# GeoWell

Innovative materials and designs for long-life high-temperature geothermal wells

## Deliverable D6.3

# Barrier definitions and risk assessment tools for geothermal wells

| Grant agreement no. | 654497 | | |
|---|---|---|---|
| Duration | 01.02.2016 – 31.01.2019 | | |
| Work package | WP6 – Risk assessment for geothermal wells | | |
| Type | R – document, report | | |
| Dissemination level | PU – Public | | |
| Due date | 30.09.2017 | | |
| Actual submission date | 29.11.2017 | | |
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| Version | 1.0 | | |
| Report no. | | | |
| Document status | | | |
| Change history | Version | Date | Changes |
| | | | |

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## Barrier definitions and risk assessment tools for geothermal wells

Report IRIS - 2017/294

| | |
|---|---|
| Project number: | 7012826 |
| Project title: | Innovative materials and designs for long-life high temperature geothermal wells – GeoWell |
| Client | – |
| Research Program | Horizon 2020 Research and Innovation Programme |
| Distribution restriction: | Public |

Stavanger, 28.11.2017

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# Executive summary

WP6 of the GeoWell project is about risk assessment of geothermal wells. Tasks 6.1 and 6.2 were completed in 2016 and provided a background on the focus of risk assessments in the geothermal and petroleum industries, and what type of methods are used for risk assessment throughout the life cycle of a well. Task 6.3 provides recommendations on the use and applicability of different methods/techniques for quantitative risk assessment of geothermal wells. The goal is to define selection criteria on the use and applicability of these methods for quantitative assessment of phenomena that cause loss of integrity and consequently flow of fluids outside the intended flow paths.

Using the competence and experience of the petroleum and geothermal industries as well as the GeoWell consortium, a well barrier approach has been taken. In order to maintain well integrity, a group of well barrier elements are needed to form an envelope able to prevent unintended flow. Barriers in all life-cycle phases are identified, however, the production phase is emphasized with regards to relevant well barrier failures. The following barrier elements have been identified and described in terms of functional properties: casing, casing cement, formation and wellhead.

A list of barrier failure modes in the geothermal production phase has been compiled using available guidelines and standards. A literature survey has been performed to identify methods to quantify risk of the selected failure modes, including models for failure mechanisms. Information about how the GeoWell industry partners quantify and manage the risk has also been gathered. With a better understanding of the main risks, and how to assess and manage them, a framework for a quantitative approach to risk assessment of geothermal barriers has been outlined. Based on the available literature for risk assessment principles and information about practices from the partners, different thoughts and processes that should govern the choice of methods are described herein.

The outset of this report and its motivation springs from a lack of guiding documents or principles for performing quantitative risk assessments for geothermal wells. While this report does not fully address this issue, it provides a set of foundations that can be used as a starting point. The failure modes covered are representative of commonly occurring problems in a geothermal context, also those operating in high temperature conditions. Failure data from Icelandic geothermal wells were also analyzed and provided valuable input in terms of highlighting frequently occurring failure modes. The framework presented tries to connect many of these failure modes with available tools for assessing them, using factors such as required input, output, complexity and resource demands as guiding selection criteria. Monitoring techniques and their connection to the failure modes also give a better understanding of how the risk assessment process can be continually updated.

Finally, the study demonstrates the application of the framework on two (high-temperature) geothermal phenomena – casing collapse due to trapped fluids behind casing, and parted connections due to excessive tensile forces. The occurrence and severity of these phenomena should increase with higher temperatures, unless measures are taken to avoid them. Solutions to these challenges are developed in other work packages of the GeoWell project. The

framework and assessment will be performed in detail for these solutions in upcoming work. The application of the framework in this report shows that a lack of historical data limits the applicability of methods based on the direct use of data, but rather scenario based modelling and more advanced use of existing data.

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# Abbreviations

| | |
|---|---|
| API | American Petroleum Institute |
| BCA | benefit/cost analysis |
| BOP | blowout preventer |
| BTC | buttress thread casing |
| CBA | cost/benefit analysis |
| CBL | cement bond logging |
| CCL | casing collar locator |
| DHSV | downhole safety valve |
| DM | decision maker |
| ERA | environmental risk assessment |
| ERI | environmental risk index |
| ETA | event tree analysis |
| FFA | functional failure analysis |
| FI | frequency index |
| FMEA | failure mode and effects analysis |
| FMECA | failure mode, effects and criticality analysis |
| FN | frequency/number of fatalities |
| GR | gamma ray |
| HAZID | hazard identification |
| HAZOP | hazard and operability |
| HRA | human reliability analysis |
| IDDP | Iceland Deep Drilling Project |
| IPL | independent protection layer |
| IRR | internal rate of return |
| ISO | International Organization for Standardization |
| LOPA | layer of protection analysis |
| MCDA | multi-criteria decision analysis |
| MPD | managed pressure drilling |
| MTTF | mean time to failure |
| NPV | net present value |
| PDC | polycrystalline diamond compact |
| PDF | probability density functions |

| PSA | Petroleum Safety Authority of Norway |
|---|---|
| PV | present value |
| QRA | quantitative risk assessment |
| RAM | risk assessment matrix |
| RAMS | reliability, availability, maintainability and safety |
| RCM | reliability centered maintenance |
| SI | severity index |
| SIL | safety integrity levels |
| UBD | underbalanced drilling |
| WBE | well barrier element |

# 1 Background information

WP6 of the GeoWell project is about risk assessment of geothermal wells. Tasks 6.1 and 6.2 were completed in 2016 and resulted in two reports, entitled "Well integrity risk assessment in geothermal wells – Status of today" [1] and "A roadmap for transferring well integrity risk assessment from oil and gas to geothermal" [2]. These reports provided a background on what is the focus of risk assessments in the geothermal and petroleum industries, and what type of methods are used for risk assessment throughout the life-cycle of a well. Some of the important findings are:

- The risk type most addressed in the literature is related to project/financial risk.

- Only about 10% of the publications reviewed cover well integrity as a topic.

- There is less focus on barriers and less use of methods associated with assessment of barriers in the geothermal industry compared to the petroleum industry.

WP6 activities have been continued with a focus on more specific examples of assessments of well integrity. The objective of Task 6.3 "develop risk assessment methods for phenomena that are currently not covered for geothermal wells, particularly at elevated temperatures up to 450°C", is to provide recommendations on the use and applicability of different methods/techniques for risk assessment of geothermal wells. The goal is to define selection criteria on the use and applicability of different risk assessment methods for quantitative assessment of phenomena that cause loss of integrity and consequently flow of fluids outside the intended flow paths in geothermal wells. Deliverable 6.3 entitled "Barrier definitions and risk assessment tools for geothermal wells" summarizes activities that have been performed as part of Task 6.3.

## 1.1 Scope

The focus of WP6 is on the production phase of geothermal wells. However, failure causes and failure modes originating from the well construction phase have also been taken into consideration.

This report primarily covers assessment of the risk, and does not go into details regarding monitoring and additional preventive/corrective measures that are impartible elements of comprehensive risk management practices. In addition, note that WP6 of the GeoWell project addresses only technical risk assessment for geothermal wells, excluding non-technical risks.

Given the wide range of geothermal energy applications, the focus here is on geothermal wells that produce thermal power at relatively high temperatures (i.e. for electricity production). Therefore, geothermal wells exposed to low temperatures (typically for heating/cooling purposes) are outside of the scope.

## 1.2 Methodology

To accomplish the objective of Task 6.3, a barrier concept based on NORSOK D-010 is used when considering different methods for risk assessment related to geothermal wells. As

mentioned earlier, the scope is limited to physical barrier elements in a well, such as casing, cement and valves that have a function to prevent flow of fluids outside the intended flow path. The operational function of different barrier elements, how they together constitute a barrier and in which life-cycle phase they should be included are described in this document.

Apart from the completion phase, it is assumed that geothermal well barrier elements are similar to those used during the life-cycle of petroleum wells. However, to get some foundation for this assumption, examples of geothermal wells have been sought, primarily well schematics for typical wells in Iceland and Italy. These examples have been compared to other knowledge, such as the well barrier elements defined in NORSOK D-010 [3].

After establishing a list of well barrier elements and how they together constitute barriers, the study has considered how these barriers might fail to perform their function, i.e. preventing unintended flow. A list of failure modes has been compiled using sources from the petroleum industry (e.g. available guidelines and standards) and experience from the GeoWell partners. Selected failure modes have been chosen based on their relevance for the GeoWell project. A literature survey has been performed to identify methods to quantify risk of the selected failure modes, including models for failure mechanisms. Information about how the GeoWell industry partners quantify and manage the risk has also been gathered.

An overview of quantitative risk assessment (QRA) methods has been created, being a subset of methods used in the GeoWell risk assessment survey (refer to [1, 2] for further details). With a better understanding of the main risks, and how to assess and manage them, a framework for a quantitative approach to risk assessment of geothermal barriers has been made. Based on the available literature for risk assessment principles and information about practices from the partners, different thoughts and processes that should govern the choice of methods are described here. Note that this report (as part of Task 6.3) aims to provide selection criteria on the use and applicability of available quantitative risk methods. Specific methods to be used for different barrier elements will not be determined in Task 6.3.

Finally, the study demonstrates the application of the framework on two geothermal phenomena (related to failure modes). These have been chosen based on the literature review and relevance for the GeoWell project.

## 1.3 Outline of the report

Chapter 2 provides the definition of a barrier and a well barrier element. This chapter also provides a list of barriers for different phases of a well's life-cycle. Different well barrier elements during the production phase are then identified.

Chapter 3 presents the ways that different well barrier elements can fail, i.e. failure modes. Some of the sources that cause these failure modes and how they can be detected, as well as the general failure consequences are also included in this chapter.

Chapter 4 starts with describing different quantitative risk assessment methods/techniques together with their use, limitations and strengths. Relevant experiences, practices and data that are in the possession of GeoWell partners are then briefly presented. Chapter 4 finally outlines a framework for selection and application of methods to use in a quantitative risk assessment for relevant failure modes and well barrier elements.

Chapter 5 first describes two common phenomena that cause loss of integrity of high temperature geothermal wells. Application of the proposed quantitative risk assessment framework is then conceptually evaluated for the selected phenomena.

Finally, Chapter 6 presents concluding remarks of this report, as well as future plans for using the outcomes of Task 6.3 in activities related to Task 6.4 and Task 6.5.

# 2 Introduction to barriers

This chapter mainly aims at providing a clear definition of a safety barrier, based on definitions available in the literature and knowledge from the Norwegian petroleum industry. The operational function of different well barrier elements (WBE) and the way they constitute a well barrier during different life-cycle phases are also included here.

## 2.1 Barrier definition

Any activity that takes place with the purpose of providing some kind of societal benefit may incur accidental events. A safety barrier can be considered a defense system put in place to reduce the risk of such events that may harm humans, the environment and assets.

Depending on the application, different terms are used as synonyms for barriers such as safety systems, safeguards and protective systems. Despite the widespread application of barriers, no commonly accepted definition of a barrier exists [4]. Several possible definitions have been proposed [4-6], one of them being [4]: "safety barriers are physical and/or non-physical means planned to prevent, control or mitigate undesired events or accidents". Safety barriers can be classified and organized in a variety of ways including passive, active, physical, technical, human, operational, organizational, and safety-instrumented system [4, 6, 7].

For practical purposes, a minimum distinction could be between "hard" barriers (or physical barriers such as mechanical, hydraulic and electronic solutions) and "soft" barriers (or non-physical barriers such as organizational solutions, human performance and communication). In this report, the term barrier will indicate physical barriers, such as equipment installed in a well, and not soft barriers.

## 2.2 Well barriers

A group of well barrier elements need to form a closed envelope to be considered a well barrier. This section briefly summarizes how the different well barrier elements described together constitute a well barrier in the different phases of the well life-cycle of a geothermal well.

### 2.2.1 Barriers in the well construction phase

The well construction phase typically consists of drilling the hole, installing the casing and cementing it when necessary / according to plan, and getting the well ready for production (completion). It will also include various contingency operations if something should happen, such as a large kick (influx of formation fluid or explosive boiling in the well).

In both petroleum and geothermal drilling, there are usually two barriers preventing inflow. The primary barrier is the fluid column. The high temperature in geothermal drilling can pose a threat to the primary barrier. Thus, continuous circulation of drilling mud or cold water through the drill string, or injection of cold water at the wellhead if the string is out of the hole, is important to control the well and prevent a kick. The secondary barrier consists of:

- Formation at the casing shoe
- The deepest casing

- Casing cement
- Wellhead with blowout preventer (BOP)

In addition, when a drill string is in the hole, the drill string with a valve preventing return flow through it would be part of the barrier if the BOP would not shear it.

During the drilling phase, the barrier elements are changed for each new section as new formation is drilled and new casings installed. The properties of the fluid column are also changed to match the challenges faced.

If the fluid column is compromised, such as a large volume of gas/steam displacing the fluid column, then the well is actively shut in by closing the BOP until the primary barrier can be reestablished.

Note that severe or even total losses of circulated fluids are more common in geothermal than in petroleum drilling due to the high permeability of highly fractured high temperature geothermal reservoirs and relatively low reservoir pressures. Several geothermal wells have thus been drilled blind, i.e. with no fluid returns to surface.

### 2.2.2 Barriers in the production phase

During the production phase, fluids are intended to flow up to surface where they can be used to produce heat and electricity in the case of geothermal or transported and sold in the case of petroleum. The barrier system should in this case prevent flow into non-producing zones, as well as be able to throttle and shut in the production as needed.

In a typical petroleum well, as shown in Section 9.4.2 in ISO 16530-2 and Figure 4.2.2 in NORSOK D-010, there will be two barriers. The primary barrier consists of:

- Formation
- Production casing
- Production casing cement
- Production packer
- Production tubing
- Downhole safety valve (DHSV) inside the production tubing

The secondary barrier described consists of

- Formation (shoe of intermediate casing)
- Intermediate casing
- Intermediate casing cement
- Wellhead and X-mas tree (including subcomponents)

In a geothermal setting, on the other hand, it is more customary to only have a single primary barrier in place, instead of two barriers as for the petroleum industry. Geothermal wells typically do not include a production tubing [8], but rather produce directly through the production casing to avoid a reduction in diameter causing lower flow rates. Thus, for a geothermal well the typical well barrier consists of (see Figure 2-1):

- Formation
- Casing
- Casing cement

- Wellhead (including subcomponents)
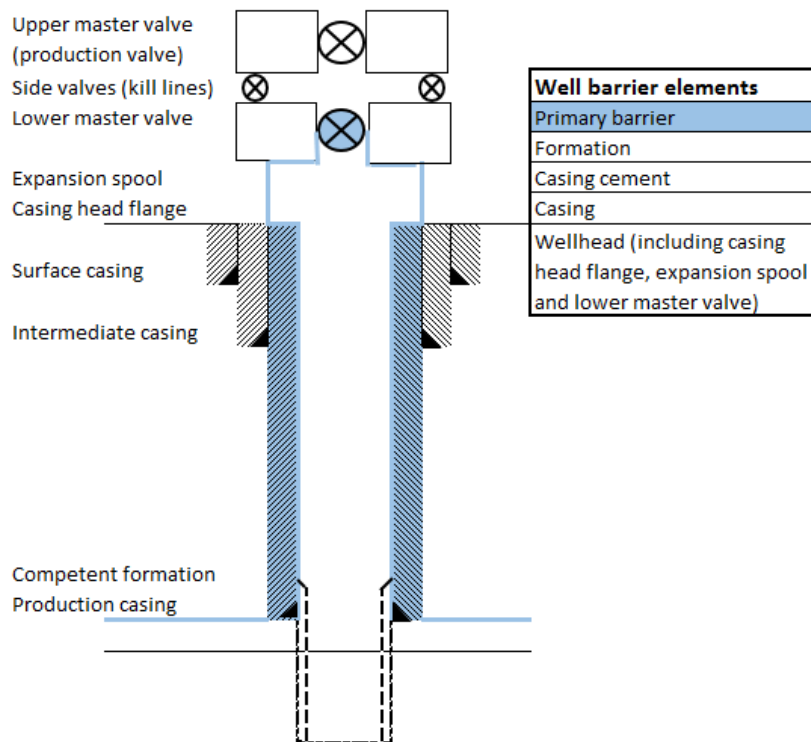


**Figure 2-1. Example of well barriers in a geothermal well [9]**

It is indicated in [9] that when ground water reservoirs are found near surface, a second and sometimes third casing in a suitable formation should be considered as a second barrier to inflow of cold fluids into the geothermal well or outflow from the well causing contamination of usable ground water resources.

### 2.2.3 Barriers in the maintenance phase

During maintenance operations, the well is shut in and production is temporarily stopped (or reduced). The barriers used will depend on the type of maintenance being performed. The barriers would either be similar to production or to well construction, depending on the scope of work. If the operation can be performed while the master valve remains functional, the barriers would remain similar to production. For more extensive work, the well will be "killed" to regain overbalanced conditions as for well construction.

In a geothermal setting, the production is stopped by quenching the well with cold water to re-establish overbalanced conditions. This cooling and later re-heating can cause deterioration of the barriers, as is described in later chapters. For some work, such as the replacement of the master valve, it may be sufficient to plug the well below it, such as with a retrievable packer or cement plug, to prevent the well from flowing. Repairs and maintenance on the wellhead will, if possible, be performed with the well shut-in but kept on bleed (small discharge to relieve buildup of gas pressure and temperature cycling). Scaling is also sometimes removed while the well is flowing in order to avoid cooling and re-heating of the casing.

### 2.2.4 Barriers in the plug and abandonment (P&A) phase

When the well has no further purpose due to low production, or becomes too costly to maintain, the well should be properly abandoned. The regulation varies by country, but typically this involves establishing cross-sectional barriers in the well above and between zones of inflow, and cleaning up the topside area by removing the wellhead and top part of the well and close off the top.

The cross-sectional barriers would consist of:

- Formation (at the bottom of the plug)
- Casing cement
- Casing
- Internal cement plug

The barriers are the same in a geothermal context as in a petroleum context. A main difference is that geothermal wells tend to cement the casings to surface, making it difficult to remove the existing casings by cutting and pulling. Thus, as described in NZS 2403:2015, a cement plug inside the innermost casing is mainly used. If the annulus is suspected of being inadequately sealing, it is important to make it sealing by squeeze-cementing from surface or through perforations.

### 2.2.5 Summary of barriers for all life-cycle phases

Table 2-1 shows a list of the most frequently used barrier elements in geothermal wells based on NORSOK D-010 with relevance based on NZS 2403:2015 distributed for the four life-cycle phases. A number of well barrier elements either associated with specific operations or not common in high temperature geothermal wells have not been included, and are instead listed in the Appendix.

**Table 2-1. Well barrier elements and their applicability to different life-cycle phases**

| WBE (conventional) | Life-cycle phase | | | |
|---|---|---|---|---|
| | Well construction | Production | Maintenance | P&A |
| **Fluid column** | X | - | X | - |
| **Casing** | X | X | X | X |
| **Casing cement** | X | X | X | X |
| **Formation** | X | X | X | X |
| **Wellhead** | X | X | X | - |
| **Drilling BOP** | X | - | X | - |
| **Drill string** | X | - | X | - |
| **Stab-in safety valve / one-way valve** | X | - | X | - |
| **Casing float valves** | X | - | - | - |
| **Cement plug** | - | - | (X)[1] | X |

## 2.3 Well barrier elements in the production phase

Each well barrier consists of one or more well barrier elements. In the following sections, these well barrier elements are described for the barrier in the production phase. The descriptions of the barrier elements include the function of the barrier element in accordance with NORSOK D010 and ISO/TS 16530-2.

### 2.3.1 Casing

Installed in the drilling / well construction phase, casings are tubulars, usually made of carbon steel, of different dimensions set at progressively deeper depths. The purpose of a casing as a well barrier element is to provide isolation that stops uncontrolled flow of formation fluid, or injected fluid, between the casing bore and the casing annulus.

To achieve this, the casing will have to be fluid tight, also in the connections, hanger and shoe (see cement). As the casing will be subjected to varying conditions over its lifetime, such as wear, fluids, temperature and pressures, the casing selection should take at least the following into consideration (see also API Spec 5CT and API Spec 5L recommended in NZS 2403:2015)):

- Loads and stresses expected during the lifetime of the well (including all planned operations and potential well control situations)

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1 During the production phase, cement plugs are used in critical situations to buy time, i.e. if the well is becoming out of control, then cement is injected on top to establish a cement plug in the production casing through a damaged interval to kill the well until a rig is moved to the site to repair the well.

- Degradation effects due to temperature, corrosion, plastic yield and wear
- Burst, collapse and tension / compression
- Connection / thread strength and tightness requirements

In particular for high-temperature geothermal wells, it is important to consider the linear expansion and contraction of casings, and issues related to thermal expansion of liquids.

### 2.3.2 Casing cement

The casing cement is the cement placed in the annulus, either between two casings or between casing and the formation. The purpose of the casing cement is to provide a continuous, permanent and impermeable hydraulic seal along the wellbore to prevent flow of fluids in the annulus. In addition, the casing cement provides structural support for the casing.

In high temperature geothermal wells, there is an additional important function of the casing cement. The casing is typically cemented to surface to reduce the elongation of the casing caused by temperature change in all phases of development, from placement to production, and later cooling and reheating because of maintenance work. Also, it reduces thermal fatigue as a result of thermal expansion and contraction.

The casing cement is prepared as a slurry, but should cure to a solid state after placement in the annulus. The following should be considered in relation to the casing cement (See also API RP 10B and ISO 10426-1)

- Casing centralization and standoff, to ensure complete circumferential cement coverage and provide sufficient pressure and sealing ability over a length of the annulus
- Use of fluid spacers, to keep the cement free of contaminants (mud) and clean the borehole walls
- Hydrostatic pressure differentials between the inside and outside of the casing
- Dynamic pressure during pumping and loss of hydrostatic pressure prior to cement setting
- Losses, which should be managed to ensure a proper cement job
- Thickening time and compressive strength development of the cement recipe
- Prevention of gas/steam migration
- Length, as required based on structural integrity, load conditions and prevention of flow
- Avoid trapped water between casings
- Future use (e.g. re-casing, sidetracks and abandonment)

### 2.3.3 Formation

This well barrier element refers to a geological formation capable of preventing flow and withstanding maximum design pressures. It is recommended practice in both petroleum (ISO 16530-2) and geothermal (NZS 2403:2015) to have the deepest part of each casing located at such a relatively impermeable and structurally competent formation. The purpose of the formation as a barrier element is to prevent flow to surface through the formations, faults or other wells, as well as prevent cross-flow of fluids.

The following should be considered for the formation (according to NORSOK D-010 and NZS 2403:2015):

- It shall be impermeable with no flow potential
- It shall bond directly to the casing cement (or alternative annulus material), plug in the wellbore or directly to the casing
- Proximity from fractures and/or faults that may lead to flow
- Ability to withstand the maximum wellbore pressure
- Effect of changes in the reservoir pressure over time (such as re-activation of faults or development of shallow steam zones)

### 2.3.4 Wellhead

The wellhead is the surface part of the well, and consists of a wellhead body, valves which can shut the well in and access ports to e.g. kill or quench the well, for monitoring wellhead pressure and temperature, as well as provide points for fluid sampling. The function of the wellhead is to prevent flow from the wellbore and annuli to the outside environment.

A geothermal wellhead typically has a wellhead flange, expansion spool, main valves and kill lines. The wellhead flange or casing head flange attaches the wellhead to the casing. An expansion spool allows the production casing to change length. The master or main line valves are intended to be able to shut in the well. If there are two main valves, the lower and upper master valves, the lower master valve would be considered part of the barrier in a single barrier system. The kill lines or side valves can have different positions in relation to the master valves. They should be able to enable sufficient water injection rates to quench the well as needed, for example if the lower master valve develops a leak [8, 10].

For the wellhead, the following should be taken into consideration:

- The pressure and temperature it will be exposed to
- Corrosive environment in and around the wellhead
- Rise and fall of wellhead due to temperature expansion and contraction of the casings.

# 3　Well barrier failures

Well barriers can fail in many ways. This chapter will list known ways the different well barrier elements can fail, i.e. failure modes. Finally, a description of the effects that can result from the failure modes is provided.

The basis for the listing of failure modes is NORSOK D-010 and ISO TS 16530-2, but also considering experience and input from both petroleum and geothermal operators as well as from published literature.

## 3.1　Failure modes

A failure mode can be defined, according to ISO TS 16530-2, as a "description of the method of failure" [11]. Examples are "leakage", "burst/rupture" and "fail to close/lock". Failure modes may be general or specific in their descriptions, often depending on the variety of the elements or equipment they apply to. Failure modes can be standardized for certain areas of application, such as the ISO 14224 standard [12], which is used to collect reliability data for oil and gas subsea equipment. A failure mode can be viewed as being between the cause of a failure and the consequence of the failure, as it does not necessarily provide information about why the failure occurred or what it may lead to, only how the failure materializes.

According to Davies et al. [13], there is little published information describing failure rates of geothermal wells. Generally, failure rates are expected to vary significantly due to the wide range of geological settings from which geothermal energy can be exploited, e.g. volcanically active regions and tectonically quiescent regions. This report however has a focus on high-temperature wells in particular, and as such the failures modes reviewed in the following sections are viewed in light of this.

### 3.1.1 Leakage (casing, cement, formation, wellhead)

A leak can occur in the casing, cement, formation or wellhead. A leak is often caused by corrosion, bad cementing of the casing, thermal cycling, wear of drill pipes or erosion.

The most serious and costly leaks (in terms of consequences) are those in the casing. A leak in the upper part of the well could lead production steam and fluid into the annulus between two casing strings. The leak can initially be small, but will grow due to the erosive/corrosive effects of steam and water. If such a leak is not repaired promptly, it can result in a dangerous release of steam (hydrothermal eruption), throwing out mud and rocks in extreme cases [14].

Leaks in the wellhead components (especially the stems and seals of the valves and flanges) tend to become larger due to high pressure fluids. Sealing the wellhead becomes more difficult because of mineral deposition during water evaporation [14], and also because of corrosion and erosion.

### 3.1.2 Fractures (formation)

Rock can fail in tension, compression/shear or from a combination of these modes as shown in Figure 3-1 [15], in cases where there is a presence of brine injection wells acting upon the reservoir pressure and temperature. While fractures within the reservoir are desired, fractures that open and extend beyond the reservoir or to the surface pose a threat to the integrity of the

well. As the formation as a barrier element is considered as a hydraulic seal, fractures providing leakage pathways would compromise its integrity. Leakage paths to surface could also arise if the pressure at the casing shoe exceeds the lithostatic pressure, and the production casing must therefore be set at a sufficient depth and inside a sufficiently strong formation.
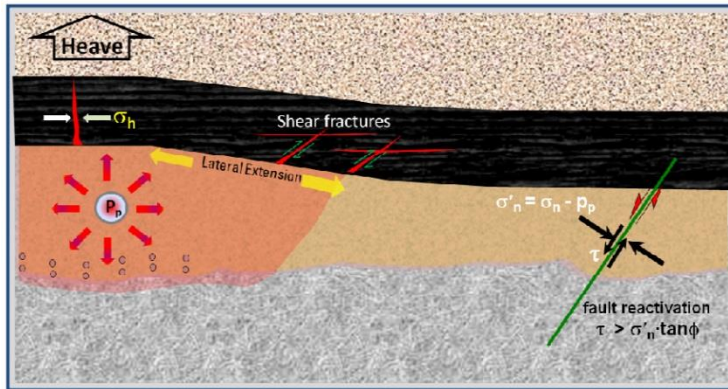


**Figure 3-1. Possible formation failure mechanisms [15]**

### 3.1.3 Material degradation (casing, cement, wellhead)

Materials in high temperature geothermal wells (e.g. casing) and equipment connected to them (e.g. wellhead) can be corroded, eroded and consequently degraded. This is due to the high temperature environment and the chemical composition of the geothermal fluid.

