Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Casing Construction for Supercritical Geothermal Power Plant - HotCaSe

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Keywords: HotCaSe, casing system, design, simulation, testing, supercritical, geothermal

ABSTRACT

In geothermal energy, a huge potential lies in hydrothermal reservoirs where ultra-high temperature fluid (400-500 degrees Celcius) can be utilized to multiply the power production output. However, the aggressive fluids and high temperatures encountered in these geothermal reservoirs are tough challenges for any materials and structures to sustain during the operation lifetime of at least 20 years. Improper materials selection and design principles may lead to serious failure events, and loss of the production well. The present paper discussed HotCaSe project, initiated and led by Equinor, with the main objective to solve the challenges related to the well construction for enabling high enthalpy (>2900kJ/kg) hydrothermal power production. At the initiation of the project, a three-day workshop, gathering personnel resources from the involved companies, R&D institutions and other national/international experts, was organized to freely scout for innovative solutions for cost-effective and reliable casing systems. To efficiently screening out the optimal solutions, preliminary modules of a design tool were developed to study the mechanical response in the casing systems under thermal loadings. The tool is currently used to evaluate the identified casing alternatives, by exploring combinations of mainly pre-existing technologies. The functional and mechanical performance of selected well completions solutions will be tested and verified, both in physical laboratory, numerical simulations with help of data computers and field testing. The successful HotCaSe project is going to contribute to access a new dimension in geothermal energy utilization, thus having a significant impact on both society and environment.

1. INTRODUCTION

Geothermal energy is today recognized as a weather independent and stable energy source with significant potential compared to other resources like hydropower, wind, and solar energy. Geothermal energy has high initial cost related to exploration and reservoir mapping and thereby high upfront risk. Even so, successful geothermal projects have lower levelized cost of electricity (LCOE) than some solar and wind energy projects. The LCOE of geothermal energy can be even lowered by hunting and harvesting geothermal power from hydrothermal HT reservoirs by producing supercritical fluid (reservoir temperature about 450-550°C and pressure up to 300 bars). In this condition, the geothermal fluid has a much higher energy (enthalpy) than steam and liquid extracted with conventional geothermal wells, thus potentially multiplying the electricity output by a factor of 5 to 10 and hence lowering LCOE of geothermal projects.

However, the aggressive fluids and high temperatures encountered in these geothermal reservoirs are tough challenges for any materials and structures to maintain their integrity during the operation lifetime of at least 20 years. The casing system, which is a composite structure with a steel casing and cement sheath on its outside, needs to be designed to protect the integrity of the geothermal well, and protecting the shallow environment against contamination, under the expected harsh conditions. Low-cost and robust casing systems are an absolute requirement for any geothermal well to lower LCOE. However, it is a tough challenge to achieve, especially for the super HT condition. Experiences have shown that the casing system may fail by a) mechanical buckling, b) tensile failure (in threaded connection or cross section), c) hydrogen embrittlement, and d) corrosion, see Figure 1 for illustration. In other words, improper materials selection and design principles may lead to serious failure events and potential loss of the production well [James Southon (2005), Kruszewski and Wittig (2017)].

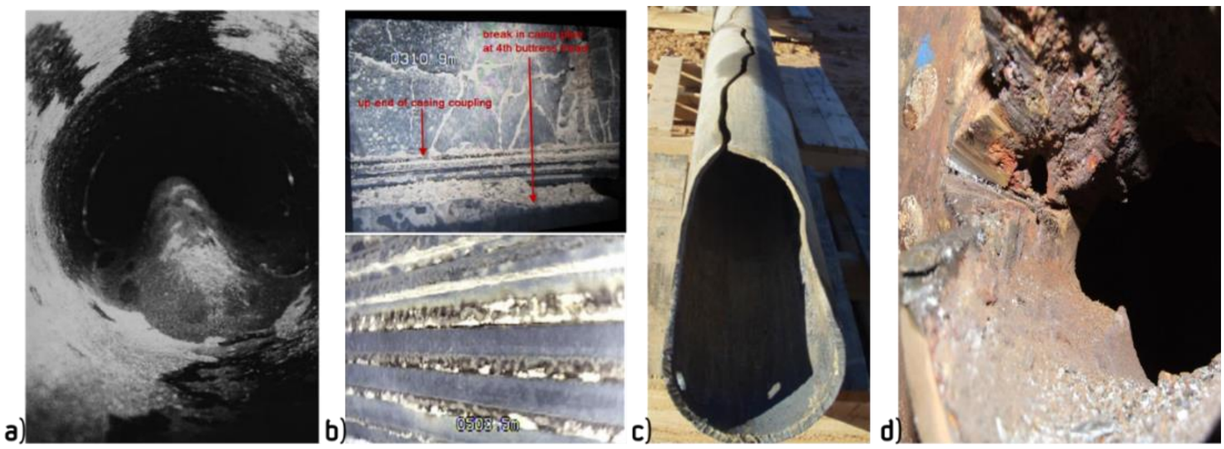

Figure 1: Failure modes in casing: a) Casing implosion/buckling, b) Tensile failure in threaded pipe joint, c) Hydrogen embrittlement and d) Corrosion

