GeoWell

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

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Reliability analysis of new developed materials and technology

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NORCE TNO innovation for life

Executive summary

High temperature geothermal wells have several challenges associated with well integrity. The Horizon 2020 project GeoWell “Innovative materials and designs for long-life high-temperature geothermal wells” have made progress towards developing technical solutions to address a few of them. This includes a casing connection technology called “flexible coupling” that can reduce axial stress caused by temperature change, cement formulations with reduced water content to reduce annular pressure build-up caused by water in the cement during temperature change, and cladding materials to reduce corrosion of the production casing.

When fully developed it is anticipated that these technologies will be able to reduce casing failures, thereby increasing the reliability of casings in geothermal wells. Increased reliability of casings can be translated into cost-savings and/or increased safety/environmental protection. The reliability of a given casing configuration will depend on the approach to design, e.g. degree of detailing probability of casing failure. The main approaches are working stress design, limit state design, load and resistance factor design and reliability-based design. All approaches are based on comparing the loads the casing will be subjected to against the ability of the casing to withstand the load. The main differences are how they deal with uncertainty (i.e. estimate it and/or use a safety factor) and what failure mechanisms are included in the analysis. For example, limit state design needs to be considered, instead of the standard working stress design, when wells are likely to exceed the yield limit such as in high temperature geothermal wells. Reliability-based design should be used if safe designs are difficult to achieve through other design approaches or there are new aspects to the operations (e.g. new technologies or conditions), while load and resistance factor design can be used on subsequent wells.

The which degree probability of failure in casings should be accepted depends on the consequences of such failures. While many failures will only have economic consequences, failures in high-temperature geothermal wells can have severe impact on environment, health and safety which must be considered.

A model for reliability-based design has been developed to analyse the developments in the GeoWell project in terms of casing reliability. The model simulates the condition of a casing through the life of the well, from installation to end of production. This includes different load scenarios, where some are certain to occur while others may occur, and degradation of casing properties. The model is described in general terms in this document, with reference to sources for details on sub-models. The sub-models for casing strengths are based on industry standards, with some parameters adopted from GeoWell project developments.

Simulations have been used to interpret how the reliability may change when going from a conventional design to a design that includes the developments in the project. Due to the limited maturity level of developments at the time of simulation, this is mostly a qualitative assessment instead of a case-based assessment. Possible ways the developments can fail to function as intended have also been discussed. In general, the flexible coupling, which is the development in the GeoWell project with the highest degree of progress, can significantly reduce casing failures if it works as intended.

Contents

1 Introduction

The GeoWell project aims to resolve issues related to very high temperature wells (up to and above 350 °C). The issues considered are mainly the problems of plastic deformation and subsequent tearing of the casing/couplings due to thermal expansion and subsequent contraction of the casing steel (a focus in Work Package 4), and collapse of the casing due to thermal expansion of water pockets in the cement (a focus in Work Package 3). The project also considers the application of composite casings (though they will not be suitable for elevated temperatures); fibre optic measurements, cladding materials to reduce corrosion and a ductile layer to allow free casing movement.

The project has worked on the development of several technologies:

- Flexible coupling
- Cement formulations with reduced water content
- Composite casings
- Casing cladding
- Ductile surface layer

In addition, experiments have been performed to improve understanding of well integrity problems. This includes experiments run by TNO to estimate material yield properties above what is available in (Standards New Zealand, 2015).

This report discusses some of the possible implications these technologies and experimental results can have on the integrity of casings in high temperature wells. More specifically, a reliability analysis will be performed to quantify the change in probability that the casing will be able to endure different conditions based on estimated knowledge.

2 Casing design

Casing design is the process of matching strength or resistance to load, subject to various constraints, in order to be confident that the strength exceeds all loads during the life of the casing, or at least what level of risk is being accepted. The design process aims to guide the choice of size, weight and grade of casing, type of connection, requirements of the materials, inspection requirements and operational procedures and precautions.

When discussing casing design, it is necessary to identify the threats to integrity of the casing, such as which loads and deterioration processes it may be subjected to. Casing designs must be evaluated in terms of how well it is able to resist such threats. The evaluation can be performed based on different principles (Aadnøy, et al., 2009), which in this chapter are divided into

- Working Stress Design (WSD)
- Limit State Design (LSD)
- Load and Resistance Factored Design (LRFD)
- Reliability Based Design (RBD)

An overview of typically considered loads and the different principles are summarized in the subsequent chapters.

2.1 Operational loads

The modelling of the forces the casing is subjected to is described in different standards and textbooks as load conditions. The load conditions refer to pressures in the annulus, pressures inside the casing, and axial forces on the casing. In addition, there can be additional loads related to bending, torsion and shear which are not covered here. According to (Aadnøy, et al., 2009), torsion and shear are normally not considered unless there are special circumstances, and bending is not considered as relevant in wells without significant dogleg.

Load conditions are typically described as either intentional or accidental (Aadnøy, et al., 2009)). Intentional loads come from planned operations, such as cementing, and have a high degree of occurrence and good ability to control the size of the load. Accidental loads are unplanned, such as a kick, and may not happen. Accidental loads are often more severe, or is an addition to existing intentional loads, and both chance of occurring and the subsequent consequence are sought to be minimized through procedures and other preventive and mitigating measures. The importance of differentiation between accidental and intentional loads varies between different design principles. Other sources use operating (service) and survival loads instead (Suryanarayana, et al., 2016).

The primary source for models and data on casing resistance calculations is ISO/TR 10400 (ISO, 2018) from 2018 (or the equivalent API bulletin 5C3 from 2018). Special considerations for high temperature wells based on practice in steam wells in Canada are described in (CAPP DACC, 2012). Advice on which load conditions should as a minimum be considered are described in national and international guidelines or code of practices. The recommendations vary depending on which applications they are written for. Examples are (Standards New Zealand, 2015) and (African Union, 2016) for geothermal, and (ISO, 2014) and (Norwegian petroleum industry, 2013) for petroleum.

The consequences of the loads on casing depend on which forces are dominating. Axial tension attempts to pull the bonds between the atoms in the material apart; and will at some point create dislocations in the material, changing its grid structure (McPherson, 2013). This point is usually referred to as the yield point of the material (McPherson, 2013), though yield strength has also been defined as the force needed to produce a 0.5% elongation of the gauge length of a specimen (Rahman, et al., 1995). Further axial forces will increase the changes to the material until it reaches its ultimate tensile strength where the material fractures and is pulled apart. A noteworthy secondary consequence of axial tension is that the increased distance between the atoms in the material makes it easier for e.g. hydrogen to enter the grid causing cracking (McPherson, 2013).

Axial compression does not have the consequence of creating a fracture, but the compressive forces can also change the material (effectively shortening it) (Kaldal, et al., 2016), or buckle if unsupported (ISO, 2018).

Internal forces act on the inside of the casing in an outwards direction, which could cause the casing to burst. When fully cemented there is no room for the casing to expand, making this a less likely scenario for geothermal wells where it is customary to cement casings to surface.

External forces act from the outside push the casing in an inwards direction, which could cause the casing to collapse. How this will manifest itself depends on the geometry of the casing and how the forces are distributed. The most commonly used model is described in (ISO, 2018) with four consequences depending on the ratio between thickness and diameter:

- Yield collapse
- Plastic collapse
- Transition collapse
- Elastic collapse

The consequence of these types of collapse can be a narrowing of the flow area reducing flow and/or preventing tools to access areas of the well below the collapse point, or fracture and leakage.

