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Improved Casing Design for Mitigation of Casing Failures in High-Temperature Geothermal Wells using State-Of-The-Art Methodology with Novel Technology

Gunnar Skúlason Kaldal[1]*, Þorri Jökull Þorsteinsson[1] and Steinþór Níelsson[1]
ÍSOR – Iceland GeoSurvey[1]*
gsk@isor.is

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ABSTRACT

Thermal and structural modeling of multi-cased high-temperature geothermal wells have shown that permanent plastic strains are formed as wells warm-up to production temperatures that subsequently can cause severe casing failures. Additionally, thermally expanding annular fluids and/or thermal cycling can contribute to collapse of the production casing, greatly impacting productivity. Casing design for deep geothermal wells has been improved and streamlined over the decades, e.g. by standardization, particularly by the New Zealand standard for deep geothermal wells. However, well design and available state-of-the-art materials have their limits. Mainly due to elevated temperatures and thermal expansion of constrained cemented casings along with harsh chemical conditions. Budget limit of geothermal projects largely prevent selection of desirable but expensive CRA materials and such materials do not solve all issues. Attempts to harness superhot geothermal resources, e.g. in the Iceland Deep Drilling Project (IDDP) and other deep drilling projects around the world, have shown that casing failures limit their success. Novel technology, e.g. improved casing selection options, novel casing connections combined with appropriate cementing procedures, have the potential to meet these goals. The paper discusses the main challenges and potential solutions for future well designs for conventional high-temperature to ambitious ultra-high-temperature geothermal wells. The patented Flexible Couplings have been developed within ÍSOR from the year 2015 within several research projects (EU Horizon 2020 supported GeoWell and DEEPEGS, and GEOTHERMICA project GeConnect) and a patent pending Annular Pressure Relief Casing Collapse Preventor is in development within the EU Horizon Europe supported project COMPASS.

1 INTRODUCTION

The design, drilling, and operation of high-temperature geothermal wells (typically > 200°C) face significant structural challenges, with the casing being a potential bottleneck for successful projects in superhot conditions. The two main failure modes for production casings have been identified as tensile rupture and casing collapse (Sveinbjörnsson, Kaldal, & Thorbjörnsson, 2015) (Thorbjornsson, Kaldal, & Ragnarsson, 2019). These failures can cause significant production problems, including restricted wellbore flow and operational safety hazards. During the well's hot, production state, the constrained casing material expands and surpasses its yield strength, generating plastic strain. Subsequent cooling can result in tensile failure as a consequence from undergoing permanent plastic deformation in the hot state. Wells can operate for years or decades without any problems, but as soon as they experience cooling, i.e. from well cleaning or being shut-in, tensile failure can occur. Casing collapse is primarily caused by Annular Pressure Buildup (APB) in the cemented annulus. APB occurs when excess water, or closed-off water, within the cement sheath thermally expands as the well warms up for the first time after drilling. This overpressure can surpass the casing's collapse resistance, leading to the collapse of the casing. Additionally, any imperfections such as eccentricity, ovality, lack of cement support, stand-off, material impurities or other perturbations to the perfect circular dimension of the production casing, can greatly affect the collapse tendency of the casing (Kaldal, Jónsson, Pálsson, & Karlsdóttir, 2013). Choosing high-collapse grades could improve the chance of the casing surviving depending on the situation.

Carbon steel that is commonly used for well casings, expands when heated, but because it is constrained by cement, the thermal expansion generates compressive stress rather than elongation. Therefore, the constrained condition, typical casing grades like K55 and L80 yield at approximately 150–200°C and 210–240°C, respectively. However, K55 may perform better in thermal wells due to its work-hardening and biaxial collapse resistance properties (Maruyama, Tsuru, Ogasawara, & Inoue, 1990). Since yield occurs at strains of 0.2–0.5% and the material can tolerate 20–30% strain at room temperature, casing design in high-temperature geothermal wells should focus on strain-based analysis rather than stress (Ingason & Árnason, Casing Failures in High Temperature Wells, 2022). Over time, corrosion processes such as hydrogen embrittlement, sulfide stress corrosion cracking, and micro-cracking from high-temperature hydrogen attack can make the steel brittle, reducing its resistance to thermal cycling.

