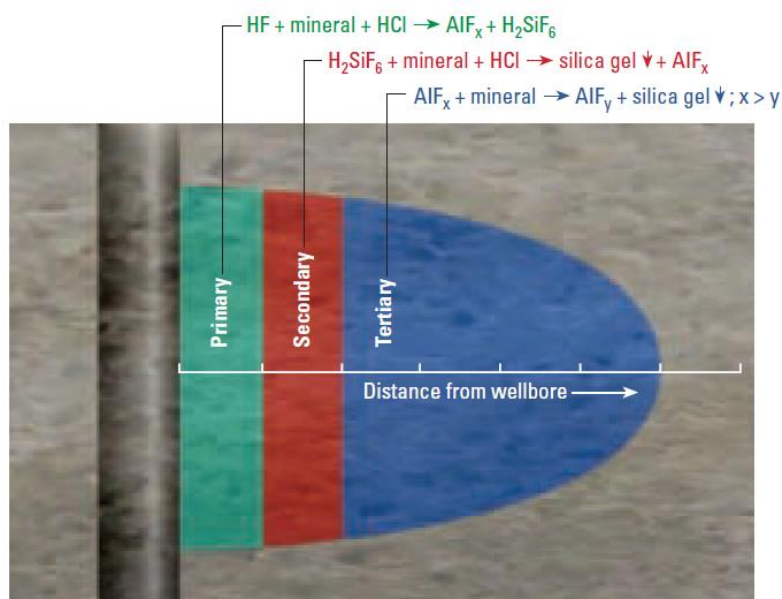


Fig. 14 Sandstone acidizing reactions for an HF-HCl treatment (Al-Harthy et al., 2009). Primary reaction: close to the wellbore, dissolution occurs when minerals get in contact with acids. Secondary reaction: farther from the well bore, the products of the primary reaction reacts with the mineral and the resting acid, producing precipitates (silicate gel). Tertiary reaction: at a greater distance, additional reactions occur, with formation of precipitates

The use of RMA shows several issues. For example, the re-precipitation of secondary reaction products and consequent plugging (Fig. 14; Walsh et al., 1982; Crowe et al., 1986), the limited range of efficiency in the reservoir around the wellbore, and the high toxicity of HCl and HF, are among the main concerns for RMA utilization in geothermal well.

In order to address those concerns, methods for chemically retarded stimulation have been developed. Among those techniques, the use of organic acids or of other types of acid system (gelling agents, emulsified solutions of aqueous acid in oil, acids dissolved in a solvent or solutions of methyl acetate; Malate et al., 1998; Portier et al., 2007; 2009) allows stimulating carbonate and sandstone formation even at high temperatures. In addition to acid treatments, the use of chelating agents (such as EDTA or NTA) has also been developed, particularly for carbonate reservoir. Both organic acid and chelating reactants are environmental-friendly, presenting a high biodegradability rate.

One important aspect to mention for a complete overview of chemical stimulation procedure, in particular in the perspective of a risk assessment, is the impact of the stimulating agents on the well casings. Indeed, the corrosive properties of the different products have important consequences on the metal tubulars. In order to minimize the effect of the chemical stimulation procedure on the casing integrity, the use of corrosion inhibitor should be included in all the acid stages. In addition, the acidification with organic acid or chelating agents induces less severe corrosion tendency compared to RMA. An appropriate and simplified fluid-placement technique can limit the casing damage, allowing at the same time an improvement of the operation efficiency.

Similarly to chemical stimulation, thermal treatment is also a typical soft stimulation technique for geothermal well (Fig. 13). The phenomenon has been characterized by observing the increasing performance of the geothermal injection wells during time. Indeed, the permeability of the reservoir could significantly be improved by the injection of cold fluids, as a function of the temperature difference between the injected solution and the reservoir (Grant et al., 2013). Even if this treatment procedure is generally unrecognized, it is often implemented for geothermal well development during freshwater injection phases. Thus, thermal stimulation can be an indirect result of drilling operation realized with cold water or could be defined as a full stage step of the soft stimulation

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procedure for a geothermal well. In this case, the injection of cold freshwater is generally realized as a first stimulation step, prior to hydraulic and chemical stimulation.

3.2 General description of soft stimulation procedure

In addition to the soft stimulation treatment procedures detailed in section 3.1, the global approach for a soft stimulation on a geothermal system includes several additional phases (Fig. 15).

The first step to improve for the purpose of a soft stimulation is to verify the equipment status, and particularly the well casing integrity (Fig. 15). For this purpose, loggings and borehole imaging allow obtaining information on the completion status on the casing. On the basis of that information, the possibility to realize a soft stimulation on the well and the eventual reparation needs previous to operations will be evaluated. This phase is strongly recommended for an on-going well, but is not necessary for a freshly drilled well.

Before the stimulation treatments, it will also be important to perform an injectivity and/or productivity tests (Fig. 15). This test represents the initial hydraulic and thermal features of the reservoir. The replication of the test after the soft stimulation phase allows evaluating the success and the efficiency of the performed treatment. In addition, the initial hydraulic tests give information about the permeable and productive zones of the well, which constitute important data for the design of the stimulation procedure.

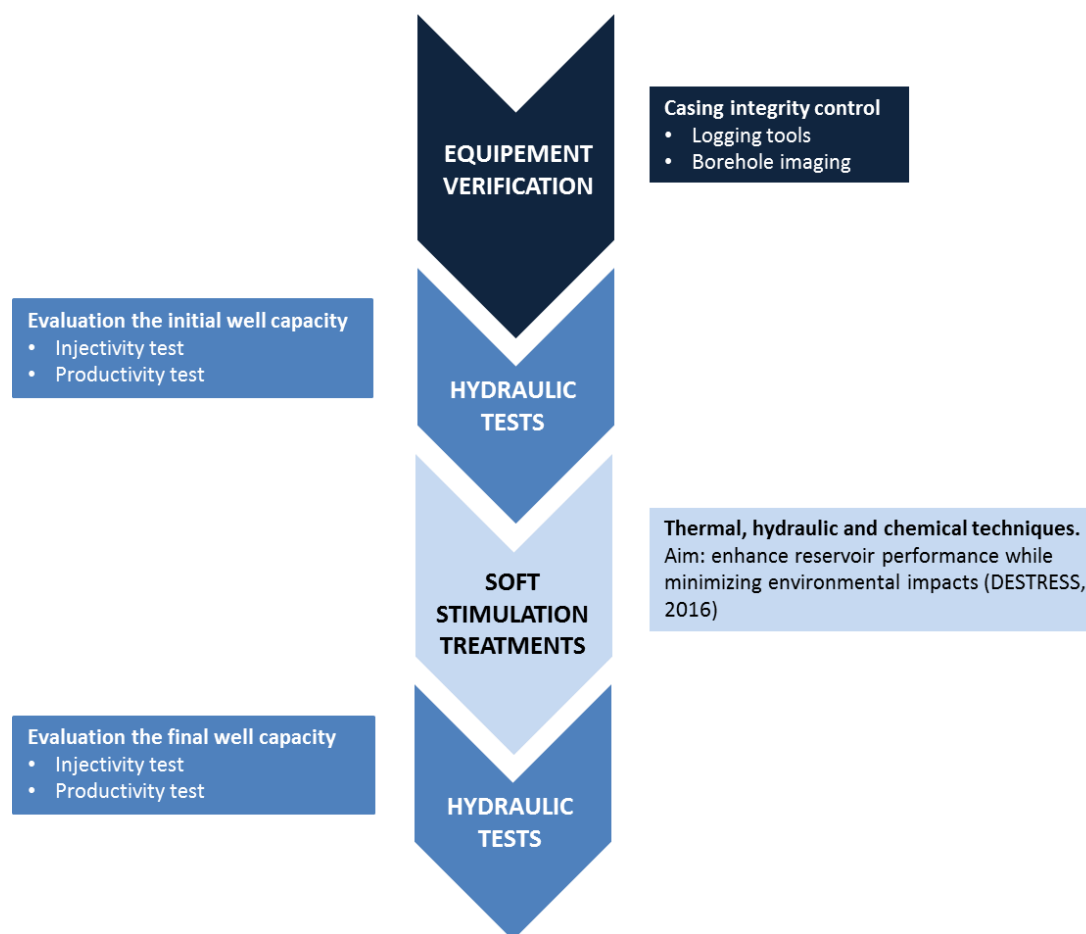


Fig. 15 The global procedure for the realization of soft stimulation treatments on a geothermal site

The realization of a soft stimulation on a geothermal site, including previous and post logging and hydraulic test phases, requires the use of several equipment (Fig. 16, modified from Reith et al., 2017).

Among them, there are the logging tools and the coiled tubing unit, necessary to evaluate the casing integrity and to perform the hydraulic tests. The latter is also essential during stimulation operations to inject the stimulation fluids and the chemicals. Both stages of hydraulic tests and stimulations treatments involve several installations at the surface for fluid circulation (pipe lines, pumps). Pools and filtration system are also necessary for the thermal and hydraulic stimulation, where the pumped brine is reinjected in the reservoir. For the chemical stimulation, a mixing device is necessary to prepare the acidizing fluids. During all the operations, several sensors are deployed to control the reservoir status and evolution. Finally, it is obviously necessary to dispose of a power source and of the security equipment, as the materials for well killing.

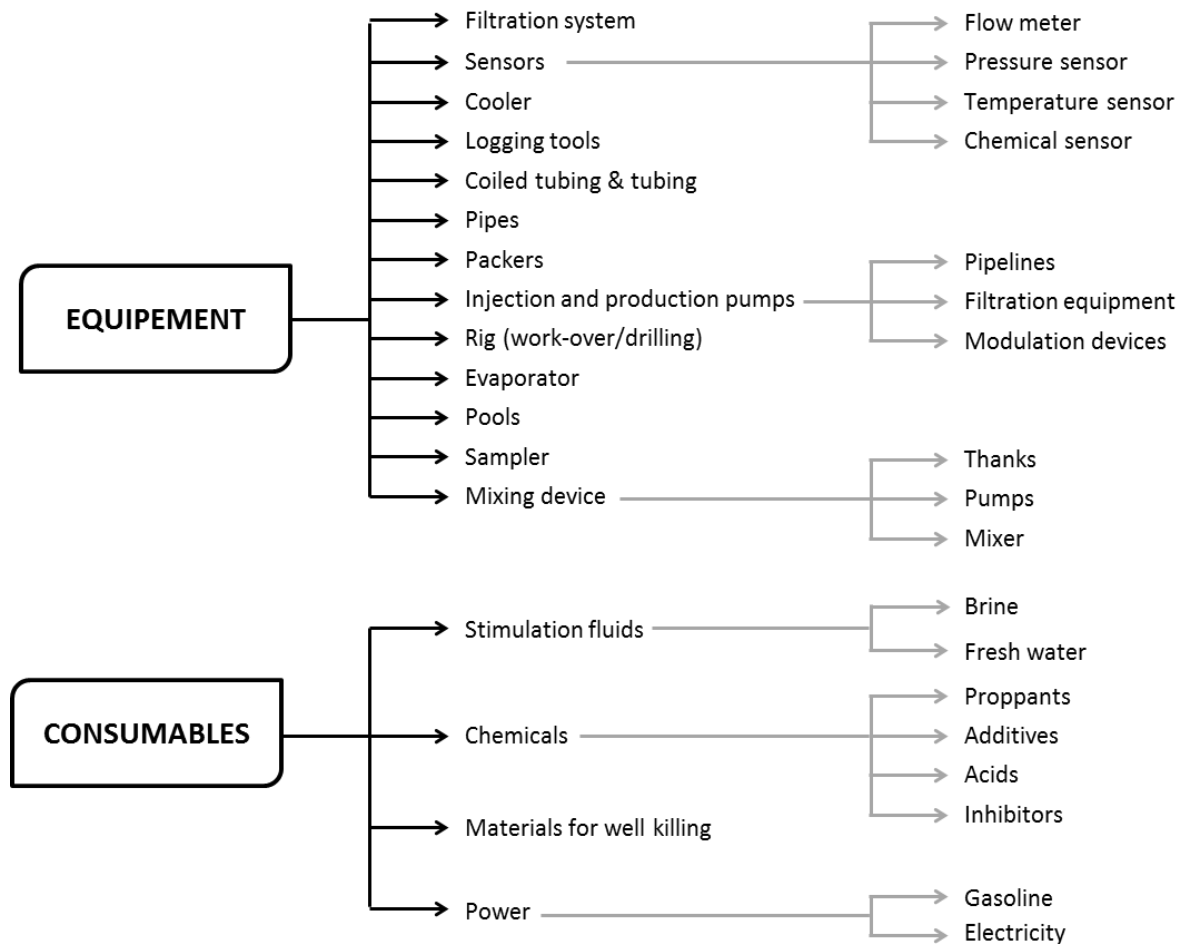


Fig. 16 2 The equipment and consumables necessary for the realization of a soft stimulation on a geothermal site (modified from Reith et al., 2017)

3.3 State of the art of the related risks

The present section has been mainly formulated on the basis of a study report elaborated by the French Institute of the Industrial Environment and Risks¹ (INERIS, 2017) and concerning the risks and potential impacts due to deep geothermal systems. Additional references are systematically specified in the text.

The risks, impacts and nuisance related to the micro-seismic activity induced by the hydraulic stimulation are not detailed in this section, as their evaluation and management are detailed in a specifically dedicated task (DESTRESS, WP 3.2). However, the reader should keep in mind that the risks related to hydraulic stimulation should be added to those discussed here for a complete risk workflow of the soft stimulation phase.

Before getting into the topic of this chapter, it is important to define several terms that will be used thereafter and in particular the meaning of impact and nuisance. It is important to keep in mind that the risks analyzed only includes the potential effects that the geothermal soft stimulation activity likely induces on humans, wildlife (flora and fauna), environment (air, water, soils) and infrastructures. The economic risks will not be included in the analysis.

- Impact

It is defined as the established damages observed on people's safety and health, on physical goods (such as infrastructure, building ...) and on the environment, including wildlife and climate.

The impacts resulted could be characterized as direct or indirect, as well as accidental or chronic. However, the latest category is generally not the consequence of the chemical and thermal stimulation operation, but rather of the day-to-day activities on the geothermal site. Thus, those impacts will not be considered for the present report.

- Nuisance

It is defined as the discomfort occasioned, mainly to people but also to wildlife, by the operations of soft stimulation on the geothermal system.

3.3.1 Potential nuisances related to soft stimulation activities

The nuisances occasioned during the phase of soft stimulation are consistent with those occurring during the drilling and well test periods. As a consequent, risk prevention for the potential nuisances due to the stimulation phase should be included in a general procedure, covering the whole well development phases.

Land use and occupation

I. Event

During the soft stimulation phase, the presence of big-size and important height machines induces a visual impact in the neighboring of the geothermal site (Fig. 17). This nuisance is particularly significant for the installation located in urban area, where housings can be very close.

¹ INSTITUT NATIONAL DE L'ENVIRONNEMENT INDUSTRIEL ET DES RISQUES

II. Risk

In term of risk, the nuisance probability is very likely, as the installation of the machine is unavoidable for the realization of the stimulations. Similarly, the nuisance gravity is significant, as the visual impact is not negligible. However, as the stimulation duration phase is short and that no indirect and/or time-delayed impacts should be caused by any eventual land use impact, no major risks is accounted for geothermal stimulation.

III. Preventive measures

Prevention measures that can be planned to prevent the landscape nuisance include the implantation of protecting wall all around the geothermal site.



Fig. 17 Landscape occupation and visual impact during a chemical stimulation operation (Rittershoffen geothermal site, France). ©és

Noise, odors and greenhouse gases emission

I. Event

The injection of acids and/or water for the thermal and chemical stimulation phases requires the uses of pumps. For acidizing treatments, engines are also necessary to generate the injection solution, as it is mainly composed of a mixture of water, acid and additional components, that needs to be blended in a specific basin or tank. In addition, all the material used to perform the soft stimulation (installations, devices, reactants ...) are generally conveyed on the site by truck on the road.

All those processes produce noises, as well as odors and gas emissions due to the combustion of hydrocarbon fuels. The realization of a soft stimulation procedure may also have consequences on the local road traffic.

II. Risk

Similarly for site occupation, the nuisance probability in term of noise, odors and greenhouse gases emissions is very likely, as the use of engine and the transport of the material necessary to soft stimulation treatments is unavoidable. The nuisance gravity occasioned by those processes is significant but, as the stimulation duration phase is short, no major risks should account for people, environment and infrastructures.

However, the occasioned nuisances could be very irritating for residents, inducing important detrimental effects on the geothermal project acceptability. By consequence, it is important to correctly take into account several parameters, as the natural environment, the social context as well

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as the available infrastructures and to evaluate the preventive measures for the soft stimulation realization as a function of the geothermal site setting.

III. Preventive measures

In order to prevent and minimize the nuisances occasioned on the residents by the use of combustion engine and the road transport, several preventive measures can be adopted. For example, anti-noise barriers can be installed on the site during the stimulation phase (Fig. 18).



Fig. 18 View of the anti-noise barriers installed on a urban working site (DIIS , 2011)

Similarly, noisy operations can be performed in such a way that the more sensitive periods for residents (night, days off ...) and for the ecosystem (breeding season, migration period ...) are avoided. When possible, combustion engine should be substituted by electrical engine and the conveyance of the material made by train and/or boat. In addition, if the road traffic is seriously impacted by the soft stimulation activity, it will be necessary to detail the transport planning and maybe to consider the construction of proper access roads. In any case, residents should be previously warned and informed.

Water resources

The consequences of stimulation on water resources concern both qualitative and quantitative aspects. Hereafter, only the quantitative nuisances on water resources will be considered, as the risk of water pollution is considered as an accidental factor and is thus discussed in section 3.2.2.

I. Event

During chemical stimulation, fresh water is needed to prepare and dilute the products which compose the injection solution used for the acidizing treatment. The volume of fresh water required for those operations varies as a function of the stimulation design and it will roughly be of several tens to a few hundreds of cubic meter. The fresh water necessary for soft stimulation can be drawn from the drinking water network or either from a river, a water body or a shallow non-potable aquifer.

The eventual nuisances concerning the use of freshwater focuses on the impact that this manipulation can have on the environment and eventually on the infrastructures, but no consequences should take place for human health and safety.

For thermal and hydraulic stimulation, the system generally works in a closed loop, where the injected fluid corresponds to the brine previously pumped from the reservoir. By consequent, no risk exists in term of water resource uses.

II. Risk

Due to the small amount of water used during the acidizing phase, the nuisance probability in term of quantitative impact on the water resource is generally not significant. Only the use of freshwater from low-flow river and/or small water bodies can induce significant impact for the aquatic environment and the relative infrastructure. However, the gravity of the risk likely induced on the water resource is important.

III. Preventive measures

It would be necessary when designing the soft stimulation process to evaluate the more appropriate fresh water sources, as a function of the geothermal site equipment, the aquatics elements (and their relative infrastructures) presented in the local environment and the considered season.

3.3.2 Potential accidental impacts related to emanation and/or fluid discharge at the surface during soft stimulation activities

Eruption of underground fluid at the surface

I. Event

The eruption, or in other terms the uncontrolled outlet, of underground fluids (gas or liquid) at the wellhead is a typical risk during the drilling phase. However, this event could occur also during the soft stimulation procedure, as the enhancement of the reservoir connectivity may induce its connection to a high pressure hydrocarbon reservoir. Thus, a blowout of liquid and gas can happen during the discharge phase that ended the stimulation treatment.

Potential effects of a surface blowout strictly depend on the temperature, the pressure and the composition of the emitted fluid. The most common accident concerns the inflammation or explosion of gases, the projection of geothermal fluid (including mineral cuttings, mud, hydrocarbons and gases) with potential burning of onsite people and gas intoxication or asphyxiation.

