

Novel Technology for Improved Casing Integrity of Wells in High-Temperature to Superhot Conditions

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ABSTRACT

Design, drilling and operation of high-temperature geothermal wells has improved substantially over the past decades. Producing superhot steam to potentially enhance the power output of a single well multi-fold compared to a conventional well also increases the demanding load on the well structure. During its lifetime, the near steady state conditions of the well, i.e. during production, are less demanding for the downhole structure than transitional periods, e.g. during thermal recovery and shut-in periods. In high-temperature geothermal wells (>200°C), the main failure modes of production casings have been identified as collapse and tensile rupture of the casing. The main cause for casing collapse is by excess annular pressure buildup (APB) in the cemented annuli due to excess water in the cement sheath that expands during thermal recovery. Furthermore, tensile failure is an effect of permanent deformation in compressive (hot) state where the yield strength of the casing has been surpassed, generating plastic strain in the material, that in tensile (cold) state results in tensile failure. Such casing failures can cause significant production problems, both in restricted wellbore flow and operational safety. Past drilling into high-temperature and superhot conditions has taught us that the casing can be bottleneck for a successful project. Two technological advancements have been in development within ÍSOR, (i) the patented Flexible Couplings are intended to solve the axial thermal expansion problem by allowing displacement of every casing joint into the connection and the patent pending (ii) Casing Collapse Preventor, an APB relief system that relieves temporary overpressure within a cemented annulus with the purpose of preventing casing collapse. These two solutions, along with proper casing cementing, work together in increasing the flexibility and structural integrity of the casing throughout its lifetime. The patented Flexible Couplings have been developed within ÍSOR from the year 2015 within several research projects. Namely, the EU Horizon 2020 supported projects GeoWell and DEEPEGS, and tested at

elevated temperature and pressure within the GEOTHERMICA supported project GeConnect. The patent pending Casing Collapse Preventor has been under development in the EU Horizon Europe supported project COMPASS (grant nr. 101084623).

1. INTRODUCTION

Casing design for deep geothermal wells has been greatly improved and streamlined over the past decades, e.g. by standardization, notably by the New Zealand standard NZS2403:1991 and its revision NZS2403:2015. However, the well design process and available state-of-the-art materials have their limits. Elevated temperatures and thermal expansion of constrained cemented casings along with harsh chemical conditions contribute to the main structural challenges. The budget limits of geothermal projects largely prevent the selection of desirable but costly corrosion resistant alloys (CRA) materials and, choosing such materials does not necessarily solve all issues. Recent examples of attempts to harness ultra-high-temperature geothermal resources (>300°C), e.g. in the Iceland Deep Drilling Project (IDDP) and other deep drilling projects around the world, have shown that the casing can be a bottleneck with severe failures that limit their success. Thus, it has become clear that for a successful project such casing failures need to be prevented. Novel technology, e.g. improved casing selection options, novel casing connections combined with suitable cementing procedures, have the potential to meet these goals in the coming years and enabling utilization of superhot resources.

The EU Horizon Europe supported research project COMPASS, coordinated by ON Power, a subsidiary of Reykjavik Energy, addresses major challenges of superhot geothermal well construction, i.e. corrosive environment, thermal expansions and contractions in casings, and annular pressure buildup (APB) in fluid trapped between casings when wells heat up. Annular pressure relief technology with a working title "Casing Collapse Protector" has been in development at ÍSOR within the project. The Casing Collapse Protector is being developed to prevent casing collapse caused by thermally expanding annular fluids. A patent application has been filed for the novel technology.

Combined, the patented “Flexible Couplings” that were developed under EU Horizon 2020 supported research projects GeoWell (no. 654497) and DEEPEGs (no. 690771) and the patent pending annular pressure relief system the “Casing Collapse Protector” in development under the EU Horizon Europe COMPASS project (grant nr. 101084623), aim to prevent the most common casing failures and with the objective to increase the structural integrity of the production casing in high-temperature and superhot geothermal wells.