Annular pressure buildup (APB) has been widely studied in oil and gas wells, particularly in uncemented casing-to-casing annuli, where it has caused serious failures such as field shutdowns in the Gulf of Mexico. Various control methods have been explored, including strengthening casings, venting or releasing trapped pressure, and balancing thermal expansion. Research by Suryanarayana et al. (2020) showed that trapped fluid pockets in cement can lead to casing collapse and that the existing New Zealand standard (NZS 2403) is inadequate for preventing such failures. They recommend a probabilistic design approach or ensuring effective cementing when design trade-offs arise. Finite-element analyses further reveal that cemented casings are more resistant to collapse, while irregular geometry or uneven loading can trigger premature failure, as demonstrated by real-world examples of casing collapse due to APB.

Stepping out of the strain dominated condition requires action to allow materials to thermally expand without generating stresses above their elastic properties. Even in a highly stressed state but below the yield point any cooling effect will allow the material a passage back to the place it was before without permanent deformations. This is the main function of the Flexible Coupling, a novel casing connection that allows each casing joint to semi-freely expand into the connection.

High-temperature geothermal wells pose significant challenges to casing integrity due to thermal expansion of steel casings. Conventional casing joints, typically 11-12 m long, are coupled with threaded connections that lack movement capacity once cemented in place. Thermal expansion constrained by the cement sheath leads to compressive stresses, which, if the temperature rises sufficiently, can surpass the yield point of the casing material, causing permanent deformation. Upon cooling, residual tensile forces may result in tensile failure. To address these issues, Flexible Couplings (FCs) have been developed to mitigate casing failures by allowing displacement due to thermal expansion at each casing joint, thereby reducing thermal stress and limiting permanent strain.

2 CASING INTEGRITY OF HIGH-TEMPERATURE AND SUPERHOT GEOTHERMAL WELLS

High-temperature geothermal wells are designed according to guidelines in standards, e.g. the New Zealand standard for deep geothermal wells (NZS 2304:2015). Although the design process results in a safe downhole structure with pressure containment between pressure barriers and to the surface, large temperature changes can lead to severe casing failures.

In an extensive survey on casing failures in Icelandic high-temperature geothermal wells (Sveinbjörnsson, Kaldal, & Thorbjörnsson, 2015) (Lohne, et al., 2017) (Thorbjornsson, Kaldal, & Ragnarsson, 2019) – including lessons learned from conventional wells and the critical limitations experienced in the Iceland Deep Drilling Project (IDDP) – concluded that two primary failure modes are responsible for compromised well integrity. The first mode is tensile rupture of the casing, identified as the subsequent consequence of permanent plastic strain; this strain is generated when the casing's axial thermal expansion is constrained by the cement sheath during the hot production state, leading to critical residual tensile forces upon well cool-down or shut-in. The second primary failure mode is casing collapse, which is largely attributed to annular pressure buildup (APB) caused by the thermal expansion of excess or trapped water within the cemented annulus as the well heats up.

Namely, thermal yielding of the casing steel that generates permanent (plastic) deformations and can subsequently lead to tensile rupture if wells cool down again due to work-overs or other reasons, and casing collapse caused by expansion of excess water in cement or enclosed water in a pipe in pipe annulus. Both failures are caused by temperature increase between drilling with circulation or injection of drilling fluids and production temperatures. An example of a failure of a 9 5/8” casing from a high-temperature geothermal well is shown in Figure 1. The well was repaired by running a 7” tie-back casing and cementing it in the well covering the damaged parts (Ingason & Árnason, Casing Failures in High Temperature Wells, 2022). Figure 1 also shows an example of a casing collapse caused by APB. In this well the collapse was punched out leaving the anchor casing, that is connected to the wellhead, exposed to the wellbore fluids.

