GRC Transactions, Vol. 46, 2022

Improved Integrity of the Production Casing in Moderate- to Ultra-High-Temperature Geothermal Wells using Flexible Couplings

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Keywords

Geothermal, High-Temperature Geothermal Wells, Casings, Flexible Couplings, Stress Mitigation, Thermal Expansion

ABSTRACT

Success of geothermal wells drilled for production at elevated temperatures can be significantly reduced by casing integrity issues caused by constrained thermal expansion as geothermal operators have frequently experienced in their operation. Ideas of deep drilling to superheated or supercritical conditions gaining five- to tenfold the power output of one well, utilizing the resource more effectively and saving drilling cost, relies on flexible mitigating technology to prevent casing failures. Casing failure was the main reason for permanent closure of the Iceland Deep Drilling Project well IDDP-1, after malfunction of surface equipment and unavoidable killing of the well, as well as limitations of the IDDP-2 well in Iceland. Casing failure can also cause significant problems in producing from conventional wells, e.g. flow restrictions, downhole logging and operational safety. Wellbore temperature changes in high-temperature geothermal wells (>200°C), once drilling and completion has been completed and injection is stopped, will result in a non-retrievable compressive thermal straining in cemented casings. Although the permanent deformation cannot be directly verified, since wells could potentially be in operation for months-years-decades in pseudo steady-state condition, subsequently it can cause severe failure, e.g. tensile rupture and collapse, in worst cases leading to well abandonment and lost investment. The technology behind Flexible Couplings is to allow axial thermal expansion of each cemented-in casing joint, thereby allowing the material to work in its elastic range and eliminating permanent straining. The risk of casing failure is thereby reduced considerably and allows wells to operate at casing strains below yield both in operation and during shut down. Novel patented, Flexible Couplings have been developed and full-scale tested in EU funded Horizon 2020 projects GeoWell and DEEPEGS, and their function at operational load has been confirmed in a surface experiment in GEOTHERMICA national co-fund project GeConnect at steam temperature and pressure of 260°C and 60 bar-g. Their use could provide significant cost savings of conventional geothermal

wells of >200°C by reducing lost investment due to casing failures, lost or limited production and additionally enable advancement of production from ultra-high-temperature wells from deep and superheated/supercritical resources.

1. Introduction

High-temperature geothermal areas have been defined by the resource temperature of 200°C or higher at 1000 m depth (Böðvarsson, 1961). Drilling wells relies on cemented steel casings with each casing joint length of around 12 m (API 5CT Range 3). The casing diameters of the wells are telescopic with the innermost casing named the production casing that can be from several hundred meters and up to several Km in length. The casing segments are connected with so-called couplings and after reaching desired length the casing string is cemented and by that it is anchored in the cement due to the couplings having wider outer diameter than the casing string. The casing is cemented in cooled conditions and the cement typically sets at temperatures of around 50°C to 100°C (depth dependent). During warm up of wells the casing warms up to production temperature and due to the material thermal expansion coefficient it builds up stress as it cannot expand axially due to the anchoring of the couplings in the cement sheath around the casing. Temperatures in conventional high-temperature geothermal well (HTGW) is typically in the range of 200 to 300°C (or higher in some cases), the first Iceland Deep Drilling Well (IDDP-1) in the Krafla geothermal field north Iceland the producing well head temperature reached 450°C at 140 bar-g (Ingason, Kristjánsson, & Einarsson, 2014). Due to extreme thermal load the IDDP-1 experienced multiple coupling and other casing failures and had to be permanently closed (Figure 1). Examples of such failures have also been found in numerous conventional HTGW which supports the need for casing failure mitigation not only for extreme cases but for the whole spectrum where annular pressures and high stresses are produced.

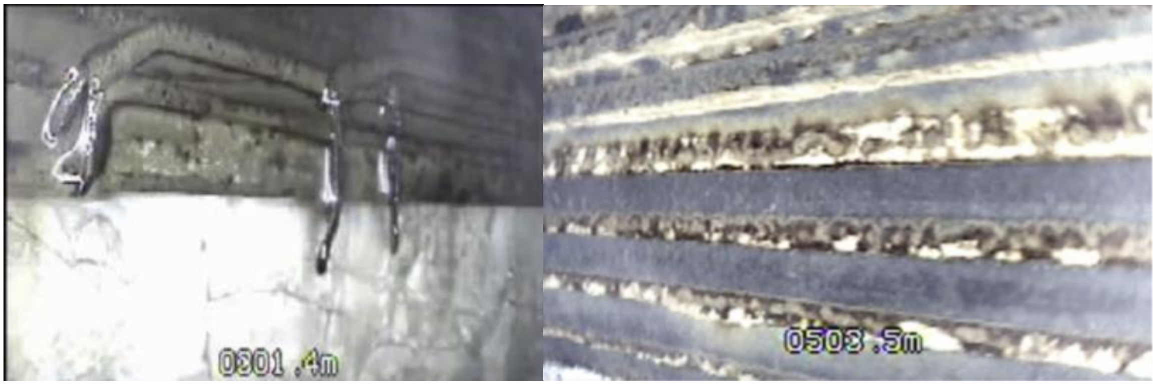

Figure 1: Casing connection failure due to casing tearing out of the coupling during cooling (left). Cut off threads in the coupling as the casing pulled out of the coupling during cooling (right). Pictures are from the IDDP-1 well (Thorbjörnsson, Kaldal, Gunnarsson, & Ragnarsson, 2017).