Geothermal fluid can contain corrosive agents such as dissolved carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), hydrogen chloride (HCl), hydrogen ($H_2$), ammonia ($NH_3$), and sulfate and chloride ions. In addition to the composition, the pH value, pressure and flow rate of the fluid can influence corrosion in downhole equipment and wells [16, 17]. Degradation may occur due to radial expansion with heat, which may break the cement sheath or create microannulus. External corrosion proceeds rapidly where metal is exposed by cement sheath failure through lost circulation zones or by dissolution by strong, hot water flows [18]. Corrosion can be very severe at the dew point, when the fluid changes from one (superheated steam) to two-phase (steam and liquid) and the pH becomes very low due to hydrogen chloride in the steam. There are different types of corrosion that can cause material degradation including $CO_2$ corrosion and sour ($H_2S$) corrosion, erosion-corrosion and pitting corrosion. Corrosion can typically occur on the outside of the casing and in the wellhead, when the well cools down and oxygen is allowed to enter without drying out all water [19].

**$CO_2$ corrosion**

Carbon dioxide is the most common corrosive element in geothermal wells and is present in almost all wells. $CO_2$ corrosion can attack both metallic and non-metallic parts of the well. One of the causes of metal corrosion is the carbonic acid formed by $CO_2$ in steam or water [20]. The aggressiveness of $CO_2$ corrosion to the metal depends on temperature, material characteristics, $CO_2$ partial pressure and various other factors [21].

**Sour corrosion**

Metallic parts of a well can be deteriorated due to contact with hydrogen sulfide and water. The reaction product of $H_2S$ and water can release hydrogen ions and cause corrosion of the metal [20].

**Erosion-corrosion**

Erosion-corrosion is the cause of mechanical removal or wear of casing's internal layers or surface layers of equipment due the fluid flow. This can result in higher rates of chemical corrosion on the inside of casings or equipment [20]. Erosion-corrosion often occurs under high flow rates and temperatures where the steam is wet (with droplets in the flow) or the steam contains solid particles [16].

**Pitting corrosion**

This type of corrosion will eventually create localized holes in the metal surface. Metallic elements such as iron (Fe) will oxidize and react with halides (such as chloride ion) [20]. Pitting may cause leakage problems and reduce the fatigue life of the metal due to stress concentrations. This localized corrosion may cause unexpected material failure, despite all precautions taken in the corrosive environment or in environments that should be harmless according to their chemical composition [22].

Geothermal steam containing volatile chloride is found in locations such as Iceland, Italy, Taiwan and the USA [23], and when the steam cools below the acid dew point, HCl dissolves in droplets, and a strong hydrochloric acid forms, where rapid pitting corrosion can occur.

**General deformation/corrosion**

Small deformations caused by surface handling or other impact damages that alter the metallurgy of otherwise homogeneous steel may set up galvanic corrosion cells in the presence of hot brines. This can initiate cracking and stresses.

### 3.1.4 Burst/rupture (casing)

Burst is a rupture of the casing wall due to the difference between the pressure inside the casing and the annulus pressure exceeds the burst resistance of the casing. Rupture can also be caused by excessive axial tensile stress caused by thermal contraction when casings cool down, i.e. due to long period shut-in or killing/quenching operations [24]. This has occurred in several wells in Iceland related to fast cooling while pumping cold water into a hot well. Analyses of these wells show that [25]:

- Failures are more likely to form near changes in outer casings, e.g. at material grade changes (T95-K55) and near casing shoes.
- The thermal difference between casing layers leads to a thermal expansion mismatch that generates stress/strain
- Rupture is more likely for quick temperature changes
- The thermal load is more severe for the innermost casing that is directly exposed to the geothermal fluid.

Figure 3-2 shows a coupling rupture (with a gap of approximately 0.4 m) at about 300 m depth in the well of Iceland Deep Drilling Project 1 (IDDP-1) [24].
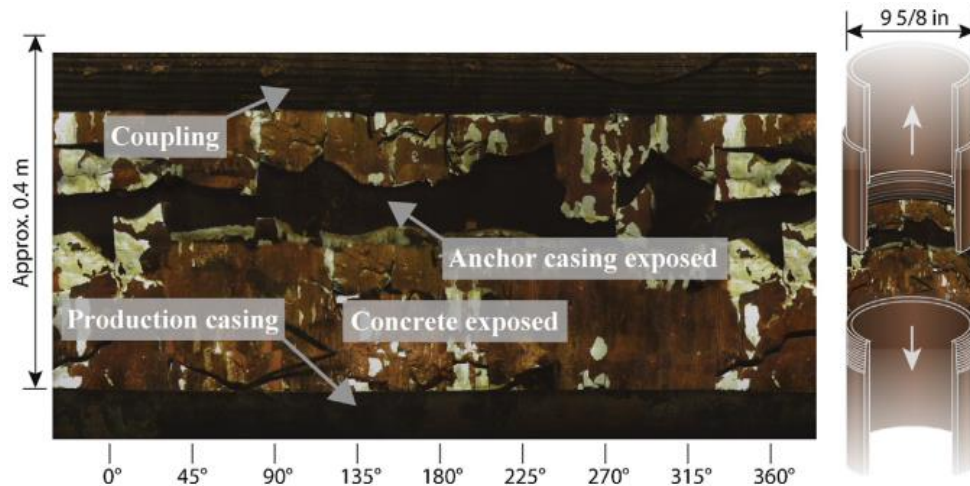


**Figure 3-2. Coupling rupture at approximately 300 m depth in the IDDP-1 well [24]**

### 3.1.5 Bulge/collapse (casing)

Imperfectly cemented portions of casing filled with fluids (water and gas/steam) are subject to thermal action because of well operations [26]. Trapped fluid behind the casing can induce casing collapse (or casing bulge collapse) during the well heat-up phase (production) as the fluid wants to thermally expand [27] and the generated pressure can easily exceed the casing collapse resistance [28]. This failure mode is more likely to happen in the casing to casing annulus, as the generated pressure due the trapped fluid often diffuses into the formation/fractures in casing to formation interval. In an event of production casing failure, the productivity of a well can be significantly affected. It has been reported that in some cases, the well flow might be choked by more than 50 percent [29].

More detailed description of casing collapse due to trapped fluid is given in Section 5.1.1.

### 3.1.6 Buckling (casing)

Increased effect of pipe elongation due to large temperature variations can lead to casing buckling in the intervals without sufficient lateral support (due to e.g. cement placement, lost circulation or hole washouts).

In order to reduce the risk for buckling and expansion, the entire length of the casings should be cemented in geothermal wells [20]. In some events, buckling does not require free radial movement, which is called local buckling. Even with sufficient lateral support through good cementation and cement bonding, local buckling may happen. When cement integrity is lost, corrosion may occur, leading to local buckling as well. Local buckling as a failure mode can affect the well integrity and can hinder running maintenance equipment in or out of the hole. As shown in Figure 3-3, casing corrosion may pose additional risks to buckling [30].

**Figure 3-3. Local buckling produced by external corrosion on casing [30]**

### 3.1.7 Plugged or choked flow (casing, wellhead)

Geothermal fluids contain elements such as calcium, silica and sulfide that can precipitate from the brine and deposit on the surface of equipment and on the casing walls. This phenomenon is known as scaling and occurs due to changes in pressure, temperature or pH value. Scaling is a considerable challenge in many geothermal wells and can cause plugging of the well and other downstream equipment. Consequently, it can reduce the well flow and power production and can incur expensive cleaning costs [16].

High temperature resources with high water ratios often have increased levels of silica that can cause scaling and deposit problems. This is in contrast to dry steam fields that do not experience silica scaling problems, but instead have aggressive corrosion problems associated with HCl, $CO_2$ and $H_2S$ attack [31].

Note that the scaling itself could act as a coating that protects the bare metal surface from direct contact with corrosive production fluids [32].

The reservoir temperature ranges of scaling depositions for common types of scaling are [9, 17]:

- Calcium carbonate (in the crystalline forms calcite or aragonite): 140-240°C [17]
- Silica scaling 240-290°C [9]
- Silica and sulfide scaling >290°C [9]

### 3.1.8 Breakdown (casing, cement, wellhead)

Breakdown can be considered as a serious damage that partially or completely impairs the functionality of the barrier element, and is typically caused by e.g. stress, fatigue, corrosion and leakage. Tensile stress may lead to the failure of the casing and cement which may fail if the stress exceeds the strength of the cement. Breakdown can often be considered the ultimate consequence, resulting from preceding failure modes having first occurred.

### 3.1.9 Spurious displacement/slippage (casing, cement, wellhead)

Spurious displacement is the unwanted movement of a barrier element, typically caused by the impact of external forces. A wash-out could occur for the formation, de-bonding could

occur in the cement/formation interface, or the wellhead could be displaced due to pressure and wellbore temperature changes.

Slippage includes fault slip, rock movement due to compaction of overburden, fault reactivation (includes fracture movements during tectonic events, earthquakes and similar events) and packer slippage due to worn/corroded casing wall.

### 3.1.10 Other failure modes (wellhead/other)

There are other failure modes, which in this context are mainly relevant for valves, including:

- Fail to open on demand: The valve does not move to an open position when an open signal is sent to it.
- Fail to close on demand: The valve does not move to a closed position when a close signal is sent to the valve.
- Fail to lock/unlock
- Spurious operation
- Insufficient power
- Abnormal instrument reading
- Overheating
- Vibration
- Delayed operation
- Missing signal/lack of functional control

## 3.2 Consequences

According to ISO 31000, risk is defined as the effects of uncertainty on the objectives and is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence [33]. This section focuses on consequences by providing a general definition and determining the consequences of potential barrier failure modes in geothermal wells.

### 3.2.1 Definition

Consequence is defined as outcome of an event that can have either positive or negative effects on the objectives. It should be noted that any event can lead to a range of certain or uncertain consequences that can be expressed qualitatively or quantitatively. Initial consequences can escalate through knock-on effects [33]. The consequences can be defined in relation to personnel's health and safety (that can be measured e.g. in loss of life), environment (such as discharges of harmful materials), assets (e.g. impact on the installations and economic losses), social impacts or reputation of the operator or to a combination of these aspects [11, 34].

### 3.2.2 Consequences of geothermal well barrier failures

A leak in the casing could cause either a release of production fluid or influx from the formation. The leak may turn into a disaster in terms of safety if it is close to the surface, but might be possible to ignore if it is e.g. close to the casing shoe. From an economic perspective, this could affect the revenue of the well and lead to a financial loss. If the enthalpy of production fluid is reduced due to mixing with low enthalpy fluids or if the flow rate is decreased due to a leak to the outside, power production from the well is also decreased. A

casing leak might be ignored, if the enthalpy drops or reduction in flow rate is minor, and consequently financial losses are within acceptable limits (often defined by the operator). The decision of when to repair the damaged casing depends on the projected decline in revenues and the rate of the decline [9]. Local regulations generally do not accept leakages of geothermal fluids to other aquifers. The operator is obliged to be diligent in any action that may affect or cause changes to a body of water. Adverse changes in the properties of water therefore shall be avoided [35].

The presence of micro annuli and cracks in the cement is natural. Exposure to the severe temperature changes that are common in high-temperature geothermal wells can have negative effects on the cement. The risk for migration of geothermal fluids through such pathways (i.e. through micro annuli and cracks) along the wellbore is generally assumed negligible but can be increased due to thermal cycling [9]. The consequences of fluid migration through cement are nevertheless similar to those already mentioned for leakage in the casing.

The wellhead consists of different elements such as connections and valves including the wellhead flange, the expansion spool, lower and upper main line valves, lower and upper main kill line valves, 4-way tee (main connection point on branch), and casing spool. Some damages to these elements could cause leakage or burst. In this case, the wellhead is not accessible, and release of lethal gasses and steam can be one of the consequences that affects personnel. In addition, interruption in the energy production for fixing the wellhead requires closing of the master valve and even quenching of the well that in turns results in economic losses [10].

According to ISO 16530-2, consequences can be categorized as none, minor, major, severe and catastrophic and in combination with likelihood of occurrence can be shown in a risk assessment matrix (RAM) to assess failure modes of each well barrier. An example of RAM is shown in Figure 3-4 [11].
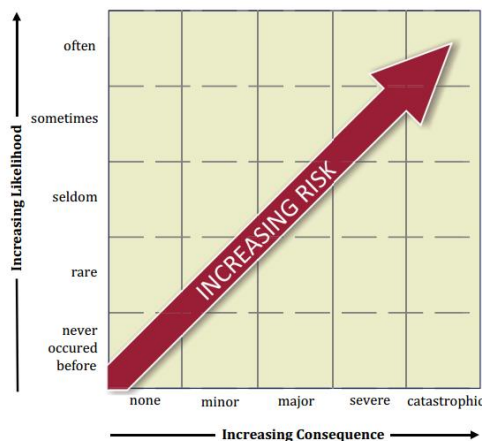


**Figure 3-4. Example of combining consequences and likelihood of occurrence in a risk assessment matrix [11]**

An example of risk matrix that comprises a summary 5x5 consequence versus probability matrix is shown in Figure 3-5. This matrix that is developed for geothermal operations in the Netherlands is supported by five further matrices in which consequences are rated in relation to people, environment, assets, reputation and social impacts [36].

| Consequence | | | | | | Increasing Probability | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Severity Rating | People | Environment | Assets | Reputation | Social | A | B | C | D | E |
| | | | | | | $10^{-6}$ to $10^{-4}$ occurrence / year | $10^{-4}$ to $10^{-3}$ occurrence / year | $10^{-3}$ to $10^{-1}$ occurrence / year | $10^{-1}$ to 1 occurrence / year | > 1 occurrence / year |
| | | | | | | Rare occurrence | Unlikely occurrence | Credible occurrence | Probable occurrence | Likely occurrence |
| | | | | | | Never heard of in the Global industry | Heard of in the Global industry | Incident has occurred in DAGO | Happens several times per year in DAGO | Happens several times per year in DAGO |
| 1 | No/negligible health effect/injury | No effect | No damage | No impact | No impact | | | | | |
| 2 | Minor/Slight health effect/injury | Slight effect | Slight damage | Slight impact | Local impact | | Manage for continuous improvement | | | |
| 3 | Major health effect/injury | Localised effect | Localized damage | Considerable impact | Regional impact | | | Incorporate risk reduction measures | | |
| 4 | Permanent disability/up to 3 fatalities | Major effect | Major damage | National impact | National impact | | | | Intolerable | |
| 5 | More than 3 fatalities | Massive effect | Extensive damage | International impact | International impact | | | | | |

**Figure 3-5. Risk matrix for geothermal operations in the Netherlands [36]**

## 3.3 Monitoring and identification for well integrity operations

The main objectives of well integrity during the production phase are to assure that the produced fluids from the reservoir are delivered through the production string without diverting outside the well configuration to the wellhead and to comply with local regulations. Lack of well integrity could lead to major problems such as underground fresh water zones contamination, surface leakage, cement damage, casing collapse, wellbore collapse and even losing the well due to hydrothermal eruption.

To verify that production fluids are delivered through a sealed flow path through the production string and well architecture, it is necessary to install monitoring or surveillance systems. Such systems are useful to gather information from well production parameters continuously to evaluate, predict and identify the integrity state, productivity and reservoir performance of the tracked well. Continuous monitoring systems can be classified in two types, surface and downhole monitoring. Both systems consist of sensors that are configured to track pressure, temperature and flow rates.

Electronic sensor surface systems are installed permanently at the wellhead and backed up by calibrated gauges to measure wellhead pressure, temperature and total flow rate (steam and water). In downhole, electronic sensor systems and flow meters are installed much closer to the production zone if the well design consists of a production tubing, and the reservoir parameters (e.g. temperatures) are not a limiting constraint for the operational functioning of sensor electronics and completion hardware. This is mainly applicable for gas, oil, water injection and production, including geothermal wells where temperatures are not exceeding 200 °C. Down hole pressure, temperature and flow rate can be tracked in real time. Downhole information is sent to surface through a downhole cable, that is clamped to the tubing string. The received information is gathered, processed and transmitted through real time communications processing systems in most cases.

Continuous downhole well parameter surveillance is not achievable in high temperature geothermal wells; so, for these cases, well logging is planned. Well logging is executed to gather downhole information and can be performed in some cases without taking the well offline. Well logging operations consist of running calipers and fluid sampling tools, pressure, temperature and spinner logging tools, gamma ray logs, cementing logs, and, in the case of

suspected corrosion, ultrasonic logs. The acquired information is used to assess the reservoir performance parameters and well integrity conditions to predict and minimize failure risks that can impact operational costs.

Well construction configuration and design might differ for different locations depending on the geographical regions, equipment technical features, production requirements, and reservoir characteristics such as depth, pressure, temperature and fluid chemistry. Nevertheless, an attempt has been made to generate a generic matrix of expected risks and failures together with appropriate means of identification in Table A.1 in the Appendix. The tools and parameters listed can be used to analyze the risk associated with a specific failure. With knowledge of typical well barrier failures from geothermal fields, the listed means of identification can be used to observe and mitigate unwanted failures during the well production phase. In connection to Table A.1, relevant monitoring tools and methods for well integrity operations are described in the following sections.

### 3.3.1 Surface monitoring

Surface surveillance is of key importance to optimize well performance and assess well integrity. Operational monitoring can be achieved by:

- *Wellhead temperature and pressure:* These are measured by electronic sensors and manual gauges. Digital information can be distributed online and thus, the information is available in real time. Manual gauge information is taken visually and compared to digital information. Records of pressure and temperature changes can be used to assess and correlate downhole communication zones, inflow of cold water into the production string, casing and cement damage, reservoir production performance changes, scale and plugging due to calcite, sulfide, and sensor failure. The records are used for modeling and prediction of future well behavior. Wellhead flanges, valves and connections must also be inspected and tested following supplier's technical guides regarding procedures, equipment, norms and schedules.
- *Flow rate and steam samples:* Flow rates are measured through flow meters (if available in the required temperature range). They can be placed at the wellhead and the production line to the steam turbines. Fluid samples can be taken at the wellhead and steam samples from the inlet line of the steam turbine to make a composition analyses of dissolved solids and gases. Drop in flow rates might indicate the presence of scale or plugging. In the case of severe deformation across the production string or leaking intervals, flow rates might also decrease.
  Changes in flow rate might be due to reservoir performance or well plugging and even loss of integrity of the casing and the cement.
- *Corrosion:* it can be identified through corrosion coupons installed at the wellhead production lines and/or wellhead lateral lines if possible. The gathered information together with flow rate and steam sample information are used to identify possible causes of plugging, especially in wells with high content of sulfide and calcite. Severe corrosion identified at the wellhead combined with pressure and high production flow rates can lead to wellhead damage to flanges, valves and connections, allowing inflow from the production string to divert at surface, affecting production rates and well integrity.

### 3.3.2 Downhole monitoring

Downhole monitoring in geothermal wells is difficult due to the high temperatures in most of the geothermal production reservoirs. Electronic sensors do not typically cope with temperatures over 175 °C during extended periods of time. In this case, it is necessary to plan a scheduled well logging operation. Downhole information is gathered by running downhole logging tools, bearing in mind that most of the logging tools other than pressure, temperature and spinner (PTS) tools are able to be run into the well once it has been cooled down and the well temperature is brought below 175 °C. The gathered information will be correlated with surface monitoring data to evaluate the well integrity status. Standard logging packages consist of cement bond logging tools, caliper, casing collar locators and gamma ray logging and if possible pressure, temperature logging combined with ultrasonic logs. Operational monitoring can be achieved by:

- **Downhole temperature, pressure parameters and flow rates:** modern tools are able to log downhole parameters in surrounding temperatures up to 400°C for short periods of time in the case that the wells have not been quenched or cooled down. Downhole parameters are used to correlate reservoir performance and to identify the conditions the cement and tubulars are exposed to. Evaluation of fatigue on casing, casing connections and even cement can be estimated under these downhole conditions in order to approximate and estimate potential failures, and loss of well integrity.

- **Casing collar locators (CCL) and gamma ray (GR) logging, caliper:** CCL tools are used to identify tubulars coupling, while GR logging tools are used to correlate depth and measuring gamma radiation of the different geological units intersected by the well. Caliper tools are used to measure the inner size of the cased strings and determine their shape. The complete set of information is associated with the cement bond logging data to identify cement presence and geometry versus depth. The main disadvantage is their operating temperature, as generally logging tools are specified for operation below 175 °C.

- **Cement bond logging (CBL):** The information gathered from the logging tools is used to identify the presence of cement behind the casing and the bond of the cement to the casing. The information is depth correlated with CCL and GR data. The main disadvantage is that the CBL by itself cannot quantify channeling and micro channeling of cement, cement compaction and strength. The CBL information can show trapped water zones, where risk of casing collapse during heat-up is high. Comprising all information from CCL, GR, CBL, pressure, and temperature helps to identify well sections where possible damage can or has occurred in casing, casing connections and cement, that may or have caused a loss of well integrity.

- **Acoustic, ultrasonic inspection and corrosion logs:** The information from acoustic logs is valuable to identify casing erosion, corrosion, plugging, and cement presence and quality, to determine well integrity. Unfortunately, if the well is not cooled down, these types of tools cannot be run downhole as their maximum working temperatures are limited mostly around 175 °C, although there are tools (such as the high temperature televiewer) capable of operating up to 300 °C. With these logs together with CBL, CCL, GR, and caliper, the integrity of the well can be evaluated.

# 4 Quantitative risk assessment for barrier elements

This chapter will present standard risk assessment methods, using ISO 31000 as a starting point, evaluate the pros and cons of each, as well as provide an evaluation of their applicability in a geothermal context.

## 4.1 Quantitative risk assessment methods

Quantitative risk assessment methods can be divided into different types, such as function analysis, scenario analysis and statistical methods. This section will provide a description of the ISO QRA methods, and compare them based on type of method, pros and cons, data requirements, complexity and uncertainty treatment.

### 4.1.1 Human reliability analysis

**Description**

Human reliability analysis (HRA) focuses on the interactions between human operators and systems, and in particular on the aspect of human reliability, defined by Swain and Guttman [37] as "the probability of a person to correctly perform an activity and perform no extraneous activity that can degrade the system". Quantitatively, this translates to the ratio between number of errors and the number of opportunities for error, where the denominator is considered equal to the number of times the task is carried out. There is a vast list of variations of HRA, generally falling into one of two categories; 1) those assessing probabilities of failure using tables or expert judgments, and 2) those that emphasize the cognitive process. The latter group needs development to be applicable to industrial applications, and would require significant resources [38].

The main steps of a HRA are outline in Figure 4-1.
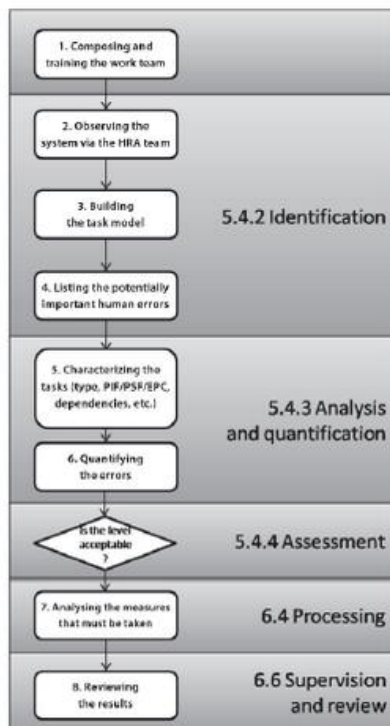
**Figure 4-1. The main steps of a human reliability analysis [38]**

From an assessment perspective, the key challenge is quantifying the error probability. Firstly, tasks can be broken into elementary tasks (as per the technique for human error-rate prediction method – THERP) or considered globally (as per the human error assessment and reduction technique – HEART, or the cognitive reliability and error analysis method – CREAM) [38]. There are challenges related to both types of approaches. The former is difficult to implement and does not consider cognitive aspects, while the latter disregards task specifics and can cause inconsistencies between different analysts. Then, an approach for assessment must be chosen. This could rely on using handbooks (such as Swain's Handbook [37]), which would require detailed databases, or based on expert judgements, which could yield large variations in estimations. Finally, performance factors must be established. These are interdependent, and quantifying the interdependence is very difficult. Moreover, performance factors presume simplified visions of human behavior, which does not necessarily apply to a particular case.

Depending on the specific HRA method, various scales for error probabilities are used. The simulator for human error probability analysis (SHERPA) method for instance, uses a simplified low/medium/high scale. This can be used for low complexity tasks where it is easy to apply, but would require significant effort for complex tasks.

The HEART method stems from the nuclear industry, and builds on the SHERPA method to build the task model, but assesses probabilities based on a predefined typology of nine generic categories to determine the probability in perfect conditions, with adjustments if the conditions are not ideal, determined by a coefficient for EPC factors characterizing the situation. The method can optionally also include 5-95% confidence intervals for the error probabilities to include uncertainty. It has been applied in the chemical industry, air transport, railway transport and medical applications [39].

A third type of HRA is THERP, which is suited in cases where the tasks can be split into elementary tasks, and where activities are related to skill-based or rule-based behavior. The guidelines of the method allow for determining nominal probabilities for each elementary task, or based on tables according to type of task category, as well as probabilities of error of recovery tasks.

**Table 4-1. Example of probability table used in THERP [38]**

| | TABLE 20-13: NOMINAL ERROR PROBABILITY FOR THE SELECTION OF VALVES FOR LOCALLY OPERATED VALVES | | |
|---|---|---|---|
| **Item** | **Selection error in the case of a valve** | **HEP** | **Factor error** |
| 1 | Clearly and unambiguously labeled, in a group of two or more valves, similar in size AND shape AND state AND marking | 0.001 | 3 |
| 2 | Clearly and unambiguously labeled, in a group of two or more valves, similar in size OR shape OR state OR marking | 0.003 | 3 |
| 3 | Not clearly and unambiguously labeled, outside of a group of valves similar in size AND shape AND state AND marking | 0.005 | 3 |
| 4 | Not clearly and unambiguously labeled, in a group of two or more valves, similar in size OR shape OR state OR marking | 0.008 | 3 |
| 5 | Not clearly and unambiguously labeled, in a group of two or more valves, similar in size AND shape AND state AND marking | 0.01 | 3 |

HRA methods are valuable in that they address human error, an important and often overlooked aspect of risk analyses, but require more resources than methods focusing on equipment and physical systems. A summary of input and output for an HRA is provided in Figure 4-2.
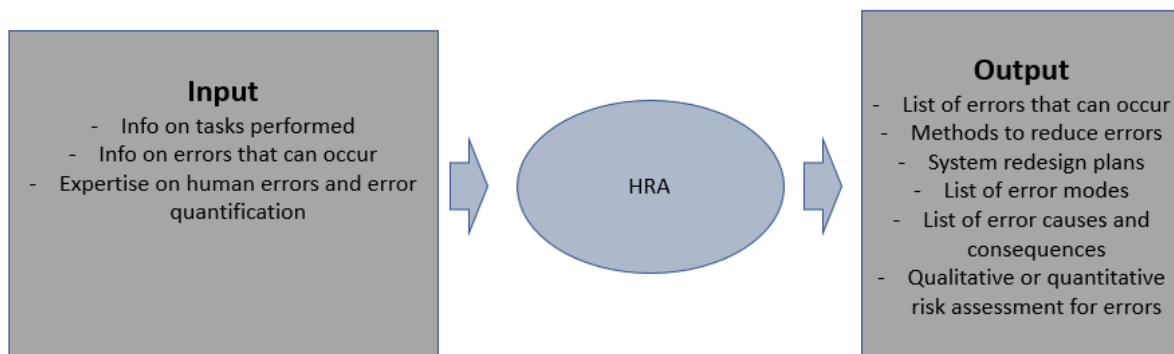


**Figure 4-2. Summary of input and output of a human reliability analysis**

**Strengths and limitations**

The advantages of a HRA is that it considers the important human aspect and formalizes this in a risk context, including human error modes and mechanisms. However, the method is challenging in terms of determining failure modes and probabilities, including partial failures and addressing poor decision-making [40].