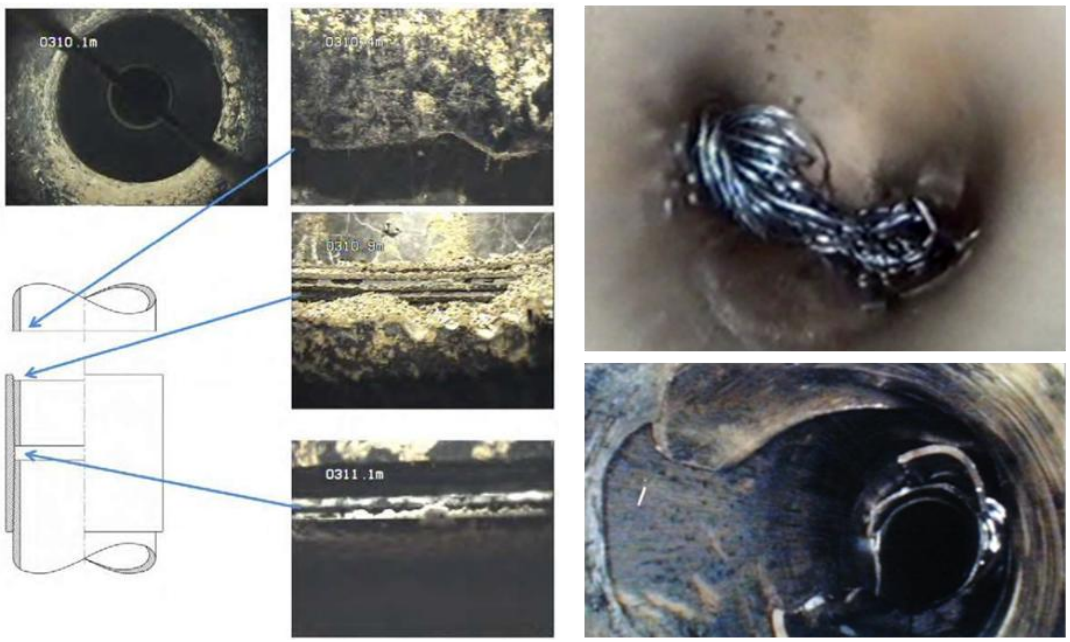


Figure 1. Left: Damages at 303 m depth of a 9-5/8" production casing (Ingason & Árnason, Casing Failures in High Temperature Wells, 2022). Right: Casing collapse of a 9-5/8" production casing in a high-temperature geothermal well with remains of slick line from a stuck logging tool. The collapse was punched out leaving the anchor casing exposed to the wellbore fluids, by courtesy of Reykjavik Energy and ON Power.

Casing failures of tensile rupture and collapse have been noticed in high-temperature geothermal wells that typically have temperatures ranging from 250°C to 300°C. Superhot wells have temperatures that can reach as high as 400°C up to 550°C depending on site conditions and depth. Superheated conditions were reached at relatively shallow depth in the first Iceland Deep Drilling Depth well IDDP-1 that was drilled in Krafla NE-Iceland where magma was intersected at 2100 m depth and during flow testing the well produced 450°C hot superheated steam at 140 bar-g (Pálsson, et al., 2014) (Ingason, Kristjánsson, & Einarsson, Design and development of the discharge system of IDDP-1, 2013). IDDP-2 that was drilled in Reykjanes SW-Iceland reached supercritical conditions at its total depth of 4565 m MD to estimated temperature of about 535°C based on alteration minerals, joint inversion of wireline logging, and rate of heating (Friðleifsson, et al., 2018). IDDP-2 was drilled by re-entering and deepening well RN-15 that had a wide production casing of 13 3/8", but prior to drilling a casing collapse that was found at 140 m depth was milled out (Stefánsson, Friðleifsson, Sigurðsson, & Gíslason, 2020). After quenching of IDDP-1 due to master valve malfunction, a video-log revealed a severe casing collapse at 610 m depth where several meters of casing had collapsed and the flow had been directed out into the annulus between the 9 5/8" production casing and the 13 3/8" anchor casing, and several tensile failures above the collapse where the pin had been pulled out of the box (Ingason & Árnason, Casing Failures in High Temperature Wells, 2022). Casing failure was observed at 2300 m depth in the IDDP-2 well.