The challenges to achieve robust casing construction for supercritical geothermal power plant are mostly related to material technologies (to develop and qualify casing and sealant materials working in such conditions) and to the lack of standards regulating the geothermal well design practices for such super high operation temperature. Assuming an initial temperature of about 100ºC in the well (when cement is set), the casing will experience a temperature change of 400ºC when operated at 500ºC. In case of ideal conditions for the conventional geothermal rigid casing system (i.e., the well annulus is cemented all the way up to surface, and the casing is bonded and anchored to cement) where no axial displacement of casing is assumed, it follows that the total axial deformation of the casing is negligible, meaning:

$$\varepsilon_T + \varepsilon_e + \varepsilon_p = 0 \quad (1)$$

where ε_T is thermal deformation induced by temperature change and ε_e, ε_p are possible elastic and plastic deformation in casing.

With a typical thermal expansion coefficient of about $1.2E^{-5}(1/K)$ for casing materials, at a change of 400ºC in temperature, the casing will experience a thermal deformation of about $\varepsilon_T = 1.2E^{-5}.400 = 4.8\ (mm/m)$. Under such significant thermal deformation, the elastic and plastic deformation will be developed in the opposite direction to the thermal deformation in order to maintain the total deformation negligible with API casing grades. NZS 2403 (Standards New Zealand, NZS 2403:2015), the most commonly used reference for geothermal well design, refers both to working stress (or elastic) design and post-yield (or strain-based plastic) design as applicable design methods. Unfortunately, few details are provided for post-yield design, where the casing is deformed plastically as for the supercritical geothermal well at hands.

In order to solve these challenges, HotCaSe project was initiated with primary objective to develop cost-effective casing system concept to TRL 4, which sustains its integrity under the supercritical geofluid conditions (400°C-500°C, H2S and CO2 environments) during its service lifetime (20 years). This present paper will discuss the R&D activities addressed in the project, which are deemed crucial to achieve the sustainable construction for supercritical geothermal power plants. The design tool was developed for efficiently screening and evaluating the technological viability of the alternative casing construction solutions. The overall structure of the design tool will be presented, discussing the main ingredients and the important well physics to be implemented for reliable geothermal well design at super HT.

2. HOTCASE PROJECT AND R&D ACTIVITIES

HotCaSe is a four-year project (from 2017 to 2021), led by Equinor (Norway) and backed up by the Research Council of Norway (ENERGIX Programme) together with national and international industries & research partners (Norway, Iceland, and France). One of the main objectives of HotCaSe project is to explore potential casing system design solution to prevent/minimize the risk to the observed casing failures, as seen in Figure 1.

As discussed, the design conditions for a super-HPHT casing system are a tough challenge. In order to arrive to a robust casing construction, novel solution strategies other than the conventional geothermal construction are probably required. Developing these strategies will require the collaboration of a number of industrial and R&D actors who together provide an understanding of the complex challenges, and sufficient research and innovation capability. In order to evaluate the technological viability of the alternative design solutions, systematic research combining experimental tests, numerical model development and design tools are needed. The research activities in the project are thus planned to be carried out in four coupled Work Packages (WP) as illustrated in following Figure 2: WP1: Mechanical characterization and constitutive modelling, WP2: Durability of materials, WP3: Casing system concept development and design tools, WP4: Verification and demonstration.