### 4.1.2 Fault tree analysis

**Description**

Fault tree analysis (FTA) focuses on the logical combinations of faults leading up to an event of interest, a so-called 'top event', and is commonly used to study in-depth particular event combinations, in order to assess the probability of the top-level event occurring. Thus, it presumes that risk identification, using e.g. process hazard analysis (PHA), failure mode,

effects and (criticality) analysis (FMEA/FMECA), hazard and operability studies (HAZOP), has first been performed, as shown in Figure 4-3.
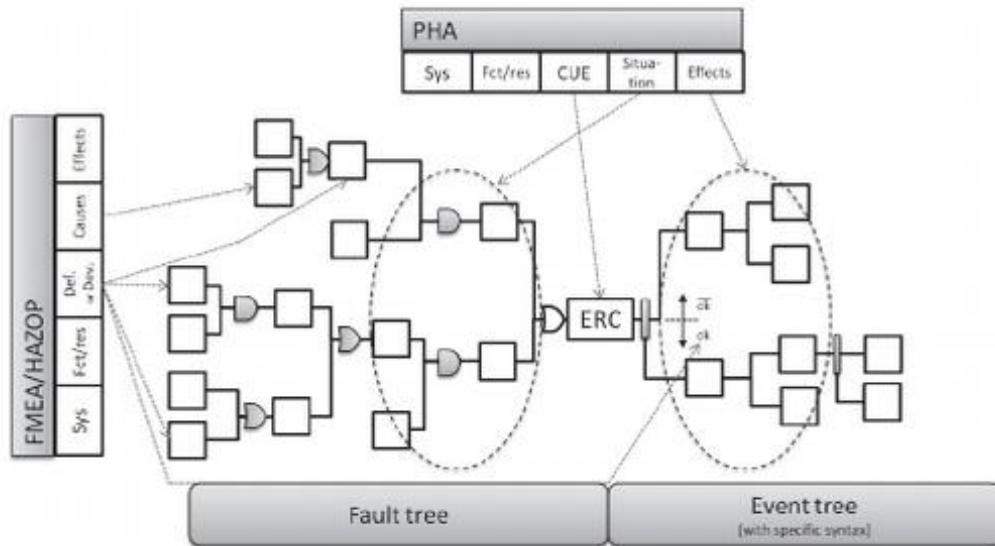


**Figure 4-3. Fault tree analysis and the need for input from other risk identification methods [38]**

The method is based on the creation of a tree with branches tying together causal factors with logical AND/OR gates, branched down to an appropriate level of detail. The main steps to construct a fault tree are shown in Figure 4-4.
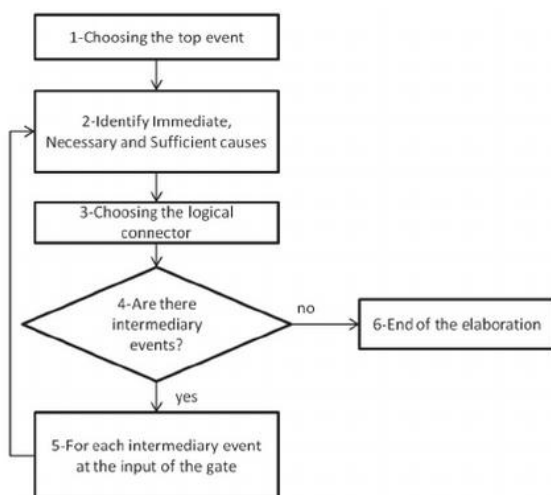


**Figure 4-4. The main steps for a fault tree analysis [38]**

The main objective after the tree is constructed is then to identify the minimum cut sets, i.e. the basic event combinations that trigger the top-level event. While an FTA is normally quantitative (enabling an overall calculation of probability of the event), it could also be performed with a semi-quantitative scale as well. A summary of input and output for an FTA is provided in Figure 4-5.
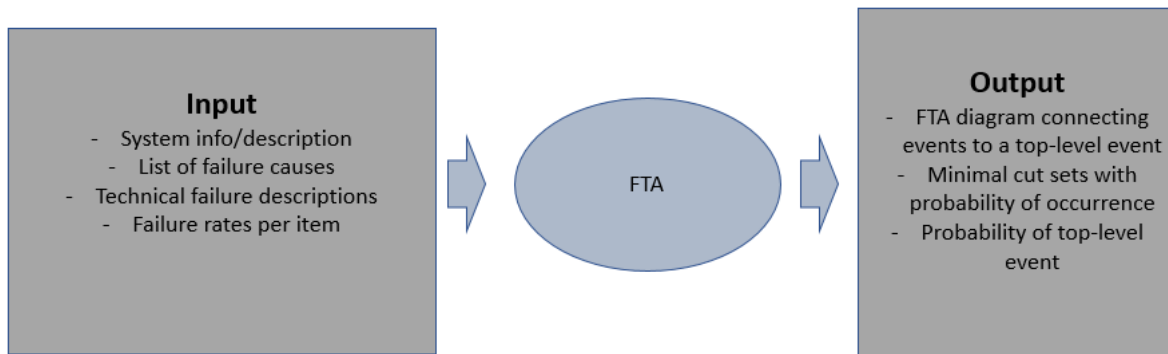
**Figure 4-5. Summary of input and output of a fault tree analysis**

**Strengths and limitations**

An FTA is both systematic and flexible, and can be used for both human interactions and physical phenomena, and is especially well-suited for systems with many interfaces and interactions. It does however not address time interdependencies, can only handle binary states, and may be difficult to use if analyzing conditional failure or degrees of failure [40].

### 4.1.3 Event tree analysis

**Description**

Event tree analysis (ETA) is similar to a fault tree, but focuses on the sequence of events following an initiating event, instead of the events leading up to it. Thus, it is very much a scenario-/function-based analysis, where the states of mitigating and aggravating events and measures (functions, systems, barriers) following the initiating event is analyzed to determine the probability of possible (negative) outcomes.

A simplified example based on well control could use a kick as an initiating event. The initiating event would then either occur during a certain timeframe, or it would not occur. If it does not occur, then there is no situation to contain and the outcome can be considered a success. However, if a kick occurs, then certain actions are required to regain control of the well. For example, the procedure might be to shut-in the well with the BOP. Events following the initial kick could then be whether the driller detects the kick and makes the decision to shut-in the well in time, and then whether the BOP successfully closes. The sequence of events continues to expand the tree until the final outcomes are reached, which in this case would be uncontrolled flow out of the well. Each event is often described in binary terms, such as success/failure or yes/no. However, it is possible to split them into multiple levels, such as a BOP being able to close 0 %, 50 % or 100 %, as long as the events are mutually exclusive. Although having increased granularity by splitting events into more than two outcomes can at times be beneficial, it makes the diagram more complex and less appealing to communicate.
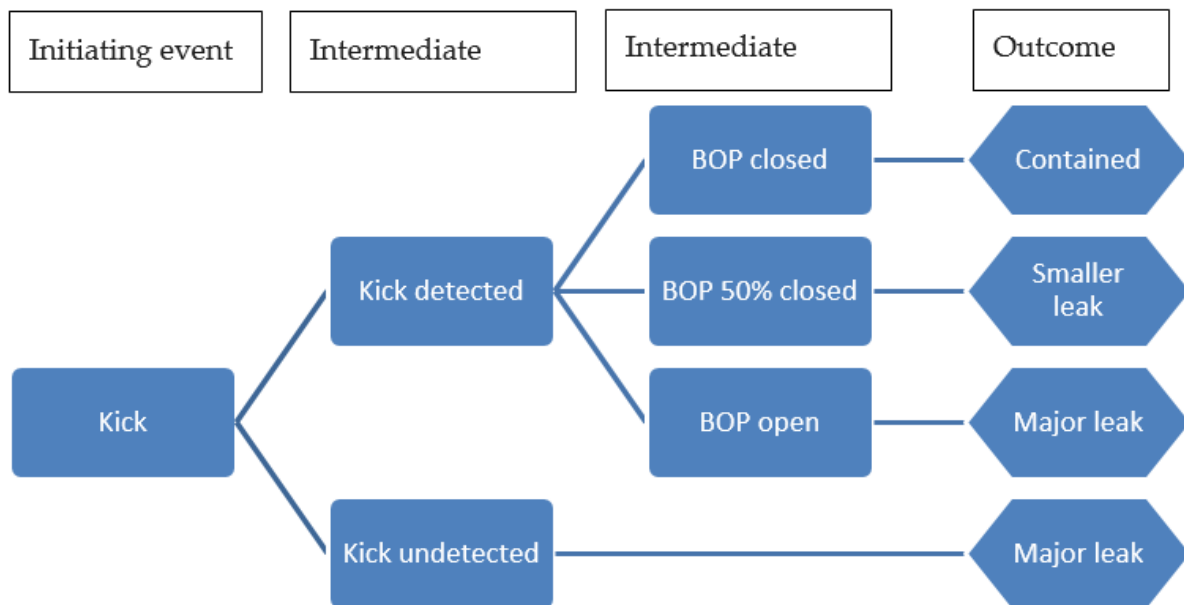
**Figure 4-6. An example of an event tree analysis**

An ETA can be used qualitatively or quantitatively. Starting with an initiating event, branching stepwise into different potential sequences of events can be a great way to brainstorm potential scenarios and sequences of events, as well as specifically considering how different functions, systems and barriers will affect the outcomes. Such a graphic tree structure is well suited for giving a group a good overview of the scenarios. A list of functions, systems and barriers to mitigate unwanted outcomes should be available for the brainstorming.

It could be possible to do a qualitative analysis of the event tree, ranking the different outcomes based on the perceived likelihood and consequences. To perform a quantitative analysis, the various paths in the event tree have to be populated with probabilities. This lends itself mostly to analyzing how well the intended safeguards and associated historical reliabilities are able to function. Calculating the probability of the outcomes is fairly straightforward, as this is achieved by simply multiplying the probabilities of each event along the path leading up to the outcome.
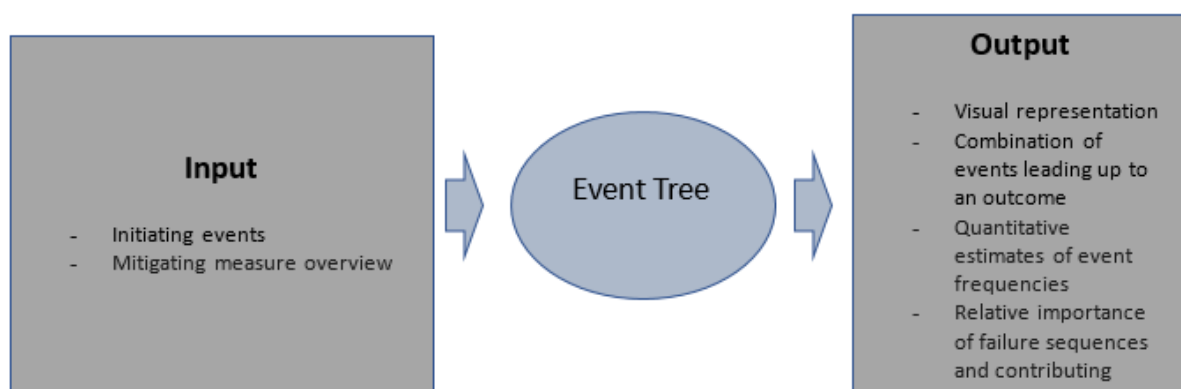


**Figure 4-7. List of input and possible output for an event tree analysis**

**Strengths and limitations**

Strengths of ETA include the following:

- ETA analyzes and displays potential scenarios following an initiating event, and the influence of the success or failure of mitigating systems or functions is represented in a clear diagrammatic way;
- it accounts for timing, dependence and domino effects that are cumbersome to model in fault trees;
- it graphically represents sequences of events which are not possible to represent when using fault trees.

Limitations include:

- in order to use ETA as part of a comprehensive assessment, all potential initiating events need to be identified. This may be done by using another analysis method (e.g. HAZOP, PHA), however, there is always a potential for missing some important initiating events;
- with event trees, only success and failure states of a system are dealt with, and it is difficult to incorporate delayed success or recovery events;
- any path is conditional on the events that occurred at previous branch points along the path. Many dependencies along the possible paths are therefore addressed. However, some dependencies, such as common components, utility systems and operators, may be overlooked if not handled carefully, and may lead to optimistic estimations of risk.

### 4.1.4 Decision tree analysis

**Description**

Decision tree analyses are one of the most commonly used tools in risk-based decision making. This method uses a visual model consisting of nodes and branches that represents decision alternatives and outcomes under uncertainty in a sequential manner [40]. The analysis describes graphically the decisions to be made, the events that may occur, and the outcomes in the form of combinations of decisions and events. The probabilities are then assigned to the events, and values are determined for each outcome. The final goal of a decision tree analysis is to determine the best course of action where there is uncertainty [41].

Figure 4-8 illustrates a simple decision tree example. As shown in Figure 4-8, the tree grows from left to right (or sometimes from top to bottom), beginning with an initial decision node (square, also called root choice node). Branches emanating from a decision node represent competing alternatives (actions/decisions) that need to be investigated. Selecting between the alternatives are within the control of the decision makers. It is conventional to designate a letter to each alternative (such as $A_1$ in Figure 4-8) [42].
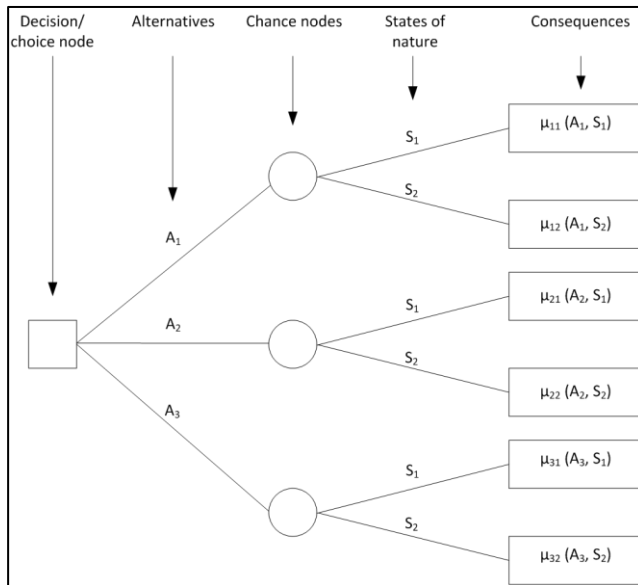
**Figure 4-8. Schematic of a generic decision tree (re-drawn based on [42])**

At the end of the alternative branches, there is an uncertainty node (circle, also called a chance node). Branches originating from a chance node represent the various states of nature with their associated probabilities. The branches end with consequences or value nodes that represent fixed values (e.g. cost, risk, benefit) [42]. Note that beyond the initial uncertainty nodes' branches, there may be more squares and more circles, which generally alternate until each pathway terminates in an end node [41]. Figure 4-9 shows a list of input and output for a decision tree analysis.
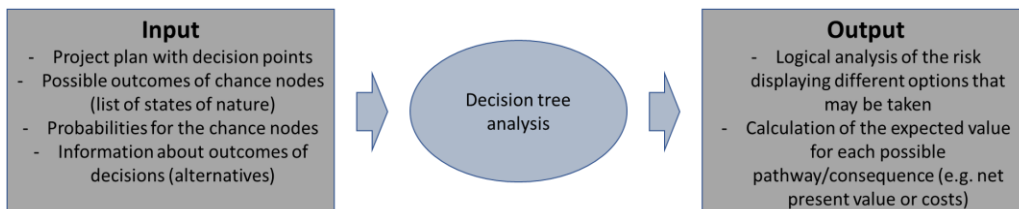


**Figure 4-9. General input and output for a decision tree analysis**

Application of decision tree analysis in the geothermal industry has been previously studied by Akar and Young [43]. They developed a methodology for decision-making on geothermal exploration at a given location to assist project developers and investors for deciding when to give up on a location. Van Wees et al. [44] have used decision tree analysis and integrated it with a value chain model for net present value (NPV) estimation to assess different decisions during the development of deep/enhanced geothermal systems. Figure 4-10 is an example of decision tree analysis for deep geothermal systems [44].

**Figure 4-10. An example of decision tree analysis for deep geothermal systems [41]**

As shown in Figure 4-10, the decision tree contains three decision nodes (go-no go decisions). The initial node is whether to explore or not to explore with seismic. The second node is to drill an exploration well or not. The third decision is to develop for production.
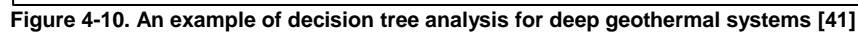
In another study, Grant (2007) tried to define some decision criteria for drilling optimization based on well injectivity within geothermal fields [45]. This was done using a decision tree of possible actions (drill/accept/sidetrack), drilling costs, and measurements of well injectivity.

**Strengths and limitations**

Decision trees rely on an integrative approach of graphical and analytic presentations [42]. Hence, details of decision problems can be better understood as the analysis can provide clear graphical representations of the situations. This feature is of great assistance when it comes to communication of the results with the stakeholders. However, the analysis can become very complex when dealing with large decision trees, causing complications with respect to communication of results. In addition, there may be a tendency to oversimplify the decision problem to be able to represent it as a tree diagram [40].

### 4.1.5 Reliability centered maintenance

**Description**

Reliability centered maintenance (RCM) is a method that originates from the aircraft industry, but that today covers many industrial areas of application, including the oil and gas industry. Its main focus is system functions, and it is defined by the Electric Power Research Institute (EPRI) as "a systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective Preventive Maintenance (PM) tasks". The main objective is to reduce maintenance costs, by developing a PM program. The main steps of an RCM are outlined below:

1. Study preparation
2. System selection and presentation
3. Functional failure analysis (FFA)
4. Critical item selection
5. Data collection and analysis

6. FMECA
7. Selection of maintenance items
8. Determination of maintenance intervals
9. Preventive maintenance comparison analysis
10. Treatment of non-critical items
11. Implementation
12. In-service data collection and updating

System definitions in the oil and gas industry are often based on corresponding hierarchies defined electronically in databases such as SAP[1], where items are allocated tag numbers. A RCM is meant to cover a system, such as a gas compression system, not the entire well or site. The FFA is performed to identify system functions and performance criteria, input interfaces required for operation, and ways in which the system may fail. Failure criticality and frequency are also assessed as part of the FFA, typically using a classification scheme such as low/medium/high. An example of a FFA work sheet is shown in Figure 4-11.



| System: Drawing no.: | | | Performed by: Date: | | | | | Page: |
|---|---|---|---|---|---|---|---|---|
| Operational mode | System function | Function requirements | Functional failure | Criticality | | | | Freq-uency |
| | | | | S | E | A | C | |
| | | | | | | | | |

**Figure 4-11. An example of Functional failure analysis [46]**

The next step is to select critical items, either by simple selection if the items are obvious (for simple systems) or by using formal analysis techniques such as FTA, reliability block diagrams or Monte Carlo simulation (for complex systems). Additionally, items with high failure rates, high repair costs, low maintainability, long lead time for spare parts or items requiring external maintenance personnel are considered critical. The assessment then further quantifies item criticality, based on operational and reliability data. Sources of data include available operating experience, data banks, data handbooks, field data, manufacturer recommendations, test data, etc. After an FMECA (see Section 4.1.9), where the most significant failure modes are identified, a Q&A process is performed to identify types of maintenance tasks, which in turn provides input to determine optimal maintenance intervals. Required quantities in this respect include failure rates, failure costs and repair costs, to name a few. Then, the tasks are judged in terms of applicability and especially cost-effectiveness (requiring a cost/benefit analysis to be performed (see Section 4.1.15)), and non-critical items are also cost-assessed. After the maintenance tasks have been implemented, follow-up data

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1 SAP or "Systems, Applications & Products in Data Processing" is a German multinational software corporation that makes enterprise software to manage business operations and customer relations (https://en.wikipedia.org/wiki/SAP_SE).

collection and updating of the maintenance plan are performed. A summary of input and output for an RCM is provided below.
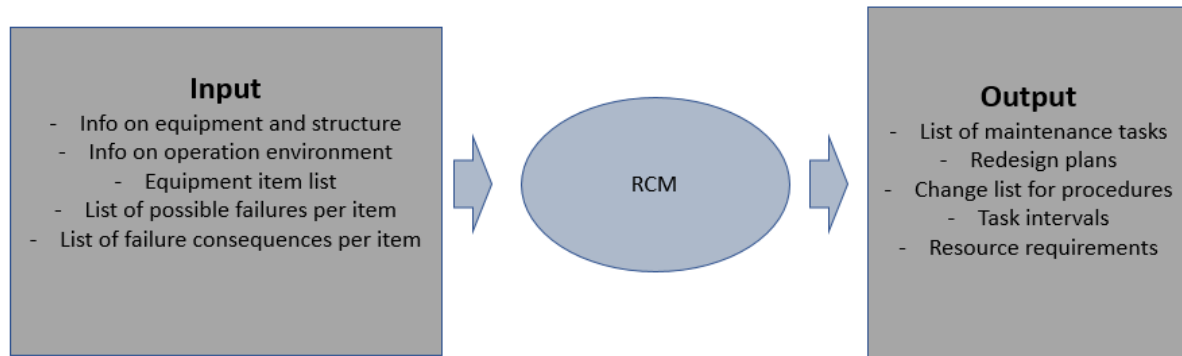


**Figure 4-12. Summary of input and output of a reliability centered maintenance method**

**Strengths and limitations**

RCM is useful for improving reliability and lifetime of engineered components and systems, and provides specific and formalized steps to identify risks, analyzing risks and evaluate risks with a maintenance plan as its main objective. Whereas other risk assessment techniques in this section are either specific tools for a particular phase of the risk assessment framework, an RCM is essentially a specific implementation covering all phases. An RCM is not well suited for non-engineered/designed systems or cases where it is difficult to map a system in terms of repairable/maintainable components. It is resource demanding and requires a good understanding of system workings and interdependencies between sub-components. Furthermore, as the steps include both using FMECA and risk matrices, the same strengths and limitations of those techniques apply to RCM as well

## 4.1.6 Risk matrix (probability/consequence matrix)

**Description**

Risk matrices are tabular mappings of probabilities and consequences, using simplified range scales for defining categories of probabilities and consequences, and also for highlighting acceptable, tolerable and unacceptable risk. The consequence is often split into various categories, such as economic, safety and environmental, to name a few. An example of a risk matrix is shown in Figure 4-13.

**Figure 4-13. An example of risk matrix [47]**

Applications of risk matrices are often for cases where obtaining precise quantitative data is either very difficult, or comes at a very high cost. It can however be an excellent tool used for screening risks, to identify those that require more in-depth analysis. Using it in cases where quantitative data is available might obscure the relation to criticality, as the discretization of continuous values allows a single cell to represent risks with varying criticality.

Examples of probability and consequence scales for industrial applications are shown in Figure 4-14, based on French regulations for risk prevention [48]:

| Assessment type | Probability class | | | | |
|---|---|---|---|---|---|
| | E | D | C | B | A |
| Qualitative (the cited definitions only apply if the number of installations and quantity of feedback are sufficient) | Event is "possible, but extremely unlikely": Not impossible in the light of current knowledge, but has not occurred anywhere in the world over a long period of installation use | Event is "highly unlikely": Has already occurred in this sector of activity, but corrective measures have been taken which significantly reduce the probability | Event is "unlikely": A similar event has already occurred in the sector of activity or in this type of organization at global level. Possible corrections made in the intervening period do not guarantee a significant reduction in probability | Event is "likely": Has happened and/or may happen in the lifetime of the installation | Event is "common": Has happened on the site in question and/or may happen several times during installation lifetime, in spite of corrective measures which may have been taken |
| Semi-quantitative | This scale takes an intermediate place between the qualitative and quantitative and allows mastery measures to be taken into consideration. | | | | |
| Quantitative (per unit and per year) | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ |

| Quantities of dangerous substances | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Q1 | Quantity Q of substance lost or released in relation to the "Seveso" threshold (%) | Less than 0.1 | 0.1 to 1 | 1 to 10 | 10 to 100 | 1 to 10 times the limit | More than 10 times the limit |
| Q2 | Quantity of substance having participated in the explosion (equivalent in TNT ) (t) | Less than 0.1 | 0.1 to 1 | 1 to 5 | 5 to 50 | 50 to 500 | Over 500 |
| Human and social consequences | | 1 | 2 | 3 | 4 | 5 | 6 |
| H3 | Total number of deaths | - | 1 | 2 to 5 | 6 to 19 | 20 to 49 | 50 and over |
| H4 | Total number injured with hospitalization >24h | 1 | 2 to 5 | 6 to19 | 20 to 49 | 50 to 199 | 200 and over |
| H5 | Total number injured with hospitalization <24h | 1 to 5 | 6 to 19 | 20 to 49 | 50 to 199 | 200 to 999 | 1000 and over |
| H6 | Total number homeless or unable to work | - | 1 to 5 | 6 to 19 | 20 to 99 | 100 to 499 | Over 500 |
| H7 | Number of residents evacuated or confined to their homes | - | Fewer than 500 | 500 to 5000 | 5000 to 50000 | 50000 to 500000 | Over 500000 |
| H8 | Number of persons without drinking water, electricity, gas, public transport for over 2h x number of hours | - | Fewer than 1000 | 1000 to 10000 | 10000 to 100000 | 100000 to 1000000 | Over 1000000 |
| H9 | Number of persons having undergone extended medical supervision | - | Fewer than 10 | 10 to 50 | 50 to 200 | 200 to 1000 | Over1000 |
| Environmental consequences | | 1 | 2 | 3 | 4 | 5 | 6 |
| Env1 | Quantity of wild animals killed, injured or rendered unfit for human consumption (t) | Under 0.1 | 0.1 to 1 | 1 to 10 | 10 to 50 | 50 to 200 | Over 200 |
| Env 2 | Proportion of animal or vegetal species destroyed (%) | Under 0.1 | 0.1 to 0.5 | 0.5 to 2 | 2 to 10 | 10 to 50 | Over 50 |
| Env 3 | Volume of water polluted (in m3) | Under 1000 | 1000 to 10000 | 10000 to 100000 | 100000 to 1 million | 1 million to 10 million | Over 10 million |
| Env 4 | Surface area of soil or underground water surface requiring cleaning (in ha) | 0.1 to 0.5 | 0.5 to 2 | 2 to 10 | 10 to 50 | 50 to 200 | Over 200 |
| Env 5 | Length of water front or water channel requiring cleaning (in km) | 0.1 to 0.5 | 0.5 to 2 | 2 to 10 | 10 to 50 | 50 to 200 | Over 200 |
| Economic consequences | | 1 | 2 | 3 | 4 | 5 | 6 |
| €15 | Property damage in the establishment (in millions of euros) | 0.1 to 0.5 | 0.5 to 2 | 2 to 10 | 10 to 50 | 50 to 200 | Over 200 |
| €16 | Loss of production within the establishment (in millions of euros) | 0.1 to 0.5 | 0.5 to 2 | 2 to 10 | 10 to 50 | 50 to 200 | Over 200 |
| €17 | Property damage or loss of production outside the establishment (in millions of euros) | - | 0.05 to 0.1 | 0.1 to 0.5 | 0.5 to 2 | 2 to 10 | Over 10 |
| €18 | Cost of cleaning or environmental rehabilitation measures (in millions of euros) | 0.01 to 0.05 | 0.05 to 0.2 | 0.2 to 1 | 1 to 5 | 5 to 20 | Over 20 |

**Figure 4-14. Examples of probability and consequence scales for industrial applications [38]**

A summary of input and output for a risk matrix is provided in Figure 4-15.
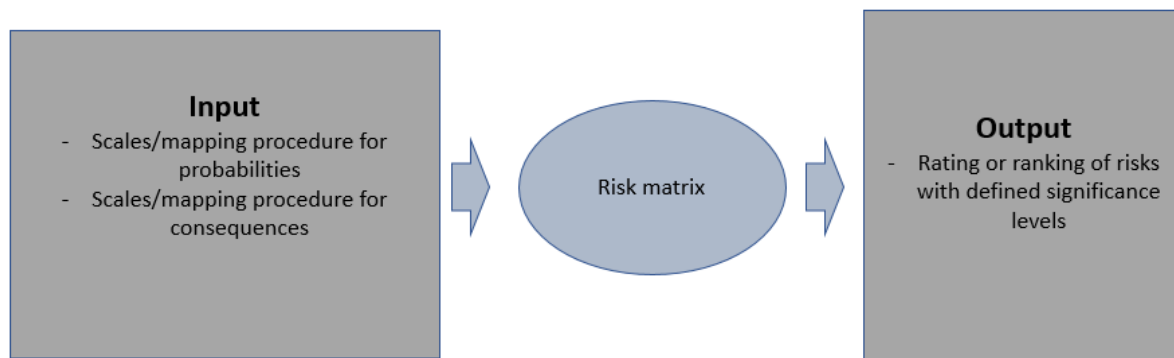


**Figure 4-15. Summary of input and output of a risk matrix**

**Strengths and limitations**

The risk matrix is a tool that is easy to use, and is therefore useful for preliminary screening of identified risks with respect to probability and consequences with little resources required. It can also be used for quantitative and qualitative assessment contexts, and a particular strength is that it is easy to communicate risks using this method. Risk matrices are however limited to preliminary analyses, and are inadequate for more in-depth risk analysis. Defining appropriate intervals (and comparing them) for probabilities and consequences may also prove challenging in some contexts, and furthermore the use and application of risk matrices are highly subjective and may be difficult to use in a uniform way. There is also a danger of disregarding risks that are deemed to be low, even if frequently occurring low risks co-acting could be regarded as medium or high risks [40].