3 IMPROVED CASING DESIGN

3.1 Casing Design Considerations

The improved design of casings for high-temperature (>200°C) and superhot geothermal wells discussed here focuses on actively mitigating thermal and pressure-induced stresses that cause the primary failure modes: tensile rupture and casing collapse. A fundamental design philosophy was adopted in the New Zealand standard (NZS2403:2015) to shift towards strain-based design where temperatures and thus thermal stresses of cemented casings exceed the yield strength of the steel. Although conventional stress-based design with defined design factors applies for most load cases e.g. for casing placement and cementing, operational loads that occur at elevated temperatures require non-linear analysis, e.g. strain-based finite-element analysis that incorporates non-linear material properties such as stress-strain curves and strength reduction at elevated temperatures. Permanent plastic strains that occur in the casings are incorporated into such analyses and the risk of failure can be assessed. Beyond structural design, fundamental research has been conducted to extend the currently available design curves for API casing grades up to 350°C in the New Zealand (NZ) standard. A study, within the GeoWell and HotCaSe projects extended the design curves to 550°C with thermo-mechanical tensile testing of geothermal casing materials as well as testing several other corrosion resistant alloys (CRA) (Gruben, et al., 2021). The results confirmed a significant reduction in material strength with increasing

temperature (Figure 2). This critical data allows for more accurate strain-based analysis, enabling engineers to design robust casings that account for the high-temperature environment and aim to prevent premature material deterioration and failure.

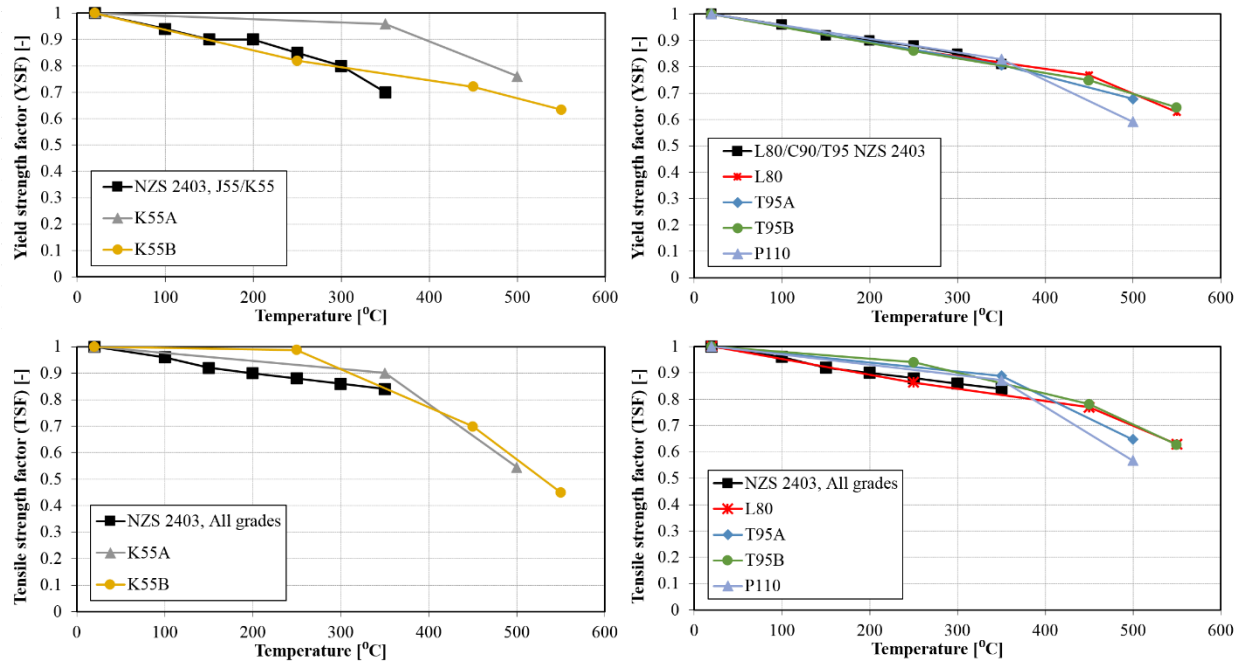


Figure 2. Yield strength factor (YSF) and tensile strength factor (TSF) for the tested K55 and L80 casing steel extending design curves from the New Zealand standard (Gruben, et al., 2021)**.**