2. CASING LOADS AND CONSEQUENCES

Drilling of wells into hot rock formations requires circulation of drilling fluids to clean out the rock cuttings and to cool the hole and the drilling equipment. After each drilling section, steel casings are run in hole and cemented up to the surface. While the casings are cemented, the cement slurry builds hydrostatic (and dynamic) pressure on the casing. The highest differential pressure occurs at the casing shoe where the hydrostatic pressure of the cement slurry acts on the outside surface of the casing with a hydrostatic water pressure inside the casing. The well design ensures that the casing withstands the differential pressure without collapsing with adequate design factor. Any cement squeezing by controlling back pressure is risky as the design factor margin is low for casing collapse. This is in part due to the casing sizes that are governed by the standardized compatibility between diameters of casings and drill bits, and hook load capacity of drill rigs. After the cement placement and a wait on cement hydration for a couple of days the drilling is continued with the next drilling section.

After drilling the last section, the well is completed by placing a perforated liner from the shoe of the last casing, the production casing, down to the bottom of the well. Well testing is conducted to predict its productivity by its injectivity index, then the well is closed and the drill rig mobilized. Now the thermal recovery initiates and the well that is full of water starts to warm up from the formation temperatures and from convection within the well. During several weeks the well builds up pressure on the wellhead as it warms up.

While the well warms up, the well materials, i.e. metals, cement and liquids, thermally expand. The constrained casing develops compressive stresses, and pressure builds up in the annulus between casings as excess water in the cement expands. Any enclosed water from the cement jobs may become problematic due to APB. Between casings the APB has no escape route but where the casing is cemented to the formation, the formation can likely relieve the pressure. This is however time dependent. The slower the well warms up, the better.

When wells are flow-tested for the first time the shallow section, that has not seen the downhole formation temperatures, experiences a sudden heat-up and thermal shock. Figure 1 shows a typical downhole temperature and pressure conditions of a high-temperature geothermal well where in this case the

uppermost 300-400 m remain relatively cool until the well is flow-tested. These conditions vary highly between wells and depend on the formation temperatures, connections to feed zones, cooling from drilling, operation of the well etc.

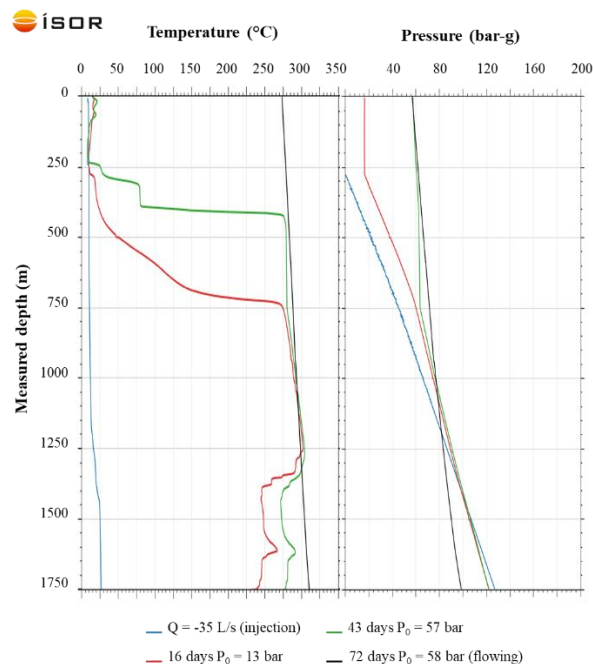


Figure 1. An example of downhole temperature and pressure conditions in a high-temperature geothermal well. The well is cooled under injection (blue), injection is then stopped. Warm-up after 16 days (red) and 43 days (green), and a flowing well (black). Note that for this well the uppermost 300-400 m, above the water table, are cool before flow-testing and are subject to thermal shock when flow initiates.