### 4.1.7 Cause and consequence analysis

**Description**

Cause-consequence analysis is a combination of fault tree and event tree analysis. Thus, this section will focus on how a cause and consequence analysis uses fault trees and events trees in combination, while specifics of the two methods are not repeated here.

As in an event tree, the consequences of an initial event are analyzed by the effectiveness of systems with an aggravating or mitigating ability, while the abilities of these systems to function effectively are modeled by fault trees. Using the example of a well control incident with a kick as an initiating event, the event tree would remain the same. However, for a better description of the events, such as the closing of the BOP, the conditions for the success or failure of the event can be elaborated through the failure logic of a fault tree.

The method is useful to analyze the sequence following a critical event, while conditioning on the behavior or state of the sub-systems. A finished cause-consequence diagram can be converted into a larger fault tree; thus, it is a useful way of splitting the visualization into more manageable parts as a step towards a complete fault tree.

A cause-consequence analysis can be used both qualitatively and quantitatively.

Starting from an initiating event, the possible consequence scenarios can be built as for an event-tree, while the failure of events can be built as for a fault tree.

Quantification of the fault trees are performed as for regular fault trees as described in Section 4.1.2, where each event is given a probability that is ultimately used to calculate the probability of the top event. This top event probability is then used as input for the corresponding event in the event tree part. The quantification of the event tree part is performed as for regular event trees as described in Section 4.1.3, by multiplying the probabilities along a path to get the probability of a particular consequence. Equal consequences in the analysis can be added together.

Figure 4-16 shows different inputs and outputs for a cause and consequence analysis.

**Input**

- Failure modes
- Failure scenarios

Cause-Consequence

**Output**

- Diagram representation of system failure with both causes and consequences
- Probability of each potential consequence
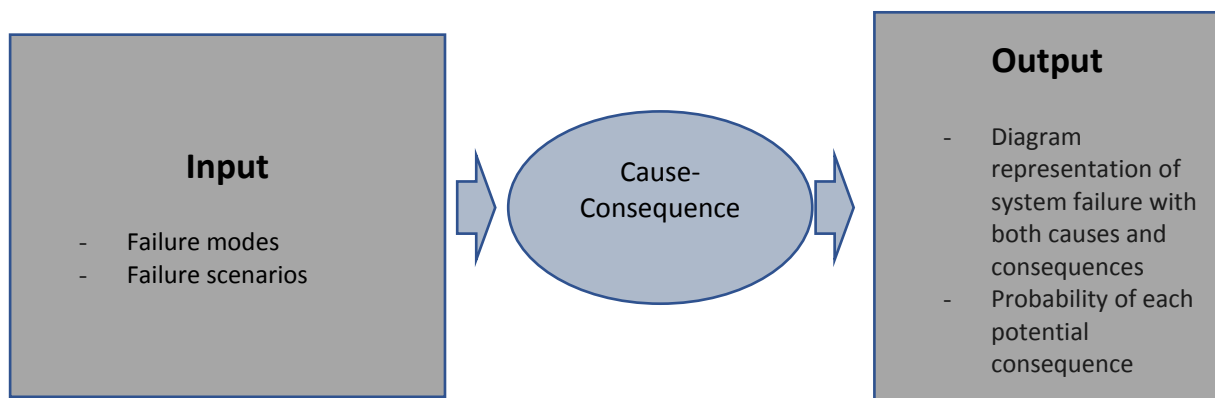
**Figure 4-16. List of input and output for a cause-consequence analysis**

**Strengths and limitations**

The advantages of cause-consequence analysis are the same as those of event trees and fault trees combined. In addition, it overcomes some of the limitations of those techniques by being able to analyze events that develop over time. Cause-consequence analysis provides a comprehensive view of the system.

Limitations are that it is more complex than fault tree and event tree analysis, both to construct and in the manner in which dependencies are dealt with during quantification.

## 4.1.8 Layer of protection analysis

**Description**

Layer of protection analysis (LOPA) is a semi-quantitative method intended to be a middle ground between a qualitative hazard analysis and a full quantitative risk analysis. It is used for estimating the risks associated with an undesired event or scenario, primarily by analyzing whether there are sufficient measures in place to control or mitigate the risk.

The method begins with an identified accident scenario that is a cause of a corresponding consequence. The layers of protection preventing the cause from leading to the undesirable consequence are then identified. The analysis is based on order-of-magnitude estimates and compared to acceptable levels, such as safety integrity levels (SIL).

LOPA provides a basis for the specification of independent protection layers (IPLs), which are systems or actions capable of preventing a cause-scenario from proceeding to the undesirable consequence that is independent of the cause and other layers of protections associated with the scenario.

LOPA can be used both qualitatively and quantitatively. Qualitatively it can be used to review the layers of protection between a cause and a consequence.

A quantitative LOPA analysis would typically be based on historical frequencies of occurrence of the initiating causes and consequences. Together with the probability of failure of each IPL, these are then used to calculate the frequency of occurrence of the undesirable consequences. The calculation is fairly straightforward multiplication of probability of cause and IPLs, but the probabilities could also be modified by other circumstances, such as the presence of a person. The analysis uses order-of-magnitude estimates for the frequencies and probabilities, and the basic level of risk is compared to risk tolerance levels to see whether further protection is required.

Figure 4-17 shows different inputs and outputs for a layer of protection analysis.
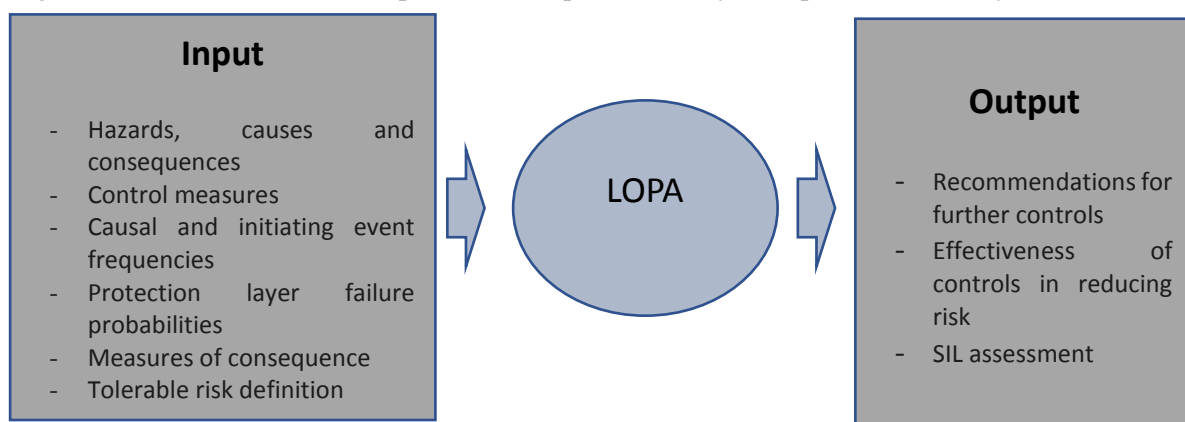


**Figure 4-17. List of input and output for a layer of protection analysis**

**Strengths and limitations**

Strengths include:

- it requires less time and resources than a fault tree analysis or fully quantitative risk assessment but is more rigorous than qualitative subjective judgments;
- it helps identify and focus resources on the most critical layers of protection;
- it identifies operations, systems and processes for which there are insufficient safeguards;
- it focuses on the most serious consequences.

Limitations include:

- LOPA focuses on one cause-consequence pair and one scenario at a time. Complex interactions between risks or between controls are not covered;
- quantified risks may not account for common mode failures;
- LOPA does not apply to very complex scenarios where there are many cause-consequence pairs or where there are a variety of consequences affecting different stakeholders.

### 4.1.9 Failure mode, effects (and criticality) analysis

**Description**

Failure mode and effects analysis (FMEA) is a technique that is useful for assessing engineered systems, system parts and physical components, in which there are (sub-)components that interact and have designed performance measures and expected lifetimes. The analysis steps consist of identifying failure modes, system effects of failures, failure mechanisms or causes and mitigating measures to prevent failures from occurring or minimizing the effect in the event that they occur. The distinction between an FMEA and a failure mode, effects and criticality analysis (FMECA) is that the latter adds a criticality evaluation or importance evaluation of each failure mode.

An FMEA or FMECA can be performed qualitatively or semi-qualitatively, but is in many cases also reliant on quantitative data, especially for systems or components that perform critical functions. The identification of failure modes is done using e.g. structured techniques such as brainstorming, and is sometimes considered a separate phase prior to conducting an FMEA/FMECA. Failure modes could also be identified based on e.g. failure statistics for similar or equivalent components/systems, or based on templates or standards such as ISO 60812 or ISO 14224.

Using failure statistics would require the availability of such data in a failure database, which could be company-specific, industry shared or publicly available. ISO 14224 is a standard for collection and exchange of reliability data for petroleum, petrochemical and natural gas industries, and adaptions of some of the information found in that could be relevant for geothermal equipment with respect to failure mode identification. Listings of failure modes for different equipment is found in Appendix B of that standard.

An illustration of an FMEA (FMECA) analysis is shown in Figure 4-18.
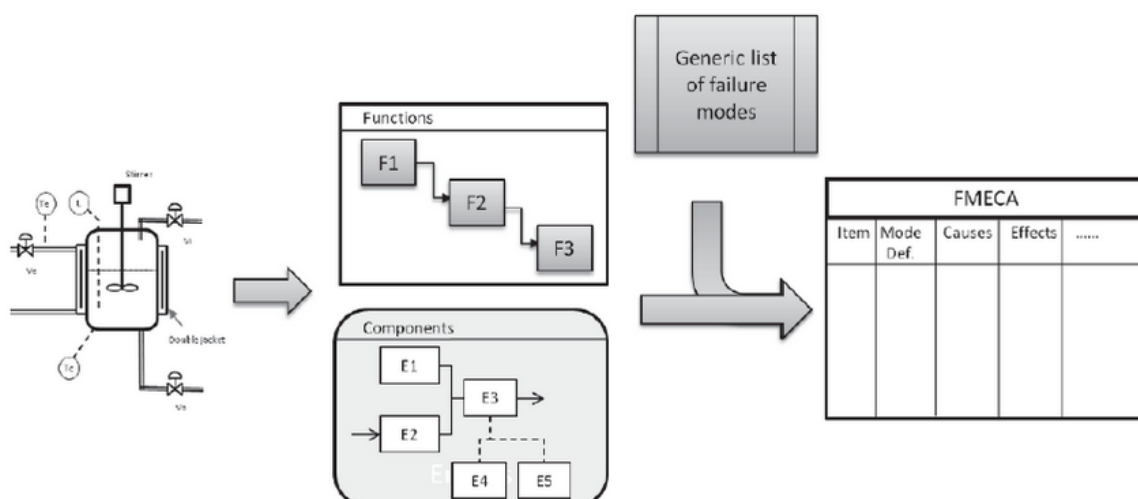


**Figure 4-18. An illustration of an FMEA (FMECA) analysis [38]**

The main steps of the analysis consist of:

1.  Analysis preparation – Defining the objectives, system boundaries, level of detail, establishing work groups, and organizing the execution. This step also entails

choosing the type of approach, i.e. qualitative, semi-quantitative or quantitative, because the scales needed to determine e.g. frequencies and severity must be defined, so that the appropriate data required can be identified. If failure detection methods are to be included in the assessment, these too must be mapped to an appropriate scale of measure. Finally, the acceptability criteria governing the level of acceptable risk should be defined.

2. System modeling – Representation of the system in a manner that allows for decomposing it into parts and components, and allowing for identification of redundancies.

3. Analysis:

   a. Identifying failure modes – A typical starting point is total loss of functionality, followed by different states of partial loss of functionality and issues such as design errors.

   b. Effects analysis – Involves mapping each failure mode to one or more immediate effects, related to the closest components and as well to the system overall.

   c. Causes analysis – Identifying the causes of the failure modes, both internal and external

   d. Assessing probabilities – Quantifying the frequency of occurrence of each failure mode, by mapping together its causes.

   e. Determining failure severity

   f. Identifying means of failure detection

   g. Identifying mitigating measures – Based on criticality and what is considered to be 'acceptable risk'.

4. Review of analysis and plans for implementation

**Strengths and limitations**

FMECA is useful for assessing engineered systems, system parts and physical components, presents the results in an intuitive and easily communicated format and identifies problems early in the design process.

One of the limitations of an FMEA/FMECA, is that it assumes that only one failure can occur at a given time, and thus is not suitable to analyze common cause failures, at least not in detail. This would require the use of a fault tree or similar technique. Furthermore, using FMEA/FMECA is somewhat limited to systems with a manageable number of components and functionalities. For more complex systems, some type of screening process should be done in advance, to only focus on the most important components and functions.

A summary of input and output for an FMEA/FMECA is provided in Figure 4-19.
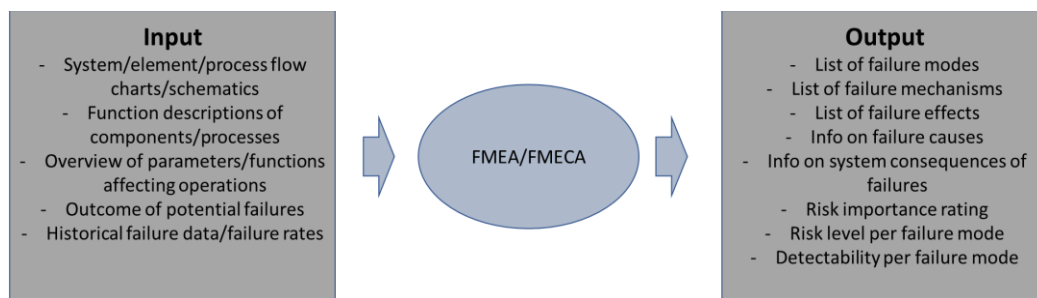
**Figure 4-19. List of input and output for an FMEA/FMECA**

### 4.1.10 Bow-tie analysis

**Description**

Bow-ties are primarily an illustrative method to describe and display what systems are capable of preventing an event from occurring, and which measures can prevent or mitigate the consequences once the event has occurred. Thus, the bow-tie focuses on one main event, and can be considered a combination of a fault tree (describing the failures of systems preventing the event from occurring), and an event tree (describing the sequence of events that must occur for the event to develop).

The bow-tie diagram consists of the main event of concern in the center of the diagram, hazards, threats or causes on the left side, and final outcomes and consequences on the right side.

Between the items on the left and the main event in the center, lines representing the mechanisms by which each cause leads to the main event are usually added. Across these lines, vertical bars are added to represent barriers that should be able to prevent the cause from developing into the critical event. Thus, this side gives an illustrative view of what barriers are in place to prevent the main event from occurring, and which pathways to the main event have insufficient barriers.

From the main event, radial lines are typically drawn to each consequence on the right side, representing the development of the main event into the different outcomes. Across these lines, vertical bars are typically added for barriers that can prevent the event from developing into the respective consequence.

It should be noted that the method can also include positive consequences, where the vertical bars rather would represent abilities to stimulate the positive consequence. In addition, factors for escalation and management function can also be shown related to the diagram.

Bow-ties are mainly visual aids showing the causes and consequences of an event, and is particularly suited to show what barriers or controls are in place for different failure pathways. It is usually considered simpler to understand than fault trees and event trees. Thus, a bow-tie can with benefit be used, even if the analysis itself is performed using other methods. An example of a bow-tie is illustrated in Figure 4-20.
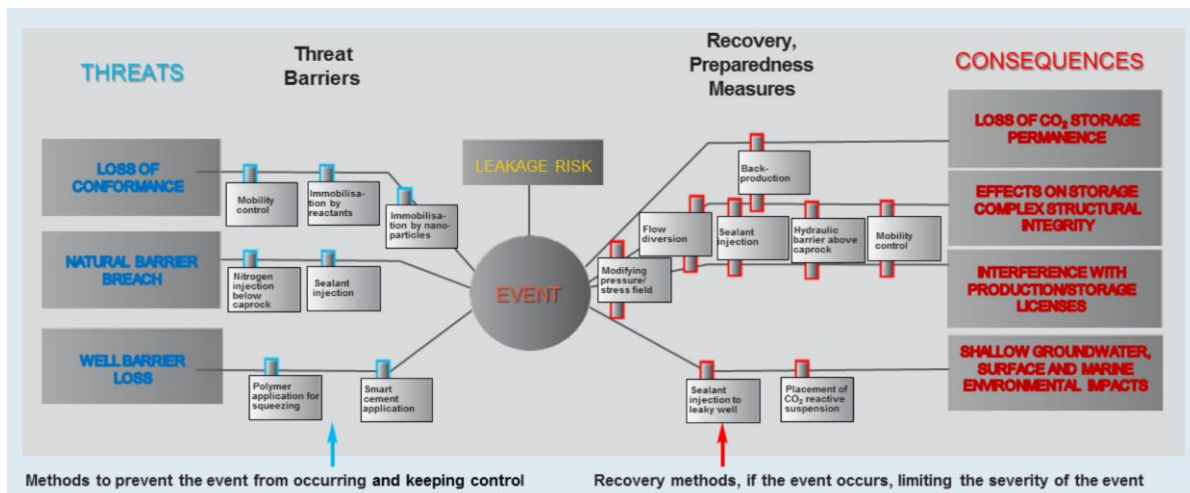
**Figure 4-20. Example of a bow-tie diagram with threats (causes) on the left, the event in the middle, and consequences on the right, with barriers shown in between on the different lines [49]**

However, some simple quantification may be performed. For example, assuming the lines representing failure pathways in the bow-tie are independent of each other, then, by attributing failure probabilities for the different items (causes and barriers) associated with the pathway, the probability of that failure pathway leading to the main event can be calculated by multiplying the different probabilities. Such an assumption is not always valid though, and might not be obvious from the bow-tie. Thus, other methods are frequently considered more appropriate to avoid such pitfalls.

Figure 4-21 shows a summary of input and output for bow-tie analysis.
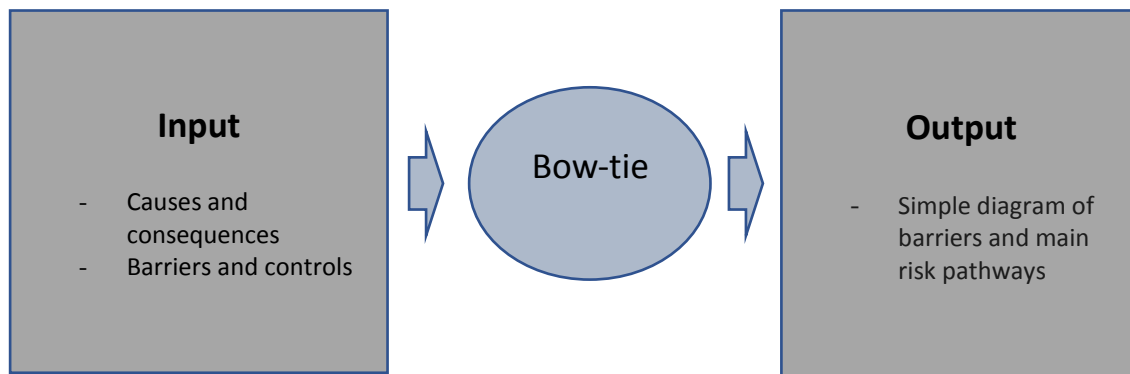


**Figure 4-21. Summary of input and output for a bow-tie analysis**

**Strengths and limitations**

Strengths of bow-tie analysis:

- it is simple to understand and gives a clear pictorial representation of the problem;
- it focuses attention on controls which are supposed to be in place for both prevention and mitigation and their effectiveness;
- it can be used for any desirable consequences;
- it does not need a high level of expertise to use.

Limitations include:

- it cannot depict where multiple causes occur simultaneously to cause the consequences (i.e. where there are AND gates in a fault tree depicting the left-hand side of the bow);
- it may over-simplify complex situations, particularly where quantification is attempted

### 4.1.11 Markov analysis

**Description**

Markov analysis can be used where the future state of a system depends only upon its present state. That the future state depends only on the present state, and not the sequence of events that led up to the present state, is referred to as the Markov or memoryless property in probability theory and statistics. This property is useful for analysis purposes, as it reduces the possible scenarios that must be considered for the different states.

This method is mostly applicable for considering maintenance of repairable systems, in particular for systems that can exist in multiple states, where analysis using reliability block diagrams would be considered unsuitable. Being based on a more generic mathematical framework, Markov analysis is more flexible than a reliability block diagram, and can be more easily adjusted to include complicating factors.

For performing a Markov analysis, the possible states the system can be in is described. For example, a retrievable downhole safety valve can be "functioning", "degraded" or "failed". It will be considered available when in the states "functioning" and "degraded", but will be considered failed when it is in the "failed" state. The evolution of the item over time, is described by a transition probability. For example, after a one-day time period, there is a 90% probability of a "functioning" DHSV to remain "functioning", a 9% probability of it becoming "degraded" and a 1% probability of it becoming "failed". A "degraded" DHSV may have an 80% probability of remaining "degraded", and a 20% probability of becoming "failed" after one day. As it is retrievable, a failed DHSV will be repaired or replaced, thus from a "failed" state it has a 100% probability of going from "failed" to "functioning". The transitions not mentioned here are assumed to have a 0% probability.

The states of a system are usually shown as circles, with curved arrows indicating the transition. The probability of the transition may be added to the arrows. An example of Markov analysis is shown in Figure 4-22.
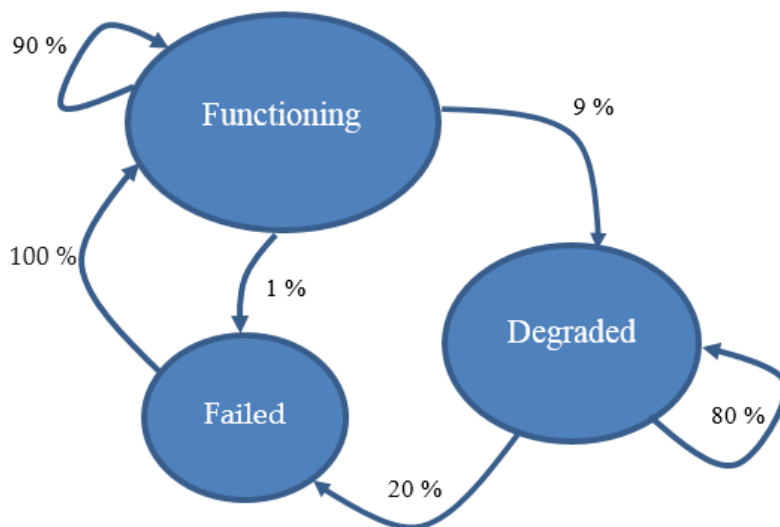
**Figure 4-22. An illustration of a Markov analysis for the example of downhole safety valve (the values shown are the transition probabilities for a one-day timeframe).**

The Markov analysis process is primarily a quantitative technique. Even though the concept of states and state changes can be useful, resulting diagrams for real systems may quickly become too complicated for brainstorming purposes. Though as a quantification tool, it is very adaptable.

The quantification in a Markov analysis is to calculate the probability of the system to be in the different states. The probability to be in a certain state is given by the probability that it has transitioned to that state from any of the states (including the state itself). Using the example of the DHSV, the probability to be in a "functioning" state is the sum of:

- the probability that it was in a "functioning" state multiplied by the probability that it remained in a "functioning" state – P("functioning" at t=0)*0.9
- the probability that it was in a "degraded" state multiplied by the probability that it transitioned to a "functioning" state – P("degraded" at t=0)*0 (cannot transition directly from "degraded" to "functioning")
- the probability that it was in a "failed" state multiplied by the probability that it transitioned to a "functioning" state – P("failed" at t=0)*1 (will always be repaired immediately)

As the probability of having been in the previous state is still unknown, the equation cannot be solved yet. Similar equations must be created for the other states as well, to obtain as many equations as there are states. However, as these equations are not independent, they are still not sufficient to solve the set of equations. One of the equations can be discarded in favor of an equation with the information that the states are mutually exclusive and collectively exhaustive, or in other words, the sum of the probabilities of being in each state is 1. The set of equations can then be solved by an appropriate method to get the probability of being in the different states.

In this case, the transitions were discrete (using probabilities of change between the states), but can also be continuous (using rates of change across the states). For such cases and more comprehensive diagrams, computational software is recommended.

Figure 4-23 shows a summary of input and output for a Markov analysis.
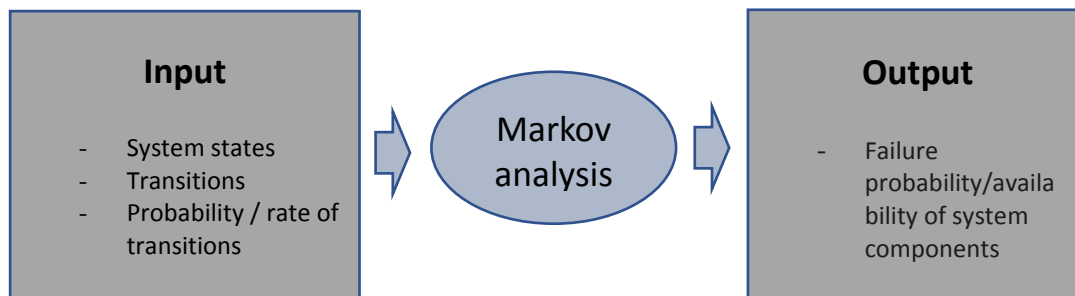


**Figure 4-23. Summary of input and output for a Markov analysis**

**Strengths and limitations**

Strengths of a Markov analysis include:

- ability to calculate the probabilities for systems with a repair capability and multiple degraded states.