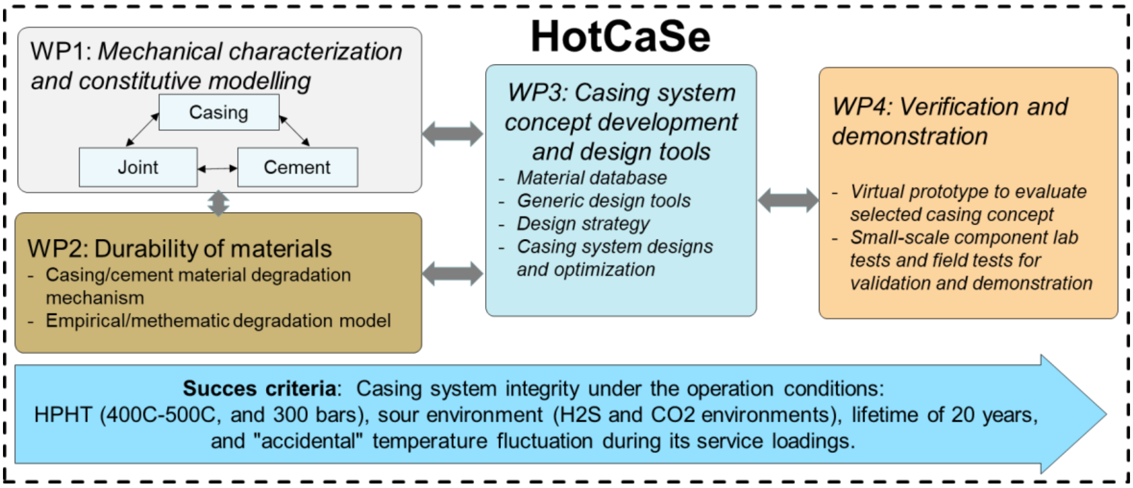

Figure 2. Project R&D activities organization.

The main R&D activities in WP3 are dedicated 1) to identify an array of alternative solution strategies for super-HPHT casing systems and 2) to establish design tools for efficient screening and evaluation of the technological viability of the alternative systems.

The experimental works are planned in WP1 to understand the performance of as-received materials and material combinations (casing, cement, coupling) in relevant environmental conditions (HPHP). The durability and long-term performance of these elementary components which are exposed to geothermal service conditions (Thermal ageing, creep, corrosion) are investigated in WP2. The outputs from WP1 and WP2 will serve as inputs for design tool and numerical model developed in WP3 to assess the system performance in simulated field conditions and, further, for technological evaluation of the various design solutions. It is to be noted that the project is not developing new material solutions for casing and cements, but rather rely on the commercially available technologies and in-kind industrial research to realize the innovative concepts.

The casing alternatives identified in WP3 will be evaluated by exploring combinations of mainly pre-existing technologies. The functional and mechanical performance of selected well completions solutions will be tested and verified under relevant HT conditions, both in physical laboratory, numerical simulations with help of data computers and field testing in WP4. The successful HotCaSe project is going to contribute to access a new dimension in geothermal energy utilization, thus having a significant impact on both society and environment [Patrick Dobson et al. (2017)].

3. CASING SYSTEMS CONCEPTS

The tough challenges imposed by the operation conditions of supercritical geothermal plants requires new and innovative solutions. At the initiation of the project, a three-day workshop, gathering personnel resources from the involved companies, R&D institutions and other national/international experts, was organized to freely scout for innovative solutions for cost-effective and reliable casing systems. Some possible well architectures as the result of the workshop are summarized and illustrated in Figure 3.

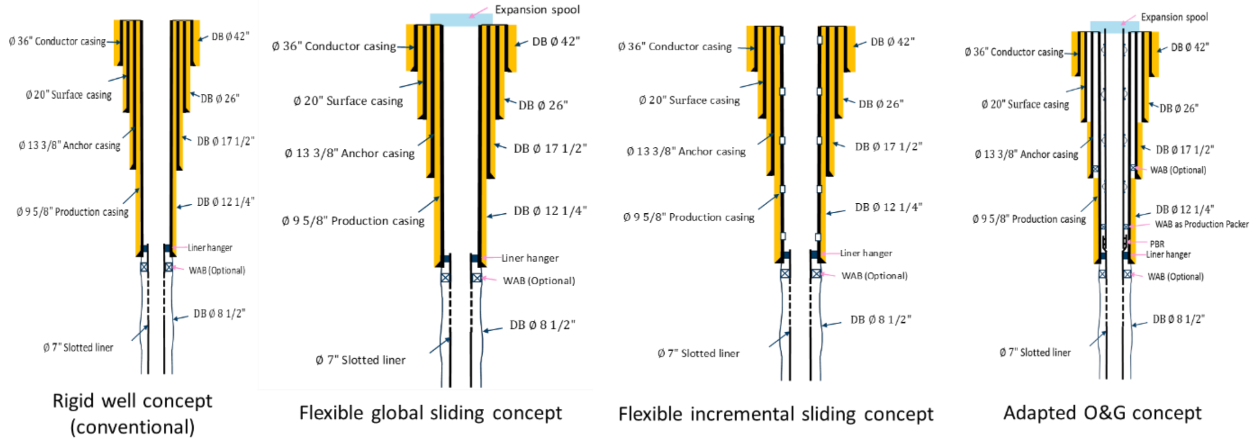

Figure 3: Possible casing system design for super-HT/supercritical geothermal wells.