Carbon steel commonly used for geothermal casings has a thermal expansion coefficient of around 0.012 mm/m°C. When a well warms up, the casings thermally expand but since they are constrained in the cement sheath, instead of elongating, they develop compressive stresses. The most common casing grades, K55 and L80, with yield strengths of 379-552 MPa and 552-655 MPa, will yield at temperatures of around 150-200°C and 210-240°C, respectively. This does not necessarily mean that L80 should be chosen over K55 e.g. due to the work-hardening characteristics of a grade K55 casing that may be superior to higher-grade casing for thermal well service where its biaxial collapse resistance is higher than that predicted by the von Mises yield criterion (Maruyama, et al., 1990). Yield occurs at strain that is near to 0.2-0.5%. The casing material can withstand strain of 20-30% when tested at room temperature and structural analysis of casings in hot wells therefore needs to be aimed at the strain rather than stress (Ingason & Árnason, 2022). However, the modification of the carbon steel casing material over its lifetime due to various corrosion forms such as hydrogen embrittlement, sulfide stress corrosion cracking and micro-cracking caused by high temperature hydrogen attack can make it brittle and

therefore lower its resistance against thermal cycling (Karlsson et al., 2022).

Additionally, a previous study has shown that the load history and sequence of loading is important to understand formation of stress and strain that lead to various failure mechanisms (Kaldal, et al., 2011). The level of permanent (plastic) strain that is developed in the casing is governed by temperature difference and if thermal cycling occurs the strain produced depends highly on the material properties of the casing material. Thermal expansion of the casing at elevated temperatures, where stresses surpass yield and permanent strain is produced, has called for strain-based mechanical design (Miller & Dall'Acqua, 2023).

A diagram shown in Figure 2 describes the thermal expansion problem of a constrained casing where if the temperature is high enough the casing material will pass the yield point and deform, and if the well cools down again for example for workovers or cleaning, the casing contracts and high residual tensile forces are generated that can lead to tensile failure. An example of such failure of a 9 5/8" casing from a high-temperature geothermal well is shown in Figure 3. The well was repaired by running a 7" tie-back casing and cementing it in the well covering the damaged parts (Ingason & Árnason, 2022).

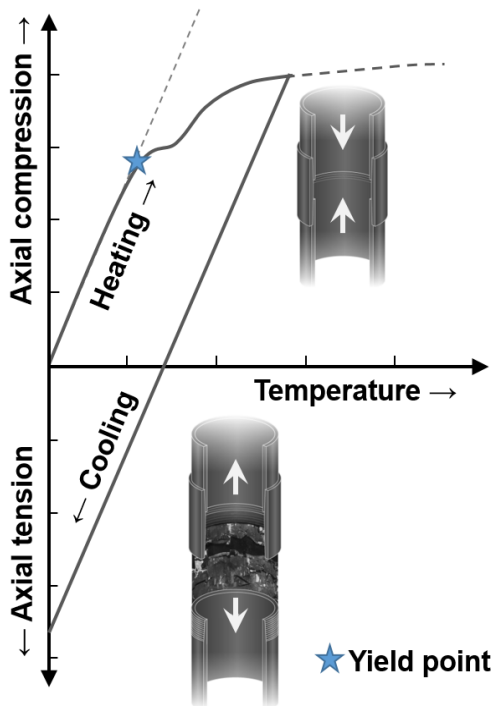


Figure 2. Concept diagram for the failure mechanism where axial tension is generated subsequent to strain that formed in compression, adopted from a diagram by Rahman & Chilingarian (Rahman & Chilingarian, 1995) (Kaldal & Thorbjornsson, 2016).

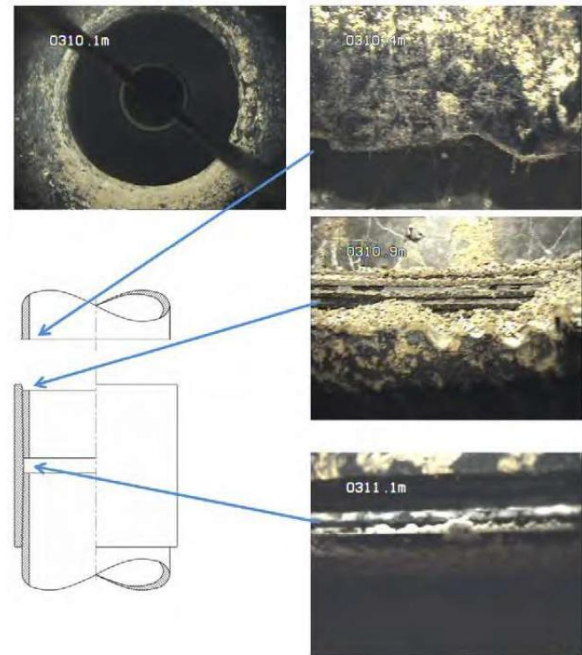


Figure 3. Damages at 303 m depth of a 9-5/8" production casing (Ingason & Árnason, 2022).