Limitations of a Markov analysis include:

- assumption of constant probabilities of change of state; either failure or repairs;
- all events are statistically independent since future states are independent of all past states, except for the state immediately prior;
- needs knowledge of all probabilities of change of state;
- knowledge of matrix operations;
- results are hard to communicate with non-technical personnel

### 4.1.12 Environmental risk assessment

**Description**

Environmental risk assessment (ERA) is often used when assessing risks of exposure of some toxic substance to plants, animals and humans. It involves creating paths from the root cause of the exposure until it has been released and exposed to the target populations in question. Properties of hazards must be understood and threshold limits for the target populations must be determined. Hazards are first identified, typically using structured techniques like HAZID, checklists, etc., then each hazard is studied in terms of how it may interact with the targets. Then the paths required for a hazard to reach its population are established, and calculations of exposure levels are performed. Based on this, a risk characterization can be made, by combining different pathways. The method is flexible in the sense that it can be performed either qualitatively, semi-quantitatively or quantitatively. As is the case with several other risk assessment methods, obtaining good data is difficult, and for an ERA the need to acquire e.g. dose response curves for the particular conditions could prove challenging.

A summary of input and output for an ERA is provided below.
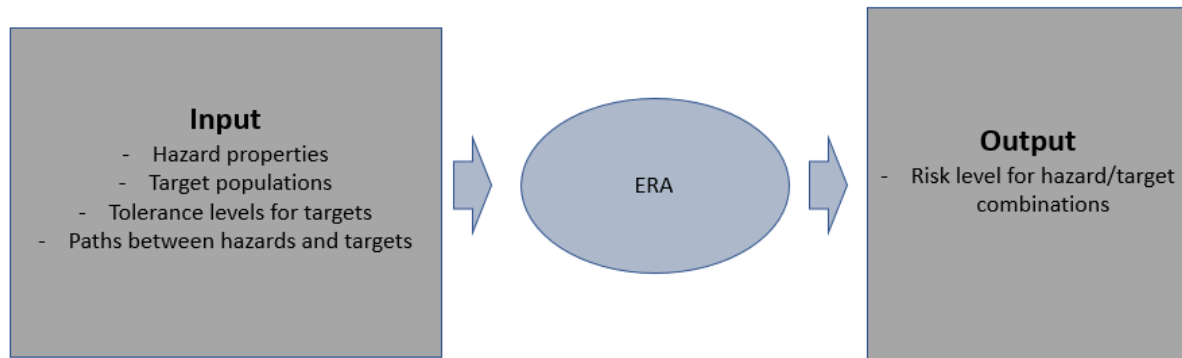
**Figure 4-24. Summary of input and output of an environmental risk assessment**

**Strengths and limitations**

The ERA is a thorough and detailed analysis that can be used for most types of risks that have an environmental impact. It does however require high quality data that can be difficult to obtain, particularly when analyzing non-chemical substances and their impact beyond human exposure.

### 4.1.13 Frequency/number of fatalities (FN) curves

**Description**

In frequency/number of fatalities (FN) curves, the relationship between cumulative frequency (F) and the number of population (N) suffering from a specified level of harm in a given population is shown graphically [50]. This is a way of representing the outputs of risk analysis where the available data is plotted onto a graph, often with logarithmic scales on both axes, as the range of values are large. High frequency events that affect high values of N are of significant interest as they may be socially and politically unacceptable. Many events have a high probability of a low consequence outcome and a low probability of a high consequence outcome [40].

To define thresholds to the FN-curves, they can be compared with international standards [51]. An example of international FN curves is shown in Figure 4-25 (originally from [52] and amended by [53]). As shown also in Figure 4-25, the FN curves provide a line describing the level/range of risk rather than a single value representing one fatalities-probability pair [40].
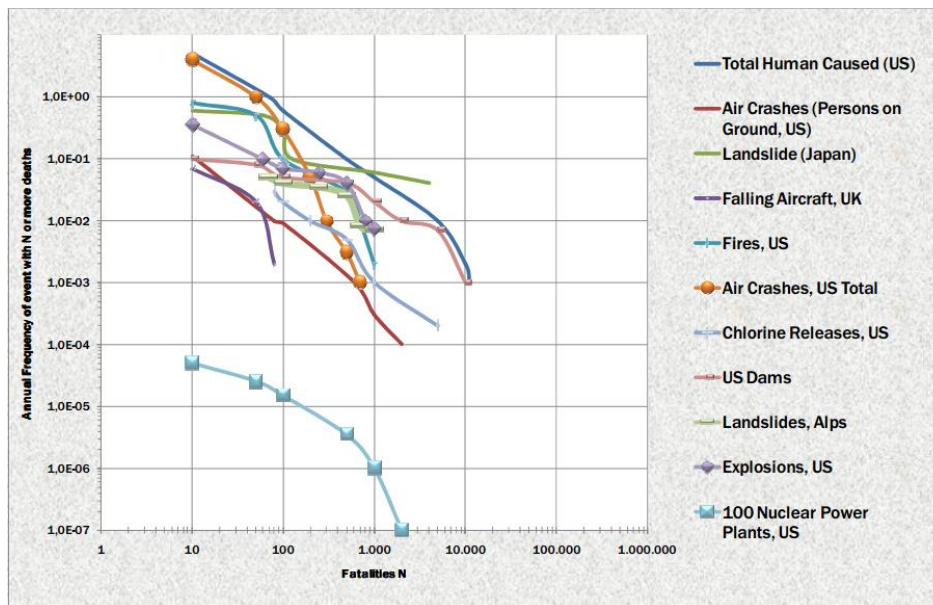
**Figure 4-25. Example of international FN curves (adapted from [52, 53])**

FN curves might also be constructed using data from simulation models instead of statistical data of past fatalities. Theoretical FN curves are most useful for system design, while statistical ones are most useful for management of an existing system. These two types of FN curves may give different information depending on the data used and assumptions made; in this case, they should be used separately. The combination of these approaches, i.e. use of historical data and theoretical data, is also common when there exists some, but not enough, historical data and there is a need for finding other points (by extrapolation or interpolation) to construct the curve [40]. Figure 4-26, based on information given in [40], lists input and output for the FN curves method.
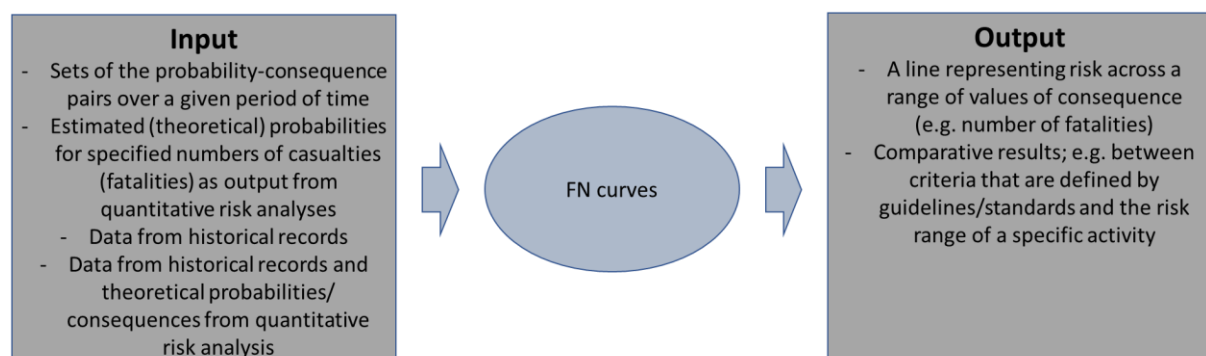


**Figure 4-26. General inputs and outputs of FN curves**

FN curves can be used to compare risks. Comparisons could be performed between predicted risks and criteria defined as an FN curve, predicted risks and data from historical incidents, or predicted risks and decision criteria also expressed as an FN curve [40]. Figure 4-27 illustrates a comparison between a few international FN curves, the FN curve of the Swiss deep heat mining (DHM) project in Basel, Switzerland, the ANCOLD guideline criteria (that was developed for large dams that might have a catastrophic impact when bursting), and the societal risk criteria from Australian New South Wales (NSW) planning guidelines [53].
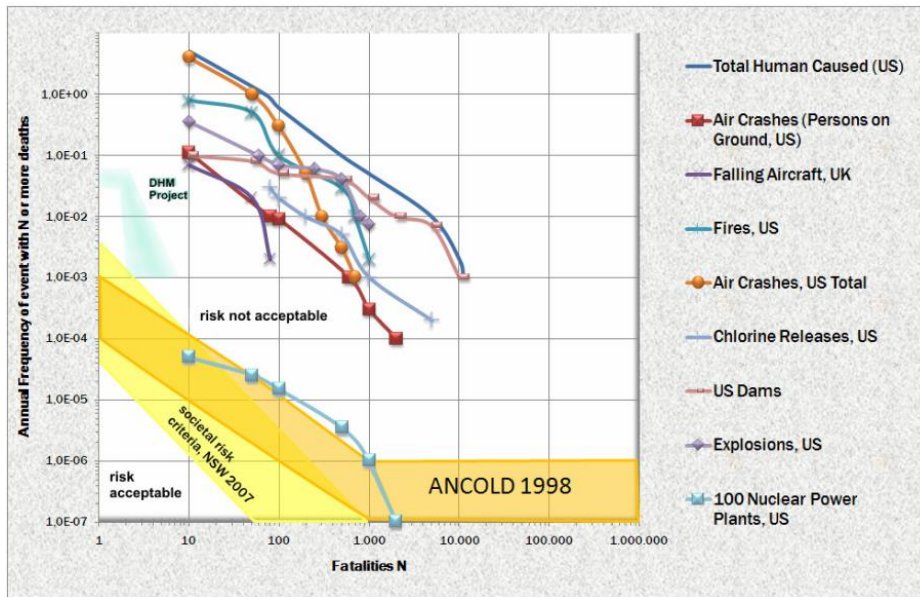
**Figure 4-27. Comparison between the FN curve of the Swiss deep heat mining (DHM) project with international FN curves and available guidelines [53]**

It can be observed in Figure 4-27 that the DHM geothermal project is located to the left of other technologies/activities, implying a lower fatality rate. This figure also shows that the DHM project is significantly safer than travelling by airplanes in the USA. Conversely, it poses a higher risk than dams that are constructed/upgraded according to the ANCOLD 1998 guidelines, but with a low number of fatalities. As is evident from the figure, the DHM project is in the area of unacceptable risk (defined by ANCOLD 1998 and 2003). Nevertheless, all other activities illustrated in Figure 4-27 are also unacceptable although they are tolerated by all societies [53].

**Strengths and limitations**

FN curves are among the methods that have been used to establish criteria for a societal acceptable level of risk to lives. These curves are a useful way to illustrate information on both frequency and consequence of an activity [40]. In addition, as shown in Figure 4-27, FN curves could be used for comparison of risks for similar situations and where sufficient data is available.

However, the acceptability criteria that FN curves provide are largely based on statistical data showing fatalities associated with activities (e.g. risk associated with smoking or flying) [53]. A limitation of FN curves is that gathering historical/empirical data or even theoretical data from simulation models might be very time-consuming [40]. Another limitation of FN curves is that they only map a particular consequence type, which is usually harm to people, and they do not say anything about the range of effects or other outcomes of incidents.

### 4.1.14 Risk indices

**Description**

Risk indexing is a process that provides a simple estimation of relative risk by scoring hazard and exposure parameters [54]. This semi-quantitative measure can be used to rate a series of risks using similar and consistent criteria so that they can be compared [40]. Different types of

risk associated with an activity can be classified according to their risk level by use of risk indices. Accordingly, the risk types that need further (or quantitative) assessment can be determined [40]. Different steps to develop a risk index is illustrated in Figure 4-28. There exist many different variations of risk indices depending on the applications and the industry. Examples are integrated risk index system, chemical scoring for hazard assessment system, priority selection and risk assessment system [54], and environmental risk index (ERI) [55].
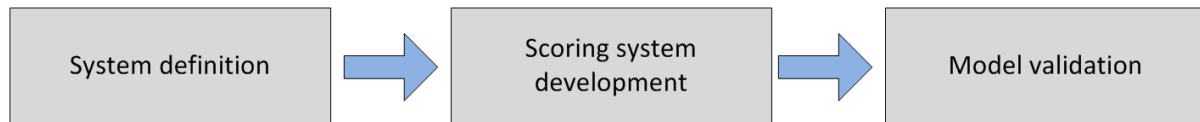


**Figure 4-28. Different steps to develop a risk index**

The indexing process starts with defining and understanding the system, as shown in Figure 4-28. For example in an environmental context, the sources of contaminants, the range of possible exposure pathways and the impact on the receptor(s) need to be first identified. In some cases, each source has multiple pathways and receptors that should be taken into consideration. The scoring system must then be developed. Scores can be applied to each component of risk, such as probability, exposure and consequence, or to factors that might increase the risk. Individual scores are combined, taking into account the physical realities of the system. Individual scores can be added, subtracted, multiplied and/or divided, and cumulative effects can be considered by summing scores, e.g. for different pathways. It is very important that the scores and the scoring method for each part of the system (i.e. sources, pathways and receptors in the environmental example) are consistently maintained [40]. An example of combining scores for risk index development is shown in Table 4-2.

**Table 4-2. Example of combining individual scores in development of risk indices [56]**

| | | **Risk Index (RI)** | | | |
|---|---|---|---|---|---|
| | | SEVERITY (SI) | | | |
| | | 1 | 2 | 3 | 4 |
| FI | FREQUENCY | Minor | Significant | Severe | Catastrophic |
| 7 | Frequent | 8 | 9 | 10 | 11 |
| 6 | | 7 | 8 | 9 | 10 |
| 5 | Reasonably probable | 6 | 7 | 8 | 9 |
| 4 | | 5 | 6 | 7 | 8 |
| 3 | Remote | 4 | 5 | 6 | 7 |
| 2 | | 3 | 4 | 5 | 6 |
| 1 | Extremely remote | 2 | 3 | 4 | 5 |

The matrix presented in Table 4-2 combines the severity index (SI) of the consequences and the frequency index (FI) by simply adding them together to obtain scores necessary for developing a risk index. After development of the scoring system, the underlying model should be validated by applying it to a known system. This is an iterative process and several different systems exist for combining the scores. Figure 4-29, based on information provided in [40], shows inputs and expected outputs from risk indices.
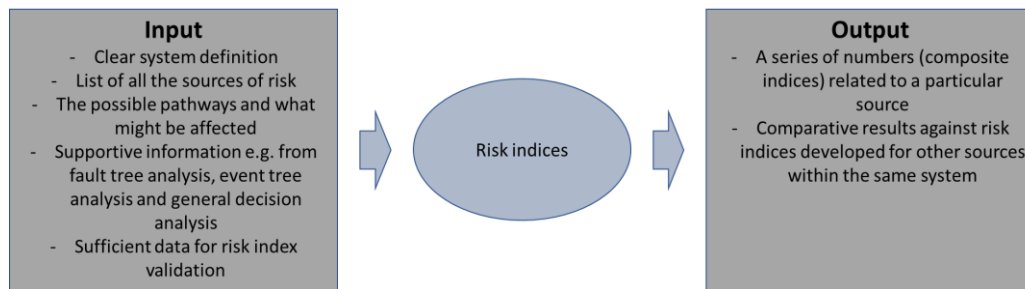
**Figure 4-29. General input and output for risk indices**

## Strengths and limitations

Risk indices have been widely used for risk assessment in different industries for cost-effective prioritization, ranking and as a screening tools that can provide results quickly [54]. Even though numbers are used in the indexing process, a risk index is essentially a semi-quantitative approach that can provide a high level assessment [57] and cannot substitute a detailed quantitative risk analyses [54]. However, such a semi-quantitative approach is of great help where the underlying model or system is not well known and the available data is limited [40, 54]. Uncertainty can be addressed in risk indices by performing sensitivity analyses to identify the most sensitive parameters via variation in the given scores. A range of different factors that could impact the risk level could be integrated using risk indices and could be represented by a single numerical score. In many cases, it is difficult to define how to combine factors and to find a fundamental model to define relationships between the individual scales for risk factors (e.g. linear, logarithmic etc.) [40].

## 4.1.15 Cost/benefit analysis

### Description

Cost/benefit analysis (CBA), sometimes called benefit/cost analysis (BCA), is a qualitative or quantitative (or a combination of both) method that can be used for risk evaluation, where total expected costs are weighed against the total expected benefits in order to choose the best or most profitable option [40]. The CBA has also been defined as an analytical tool for judging the economic advantages or disadvantages of an investment decision by calculating and comparing its benefits and costs providing a basis for investment decision-making [58]. Figure 4-30 shows input and expected output for a CBA.

In CBA, costs include resources expended and negative outcomes, while benefits include positive outcomes, negative outcomes that have been avoided and resources that have been saved by an action/decision. Based on the project objectives, the CBA aggregates the monetary value of all positive (benefits) and negative (costs) effects of the intervention to all stakeholders that are included in the scope [40]. These values are adjusted (discounted) for different time periods in which costs and benefits occurred and then summed to calculate the net total benefit. The performance of the project can be measured and expressed by economic indicators such as net present value (NPV) and internal rate of return (IRR), allowing comparability and ranking of competing projects/alternatives [58]. These indicators then become inputs to the decision-making process, e.g. a positive NPV associated with an action would normally mean the action should occur [40].
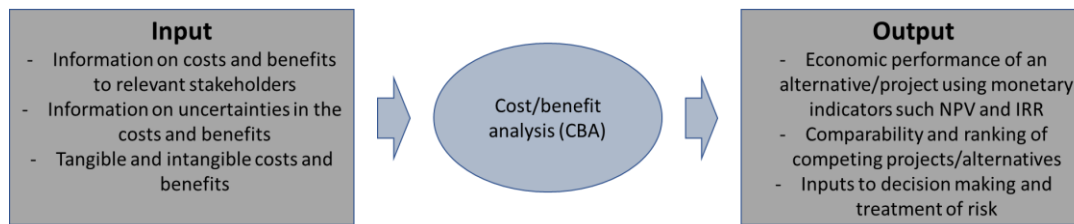
**Figure 4-30. General input and output for a cost benefit analysis**

There are many examples of using CBA in both the petroleum and the geothermal industries. In a study by McMillen, it is suggested that performing a cost benefit analysis ensures that the environmental protection regulations are protective yet cost-effective, i.e. do not impose an unnecessary economic burden on society [59]. Garcia et al. used CBA to analyze the impact of different retrofitting interventions (including installing a geothermal heat pump) on improvement of the energy efficiency and economics of the energy systems of four case studies in a specific geographical location [60]. Mackenzie et al. provided a cost-benefit analysis of the single versus multiple leg approach for the geothermal well design. Using CBA, they showed that use of multiple-leg wells was a very practical and cost effective technique for optimizing well performance in the expansion project of the San Jacinto-Tizate geothermal field in Nicaragua [61]. In another study, Gallaher et al. [62] presented the findings from a retrospective cost-benefit analysis of technology development that has been supported by the Office of Energy Efficiency and Renewable Energy (EERE) of the U.S. Department of Energy (DOE) through Geothermal Technologies Program (GTP). The main purpose of the study was to estimate the return on investment to the society by comparing historical economic activity with GTP's investment to what would have likely happened in the absence of EERE GTP. GTP has focused on four main areas, including development of polycrystalline diamond compact (PDC) drill bits, binary cycle, TOUGH (reservoir) models and high temperature cement. Table 4-3, which is an example of outputs from a cost benefit analysis, lists the main findings of the CBA performed in [62].

**Table 4-3. Findings of the cost benefit analysis performed for Geothermal Technologies Program of U.S. DOE [62]**

| Metric | PDC Drill Bits | Binary Cycle Plants | TOUGH Models | High-Temp Cement |
|---|---|---|---|---|
| PV[a] of total benefits at 7% (thousands $2008) | $7,813,212 | $42,848 | $219,445 | 1,013 |
| PV[a] of program cost for selected case studies at 7% (thousands $2008) | $26,461 | $26,819 | $8,619 | 1,938 |
| PV[a] of net benefits at 7% (thousands $2008) | $7,786,751 | $16,029 | $210,826 | -925 |
| PV[a] of net benefits at 3% (thousands $2008) | $18,473,186 | $35,568 | $446,302 | 162 |
| BCR at 7% | 295.3 | 1.6 | 25.5 | 0.5 |
| BCR at 3% | 451.4 | 1.9 | 39.3 | 1.1 |
| IRR | 139% | 16% | 48% | NA |

[a] Present value (PV) base year is 1976. Benefits were accrued for following periods for PDC drill bits (1982-2008), binary cycle plants (1984-2008), TOUGH models (1980-2008), and high-temperature cement (1999-2008)

**Strengths and limitations**

CBA is a method that can be used in many fields for comparing economic sustainability of possible alternatives [60]. The method provides transparency in decision making and uses a

single metric for comparison, making it useful for communicating knowledge while still being quite detailed in scope. The assessment of non-economic benefits and, in some cases, the discount rate to use, is however difficult to assess, and may yield a large span in results. It is often difficult to estimate benefits that accrue to a large population; particularly those benefits that are not exchanged in the markets. With respect to the discounting process, benefits gained in the long-term future can have negligible influence depending on the discount rate (percentage) used in the analysis [40].

### 4.1.16 Multi-criteria decision analysis

**Description**

Decisions are strongly related to comparison between different points of view that can be roughly defined as criteria. Multi-criteria decision analysis (MCDA) takes in to account the advantages and disadvantages of a plurality of points of view. Different MCDA methods and techniques have been developed to support decision makers (DM) in their decision processes [63]. Despite the diversity of approaches, methods and techniques for MCDA, they all have similar elements including a finite/infinite set of options (actions, alternatives, solutions, etc.), at least two criteria, and at least one decision maker [64]. MCDA uses a range of criteria to objectively assess a set of options (alternatives) to distinguish between preferred and inappropriate options. Ranking and aggregating the options is performed by development of a matrix of options and criteria, and finally providing an overall score for each option [40]. Different inputs and expected outcome of an MCDA is shown in Figure 4-31.
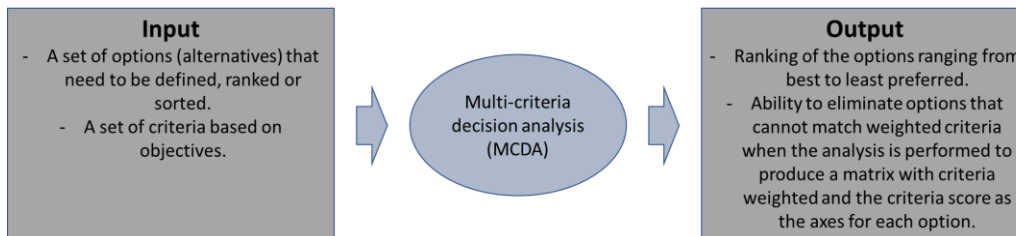


**Figure 4-31. General inputs and outputs of multi-criteria decision analysis**

Figure 4-32 shows the MCDA steps established to compare different technologies in the context of energy supply in Switzerland [65].
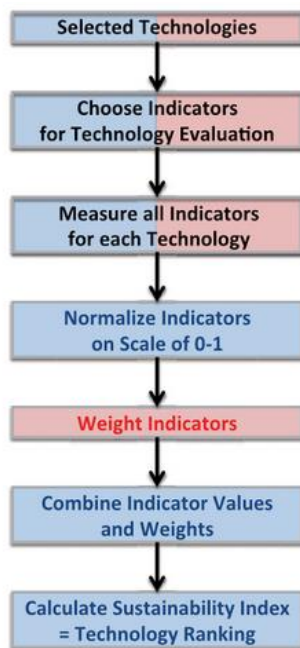
**Figure 4-32. Different steps of multi-criteria analysis process for the example of energy supply technologies (color index; blue as objective steps, red as subjective steps) [65]**

As shown in

Figure 4-32, first the alternatives (in this case the technologies) for comparison need to be defined. These alternatives are deep geothermal system with and without heat, biogas combined heat and power, solar photovoltaic panels, onshore wind and offshore wind (from Germany) in the study by Hirschberg et al. [65]. Based on the objectives of the study, a set of criteria (indicators in

Figure 4-32) are then established. The criteria selected for the evaluation of technologies in [65] are:

- Environment: climate change, human toxicity, formation of particulate matter, ionizing radiation, water depletion and metal depletion
- Economy: average generation cost
- Social: severe accident risks other than induced seismicity
- Security of supply: energy resource autonomy and equivalent availability factor

By aggregating the criteria, a single comprehensive index value can be calculated. This index reflects the ranking between the technologies, from the most preferred to the least preferred. The indicators are each weighted based on the individual user preferences to calculate the overall index (in this case, the sustainability of the concerned technologies). It should be noted that the results for the overall index obtained for each technology might differ depending on the weighting of the indicators [65]. An example of output of the MCDA for ranking concerned technologies in [65] is shown in Figure 4-33. This ranking has been performed based on equal weighting of the aforementioned criteria but with emphasis on climate protection among environmental indicators and continuity of electricity supply among security of supply criteria.
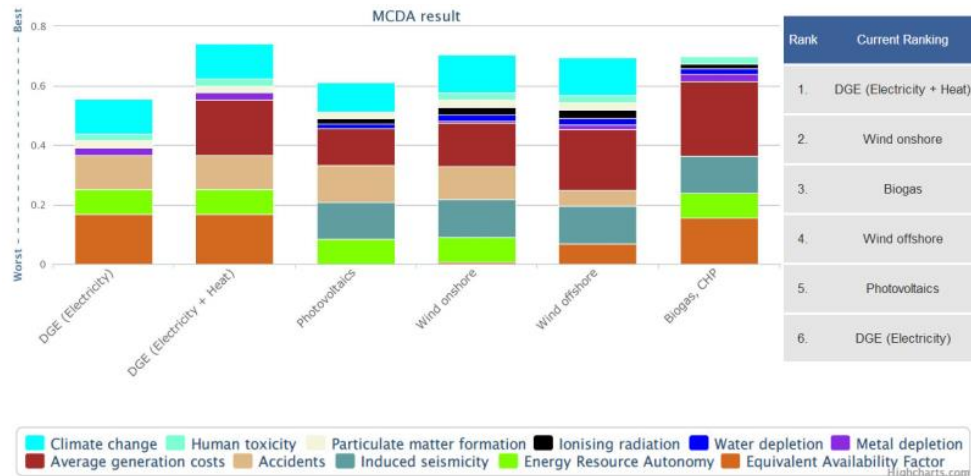
**Figure 4-33. Example of MCDA application for ranking between different technologies in the energy mix of Switzerland [65]**

## Strengths and limitations

MCDA is an activity that helps decision making in terms of choosing, sorting, or ranking options (alternatives) [64]. This analysis provides a simple structure for efficient decision-making and presentation of assumptions and conclusions. MCDA can also help achieve an agreement on a decision when different stakeholders have different conflicting objectives, when tradeoffs need to be made, and when the analysis faces complex decision-making problems [40].

While MCDA shows the relative strengths and weaknesses of different options, it does not provide a definitive ranking between alternatives [65], i.e. it cannot provide a conclusive (unique) solution to the decision-making problem. MCDA can also be affected by bias and poor selection of the decision criteria. In addition, aggregation algorithms that calculate criteria weights from stated preferences of stakeholders, or aggregating differing views, can obscure the true basis of the decision [40].