II. Risk

Until today, any blowout accidents during soft stimulation procedure have been recorded for geothermal sites. However, even if the probability of an event is very low, its gravity is significant, as it may seriously attempt to health and safety of people working on the site. Geothermal site infrastructures as well as the local natural environment could also be damaged and/or impacted by the advent of an underground eruption.

III. Preventive measure

The technical prevention measures for an eventual fluid/gas eruption at the surface are the same than those deployed during the drilling phase of a geothermal well (blowout preventer and viscous plug).

In addition to those preventive installations, it will be important to have a good knowledge of the local geological context so as to know the lithological, fluid and gas components of the reservoir. It will also be important to check and adapt the features of the human team(s) working on the site and

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particularly, the preparation and the experience of the staff and their respect of the QHSE norms during the activity.

Leakage or spillage of a surface reservoir

I. Event

Fluid leakage or spillage can occur on the site, for example as a seepage or overflow of the reservoirs containing fuels, oils, acids or other additives that are present on the geothermal site. Fluid losses can also occur during transfer and/or mixing of those products, when the material is supplied, or while preparing the mixtures for the acid treatment or even when the products are stored before their elimination. An overflow may also happen on the basin dedicated to the storage of brine and/or freshwater (Fig. 19).

In addition to all those processes, external causes can also induce product spillage during soft stimulation activities. In particular, floods and/or significant amount of rain, could results on the spillage of industrial open-reservoir.



Fig. 19 Basin for brine storage during the chemical stimulation at the Rittershoffen geothermal site (France). ©és

II. Risk

There is a probability that a leakage or spillage event occurs at the surface of the installation during a thermal or chemical treatment. However, the gravity of this eventual accident is limited. Theoretically, no injuries should be induced to the human being, both on site workers and resident. Damage can be associated to the natural environment, as soils, surface water and potentially to the local flora and wildlife. The geothermal site installations as well as eventual recreational infrastructures and activities situated in the proximity of the impacted area can be damaged. However, as the consequences are spatially localized and temporary, the nuisances induced by this type of accident only have minor impact.

III. Preventive measure

In order to minimize the chance of a leakage or spillage event on the site, it will be important to verify the condition and the suitability of the infrastructures present on the site as a function of the operations that will be realized. Otherwise, storage and operation facilities should be prepared to allow optimal conditions for the manipulation of the products during the stimulation treatment. In addition, it will be important to also verify the material and the competences of the working companies.

Leaching on the primary or secondary circuit

I. Event

Similar to reservoir and tanks leakage or overflow, a leakage event can also occur on the primary or secondary circuit of the plant installation (Fig. 20). During soft stimulation treatment, the leakage potentially concerns fluid as the geothermal brine, natural water or chemical stimulation fluids containing acids and other additives.

The main mechanisms inducing this type of event are linked to the quality and the state of the circuit. In addition to eventual defaulted pieces, the main failures can result from the corrosion processes affecting the installation during geothermal water circulation period. When it concerns the circuit metallurgy, the corrosion effect can induce important leakage problems.



Fig. 20 Surface circuits for the preparation and the mixing of acids for chemical treatment at Rittershoffen geothermal site (France). ©és

II. Risk

The risk of leakage from the surface circuits during acidizing and/or thermal stimulation is important only when it concerns the aged installation, where fluids circulation have already occurred over a long period of time before the stimulation operations begins. In such case, major spill risk would more likely arise during the plant operation period and not during the soft stimulation, of which the period is much shorter. On the opposite, no spill problems should be observed on new well and surface installation. Thus, the potential occurrence of surface circuit leakage event is quite low.

The gravity of fluid spill from of the primary or the secondary surface circuit during soft stimulation is quite limited, mainly resulting in contamination of the natural environment as soils and surface water by runoff and infiltration. The latter can also induce a possible pollution of ground water. Consequences for human health and safety are of minor gravity and resulted from the indirect damages caused to the environment.

III. Preventive measure

Among the main preventive measure to consider in order to avoid this type of accident, it is important to verify the infrastructure conditions before starting the soft stimulation operations. If important damages are identified in the equipment containing the fluid circuits, it will be important to fix or change the faulty pieces before starting the treatments (Fig. 21).

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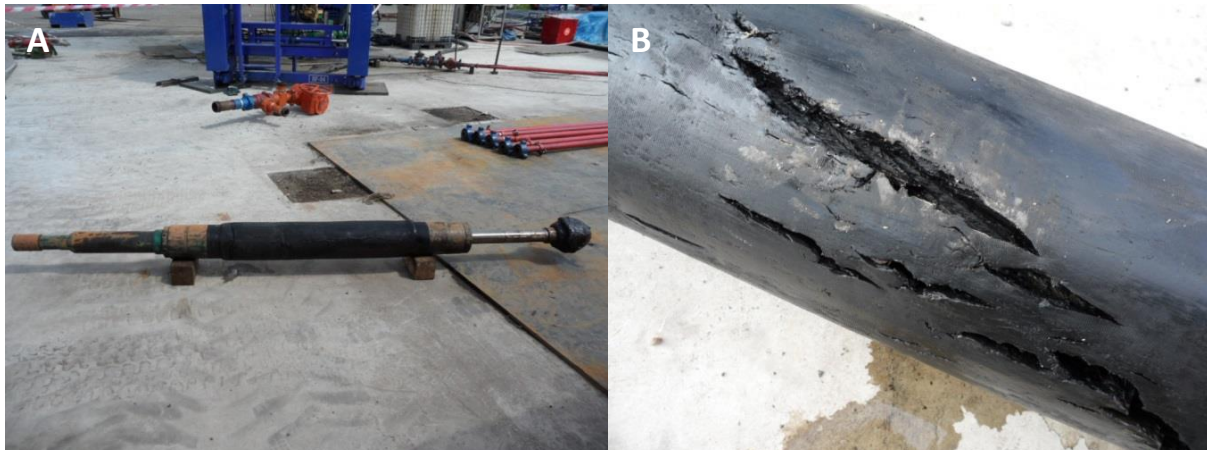


Fig. 21 A) A packer deployed on coiled tubing to isolate the preferred treatment zone. B) A cracked packer damaged during the operations of chemical stimulation at Rittersshoffen geothermal site (France). ©és

Emissions of important quantity of gases dissolved in the fluid

I. Event

In this case, the undesirable event is the unexpected critical degassing of the geothermal fluid. This process can particularly occur during well cleaning phases, which are often carried out during soft stimulation procedures.

The main mechanism involved in this type of event concern an arrival of fluid very enriched in dissolved gas.

II. Risk

The probability of a critical degassing during soft stimulation treatment is very low, as to this date no such accident has ever been reported to have occurred at geothermal installation.

However, the gravity of such an event could be very important, particularly in confined environment. Nevertheless, such conditions are rare for geothermal stimulation operations, which are likely to be performed outdoor.

In conclusion, even if the risk for human, infrastructure and environment are limited, it should be noted that important degassing could have long-term and indirect consequences, as the impacts on the climate and on atmospherically processes, like acid rains.

III. Preventive measure

The prevention measure for important outgassing corresponds to those used to control a fluid eruption, and particularly the presence of a blowout preventer and the implementation of a viscous plug. Other preventive actions already cited in the previous paragraph concerning the fluid eruption risks are also important in the present case (good knowledge of the brine and the reservoir, experience and preparation of the working team)

3.3.3 Potential accidental impacts related to underground contamination during soft stimulation activities

Fluid intrusion in an aquifer

I. Event

During the soft stimulation phase, it is possible that a fluid intrusion occurs in the aquifer layers, likely used for drinkable water, irrigation, industrial purpose, etc. The source of the contamination can be the chemical fluid used for soft stimulation, the geothermal fluid or even gases.

A fluid intrusion during the soft stimulation treatment is mainly resulted from sealing defaults of the well tubing, corresponding to a breakout or perforation of the well casings. Currently, damages to the well structure are induced over a long time period, such as the operation phase. Among the main factors inducing casing defaults and relative fluid losses, the most important are:

- Corrosion: this process is induced by the aggressive chemical composition of the brine and lead to severe damage in the installation (Fig. 22)
- Thermo-mechanical constraints: the wells, particularly deep geothermal wells, are subjected to different constraints, both thermal and mechanical, which can strongly impact their integrity.

Occasionally, initial defaults of the material and erosion processes (physical erosion and erosion induced by the tool transit during well life) can affect the well integrity.

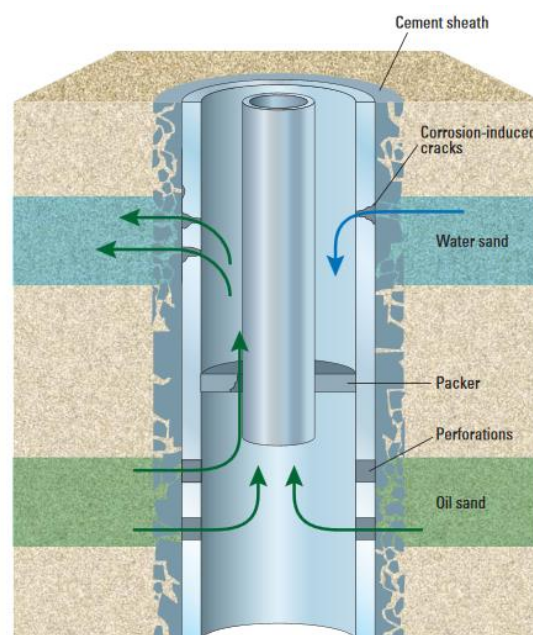


Fig. 22 Corrosion impacts on casing integrity (Abdallah et al., 2013)

II. Risk

The severity of a fluid intrusion in an aquifer depends on the flowrate, volume, temperature and chemistry of the fluid. Similarly, it is also influenced by the type of exploitation of this aquifer. An intrusion of the acidizing treatment fluid in a drinkable water aquifer would have significant consequences compared to the intrusion of fresh water used during thermal stimulation in an unexploited aquifer.

As mentioned before, the risk of groundwater contamination from well fluid leakage would likely occur during the stimulation of an already existing and operating well than of a newly drilled well.

III. Preventive measure

The preventive measure necessary to avoid this type of accident includes an attentive verification of the well conditions before starting the soft stimulations. If important damages and/or fluid losses are identified, it will be important to repair or change the defaulting tubing before starting the treatments.

4 Operational soft stimulation risk workflow

During all the risk study, an expert team is required, gathering a wide range of skills. This team should be constituted by experts from different fields, such as geology, geophysics, drilling, environment and management. A non-exhaustive list of all the most important skills that need to be represented in the team is as follows:

- A reservoir expert
- A geology expert
- A geophysics expert
- A drilling expert
- A drilling platform expert
- A health and security expert
- A quality expert
- An environmental expert
- A geochemist expert
- A project management representative
- A soft stimulation service company representative

It is important to note that a person may have several expertises. Furthermore, this list is an “ideal case” but may be reduced and/or adapted as a function of the experts potentially available.

4.1 Context

As proposed by the IRGC (2008) and the ISO norms, the definition of the context for the study is the preliminary step for a risk assessment. The context settings are intended to be the base of all decisions taken during the risk assessment procedure, as it defines the limits of the study as well as all the detailed specifications of the system that should be assessed (site description, stimulation design, etc.)

What

The information needed to set up the context mainly concerns an accurate knowledge of the drilling site and a detailed program of the chemical stimulation.

Who

The context is defined by the team presented above.

When

As mentioned, the context definition should be done at the very beginning of the study, before undertaking the first phase of the risk assessment procedure, the risk identification. Several context revisions may be necessary all along the procedure, when an indirect modification is engendered by a deviation from the initial system (ex. Changes in legal context, modification of the chemical stimulation planning ...).

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How

To set up the context, each member of the team should describe the elements of the system corresponding on its field expertise in detail. All the specifications should be communicated and discussed to establish a final and accepted version.

The following sections describe the items that should be filled out and discussed by the expert team.

4.1.1 Site settings

The site setting definition is a key step to establish the general context of the stimulation procedure and thus undertake the risk assessment approach. For the site settings elaboration, several sub-systems will be analyzed forming the global site framework. As presented in Fig. 23, the main units proposed to be taken into account in the present work are: the geological settings, the boreholes, the stimulation site, the on-site human activities, the natural environment and the human environment, with the relative infrastructures.

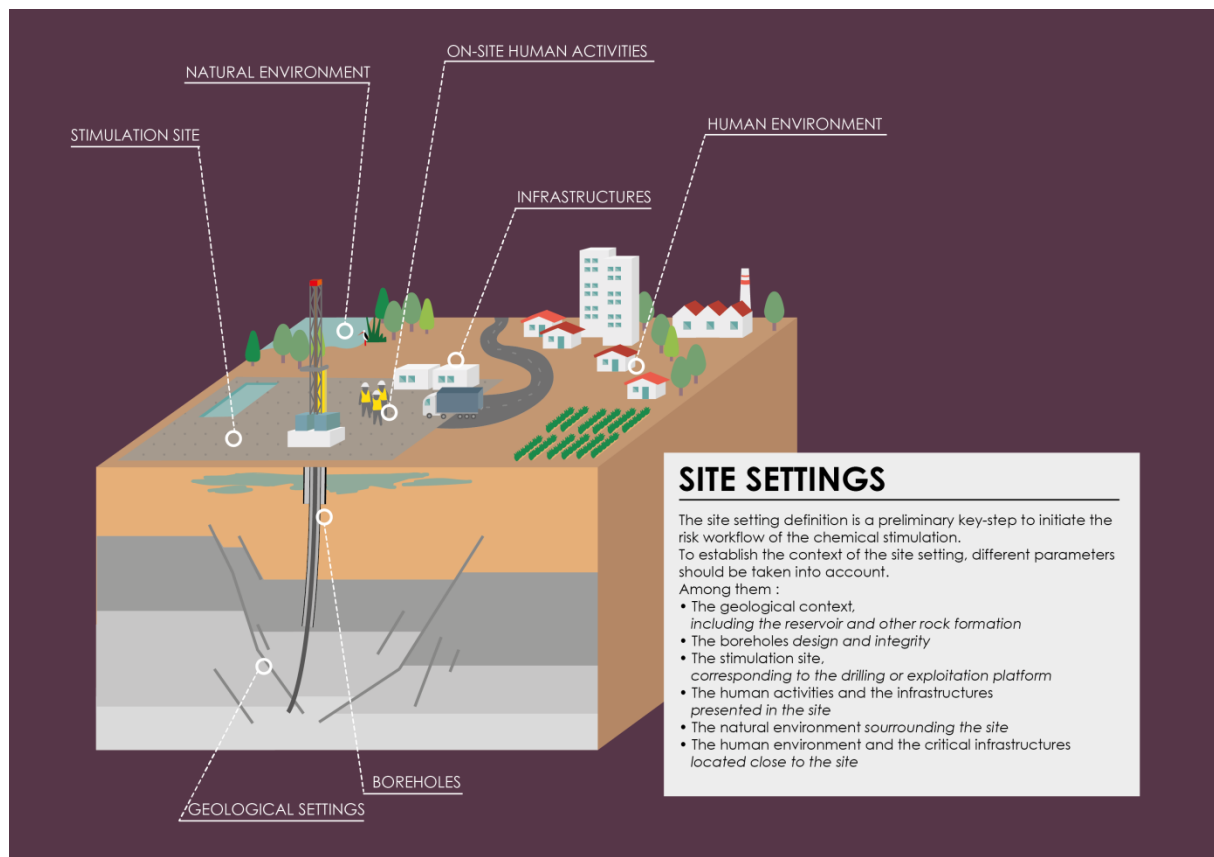


Fig. 23 The site settings: a global view and the integration of the different elements composing the global context

Hereafter, each sub-system will be analyzed and the main items to describe highlighted.

Geological settings

To define the site setting, one main issue is to precisely describe the geological context of the stimulation site, including the geothermal reservoir parameters, but also information about the general geological context surrounding the reservoir itself.

- Reservoir information

Among the main information concerning the reservoir, it is important to include items such the lithological features, the physical properties (temperature, pressure, ...), the geochemical issues (composition, hydrocarbon, ...) and the tectonic conditions. Table 2 presents a detailed list of the specifications for the reservoir context.

Table 2 Specification list for the reservoir information to include in the site settings

Item	Comments
Rock type	Crystalline basement, sedimentary formation, accurate definition of reservoir lithology
Porosity/permeability	Matrix, fractures ...
Depth	Top and base depths
Temperature	Temperature at the level of reservoir, temperature gradient ...
Pressure	
Hydrocarbon	Presence of hydrocarbon reservoirs in the surroundings
Geochemistry	Geothermal fluid chemical composition: chemical composition, mineralogy of solids content, dissolved gases ...
Tectonic stress field	Orientation and magnitude of the principal stress

i. Other rock formations (outside reservoir)

A similar analysis should be made for the rock formations surrounding the reservoir, mainly the presence of other sensitive rock formations as deep aquifers, hydrocarbon reservoir and also the exploitation of other geological resources. The different elements are described in Table 3.

Table 3 Specification list for the other rock formations to include in the site settings

Item	Comments
Hydrocarbon	Presence of hydrocarbon reservoirs on the site underground
Sensitive rock formations	Clays, saline formations ...
Deep aquifers	Presence and potential natural inter-connections with rock formation
Underground exploitation	Mines, quarry, gas storage ...

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Boreholes

Information on the boreholes into which the chemical stimulation will be performed is necessary for the site settings definition. In particular, it is important to describe the borehole completion, the status of the borehole prior to the stimulation and its connection with the reservoir. Details on the borehole information are mentioned in Table 4.

Table 4 Specification list for the boreholes to include in the site settings

Item	Comments
Completion	Scheme, casing diameters and grade, cementation ...
Status	Casing integrity, corrosion, possible leaks ...
Reservoir	Type of connection between reservoir and borehole open-hole section: simple/multiple fractures, matrix,...

Stimulation site

This part of the site settings describes in detail the site where the stimulation will be performed, which could be either a drilling or an exploitation platform. Details in terms of location, access, facilities and on-site fixed and mobile equipment should be indicated, as presented in Table 5.

Table 5 Specification list for the stimulation site to include in the site settings

Item	Comments
Site access	Platform circulation ways, parking lots, access control, site security
	Presence of buildings and base camp
	Piping and drilling rig: characteristics, auxiliary facilities, surface area ...
Infrastructures	On-site auxiliary equipment and storage places
	Machinery and vehicles
	Servicing: water and gas supply, electrical, phone and Internet networks
	Dimensions
Platform design	Structure: type of concrete, loading capabilities ...
	Rainwater and wastewater draining system

On-site human activities

Details should be described concerning all potentially on-going human activities on the site during the soft stimulation treatments. In particular, it will be important to define the number, the origin and the experience of the people, the execution of simultaneous activities and the controls of the QHSE² policy. Table 6 lists the information required about the on-site human activities.

Table 6 Specification list for the on-site human activities to include in the site settings

Item	Comments
Company	Number of companies on site and of people in each company Simultaneous activities between different companies Languages Training and experience of involved workers
QHSE	Prevention plan, regular safety meetings, emergency and rescue simulation exercises, training, work schedule, working conditions, work permits, personal protective equipment

Natural environment

Detailed specifications should be given also concerning the natural environment and its eventual pollution sensitivity. As detailed in Table 7, climate, fauna and flora, surface water and groundwater, soils and air conditions should be included, as well as all the existing measures taken for their protection and for pollution prevention.

Table 7 Specification list for the natural environment to include in the site settings

Item	Comments
Climate and air	Seasonal meteorological and climatic conditions (excluding catastrophic events)
Fauna and flora	Protected area and/or species around the site, critical period during the year ...
Groundwater	Depth, utilization purpose...
Surface water	River or water bodies around the site, flowrate, utilization purpose ...