APB has been extensively studied in uncemented casing-to-casing annulus in oil and gas wells (Jandhyala & Chiney, 2014). Collapse due to APB in casing pipes of deepwater oil and gas wells in the Gulf of Mexico led to shutdown of the oil field. Control measures for trapped annular pressure (TAP) have been evaluated and reviewed, including increasing casing strengths, eliminating trapped annular pressure, releasing trapped pressure at surface or by using rupture disks, balancing the expansion volume and blocking heat transfer (Dong & Chen, 2017). Suryanarayana et al. 2020 evaluate casing collapse due to APB of trapped fluid pockets in cement between casings and present quantitative basis of design such that the outer string bursts and relieves APB before the inner string collapses. They note that the design basis in the New Zealand standard (NZS 2403) of maintaining ratio of 1.2 between API collapse rating and API burst rating is not adequate basis of design as the burst rating is not representative of the rupture limit of the outer casing. Instead, they propose to use a probabilistic design, however, noting that it may sometimes lead to infeasible choices for the outer or inner string, where the recourse is to ensure good cementing (Suryanarayana, et al., 2020). Results from finite-element model analyses of casings have shown that casings supported by cement have higher resistance to collapse, and that non-uniform geometry and/or loads can severely impact the structural stability and cause premature collapse (Kaldal, et al., 2013), see Figure 4. An example of casing collapse caused by APB is shown in Figure 5. In this well the collapse was punched out leaving the anchor casing, that is connected to the wellhead, exposed to the wellbore fluids.

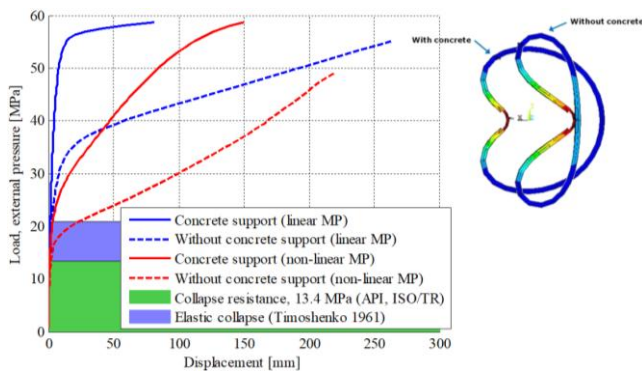


Figure 4. Finite element analyses of the effect of cement support on casing collapse. Load-displacement curves show the difference of collapse and post-collapse behavior of cement-supported and non-cemented casing.



Figure 5. Casing collapse of a 9-5/8” production casing in a high-temperature geothermal well with remains of slick line from a stuck logging tool. The collapse was punched out leaving the anchor casing exposed to the wellbore fluids, by courtesy of Reykjavik Energy and ON Power.

3. IMPROVED CASING INTEGRITY WITH NOVEL CASING TECHNOLOGY

The severe casing failures discussed above have called for improved reliability of the downhole structure. The nature of the harsh chemistry of geothermal wells limit material selection for casings. Materials are selected for resistance to H₂S attack to minimize the possibility of failure due to hydrogen embrittlement and sulfide stress corrosion. The New Zealand code of practice for deep geothermal wells states that materials should conform to ANSI/NACE MT 0175/ISO 15156; e.g. K55, L80 type 1, C90 and T95 (NZS 2403, 2015). This constrains

the selection as increasing the material strength unfortunately can produce negative effects such as hydrogen embrittlement that in turn can lead to premature tensile failures.