### 4.1.17 Monte Carlo simulation

**Description**

Monte Carlo simulation is a powerful numerical method that is used in many applications especially for complex systems to evaluate the effects of uncertainty on them [66]. This method is often used for two different purposes; 1) uncertainty propagation on conventional analytical models, or 2) probabilistic calculations when it is difficult/impossible to use analytical methods [40].

Physical systems are described by probability density functions (PDF). Once these functions are known, the Monte Carlo simulation can proceed by randomly sampling from them. Many simulations (in the range of thousands) are then performed, and the desired outcome is taken as an average over the number of observations, which might be a single observation or millions of observations. Modeling of a process by one or more probability density functions, and the use of random sampling techniques to arrive at a solution of a physical/mathematical problem, are the essential components of a Monte Carlo simulation [67].

For each uncertain variable, the possible values for a probability distribution are defined. The type of distribution that can be selected is based on the conditions surrounding that variable [67]. Common distribution types, e.g. normal, triangle and lognormal, are shown in Figure 4-34. Note that even empirical distributions derived from observations of related systems can be used to determine distribution type of the input variables [40].

| (a) Normal | (b) Triangle | (c) Lognormal |
|:---:|:---:|:---:|
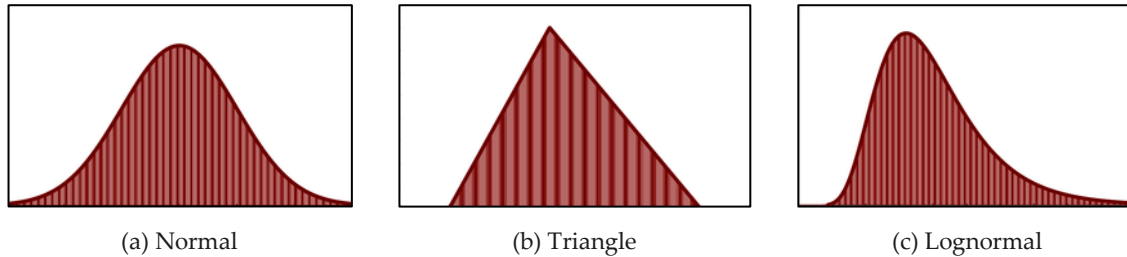
**Figure 4-34. Common distribution types**

The range of possible outcomes and the relative frequency of values in that range can be evaluated by quantitative measures of the concerned system or process such as cost or duration of a project [40]. Different input and expected output for a Monte Carlo simulation are shown in Figure 4-35.

**Input**
- A model of the system
- Information on the types of inputs
- Information on the sources of uncertainty
- Input data with uncertainty is represented as random variables
- Distribution type

Monte Carlo simulation

**Output**
- Results expressed as the probability or frequency distribution
- Identification of the main functions within the model with the greatest impact on the output
- The entire distribution of outcomes
  - The probability of a defined outcome
- The value of an outcome in which the problem owners have a certain level of confidence that it will not be exceeded or beaten (e.g. a cost that there is less than a 10 % chance of exceeding)

**Figure 4-35. General input and output for a Monte Carlo simulation**

Arild et al. [68] stated that uncertainty in a complex system can be treated using a general framework from Rocquigny [69], as shown in Figure 4-36. In such a framework, it is assumed that the input parameters can be categorized in three main groups; uncertain inputs (typically described by means of probability distributions), known inputs (such as well geometry and other well design variables) and other variables of relevance. The input parameters are fed into a model, which in general can be regarded as a numerical function linking inputs to outputs; examples being deterministic functions for fluid flow or material degradation. The results are variables or parameters of interest to the stakeholders. Uncertainty is propagated by means of Monte Carlo simulation, and sensitivity analyses provides information about the importance of the input parameters, which subsequently can be used to prioritize risk-reducing measures.
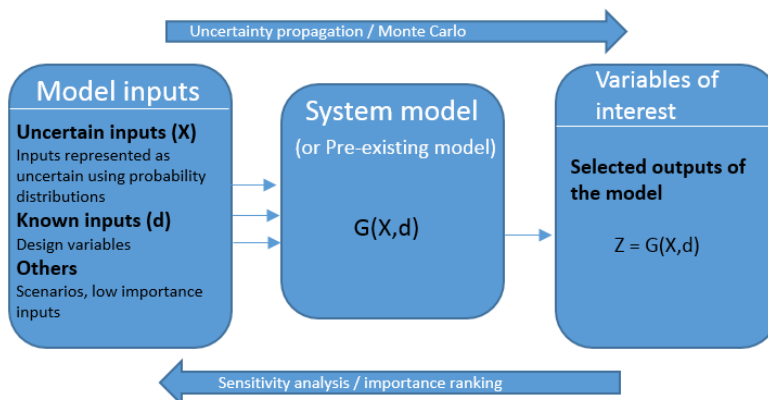
**Figure 4-36. General diagram for assessing the variables of main interest with uncertainty [68]**

Monte Carlo simulation is one of the most used methods for risk assessment in geothermal publication [1], mainly to evaluate financial risk related to geothermal project development, e.g. references [70-73].

**Strengths and limitations**

The Monte Carlo simulation can address large and complex systems that would be very difficult to understand and solve by an analytical method [67]. However, it might be a challenge to model and to engage the stakeholders when facing such systems. Another limitation is that high-consequence/low probability events might not adequately be highlighted by the method; hence, not allowing an organization's risk propensity to be reflected in the analysis. Moreover, the method relies on the validity of distributions to represent uncertainties in parameters.

Monte Carlo simulation can simply be developed using spreadsheets and other conventional tools. There are also sophisticated but inexpensive tools that are readily available to assist when evaluating systems that are more complex. In previous years, the number of iterations (that is directly related to the accuracy of the solutions) required for Monte Carlo simulations could make the process time consuming. Nowadays, advances in computers and theoretical developments have made processing time almost insignificant for many applications [40].

### 4.1.18 Bayesian statistics/Bayes nets

**Description**

Bayesian statistics is a mathematical method that enables a consistent treatment of available and new information. The basic premise is that one is uncertain about the outcome of a parameter of interest, which is described with a probability distribution. The distribution is called the prior. New information concerning the parameter can be obtained, which one would want to take into account by modifying the prior. The accuracy, or the likelihood of the new information, is also represented by a distribution. Using Bayes formula:

$$P(A|B) = \{P(A)\,P(B|A)\} / \sum_1^i P(B|E_i)\,P(E_i)$$

where the probability of X is denoted by P(X); the probability of X on the condition that Y has occurred is denoted by P(X|Y); and $E_i$ is the $i^{th}$ event.

The two distributions, representing ones understanding of the existing state of nature and the new information gained, can be merged by giving each event the appropriate weight that is consistent with the existing representation of uncertainty.

The method is well suited for decision-making, and concepts frequently used in medicine and the petroleum industry, such as "Value of Information" and "Value of Control", make liberal use of it. The extension of Bayesian statistics to cases where the relationship between what information an outcome will give, such as dependency through several layers of parameters, is called Bayesian nets.

Bayesian nets use a graphical model to represent a set of variables and their probabilistic relationships. It consists of nodes (typically a circle) that represents random variables, and arrows between the different nodes. An arrow pointing from a node "A" to a node "B" indicates that the outcome of node "A" will have an influence on what the outcome of node "B" can be. The random variables will be assigned prior distributions, while the influence between nodes are described by conditional probability distributions.

Figure 4-37 shows a summary of input and output for Bayesian nets.



**Input**

- System variables
- Causal links between variables
- Prior and conditional probabilities

Bayesian nets

**Output**

- System states
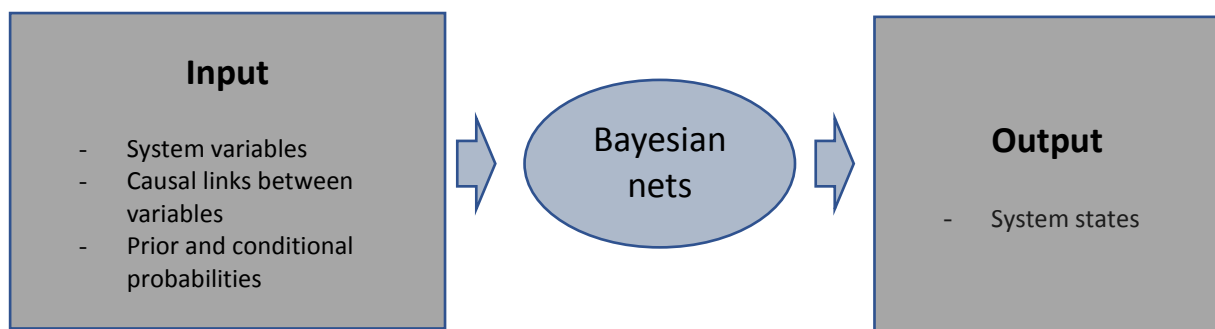
**Figure 4-37. Summary of input and output for Bayesian nets**

**Strengths and limitations**

Strengths:

- Consistent treatment of uncertainty
- Strong support for decision-making

Limitations:

- Defining all interactions in Bayesian nets for complex systems is problematic;
- The Bayesian approach needs the knowledge of a multitude of conditional probabilities that are generally provided by expert judgments.
- Software tools can only provide answers based on these assumptions.

### 4.1.19 Summary of QRA methods

Table 4-4 provides a list of QRA methods, showing their relevance to each risk assessment phase, classification in relation to resource demands, degree of uncertainty and complexity, as well as require inputs and typical output.

**Table 4-4. Summary of strengths and limitations of different quantitative risk assessment methods (RI = Risk identification; RA = Risk analysis; RE = Risk evaluation. D1 = Resources and capabilities; D2 = Nature and degree of uncertainty; D3 = Complexity. H = High; M = Medium; L = Low)**

| QRA method | Risk assess-ment phase | | | D1 | D2 | D3 | Applicability w.r.t WBE's | Applicability w.r.t failure modes | Input | Output |
|---|---|---|---|---|---|---|---|---|---|---|
| | RI | RA | RE | | | | | | | |
| HRA | X | X | X | M | M | M | All | Only human error failure modes | - Info on tasks performed<br>- Info on errors that can occur<br>- Expertise on human errors and error quantification | - List of errors that can occur<br>- Methods to reduce errors<br>- System redesign plans<br>- List of error modes<br>- List of error causes and consequences<br>- Qualitative or quantitative risk assessment for errors |
| FTA | X | X | X | H | H | M | Difficult to obtain failures rates related to cement and formation | Most, but not suited where time interdependencies are present, or for e.g. material degradation, etc. where there is a degree of failure. | - Info on equipment and structure<br>- Info on operation environment<br>- Equipment item list<br>- List of possible failures per item<br>- List of failure consequences per item | - List of maintenance tasks<br>- Redesign plans<br>- Change list for procedures<br>- Task intervals<br>- Resource requirements |
| ETA | X | X | | M | M | M | All, but limitations as above if combined with FTA. | All, but limited if event frequencies are required | - Initiating events<br>- Mitigating measure overview | - Visual representation<br>- Combination of events leading up to an outcome<br>- Quantitative estimates of event frequencies<br>- Relative importance of failure sequences and contributing events |

| Method | | | | | | | Applicability | Limitations | Inputs | Outputs |
|---|---|---|---|---|---|---|---|---|---|---|
| DTA | | X | X | H | H | M | Mostly relevant for WBE's that can be operated directly | All, but limited if event frequencies are required | - Project plan with decision points<br>- Possible outcomes of chance nodes (list of states of nature)<br>- Information about outcomes of decisions (alternatives) | - Logical analysis of the risk displaying different options that may be taken<br>- Calculation of the expected value for each possible pathway/consequence (e.g. net present value or costs) |
| RCM | X | X | X | M | M | M | Limited to repairable/engineered elements | Limited to failure modes where failure/reliability data can be obtained | - Info on equipment and structure<br>- Info on operation environment<br>- equipment item list<br>- list of possible failures per item<br>- list of failure consequences per item | - List of maintenance tasks<br>- Redesign plans<br>- Change list for procedures<br>- Task intervals<br>- Resource requirements |
| Risk matrix | X | X | X | L | M | L | All | All | - Scales/mapping procedure for probabilities<br>- Scales/mapping procedure for consequences | - Rating or ranking of risks with defined significance levels |
| Cause and conse-quence analysis | | X | X | H | M | H | See FTA/ETA | See FTA/ETA | - Failure modes<br>- Failure scenarios | - Diagram representation of system failure with both causes and consequences<br>- Probability of each potential consequence |
| LOPA | | X | X | M | M | M | Difficult to obtain failures rates related to cement and formation | Limited to failure modes where failure/reliability data can be obtained | - Hazards, causes and consequences<br>- Control measures<br>- Causal and initiating event frequencies<br>- Protection layer failure probabilities<br>- Measures of consequence<br>- Tolerable risk definition | - Recommendations for further controls<br>- Effectiveness of controls in reducing risk<br>- SIL assessment |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| FMEA/ FMECA | X | X | X | M | M | M | Difficult to obtain failures rates related to cement and formation | Limited to failure modes where failure/reliability data can be obtained | - System/element/process flow charts/schematics<br>- Function descriptions of components/processes<br>- Overview of parameters/functions affecting operations<br>- Outcome of potential failures<br>- Historical failure data/failure rates | - List of failure modes<br>- List of failure mechanisms<br>- List of failure effects<br>- Info on failure causes<br>- Info on system consequences of failures<br>- Risk importance rating<br>- Risk level per failure mode<br>- Detectability per failure mode |
| Bow-tie analysis | | X | X | L | L | L | All | All | - Causes and consequences<br>- Barriers and controls | - Simple diagram of barriers and main risk pathways |
| Markov analysis | | X | X | H | L | H | Limited to repairable/engineered elements | Limited to failure modes where failure/reliability data can be obtained | - System states<br>- Transitions<br>- Probability / rate of transitions | - Failure probability/availability of system components |
| ERA | X | X | X | M | H | M | All | Only failures modes resulting in direct exposure to humans/environment | - Hazard properties<br>- Target populations<br>- Tolerance levels for targets<br>- Paths between hazards and targets | - Risk level for hazard/target combinations |
| FN curves | X | X | X | M | M | M | All | Only critical failures modes resulting in direct exposure to humans | - Sets of the probability-consequence pairs over a given period of time<br>- Estimated (theoretical) probabilities for specified numbers of casualties (fatalities) as output from quantitative risk analyses<br>- Data from historical records<br>- Data from historical records and theoretical probabilities/ consequences from quantitative risk analysis | - A line representing risk across a range of values of consequence (e.g. number of fatalities)<br>- Comparative results; e.g. between criteria that are defined by guidelines/standards and the risk range of a specific activity |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Risk indices | X | X | X | L | M | L | All | All | - Clear system definition<br>- List of all the sources of risk<br>- The possible pathways and what might be affected<br>- Supportive information e.g. from fault tree analysis, event tree analysis and general decision analysis<br>- Sufficient data for risk index validation | - A series of numbers (composite indices) related to a particular source<br>- Comparative results against risk indices developed for other sources within the same system |
| CBA | X | X | X | M | H | M | All | All, but many failure modes may be difficult to express in terms of costs | - Information on costs and benefits to relevant stakeholders<br>- Information on uncertainties in the costs and benefits<br>- Tangible and intangible costs and benefits | - Economic performance of an alternative/project using monetary indicators such NPV and IRR<br>- Comparability and ranking of competing projects/alternatives<br>- Inputs to decision making and treatment of risk |
| MCDA | X | X | X | M | H | M | All | All | - A line representing risk across a range of values of consequence (e.g. number of fatalities)<br>- Comparative results; e.g. between criteria that are defined by guidelines/standards and the risk range of a specific activity | - Ranking of the options ranging from best to least preferred.<br>- Ability to eliminate options that cannot match weighted criteria when the analysis is performed to produce a matrix with criteria weighted and the criteria score as the axes for each option. |
| Monte Carlo simu-lation | | | X | H | L | H | All | All | A model of the system Information on the types of inputs Information on the sources of uncertainty Input data with uncertainty is represented as random variables Distribution type | |

| Bayesian statistics and Bayes nets | X | X | H | L | H | All | All | - System variables<br>- Causal links between variables<br>- Prior and conditional probabilities<br>- (See MC) | Results expressed as the probability or frequency distribution<br>- Identification of the main functions within the model with the greatest impact on the output<br>- The entire distribution of outcomes<br>- The probability of a defined outcome<br>- The value of an outcome in which the problem owners have a certain level of confidence that it will not be exceeded or beaten |

## 4.2 Industry and research experience and practices

To gain insight into which QRA methods are being applied in the industry and for what purposes, a questionnaire was issued to the industry participants of the GeoWell project, prompting for feedback as to how they analyze, evaluate and reduce risk related to failure of the well barrier elements. Additionally, similar feedback was obtained from the research partners, giving examples of principles and methods that they have worked with or developed. The input from the partners was supplemented with published literature experience where necessary.

### 4.2.1 Use of QRA methods and techniques

This section outlines what methods and techniques for risk assessment (related to the WBEs) the industry partners and academic partners commonly use, and what their experience with these are.

In relation to elements such as well design, the impression based on the feedback received, is that there seems to be a reliance on standards or company experience, for the choices made. Due to the high temperature, higher-grade casings are used, thus basing the decision on a best available technology approach.

Related to temperature cycling, there have been set limits to how many cycles (well interventions) that can be made before the well is considered spent. Such a limit would be a comparison between probability of failure within that time and benefit of keeping the well in production. The damage a temperature cycle would cause would be conditioned on how it was performed. Although this effect could be considered within the cycling limitation, it is more commonly based on historical experience.

**TNO risk assessment experience**

Some examples of risk assessments for well barriers used by TNO include fault tree analysis, risk matrices, failure mode and effects analysis, bow-tie analysis, Monte Carlo simulations, and Bayes nets. Those that have been quantitative are the Monte Carlo simulations and the Bayesian statistics, while the use of risk matrices has been semi-quantitative. The remaining methods of fault tree analysis, failure mode and effects analysis, and the bow-tie analysis have been mainly qualitative assessments.

Among the Monte Carlo simulations and the Bayes nets, quantitative data have been used, primarily acquired from simulations and modeling, while based on physical well sites. As subsurface data can often be uncertain, the use of Monte Carlo simulations has proven effective, with distributions being sourced from literature and expert opinions. This has mostly been from applications within the oil and gas realm, but sources of geothermal data are also growing each year. TNO has used Monte Carlo simulations also from a financial risk point of view, where again, the unknown subsurface variables have been sampled to produce cost estimates of geothermal energy production. The experience with Bayes nets has been complex, since they can easily become unmanageable with too many nodes and states within those nodes. If maintained, they can offer valuable information on different options, for example choosing between different production capacities to see if there is any reduction in leakage risk.

For the risk matrix, semi-quantitative data has been used, primarily by using a scale for likelihood and consequence. Various criteria of interest (e.g. a potential barrier failure, a leakage pathway, or an event) are placed at a location in the matrix, and can then be compared between each other or between scenarios. This allows the user to either find the highest risk within the system or between two different setups, albeit on a high level.

Qualitatively, TNO has looked at risks through fault tree analysis, failure mode and effects analysis, and bow-tie analysis. Fault tree analysis is a convenient, visual way to view the potential barriers before the event occurs, as well as the minimum cut sets that could cause the event to occur. This methodical approach has been used to show the barriers and how they relate to each other, regarding risk assessment. The failure mode and effects analysis has been used in workshop sessions, where TNO would lead the interested parties (such as well operators) in a discussion of the potential failures and effects specific to their case. This makes the participants aware of potential risks they may confront. Lastly, the bow-tie diagram has also been used for a more visual role, to show the potential steps to take to eliminate threats or consequences.

Often a single risk assessment method is not sufficient when examining oil and gas wells or geothermal wells. TNO bases their decisions on what data (quantitative and qualitative) are available, and the above are just a few examples of how the different risk assessments have been applied.

**IRIS risk assessment experience**

Risk assessment at IRIS is closely linked to the academic work within risk performed at the University of Stavanger. There, the Bayesian approach to probability (i.e. interpreting probability as a subjective measure of belief that an event will occur), rather than a frequentist

approach (i.e. interpreting probability as the relative frequency that would result from large number of trials), is followed. This has led to a foundation in which each case (for example a well) is unique, and should be treated as such. Primarily, this means that historical frequencies should not be used directly, but rely more on expert judgements from those with both past experience and knowledge of the upcoming operations. The modeling approach frequently used is to try to separate case specific parameters from more generic parameters where historical data will be more representative. The method used for this has previously been fault trees [74], whilst now, influence diagrams for representation and Monte Carlo simulation for computation dominate [75]. The computational models tend to use fairly simple physical models, as the inaccuracies in these tend to be less important than keeping track of the overall uncertainty in the model and the impact of human error.

### 4.2.2 Analysis of failure modes for geothermal production wells

This section presents an analysis based on failure reports for geothermal wells in Iceland. All high-temperature geothermal fields in Iceland are located within active volcanic zones and dominated by postglacial and quaternary formations. Thus, the geology type for all fields correspond to younger volcanic/volcanoclastic reservoir rocks classified as Geology Code 3 in [76, 77].

The data set was further re-interpreted by the authors. The re-interpretation was done to align failure mode classifications and number of failures, classify wells into production wells and non-production wells and estimate shut-down/abandonment time. The section should be read keeping in mind that there is substantial uncertainty related to how data are interpreted. In particular, estimates of mean time to failure (MTTF) should only be considered as very rough estimators, not accurate figures based on a uniform data collection procedure. However, the analysis provides some indications of what failure modes are most frequently occurring for high temperature geothermal wells in this particular region.

The compiled data consists of 235 wells[1], including production wells, exploration wells, injection wells, monitoring wells, marginal producers, idle producers, and shut-in/plugged and abandoned wells. Failure statistics show that there were 19 wells, or 8.1%, of 235 wells in the data set that had bulges/collapses or tensile ruptures, and also unknown blockages. Casings in 11 wells (4.7%) had bulges/collapses, 12 wells (5.1%) had tensile ruptures, four wells (1.7%) had both bulges and tensile ruptures, and another four wells (1.7%) had bulge/collapse and unknown blockages. It should be noted, however, that not all of the 235 wells have been checked, and therefore the number of wells with damaged casing could be considerably higher.

As the focus of this report is on the production life-cycle phase, a screening was performed to include only wells assumed to be producing currently, or up to some point since being completed. As the current state of all wells was not known, interpretations were necessary.

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1 The number of unique wells may actually be slightly lower, as this number is based on unique equipment codes, and could therefore contain multiple entries for the same wells. However, the magnitude of the deviation is not significant (less than 10).

Wells included in the further analysis, therefore, consisted of wells with a current status as producing or marginally producing, or wells that originally were producing, but due to failure or other reasons currently are either shut-in, abandoned, injectors, monitoring wells or other. For this group of currently non-producing wells, only wells with a known year of production cessation were included.

Applying this screening resulted in a total of 136 production wells, of which 110 (81%) are interpreted as currently producing. For the 136 wells, the mean wellhead elevation is 316 m (maximum 609 m) and the mean total depth is 1843 m (minimum of 342 m, maximum of 3322 m). The distribution of the wells by total depth is shown in Figure 4-38.
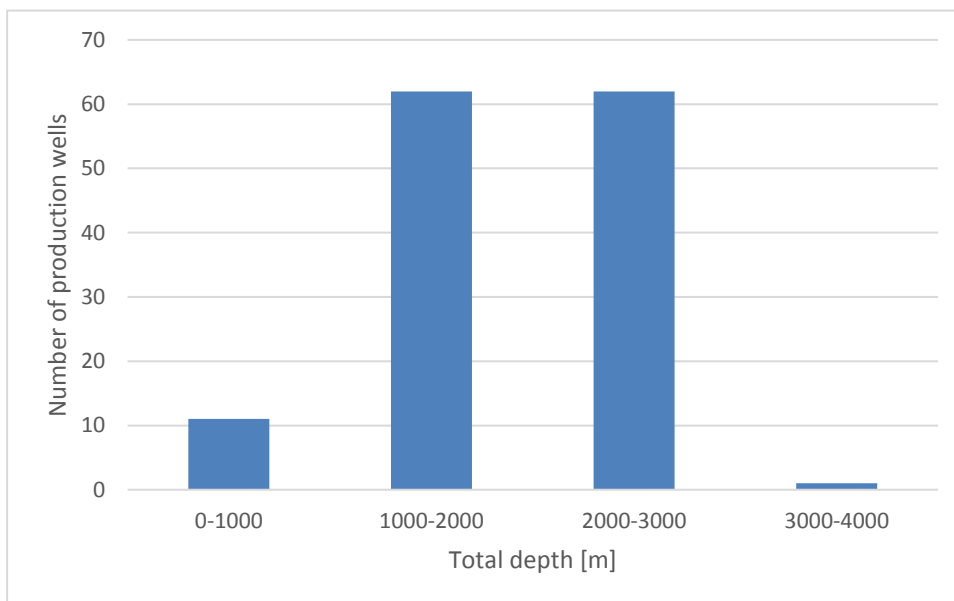


**Figure 4-38. Distribution of the production wells based on total depth**

The wells consist of approximately an even split between vertical wells (52%) and deviated wells (48%).

As shown in Figure 4-39, when the wells are classified by resource code as per Sanyal (2005) [78], nearly all of the wells are either high temperature (230 - 300°C) or ultra-high temperature (>300°C).
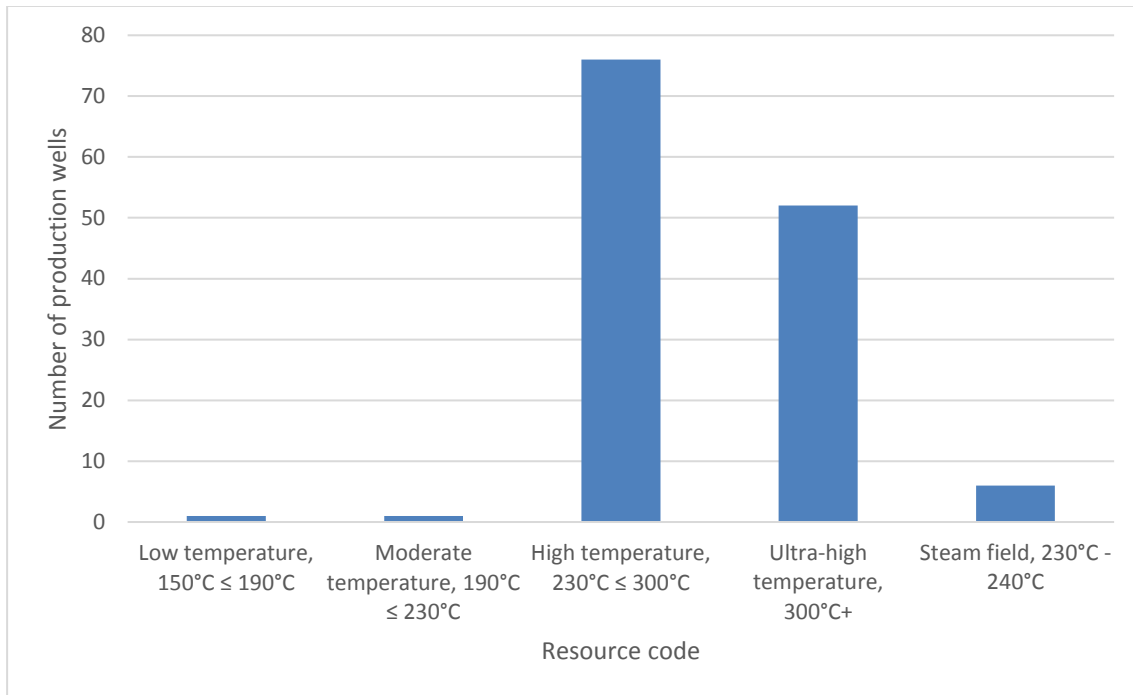
**Figure 4-39. Distribution of the 136 production wells based on the resource temperature**

The production casing diameters used are either 9⅝ inch (53%) or 13⅜ inch (44%), with a few exceptions using 5 inch or 7 inch production casing diameters.