IDDP-2 was drilled to 4659 m in Reykjanes geothermal field in Iceland with the aim to achieve supercritical fluid, but due to casing failures it failed to produce sufficiently. These are only two examples of wells where the aim is to get high temperature fluid from deep sources, but the current well technology used is not capable of withstanding the load. There is therefore an emerging need for solutions that allow the casing to expand/contract axially during warm up and cool down as for maintenance. In Iceland the geothermal industry has supported the patented innovation of the Flexible Coupling (FC) as a promising step to overcome the casing failures or at least to minimize the probability of these. The concept of the Flexible Coupling is to allow each casing joint to expand due to thermal expansion into the coupling and thereby reducing the strain level to its elastic range and if maintenance, cleaning or quenching of the well is needed, it allows the casing segment to contract during cooling. Flexible Couplings have been tested in two third-party laboratories, have been applied in HTGW well in Iceland (Thorbjornsson & Kaldal, 2021), surface tested for verification of casing sliding in the cement sheath, as will be discussed in this paper. All these tests were conducted to verify both sliding capability as well as strength of the Flexible Coupling in full dimension of 9 5/8" and 13 3/8" prior to production of FCs for field testing in a HTGW in the Nesjavellir geothermal area 2020.

2. Casing Failure Mitigating Principle

The downhole temperature distribution of a casing at the moment the cement sets and constrains a casing provides the basis for subsequent thermal stress development in a casing-cement structure. Previous study has shown that load history and sequence of loading is important to understand casing failure mechanisms (Kaldal G. S., Jonsson, Pálsson, Karlsdóttir, & Thorbjornsson, 2011). When wells warm-up after circulation or injection is stopped, thermal expansion generates compressive plastic strains in commonly used medium carbon steels used. The casings that are constrained by cement, are plastically deformed and effectively geometrically shortened from their initial length. If wells are allowed or needed to cool down after reaching high temperatures, for example for workovers or cleaning, the casing contracts and residual tensile forces are generated (Figure 2). These residual forces can be substantially reduced by reducing permanent straining in the hot state by implementing expansion allowance.

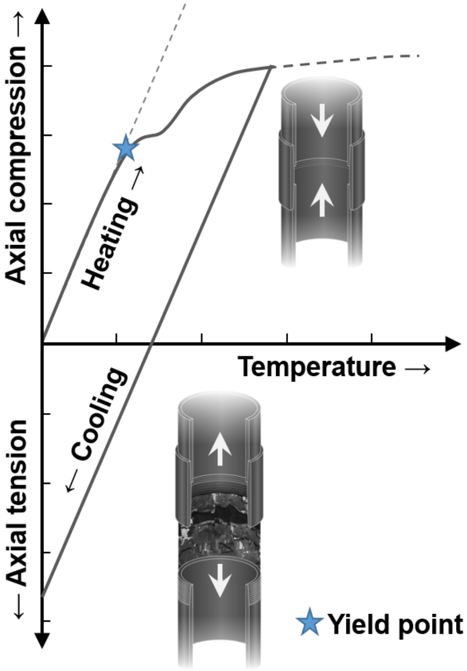

Figure 2: Concept diagram for the failure mechanism where axial tension is generated subsequent to strain that formed in compression (adopted from a diagram by Rahman & Chilingarian (Rahman & Chilingarian, 1995)) (Kaldal & Thorbjornsson, Thermal expansion of casings in geothermal wells and possible mitigation of resultant axial strain, 2016).

In an extreme case of the IDDP-1 well numerous failures were found in the production casing after the well had been shut-in and killed by water from its 450°C production temperature, one of those is shown in Figure 3. Due to the high temperature the contraction displacement at this failure was extensive or about 40 cm. For conventional wells, typically operating in temperature range of 200-300°C, though operating at lower temperature the observed failures can be severe nonetheless as a study on casing problems of a set of around 250 wells in Iceland has revealed (Thorbjornsson, Kaldal, & Ragnarsson, 2019). Tensile failures have both been seen in threads at the connection or in the pipe body near to collapsed (bulged) casing. Hydrogen attack and related corrosion phenomena (e.g. Thorbjornsson I. , 1995; Karlsdottir & Thorbjornsson, 2012; Thorbjornsson I. , et al., 2020), can promote tensile failure since the material becomes brittle and therefore can take up less strain before failure occurs.

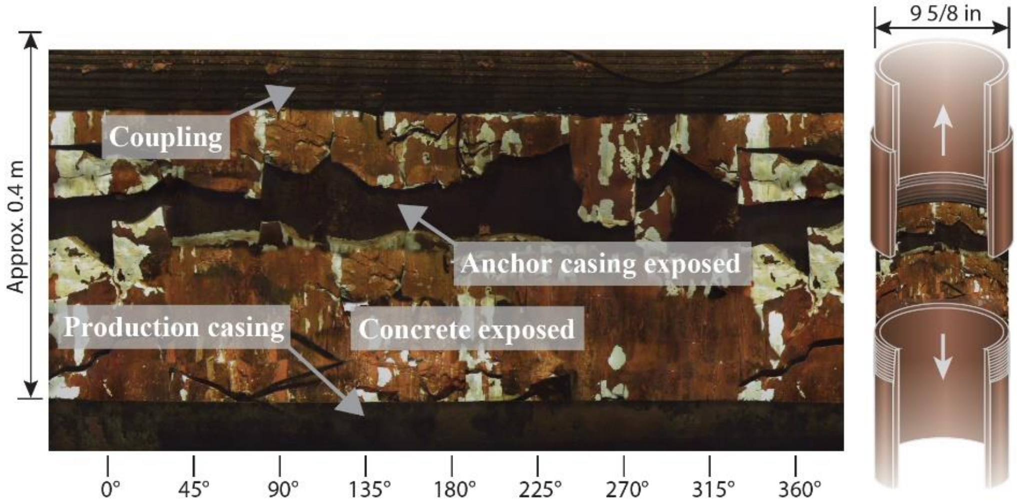

Figure 3: Coupling failure due to casing thermal contraction in the production casing of the IDDP-1 well. The failure occurred while the 450°C hot well was killed with cold water (Kaldal G. S., Jonsson, Palsson, & Karlsdottir, 2016).