The development and testing of the Flexible Coupling (FC) has been thoroughly described in previous conference papers (Kaldal & Thorbjörnsson, 2016) (Thorbjörnsson, et al., 2017) (Thorbjörnsson, et al., 2019) (Thorbjörnsson & Kaldal, 2020) (Kaldal & Thorbjörnsson, 2022) (Kaldal, et al., 2022) (Kaldal, et al., 2024). Flexible Couplings were designed with the objective of allowing displacement due to thermal expansion of each casing joint. Therefore, lowering the development of thermal stress in the casing string and most importantly limiting permanent (plastic) strain caused by constrained thermal expansion. The novel casing connection has been developed for the two most common sizes for production casing sizes 9 5/8” (244.5 mm) and 13 3/8” (339.7 mm). A drawing of the FC (Figure 6) shows the sliding mechanism and thermal gap within the connection. The casing is run in hole as usual and cemented. However, the buttress threaded connection (BTC) is made up to a torque level, instead of relying on a triangular mark on the casing.



Figure 6. The Flexible Coupling (FC) enables thermal expansion of casing joints where the allowed movement (blue arrow) closes the thermal gap (green arrow) within the FC, limiting thermal stresses in the casing.

The principle is to rely on movement of the casing joints within the cement sheath. The casing is constrained at the connections that stick out into the cement. As the movement is only allowed at one side into the connection, the cement around the FC and the casing near its rigid end generate an intermediate sealing outside of each casing joint. This may sound cautious in terms of conventional zonal-isolation of well barriers. However, zonal-isolation properties of the cement sheath of wells drilled into fracture dominated geothermal systems is less important than for oil and gas wells, where it is fundamental. Additionally, the outer casing, the anchor casing connected to the wellhead provide the main pressure barrier of HT wells. Nevertheless, a thorough well design with a relevant casing design, e.g. the depth of

the anchor casing, conforming to each case is a requirement for using the technology.

The FCs have been tested in a relevant environment at well conditions of 260°C @ 60 bar-g where the connection was cemented into a full joint length into a casing-to-casing experimental setup and function tested with repeated thermal cycles. The experiment showed that the inner 9-5/8" casing adapted with a FC expanded and moved in the cement sheath closing the thermal gap inside the coupling, confirming the function and keeping the stress level in the casing below the yield point of the K55 casing material (Kaldal & Thorbjornsson, 2022). A full casing with FCs was run in hole for the first time in well NJ-37 by ON Power, a subsidiary to Reykjavik Energy, in the geothermal field Nesjavellir in SW-Iceland in February 2025. Initial casing integrity was monitored with downhole caliper, video, optical and acoustic logs with cold injection on the well by the end of the drilling. The well is currently undergoing thermal recovery. Pressure, temperature and spinner (PTS) and high-temperature caliper logging will be conducted to monitor and confirm the closure of the FCs after the well heats-up.

The Annular Pressure Buildup - Casing Collapse Preventor (APB-CCP) technology has been in development within the COMPASS project. It is designed to relieve annular pressure in a cemented annulus. A patent application has been filed (Icelandic patent application no. 050685). The invention works on the principle that the pressure propagates through the micro annulus that is formed between the production casing and the cement sheath and into the APB-CCP that is placed in the casing wall (Figure 7). If high enough, the pressure will activate the pressure release element and pressure will be temporarily relieved into the wellbore. This will likely only occur once in the lifetime of the well during its initial warm up during thermal recovery and flow-testing after drilling. When the annular pressure has been reduced the pre-set element shuts off and seals the casing again. The APB-

CCP "patent pending" technology's (Figure 8) main objective is to mitigate annular pressure development in a cemented annulus in high-temperature geothermal wells. Prototypes have been built and tested for operational pressures and function at ambient temperature. Operational testing within a cemented annulus will be performed in a full-scale test setup within the COMPASS project where questions regarding pressure relief through cemented annulus through the APB-CCP element will be investigated.