² QUALITY, HEALTH, SAFETY AND ENVIRONMENT

Soils	Type of soils
Human environment and neighboring infrastructures	
Information on the human environment and the neighboring infrastructures are necessary to set up complete site settings. It is thus important to specify the geographical, social and economic context, the acceptability devoted to geothermal project, and also to clearly define the visual environment close to the stimulation site and the acceptable noise level. All those items are detailed in Table 8.	
Table 8 Specification list for the human environment and neighboring infrastructures to include in the site settings	
Item	Comments
Geographical context	Population density: rural or urban area
	Land use: cultivation, animals farming ...
	Transport networks to access the site: presence and types of roads, railways, waterways, maritime ...
Social and political context	Political situation
	General level of acceptability toward industrial project and geothermal project
Economical context	Neighboring economic activities: industry, tertiary, presence of sensitive infrastructures ...
Cultural and architectural context	Types of neighboring housing, architectural and cultural heritage buildings ...
Nuisance	Visual environnement and ambient noise level

4.1.2 Stimulation design

The definition of the context for the soft stimulation risk assessment procedure aims to give an exhaustive overview of all the elements concerning the stimulation treatment design, from the conception toward the logistics features.

It is important to note that some items of the site settings, and particularly the stimulation site and the on-site human activities may change if the stimulation design is continuously modified. The other items are, on the contrary, related to the general environment of the site and thus, do not depend on the stimulation design.

Conception

The stimulation design includes different conception steps. In addition to the injection methodology, describing the protocol of the whole soft stimulation treatment performing further preliminary studies are necessary. This phase allows characterizing the reservoir and the stimulation fluids

properties, as well as their interactions. Additional details on the different items to discuss concerning the conception of the soft stimulation design are reported in Table 9.

Table 9 Specification list for stimulation conception to include in the stimulation design

Item	Comments
Preliminary investigations	Laboratory tests on representative cuttings and/or cores, compatibility with geothermal fluid Feasibility study and experience of the service company
Injected stimulation fluids	Chemical and physical characteristics, expected effect and efficiency, toxicity and safety data sheet
Injected additives	Inhibitors, clay control ...
Injection methodology	Volume of stimulation fluid, applied flowrates and pressures Flushes sequence and washing out sequence, Depth of injection; wellhead or downhole injection, Drilling strings, coiled tubing, packers, ...

Logistics

As presented in Table 10, the logistics context of the stimulation design setting concerns the needed equipment, its transportation and storage modes on the site, the mobilized human resources and the duration of the operations.

Table 10 Specification list for stimulation logistics to include in the stimulation design

Item	Comments
Transportation and storage mode	Access: road, rail ... Transportation and storage form of the chemicals and additives: powder, fluids ... Storage container: open or closed tanks, jerry cans ...
Equipment	Vehicles, tanks, mixing units, pumping units, pipes ...
Human resources	Number of person, company affiliation, experience ...
Date and duration of the operations	Related to the seasonal meteorological conditions

4.1.3 Model limits

This section aims at defining the limits to the execution of the stimulation risk assessment study. It includes the limits of context, exposure and vulnerability beyond which the surrounding human and natural environment will not be impacted by the stimulation.

Threshold for risk assessment for soft stimulation

- Regulatory context and threshold

The thresholds that are defined by regulation are mandatory and must be imperatively respected. This includes all the regulation linked to the Public Health Code, the Environmental Code, the Labor Code and the Mining Law.

- Ethical context and threshold

In some cases, the QHSE policy of the site owner or the operating company may be more restrictive than the regulation, for internal ethical reasons. Thus, the applied threshold may be strict than those defined by regulation.

Conceptual limits of impacted medium

During the context definition, it is important to identify the elements of the natural and human environment considered as potentially damageable by the soft stimulation procedure. This choice should be adapted for each case study, as a function of the site settings and the stimulation settings previously defined. Indeed, it is important to emphasize that the risk assessment procedure will not take into account the damages done on external elements not mentioned in the conceptual limits.

For a classical soft stimulation treatment, it is suggested to consider in the study the mediums composing the human and wild life environment, i.e. fauna, flora and humans, and also the life environment medium, including waters, air, soils and infrastructures (Fig. 24).

The reservoir could be considered as an impacted medium, but in the present case it was deliberately not taken in account because eventual damages on the resources are further translated into economic effects, which are not considered in this study. Acceptability is part of the context and a potential risk source. However, it is not considered as a directly damageable parameter, but rather as a consequence of the damages on the natural and human environment mediums.

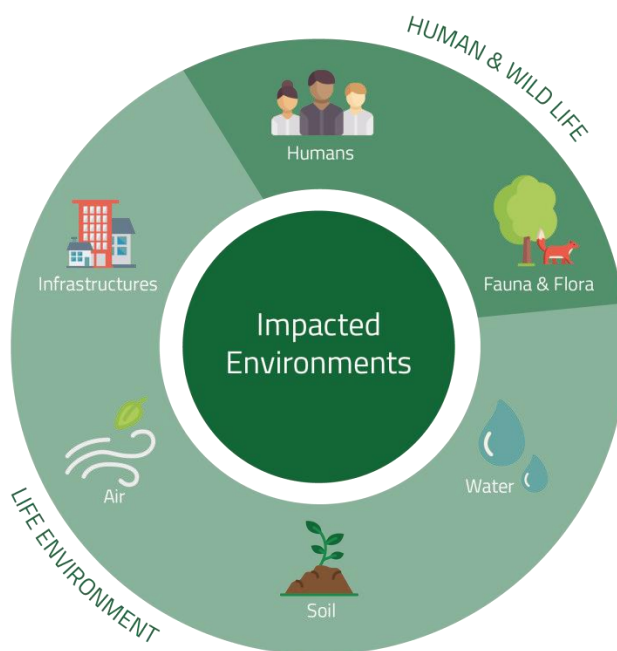


Fig. 24 The impacted environment defining the conceptual limits of the model

Geographical limits

For the context definition, it is important to fix the geographical limits of the risk assessment study. Hereafter, numerical values are proposed for several items, based on the geothermal experience in the Upper Rhine Graben (Table 11). Those geographical limits were defined *a priori* in order to estimate the maximum area that could be impacted by potential nuisances and pollution. However, it is strongly recommended to re-evaluate these values as a function of a given project’s context.

Table 11 Geographical limits for impacts on human, wildlife and life environment to include in the general context

Item	Geographical limit
Natural and human environment	
Fluid leakage at the surface	~100 m around fluid transportation paths and stimulation site
Fluid leakage in borehole	~1 km around the stimulation site
Gas emissions	~1 km around fluid transportation paths and storage location
Infrastructures and human environment	~10 km around the stimulation site and directly around fluid transportation paths and storage location
Acceptability	No limit, as the information of any incident can easily be spread worldwide

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Temporal limits

Similar to the geographical limits, temporal limits should be defined for the risk assessment study. For the present work, it is suggested to fix the temporal limit of the procedure immediately after the end of operations and the total demobilization of the service company's equipment for human and infrastructures. Concerning the natural environment and wildlife, risks may continue until the total consumption, disappearance or degradation of the chemical agents. These processes might take from some tens of days to several years depending on the type of chemical. It is important to note that indirect risks may continue for people and infrastructure also after the end of the operations, if the natural environment is impacted.

No temporal limits are fixed for the acceptability issues, as the information of any accident during or after the operation may damage the geothermal project perception.

Natural risk

Natural risks should also be taken into account for the definition of the global context. The potential impact of natural risk should be evaluated as a function of their probability of occurrence, regarding the duration of stimulation operations (1 to 2 weeks) and the temporal limits described above.

Seasonal events should be taken into account in the stimulation design in order to schedule the most appropriate period for the operations.

Additional limits

Even if financial risks are not taken into account in this study, the context of the study may be strongly influenced by economic criteria. For example, the choice of the stimulation design and the risk treatment measures depend on the financial aspects of the project. Thus, when discussing the context, these parameters should also be satisfied.

4.1.4 Summary

As presented in the previous sections, the establishment of the context should take into account several parameters, concerning the site settings, the stimulation design and the model limits. In order to summarize the different items to discuss, a general context checklist is proposed in Fig. 25.

However, it is important to highlight that the proposed approach is not intended to be exhaustive but can in theory suits for all possible contexts. Indeed, the role of the expert team is to have a critically examination of all the items and to adapt the procedure following the features and constraints of the analyzed project.

Risk assessment for soft stimulation treatments of geothermal reservoirs

CONTEXT CHECKLIST

Tick-out items while establishing the context □

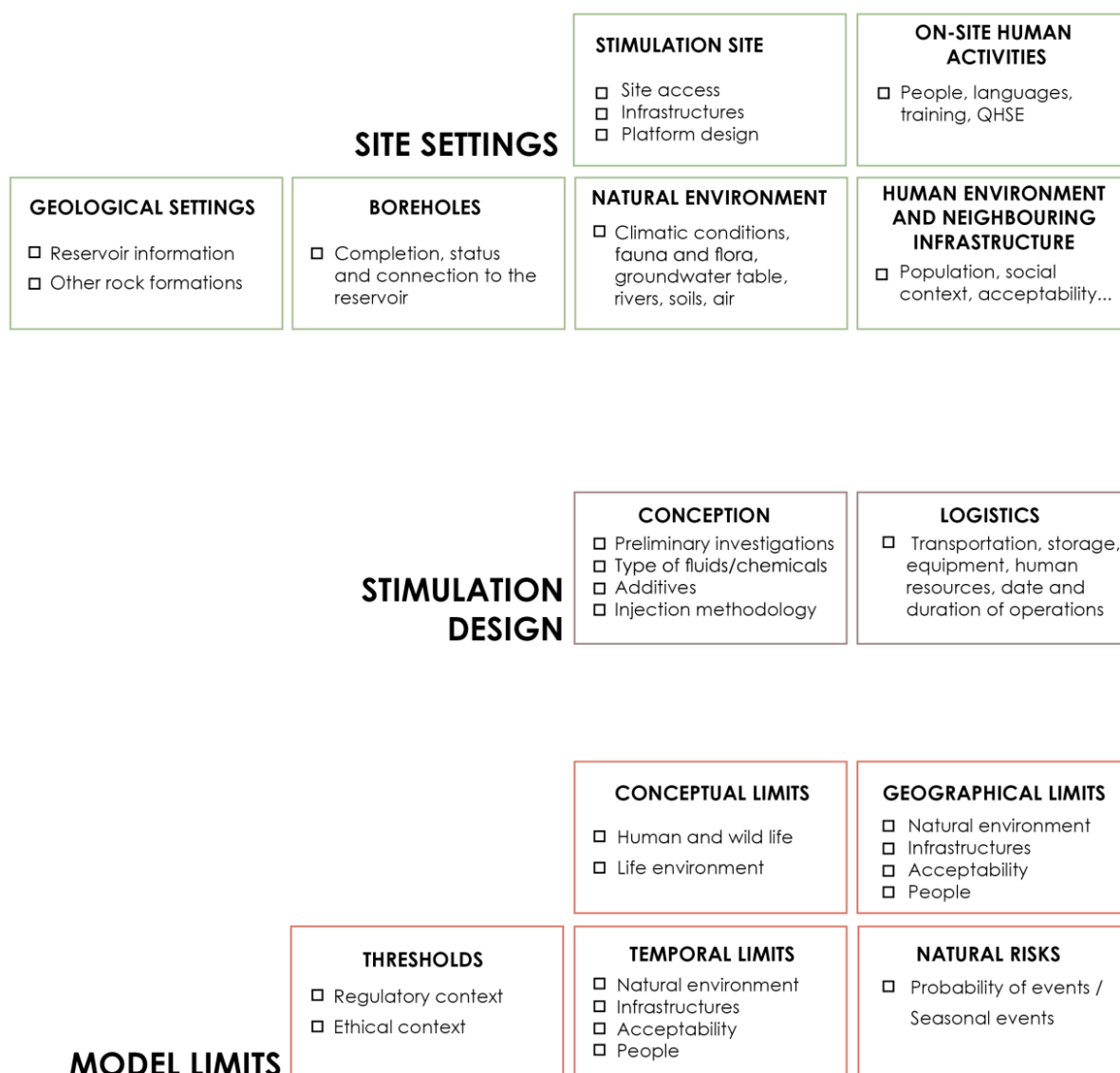


Fig. 25 A checklist presenting the main items to consider while establishing the context

4.2 Risk identification

The risk identification aims to obtain a complete list of the expected risks of the soft stimulation. As presented in section 2.3, the classical methods usually applied to perform this first phase of the risk assessment are brainstorming, checklist, environmental risk analysis and scenario analysis.

Following an attentive analysis of each method, it is suggested here to mainly combine the **brainstorming** and the **checklist tools**. Both of them do not require abundant and statistical data on previous accident or failures; information that is not available in the soft stimulation treatment in the geothermal field. The brain-storming gives the chance to take into account all the ideas coming from the expert, while the checklist serves as a guideline structuring the whole procedure. It is suggested, to perform the risk identification phase, to apply a procedure of “semi-guided” brainstorming, based on the improvement/creation of a checklist concerning the soft stimulation procedure.

A scenario analysis approach can also be included in the method. In this case, an analysis of all the phases of the soft stimulation procedure and of all the possible deviation to the main scenario will be done.

To implement the “semi-guided” brainstorming procedure and identify the risks related to the soft stimulation procedure, several steps are necessary. All of them can be realized through the collaboration of a multidisciplinary expert team and the designed facilitator (Fig. 26).

Meeting preparation

Before starting the risk identification procedure, the facilitator has to prepare several documents (Fig. 26):

- Methodology

The facilitator prepares a document explaining the methodology of the ongoing brainstorming, in order to present it to all the participants. The risk identification procedure should take place according to the following steps:

- Constitution of the expert team constitution
- Discussion of the different phases of the soft stimulation through the “semi-guided” brainstorming method
- Results presentation in an enhanced checklist integrating newly identified risks

- Context

The facilitator prepares a document summarizing the context of the study. It could be either a complete report or it may be presented as a global sketch representing all the context elements and their specifications of the studied soft stimulation procedure.

- Checklist

Based on his experience and/or on existing documents, the facilitator creates and/or improves a checklist that covers the most expected risks for soft stimulation. The checklist should be a structured document, where risks are listed to logically follow a chronological, geographical or activity-linked distribution.

- Soft stimulation context

The facilitator prepares a document concerning the soft stimulation planning; where all the phases are identified and explained. This document will be based on the previously discussed context of the soft stimulation.

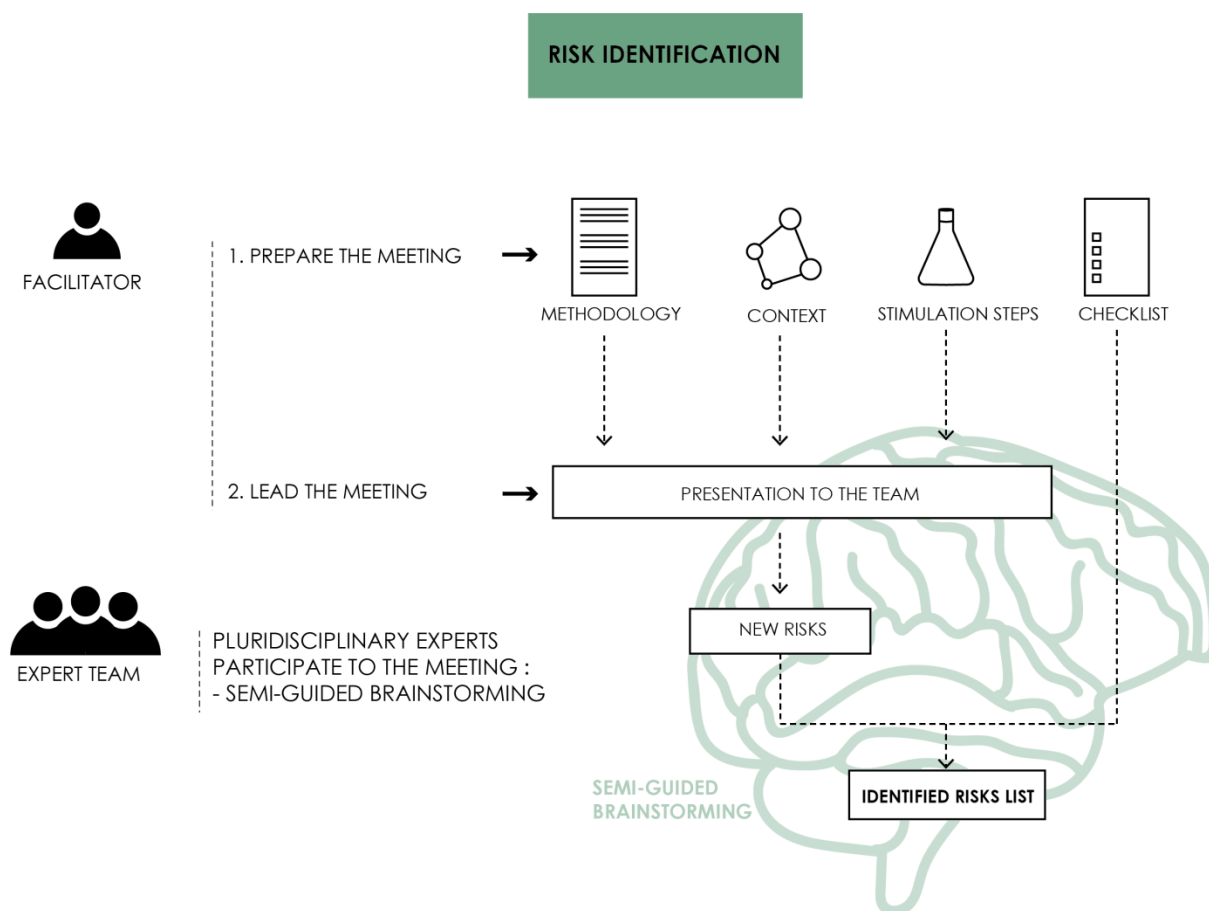


Fig. 26 Workflow for the risk identification phase

Realization of the semi-guided brainstorming

After the meeting preparation, the phase of risk identification starts. This procedure begins with the presentation of the methodology and of the context of the study to all the participants.

Then, an inventory of all risk ideas raised by the experts during the brainstorming procedure is gathered for each stimulation phase (Fig. 26). In all of the procedure, the facilitator has the task to guide the expert team with clues from the existing checklist. In order to boost the procedure, the facilitator could also rely on the established planning of the soft stimulation and the analysis of different deviation scenarios. In parallel, the facilitator should update the existing checklist with the new identified risks. Once the procedure is closed, the enhanced checklist is presented to the expert team in order to be collectively validated (Fig. 26).

It is important to note that the experts are not necessarily familiar with risk studies as the difference between the notions of risk, danger, cause, etc. is not so intuitive, thus the final checklist may contain confusions between those points. As a result, not only risks, but also causes or consequences that may lead to dangerous situations should be included in the final document. Thus, it is suggested to organize the results of the risk identification phase before starting the risk analysis procedure to clearly identify the nature of each item identified during the “semi-guided” brainstorming.

4.3 Risk analysis

The risk analysis phase consists in the classification and the analysis of the results issued from the precedent phase. It must allow identifying the different risks for each phase of soft stimulation procedure recognizing the corresponding causes and consequences in a given security context. To perform the risk analysis, it is suggested to implement the **environmental risk assessment** method, as it allows a very detailed understanding of the problems by the contribution of an expert team.

The risk analysis phase should start with the creation of an analysis document, containing all the items that should be discussed to characterize the risk and in particular: the soft stimulation phase, the risk, the cause, the consequence and the security context (Table 12, Fig. 27).

Table 12 An example of a document analysis for the risk analysis. In red, the items that were previously gathered during the risk identification phase and in black the elements discussed during the risk analysis phase.