Typical axial forces causing tension or compression are (based on (Aadnøy, et al., 2009), (Standards New Zealand, 2015))

- Temperature changes
- Hanging casing
- Standing casing
- Shocks (when running casing)
- Induced tension while cementing
- Buoyancy effects (pressure)
- Bending

Typical internal forces acting on the casing may be caused by pressures during (based on (Aadnøy, et al., 2009), (Standards New Zealand, 2015))

- Kick
- Pressure test
- Temperature change
- Circulation
- Injection
- Cementing
- Evacuation (loss of mud column)

Typical external forces acting on the casing may be caused by pressures from (based on (Aadnøy, et al., 2009) and (Standards New Zealand, 2015))

- Temperature expansion of annular fluids
- Formation pressures
- Cement
- Settled fluid

The difficulty in casing design reside in the uncertainty inherent in the design. There is uncertainty regarding what loads the casing will be subjected to through its service life, as well as how it will degrade over time due to well conditions. The resistance of the casing to these loads is also uncertain, due to manufacturing variations such as consistency, ovality and uniformity of wall thickness as well as imperfections that may go undetected. How these uncertainties are approached is the main difference between different design principles described next.

2.2 Working Stress Design

Working Stress Design (WSD) or Allowable Stress Design (ASD) is considered the traditional method for structural design (Madsen, et al., 2006), and when conditions allow it will produce safe design through simple calculations.

The basis for WSD for casings is to use deterministic minimum properties in formulas, such as those given in (ISO, 2018), to calculate the minimum strengths of the design, and then take a prescribed fraction of that to use as the “allowable” or “working” stress of the design. The loads, as described in Chapter 2.1, are usually at the high end of expected loads and are compared to this "working" stress limit. The prescribed fraction is usually referred to as a design safety factor, and will depend on whether collapse, burst or axial failures are considered. The safety factors are typically based on industry common practice and experience, but usually lack a documented basis for their value. The intention of the safety factor is to account for any non-conservatism in models and assumptions as well as other uncertainty. Table 1 shows some values recommended by different sources.

Table 1. Examples of safety factors

	Norsok D-010 (Norwegian petroleum industry, 2013)	**NZS 2403** (Standards New Zealand, 2015)	**Shell Level One** (Aadnøy, et al., 2009)	**Typical range** (Aadnøy, et al., 2009)
Burst	1.10	1.50	1.25	1.00 - 1.25
Collapse	1.10	1.20	1.00	1.00 – 1.10
Axial	1.25	1.80	1.30	1.30 – 1.90
Tri-axial	1.25	1.25	1.25	1.25

The elastic limit is used as the strength limit in working stress design. This means that exceeding this limit only indicates the onset of plastic deformation and will not necessarily have any immediate negative consequences.

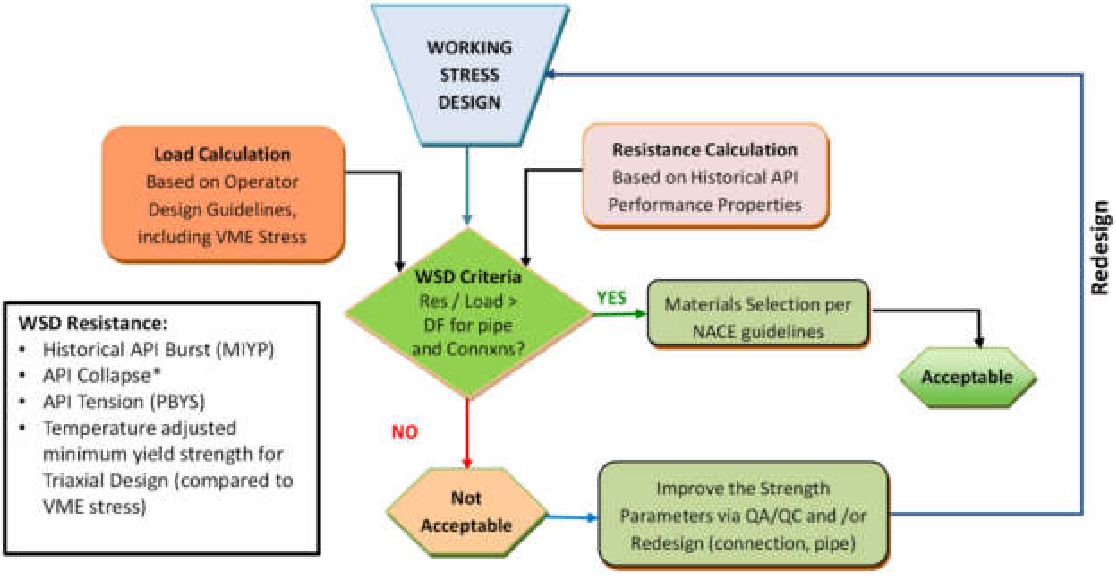

Figure 1. Working stress design approach as illustrated in (Suryanarayana, et al., 2016).

While working stress design is considered a useful and safe approach to casing design, it may be considered overly safe in applications where a failure is not considered to have severe consequences. It must also be noted that failures do occur, despite basing the design on this "safe approach". In addition, some applications make it impossible to achieve a satisfactory working stress design due to availability of designs capable of withstanding the defined loads. In such cases WSD requires the designer to compromise the principles of WSD, making the safety of the design difficult to determine.

Thus, while easy to apply, the approach has limited usefulness as decision support (only a design check) and does not explicitly show what levels of risks have been accepted. A design is accepted when

$$Load \times Safety\ factor \leq Design\ strength$$

2.3 Limit State Design

While WSD is more of a design check, where (ISO, 2018) uses the term design check equations for the ability of a casing to resist loads, another option is to check if the casing will survive loads using limit state equations. This approach is referred to as limit state design (LSD).

LSD may have had a broader meaning in its inception covering all possible limits, but over time it has become more closely associated with design based on maximum strength (plastic design) (Fritz Lab, 1960). In casing design, both ultimate limits which address complete failure, such as rupture, and serviceability limits which restricts normal use or affects durability, such as buckling beyond permissible limit, are used (Aadnøy, et al., 2009) and (Maes, et al., 1995).

Load conditions are usually defined as in WSD, but different safety factors are used based on the seriousness of consequences and frequency of occurrence.

The limit state equations used in LSD are usually similar to those used in WSD. The ISO standard (ISO, 2018) describes both design check equations and relates them to the equivalent limit state equation. A main difference is the use of nominal values in WSD, while LSD try to use actual values determined from respective probability distributions (Maes, et al., 1995).

One of the benefits of LSD is that infrequent severe loads that the casing should just survive if they occur will not create as high demands on the casing requirements. Thus some (Aadnøy, et al., 2009) suggest a combined approach where WSD is used for normal loads while LSD is used for infrequent survival-type loads.

The flow of LSD will look similar to Figure 1, but with changes to the calculation models and values used.

2.4 Load and Resistance Factor Design

Loading and resistance factor design (LFRD) is a middle ground between a full reliability-based design process and the earlier design processes. As a full reliability-based design process is a more intensive process, the relative ease of WSD or LSD is often desired. Thus, to include an assessment of uncertainty and make sound judgements based on acceptable failure probabilities, the LFRD approach aims to develop safety factors from a full probabilistic analysis. This provides a documented foundation for safety factors that are actually founded on the associated uncertainty.

Due to the difference in type of uncertainties associated with strength and loads respectively, both load factors and resistance factors are developed that are multiplied with the load and resistance respectively. The factors are associated with a casing population, usage distribution and design criteria.