Rigid well concept: Rigid casing system concept is regarded as the conventional casing construction for geothermal wells. The main idea of this well design is to allow only for negligible displacement of the casing under thermo-mechanical loadings during operations. In this concept, anchor casing/production casing are cemented all the annuli, slotted liner is used in the production section as illustrated in Figure 3. In addition, excellent bonding characteristics at casing/cement and cement/formation interfaces are required to constraint displacement of casing under temperature change. The conventional concept has experienced numbers of failure in axial tensile or local implosion collapse in the past, as seen in Figure 1. Several measurements can be envisaged to address these to failure modes in the casing concept. However, any significant improvement of the conventional concept to sustain the high temperature loading conditions will be dependent mostly on the advance in material technologies, e.g. development of casing materials with low elastic Young's modulus, low thermal expansion, and sealant materials with significantly low Young modulus. Reducing the cement Young modulus leads to a significantly decrease in the contact pressure and hoop stress in the casing, thus minimizing the risk of the casing collapse. On the other hand, low Young modulus sealant solutions will not help to have an elastic design. For the operation temperature at hands (i.e. 500C), standard API grades will deform plastically since the thermal stress exceeds their yield stress. Finding a commercial casing material with lower thermal expansion and Young's modulus than the carbon steels may be more reasonable, but eventually more expensive. Titanium alloys offer such possibilities, with about half Young's modulus and 67% thermal expansion in comparison with the carbon steels. Recently, TIMET (PCC Metal Groups) have developed a new grade of Titanium alloy, which exhibits a corrosion performance for geothermal applications and is reachable from economical point of view [MacDonald and Grauman (2019)]. However, the performance of these alloys in super-HT (up to 500C) and supercritical geofluid conditions is yet to be verified.

Flexible global sliding concept: In contrary to the rigid well construction, the main idea of this concept is to allow the production casing to "freely" deform in the axial direction (i.e., along the well depth) during the well heat up, thus minimizing the axial thermal stress developed in the casing. The upward thermal displacement of casing is then to be accommodated by expansion spool and/or a telescopic/expansion joint on surface. However, the casing is not "totally" free. The expansion in the axial direction of the latter is hindered by the self-weight and the friction at casing/cement interface during the well heat-up, thus compressive thermal stress will be developed in the casing to a point where friction is overcome. The feasibility of this global sliding concept is mostly dependent on the capacity of the casing to win over the resisting friction force and its self-weight to grow up to the surface. To favor the casing sliding, a low friction coefficient at the casing/cement interface is desired. The ductile layer solutions as developed in EU-GEOWELL project [Ragnarsson et al. (2018)] can offer such possibilities where a theoretical friction coefficient value $\mu = 0.1$ can be expected. In addition, the casing segment joints need to be flush, e.g., flush couplings (for example Tenaris Blue-Near Flush, or welded pipe connections). The reason is to avoid anchoring points in the cement which prevent the expansion of casing in the axial direction. When the well is cooled down, the casing shrinks, resulting in a "gap" between casing and cement. Hence, the casing will then be free to contract, and tensile thermal stress is eliminated. As the result of "free expansion", a well head with expansion spool or telescopic joints which can accommodate about 15m-20m of thermal axial downward shrinkage of the casing is required.

Flexible incremental sliding concept: Similar to the flexible global sliding, the idea behind the present concept is to minimize the risk of tensile failure by allowing the temperature induced expansion/contraction of the production casing to take place. This also requires a low friction coefficient at the casing/cement interface. However, contrary to the global sliding concept, the incremental sliding of casing segments relies on the local sliding of each individual casing segment, and the axial thermal expansion is to be accommodated incrementally using flexible joints, instead of the conventional couplings.

The benefits of this concept for the casing's axial sliding are twofold: 1) reducing the contact surface from thousand-meter length of the casing to 12m long casing segments and 2) eliminating the effect of the self-weight of the above pipe section on each casing segment.

Adapted O&G concept: This concept is based on the conventional O&G well constructions. In this presented concept, the annulus between the production casing and the anchor casing are not cemented all the way from the casing shoe to the surface. Only the segment from the production casing shoe to anchor casing shoe is cemented. The main differences between this concept and the conventional O&G well completion is:

- The drilling fluid needs to be displaced from the annuli, which is not cemented, to avoid pressure build-up when heating the well. Alternatively, it needs to have possibility to bleed off at the wellhead.
- The production tubing is free to expand. The upwards displacement directly induced by temperature of the tubing and production casing are taken up by an expansion spool and/or a telescopic/expansion joint on surface. The expansion/telescopic joint, should be able to accommodate up to 15-20m of casing expansion, and work properly at temperatures up to 500C.