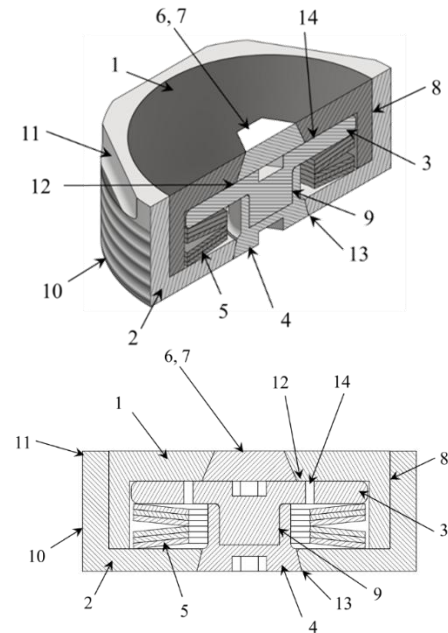


Figure 8. The patent pending "Casing Collapse Protector" technology for Annular Pressure Buildup Relief (APBR) intended for High-Temperature Geothermal Wells to mitigate casing collapse of the production casing that can occur if enclosed or excess water exists in a cemented casing-to-casing annulus.

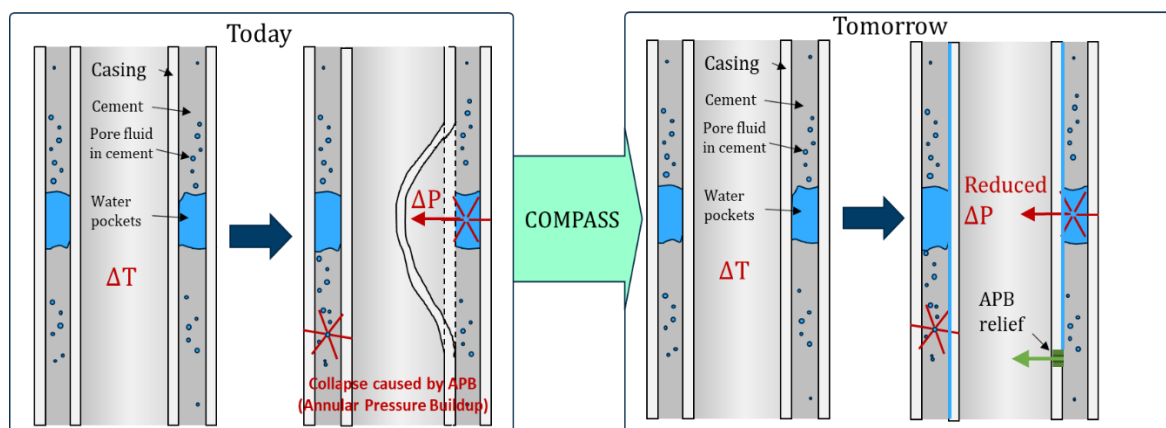


Figure 7. Illustration of the principle of the APB pressure relief concept for collapse prevention developed within the COMPASS project. Left: casing collapse form annular pressure buildup due to thermal expansion of entrapped annular water. Right: Temporary pressure relief through the APB-Casing Collapse Protection leaving the casing intact.



Figure 9. A prototype of the APB-Casing Collapse Protector fitted into a 13-3/8" casing.

The combination of using both the patented “Flexible Couplings” and the patent pending annular pressure relief system the “APB-Casing Collapse Protection” technologies, aims to prevent the most common casing failures of tensile rupture and casing collapse, with the objective of increasing the structural integrity of the production casing in HT to superhot geothermal wells.

4. CONCLUSIONS

The two most common casing failures have been identified as tensile rupture caused by permanent straining due to constrained thermal expansion and casing collapse caused by APB. The patented Flexible Coupling has been developed for mitigation of casing failures caused by constrained thermal expansion, and the not yet as well-advanced APB-Casing Collapse Protection technology that is currently being developed and will be tested in a simulated full scale experiment. Both technologies are not yet commercially available but aim to advance the integrity of high-temperature geothermal wells as well as to enable the drilling and operation of future superhot wells, e.g. in projects IDDP and KMT.

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