This means that if a load $Q(\bar{x})$ adjusted with a relevant load factor L_f is less than the resistance to that load $R(\bar{x})$ adjusted with a relevant resistance factor R_f, for a set of deterministic parameters $\bar{x}$, then the probability of failure p is less than the target failure probability p^*:

$$L_f \times Q(\bar{x}) \leq R_f \times R(\bar{x}) \rightarrow p \leq p^*$$

2.5 Reliability-Based Design

Reliability-based design (RBD) aims to eliminate the need for safety factors by explicitly considering both the epistemic and aleatoric uncertainty related to the loads, material properties and models. This means that uncertainty, frequency of occurrence and variability of all characteristic variables that define load and strength are considered and represented by distributions (Aadnøy, et al., 2009). It is important to capture all failure mechanisms and understand the accuracy of the models and the data.

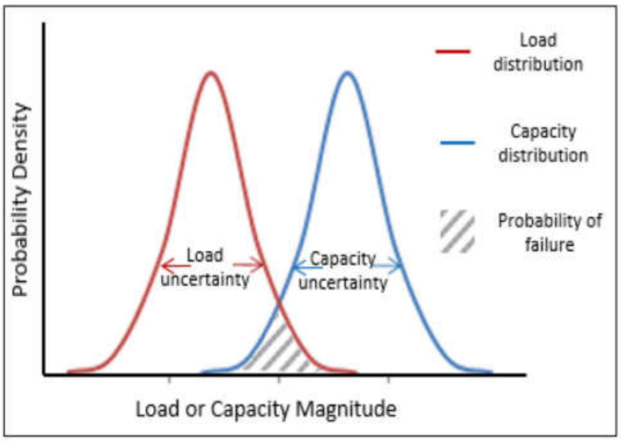

Figure 2. Reliability-based design result as exemplified by (Das, et al., 2018)

Designs are evaluated by comparing the resulting load distributions $Q(\bar{x})$ with the capacity distributions $R(\bar{x})$ to calculate a probability of failure P_f, which should be smaller than a target failure probability for the design to be accepted. This is illustrated in Figure 2 and can be written as

$$P_f = P[g(\bar{x}) < 0] \text{ where } g(\bar{x}) = R(\bar{x}) - Q(\bar{x})$$

The parameters $\bar{x}$ are here described by distributions instead of deterministic parameters.

The variables related to the casing, such as yield strength and thickness, are typically easy to translate into an appropriate distribution, as it is relevant to base these on measurements from samples of a manufactured population, such as the ones included in (ISO, 2018). Some variables must be represented differently, like sharp end imperfections which is typically represented by probability of presence and distribution of depth if present.

Variables related to the load are typically considered more difficult to quantify. There are many reasons for this, some of which are mentioned in (Aadnøy, et al., 2009). Any accidental load will, like sharp end imperfection, be best represented by a probability of occurrence with a corresponding distribution of the magnitude. The most severe loads are typically rare occurrences, partly due to all the efforts made to avoid them, and will therefore have very limited historical data. In addition, while each casing can to some extent be considered unique, they are for the most part considered part of a well-defined population. Each well, on the other hand, is often considered completely unique, living its own life based on operational practices and the environment it is drilled into, and therefore not suitable for using statistics in a frequentist' point of view. However, from a Bayesian point of view it is important to reflect the subjective knowledge one has about the loads. Both lack of data and representativeness of data can be overcome through modelling and statistical methods. However, it is clear that representing the strength of the casing is easier due to the possibility of using the same representation for multiple wells, while representing the load must be adapted to each well.

Due to the increased difficulty of quantifying distributions for load, it has been suggested (e.g. in (Suryanarayana, et al., 2016)) to use a distribution for the resistance to load but a deterministic worst case as load. While it is a valid shortcut to assess validity of the design, it is less suitable for fine-tuning acceptability of design or consider operational changes when performing the analysis as a quantitative risk analysis (QRA).

Because RBD uses probability distributions to represent properties, the complexity of the calculations is higher than for deterministic design approaches. Performing straight forward Monte Carlo-simulations is possible but will usually require a significant amount of calculation time to get useable results due to the small probabilities of failure investigated. As is explained in (Aadnøy, et al., 2009) and (ISO, 2018), an alternative is to use first order reliability methods (FORM) to get an analytical approximation for the main quantity of interest (failure probability). Another method is to do importance sampling to focus samples around the area of interest, as is explained in (Shayanfar, et al., 2017).

2.6 Discussion

Structural strength and design load is in (Fritz Lab, 1960) said to be based on six “limits of structural usefulness”: 1. Yield point strength, 2. Maximum (plastic) strength, 3. Large deflections, 4. Instability, 5. Brittle fracture and 6. Fatigue (Endurance limit). Of these, only 1, 4 and 6 are usually considered in WSD. LSD could be considered for all of them.

To compare the approaches to design it can be useful to divide aspects of design into parts:

- Intentional loads (Pressures and forces on casing that are unpreventable or chosen)
- Accidental loads (Pressures and forces on casing that one tries to prevent and thus has a low chance of occurring)
- Elastic limit (Casing strains not causing permanent deformation)
- Plastic limit (Casing strains causing permanent deformation)
- Manufacturing tolerances (Deviations from the planned manufactured casing, such as non-nominal thickness, eccentricity and sharp imperfections)
- Wear and corrosion (Reduction of casing properties over time due to environment)
- Acceptance criteria

WSD must satisfy intentional and accidental loads, requires the elastic limit to not be exceeded, and nominal tolerances (ISO, 2018). The safety factor is then meant to compensate for uncertainty in loads and tolerances, modelling error of the limit model and wear and corrosion if not included. LSD includes intentional and accidental loads, but with different safety factors. Accidental loads can exceed the yield point and endure some plastic deformation due to their rarity (casing should only survive, not be ready for next accidental load), while intentional loads should remain in the elastic region. Manufacturing tolerance and wear and corrosion are treated similarly. RBD will treat them as uncertain and try to model their stochastic properties.

If a complete reliability-based design process is used, the ability to limit certain loads can be included as part of the assessment and provide guidance on how to determine operating envelopes and which operations are critical to the survival of the casing. Thus, a reliability-based casing approach is recommended for new or difficult geothermal fields.

3 Consequences

The use of geothermal energy generally has a low environmental impact; exploitation of low temperature geothermal resources hardly ever has notable environmental effects. Most environmental impacts occur with the exploitation of high-temperature geothermal resources (see (Hunt, 2001)). This chapter will identify possible consequences for environment, health and safety, though it is important to remember that these impacts can be managed by proper site characterisation, selection and design of the geothermal facility in combination with proper inspection, maintenance and monitoring and preparation of corrective measures. Casing integrity is only one part in leakage prevention.

Information for this report section was acquired from selected references on geothermal energy in general and was than linked to possible consequences of failure of high- temperature geothermal wells in particular. Examples have been used from several regions in the world including North America, Australia and New Zealand, which are not necessarily representative for Europe in all cases. Future work should further clarify the relevance of the consequences described in this section for high-temperature geothermal energy production in Europe.

Two well failure modes are considered here, either collapse or burst of the casing. This may lead to the rupture of the casing and possible intrusion or extrusion of fluids. Depending on the state of the cement sheaths and other casings the fluids may migrate upwards along the well bore or laterally into permeable rocks or along fractures. Eventually the fluids may reach potable groundwater resources, soil, surface waters or the air.