It is to be noted that each of envisaged well concepts represent both advantages and drawbacks. An initial evaluation of these concepts has shown that there exists no optimal solution to solve all the present challenges in supercritical geothermal well construction in a both cost-efficient and reliable way. The optimal solution may consist of hybrid elements from different concepts. The developed design tool is then crucial to efficiently evaluate the identified casing alternatives, by exploring combinations of mainly pre-existing technologies.

4. DESIGN TOOLS

HotCaSe design tool, Casinteg, is developed to assess the mechanical integrity of casing structure by studying its mechanical response under thermal loadings, which is complementary to the project partner CURISTEC software that has a focus on the cement integrity. However, the degree of physic mechanisms accounted for in the two software is equally complex, and the cement material properties in HotCaSe software should be properly described in order to represent a reasonable boundary condition around the casing. In that regard, the residual stresses in cement/casing after hydration and curing process are of importance to be considered in the casing integrity evaluation. The commercial software, e.g., CurisIntegrity, can provide these inputs as initial conditions for Casinteg models.

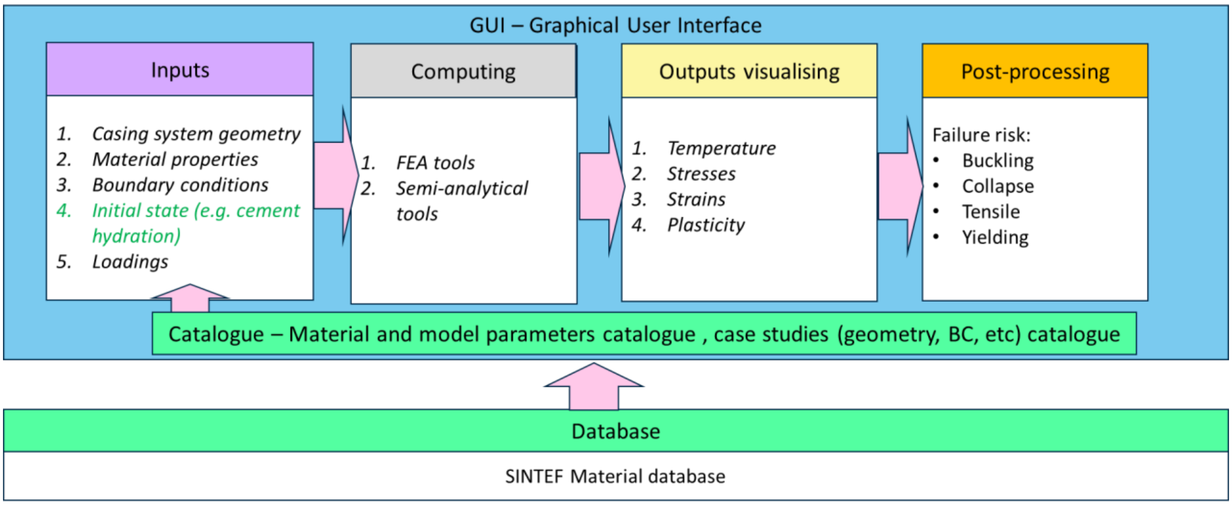

Figure 4: Preliminary design tool - Casinteg structure

The preliminary design tool architecture was proposed as illustrated in Figure 4. This structure reflects that the essence of Casinteg constitutes of different modules, namely Database/catalogue, Inputs, Computing, Output, and Post-processing. A smooth connection and workflow between different modules will be ensured by a GUI platform: 1) Creation of Input files based on the data extracted from Database catalogue, 2) Running calculations modules with created input files, 3) Visualization of calculated results, 4) Post-processing stresses/strains in the casings and analyzing the risks for failure based on selected design approaches (i.e., Work Stress Design, Limit State Design and Reliability Based Design).

4.1 Database

HotCaSe database aims at structuring the research knowledge from experimental testing in a systematic manner. The database consists of documenting the material to be tested, chemical composition, manufacturing process, specimen's geometry, samples from which the specimen have been cut, the testing procedure (Temperature, Environment, Mechanical loading, Loading rate, etc), see Figure 5 for the database structure illustration. These data can easily be accessed and searched for further analysis through a web-based digitalised platform. The experimental results from tested materials can be assessed and compared systematically, thus supporting material selection and providing inputs to Casinteg models.