Phase	Risk	Cause	Security context	Consequence
P1	R1	C1	SC1	Cq1
P1	R2	C1	SC2	Cq1
P2	R3	C2	SC3	Cq2
...
Pn	Rn	Cn	SCn	Cqn

The task of the facilitator is to prepare the document by introducing all the items gathered during the risk identification phase, while distributing them into the appropriate category (Table 12, Fig. 27). Then, each expert will participate in order to complete the items associated with their specialties (Fig. 27). It is likely that many experts may have to be involved because the domain of the causes of a risk may differ from the domain of the consequence (e.g. a drilling accident may have impacts on the environment, so both drilling and environmental experts may be needed).

It is important to note that each line of the analysis document must correspond to a different situation. Practically, as the same risk may have different causes and/or consequences and/or security contexts, it is important to have a specific line dedicated to each combination of factors. By consequent, the same phase/risk/cause/consequence/security context may be cited several times, but it will not be possible to have several causes, consequences, security context on the same line (Table 12).

This document can be filled in without taking the order of the columns in account. The fill in order will depend on the facilitator, the expert team and also on the context of the study. In any case, it could be useful to answer to a specific question to complete each column.

- Phase: *when does the triggering event take place in the stimulation program?*
The answer must be a phase of the chemical stimulation. In general, it can be suggested to consider six main phases: design, transport, storage, preparation, acid job and post job.
- Risk: *what is the type of risk incurred?*

- For example, if one gets burned by the geothermal water, then the risk is the risk of burns.
- Cause: *why does the risk and/or the damage occur?*
 If the consequence is a pollution of groundwater, then the cause can be a leak in the casing because of wrong inhibitor or casing failure.
 - Security context: *what are the existing prevention and mitigation measures related to the risk/cause the/damage?*
 The answer of this question can be existing standards or regulations, established procedures, safety meetings, established regular controls, etc.
 - Consequence: *to what does the damage correspond?*
 The answer may be pollution, injuries, destruction of building, etc.

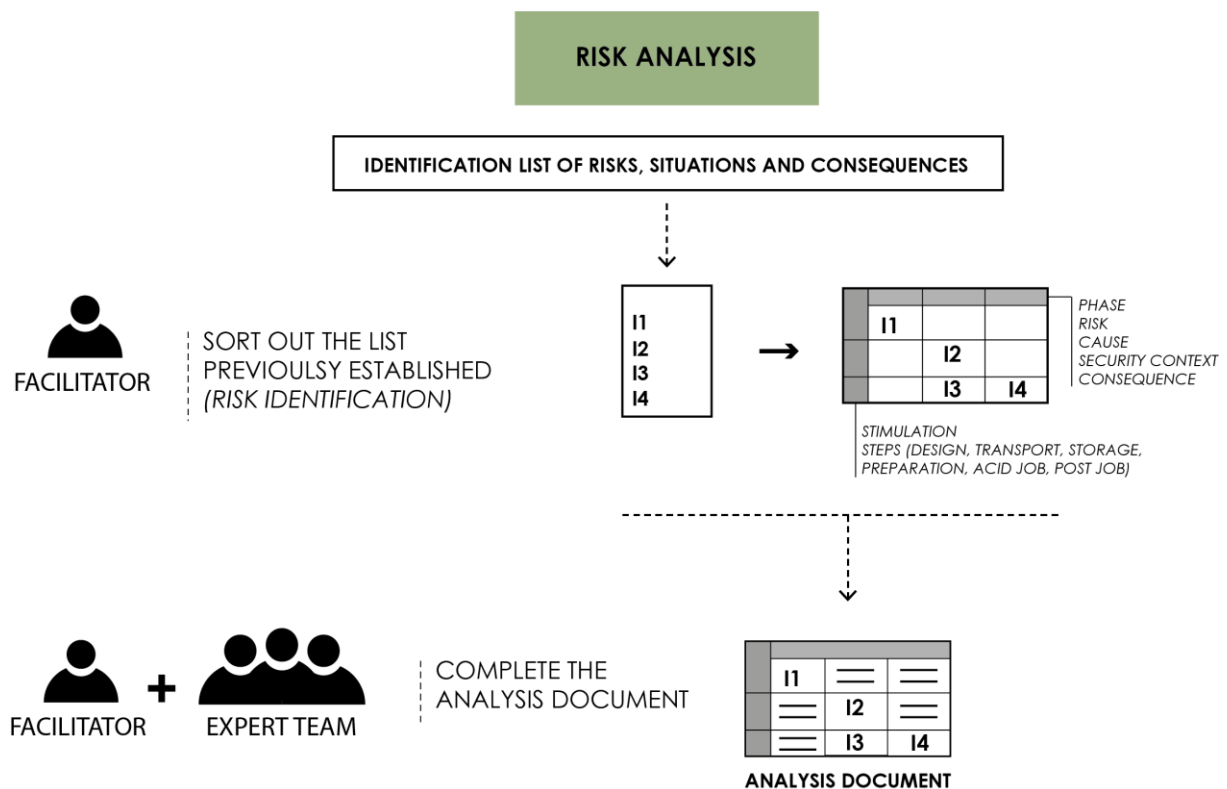


Fig. 27 Workflow for the risk analysis phase

4.4 Risk evaluation

This phase consist in the evaluation of the global importance of each risk compared to the project thresholds. The suggested methodology is the **environmental risk analysis**, as it is the only tool that allows obtaining a semi-quantitative risk evaluation.

The aim of this phase is to classify and rank the different risk in order to determine the gravity of each risk and the necessity of remediation measures when the risk gravity overcomes the thresholds fixed for the analyzed project. The aim of this phase is to classify and rank the risk level by determining their probability and gravity as well as to identify the necessary remediation measures when the risk gravity overcomes the established threshold for the analyzed project.

Thus, to evaluate the risk, it will be necessary to quantitatively estimate the probability and the gravity of each risk but also to fix a numerical value as threshold for acceptable risk (Fig. 28). The definition of the quantitative scales of the different parameters and of the thresholds for risk evaluation should be done by the facilitator in cooperation with the expert team during the risk

evaluation phase. However, those estimations can also be proposed at the beginning of the risk assessment procedure, during the context set up.

All the steps to perform the risk evaluation are detailed hereafter and to better illustrate the procedure, four fictive examples are presented for each step.

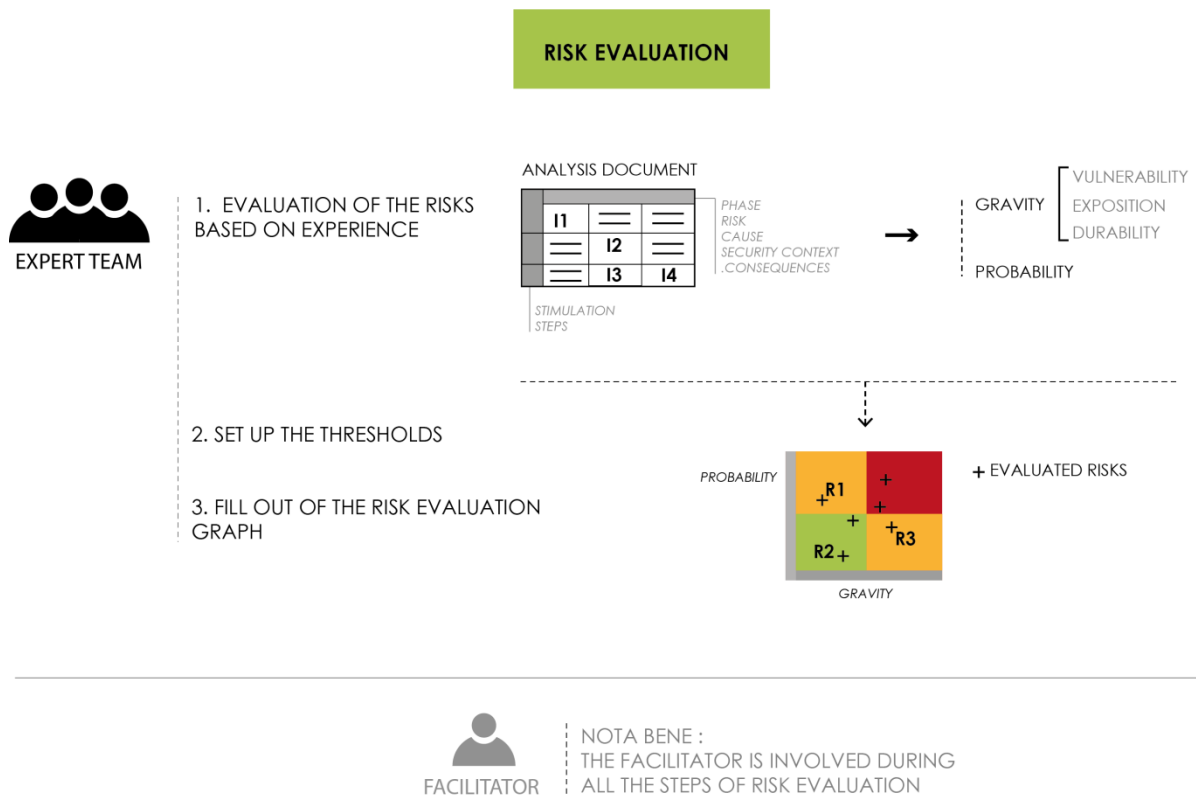


Fig. 28 Workflow for the risk evaluation phase

Probability

First of all, it is necessary to define the probability of each risk, following a quantitative scale previously defined in the context of the study (Fig. 28). The scale can be adapted depending on the available data and on the precision needed in the study. As generally low amount of data are available, it is suggested to choose a four-level scale: 1=almost never, 2=sometimes, 3=often, 4=almost always.

In general, it is important to note that most of the soft stimulation risks will have very low occurrence probability due to a number of existing security measures which act as prevention instruments.

Examples

- **R1**-The risk of burns by touching a hot pipe during the post acidification washing-out could be rated as almost never: **probability=2.**
- **R2**-The risk of pollution during the transport of the acid onsite could be rated as sometimes: **probability=2.**
- **R3**-The risk of noise nuisance for neighborhood due to the use of acid equipment could be rated as often: **probability=3.**
- **R4**-The risk of acid burns by being in contact with acid onsite because of a high pressure hose failure could be rated as often: **probability=3.**

Gravity

Once the probability is detailed, the gravity of the consequence of each risk should be defined, respecting the scale designed in the context of the study (Fig. 28). Once again, the scale can be adapted depending on the precision needed in the study. However, due to the classical low amount of feedback on accident for the soft stimulation procedure, it is suggested to choose a four-level scale: 1=almost no damage, 2=minor damage, 3=major damage, 4=exceptional damage.

The gravity of each risk is resulted from the combination of several parameters (Fig. 28):

- The vulnerability, which is the sensibility of the impacted medium to the related danger
- The exposition, which defines the amount of time during which the impacted medium is in contact with the related danger
- The lastingness, which defines how long the negative effects or damages will last.

Depending on the precision needed for the study, those parameters can be evaluated directly as a single gravity concept, or separately and combined after into an integrative gravity concept. In the last case, each parameter is rated on a scale. Then the ratings are added or multiplied and finally normalized to obtain a global gravity factor in the same scale as the probability.

Examples (the gravity is estimated as a single gravity concept)

- **R1**-The risk of burns by touching a hot pipe during the post acidification washing-out could be rated as minor damage: **gravity=2**.
- **R2**-The risk of pollution during the transport of the acid onsite could be rated major damage: **gravity=3**.
- **R3**-The risk of noise nuisance for neighborhood due to the use of acid equipment could be rated as almost no damage: **gravity=1**.
- **R4**-The risk of acid burns by being in contact with acid onsite because of a high pressure hose failure could be rated as major damage: **gravity=3**.

Representation

Once the probability and gravity of each risk are evaluated, a representation in the form of graph or table should be made to help visualizing the risk ranking and the sensibility to the different parameters (Fig. 28, Fig. 29).

The graph method is well adapted if one wants to represent graphically the position of the risk relatively of the gravity and probability thresholds.

Examples

- **R1**-The risk of burns by touching a hot pipe during the post acidification washing-out could be rated as **2 and 2** (resp. gravity and probability).
- **R2**-The risk of pollution during the transport of the acid onsite could be rated as **3 and 2** (resp. gravity and probability).
- **R3**-The risk of noise nuisance for neighborhood due to the use of acid equipment could be rated as **1 and 3** (resp. gravity and probability).
- **R4**-The risk of acid burns by being in contact with acid onsite because of a high pressure hose failure could be rated as **3 and 3** (resp. gravity and probability).

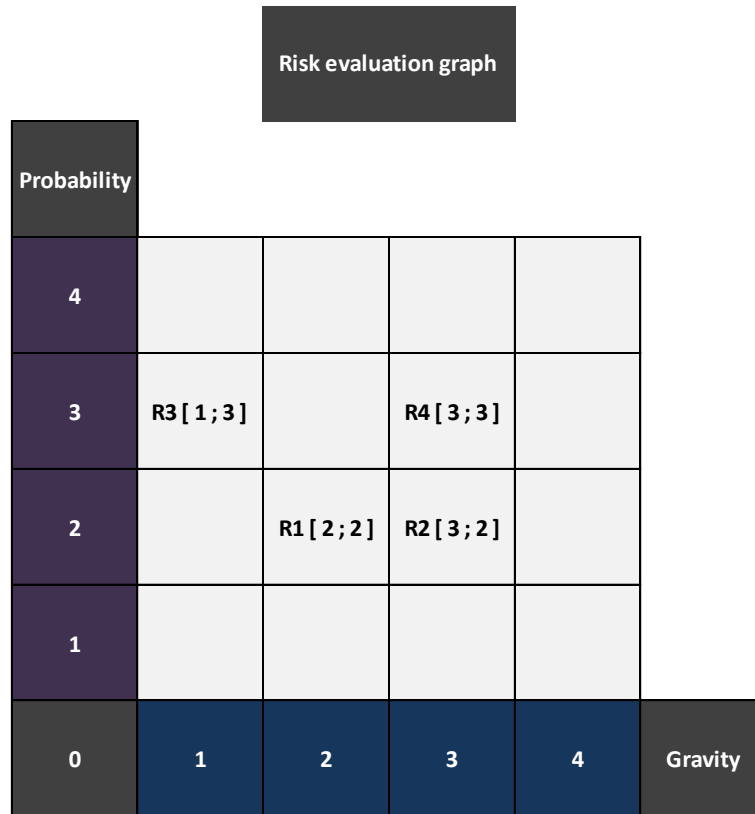


Fig. 29 Risk evaluation graph including the four examples of risk

The table method is more suitable to evaluate the tolerability of a risk when it is characterized by more than two parameters, e.g. probability, vulnerability and exposition (see Table 13). Then the threshold will be defined as the maximum value acceptable for the combination of the four parameters (sum, multiplication or another operation).

Table 13 Example of risk evaluation table with four parameters scaled between 1 and 4. In this case, the total value is defined as the multiplication of all the factors

Risk	Sensibility	Exposition	Duration	Probability	Formula
Rx	1 - 4	1 - 4	1 - 4	1 - 4	S x E x D x P
R1	1	2	1	4	S x E x D x P
R2	3	4	4	4	S x E x D x P
R3	1	1	3	1	S x E x D x P
R4	3	4	2	3	S x E x D x P
R5	1	1	4	1	S x E x D x P

Thresholds

Once the risks are represented on a graphical support, it is necessary to report the tolerance thresholds defining the risk acceptability for the present study (Table 13). The comparison of the threshold and the risk final rating allows identifying the acceptability of the risk for the studied project.

Different methodologies can be used to define the potential thresholds. Some of the most common methods are presented below. However, the choice of the threshold depends on the context of the soft stimulation procedure and should be adapted for each study.

- Graph - double threshold

If the evaluation is represented on a graph, it is possible to use two thresholds, one for the probability and the other for the gravity. This way the graph is separated in four parts and the risks rated in the top right quarter are considered as not tolerable (see Fig. 30).

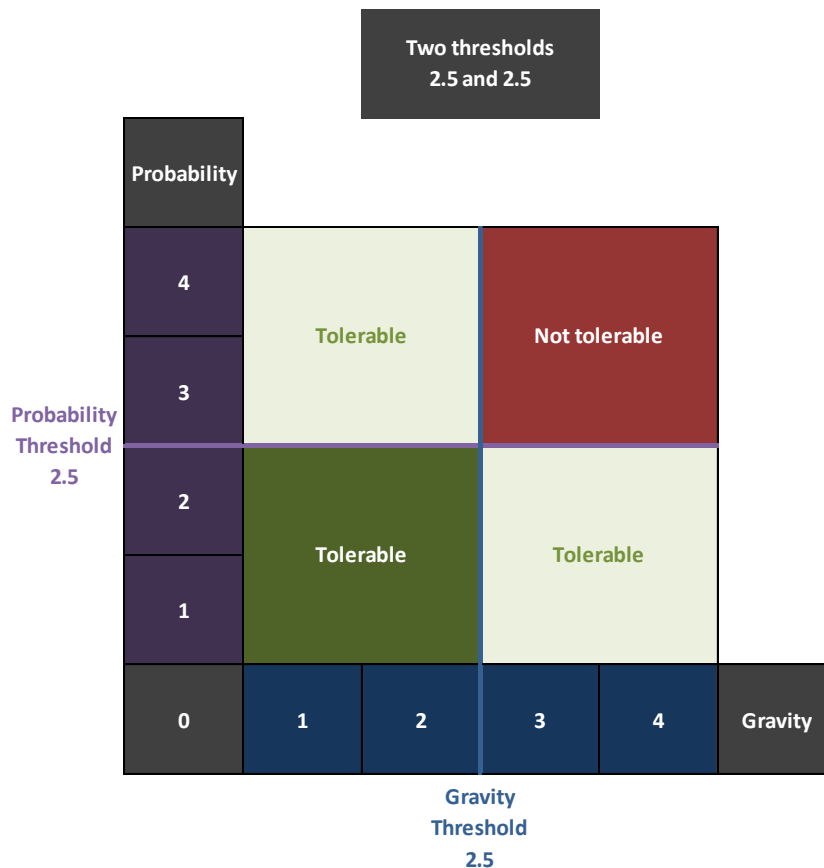


Fig. 30 Example of risk evaluation graph with two thresholds

- Graph - multiplied threshold

If the evaluation is represented on a graph, it is also possible to multiply the ratings of the probability and the gravity. This way the graph is separated in X*Y parts corresponding to the products of the ratings, and the threshold gives the upper acceptable value of the tolerable product (see Fig. 31). It is possible to change the product into an addition or another operation depending on the shape of the threshold needed (see Fig. 32).

- Table

If the evaluation is represented on a table, the different parameters are combined in a single one using series of operations. The results are then compared with the determined threshold to know whether the risk is tolerable (see Table 14).