3.1 Fluid pressure, temperature and phase change

Migration of high-temperature liquids and simultaneous lowering of the pressure may lead to phase changes by the creation of steam (flashing). The mobility of steam is much higher than that of water and consequently steam can enter smaller pores than water and moves much quicker along fractures (Hunt, 2001).

In rare instances hydrothermal eruptions may occur. When the steam pressure in very shallow aquifers would exceed the overlying lithostatic pressure, the overburden may breach, resulting in crater-like shapes at the earth's surface (Hunt, 2001).

The increased flow of heat may alter the quality of groundwater and surface waters and impact fish, birds and animal populations and vegetation. Changing temperature may have an effect on the dissolved matter in the groundwater.

3.2 Composition of produced fluids

Depending on the type of geothermal reservoir, the fluids can be acidic ($pH < 5$) and very saline to alkaline and very low salinity (Hunt, 2001). Most high temperature waters produced from geothermal reservoirs contain high concentrations of at least one of the following toxic chemicals: lithium, boron, arsenic, hydrogen sulphide, mercury and ammonia in some instances (Hunt, 2001).

It is prescribed that contact with groundwater will be avoided and wells are properly isolated so that fluids cannot enter these groundwater zones. A tank or pond is constructed which can hold any released liquids from the geothermal plant (Mannvit hf, 2013).

The predominant gases in high-temperature geothermal fields are CO_2 and H_2S; the concentrations strongly vary from site to site. Different exposure standards exist for these gases (Hunt, 2001). At low concentrations of about 0.3 ppm, hydrogen sulphide is recognizable by the odour of 'rotten eggs'. At concentrations greater than 150 ppm the characteristic smell has disappeared. Often this gas is re-injected (Mannvit hf, 2013).

Generally, CO_2 is the most abundant gas in geothermal fluids but it is not highly toxic. The amount of CO_2 emission from high-temperature geothermal power plants can be high, due to the high natural content of this gas. As capturing CO_2 is very costly, this type of gas separation is not commonly applied. In some cases, like in Turkey, the CO_2 is captured, cleaned and then used for producing soda water (Mannvit hf, 2013).

Geothermal gases may also contain ammonia (NH_3), traces of mercury and boron (B) vapour, and hydrocarbons like methane (CH_4). Boron, NH_3, and Hg may end up in the soil and vegetation or in the aquatic environment ((Hunt, 2001), (Webster, 1995)).

3.3 Incidents with high-temperature geothermal energy exploitation

Some examples of incidents with high-temperature geothermal projects have been documented. A few are mentioned here.

In June 1991 an uncontrolled release of steam occurred at a high-temperature drilling site on the Hawaiian island (Anderson, 1991). The blowout was stopped within 31 hours. Apparently, the drill bit hit a pocket of high-temperature and high-pressure water, which then rushed as steam to the surface. The blowout preventer did not work properly. With the steam also some H_2S escaped, which did not cause any illness.

In April 2009 the 4 km deep well Habanero-3 (Cooper Basin, South Australia) had a casing failure and steam started to escape from the well. The company Geodynamics was in the final stages of commissioning a one-MW EGS demo. The EGS was constructed in a 1,000 square kilometre slab of hot granite at about 4 km depth ((Holl, 2015) and (New Scientist, 2009)). Detailed investigation indicated that an air pocket was left between the rock formation and the casing due to an incomplete cement job (Budd, 2013). The casing contracted and expanded as a consequence of water cycled through the well leading to strain hardening and eventually failure of the steel.

In May 2012 a blowout incident happened while drilling a high-temperature geothermal well at Alasehir (Western Turkey). At a depth of about 1,000 m the well reached the high-temperature and high-pressure fluids which rose up through the well, which automatically triggered the closure of the wellhead preventer system. High-pressure fluids then migrated along the fault zone transecting the overburden and was ejected at the surface. The very high mineral content influenced the groundwater quality. Some substances like arsenic and boron exceeded the maximum concentration limits (Rabet, et al., 2017).

The Occupational Safety & Health Administration (OSHA) of the US Department of Labor reported a number of incidents with workers on (high-temperature) geothermal sites. In April 1996 a worker from Acme temporary Services received serious burns as hot water sprayed out during a well shut down for periodic cleaning. A consultant from a geothermal utility was exposed to a release of H_2S near the wellhead. He was revived with oxygen. In August 1994 an employee entered a manhole to rebuild a pressure reducing valve. He was exposed to H_2S levels of 8 ppm and had to recover from pneumonia.

3.4 Discussion

Possible consequences of high-temperature geothermal energy exploitation need to be properly evaluated in an impact assessment. This evaluation should be based on a thorough site characterisation as these geothermal sites are highly variable in geology, contained fluids and land use. These effects relate to the environment (soil, groundwater, surface water and air quality, flora and fauna), health and safety of workers and neighbouring population. Proper measures to avoid or reduce the possible impacts to an acceptable level need to be implemented, starting with the site selection itself, well design, safe production and injection schemes, inspection and maintenance, training and contingency measures.

4 Review of GeoWell developments

The partners in the GeoWell project have several developments which can impact the reliability of the casing in high temperature geothermal wells. This chapter gives a short description of them to give some background for what kind of improvements they can achieve. Note that some of the developments are patented or will be considered for further development and cannot be described in detail. Some of the reports are confidential to the consortium for the same reason.

4.1 Flexible coupling

Casing failures can be caused by excessive axial stresses due to temperature cycling in high temperature wells. Mitigation of this is investigated in other parts of the GeoWell project, developing a flexible coupling between casing elements. The purpose of the flexible coupling is to allow each casing element to expand axially into the coupling, keeping compression stresses below yield stresses. This way, the risk of reaching plasticity and collapse of the casing can be reduced (Kaldal, et al., 2016).

The flexible coupling is based on a design with a movable sled and two coupling segments that are connected with dowel pins. When inserted in the (cool) well, the coupling will be in an open position allowing for one of the casing ends to slide axially (due to thermal expansion) until the coupling reaches a closed position. The coupling is intended for the innermost casing, i.e. the production casing, and is not designed and intended to be a gas tight barrier. However, the tight fit between the sled and the coupling segment should ensure proper sealing capacity. In its closed mode, the flexible coupling is intended to protect the casing from plastic (permanent) deformation by forming a mechanical connection between the sled and one of the coupling segments.

Prototypes of the flexible coupling have been tested as part of the GeoWell project, mapping their mechanical performance during compressional/tensional loads, as well as leakage rates when pressurized. All tests performed so far are done at room temperature.

From a well integrity perspective, a flexible coupling operating according to its intention will improve the reliability of the production casing by protecting it from plastic deformation. However, the flexible coupling introduces failure modes different from those of a conventional casing coupling:

1) Additional possible leakage paths through e.g. the dowel pins
2) Flexible coupling failing to close (during heat-up)
3) Flexible coupling failing to open (during cool-down)

Cases 2) and 3) could be caused by malfunction or improper temperature requirements (too stiff or soft response to axial casing strain).