To reduce likelihood of casing failure caused by thermal expansion, a mitigating principle has been proposed and developed where displacements within the casing string are enabled. By doing so, axial thermal compressive stresses can be controlled to be below yield. This can be done by selecting a proper displacement capacity for the downhole temperature ranges that are anticipated, in essence to increase the elastic range of the casing material by delaying production of above yield stresses (Figure 4).

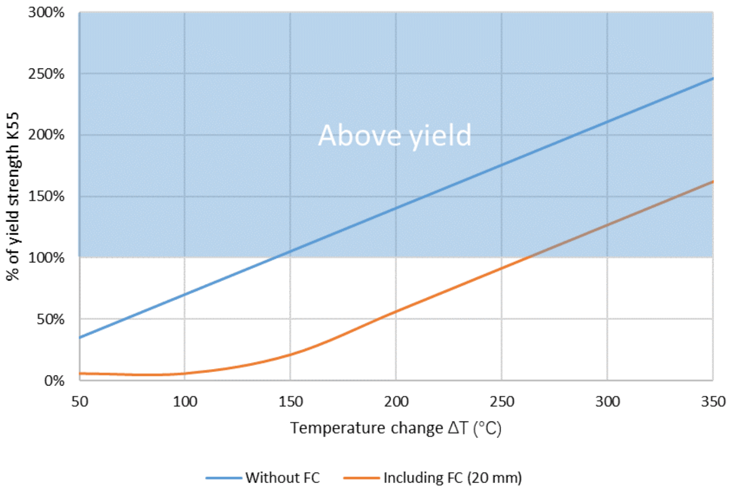

Figure 4: Calculation of yield of conventional casing system compared to using Flexible Coupling with 20 mm displacement capacity for API K55 grade. Temperature difference of around 142-207°C leads to yield in conventional system versus 270-335°C using Flexible Coupling, assuming K55 yield range of 379-551 MPa (Kaldal, et al., 2022).

3. Research and Development

The principle of the Flexible Coupling described in the previous section was implemented in research and development where the initial idea was brought from a concept to practice, within EU funded Horizon 2020 projects GeoWell and DEEPEGS. The FC was designed within boundaries of standardization for casings, e.g. in terms of materials, sizes and structural strength. Two sizes have been developed up to now for casing sizes 9 5/8” (244.5 mm) and 13 3/8” (339.7 mm), the most common sizes for production casings in geothermal wells. A prototype built within the GeoWell project and a drawing showing the sliding mechanism are displayed in Figure 5.

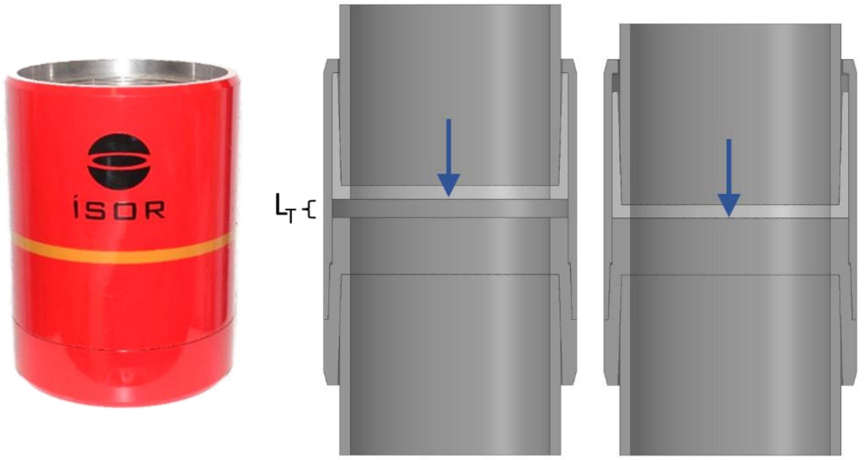

Figure 5: Flexible Coupling prototype – 9 5/8” (left). Sliding principle of FC enabling expansion of cemented-in casings (right).

Multiple load cases needed to be considered for safe running of casing downhole and for operation throughout a well's lifetime (Figure 6). During installation while the casing is run in hole, the loads are governed by the rotational and axial loads, i.e. torque during make-up and tension due to weight of the casing. While installing the casing, compression loads can occur near its shoe due to buoyancy effect. For the principle to properly work, it is essential that the FCs remains in their open position until the casing has been cemented. During cementing, external pressure loads are formed due to hydrostatic pressure differences inside the casing and outside the casing, this does not affect the flexible coupling which has collapse strength far beyond that of the casing. After cementing, drilling is continued and well completed with conventional methods. Operational loads are governed by wellbore pressure and temperature changes. As wells warm up after drilling fluid circulation or injection is stopped, the casing thermally expands and generate stresses that once high enough the FCs start to close. Once the well is fully hot, the FCs are designed such that all the connections will be closed with residual compressive stress to approximately 30-80% of the yield strength of the casing. This will ensure that plastic strains cannot form and that the connections remains in a closed position.