The age of the production wells was assumed based on the date of completion, showing that most wells were completed during the last two decades.

While there was insufficient data to be able to make sound estimates of the total time in operation for the production wells, rough estimates were made on the basis of current well status and year the failure was detected. The numbers should only be considered indicative, and are surely overestimations, as neither downtime (planned or due to failure) nor exact shut-down dates were available. Accepting these limitations, the total years in service amounts to 2170 operating years, or approximately 16 operating years per well. The distribution of the production wells by estimated years in service is shown in Figure 4-40.
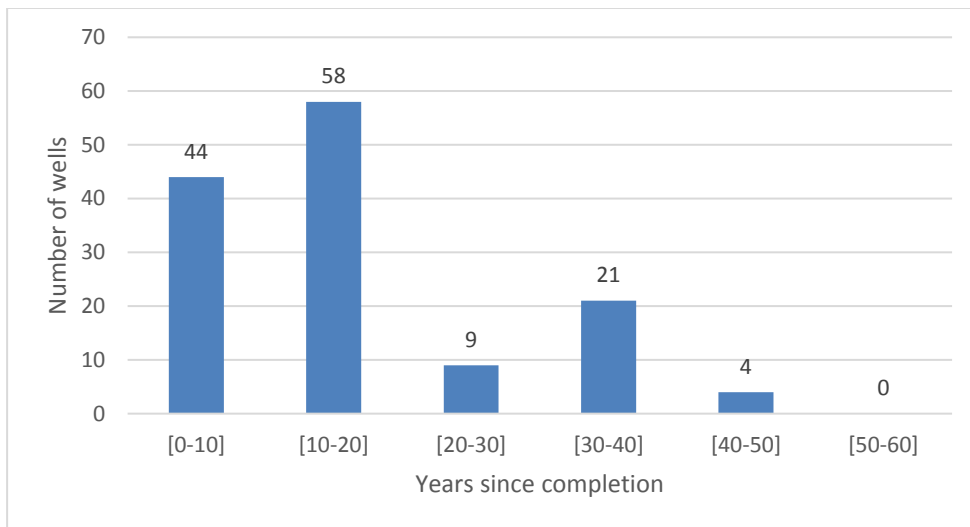
**Figure 4-40. Distribution of the 136 production wells based on the estimated years in service**

The wells were investigated with respect to failure records, based on an initial classification by the operator. For failure records where additional descriptions of the failure were provided, interpretations were made as to the failure mode. In the original data set the following six failure modes were applied:

- Bulge/collapse
- Tensile rupture
- Corrosion
- Scaling
- Eruption
- Other/unknown

After reassessments were made based on failure descriptions, the failure modes were split across different barrier elements, and additionally reclassified to a somewhat higher level of generality and to conform to the failure mode listing in section 3.1. Using this new classification scheme, tensile rupture and eruption are part of burst/rupture, corrosion is part of material degradation, and scaling is part of plugged/choked. Thus, the following failure modes were used in the further data analysis:

- Casing – Bulge/collapse
- Casing – Burst/rupture (including tensile rupture)
- Casing – Material degradation (wear, corrosion, etc.)
- Casing – Plugged/choked (e.g. scaling)
- Casing – Leakage
- Casing – Other/unknown
- Wellhead – Leakage
- Wellhead – Material degradation (wear, corrosion, etc.)
- Wellhead – Spurious operation
- Wellhead – Burst/rupture
- Wellhead – Scaling
- Wellhead – Other/unknown

- Packer – Leakage

The above list could have included more barrier elements and failures, but has been limited to only those that have occurred at least once.

Examining the failure records shows that 60% of the 136 wells do not have any recorded failures, while 40% have one or more failures. A total of 75 failures were recorded, giving an average of 0.55 failures per production well. The failure data does not give any indication that failures occur more frequently for ultra-high temperature production wells; the proportion of failed wells is roughly the same as for high-temperature production wells. However, the number of failures in each category is not sufficiently large to make any generalizations in this respect.

The recorded failures were further examined with respect to well barrier elements and failure modes. The distribution of the 75 recorded failures is shown in Figure 4-41.
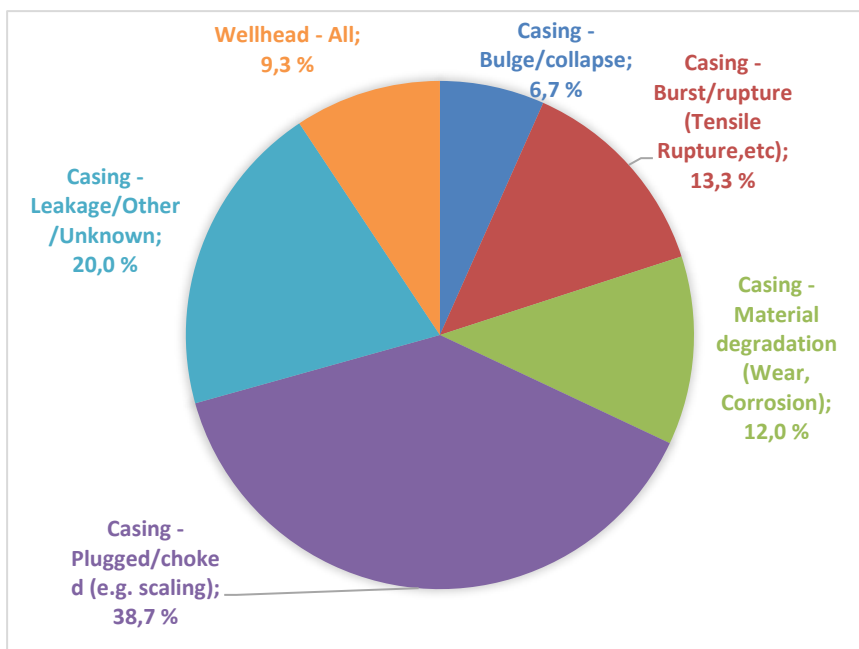


**Figure 4-41. Distribution of different failure modes for the 136 production wells**

The figure shows that nearly all failures are related to the casing, with plugged/choked constituting more than a third of all recorded casing failures. This failure mode includes obstruction of flow as well as scaling, i.e. that mineral depositions on the casing wall causing a reduction of the cross-section. According to Argueta (1995) [79], deposition of scale is a major problem in geothermal wells. The most common are calcite scale ($CaCO_3$), which occurs where flashing starts of the uprising high temperature water (brine), which is saturated with respect to calcite. Upon flashing the $CO_2$ dissolved in the water enters the steam phase, changing the pH of the liquid which becomes supersaturated and calcite deposits are formed. Other common types of scale are silica ($SiO_2$) and sulfides.

Another commonly occurring failure mode is burst/rupture, including tensile rupture, i.e. failure caused by axial tension where the casing is torn apart at the connections (or casing body). High tensile loads can occur if wells cool again after production (of hot water and/or

steam) where the casing stresses have gone past yield in compression due to thermal expansion. Further details on this failure mode can be found in Section 5.1.2.

Material degradation, in particular corrosion, constitutes 12% of the failure modes recorded. Corrosion yields loss of material thickness that in turn may cause leakage or structural problems. Another main form of corrosion in geothermal environments, only detected by destructive tests, is hydrogen embrittlement of the material.

Bulge/collapse (i.e. partial or full collapse of the casing, see Section 5.1.1) is also recorded for multiple wells.

Approximately 10% of the failures are related to the wellhead, where burst/rupture is the most frequent failure mode. Other recorded failure modes for the wellhead include leakage, spurious displacement and plugged/choked (scaling). 20% of the failures recorded fall into the other/unknown category.

As previously mentioned, there is not sufficient information available to make sound estimates of operation times, and therefore is it not possible to produce reliable MTTF estimates. However, if considering only the interpretations of MTTF as suggestive at best, some calculations can be made based on the aforementioned assumptions. While the numbers in themselves are not of particular use, the relative comparisons between different failure modes at least give an idea as to their frequency of occurrence.
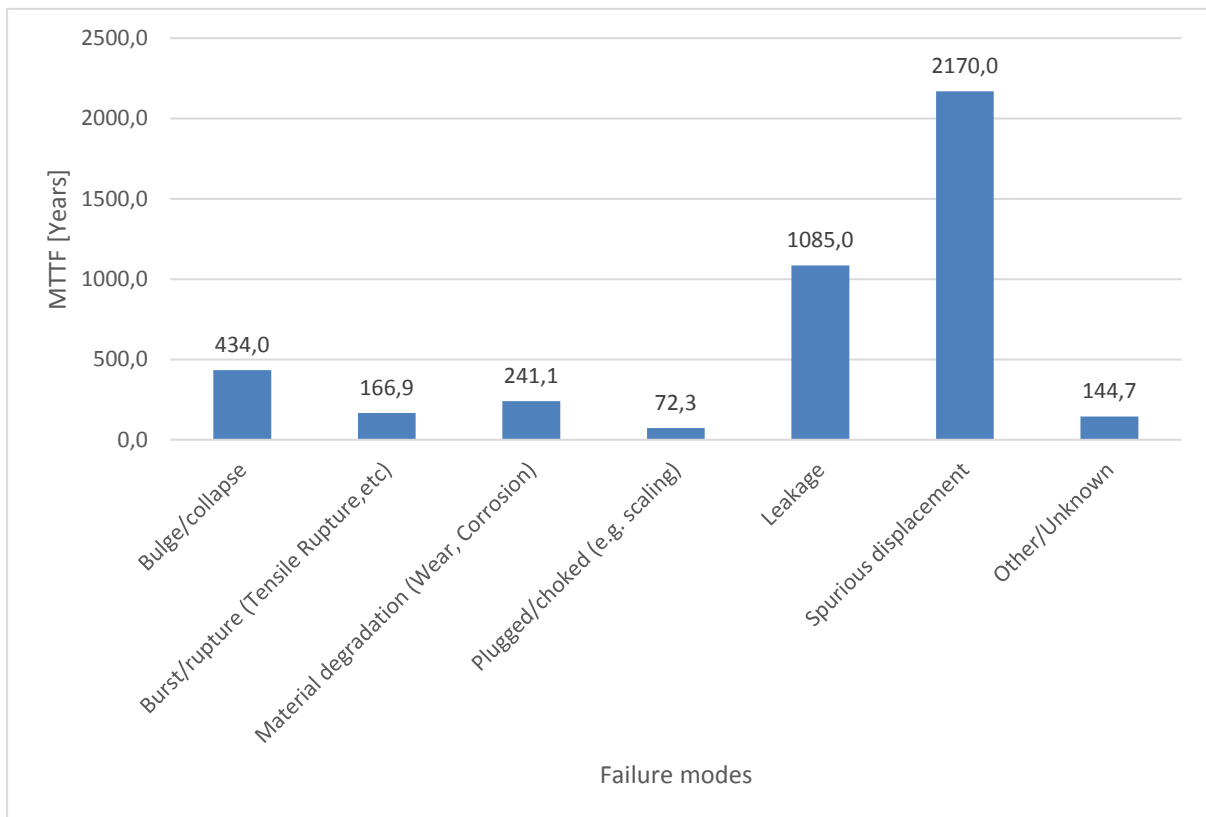


**Figure 4-42. Estimated MTTF for different failure modes in the 136 production wells**

Figure 4-42 indicates the same as Figure 4-41, that scaling, tensile rupture and corrosion are relatively frequently occurring compared to other failure modes.

As the operation time is likely to be overestimated (since shut-down times are not subtracted) and all possible failures are not likely to be recorded, the actual MTTFs are likely lower, and conversely, the failure rates are likely higher.

The data set does not include failures from other well barrier elements, such as the formation or cement. There could be failures on these as well, but both monitoring and recording of such failures are more difficult than for well equipment, where sensors enable feedback of data and evaluations of failure modes.

### 4.2.3 Software and risk assessment tools and models

This section will outline what types of software tools or models are used to model or provide input to the QRA, based on the GeoWell partners experience and published literature. A comprehensive listing of software tools for risk assessment can also be found on the website of ROSS Gemini Centre[1].

**TNO - software and tools**

For many projects, TNO produces the risk assessments case-specifically, which involve combining aspects of different methods. For a project dealing with financial risk of geothermal projects, Excel was used to develop a time series model that worked in conjunction with an add-in called Crystal Ball. This enables Monte Carlo simulations, where the add-in runs the base simulation, varies the input parameters, and runs the updated simulation. This repeats over a user-defined number of times, and Crystal Ball tracks the instances and creates sensitivity plots for the model run, along with probabilities and ranges of outcomes. For the failure mode and effects analysis, TNO has made a database of failure modes, which can be narrowed down based on an online questionnaire. Lastly, for Bayesian networks, TNO has used the program HUGIN Expert, which is a software that helps to visually build Bayesian networks and then calculate the probabilities of the possible outcomes. With the developer version comes the functionality of using the HUGIN library to run Bayesian networks outside of their proprietary software environment and in other programs such as MATLAB.

**IRIS - software and tools**

IRIS has considerable experience developing software tools for risk assessments, both for purely academic purposes and for industrial applications. For simple solutions, MATLAB is often used for Monte Carlo simulations due to the ease of writing iterations in simple code using the matrix structures. For more advanced purposes, however, at least when the user-interface is of importance, such code is typically programmed in C# where a proprietary library can support the development process.

## 4.3 Quantitative risk assessment framework

A framework, providing guidance on the applicability of QRA methods, is described here. This is based on the features of QRA methods and their relevance to the failure modes. The

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1 http://www.ntnu.edu/ross/info/software

framework is inspired by the works presented by Aven [80] and Abrahamsen et al. [81], but focuses on which methods to use rather than the decision-making principles.

Risk is not defined identically in several of the relevant literature sources. The definition of risk has evolved over time in an attempt to correct misconceptions and shortcomings. Commonly, risk has been defined as the probability of occurrence of an unwanted event multiplied by the consequences of that event, i.e. the expected value. Although useful for comparing alternatives with similar consequences, the shortcomings in other cases (e.g. lottery examples) encourage the use of other definitions to dissuade such misconceptions. The ISO 31000 standard [33] defines risk very generally as the effect of uncertainty on outcomes. This is considered a modern definition, although it can give an impression of being related to uncertainty in parameters described by input distributions propagated through models. Such an interpretation suggested here, gives support to a risk assessment simply by finding a distribution for the input parameters and running them through the model. To satisfy the need for describing the implications of the assumptions, as well as expertise and accumulated knowledge used for the distributions and models used, the Petroleum Safety Authority of Norway (PSA) [82] incorporated elements from [80] to redefine risk as "the consequences of the activities, with associated uncertainty". The argumentation was that important decisions are being taken without understanding the implication that the circumstances in which they are taken may be slightly different from previous experience. Note that the underlying definition of risk has not changed, and the redefining of risk is introduced to rectify misconceptions observed.

Based on the above, risk assessment can be considered an investigation into the effects that uncertainty has on the consequences. The intention of a quantitative risk assessment, as referred to in this document, is to support decision-making by providing numbers on how much effect uncertainty has on the consequences. To accomplish this, the risk assessment typically uses variants of the methods described in Section 4.1, together with phenomenological knowledge (often encapsulated in physical models).

A general framework for risk assessment of geothermal wells has been developed, using ISO 31000 as a point of departure, as shown in Figure 4-43. Thus, the main steps of the geothermal wells' risk assessment include:

- Establishment of the context;
- a risk assessment sub-divided into risk identification, analysis and evaluation;
- monitoring and risk reduction;
- continuous communication with stakeholders and risk review.

The framework presented here gives guidance on the risk assessment process and is as such a specific implementation of the ISO 31000 framework. In particular, it supports the selection of risk assessment methods on the basis of the assessment context and other selection criteria.
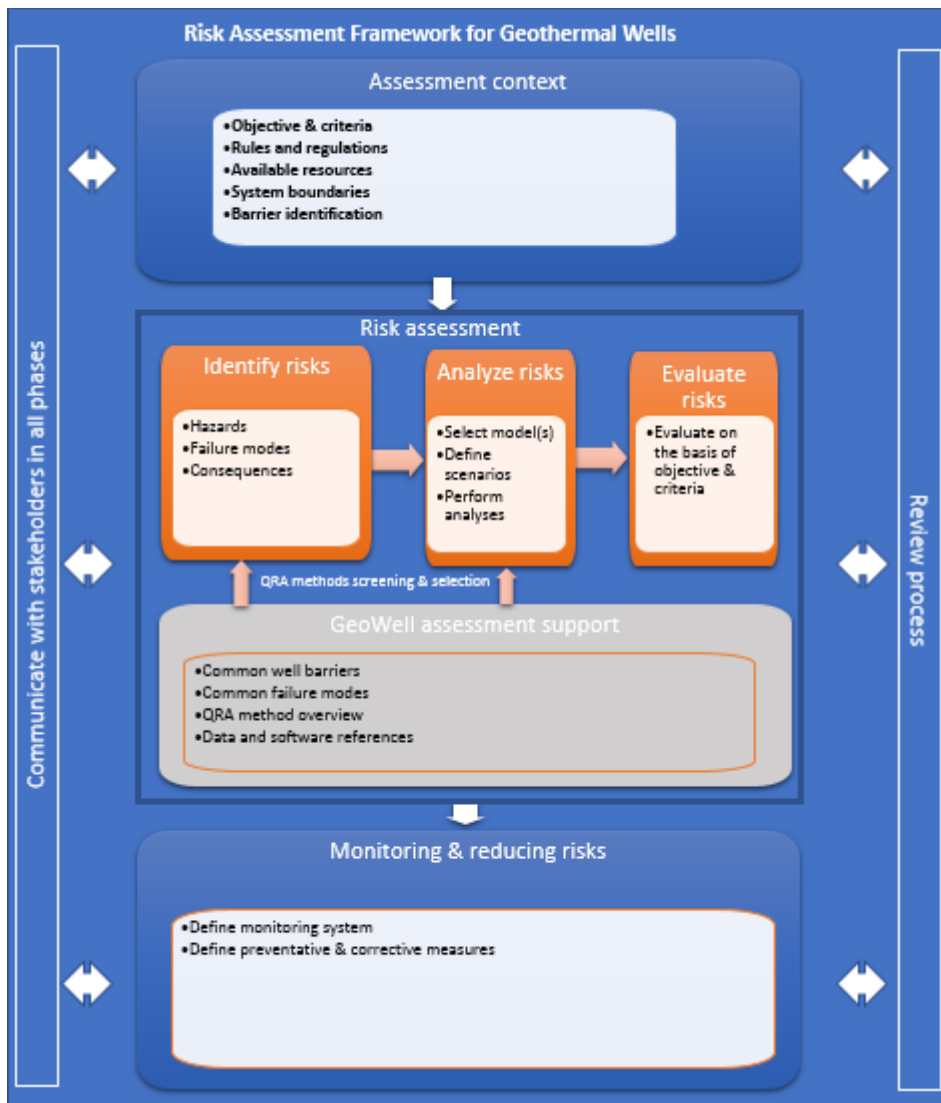
**Figure 4-43. The framework for risk assessment of geothermal wells**

The following sections outline the main steps of the framework.

### 4.3.1 Assessment context

To perform any risk assessment, it is first necessary to outline the context of the assessment. The assessment objectives and decision criteria must be defined, in order to ensure that the subsequent steps will result in meeting the objectives, and the analyzed risk can be evaluated in terms of acceptability. Objectives should include any company policies relevant to the risk context, regulations or requirements as to how the risk assessment is conducted or what it must contain as a minimum. Another important factor that will impact the subsequent steps is the availability of resources. This includes budget and personnel resources, competence and skills, and data and information concerning the well in question, as well as any resources that could be used to infer failure statistics, either in-house or external databases. The system boundaries will define which elements are included or excluded in the risk assessment. The characteristics of the well would typically include the barrier design and vulnerability of impacted elements (how robust the decision will be to changes). This framework provides

support to the boundary description by outlining relevant well barrier elements. The contents of Chapter 2 can be used as a starting point.

### 4.3.2 Method screening and selection

During the risk assessment process, risk will be identified, analyzed and evaluated. However, the way this is performed depends to a large degree on the choice of methods and techniques applied. In this framework, the screening and selection of relevant methods for risk assessment can be seen as a process of decision making, as illustrated in Figure 4-44.
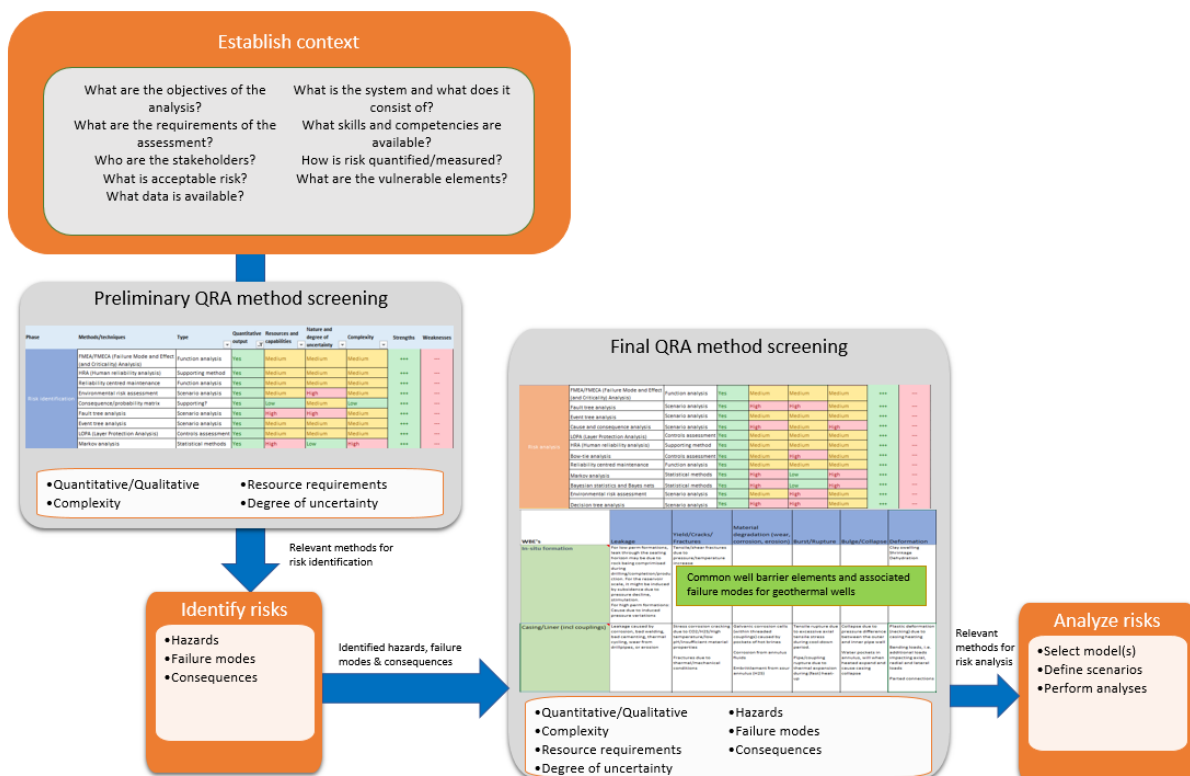


**Figure 4-44. Screening and selection of methods in the risk assessment framework**

Once the assessment context has been established, the ways to identify risks are narrowed down, due to e.g. the requirements, available resources, and types of risks to consider. The framework structures this process of screening risk identification methods using a list of QRA methods (based on ISO 31010), where methods are categorized. These categories are qualitative/quantitative, resource requirements, complexity, and degree of uncertainty, in addition to strengths and weaknesses, as summarized in Section 4.1.19. The result is a method selection basis for risk identification techniques. After the risk identification step, a further screening can be performed (and is necessary), as the assessment at this stage outlines what are the hazards, failure modes and consequences of interest, and as such it becomes clearer how to approach the more in-depth risk analysis.

For example, the implication of the well design on the choice of method relates to relevant failure modes and the amount of experience that exists for the design. Known failure modes related to well barrier elements have been discussed in Chapter 3, though this list is not exhaustive or expected to cover the most significant failure modes of new solutions and

materials. Thus, for any well under consideration, which failure modes are relevant must be adapted based on the existence of threats capable of causing different failure modes.

The different methods listed in Section 4.1 are suitable for some situations more than others. For example, reliability centered maintenance is only useful for situations where there are failures that can be prevented through maintenance activities. Others, like LOPA, are more suitable for assessing control measures, where there can be defined only one or few known threats to failure. Some methods, like bow-ties, are more suited for communicating than quantifying the risk. Statistical methods, such as Monte Carlo and Bayesian statistics, are more appropriate to infer relevant data from other sources, such as historical data or phenomenological knowledge, and are frequently used in conjunction with the other methods for this purpose.

In addition to the applicability of the different methods to the different failure modes of the well barrier elements, selecting which methods to use also depends on the assessment context. If the objective of the analysis is only to comply with rules, whether governmental regulations, industry standards or company procedures, then often simpler methods capturing uncertainty to a limited degree can be used. For example, if the objective is to verify that the probability of a failure developing into an undesirable consequence is below a certain threshold, then the rough uncertainty treatment of a LOPA analysis could be sufficient. However, if the objective is also to optimize design of protecting layers or minimize the potential for severe consequences, a more detailed treatment such as cause- and consequence analysis could be warranted. At times, rules and regulations may require the analysis to be performed in a specific way, or even using a specific method. Then of course, the choice of method will be limited to those satisfying the requirements given. However, additional considerations should be made if the analysis could not be performed according to the intention of the rule due to e.g. insufficient data.

The input required for the different methods differ, and the availability and relevance of data has a strong implication for the usefulness of the methods. For example, if a huge database of highly relevant data is available, then methods relying on more or less direct application of frequencies, such as risk matrices or fault trees, can be sufficient. However, where direct experience from similar situations are unavailable, then either a simpler semi-quantitative treatment is relevant, or using more advanced statistical methods to quantify the uncertainty in a way that is consistent with partly relevant data and other areas of knowledge (such as models of material physics). The latter is particularly important to consider when pushing the boundaries of regular operations or adopting new technologies.

More advanced methods would typically be able to give a better-founded quantification. However, if the analyst applying the method is inexperienced with the method, there will be an increased likelihood of inaccuracies in the modeling approach, which will reduce the overall value of the analysis. Thus, lack of experience with methods should restrict the use of those methods. At least, the implications of level of expertise with the method should be considered against the benefit it is thought to provide. In addition, some methods will also be more time and resource consuming than others. A detailed statistical analysis can take a significant of time to set up and gather data, while methods relying heavily on detailed input from experts will require extensive use of personnel occupied with other activities. Such

considerations should also be taken into account when deciding how to approach the risk assessment.

Other constraints and policies may also be relevant. For example, availability of software to assist with the analysis can guide the available choices, or the decision makers may have preferences on how the analysis should be communicated.

# 5 Risk assessment for selected geothermal phenomena

The most challenging difference between conventional oil and gas wells, and high temperature geothermal wells is temperature variations of a couple of hundreds degree Celsius in the latter. Thermal cycling when heating and quenching, such as when a well is flow tested, during production, and when it needs to be stopped and cooled down, can cause failures in the body of the casings and in the connections.