4.2 Cement formulation

Presence of residual water after hardening of the cement can impose a well integrity issue due to the risk of having water pockets between casing strings. As the well is heated, pressure increase caused by expanding water can ultimately lead to collapse of the production casing. WP3 of the GeoWell project deals with new cement formulations with reduced water content compared to conventional cement. Such technologies could be very suited for reducing the risk of water pockets, however, the density and viscosity of the achieved cement slurries could be challenging when it comes to placement of the cement in the well especially because of risk of fracturing the formation caused by excessive hydrostatic pressure. Studies of cement compositions and their implications in terms of placement of cement in the well are reported in (Heege, et al., 2019). Measures to reduce slurry densities have been proposed, e.g. by using hollow (micro) glass spheres. Viscosity of the slurry should be kept sufficiently low to ensure proper displacement properties. This can be achieved by using plasticizers etc. Further work is needed to ensure that relevant technologies for modifying density and viscosity are qualified for downhole applications. For instance, one should ensure that the hollow glass spheres used to modify density will survive batch mixing and pumping. In addition, one should evaluate the risk of glass spheres migrating in the annulus before cement is hardened (causing heterogenous cement quality).

4.3 Casing cladding

The GeoWell project has looked into possible use of material combinations such as cladding higher alloyed (higher cost) corrosion resistant materials on lower alloyed (lower cost) material in (Thorbjornsson, 2016). The cladded corrosion resistant material is in direct contact with the steam/brine but is only a thin layer on the base material of commonly used carbon steel which in turn is protected from the steam by the thin corrosion resistant layer. This material combination is ideal to optimize the corrosion resistance with respect to cost, to prevent galvanic corrosion between the high alloyed layer and the base material, and to avoid damaging effect of different thermal expansion coefficients for the thin layer and the base material.

Carbon steels/low alloy steels are durable materials in a geothermal context, but not suited for low-pH conditions and the presence of condensate on the material surface. Higher austenitic grade stainless steels are good candidates for T > 250°C steam conditions. Nickel-based alloys are robust to harsh environments, but even higher alloy types are subject prone to certain degrees of corrosion damage. Titanium alloys tested have concerns regarding narrow pitting and material strength at higher temperatures (>400°C), as well as low pH environments at temperatures >80°C.

Of the materials tested the N06625 based nickel alloy and the R52400 titanium alloy seem to be the least effected by corrosion. The austenitic stainless steel S31254 is a promising candidate material and performs well in the majority of the tests except in the heat exchanger experiment where intergranular stress corrosion cracking was observed.

Improvements in the integrity of the cladding material obviously improves the casing and coupling integrity as well. Using highlighted candidate materials as coating layers on casings and couplings will likely yield a reduced risk of corrosion, implying that the risk of material weakening is lower. Risks such as well contamination caused by the corrosion of the cladded element would also be lower.

4.4 Ductile layer

In order for the flexible connectors between casing elements to absorb axial expansion and contraction due to temperature variations in the well, it is essential that the casing can move smoothly relative to the cement sheath. However, in a properly cemented well section the bond between casing and cement is strong, causing the casing steel (with its much higher thermal expansion coefficient than the cement) to be locked in position. In this situation, debonding can ultimately occur, implying several well integrity risks:

1) Reduced well lifetime due to casing corrosion if the cement sheath does not provide sufficient protection against corrosive fluids
2) Establishment of a fluid migration path outside and along the casing
3) Increased mechanical loads on the casing string if it has not bonded properly to the cement

To gain effect of the flexible casing connector the friction forces between cement and casing should be sufficiently low. Development of a ductile intermediate layer could offer a solution to this and has been investigated in other parts of the GeoWell project (Vercauteren, et al., 2019). The intermediate layer material should fulfil certain requirements, such as being high temperature/high pressure resistant, environmentally friendly and low cost. The ductile layer must allow axial movement, assure zonal isolation and resist radial forces due to temperature cycling. The intermediate layer should allow a high-pressure resistance in the radial direction (normal to the casing/cement interface) and a low resistance to flow in the axial direction. This can be described as asymmetric frictional properties.

Friction tests were performed at TNO using samples of candidate materials. The geometrical setup was based on using a steel plate coated with intermediate layer on both sides and squeezed between concrete plates. The steel plate was displaced perpendicular to the loading force, replicating the casing movement while being radially loaded (with up to 24 MPa pressure) against the cement. Coefficient of friction values, being the ratio between friction force and normal force, were measured. Friction tests indicated that only a thin layer of ductile layer needs to be applied to obtain a low friction coefficient. Further tests are necessary to investigate the concept at relevant high-temperature conditions.

5 Model

To analyse the reliability changes of the technologies developed in the project, an analysis based on reliability-based casing design is performed. The analysis will only focus on the changes caused by the developments in the project. Due to the complexity involved with a full reliability-based casing design approach, several assumptions and limitations have been made. These are described first, before the implemented model meant to quantify the changes are described.

5.1 Assumptions

The work focuses on the changes caused by the technological developments in the GeoWell project, outlined in the previous chapter. These changes are predominantly a possibility of changed axial stress by implementing a flexible coupling, changed annulus pressure caused reduced water content in the new cement formulation, and reduced corrosion of casing by adding a corrosion resistant cladded material.

The sub-models used in the approach are selected based on availability; not for state-of-the-art accuracy. The objective is to provide a foundation for comparison, where the ability to estimate accurately is not as big concern as if the objective where to estimate the reliability for a specific well.

Plastic deformation is a greater concern for geothermal wells than traditional petroleum wells. While anything more advanced than working stress design should include plastic deformation, it is difficult to model collapse for plastic deformation and would normally require finite element modelling. The model includes plastic deformation in the axial considerations, but not for collapse. This is justified as tensile failure of the casing that occurs during cooldown, which coincides with a cooldown of the annulus and an associated equalization of pressure between the inside and outside of the casing. Consequently, only the axial forces are considered relevant, though this may not be true during transient conditions or high formation pressures. During production temperatures, any plastic deformation in radial direction will be considered a failure due to the narrowing of the flow area. While a decision should consider the consequences of the severity of this through an acceptable deformation, it is in this model set to zero.

The new technologies developed are assumed to have been tested in in-situ environment (temperature etc.) with results consistent to those obtained at low temperatures in the lab tests performed in the project.

5.2 Description

The model developed to quantify the life of a casing is based mainly on the equations in (ISO, 2018), following the suggestions in (Standards New Zealand, 2015) to make it suitable for geothermal purposes. The model is a simulator attempted illustrated in the figure below.