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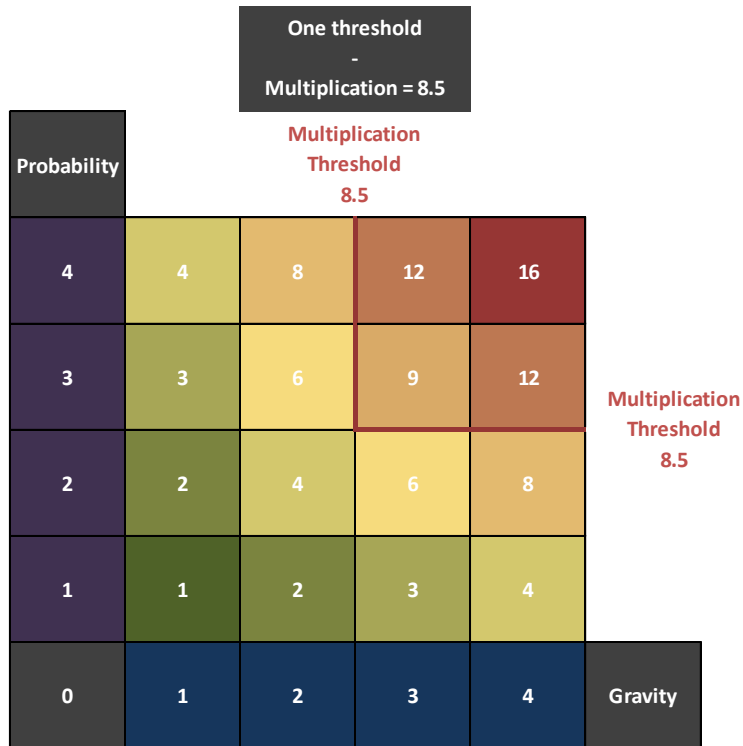


Fig. 31 Example of risk evaluation graph with one multiplication threshold

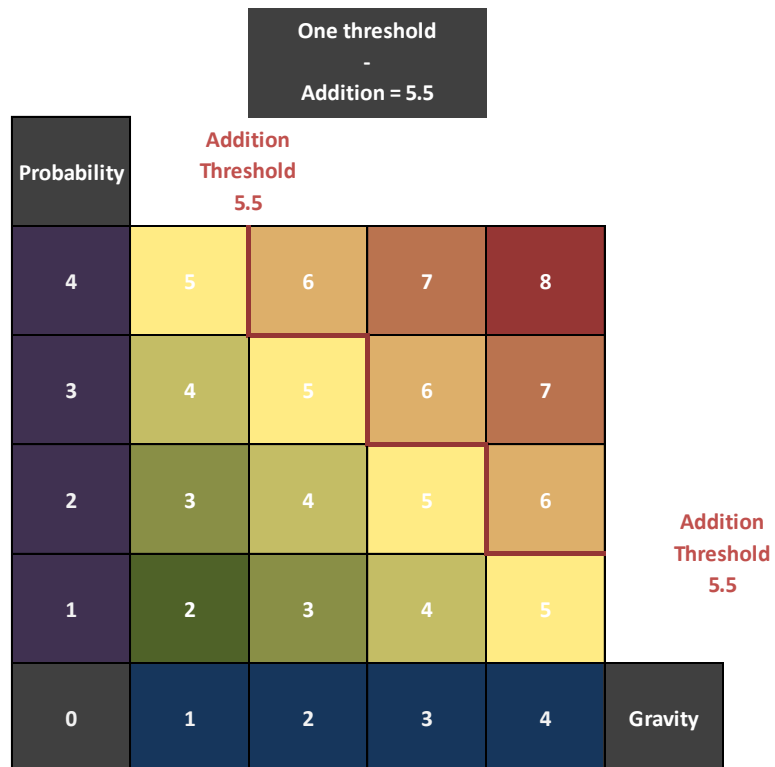


Fig. 32 Example of risk evaluation graph with one addition threshold

Table 14 Example of risk evaluation table with a 4 parameters threshold

Risk	Sensibility	Exposition	Duration	Probability	Formula	Threshold	Result
Rx	1 - 4	1 - 4	1 - 4	1 - 4	S x E x D x P	18	X
R1	1	2	4	3	S x E x D x P	18	24
R2	3	1	1	3	S x E x D x P	18	9
R3	2	2	2	1	S x E x D x P	18	8
R4	1	3	4	4	S x E x D x P	18	48
R5	3	1	1	4	S x E x D x P	18	12

Risks and thresholds comparison

Once that the thresholds have been graphically selected, a combined representation of the risks and the thresholds should be done on the same support, in order to compare them (Fig. 32 and Fig. 33). Whether one or several risks are above the threshold, a risk treatment phase should be achieved (Fig. 33).

Examples

- **R1:** The risk of burns by touching a hot pipe during the post acidification washing-out could be rated as **2 and 2** (resp. gravity and probability).
- **R2:** The risk of pollution during the transport of the acid onsite could be rated as **3 and 2** (resp. gravity and probability).
- **R3:** The risk of noise nuisance for neighborhood due to the use of acid equipment could be rated as **1 and 3** (resp. gravity and probability).
- **R4:** The risk of acid burns by being in contact with acid onsite because of a high pressure hose failure could be rated as **3 and 3** (resp. gravity and probability).

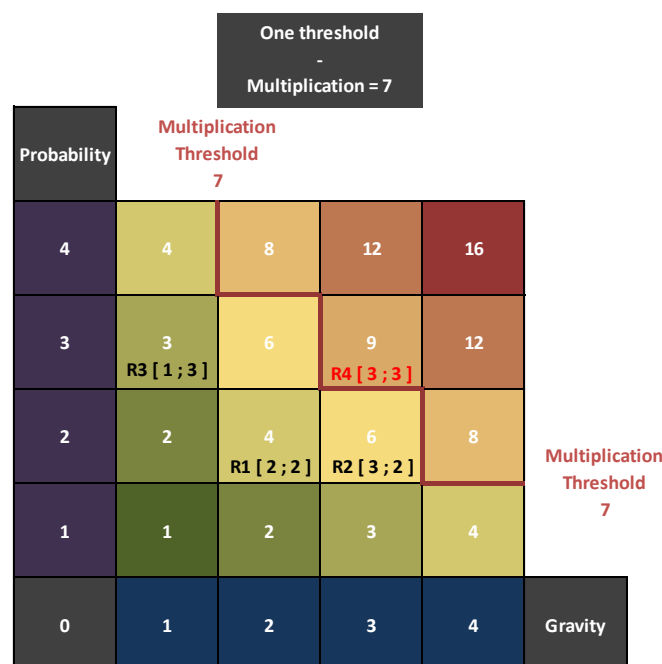


Fig. 33 Risk evaluation graph including the four examples of risk and a multiplication threshold. In this case, the risk R4 is above the threshold and will need to be considered in the mitigation treatment phase

4.5 Risk treatment

This phase, which correspond to the last step of the risk assessment procedure, is necessary if at least one risk has been rated above the threshold during the risk evaluation. The purpose is to change the context and/or the existing security measures in a way that the probability or the gravity of the intolerable risks shifts from above to under the threshold. This change is called a risk treatment measure, and it can be implemented through several steps (Fig. 34).

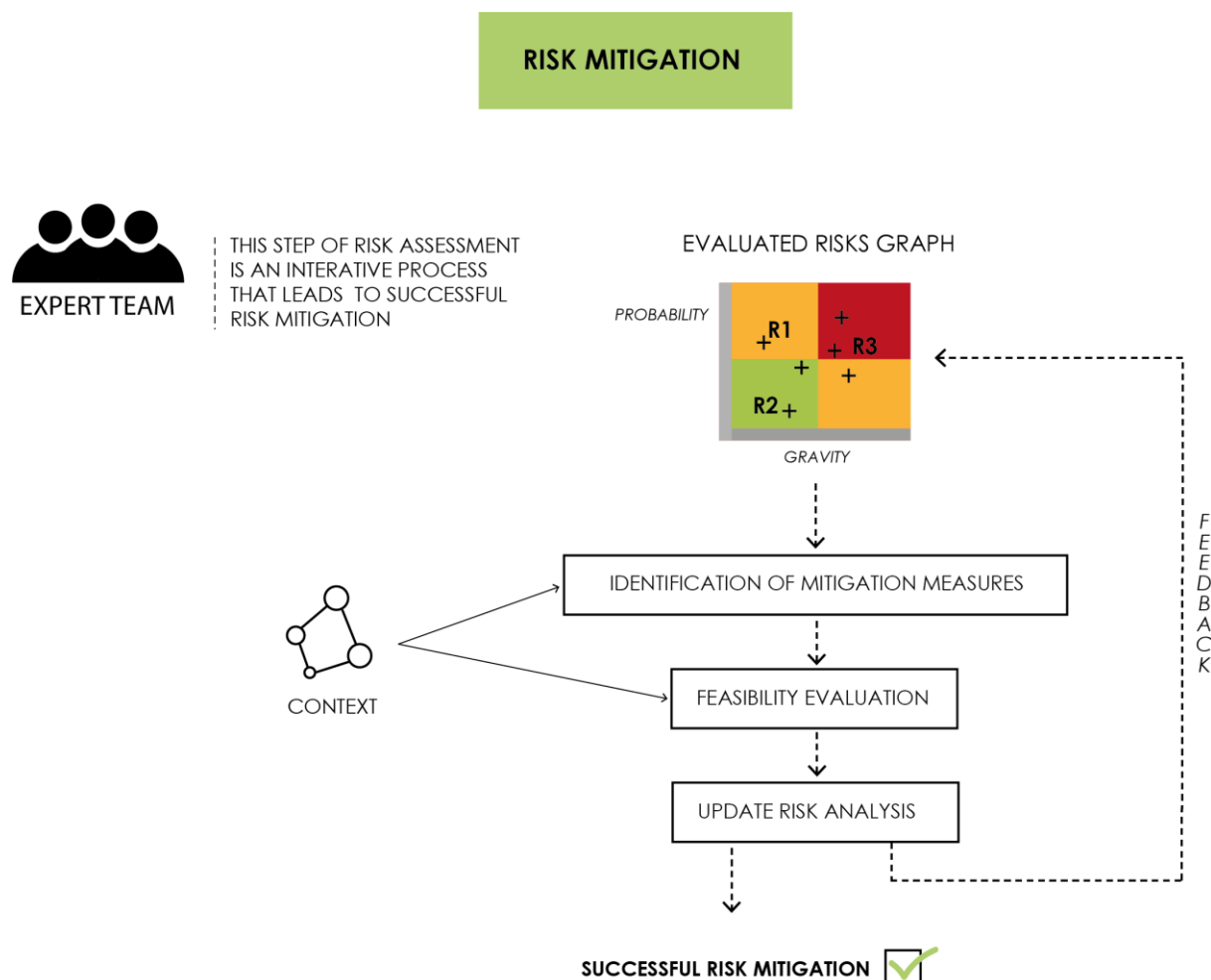


Fig. 34 Workflow for the riskreduction phase

Identify the potential risk reduction measures

While considering a given critical risk, all the context elements are re-discussed in order to identify those that could influence the probability or the gravity of the risk. It can be either an element of the site settings, the stimulation design or the model limits. Once identified the major points influencing the risk gravity or probability, a list of the modifications of the context should be prepared (Fig. 34). Those modifications correspond to the potential risk treatment measures.

This process of context re-evaluation should be repeated for each critical risk.

Consolidate the treatment measures

All the identified treatment measures should be evaluated together, in order to discuss their compatibility with the technical, social, financial and schedule constraints. This step will allow ending up with a final and integrative list of treatment measures for all critical risks (Fig. 34).

Reiteration of the risk assessment procedure

On the basis of the retained treatment measures, all the risk assessment procedure should be repeated in order to re-evaluate the efficiency of the retained controls and the eventual residual risks (Fig. 34).

Thus, the context should first be updated in order to represent the new constraints. Then, the risk identification phase should be duplicated, as the changes in the context may remove or add some risks from the checklist. Similarly, the risk analysis phase should be repeated for all risks because the changes in the context may have changed the security context, the triggering events, the consequences, etc. Finally, the risk evaluation phase is also reiterated for all risks. The comparison of the new results with those obtained by the initial risk assessment will allow knowing whether the treatment measures are effective.

Once again, if at least one risk is evaluated above the threshold, the treatment procedure should be started again. At the end of the treatment phase, all risks must satisfy the evaluation threshold.

4.6 Global workflow

To summarize, the risk assessment procedure for soft stimulation is composed of several phases, including the context, the risk identification, the risk analysis, the risk evaluation and the risk treatment measures (Fig. 35). All of them are implemented by a facilitator and a team of experts. The different methods used for risk assessment are brainstorming, scenario analysis, checklist, and environment risk assessment (Fig. 35).

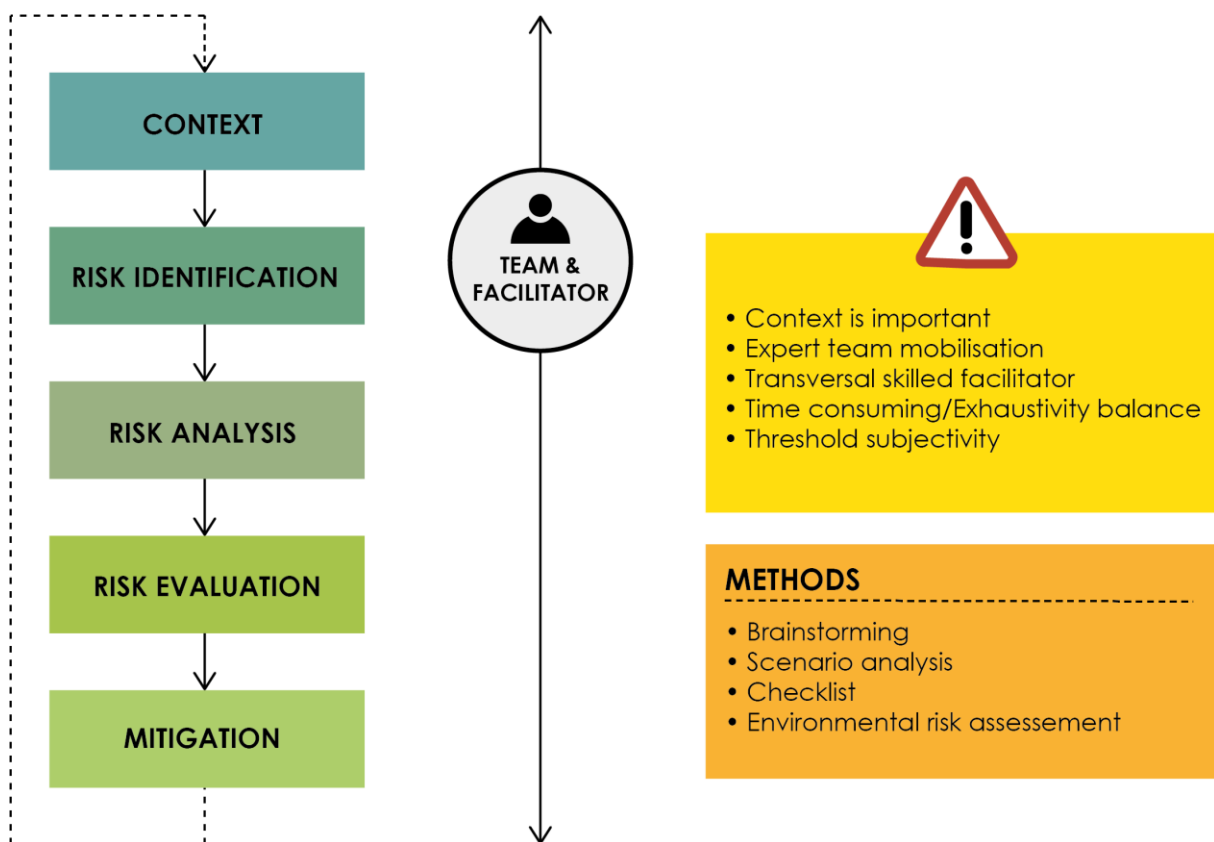


Fig. 35 Global workflow for the risk assessment of the soft stimulation procedure

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For a successful risk assessment procedure, the first phase of context definition is very important. Similarly, the experience of the mobilized team and of the chosen facilitator can have a strong influence on the quality of the procedure. The final results of the whole procedure will depend on the allowed time and on the extend of the approach. Both factors are strictly connected and a balance should be defined as a function of the goal and the context of the study. Finally, the level of acceptable risk only depends on the defined thresholds, which are very subjective. Thus, the same risk may be considered and mitigated differently depending on the context of the study.

5 A case study

The site chosen to practically illustrate the risk workflow analysis for soft stimulation treatments is a deep geothermal site recently drilled, located in Illkirch Graffenstaden, the urban area of Strasbourg (France, Fig. 36). The reservoir geological context corresponds to a faulted and fractured site composed of hard rocks. The presence of a shallow fresh water aquifer is one of the major challenges of the selected site.

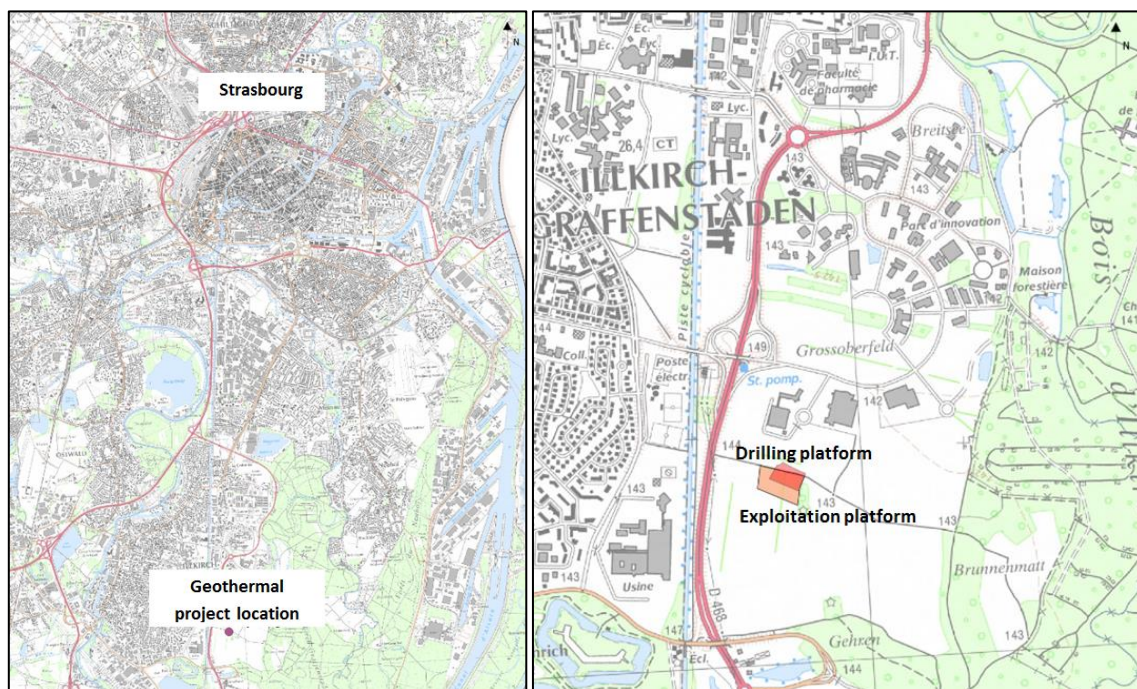


Fig. 36 The location of the geothermal project discussed in the case study and the detail of the platforms. ©és

The present case study is mainly focused on the chemical stimulation analysis. However, additional risks related to thermal and hydraulic treatments will be mentioned, in order to give a complete overview of the risk analysis task for the soft stimulation phase.