Computer aided design (CAD) with finite-element method analyses (FEM) was used to design, evaluate and improve the Flexible Coupling, both prior to prototyping and for improvements after and between prototype test phases (Figure 7).

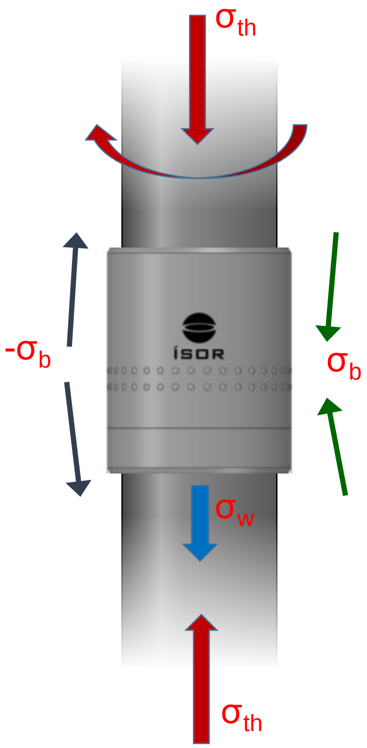

Figure 6: Main load cases that were considered for installation and operational loads.

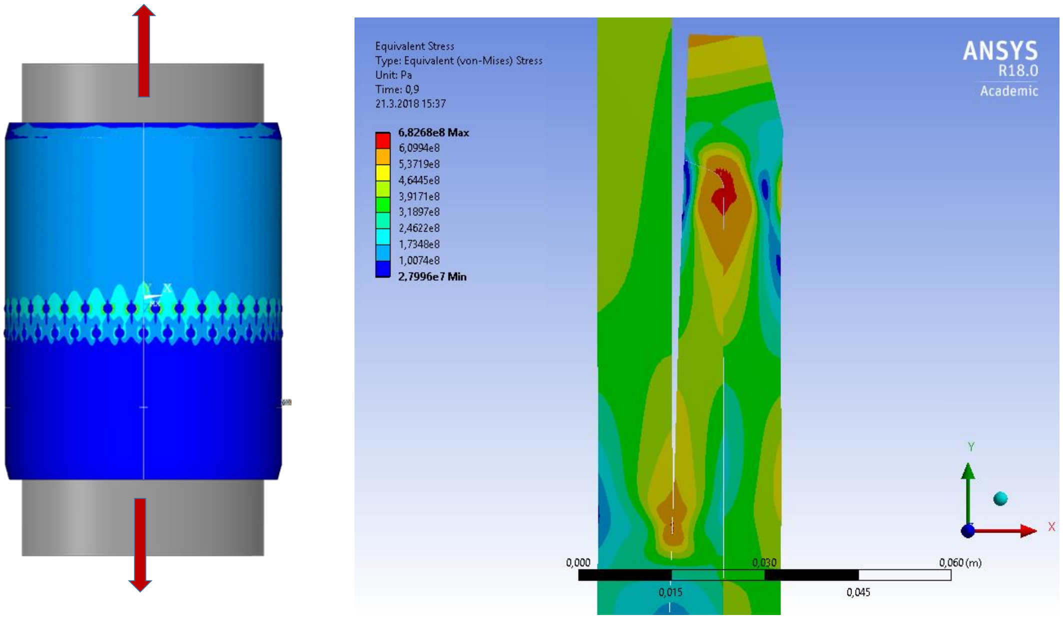

Figure 7: Structural finite-element analysis was used throughout the R&D process to identify critical areas and improve features to make the FC balanced, e.g. in terms of minimizing stress concentrations and material usage and maximizing its function and ultimate tensile load capacity.

4. Functional Testing at Ambient and Field Conditions

Flexible Couplings were tested in full scale 9 5/8” and 13 3/8” casing sizes. Prototypes were made in L80 (AISI 4140-4) medium carbon steel, suitable for J55, K55 and L80 casing material. In third party laboratory at SINTEF in Trondheim Norway (www.sintef.no). the first three 9 5/8” Flexible Couplings were tested at ambient temperature with pressurized water (Figure 8). These prototypes were tested both in straight tension and compression and with bending representing dogleg of 2.5 and 5 degrees pr 30 m. Testing revealed that the dogleg had no influence on the Flexible Coupling function to allow expansion nor contraction of casing into the connection. After these tests the further testing was done at NORCE (www.norce.no) laboratory in Stavanger Norway.

Figure 8: Flexible Coupling prototype testing at ambient temperature at SINTEF, Norway.

At NORCE, one 9 5/8” and three 13 3/8” were tested in the same setup as earlier used but now only with straight movement in both tension and compression. All prototypes in both laboratories were at the end of test cycles tested for ultimate tensile loading. During intervals between prototype testing, development work to implement learning into design was carried out resulting in some changes in ultimate loading as can be revealed in Table 1.