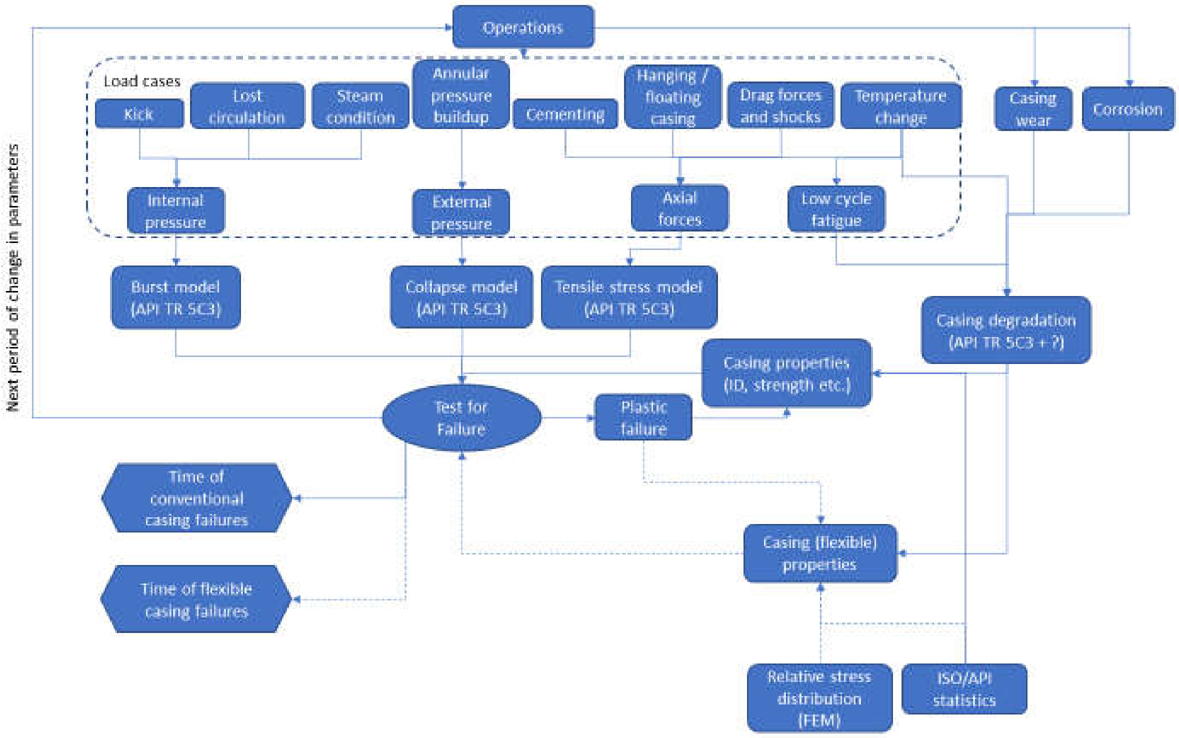

Figure 3. Flow schematic of a reliability-based casing design simulator

The simulation consists of running through different conditions and processes a casing may be subjected to through its service life. For each time step of the simulation, processes degrading the casing and any change in load condition is quantified and used to change the casing properties and check it for failure. The check for failure is performed for regular casing and casing using flexible coupling to log the differences. Aspects not considered changed by the developments in the GeoWell project have been omitted. The individual parts of the model are in the remainder of this chapter briefly discussed, and their source referenced.

5.2.1 Operations

The operations describe what can happen (in terms of load cases and degradation) at different stages of the service life of the casing, from it is installed until it either fails or is no longer needed (abandonment).

The life of the casing begins by being run into the hole (suspended given buoyancy by liquid in the well). Depending on the buoyancy, this is either a compressive or tensile effect. If the running of the casing suddenly stops, the shock will contribute with a predominantly added tensile effect if the stop is with the casing suspended freely, or as an added compressive effect if movement was restricted at shoe downhole (e.g. hitting bottom). When running casing the same fluid is assumed on the outside as the inside. The temperature during this stage will be in a cooled well.

With the casing at bottom, it will be cemented in place. As described in (Standards New Zealand, 2015) this will create loads as the cement is inside the casing, and when setting it outside the casing. These loads stem from the increased internal and external pressure caused by hydrostatic difference (and friction while pumping). The casing will also experience axial forces from the difference in pressure, as well as possible added tension from surface.

Depending on the well, drilling may continue after the casing is set. Several unwanted situations may occur during drilling, such as heavy fluid losses causing loss of hydrostatic column or influxes of gas that may be shut in, giving a high pressure in the wellbore. Apart from these situations, regular drilling will maintain circulation and cooling of the well. The pressure will be a hydrostatic column along with friction from the circulation. When drilling inside the casing in deviated wells, the drillstring may also grind against the casing wall causing wear to the casing that reduces the casing thickness.

When the well is ready for production the wellbore will go from relatively cool to production temperatures.

During regular production, there are no significant changes in the system. The only changes are time dependent processes such as corrosion, erosion and relaxation processes that change the properties of the casing.

On some occasions during production there will be a need or desire for interventions. The type of intervention method decides the change in the well. It is recommended to minimize the temperature reduction (Standards New Zealand, 2015) to make the load cases as small as possible, but often it would be needed to quench the well. This temperature reduction and subsequent temperature increase as production resumes will cause changes to the axial load cases.

5.2.2 Degradation models

Degradation of the casing is mostly driven by corrosion or erosion (wear). Corrosion typically occurs during production of reactive fluids, while wear is mostly considered when doing work inside the casing. Degradation during production is included as a constant change in wall thickness over time. This means that the corroding effect is considered as uniform corrosion/erosion, and not pitting corrosion which would be more like local deep imperfections.

5.2.3 Physics models

To calculate the pressures and loads, some simple models for the pressures and temperatures are needed.

The fluid model used is a simple Newtonian steady state calculation with a PVT model with constant density change in both pressure and temperature. The properties can be different depending on which phase the fluid is in. The model is used to calculate hydrostatic and flowing fluid pressures.

The steady state temperature model is simple with constant temperature losses in the flow, whether when pumped from surface or produced from reservoir. Transient effects are not considered.

5.2.4 Strength models

The resistance of the casing to withstand loads are based on the recommendations in the New Zealand Code of Practice 2403:2015 (Standards New Zealand, 2015). There it is recommended to use API TR 5C3 (equivalent to ISO 10400 (ISO, 2018)) to calculate axial strength, internal pressure resistance and collapse resistance adjusted for temperature, corrosion, erosion, wear and potential casing damage. For thermal yield, then (CAPP DACC, 2012) is suggested used as a basis.

While (ISO, 2018) includes several equations for calculating strength, they have also compared the performance of the different equations to experimental data resulting in recommendations for which equations perform better and some data on how well they perform. The recommendations have been followed in the model, and the estimated accuracy of the equation has been used.

6 Results

The objective of the results produced in this section is to compare the change in reliability of the casing the new technologies developed in the GeoWell project are likely to produce compared to current solutions, primarily the flexible coupling. Therefore, there will be no attempt to create accurate cases or create reliability numbers for future use. The numbers produced are to be relative to each other, and not interpreted in absolute value.

6.1 Scenario description

The scenarios used to analyze how the technologies developed in the GeoWell project contribute to improvement in reliability are described in this section.

Wells under consideration are deep high temperature geothermal wells, by which a depth of more than 1 km depth and a temperature above 200 °C is meant (Kaldal, et al., 2016). In all scenarios the wells are considered vertical. The produced fluid is water with possible contaminants.

Properties of casing are assumed as in published data, with material and manufacturing variability as in the tables in (ISO, 2018), temperature effect on yield strength as a combination of data in (Standards New Zealand, 2015) and experiments in GeoWell (TNO, 2018). Due to the generic form of the analysis, the ensemble values in (ISO, 2018) are used instead of a specific distribution based on a uniform population of casings.

The yield point of the casing material is assumed to follow the reduction factor given in (Standards New Zealand, 2015) and (TNO, 2018) for temperature. It should be noted that the values given in the New Zealand code of practice refers to a 5% uncertainty in their values based on the sources they have used, but that the values are conservative (meaning they should be in the low end of the population). The results from TNO are just below these values, and the combined data should be used to give a better description of the uncertainty in strength temperature. However, in the model this has been treated as a deterministic reduction factor.

To evaluate the change in reliability between casing with regular connections and one with the flexible coupling, the following results will be used:

- Stress difference when flexible coupling is stuck in position.
- Stress difference when flexible coupling is working as intended.
- Stress difference when flexible coupling becomes stuck in closed position

Finally, a simulation through example lifetimes of the flexible coupling will be provided to illustrate reliability-based casing design. This is exemplified on a well with 60 °C temperature during drilling and cementing, and 260 °C during production. The working and produced fluids are water, while the cement slurry has a density of 1700 kg/m^3. The casing is 1500 m long with connections every 12 m.