5.1 CONTEXT

5.1.1 Geological settings

Reservoir information

- **Rock type:** granite & sandstone
- **Porosity and permeability:** fractures permeability and low matrix porosity
- **Depth of reservoir:** 2.5 to 3 km (Fig. 37)
- **Temperature:** 150 to 160° C
- **Reservoir pressure :** 250 to 300 bar
- **Geochemistry of the fluid:** NaCl dominated brine with TSD = 100 g/L; presence of gas (mainly CO₂) with a gas liquid ratio (GLR) of 1:1; no presence of hydrocarbons.
- **Tectonic context:** extensional tectonic regime

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Other rock formations

- **Hydrocarbons:** presence of hydrocarbon reservoir in the shallow layers
- **Sensitive rock formations:** clays (Jurassic) and saline rocks (Tertiary)
- **Deep aquifers:** sensitive but not exploited deep aquifers (Dogger)
- **Aquifers-reservoir connection:** potential natural inter-connections between aquifers due to vertical faults
- **Additional exploitation:** oil field in the reservoir

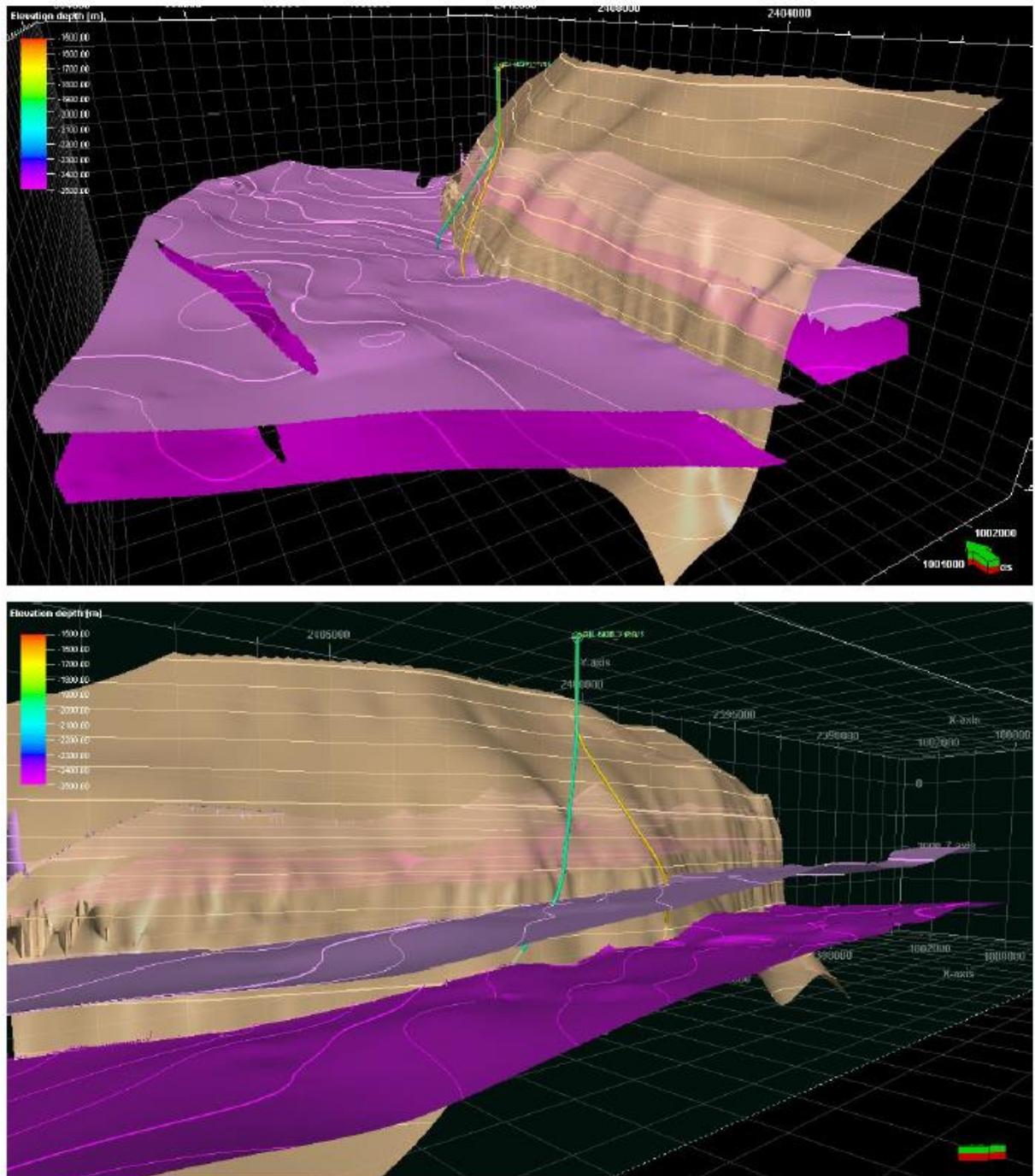


Fig. 37 The geological model of the geothermal project discussed in the case study. The wells, the bottom and the top of the reservoir as well as the fault plan are represented

5.1.2 Boreholes

Borehole completion

- Directional well with a classical borehole completion scheme, with triple casings: 17^{1/2}, 13^{3/8}, 9^{5/8} and a downhole 8^{1/2} of 800 m (Fig. 38).

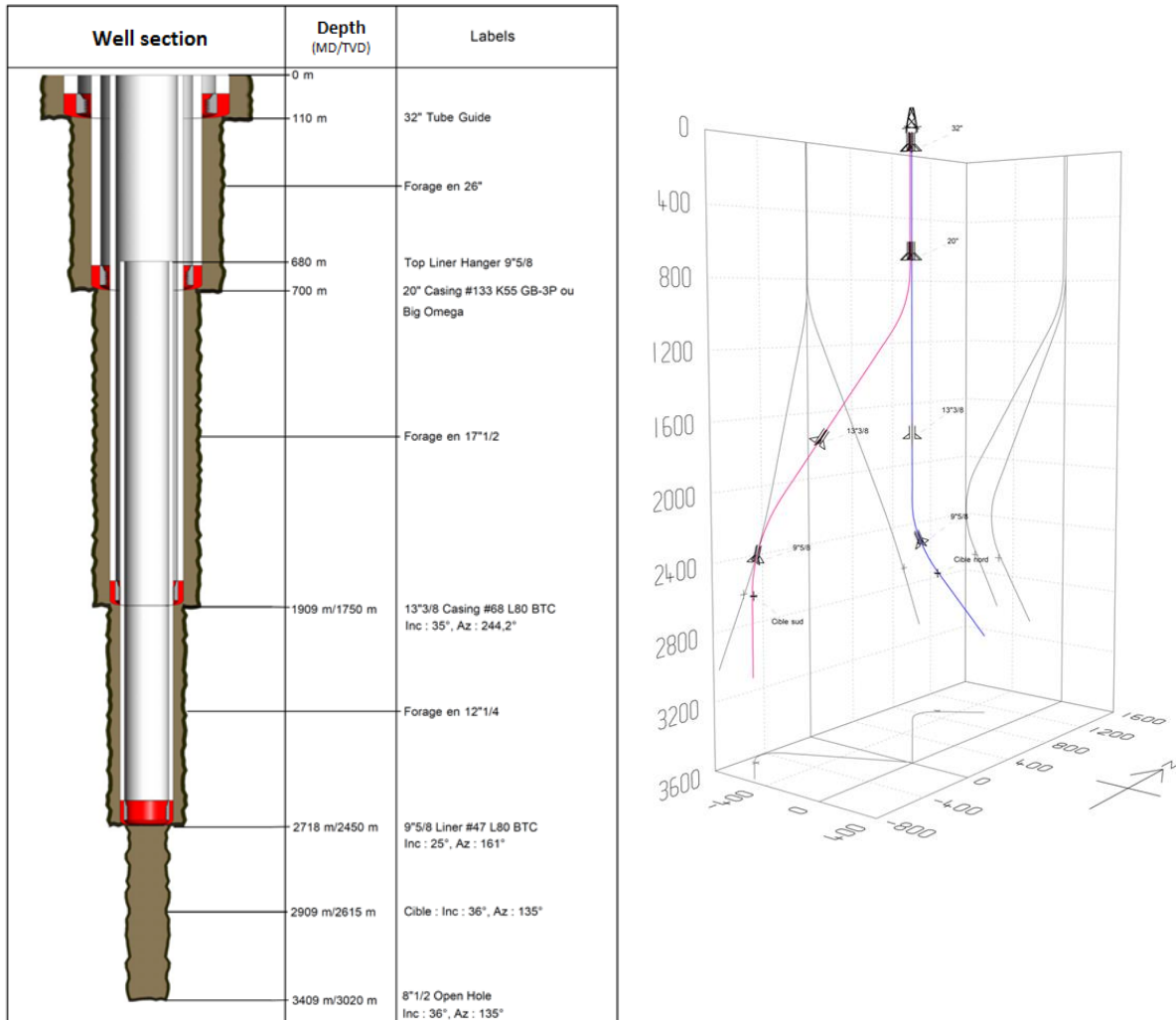


Fig. 38 The well completion schema and the well directional trajectories of the site selected for the case study

Status of borehole

- The casings are news and the well is fully cemented.

Connection between the reservoir and the borehole

- The reservoir is a fractured type, dominated by a (single) fault structure (Fig. 38). The connection with the borehole may eventually occur also through the damaged zones surrounding the well.

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5.1.3 Stimulation site

The stimulation site corresponds to the drilling platform (Fig. 39).



Fig. 39 Study site drilling platform ©és

Site access

- The access to the site is provided by a provisory gravel road after passing a security control. There are isolated parking lots.

Infrastructure

- **Buildings:** presence of a base-camp
- **Drilling rig:** rig SMP 106
- **Basins:** mud pit onsite
- **Auxiliary equipment and storage places:** presence on site (Fig. 40)
- **Machinery and vehicles:** forklift and cranes
- **Piping:** presence on site
- **Site servicing:** electricity, telephone, fire hydrant, internet but no gas supply

Platform design

- **Dimensions:** 1,5 ha
- **Structure:** 25 t/m²
- **Draining system:** presence of a drainage system on the working and storage zones of the platform

Human activities

- **People on site:** 20 to 30 persons
- **Simultaneous activities:** no activity of different companies at the same time
- **Languages:** French, German and English
- **Training and experience:** highly trained workers, with references and verified experience
- **QHSE:** presence of a coordinator for the security and safety protection of the workers on site. QHSE service is provided by the drilling company



Fig. 40 Sulfuric acid storage on site

Natural environment

- **Climatic conditions:** summer season with presence of thunderstorm
- **Fauna and flora:** protected zones closed to the site (Fig. 41).
- **Groundwater:** presence of the Rhine aquifer, from 0 to 107 m depth. Installation of a water quality management plan, including a piezo metric model of the aquifer
- **Rivers:** presence of four rivers around the site; Rhone to Rhine canal (350 m), Schwarzwasser stream (700 m), Rhin Tortu stream (1 500 m), Ill river (800 m), Rhine river (4 000 m)
- **Soils:** arable land
- **Air:** presence of toxic gas detectors and alarms as well as wind socks on site

Human environment and neighboring infrastructures

- **Population density:** urban area with low population density
- **Social & political context:** **positive** political support on the project and positive feedback from the population
- **Acceptability:** rather good for the project, despite acceptability issues for other neighboring projects
- **Transport networks:** access to the site by road (main road and highway), but no other access options
- **Neighboring infrastructures and cultural heritage:** mainly tertiary buildings and offices, with no cultural and historical heritage nearby (> 1 km)
- **Land use:** presence of farmers but no animal farming
- **Neighboring economic activities:** a mix of tertiary sector and industries
- **Visual environment and ambient noise:** the project is located far away from houses (> 400 m)

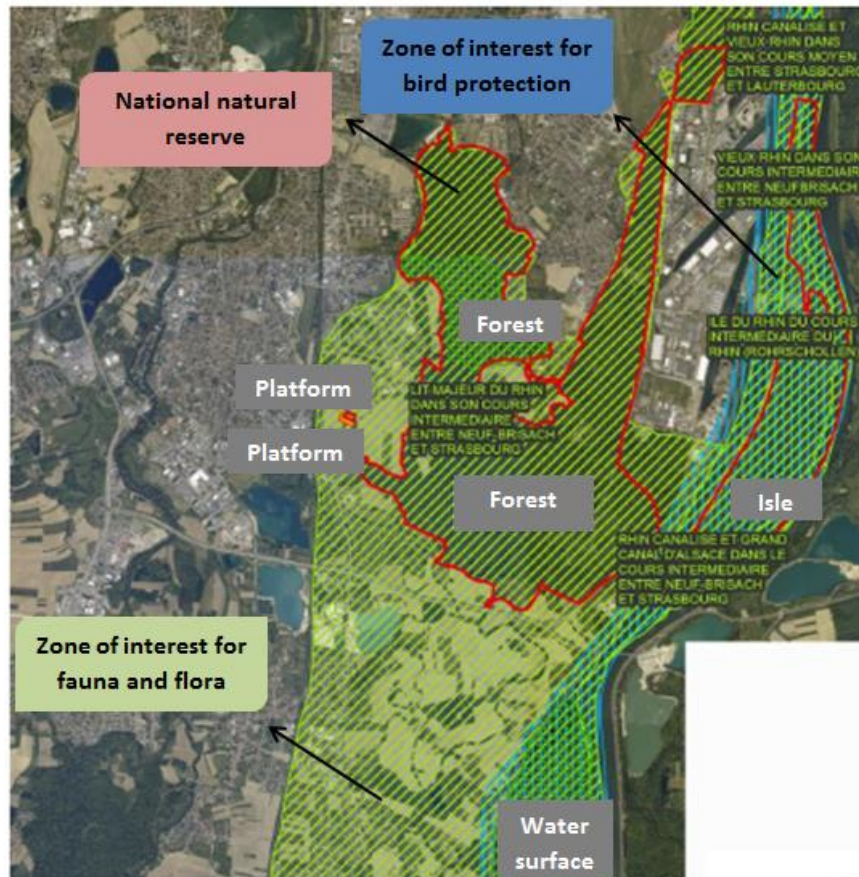


Fig. 41 The natural protected areas closed to the case study site

5.1.4 Stimulation design

Preliminary investigations

- Laboratory tests on representative cuttings and cores, compatibility with geothermal fluid, feasibility study, experience of the service company

Injected stimulation fluid

- Biodegradable and green product, with a retarded reactivity and a low corrosion tendency. The aim of this chemical is to dissolve minerals clogging the fractures, particularly sulphates and carbonates.
- HCl will also be used.

Injected additives

- Corrosion inhibitor, clay stabilizer (NH₄Cl) and intensifiers.

Injection methodology

- Triple phase injection (pre-flush, main-flush and post-flush) ending with a washing-out phase. Injection with low head pressure (< 100 bar), with possible selection of preferential zones.

Transportation mode

- Transport of the chemicals by road (truck), as a solid powder (dry). Chemicals mixing and preparation will be done on the site

Storage mode

- The chemicals will be stored in a shelter as a powder (dry)

Equipment

- Vehicles, tanks, mixing units, pumping units, high-pressure pipes and high-pressure holes

Human resources

- 5 persons: 1 supervisor and 4 technicians

Date and duration of the operation

- End of the summer (August), during 1 week

5.1.5 Model limits

Threshold for risk assessment for soft stimulation

- **Regulatory context and threshold**

The evaluation of the regulatory context and threshold for the natural environment has been subcontracted to a consulting office.

A security and safety official coordinator subcontracted by the contracting authorities is involved in the detailed stimulation design and will supervise the stimulation operation in order to guarantee their conformity regarding the Labor Code and the Public Health Code.

- **Ethical context and threshold**

The ethical context is constrained by the certification ISO 14001 for the environmental concerns and by the certification OHSAS 18001 for Health and Safety.

Conceptual limits of impacted mediums

- **Human and wild life**

- Fauna and flora

An impact study has been carried out to characterize the vegetal and animal species threatened by the stimulation operations.

- Human

The whole human beings potentially impacted by the stimulation operations, with no geographical limits, will be included in this study.

- **Life environment**

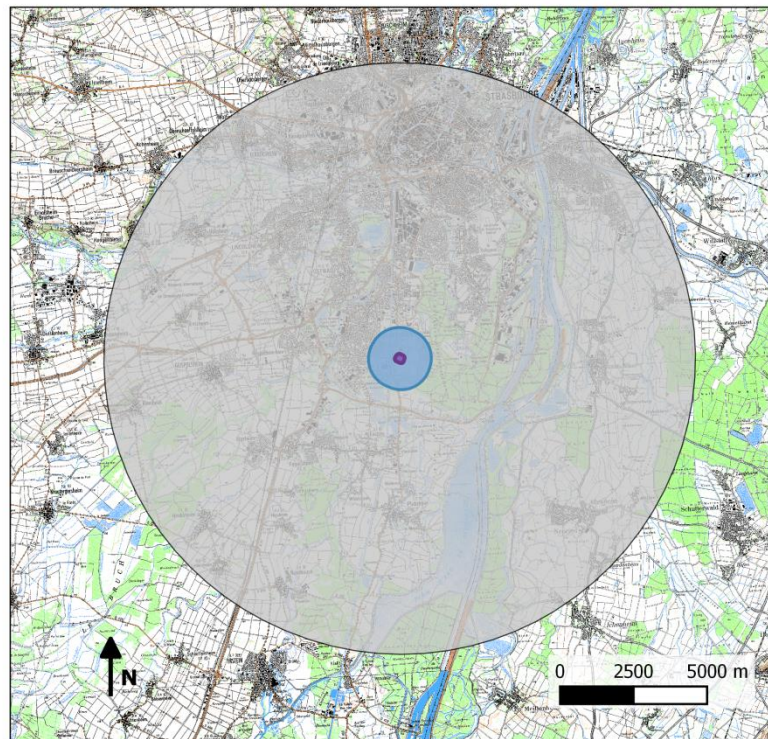
- Water: surface and subsurface water
- Air: atmosphere and climate
- Soil
- Infrastructures: the entities necessary for human life (hospital, surgery ...)

Geographical limits

- **Natural environment**

- Fluid leakage on surface: 100 m around fluid's transportation ways and storage location (Fig. 42)
- Fluid leakage in borehole : 1 km around the stimulation site (Fig. 42)

- Gas emission : 1 km around fluid's transportation ways and storage location (Fig. 42)



Caption

- Surface fluid leakage zone
- Underground fluid leakage and gas emission zone
- Human environment

Projet : Illkirch
Date : 19/02/2018
Auteur : R. HEHN
Projection system: RGF93 Lambert 93
Scale: 1/150 000

ES-Géothermie
26 Boulevard du Président Wilson
67000 Strasbourg



Fig. 42 Geographical limits for the risk on infrastructures, human and natural environment

- **Infrastructures:** 10 km around the stimulation site (Fig. 42). This area is prone to the risk of induced seismicity and the potentially felt earthquake on surface
- **Transportation:** this activity will be fully subcontracted to either the transportation company or the stimulation service company and would not be taken into account in the present study
- **Acceptability :** no limit, as the information of any incident can easily be spread worldwide
- **People:** for the potential impact on human beings, the geographical limits are the same as those defined for the natural environment and the infrastructures

Temporal limits

- **People/infrastructures:** risks is negligible immediately after the end of operations and total demobilization of the service company's equipment (Fig. 43)
However, indirect risks chronologically delayed can remain if the environment is somehow affected.
- **Environment:** after total consumption/disappearance/degradation of chemical agents. This limit can vary from some tens of days to several years regarding the type of chemical (Fig. 43).
- **Acceptability:** no limits, as for geographical limits (Fig. 43).

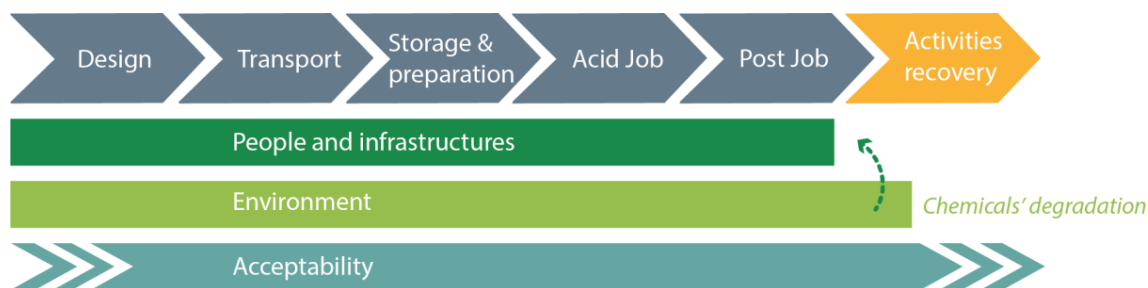


Fig. 43 The temporal limits of the risks on human, infrastructures and environment for the chemical stimulation procedure of the case study. Acceptability is also presented to highlight that the consequences of geothermal activities on the popular acceptability

Natural risk

- **Natural risks:** they should be taken into account as a function of their probability of occurrence, regarding the duration of stimulation operations (1 to 2 weeks) and the temporal limits described above.
- **Seasonal events:** they should be taken into account in the stimulation design in order to schedule the most appropriate period for the operations.