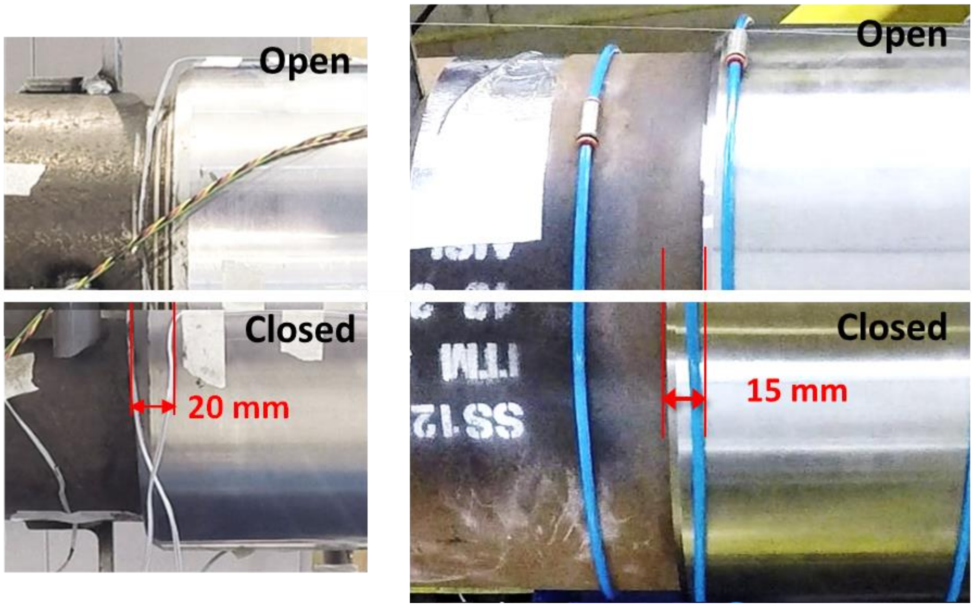

Figure 9: Function of the FC tested by hydraulic jacks at ambient conditions: 9 5/8” with 20 mm travel capacity at SINTEF, Trondheim, Norway (left) and 13 3/8” with 15 mm travel capacity at NORCE, Stavanger, Norway. The sliding function testing showed that a consistent force of 200 kN and 300 kN was needed in order to move the sliding part of the FC.

Table 1: Test results from Flexible Coupling prototype tests in two diameters; 9 5/8” and 13 3/8”.

Prototype:	Start force	Sliding force	2.5° bending: Sliding force	5° bending: Sliding force	Ultimate tensile load
	(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

With a safety factor from the NZS 2403:2015 standard safety load for working stress design of 1.8 the safe running load of the casing in hole can be set to 2444 kN (250 Tonnes) for the 13 3/8” casing and 1667 kN (170 Tonnes) for the 9 5/8” casing. In both cases this can allow casing length of 2430-2470 m with 68 lb/ft casings, hanging free in air with no fluid in the wellbore. If fluid is present in the wellbore as normal is the case the casing length can be calculated with regards to buoyancy that will increase the allowable casing length. If the need is for higher loading the design of Flexible Coupling allows for higher strength material than tested.

Within the GEOTHERMICA national co-funded project GeConnect, the FC was tested in a surface experiment where a casing equipped with a FC was cemented into an external casing simulating well conditions (Figure 10). Together with the FC, cement sheath integrity and the cement-metal boundary were tested and evaluated by applying thermal cycling loads at moderate (~120°C) to high temperatures (262°C). The experiment was conducted in November and December 2021 at the geothermal field Hverahlíð which is a part of the Hellisheiði power plant (303 MW electricity and 133 MWt of hot water) operated by ON Power a subsidiary of Reykjavik Energy. Experimental parameters were monitored using various scientific measurement equipment, i.e. pressure, temperature, displacements and strain, as well as distributed strain and temperature along the inner casing using optical fibers conducted by GFZ (German Research Centre for Geosciences). The displacement of the thermally expanding casing into the FC was monitored with a monitoring rod that was lead through a stuffing box where a proximity sensor could be used for data recording (Figure 11).