The importance of cladding material on casing reliability is illustrated by considering the case where corrosion is removed due to the cladding material protecting the casing. Note that the effect of the cladding material itself on stresses is not considered. The rate of corrosion per year is set to a triangular distribution with a minimum value of 0, most likely 0.1 mm based on value reported in (Thorbjornsson, 2016) and a high maximum of 3 mm based on a worst case value reported in (Petrowiki).

Interventions that require quenching the well down to working temperature follows a stochastic process that on average require 5 interventions over 20 years.

6.2 Simulations

The first simulation illustrates the compressive forces after a temperature increase in a free-moving regular casing where the connections are anchored in the cement preventing any axial movement of each casing segment. Based on elastic theory, this creates axial stress calculated as $\sigma_T = \alpha \Delta T E$ where α is the thermal expansion coefficient, ΔT is the temperature change and E is Young's modulus for the material. This is compared to the yield strength of such a casing. The yield strength is shown with uncertainty percentiles based on a probabilistic description of a new casing as described in (ISO, 2018), and including the reduction in material yield strength based on temperature based on (Standards New Zealand, 2015) and (TNO, 2018). According to (Kaldal, et al., 2016), 200 – 350 °C changes in wellbore temperature are not unexpected in high temperature geothermal wells. The flexible coupling will start to close as the stress reached 70% of the nominal yield stress of the casing and allows for up to 20 mm elongation to keep the stress at that level.

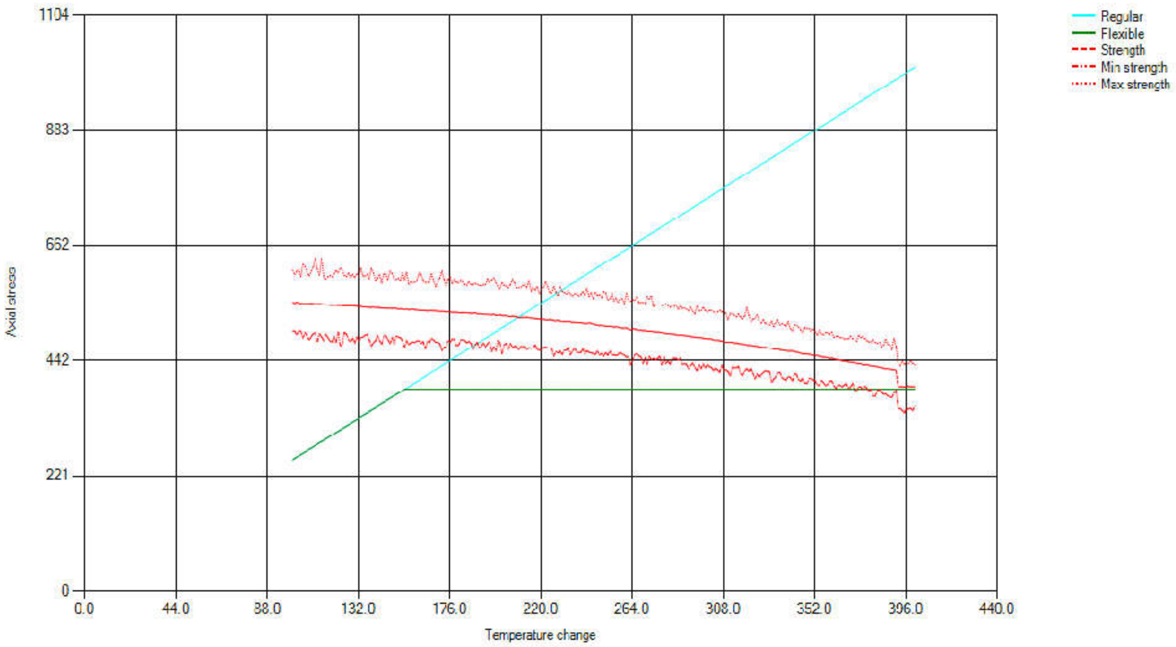

Figure 4. Axial stress versus temperature change from a 60 °C initial well temperature based on elastic theory.

From Figure 4 it is clear that with the flexible coupling working as intended, the temperature expansion will not cause the casing to go into yield as early as a conventional coupling would. However, even then the casing may reach yield stress due to uncertainty related to actual casing yield strength and change in properties with temperature. Casings that are cemented in tension, as is a common practice in high temperature wells (Standards New Zealand, 2015), will allow the curves to be shifted down by initial tension.

A simulation was also run using the complete model described in Chapter 5. It simulates what happens with an L80 casing over 25 years based on the scenario description given in Section 6.1. The number of failures that occurred during the simulation are shown as a function of time in Figure 5.

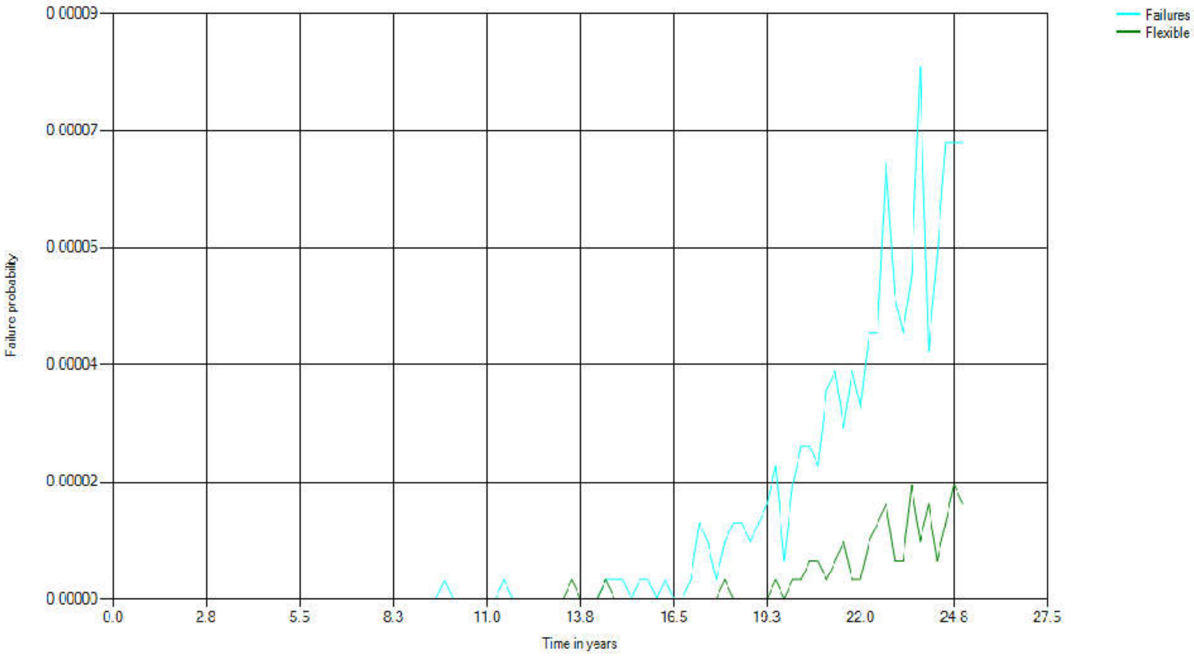

Figure 5. Time of failure for the casing over a 25 year period using conventional or flexible coupling

This gives a total failure probability of around 0.10 % for the service life of the casing, while a functioning casing with flexible couplings are estimated to 0.02 %. A flexible coupling has in this simulation contributed to a substantial improvement in reliability. As mentioned before, these values are not intended to reflect any actual well, but rather serve to show how reliability-based casing design can analyse the gain in reliability by new technologies. A representative case can be performed when more relevant data are available.