Choice of the retained scenario for risk analysis and evaluation

- **Criteria for risk evaluation:** in the framework of the previously proposed risk analysis approach, it is necessary to better define the criteria for risk evaluation. For this study, the risk gravity and occurrence will be evaluated on a scale from 1 to 4 and the threshold calculated by multiplication of the two criteria. The maximum threshold tolerated value will be set at 7.

5.2 Risk identification

In the first phase of the risk identification, the facilitator has to prepare all the documents for the presentation of the “semi-guided brainstorming” to the expert team.

First of all, the facilitator introduces the composition of the expert team (Fig. 44). At this moment, it is interesting to highlight the optimal constitution of this team and at the same time the experts that are concretely involved. This information allows understanding rapidly the domain of expertise presented for the risk assessment procedure and the themes which will be more difficult to process. Afterwards, a support for the explanation of the risk assessment procedure, with a focus on the risk identification phases and the “semi-guided” brainstorming approach are presented (Fig. 45). The methodology of the brainstorming is discussed in detail, in order to give all the participants a total comprehension of the procedure.

Finally, the facilitator presents the context of the study and exposes the different steps of the soft stimulation (Fig. 46, Fig. 47). In the case study presented here, the risk assessment will be based only on the chemical stimulation treatment. The latter is composed of 6 different phases, including: design, transport, storage, preparation, acid job and post job.

The design phase consists of all the preliminary tests performed in laboratory to the selection of chemical products and verification of their compatibility with the geological, platform and environmental settings. The transport of all of the material is realized by truck from the warehouse and then by crane on the platform. The storage of the product is made in closed tanks on the site. Chemical products are transported and stored on their dry form. The preparation of the chemical

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stimulation consists of in a preliminary step of acid hydration, followed by the preparation of the acid mixture.

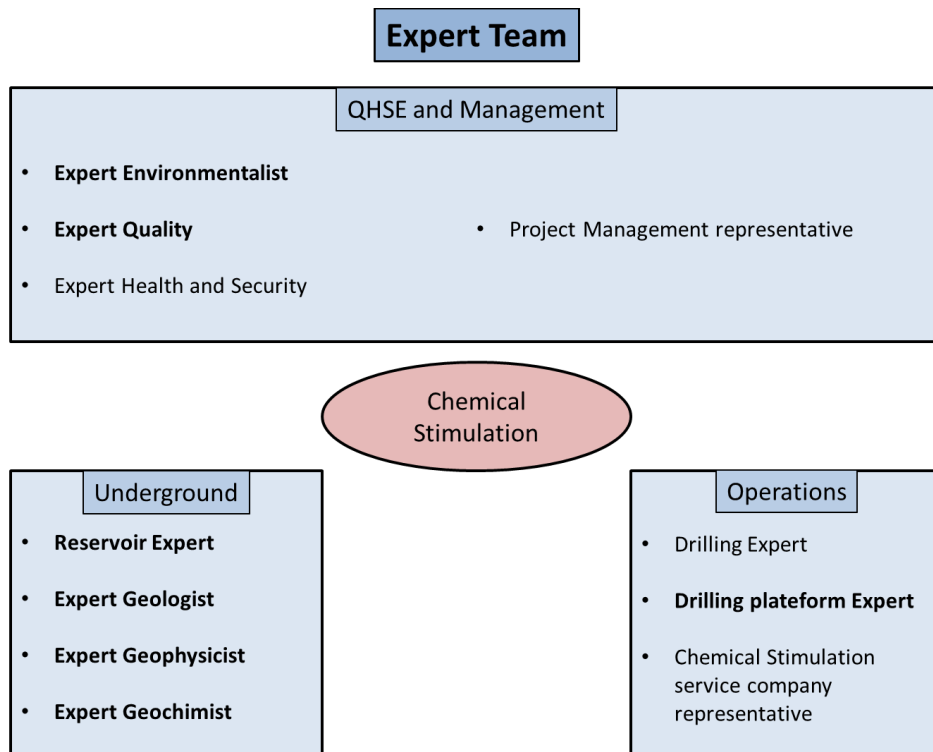


Fig. 44 The composition of the expert team (bold) and the theoretical optimal constitution of the expert team

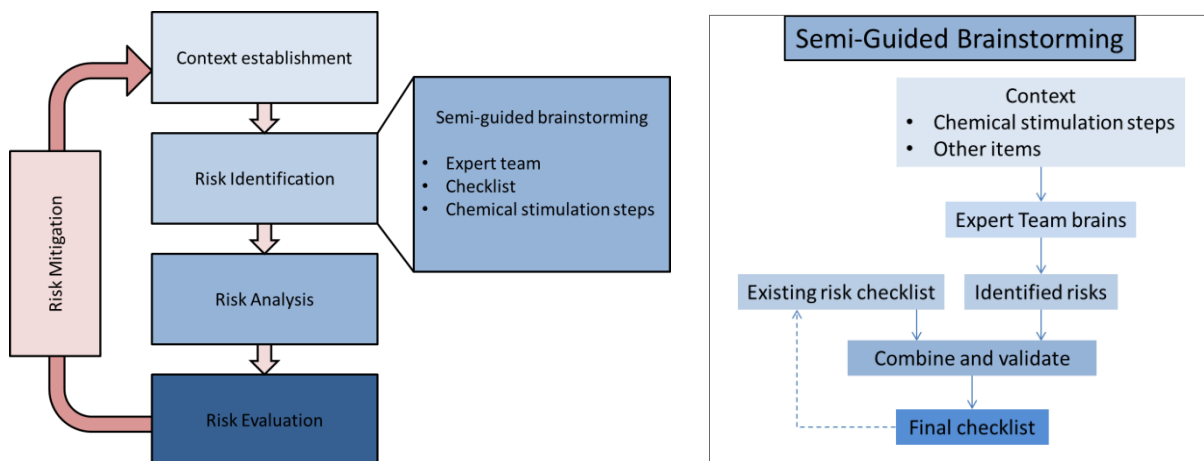


Fig. 45 Place of the brainstorming in the global risk assessment workflow

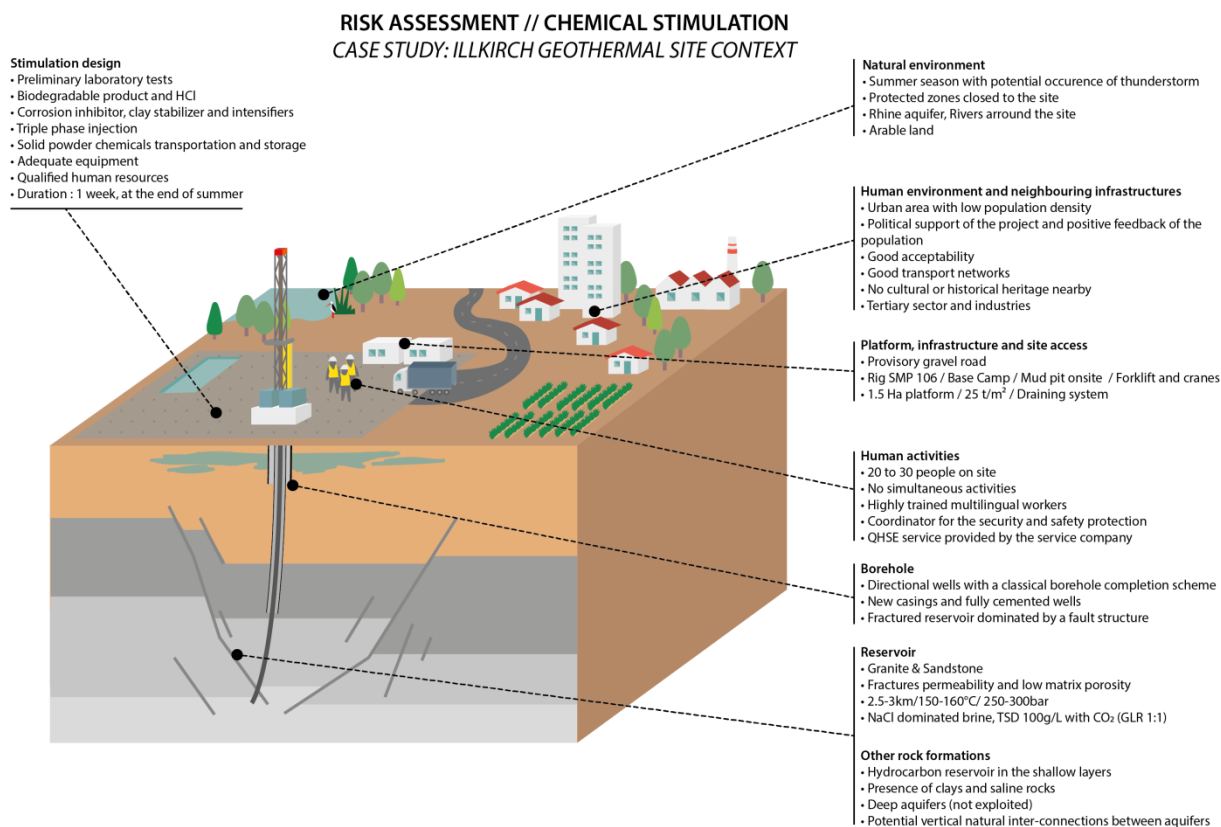


Fig. 46 Presentation of the context of the risk assessment study

Then, the equipment for the chemical product injection is installed in the well. At this stage, the acidizing treatment starts and the chemical products are injected. This phase, called acid job step, also includes a period where the chemicals reacts in the reservoir. The chemical stimulation ends with the post job phases, where a production phase is implemented in order to clean the well and to verify the reaction of the chemicals. In this phase the management of all the wastes takes place.

Among the documents that the facilitator has to prepare, one is the initial checklist. For this study case, the initial checklist has been extracted from the results of the precedent risk identification phase lead by EnBW for the economic risk analysis (Table 15; see Reith et al. 2017). In particular, risks implicating human and natural environments have been taken into account.

Once the initial preparation is achieved, the semi-guided brainstorming is started with the identification of new risks based on the context and the defined steps of the chemical stimulation. All the identified risks were catalogued and validated via the comparison to the initial checklist. The result of the risk identification phase is a final checklist, presented in Table 16.

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STEPS OF THE CHEMICAL STIMULATION

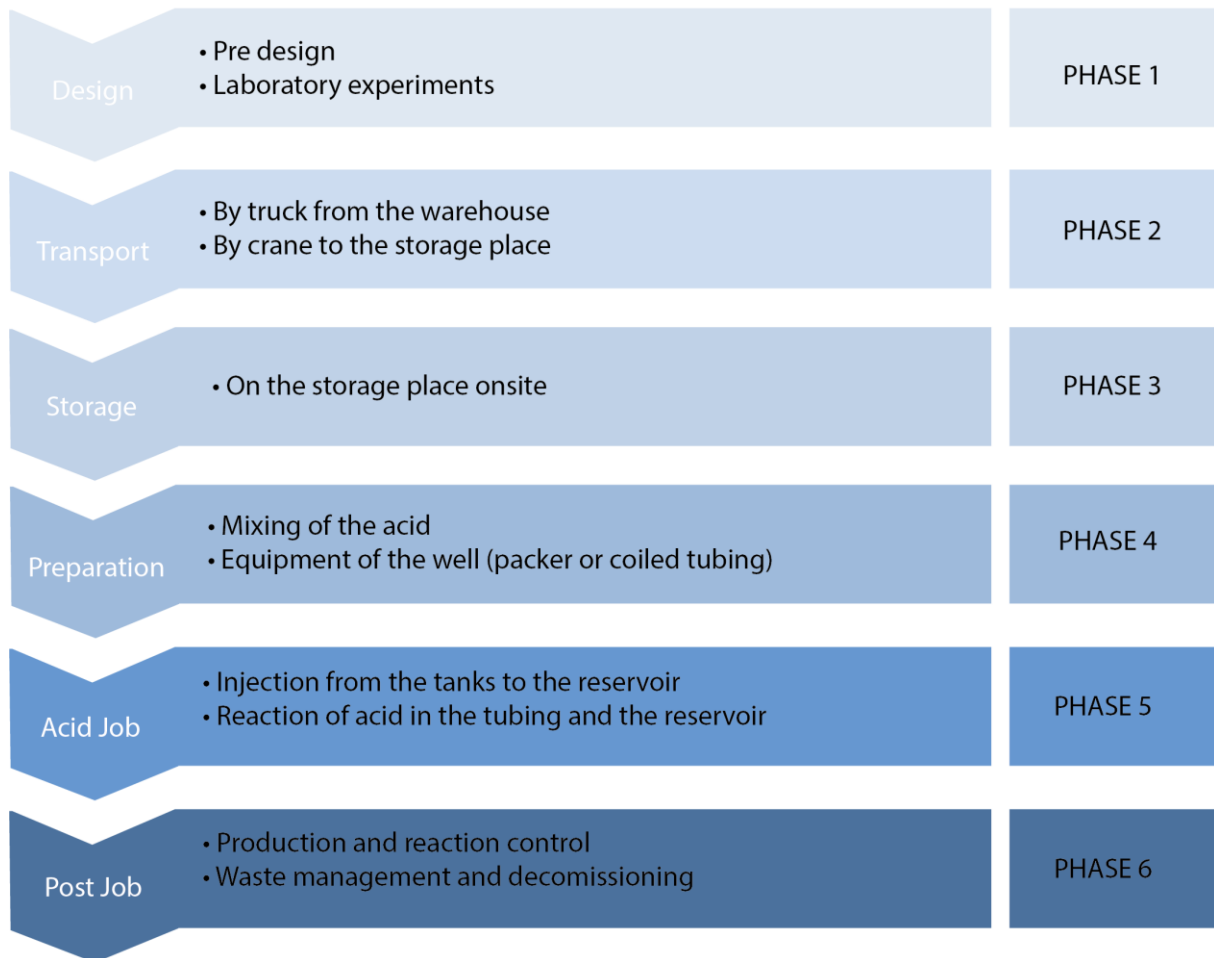


Fig. 47 Presentation of the steps of the chemical stimulation for the scenario analysis

Table 15 Initial risk checklist (adapted from Reith et al., 2017)

Phase	Risk	Causes
Transport and storage	Leakage in flowback reservoir	Leakage through corrosion or mechanical damage
Transport and storage	Accidental disperse of hazardous materials (acids, fuel, flowback) on ground	Traffic accident
Injection	Well damage	Injection pressure damages casing cement, Poor cement job Through shearing processes
Injection	Causalities through pipe failure	High pressure pipe failure
Reaction	Induced seismicity (with time delay after injection)	High pressure within formation
Reaction	Unwanted subsurface hydraulic connections	Too effective stimulation Wrong doublet design (orientation) High conductive fault planes

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Table 16 Final checklist resulting from the semi-guided-brainstorming on the chemical stimulation for the case study

Phase	Risk
Design	Office work related musculoskeletal disorder
Design	Chemical burns due to laboratory accident
Design	Injury due to laboratory accident
Transport	Truck accident with damages on infrastructures
Transport	Truck accident with injury on people
Transport	Truck accident with damages on surface water
Transport	Truck accident with damages on soil
Transport	Crane accident on site with release of chemicals on the platform and damage on nearby environment
Transport	Crane accident on site with release of chemicals and acid burns
Transport	Crane accident on site with injury
Storage	Leakage on the storage place because of accidental damage on acid reserve and damage on nearby environment
Storage	Leakage on the storage place because of accidental damage on acid reserve and damage on people
Preparation	Chemical burns due to acid manipulation
Preparation	Injury due to accident during coiled tubing and packer jobs
Preparation	Noise and vibration nuisance due to mixing machines
Acid job	Injury due to high pressure accident
Acid job	Acid burns due to high pressure accident
Acid job	Pollution of nearby environment due to high pressure accident
Acid job	Corrosion of the casing due to bad injection procedure, or

	inhibitor, or equipment and pollution of the aquifer
Acid job	Major accident on surface due to gas kick or blow out and people injury
Acid job	Major accident on surface due to gas kick or blow out and damage to the well leading to pollution of aquifer
Acid job	Induced seismicity created by high pressure injection and damage on nearby infrastructures
Acid job	Induced seismicity created by high pressure injection and harm on people
Post job	Release of reaction-produced gas in the air, with pollution of the nearby environment
Post job	Release of reaction-produced gas in the air, with harm on people
Post job	Production of unreacted acid in mud pit, leaking out in the nearby environment
Post job	Burns due to high production temperature
All	Atmospheric pollution due to all the operations

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5.3 Risk analysis

Strictly speaking, the identified risks listed in Table 16 includes not only the risks, but also some causes of consequences to whom they could be related. In order to exactly define the cause, consequences and the existing security context for each risk, the second phase of risk analysis are developed.

Taking advantage of the precedent brainstorming, the same team has been mobilized for this phase. The risk analysis leads to an analysis document, presented in Fig. 48.

Phase	Risk	Cause	Security context	Consequence
Design	physical harm	bad ergonomy of working place	Labour doctor consulted	musculoskeletal disorder
Design	chemical burn	laboratory accident	Security measures and formation of the stimulation service company	severe injury
Design	explosion or heat production	laboratory accident	Security measures and formation of the stimulation service company	severe injury
Transport	Infrastructure damage	road accident	Control of driving skills by the employer and respect of circulation code	destruction of 1st priority infrastructure
Transport	Physical and psychological harm	road accident	Control of driving skills by the employer and respect of circulation code	casualties, injury, post-traumatic stress
Transport	environmental harm	road accident	Control of driving skills by the employer and respect of circulation code	pollution of soil, fauna and flora damage
Transport	environmental harm	road accident	Control of driving skills by the employer and respect of circulation code	pollution surface water, large scale fauna and flora damage
Transport	environmental harm	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite	pollution of nearby environment
Transport	chemical burn	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite	severe injury
Transport	physical harm	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite	casualties, injury
Storage	environmental harm	storage integrity issue	Respect of working procedure onsite and of the storage regulation	pollution of nearby environment
Storage	chemical burn	storage integrity issue	Respect of working procedure onsite and of the storage regulation	severe injury
Preparation	chemical burn	manipulation accident	Formation of operators	severe injury
Preparation	physical harm	operation accident	Formation of operators, respect of working procedure onsite	casualties, injury
Preparation	noise and vibration nuisance	working operation	Far from houses	nervous breakdown
Acid Job	physical harm	operation accident	Respect of working procedure onsite, formation of operators and certified equipment	casualties, injury
Acid Job	chemical burn	operation accident	Respect of working procedure onsite, formation of operators and certified equipment	severe injury
Acid Job	environmental harm	operation accident	Respect of working procedure onsite, formation of operators and certified equipment	pollution of nearby environment
Acid Job	environmental harm	well integrity accident	Respect of injection procedure	pollution of aquifer
Acid Job	physical harm	unexpected geological response	Presence of BOP	casualties, injury
Acid Job	environmental harm	well integrity accident	Adequate well completion	pollution of aquifer
Acid Job	Infrastructure damage	Induced seismicity	Respect of regulation	destruction of 1st priority infrastructure
Acid Job	physical harm	Induced seismicity	Respect of regulation	casualties, injury
Post job	environmental harm	unexpected reaction/corrosion products	Adequate design of the chemicals	Pollution of environment
Post job	physical harm	unexpected reaction/corrosion products	Adequate design of the chemicals. Gas detectors in surface	casualties, injury, disease
Post job	environmental harm	Leakage out of the mud pit	Adequate design and construction of the mud pit	pollution of nearby environment
Post job	physical harm	Hot pipes and fluid	Respect of working procedure onsite	injury
All	environmental harm	working operation		Air pollution

Fig. 48 Analysis document including risks, causes, consequences and security context of the chemical stimulation for the study case

5.4 Risk evaluation

On the basis of the precedent risk analysis, the same expert team performs the risk evaluation phase. Risks are evaluated using two parameters, frequency and gravity. As presented during the context definition (cf. section 5.1), both factors are rated between 1 and 4 and then multiplied together to get the final rate. The tolerability threshold of the multiplication is set at 7, which allows taking into account risk with low frequency (2) but high gravity (4) or the opposite.