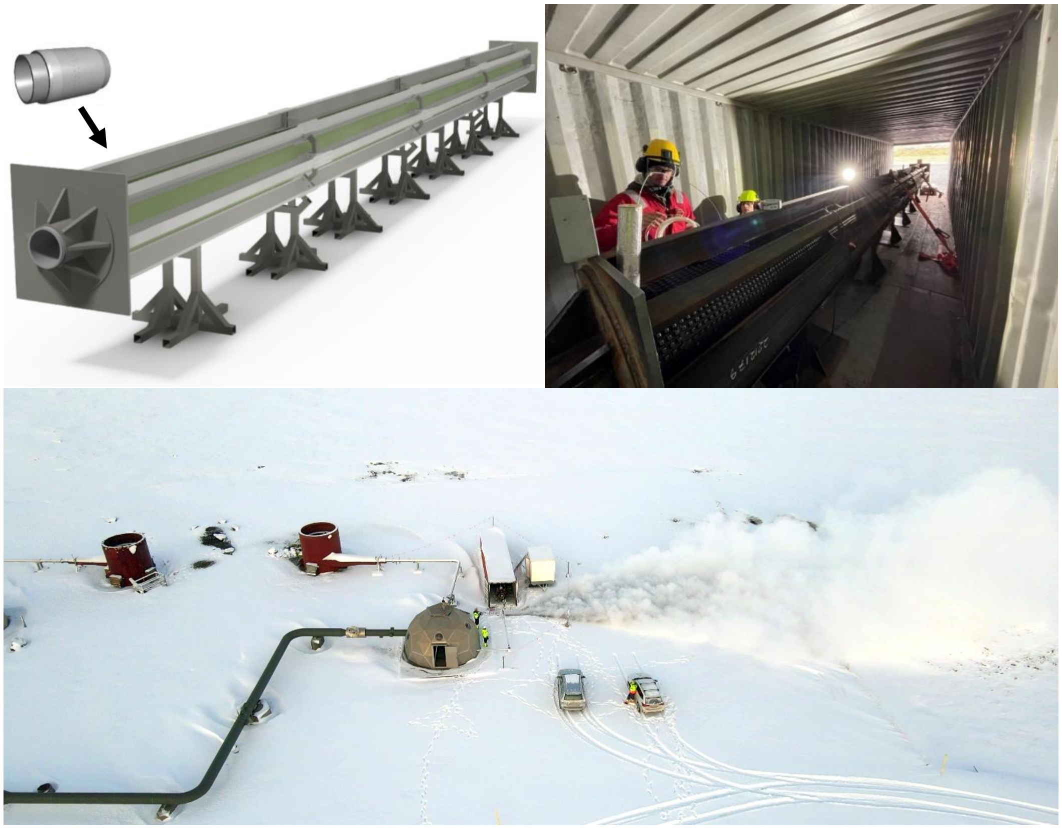

Figure 10: Experiment on the surface where a casing joint (10 m) equipped with a Flexible Coupling was cemented into another casing and expansion forces held with structural beams to simulate the confined downhole conditions. Steam from well in Hverahlíd, Iceland, operated by ON Power a subsidiary of Reykjavik Energy, was used to heat up the casing experimental setup to maximum temperature of 262°C and 57 bar-g pressure.

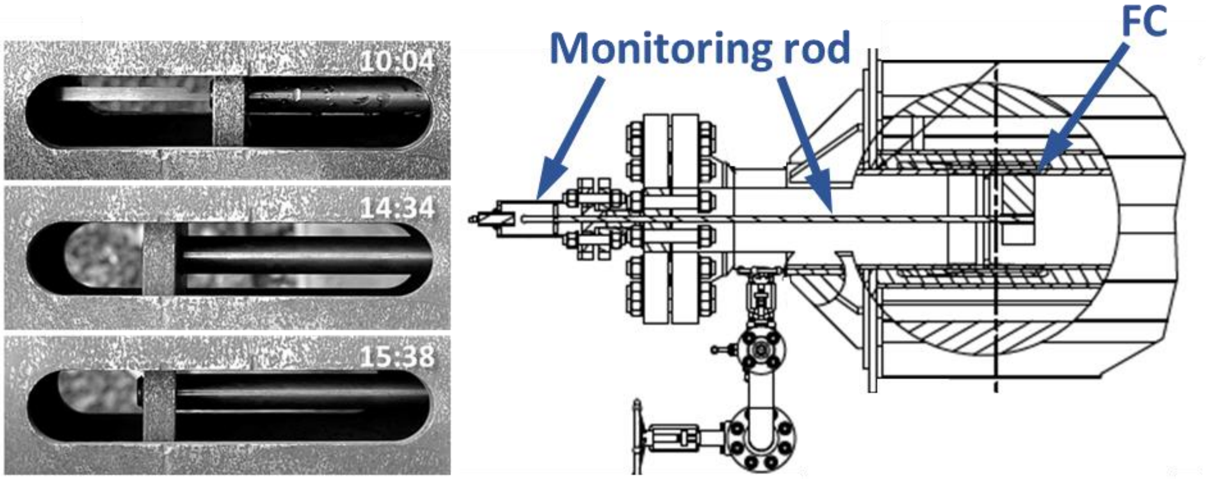

Figure 11: Monitoring of displacement of casing into the FC in surface experiment (right). Displacement of casing expansion into the FC monitored with a proximity sensor, initial position and after closure (left).

Total of five thermal cycles were conducted. The casings expansion and displacement into the FC was closely monitored and the results showed that the FC closed when the casing expanded and opened again while the casing cooled down, verifying its function.

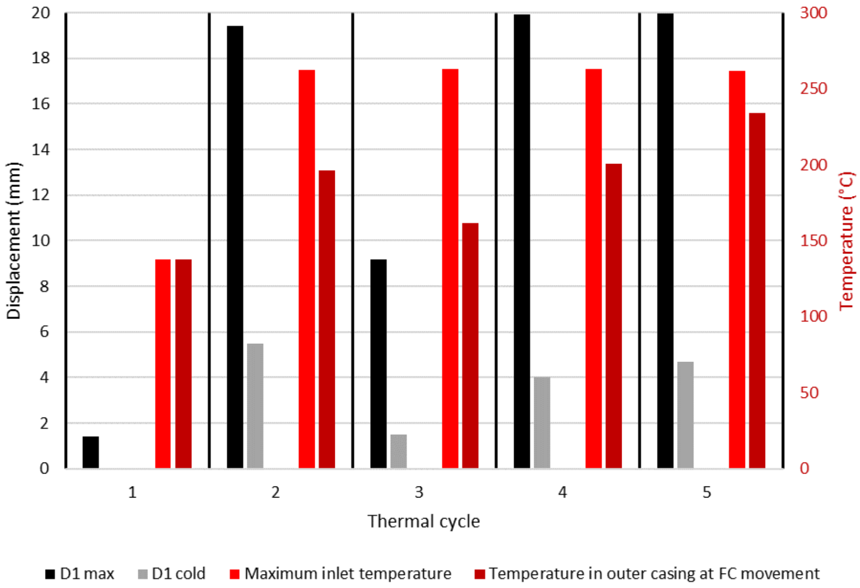

Figure 12: Summary of results of thermal cycling testing in an experiment conducted at the surface verifying the function of a cemented in Flexible Coupling at relevant temperature. Note that full closure was not obtained in thermal cycle nr. 3 due to a failure in the test frame, later repaired (Kaldal, et al., 2022).