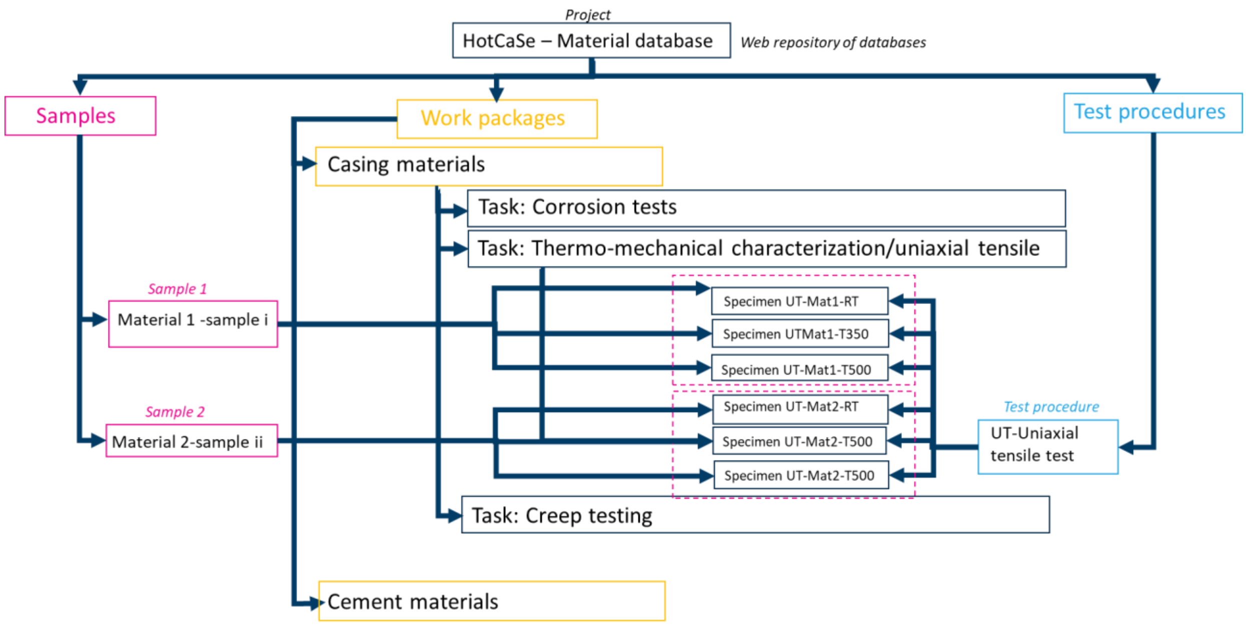

Figure 5: Illustration of database structure

4.2. Computing tools

In order to efficiently evaluate the identified casing alternatives, an "in-house" FEM software Casinteg was developed in HotCaSe, based on simplified axisymmetric assumption. This allows to calculate stresses developed in casings of casing-cement composite structure under thermal loading, and to capture different possible physics of the investigated systems under various loading scenarios and boundary conditions (BC). Experimental data from WP1 will be used as inputs to the models established in Casinteg. The knowledge of material degradations from WP2 will be coupled in the models in order evaluate the effect of casing degradation on the casing structure integrity after a designed service time.

The design of casings shall include consideration of the effects of all combinations of pressure, temperature, and temperature change that may occur at any time or depth during the drilling and operation of the well. As discussed, for super-HT geothermal power plant the casing may be expected to thermally yield under extreme temperature operation loadings, thus strain-based design approach may be required. NZS 2403 [Standards New Zealand, NZS 2403:2015] refers to seminal work by Holliday (1969), and to Industry Recommended Practice #03 [Enform Canada, IRP3:2012], but provides no quantitative basis for the application of post-yield design. In addition, it is to be noted that Holliday approach does not account for any possible stress relaxation due to creep (viscous) behavior of casing materials that could occur above 200°C [Standards New Zealand, NZS 2403:2015]. To increase the flexibility in super HT casing design, three material models, namely Thermo-Elastic, Thermo-Plastic, and Thermo-Plastic-Creep, were implemented in Casinteg accounting for the temperature dependency of elastic properties (Young modulus, poison's ratio), plastic properties (yield stress and work hardening), and creep properties.

Figure 6 shows an illustration of the effect of the three implemented material models on the stress evolution in the casing of a 12m long composite structure (casing, cement and formation) subjected to an operation temperature of 500ºC during 1000 days, see Figure 6a for illustration of the model boundary conditions and the temperature loading profile. The casing material under investigation is a typical API carbon steel. It can be seen that the thermo-plastic behavior is crucial to be accounted for during the warm-up (from 50ºC to 500ºC). Modelling the casing with the thermo-elastic model overshot significantly the actual stress in the casing. On the other hand, the creep behavior dictating the stress relaxation in the casing under constant strain, is of importance to be considered when dealing with cyclic loading. It is to be noted that due to lack of the creep data for the API carbon steel under hand, creep test data of an austenitic steel were used. However, the results depicted that the creep behavior of casing cannot be neglected for a reliable design of geothermal casing systems, especially when dealing with super-HT applications.