This chapter focuses on two phenomena that are specifically related to high temperature geothermal wells, and failures modes arising due to these. The relevance to the scope of the work in the GeoWell project and to the high temperature geothermal wells has been the basis for selecting these phenomena. These phenomena are then used as examples for illustrating how the preceding risk assessment framework can be applied.

## 5.1 High temperature geothermal phenomena

### 5.1.1 Casing collapse due to the trapped fluid

In geothermal wells, cement should reach the surface when the casing is cemented [83] as imperfectly cemented portions of casing filled with fluids (water and gas) are subject to thermal action because of well operations [26]. During the well heat up phase, the trapped fluid behind the casing wants to thermally expand [27]. The generated pressure due to expansion can exceed the casing collapse resistance of most standard API casings [28]. Expansion of trapped fluids causing excessive pressure loads can induce casing collapse (or casing bulge collapse), an example of which is shown in Figure 5-1 [84]. This failure has been extensively referred to as one of the most common phenomena in geothermal wells [26-29, 83, 84].

Casing collapse is generally caused by excessive net external pressure. For cement supported casings, instability in the annulus due to e.g. off-centered casing, trapped fluid, defects (such as pitting due to external corrosion), and external casing damage can result in casing collapse. Instability caused by an off-center casing can result in fluid (water/mud) entrapment on one side of the annulus [84].
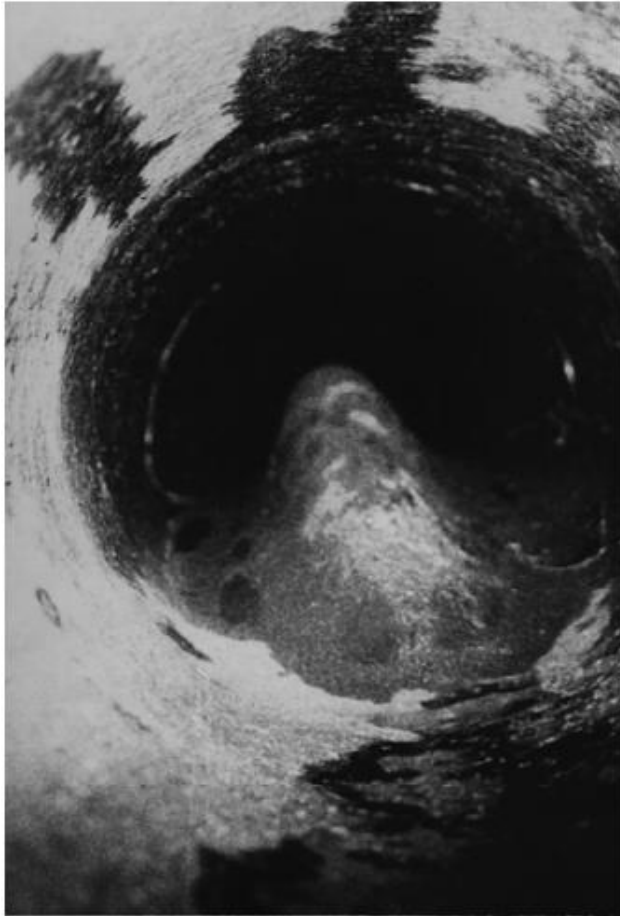
**Figure 5-1. Production casing collapse due to trapped water in the annulus [14]**

Note that this section covers only casing collapse due to trapped fluid expansion. This failure typically occurs in the production phase of a well's life-cycle, as stresses consistently change with time in this phase [27]. The most harmful fluid pockets are those between the production casing and the external casing [26], as the production casing failure can significantly affect the productivity of a well [29]. In case of trapped fluid in the casing to casing annulus, the production casing is collapsed and ruptured to the extent that the well flow is reduced. It has been reported that in some cases, well flow might be choked by more than 50% [29]. Statistically, higher numbers of failures occur in the shallower zones of the well (less than 500 m) where the thermal stresses are greatest [26]. Casing collapse due to the trapped fluid is usually located in the body of the casing and not at the couplings (i.e. couplings on the production casing). This is because the trapped fluid occupies less annular space at the couplings than in the body of the casing. In addition, any yielding of the coupling may result in the loss of sealing capacity that provides a pressure relief for the expanding trapped fluid [29].

Deformation of casing is usually located on one side of its circumference, according to video records from downhole video cameras of some geothermal wells in a study by Southon [29]. Although symmetrical collapse of the casing can occur if the pressure difference between the outer and inner wall exceeds the collapse resistance of the casing [85], there has not been any observation of a complete casing collapse due to trapped fluid in [29]. This is because the fluid is most probably trapped in channels rather than as a full annular slug of fluid during cement

placement. As stated by Southon [29], it should be noted that lack of observation does not necessarily mean symmetrical collapse of the casing and collapse at couplings does not exist.

In a collapse event, the geometry and the volume of the trapped fluid can determine the size of the casing collapse and the degree of casing deformation [28, 29]. In case of entrapment of mixture of water/mud and gases, certain parameters have a main influence on the critical stress state for the uncemented pocket. These parameters include the volume percentage of the gases, the type of gases in the mixture, the volume percentage of water if it is present together with other gases, and the casing thickness (lower thicknesses are more detrimental) [26]. If the trapped-water location has formation outside it, the casing will almost certainly not collapse. This is because the fracture gradient is usually low enough to allow the pressure to bleed off into a fracture [83].

Different parameters can reduce the collapse resistance and increase the risk of casing collapse, such as geometric imperfections (e.g. average outside diameter, average wall thickness, and ovality), eccentricity [84], presence of voids and cement channels, and pressure decline inside the well [86]. Casing collapse resistance is highly dependent on the presence of voids (that can be filled with fluids such as water) and can be reduced by up to 60% according to a finite element analysis of a case study presented in [86]. Eccentricity, however, exhibits only minor effects on the casing collapse according to the results of the same study.

There are different preventive and remedial options that can be taken into consideration in the construction and production phases to reduce the risk of casing collapse due to the trapped fluid or to keep the deformation at a minimum level:

- Reduce the volume of trapped fluids by improved cementation and focus on best practices – It is critical that no fluid be trapped between the cement and the casing, especially in intervals where one casing is inside another [83]. The volume of fluids can be minimized through efficient mud displacement during cementing and achieving a good cement bond [28, 29]. Preparation of high quality cement slurry and use of a cement slurry with zero free water under all pumping conditions and slurry temperature variations are also important to minimize the trapped water in the annulus [29]. During well construction, flushing and backfilling the annulus is an option when cement is not circulated to surface. The annulus can be immediately flushed with enough water to make sure no cement is left between the casing strings before the cement has a chance to set [83].
- Adaption of the design of liner overlaps and use of tieback or external casing packers – This is to allow fluid leak-off [28, 29], or increase the compressibility of the annulus and its containment to reduce annular pressure build-up [26, 28, 29].
- Select casing with higher collapse resistance to withstand higher pressure build-ups [26, 28] – The casing collapse resistance should be higher than the pore pressure or even the fracture pressure of the formation to avoid annular pressure build-up between casing and formation. This can lead to fluid leak-off to the formation prior to a casing collapse. However, this option is often not feasible or practical, especially for large diameter casings at deeper depths [28].
- Applying a slow heating-up process during the first production test – This is to provide more time for trapped fluids in the casing annuli to leak-off through different flow

paths such as micro-annuli and casing couplings, or paths towards the formation. By keeping the flow rates low or by stopping the pump several times before full production temperature is reached [28], the pressure may be relieved prior to reaching critical levels [29].

### 5.1.2 Parted connections due to excessive tensile forces

In order to shut-down wells permanently or for maintenance, the well needs to be cooled with quenching water. Rapid shut-down of a well with a resulting sudden temperature decrease causes quick material shrinkage and consequently the generation of large tensile forces [87]. This can lead to pulling the casing segments out of their couplings, and in some instances, parting of the casing body [85]. This is another important phenomenon in high temperature geothermal wells that is covered in this section.

The design of casings and couplings in high temperature geothermal wells is generally based on the available designs from the petroleum industry. Currently, a common design to connect casing segments in geothermal wells is buttress thread casing (BTC). These connections are designed to have similar strength as the casing body and, as they are originally designed for the petroleum industry, they must remain pressure tight. However, such threaded couplings provide no room for axial displacements, as no consideration is taken into account to reduce the axial strain that builds up due to thermal expansion [88].

The curing temperature of the cement is used as the initial condition for calculations of thermal stress and strain. Figure 5-2 illustrates the failure mechanism that can occur due to high temperature variations and subsequent generation of axial tension in the casing and couplings. As shown in the figure, temperature increase during the initial discharge of the well can generate stresses reaching the yield strength. Plastic strain could subsequently be formed in the casing during the compressive state. The plastic strains are permanent and form a constrained casing that geometrically shortens. When the well cools down to the initial curing temperature of the cement, the plastic strain leads to the generation of tensile forces due to casing contraction. If the tensile stress is large enough to exceed the coupling joint strength of the casing, it can cause casing failure and axial tearing at the coupling, where the pin is torn out of the box, either by the threads or by rupture of the body near the first threads of the casing [87, 88].
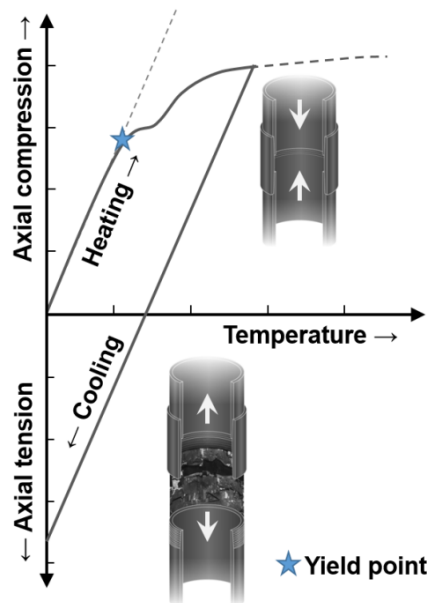
**Figure 5-2. Generation of axial tension (during cooling) subsequent to strain formation during compression state (heating)**

An example of such a phenomena that resulted in failures in couplings has happened in IDDP-1, when the well was quenched with cooling water due to a situation where the main wellhead valves were not functioning [88]. A video log of the IDDP-1 well revealed three failures of the production casing at couplings, at approximate depths of 300 m, 356 m and 505 m. The casing had been pulled down and consequently torn apart from the coupling presumably due to tensile stresses from thermal contraction. One of the failures has been shown previously in Figure 3-2, where the coupling ruptured at a depth of ca. 300 m [24]. In all three cases, the failures exposed the cement and external casing to the geothermal fluid. The direct contact of the fluid to the anchor casing (the casing the wellhead is resting on) could cause potential corrosion problems. Also, the thermal insulation provided by the cement in between the casing layer was lost [24].

Note that in some cases, premium couplings with more complex thread designs are chosen that have metal-to-metal seats. The seat instead of the threads absorbs the compressive forces. However, the threads take up the full load during tension (cooling) and coupling rupture might still happen.

## 5.2　Probabilistic risk assessment methods

This section provides a discussion on the selection of applicable QRA methods and techniques, using the phenomena in Sections 5.1.1 and 5.1.2 as examples. Considerations in this respect concern the overall objective of the risk assessment, the available resources and the available data. The examples provided here are of a conceptual high-level type, serving mostly as illustrations of how the framework in Section 4.3 is applied to specific phenomena.

### 5.2.1 Casing collapse due to the trapped fluid

As seen in Section 3.1.5, casing collapse due to trapped fluids is a common failure type in high temperature geothermal wells, and occurs due to temperature change. Such a collapse can choke the well flow, making the consequence of a failure largely an economic concern. There

are several methods to reduce the risk related to this type of failure, such as operational procedures, casing material selection and cement formulation. As the implementation of some of these methods can be associated with a cost, an economic analysis to optimize the selection and risk accepted can be warranted. In addition, as there are already suggested risk reducing measures, discussing and mapping them in a bow-tie diagram (or influence diagram) is useful for communication and discussion purposes.

A collapse itself is a structural integrity problem, which is modeled as a comparison of material strength versus loads. Although this is a frequently occurring type of failure, the number of factors, such as design parameters and well specifics, influencing the occurrence and severity are also large. It means the data sets relevant for a specific set of factors may not be large enough to make a direct comparison of solutions. Thus, from a quantitative risk perspective, the main question is what are the strengths and loads, and what uncertainties are associated with these quantities.

Material strength is a property of the casing material that has typically been tested in a laboratory. Thus, although the specific casing installed might not have been tested, the population it belongs to will have a reasonably well-known strength. However, this strength may degrade due to downhole conditions, and an identification of these conditions and processes must be performed. Degradation may not be significant in all cases, and one may want to accept a certain level of uncertainty related to the material strength. Then, a risk matrix may be useful to screen which, if any, of the identified threats must be considered more explicitly in the assessment.

Loads are dependent on the well condition and its operation. For this reason, it is useful to create load-scenarios, which can be structured as a tree (decision tree if there are active decisions, or more like an event tree if not). Probabilities on the nodes of the tree may be difficult to populate. However, there are several ways to estimate these, such as directly based on information from logging activities, Bayesian inference using data from earlier wells, or models based on physics in conjunction with Monte Carlo simulation. Combining different methods would yield a higher confidence in the result (and thus reduced uncertainty), but it may also be sufficient to use only one, if there is enough background data for it.

A cost-benefit analysis is a natural basis for decision making, given that most cases of casing collapse have a negative effect on the economy of the well, and the analysis would be used to determine which risk reducing measures to implement.

### 5.2.2 Parted connections due to excessive tensional forces

As the connections are subjected to large temperature changes, the threads in the connections will be under a significant amount of stress. As these temperature changes increase, the strength of the connections might be exceeded causing the casing to be pulled apart at the connection. This results in an exposed portion of the annular cement, and a leak path for fluids flowing into or out of the well.

To prevent such failures, stronger threads are traditionally used. However, as wells are drilled into increasingly high temperatures, stronger threads are not sufficient to overcome the problem. Thus, a new flexible coupling capable of absorbing the temperature change is under development in the GeoWell project.

The use of flexible coupling can be considered as a risk reducing measure. Thus, it would be prudent to perform a probabilistic risk assessment to support the decision on whether to implement the measure or not. This support would take the form of a comparison of the risk associated with the existing best practice versus the newly developed flexible coupling. The assessment is here only outlined and the assumed qualities of the two cases have not been through a process of identification and validation. Thus, the assumed qualities are only for illustration purposes.

The possible consequences of using one coupling over the other is not radically different. The flexible coupling, being a slightly more complex technological device than regular couplings, might have additional failure modes. However, the consequences of these would not be considered more serious than the consequences of a parted connection. This means there is no change to the weight given the pre-cautionary principle, and the two cases can be compared directly by preferred reduction in consequence and probability.

There are requirements to consider for casing design in both NORSOK D-010 and New Zealand Code of Practice for Deep Geothermal Wells. The design is based on making sure the structural integrity of the casing will be maintained under the anticipated loads and conditions. However, as discussed in [89], there are many options to use for loads and conditions, and how to consider what is sufficient. Simpler methods such as worst-case load, standard safety factor and choosing a material that is rated to surpass this may be time- and cost-efficient under known conditions where the additional cost of higher grade materials is small. However, in situations where the load and threats are less certain, the safety factor may not be representative, and the consequences of the choices may not be trivial, a risk based approach should be used. This is occasionally done in practice [90].

The failure of casing connections is a known problem, and some field experience exists should be available for an analysis. Thus, for medium temperature wells, relevant historical data can be gathered for a frequency analysis. However, for increased temperatures, there exists less historical data. In order to get more representative solutions at these temperatures, models of the physics involved should be used, to infer from the historical data what this would relate to at higher temperatures.

As the installed coupling is a part of the system where failures are not prevented through maintenance (preventive maintenance) and there is no temporal decision associated with it, methods focusing on actions, maintenance and decisions are not relevant as the main angle of approach. Due to data existing but not being directly relevant, a modeling approach using Monte Carlo simulations together with Bayesian statistics, to make use of the existing data can be considered useful. The model would consist of two parts; one part that models the strength of the material to withstand loads, and one that models the loads it will be subjected to. For the first part, simplified models of the physics can be developed from textbooks or standards. It is important to assess the representativeness of such simplified models in the analysis, as well as degradation mechanisms that will interact with the loads. The loads are partly managed by the operations in the well, and the relationship between loads and procedures to reduce the loads can be considered using for example fault trees. The criteria used to decide which coupling to use would typically be a combination of cost and change in probability and

consequences of undesirable events. Thus, a cost-benefit analysis would be the suggested overlying method to use for decision purposes.

# 6   Concluding remarks

This report has presented typical geothermal well barrier elements that should be considered for a quantitative risk assessment, and which failure modes are relevant for each. Some potential consequences resulting from these failure modes are also outlined. Chapter 4 described different methods for performing quantitative risk assessment and outlined a framework for how methods should be selected, based on properties of the different methods, assessment context and other relevant selection criteria. Chapter 5 described two examples of failure modes typical for high temperature geothermal wells, with a basic proposal for how these can be addressed from a quantitative risk assessment perspective, using the proposed framework as a foundation. This forms a basis that will be concretized in work task 6.4 of the GeoWell project, where the framework will be set in context with European legislation. Then, in work task 6.5 of the GeoWell project, two of the solutions developed in GeoWell (cement mixtures and procedures to reduce water pockets and flexible couplings) will be analyzed through a reliability analysis.

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# Appendix. Monitoring tools/techniques for different barrier elements and events

Table A.1 presents a matrix of expected risks and failures together with appropriate means of identification for different barrier elements (shown in Figure A1) in the well production phase. The monitoring tools and parameters listed can be used as input to analyze the risk associated with a specific failure. With knowledge of typical well barrier element failures from geothermal fields, the listed means of identification can be used to observe and mitigate unwanted failures during the well production phase. Table A1 provides an overview of available monitoring techniques, and indicates which barrier elements and failure modes they are applicable to.
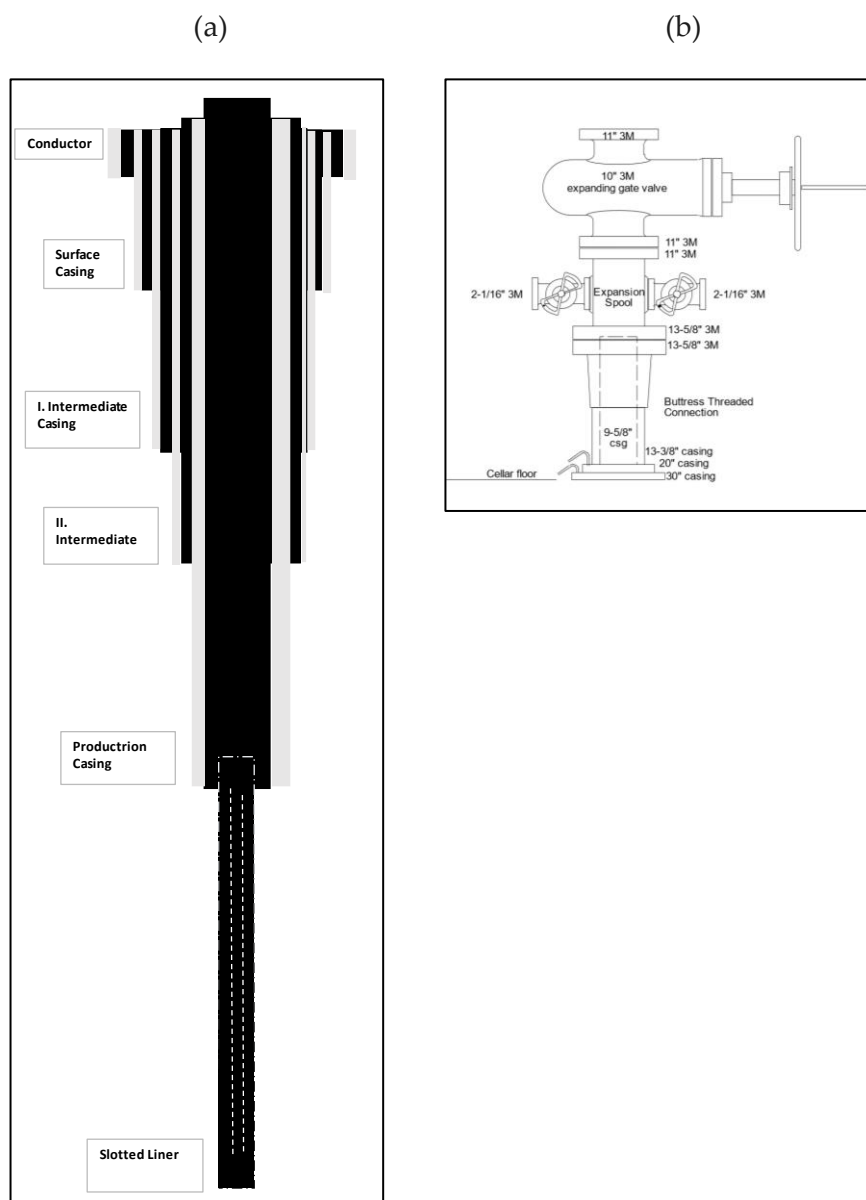
(a)                                                          (b)



**Figure A1. Schematics of (a) casings and (b) wellhead for high temperature geothermal wells**

**Table A1. Different tools and methods for monitoring and identification of failures in high temperature geothermal wells**

| Monitoring | Tools & Logging | Barrier → Risk ↓ |
|---|---|---|

*Barrier groups (Downhole):* Slotted Production Liner*; Top Packer Liner Hanger; Production Casing; Cement – Behind Production Casig; Intermediate Casing I – (ANCHOR), Intermediate Casing II, Surface Casing, Conductor Casing; Cement – Intermediate Casing I – (ANCHOR), Cement – Intermediate Casing II, Cement – Surface Casing, Cement – Conductor Casing.
*Barrier groups (Surface):* Wellhead Pressure, Casing Head: Expansion Spool, Production, Intermediate I (ANCHOR), Intermediate II (Pressure Seal), Wellhead Flange A, B, C; Master valve, lateral side valves.

**Risk columns per barrier**

- *Slotted Production Liner*:* Material Degradation; sanding up; accumulating heavy metals; Burst; Collapse; Buckling; Deformation; Break Down; Corrosion; Erosion; Scaling
- *Top Packer Liner Hanger:* Degradation; Lekeage; Loss of anchor force; Scaling; Displacement; Yield and Deformation
- *Production Casing:* Leakge; Yield Cracks and Fractures; Material Degradation; Burst; Collapse; Buckling; Deformation; Break Down; Corrosion; Erosion; Displacement; Scaling
- *Cement – Behind Production Casig:* Leakge; Yield Cracks and Fractures; Material Degradation; chemical attack; mud pockets/voids; Micro Annulus; loss of compressive stength; Break Down
- *Intermediate Casing …:* Leakge; Yield Cracks and Fractures; Material Degradation; Corrosion; Erosion; Displacement
- *Cement – Intermediate …:* Leakge; Yield Cracks and Fractures; Material Degradation; chemical attack; Micro Annulus; Break down, loss of strength
- *Wellhead Pressure, Casing Head …:* Leakge; Fatigue; Corrosion; Plugging Scaling; Erosion
- *Master valve, lateral side valves:* Fatigue; Corrosion; Erosion; Plugging and Scaling; Chocked Flow

**Failure (per barrier group)**

- Slotted Production Liner: Plugging, Formation Damage, Wellbore Instability, Sand Production, Connection Failure
- Top Packer Liner Hanger: Fluid Losses, Gas Migration, Slotted Liner Displacement
- Production Casing: Casing Damage, Connection Failure, Fluid Losses, Influx, Formation Failure at Shoe, Plugging
- Cement – Behind Production: Poor Cement, No Zonal Isolation, Fromation Failure, Fluid/Gas Migration
- Intermediate Casing: Casing Damage, Connection Failure, Fluid Losses, Influx, Formation Failure
- Cement – Intermediate: Poor Cement, No Zonal Isolation, Formation Failure, Influx, Gas Migration, Contamination of Fresh Water Reservoirs
- Wellhead: Ground Contamination, Pressure Integrity Loss, Leakage
- Master valve: Vavle Blocking, Pressure, Integrity Loss, Leakage, Formation Damage, Contamination

**Monitoring rows**

| Category | Tool / Logging | Marked failures (×) |
|---|---|---|
| **Pressure** | Surface Sensor | Cement–Behind Production (Leakge); Wellhead (Leakge); Master valve (Chocked Flow) |
| | Surface Gauge | Cement–Behind Production (Leakge); Wellhead (Leakge); Master valve (Chocked Flow) |
| | Donwhole Survey <400°C | Top Packer (Scaling); Production Casing (Leakge); Cement–Behind (Leakge); Intermediate Casing (Leakge); Cement–Intermediate (Leakge) |
| **Temperature** | Surface Sensor | Cement–Behind Production (Leakge) |
| | Surface Gauge | Cement–Behind Production (Leakge) |
| | Donwhole Survey <400°C | Top Packer (Scaling); Production Casing (Leakge); Cement–Behind (Leakge); Intermediate Casing (Leakge); Cement–Intermediate (Leakge) |
| **Geometry, Tolerances, Gaps, States** | Surface Coupons | Wellhead (Corrosion, Plugging Scaling, Erosion); Master valve (Corrosion, Erosion, Plugging and Scaling) |
| | Cathodic Protection Evaluation Tool <70°C | |
| | USIT (Ultrasonic Inspection Tool)<70°C | |
| | RST (Reservoir Saturation Tool)>125°C | Intermediate Casing (Material Degradation) |
| | UCIT (Ultrasonic Corrosion Inspection Tool)<70°C | Slotted Liner (Corrosion); Production Casing (Corrosion); Cement–Intermediate |
| | Electro Magnetic Tool (EMT)<70°C | |
| | Acoustic<70°C | |
| | Compensated Acoustic Velocity<70°C | Intermediate Casing |
| | CBL<150°C | Cement–Intermediate (Micro Annulus; Break down, loss of strength) |
| | CCL<150°C | Top Packer (Lekeage); Top Packer (Displacement, Yield and Deformation) |
| | Gamma Ray < 300°C | Top Packer (Scaling); Top Packer (Displacement, Yield and Deformation); Cement–Behind (Leakge) |
| | Caliper < 150°C | Slotted Liner; Top Packer (Scaling); Production Casing |
| | Televiewer*(300°C) | Cement–Behind Production (chemical attack) |
| | Special Geothermal Tools PTS CCL <350°C | |
| | Downhole Camera < 75°C | Slotted Liner; Top Packer (Lekeage, Displacement, Yield and Deformation); Cement–Behind (Leakge) |
| | Impression Blocks | Top Packer (Lekeage); Production Casing (Break Down) |
| | Wire Baskets | Slotted Liner (Collapse, Buckling, Deformation); Top Packer (Lekeage); Production Casing (Burst, Collapse, Buckling, Corrosion) |
| **Total Flow Rate (2-phase flow, total steam and water flow)** | Flow meter Spinner < 140°C; at Turbine | Slotted Liner (sanding up); Top Packer (Degradation); Production Casing (Leakge); Cement–Behind (Leakge); Wellhead; Master valve (Chocked Flow) |
| **Chemical Samples** | Sample Separator of Steam and Water Phases | Slotted Liner (sanding up); Top Packer (Lekeage); Production Casing (Leakge); Cement–Behind (Leakge); Wellhead; Master valve |
| | Ultrasonic Inspection | Slotted Liner (accumulating heavy metals); Wellhead; Master valve |
| **Output Test** | Silencer/Separator diverted flow | Slotted Liner (Material Degradation); Wellhead; Master valve |

Note: The definitions and classifications of barrier elements, failures and risks are not consistent with what have been described in the main part of the report.