The results of the evaluation are presented in Fig. 49, where the risks exceeding the tolerated threshold are already identified.

From those ratings, a graphical representation of the risks has been created summarizing the position of each risk in a “probability-gravity” graph (Fig. 50). At the same time, the fixed threshold of 7 is represented on the graph.

The results show that four risks are above the threshold: R15, R19, R23 and R25 (Fig. 50). Those risks are related to nuisance, aquifer pollution, induced seismicity and corrosion. A risk treatment phase is necessary to evaluate the security possibilities to lower the critical risks gravity and probability.

Référence	Phase	Risk	Cause	Security context	Consequence	Frequency	Gravity	Final level
R1	Design	physical harm	bad ergonomy of working place	Labour doctor consulted	musculoskeletal disorder	2	2	4
R2	Design	chemical burn	laboratory accident	Security measures and formation of the stimulation service company	severe injury	2	3	6
R3	Design	explosion or heat production	laboratory accident	Security measures and formation of the stimulation service company	severe injury	2	3	6
R4	Transport	Infrastructure damage	road accident	Control of driving skills by the employer and respect of circulation code	destruction of 1st priority infrastructure	1	3	3
R5	Transport	Physical and psychological harm	road accident	Control of driving skills by the employer and respect of circulation code	casualties, injury, post-traumatic stress	1	4	4
R6	Transport	environmental harm	road accident	Control of driving skills by the employer and respect of circulation code	pollution of soil, fauna and flora damage	1	2	2
R7	Transport	environmental harm	road accident	Control of driving skills by the employer and respect of circulation code	pollution surface water, large scale fauna and flora damage	1	4	4
R8	Transport	environmental harm	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite	pollution of nearby environment	1	2	2
R9	Transport	chemical burn	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite	severe injury	1	3	3
R10	Transport	physical harm	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite	casualties, injury	1	4	4
R11	Storage	environmental harm	storage integrity issue	Respect of working procedure onsite and of the storage regulation	pollution of nearby environment	2	2	4
R12	Storage	chemical burn	storage integrity issue	Respect of working procedure onsite and of the storage regulation	severe injury	1	3	3
R13	Preparation	chemical burn	manipulation accident	Formation of operators	severe injury	2	3	6
R14	Preparation	physical harm	operation accident	Formation of operators, respect of working procedure onsite	casualties, injury	1	4	4
R15	Preparation	noise and vibration nuisance	working operation	Far from houses	nervous breakdown	3	3	9
R16	Acid Job	physical harm	operation accident	Respect of working procedure onsite, formation of operators and certified equipment	casualties, injury	1	4	4
R17	Acid Job	chemical burn	operation accident	Respect of working procedure onsite, formation of operators and certified equipment	severe injury	1	3	3
R18	Acid Job	environmental harm	operation accident	Respect of working procedure onsite, formation of operators and certified equipment	pollution of nearby environment	1	2	2
R19	Acid Job	environmental harm	well integrity accident	Respect of injection procedure	pollution of aquifer	3	4	12
R20	Acid Job	physical harm	unexpected geological response	Presence of BOP	casualties, injury	1	4	4
R21	Acid Job	environmental harm	well integrity accident	Adequate well completion	pollution of aquifer	1	4	4
R22	Acid Job	Infrastructure damage	Induced seismicity	Respect of regulation	destruction of 1st priority infrastructure	2	3	6
R23	Acid Job	physical harm	Induced seismicity	Respect of regulation	casualties, injury	2	4	8
R24	Post job	environmental harm	unexpected reaction/corrosion products	Adequate design of the chemicals	Pollution of environment	3	2	6
R25	Post job	physical harm	unexpected reaction/corrosion products	Adequate design of the chemicals. Gas detectors in surface	casualties, injury, disease	3	4	12
R26	Post job	environmental harm	Leakage out of the mud pit	Adequate design and construction of the mud pit	pollution of nearby environment	2	2	4
R27	Post job	physical harm	Hot pipes and fluid	Respect of working procedure onsite	injury	2	3	6
R28	All	environmental harm	working operation		Air pollution	4	1	4

Fig. 49 Results of the risk evaluation, with the frequency and gravity rated in a 1-4 scale. The risks overpassing the tolerated threshold (7) are identified in red

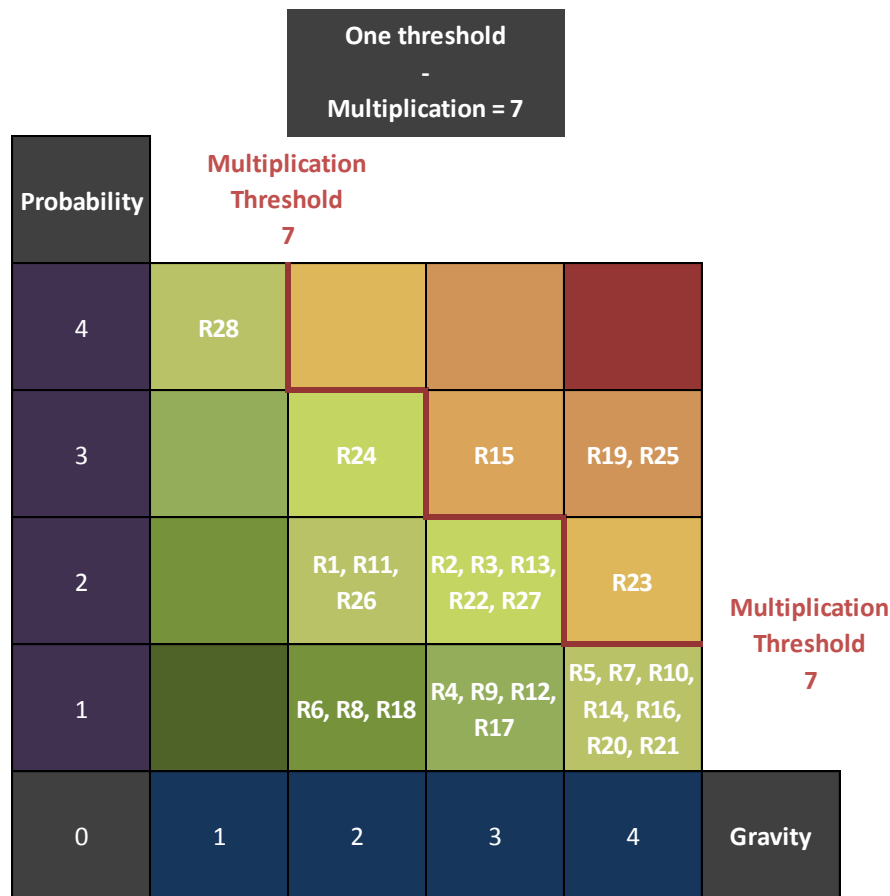


Fig. 50 Risk evaluation map of the soft stimulation for the study case

5.5 Risk treatment

For all the previous risk assessment phases, the security context taken into account corresponds to the compulsory measures and existing regulations.

However, additional extra security measures are systematically planned for the geothermal project in the French graben context, despite the constraints of the regulation. The aim of those measures is to lower the risk on the items that were already identified as critical in previous experiences.

The concerned risk treatment measures are listed below:

- **Noise insulation of equipment** to reduce the nuisances. The selection of low noise and vibration equipment is a part of the technical analysis specifications of the tender that will be published for the chemical stimulation services.
- **Consideration of initial well integrity** to choose the adequate acid injection methodology and design. The integrity of the casing and the cementation are inspected after the drilling phase to know the initial state of the wellbore integrity. The study of those logs helps determining the safer stimulation design for the wellbore.
- **Adequate BOP and wellhead dimensioning** to ensure the resistance of the surface installation in case of gas connection at the reservoir depths. The final depth of the well is under 2 500 m TVD. If a gas kick occurs at the last sediment layer depth, the pressure in surface could rise 200 PSI. In consequence, the BOP and the well head will be dimensioned for 3000 PSI.

- **Fine monitoring of the induced seismicity**, real time expert analysis. From the regulation, only 4 seismic stations are needed. But during the stimulations, a secondary network of 15 temporary stations will be used, and a crisis team of seismologist will follow the seismicity in real time.
- **Adequate choice of inhibitors**. Depending on the composition of the geothermal water, the rock formation, the casing and the acids, the inhibitors will be designed to ensure the lower corrosion, fluid-fluid and fluid-rock unexpected interaction.
- **Chemical control of produced water**. A washing out is planned after the chemical stimulation. During this washing out, the main chemical parameters of the produced water will be monitored (pH, Ec, density, etc.) so that any production of acid will be detected. If acid is detected on surface, particular measures will be taken to ensure the security of the mud pit.
- **Insulation of pipes**. The production line can be at a temperature higher than 100°C during the washing out. To be sure that no contact is possible with the heated tubes, the production line will be built in a gutter protected on the top by a duckboard, making it impossible to be directly in contact with the tube.

Thus, a new evaluation of risks has been made, taking into account those mitigation measures. The results are presented in Fig. 51, where the evolution of the risk level from before and after the application of the mitigation measures is shown. From those new ratings, a new risk map (see Fig. 52) has been updated summarizing the position of each risk in the frequency gravity graph. From those results, it appears that after mitigation, no risks are above the threshold.

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Référence	Phase	Risk	Cause	Security context	Mitigation measures	Consequence	Before mitigation			After mitigation		
							Frequency	Gravity	Final level	Frequency	Gravity	Final level
R1	Design	physical harm	bad ergonomy of	Labour doctor consulted		musculoskeletal	2	2	4	2	2	4
R2	Design	chemical burn	laboratory accident	Security measures and formation of the		severe injury	2	3	6	2	3	6
R3	Design	explosion or heat production	laboratory accident	Security measures and formation of the stimulation service company		severe injury	2	3	6	2	3	6
R4	Transport	Infrastructure damage	road accident	Control of driving skills by the employer and respect of circulation code		destruction of 1st priority infrastructure	1	3	3	1	3	3
R5	Transport	Physical and psychological harm	road accident	Control of driving skills by the employer and respect of circulation code		casualties, injury, post-traumatic stress	1	4	4	1	4	4
R6	Transport	environmental harm	road accident	Control of driving skills by the employer and respect of circulation code		pollution of soil, fauna and flora damage	1	2	2	1	2	2
R7	Transport	environmental harm	road accident	Control of driving skills by the employer and respect of circulation code		pollution surface water, large scale fauna and	1	4	4	1	4	4
R8	Transport	environmental harm	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite		pollution of nearby environment	1	2	2	1	2	2
R9	Transport	chemical burn	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite		severe injury	1	3	3	1	3	3
R10	Transport	physical harm	crane accident	Control of crane driving skills by the employer and respect of working procedure onsite		casualties, injury	1	4	4	1	4	4
R11	Storage	environmental harm	storage integrity issue	Respect of working procedure onsite and of the storage regulation		pollution of nearby environment	2	2	4	2	2	4
R12	Storage	chemical burn	storage integrity issue	Respect of working procedure onsite and of the storage regulation		severe injury	1	3	3	1	3	3
R13	Preparation	chemical burn	manipulation accident	Formation of operators		severe injury	2	3	6	2	3	6
R14	Preparation	physical harm	operation accident	Formation of operators, respect of working procedure onsite		casualties, injury	1	4	4	1	4	4
R15	Preparation	noise and vibration nuisance	working operation	Far from houses	Noise insulation of equipment	nervous breakdown	3	3	9	3	2	6
R16	Acid Job	physical harm	operation accident	Respect of working procedure onsite, formation of operators and certified equipment		casualties, injury	1	4	4	1	4	4
R17	Acid Job	chemical burn	operation accident	Respect of working procedure onsite, formation of operators and certified equipment		severe injury	1	3	3	1	3	3
R18	Acid Job	environmental harm	operation accident	Respect of working procedure onsite, formation of operators and certified equipment		pollution of nearby environment	1	2	2	1	2	2
R19	Acid Job	environmental harm	well integrity accident	Respect of injection procedure	Consideration of initial well integrity	pollution of aquifer	3	4	12	3	2	6
R20	Acid Job	physical harm	unexpected geological response	Existance of BOP	Adequate BOP and wellhead dimensionment	casualties, injury	1	4	4	1	3	3
R21	Acid Job	environmental harm	well integrity accident	Adequate well completion		pollution of aquifer	1	4	4	1	4	4
R22	Acid Job	Infrastructure damage	Induced seismicity	Respect of regulation	Fine monitoring of the induced seismicity, real time expert analysis	destruction of 1st priority infrastructure	2	3	6	1	3	3
R23	Acid Job	physical harm	Induced seismicity	Respect of regulation	Fine monitoring of the induced seismicity, real time expert analysis	injury	2	4	8	1	4	4
R24	Post job	environmental harm	unexpected reaction/corrosion	Adequate design of the chemicals	Adequate choice of inhibitors	Pollution of environment	3	2	6	2	1	2
R25	Post job	physical harm	unexpected reaction/corrosion	Adequate design of the chemicals. Gas detectors in surface	Adequate choice of inhibitors	casuaties, injury, disease	3	4	12	2	2	4
R26	Post job	environmental harm	Leakage out of the mud pit	Adequate design and construction of the mud pit	Chemical control of produced water	pollution of nearby environment	2	2	4	2	2	4
R27	Post job	physical harm	Hot pipes and fluid	Respect of working procedure onsite	Insulation of pipes	injury	2	3	6	1	2	2
R28	All	environmental harm	working operation			Air pollution	4	1	4	4	1	4

Fig. 51 Results of the risk mitigation, with the frequency and gravity rated in a 1-4 scale

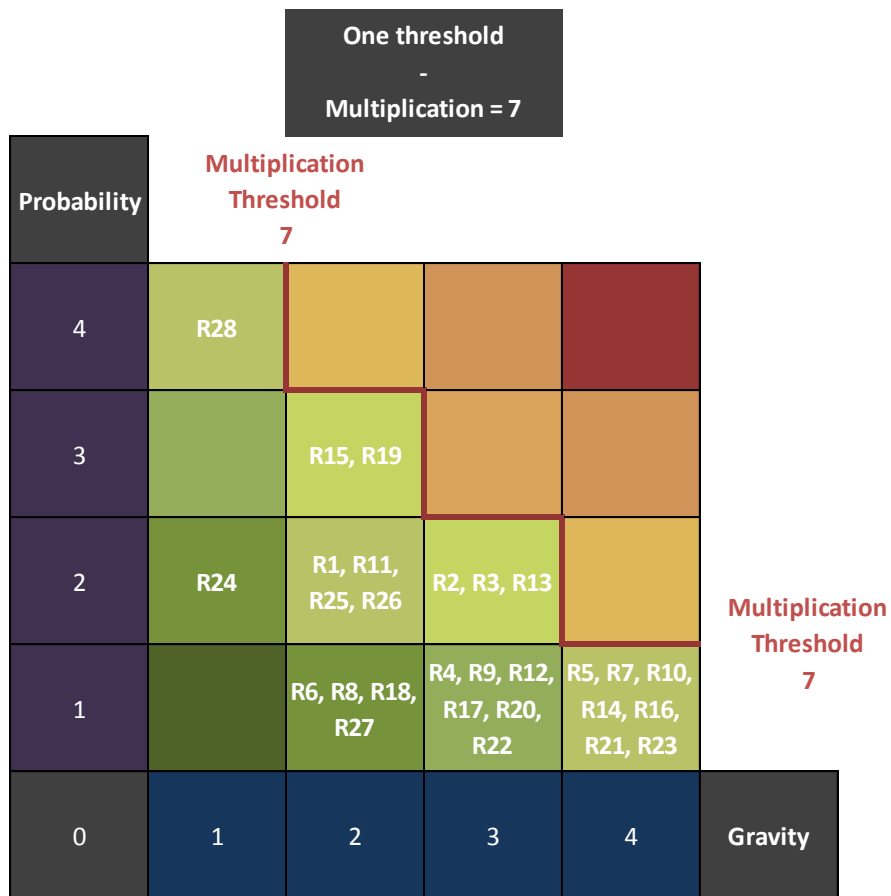


Fig. 52 Risk evaluation map of the soft stimulation for the studied case after the mitigation phase

6 Conclusion

6.1 Theoretical concerns

Risk assessment of chemical stimulation for enhancing geothermal reservoirs is a global and integrative method to lower the risk of geothermal projects. It is composed of different phases, from the identification of the different risks to the treatment of most critical ones. It usually starts before the realization of the project and can be updated at any time of the operations to ensure the validity of the hypothesis and to take into account the modification and the evolution of the context. At the end of the project, a feedback on the risk study is very important to capitalize on the findings, issues and possibilities of enhancement for the future projects.

Based on the bibliography and standardized guidelines, several methods are commonly used for risk assessment in the drilling industry. All of them have their benefits and drawbacks and can answer to different needs, depending on the complexity of the project, the means available and the objectives of the study. In that context, the geothermal industry has to face a major issue because one of the most important inputs for risk studies is historical records. Indeed, the identification of risks is highly based on what is known on precedent accidents, but such unexpected events during chemical treatments are rare and sparsely documented in the geothermal industry. To face this major lack of information, this report presents a methodology focusing on promoting imagination and large scale expertise in technical realization of a chemical stimulation. This methodology comprises four risk assessment methods such as Brainstorming, Scenario analysis, Checklist and Environmental Risk Assessment.

6.2 Case study

The presented methodology has been applied to the on-going Illkirch-Graffenstaden geothermal project located close to Strasbourg urban area where the Rhine aquifer is relatively thick. This report presents all documents used, from the risk identification to the treatment of critical risks related to chemical stimulation.

The methodology revealed that the risks have globally a very low probability of occurrence, which makes them very hard to evaluate as very few historical records can be taken as references. However, the risks associated with a potential chemical stimulation are not very different from the classical risks associated with drilling operation. In consequence, a large scale of security, risk treatments and prevention measures are already deployed on the drilling site, which lowers again the probability of occurrence of any eventual accidents.

Finally, the very detailed context of the project and the brainstorming-based method allowed establishing a list of major risks associated to the potential chemical stimulation of the Illkirch Graffenstaden geothermal site. The analysis of the risks of a chemical stimulation, with the compulsory security context (based on the regulation) revealed that induced seismicity, aquifer pollution and nuisance are the most critical risks to be considered. Based on the experience from former Rhine Graben geothermal projects, some additional mitigation and prevention measures are already planned. The study showed that those measures lower the risks of the critical risks level to a tolerable level.

6.3 Perspectives

The elements of the proposed risk assessment methodology are presented as series of roadmaps describing each step of a risk assessment study for a chemical stimulation. Figures and Tables are summarizing the key points, whose details can be found in the text, and a final case study gives an example of application of the methodology with relevant workflows. Following those roadmaps, any reader can base and develop his own risk assessment study, depending on its needs and the available inputs.

The environmental risk assessment presented in this contribution constitutes a part of a more global risk assessment study, taking into account the economic risk assessment, the communication and the feedbacks. The environmental risk analysis allows lowering the risk for the living and the environment to a level acceptable from the regulation and ethical point of view. But the methodology doesn't take the cost of the different mitigation or prevention measures into account. In consequence, an economic risk assessment is necessary for the complementarity of the global risk assessment of the project to ensure the achievability of the operations, in terms of technical and financial needs and limits.

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Project Lead	GFZ German Research Centre for Geosciences Telegrafenberg 14473 Potsdam (Germany) www.gfz-potsdam.de/en/home/
Project Coordinator	Prof. Ernst Huenges huenges@gfz-potsdam.de +49 (0)331/288-1440
Project Manager	Dr. Justyna Ellis ellis@gfz-potsdam.de +49 (0)331/288-1526
Project Website	www.destress-h2020.ch
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