Figure 13 shows results of thermal cycle nr. 2 of 5 that were conducted in the surface experiment within the GeConnect project where downhole conditions were simulated and the function of the Flexible Coupling (FC) was shown. The results show a displacement of a cemented casing, closing the FC relieving compressive axial thermal strain (Kaldal G. S., et al., 2022). For reference onset of yield occurs at around compressive strain of 1850 με (379 MPa) for the API K55 casing used in the experiment, where for a maximum temperature change of 262°C for a fully constrained casing the resulting strain level of 3400 με surpasses the yield point significantly.

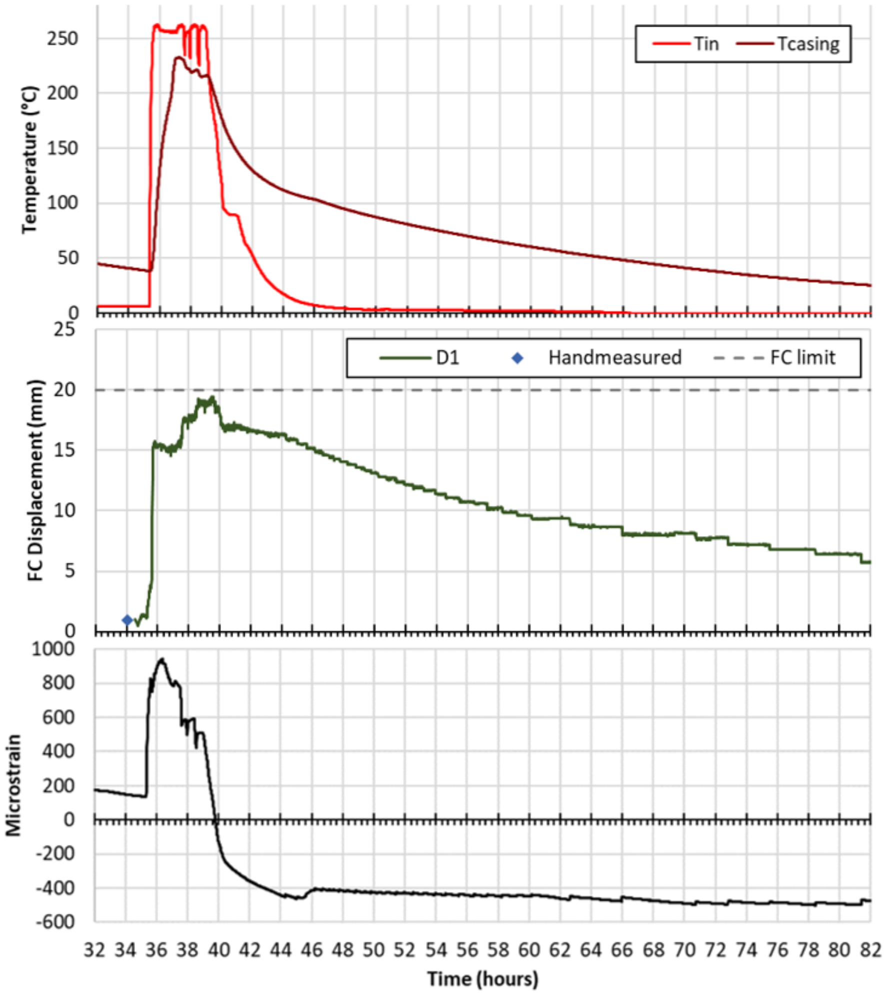

Figure 13: Results of thermal cycle nr. 2 of 5 conducted in an experiment (GeConnect) simulating downhole conditions where the function of the Flexible Coupling (FC) has been shown with a displacement of a cemented casing, closing the FC relieving compressive axial thermal strain (Kaldal, et al., 2022). For reference onset of yield occurs at around compressive strain of 1850 με for the API K55 casing (compared to 3400 με for ΔT of 262°C for a fully constrained casing).

5. Field Test – Running Flexible Couplings in Hole

In the summer of 2020, ON Power, a power company in Iceland, drilled a well into their high-temperature field at Nesjavellir in SV-Iceland and showed interest in testing using 13 3/8” FC prototypes that were produced within the H2020 supported project DEEPEGS. The FC connections were produced and ready by the time the drilling started. In preparations to remove conventional buttress thread connection (BTC) from the already purchased casings, a hydraulic power tong was hired, capable of both removing the old couplings and making up the connection of the FC to the required torque. Removing the couplings at the drilling company facility proved, however, to be difficult and it was decided to remove them on the drilling rig instead. Therefore, the FCs were placed hand-tight at the opposite end of the BTC connections prior to delivering at the drill site. During running in hole the casing couplings were still difficult to remove without damage to the casing, due to this only one FC was successfully installed to a depth of 953 m MD measured from the rig floor and the rest were of conventional BTC couplings. A video log was conducted and it confirmed that the FC was in its open position as it should be, after well completion and before the well was warmed up (Figure 14).