Adhering to guidelines in the NZ standard the casing material tensile yield and ultimate strengths are de-rated at elevated temperatures with a temperature reduction factor. This affects collapse and burst strengths as depicted in Figure 3, as wells warm up and become fully hot. Note that structural support of cement has been shown to have a positive effect on collapse resistance of casings (Kaldal, Jónsson, Pálsson, & Karlsdóttir, 2013).

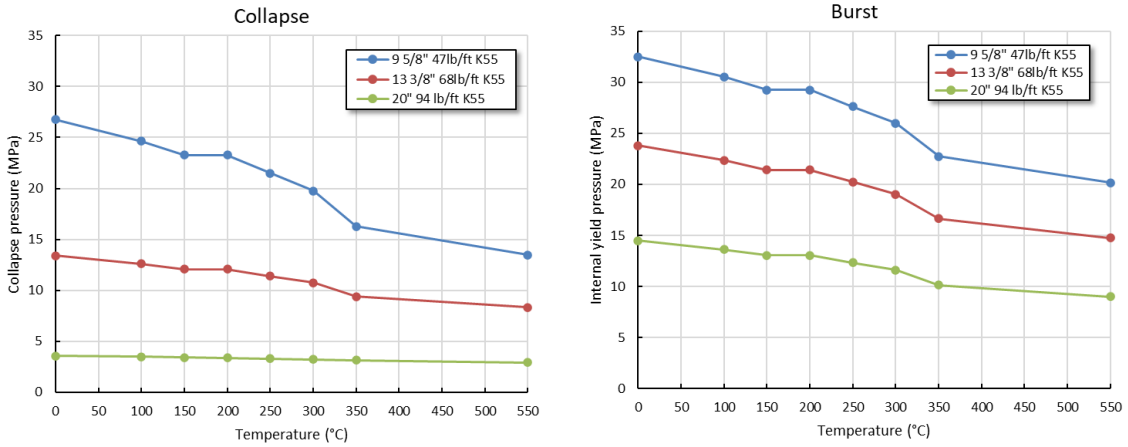


Figure 3. Calculated collapse resistance (left) and internal yield pressure (right) of common casing sizes de-rated according to design curves in NZS2403:2015 up to 350°C and extended to 550°C according to tensile test data shown in Figure 2.

Embrittlement caused by H_2S rich environment reduces the steel's ductility making it prone to premature brittle fracturing. The material becomes less resistant to thermal cycling where the increased brittleness lowers the material's ability to absorb strain making it more susceptible to crack initiation and subsequent catastrophic failure under fluctuating loads or low-cycle fatigue. The phenomenon of embrittlement underscores the need for solutions to minimize its effect.

3.2 Mitigation of tensile failures (axial thermal expansion)

To solve the axial thermal expansion problem and mitigate the risk of tensile rupture, the Flexible Coupling (FC) technology has been developed. The FC is a patented solution that allows for the axial displacement from thermal expansion of each cemented-in casing joint. By allowing this movement, see Figure 4, the casing material can work within its elastic range, thereby eliminating the permanent plastic straining, which considerably reduces the risk of casing failure. The FCs, are designed with a sliding mechanism and a thermal gap within the connection, enabling casing joints to move within the cement sheath. This movement prevents excessive stress buildup and ensures the casing material remains below its yield point during thermal cycling. The residual tensile stress in a well that for some reason cools down is minimized. By mitigating this high-magnitude tensile stress the risk of triggering an embrittlement-related failure is drastically reduced as the material will no longer be under high sustained loads that drive crack growth in brittle materials.