Further, in order to represent the initial conditions in the casing system prior to any warm-up operation, the effect of the casing installation/cementing/cement curing sequence should be considered in a reasonable way. Casinteg is able to model the residual stresses in the casing pipe as the result of its buoyed self-weight during the casing installation. In addition, the coupling with cement hydration simulation results is essential to capture the contact pressure from the set cement on the casing outer surface. After filling the annuli with the slurry, the contact pressure seen by the casing outer surface is the hydrostatic pressure of the "liquid" slurry along the well depth h, $\sigma_r = \rho_c g h$ (in which ρ_c is the density of slurry/cement and g the gravity). Assuming isochoric curing, the contact pressure on the casing from the set cement after hydration remains the same as hydrostatic pressure $\sigma_r = \rho_c g h$. However, the hypothesis of isochoric curing can hardly be true in reality. Cement materials tend to shrink (or swell) when hydrating, which consequently results in a decrease (or increase) of the contact pressure as compared to the isochoric curing case. Figure 7 shows an example of such coupling, in the sense that the results of a cement hydration simulation was used as inputs for calibrating Casinteg well models to get the reasonable contact pressure on to the casing outer surface after cement setting.

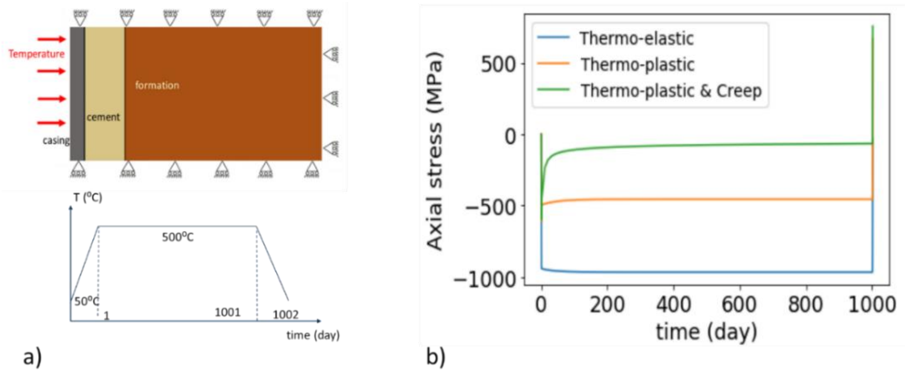

Figure 6: Casinteg model of 12m long composite structure (API carbon steel casing, cement and formation): a) Illustration of model boundary conditions with temperature loading profile (including warm-up, operation, and cool-down), and b) axial stress in the casing with three implemented casing material models.

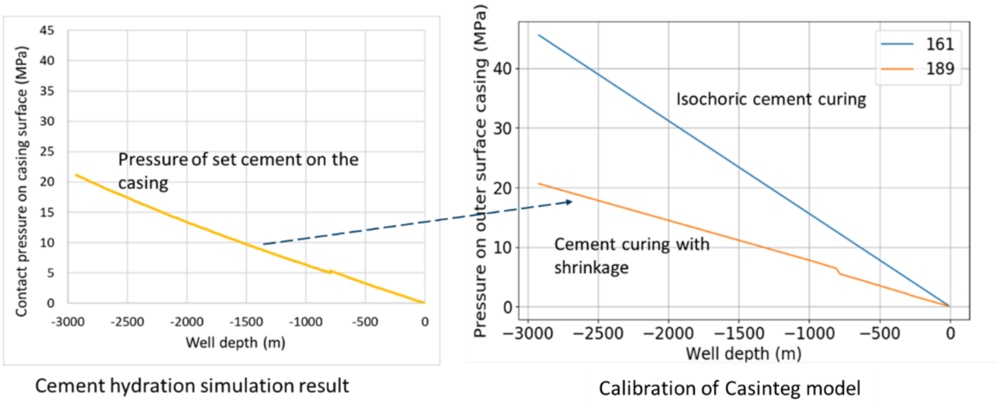

Figure 7: Illustration contact pressure from the cement on the casing along the well depth (2900m deep full well simulation), for isochoric cement curing and for cement curing with shrinkage calibrated based on inputs from cement hydration simulation.