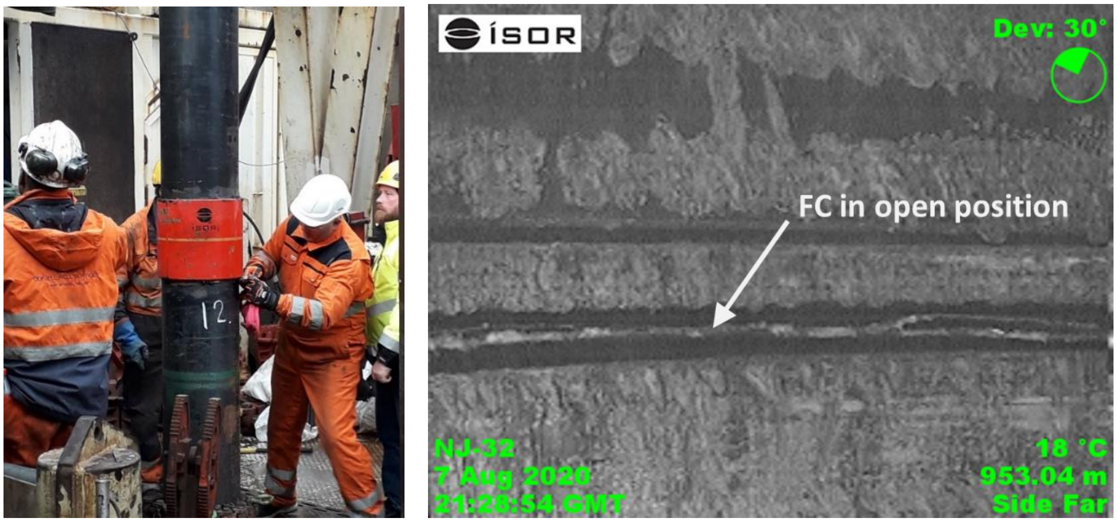

Figure 14: Casing run in hole with Flexible Coupling in well NJ-32 at Nesjavellir, Iceland (left, picture by Tobias Weisenberger). Video log of FC at 953 m depth MD from the rig floor showing its initial open position prior to the well heating up and closing the gap (right).

Conclusions

The concept of enabling axial displacement of the production casing in high-temperature geothermal wells has been shown to be possible with the use of Flexible Couplings. This patented concept will lower the risk of casing damage and flow restriction, enabling cost saving through an increased number of successful wells. Not only are the geothermal wells around 30% of the CAPEX for a new geothermal power plant, but the need for make-up wells is costly for the longer operation of power plants. Enabling use of superheated/supercritical areas are also an area where this novel technology is essential as current technology with fixed couplings have shown to be insufficient with casing failures as a result of constrained thermal expansion. In near future a full casing string with Flexible Couplings will be used in Iceland, where already 85 Flexible Couplings are available for full scale operation of this new technology.

Acknowledgement

The work presented here has been supported by EU Horizon 2020 through projects GeoWell (no. 654497) and DEEPEGS (no. 690771), and the GeConnect (no. 731117) project funded through the ERANET co-fund GEOTHERMICA, from the European Commission, Technology Development Fund (Iceland), Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages (Germany) and Ministerie van Economische Zaken (The Netherlands). We would like to kindly thank our partners for their valuable contributions in the previously mentioned projects.

REFERENCES

Böðvarsson, G. (1961). Physical characteristics of natural heat resources in iceland. *Jökull*, 29-38.

Ingason, K., Kristjánsson, V., & Einarsson, K. (2014). Design and development of the discharge system of IDDP-1. *Geothermics, 49*, 58-65.

Kaldal, G. S., & Thorbjornsson, I. (2016). Thermal expansion of casings in geothermal wells and possible mitigation of resultant axial strain. *European Geothermal Congress, Strasbourg, France, 19-24 Sept 2016.*

Kaldal, G. S., Jonsson, M. T., Palsson, H., & Karlsdottir, S. N. (2016). Structural modeling of the casings in the IDDP-1 well: Load history analysis. *Geothermics*, 1-11.

Kaldal, G. S., Jonsson, M., Pálsson, H., Karlsdóttir, S. N., & Thorbjornsson, I. (2011). Load History and Buckling of the Production Casing in a High Temperature Geothermal Well. Stanford: Stanford University, PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering.

Kaldal, G. S., Lipus, M., Jónasson, H., Guðmundsson, L., Gunnarsson, B. S., Thorbjornsson, I., & Einarsson, G. M. (2022). *Experimental Results of Surface Demonstration.* Reykjavik: ÍSOR - Iceland GeoSurvey.

Karlsdottir, S., & Thorbjornsson, I. (2012). Hydrogen Embrittlement and Corrosion in High Temperature Geothermal Well. *Nace International Corrosion Conference & Expo 2012.* Salt Lake City: NACE.

Rahman, S. S., & Chilingarian, G. V. (1995). *Casing design theory and practice.* Amsterdam - Lausanne - New York - Oxford - Shannon - Tokyo: Elsevier.

Thorbjornsson, I. (1995). Corrosion fatigue testing of eight different steels in an Icelandic geothermal environment. *Materials and Design*, 97-102.

Thorbjornsson, I. O., & Kaldal, G. S. (2021). Flexible Couplings for Improved Casing Design in High-Temperature Geothermal Wells. *World Geothermal Congress.* Reykjavik.

Thorbjornsson, I., Kaldal, G. S., & Ragnarsson, Á. (2019). Testing Flexible Couplings for Geothermal Wells. *GRC Transactions, Vol. 43.* Palm Springs: Geothermal Resources Counsil.

Thorbjornsson, I., Kaldal, G., Krogh, B., Palsson, B., Markusson, S., Sigurdsson, P., . . . Jonsson, S. (2020). Materials investigation of the high temperature IDDP-1 wellhead. *Geothermics*.

Thorbjörnsson, I. Ö., Kaldal, G. S., Gunnarsson, B. S., & Ragnarsson, Á. (2017). A new approach to mitigate casing failures in high-temperature geothermal wells. Salt Lake City: Geothermal Resources Counsil.