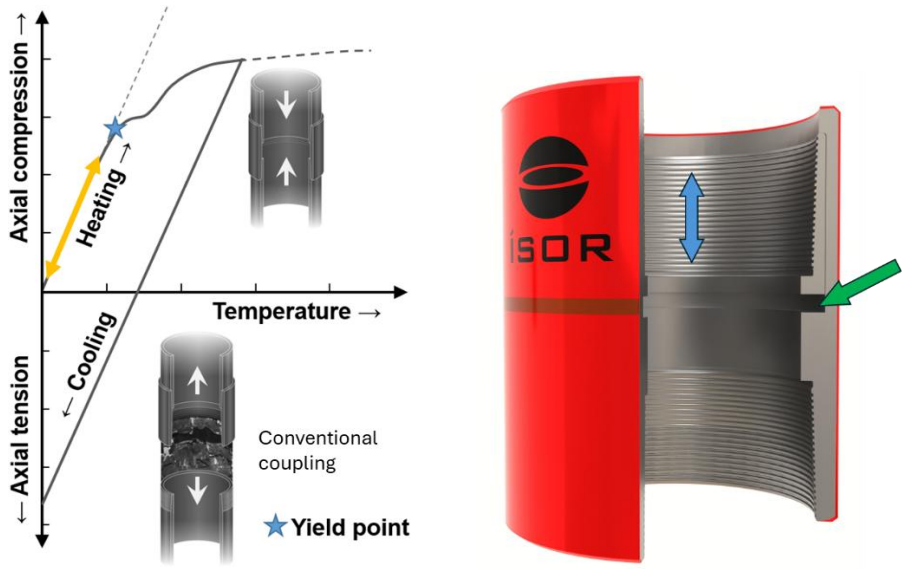


Figure 4. Left: Concept diagram for the failure mechanism where axial tension is generated subsequent to strain that formed in compression, and the principle of utilizing the elastic range of a casing with Flexible Couplings (FC) orange arrow, modified from a diagram by Rahman & Chilingarian (Rahman & Chilingarian, 1995). Right: The 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.

FCs have been developed for the two most common production casing sizes, 9 5/8" and 13 3/8", used for high-temperature geothermal wells. By addressing constrained thermal expansion, FCs aim to enhance the structural integrity and reliability of production casings in high-temperature geothermal wells, reducing the risk of tensile rupture and improving overall well performance. Flexible Couplings have undergone extensive testing in multiple phases, including full-scale laboratory and field tests. Prototypes of 9 5/8" and 13 3/8" casing sizes were tested under ambient conditions and simulated operational loads at SINTEF and NORCE in Norway. Tests included tension, compression, and bending scenarios, confirming the FC's ability to allow expansion and contraction without failure. Sliding function tests demonstrated travel capacities of 15-20 mm, requiring consistent forces of 170-300 kN for movement. Ultimate tensile loading tests validated the strength and reliability of the FCs, with results summarized in Table 1.

The function testing of a 9 5/8" FC of the most recent prototype with a 15 mm thermal gap was conducted within the COMPASS project at NORCE in Stavanger, Norway, using a 1500-ton tension/compression frame. The sliding function of the movable component was monitored, with axial forces ranging between 12-15 tonnes required for movement. Pressure containment tests showed the connection held 165 bar in the open position for 15 minutes, though lower interference fit resulted in reduced pressure containment in the closed position. The test demonstrated the lower margin of the chosen tolerances that can from the previous experience be calibrated for optimal performance. The ultimate tensile strength test demonstrated the coupling's reliability, breaking at 317.5 tonnes tension, exceeding the previous maximum tensile limit. Same prototype version was tested in the DEEPLIGHT project for its ultimate torque capacity investigating torsional loads for make-up as well as for a rotating casing, e.g. for the potential of casing while drilling (CwD) with novel electric pulsed power (EPP) technology. The tested prototype's ultimate torque capacity was approximately 76000 Nm, or six times its

defined make-up torque of 12500 Nm. It's pressure capacity under load was tested up to 165 bar (in some instances up to 187 bar-g) with very limited seepage; 1.2 mL/min at 37500 Nm and 0.4 mL/min at 75000 Nm. These results highlight that the FC can sustain significant torque loads beyond the make-up values with no catastrophic leakage occurring.