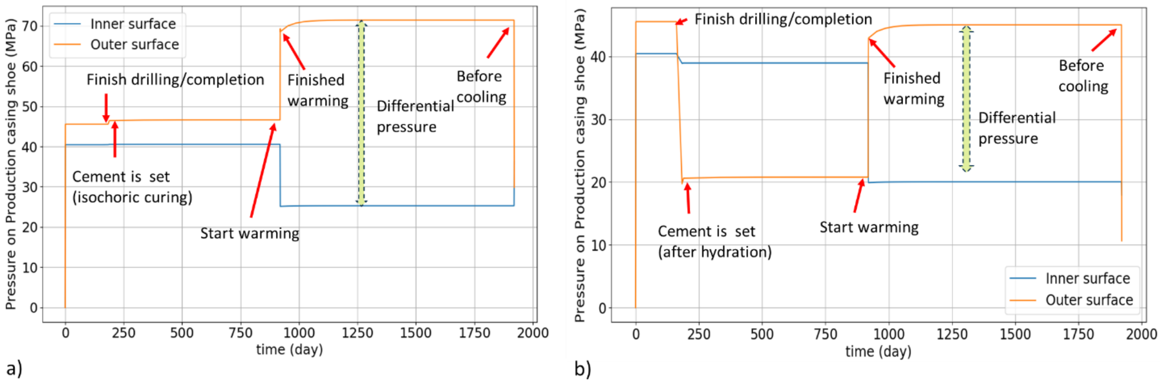

Figure 8: Evolution of pressure on the production casing (at casing shoe) during different stages of the well life cycle. a) Isochoric curing of cement, and b) cement curing with shrinkage.

The realistic contact pressure on the casing due to the set cement is crucial to evaluate the risk for casing collapse, which is directly dependent on the differential pressure between the inner and outer surface of the casing. Figure 8, illustrating the pressure on the production casing (at the casing shoe) during different stages of the well life cycle, shows the necessity to account for the cement shrinkage when curing to have a more realistic differential pressure, and consequently a better understanding of the casing collapse behaviour.

Preliminary verifications confirmed a good agreement between Casinteg and ABAQUS for both modelling the heat transfer by conduction, and stress analyses, while Casinteg dominates in terms of computational efficiency. A Casinteg analysis of full geothermal wells including complex loading history during its life cycle takes about one or two minutes of CPU time, while it may take days for ABAQUS to perform the same job.

CONCLUSIONS

Well construction for supercritical geothermal power plant is a challenge, due to the tough design conditions for casing systems. The present paper discussed HotCaSe project, initiated and led by Equinor to solve the challenges related to casing construction for supercritical geothermal power plants. At the initiation of the project, a three-day workshop, gathering personnel resources from the involved companies, R&D institutions and other national/international experts, was organized to freely scout for innovative solutions for cost-effective and reliable casing systems. Some possible well architectures as the result of the workshop were summarized and discussed. The design tool was developed to efficiently evaluate the identified solutions. The main concluding remarks of the present paper are:

- Four well concept categories were presented and discussed. There probably exists no optimal solution to solve all the present challenges in supercritical geothermal well construction both in a cost-efficient and reliable way. The optimal well construction may consist of hybrid element of different concepts. An efficient design tool is needed for screening out the viable solution.
- The in-house design tool, Casinteg, is developed to study the mechanical response in the casing systems under thermal loading. The tool is a simplified code but is an efficient tool adapted for full geothermal well structure analyses. Three casing material models, namely Thermo-Elastic, Thermo-Plastic, and Thermo-Plastic-Creep, were implemented in Casinteg accounting for the temperature dependency of elastic properties (Young modulus, poison's ratio), plastic properties (yield stress and work hardening), and creep properties. A full well simulation, accounting for complex loading histories during its life cycle loading takes about one or two minutes, depending on the selected casing material models.
- The preliminary modules of the developed tool can be used to provide a better understanding of the involved physics in super HT geothermal wells, and to efficiently evaluate the identified alternative casing systems. Preliminary verification studies showed a good agreement between Casinteg and ABAQUS simulation results for the heat transfer analyses and stress analyses of geothermal wells, while Casinteg simulations are more advantageous in terms of computational efficiency. A Casinteg analysis of full geothermal wells takes about one or two minutes of CPU time, while it may take days for ABAQUS to perform the same job.
- Further development is still needed for Casinteg to be a reliable design tool. However, with its flexibility and efficiency Casinteg is expected to contribute bridging the knowledge gap in the current standard codes for designing the robust casing system in super HT geothermal wells.

ACKNOWLEDGEMENT

The authors would like to thank HotCaSe project and Research Council of Norway for their financial support.

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