7 Discussion

A reliability-based design model has been used in the investigation of what reliability improvements technology developments can provide. Although the model is based on established equations used in petroleum activities, there are many effects specifically related to temperature that has not been covered to the extent it may deserve. While a significant sample size exists for the yield strength of many types of casing materials at low temperatures, the published data for high temperature is significantly lower. Temperature has an increased effect on many other parameters as well, such as Young's modulus. It should therefore be kept in mind that some aspects of the model related to temperature are based on a weak foundation.

The flexible coupling under development at ÍSOR as published in (Kaldal, et al., 2016) has been further developed in the GeoWell project as discussed in Section 4.1. The technology aims at increasing the reliability of production casings in high temperature geothermal wells, where thermal expansion of casing is a particular cause for concern. The idea is that the coupling shall absorb some of the thermal expansion before it goes beyond the yield point and into plastic deformation. Considering such a technology using working stress design or even limit stress design is not well suited for analysing such an idea. The transition from a safe design to an unsafe design will not be smooth due to how the absorption mechanism works. A deterministic study will then be either safe or unsafe, while uncertainty in the casing properties could give greater chance of failure or lower chance of failure than intended from the safety factors. The technology has therefore been considered using reliability-based design approaches.

The flexible coupling is a new technology which will undergo further testing until it is qualified. Tests performed in the GeoWell project have not revealed any showstoppers or surprising failure modes, but there are often surprises with new technologies making it useful to consider some possible unintended performance issues.

Based on typical failure modes for active equipment, it is conceivable that a flexible coupling instead of moving with the thermal expansion of the casing can become stuck in place. One scenario for getting stuck would be in an open position where any thermal expansion will not cause the flexible coupling to move, making it as rigid as a regular coupling. Disregarding differences in manufacturing etc. due to being a less proven technology, the scenario would then imply that the flexible coupling behaves as any other coupling.

Another scenario would be that the flexible coupling initially functions as intended and absorb the thermal expansion beyond a certain percentage of the yield strength. However, staying in this high temperature condition during production might have some unintended effects where it gets stuck in this position, preventing the movement back to the initial position when the well is cooled. This means that, similar to plastic deformation through compression as described in (Kaldal, et al., 2016), the casing segment will have less length to return to through elastic strain. What is worst of plastic deformation and allowed expansion depends on the amount of free movement allowed by the flexible coupling, what stress is constrained before movement in the flexible coupling occurs, and how the material responds in the area of plastic deformation.

While the scenarios discussed here “might” be possible, there has been no evidence indicating that they can occur or how likely this may be. The simulations performed for these scenarios indicate that for the most part the flexible coupling would perform at least as good as a conventional coupling related to the casing failures described in (Teodoriu, 2015). However, it should be noted that this assumes the same principles are used. If a casing would normally be cemented with tension to reduce compression during warm-up, but this is not done using the flexible coupling due to its ability to absorb compressional forces, a situation where the casing is prevented from expanding will result in much earlier yield failure than for the conventional case.

Leakage has not been considered in this report, but some leakage has been found in the experiments performed with the flexible coupling. Leakage through damaged threads is a common problem if procedures for making up the connection are not followed or are incorrect. The flexible coupling as described in the GeoWell project is not restricted to specific types of threads and these types of failure will therefore not change from a conventional setup. Other leakage related to the dowel pins have been observed in the test, but further development of the flexible coupling will hopefully eliminate this problem.

while allowing the casing to expand axially. The layer will add some friction to the axial movement compared to free movement that will increase the amount of stress absorbed in the casing before the flexible coupling will start to move, due to some of the axial force being absorbed by the friction. This might mean that the flexible coupling will not start to absorb the axial expansion before a stress equal to a higher percentage of the nominal yield strength than intended has been reached. Related to Figure 4, this would compare to a delayed bend on the green line, causing a much greater likelihood of going into yield. However, it is natural to believe that the friction will be less than that caused by cement-casing bond, or by using a conventional coupling. As discussed before, this will have a potential to cause failures due to the inherent uncertainty in casing properties, depending at what stress level the coupling is set to initiate movement.

Axial thermal expansion is not the only challenge for casings in high temperature geothermal wells discussed in the GeoWell project. As mentioned in Section 4.3, corrosion can be a major problem in these wells, making the casing deteriorate quickly. To achieve a longer service life of the casing it is therefore relevant to combine the use of the flexible coupling with cladding materials that prevents direct exposure of the more easily corroded casing material. The intended effect of cladding materials is a reduction in corrosion rate on the casing resulting in increased service life. Introducing cladding material can on the other hand introduce new undesirable consequences as discussed in 4.3. How it will work together with the flexible coupling is also an unknown, as it might have both negative and positive effects when used together.

Collapse is usually considered the most relevant casing failure in oil and gas wells due to the lower resistance against casing collapse. During production, the load conditions in these wells, as described in e.g. (ISO, 2018) and (Norwegian petroleum industry, 2013), usually considers influx or heating of the annular fluid volume. In geothermal wells, the annular volume is usually filled with cement, but as mentioned in Section 4.2 water in the cement can cause high pressures that can collapse the casing. The effect of reducing the water content will not be discussed in quantitative terms as a model for relating cement water content to existence and size of water pockets is lacking. Developing low water content cement is difficult as it is easy to have to compromise other desirable cement properties, such as density and viscosity required for easily placing the cement. A high density and viscosity cement also put an increased outer load on the casing during cementing, which may give an early collapse in the casing. Introducing new materials to the cement as replacement for water also introduces uncertainties in how the cement will react when pumped; and will require significant study.

A reliability-based design is usually based on achieving a design with a probability of failure less than a certain predetermined value. A recommended value from (ISO, 2018) is 0.005, or 0.5% probability of failure, though there is no justification provided. From a risk-based perspective, it can be useful to consider what is an acceptable design based on the consequences of any failures. In Chapter 3 some of the HSE consequences of leakage from a well have been discussed. If these consequences can be avoided, the question of casing design can be more directly related to an economic question. The economic value of introducing new technologies, such as the flexible coupling, or better materials, such as casing of higher grade, can then be directly compared to the economic cost of work and lost production from well failures. Such an evaluation has not been performed here but is a possible suggestion for further work.

8 Suggestions for future development

The model used in this work has not been validated, as only the sub-models have been checked with published examples to verify their implementation. Further work to properly assess distributions used and verification against tests and field data, such as those referred to in (Lohne, et al., 2016).

It is clear from the results that the stress level required before the flexible coupling starts movement and the length of the movement are important design parameters. Optimal choices will depend on the conditions it will be used in as well as the materials used. A more complete reliability-based process should be developed specifically for evaluating these as the coupling gets closer to commercial use.

The “identified” possible failure scenarios for the flexible coupling mechanism needs a better foundation to determine if they are realistic threats or just pessimistic constructs. More detailed work on how such a technology can fail to function as intended (while it may still outperform conventional counterparts) could introduce new scenarios. Work on what conditions could result in such failures to function would be needed to determine if they are possible threats and how it can be determined how likely they are.

Evaluating different cement formulations with a focus on water content causing collapse has not been performed to a degree where the effect of the cement formulation can be reflected in its impact on casing reliability. How cementing simulators can be used to quantify what happens with the water content in the cement could be an interesting area of study.

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