Table 1. Test results from Flexible Coupling prototype tests in two diameters; 9 5/8" and 13 3/8". Start force is the force needed to initiate displacement, sliding force is the force needed to maintain movement, and ultimate tensile load to failure (Kaldal & Thorbjornsson, 2022). The test of prototype nr. 9 was conducted under the COMPASS project.

Prototype:	Start force	Sliding force	2.5° bending: Sliding force	5° bending: Sliding force	Ultimate tensile load (at failure)
	(kN)	(kN)	(kN)	(kN)	(kN)
1 – 9 ⅝"	200	200	200	200	1837
2 – 9 ⅝"	300	300	300	300	1926
3 – 9 ⅝"	320	320	320	320	3135
4 – 9 ⅝"	247	176-219	- not tested -	- not tested -	3032
5 – 13 ⅜"	267	189-229	- not tested -	- not tested -	3922
6 – 13 ⅜"	228	196	- not tested -	- not tested -	4452
7 – 13 ⅜"	173	173-177	- not tested -	- not tested -	4429
8 – 13 ⅜"	221	170-200	- not tested -	- not tested -	4580
9 – 9 ⅝"	120	150	- not tested -	- not tested -	3175

More advanced testing of the FC technology was conducted in the GeConnect project, where an externally cemented FC was tested in a full-scale surface experiment. The test utilized geothermal steam at operational conditions of (260°C and 60 bar-g). The results confirmed the function of the FC at operational load, demonstrating its efficacy in mitigating thermal stress in a relevant environment. The development and testing of the Flexible Coupling has been thoroughly described in previous conference papers (Kaldal & Thorbjornsson, 2016) (Thorbjörnsson I. Ö., Kaldal, Gunnarsson, & Ragnarsson, 2017) (Thorbjornsson, Kaldal, & Ragnarsson, 2019) (Thorbjörnsson & Kaldal, 2020) (Kaldal & Thorbjornsson, Improved Integrity of the Production Casing in Moderate- to Ultra-High-Temperature Geothermal Wells using Flexible Couplings, 2022) (Kaldal, et al., 2022).



Figure 5. Well NJ-37. Flexible Couplings were run in a full casing string in February 2025 (left). Flow-testing of the well after thermal recovery in October 2025 (right).

In February 2025, in a collaboration with ON Power a subsidiary of Reykjavik Energy, a full 13 3/8" casing with FCs was installed in a 2150 m deep well (NJ-37) at the Nesjavellir geothermal field in Iceland (Figure 5). Initial integrity was monitored through various logging techniques during cold water injection. Thermal recovery and

flow testing were conducted, with further monitoring using pressure, temperature, spinner, and high-temperature caliper logging. While HT caliper logging could not confirm the closure of the thermal gap due to low spatial resolution, alternative high-temperature logging solutions are being considered.

3.3 Mitigation of Casing Collapse

Annular Pressure Buildup (APB) of trapped fluids behind the casing in the pipe-in-pipe annulus is a known cause of casing collapse during well warm-up. Collapse typically occurs as bulges intruding into the wellbore, reducing flow throughput. Mitigation strategies include selecting high-quality casings and cement, limiting thermal cycling, and allowing slow warm-up to dissipate excess water pressure. A novel solution developed in the COMPASS project introduces a pressure-relief mechanism through the casing wall, termed Annular Pressure Buildup Relief (APBR). This technology temporarily releases annular pressures into the well when nearing collapse pressure and then sealing again once pressure reduces. Prototypes have been designed, built and tested under the COMPASS project. A set pressure of 175 bar-g was selected for large-scale testing.

The Annular Pressure Buildup - Casing Collapse Preventor (APB-CCP), see Figure 6, is a patent-pending technology currently under development. It is designed to be an active defense against casing collapse in high-temperature geothermal wells. The device is situated in the casing wall and operates on a simple principle: when the trapped fluid in the cemented annulus thermally expands—a process that typically occurs during the well's initial warm-up (thermal recovery/flow testing)—the resulting pressure propagates through the micro-annulus and into the APB-CCP. If this pressure exceeds a pre-set threshold, see Figure 7, a specialized release element in the CCP activates, allowing the excess pressure to be temporarily vented into the wellbore. Once the annular pressure is successfully reduced below the critical collapse level, the element automatically shuts off, re-sealing the casing. This mechanical safety feature is intended to function primarily once in the well's lifetime to mitigate the critical pressure peak that commonly causes casing collapse.

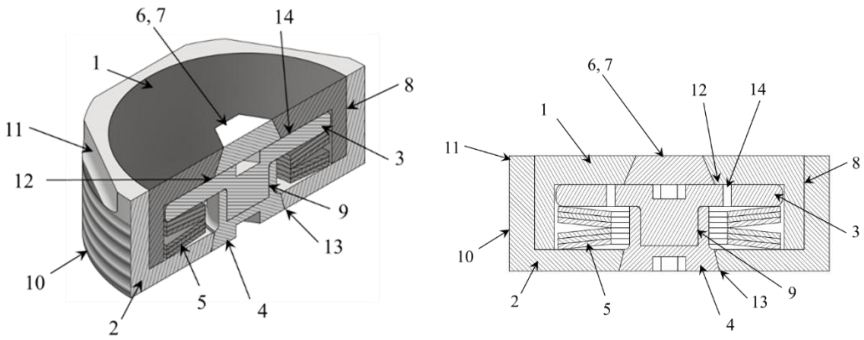


Figure 6. The patent pending "Casing Collapse Protector" technology for Annular Pressure Buildup Relief (APBR) intended for High-Temperature Geothermal Wells to mitigate casing collapse of the production casing that can occur if enclosed or excess water exists in a cemented casing-to-casing annulus (pipe-in-pipe).

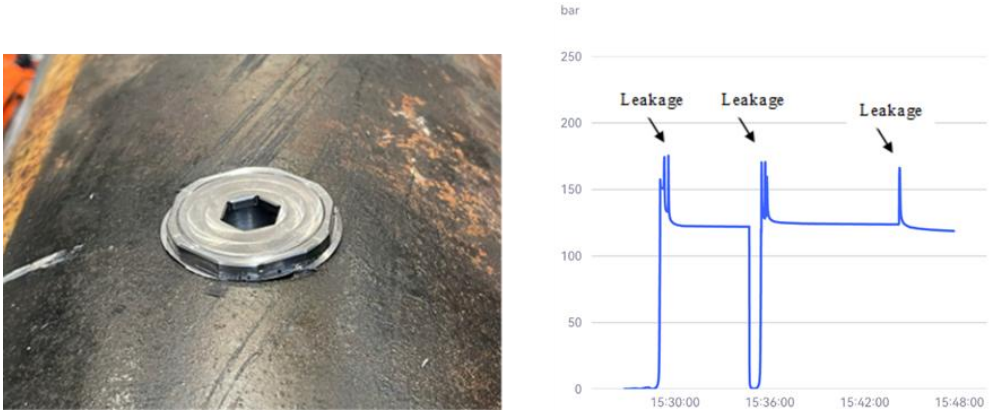


Figure 7. The APBR prototype (V2.0) is fitted into a 9 5/8" casing (left) and calibration of set pressure of 175 bar-g for a large-scale function testing within the COMPASS project (right).

CONCLUSIONS

Casing integrity at elevated temperatures in harsh chemical environments is an issue that persists all around the world. The paper addresses the main failure modes of casings and discusses mitigating actions. The main findings from the provided research converge on a conclusive strategy for improving well integrity in high-temperature and superhot geothermal environments. The conclusion is that conventional casing design is in part inadequate because it fails to accommodate the extreme thermal loads, leading to two primary failure modes: tensile rupture from permanent plastic strain and casing collapse from Annular Pressure Buildup (APB), as dramatically confirmed by failures in the IDDP wells. The development and testing of Flexible Couplings and APBR technology represent significant advancements in mitigating casing failures in high-temperature geothermal wells. FCs effectively address constrained thermal expansion, while APBR provides a solution for annular pressure buildup. These innovations enhance the structural integrity and reliability of production casings, contributing to a more successful drilling and utilization of superhot geothermal resources in future projects.

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