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Casing Connection Evaluation for High-temperature Geothermal Applications – A Case Study

Mark Droessler[1], Gang Tao[1], Kirk Hamilton[1], Barry Skelton[2], and Masaki Yoshikawa[3]

[1]C-FER Technologies (1999) Inc., 200 Karl Clark Road, Edmonton, Alberta, T6N 1H2 Canada

[2]JFE Technical Center, 31 Jurong Port Rd, #05-10 Jurong Logistics Hub, 619115 Singapore

[3]JFE Steel Corporation, 1, Kawasaki-cho 1-chome, Handa, Aichi 475-8611 Japan

m.droessler@cfertech.com; g.tao@cfertech.com; k.hamilton@cfertech.com; barry.skelton@jfetc.com; ma-yoshikawa@jfe-steel.co.jp

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ABSTRACT

Casing connection integrity is a critical element in ensuring structural integrity and pressure containment of casing strings throughout the life of a geothermal well. A primary loading mechanism for cemented intermediate and production casing strings is constrained thermal expansion and contraction. Sufficient temperature variations can lead to thermally-induced axial loads in the casing string that exceed the elastic limit, resulting in plastic deformation. Accordingly, traditional connection performance envelopes that are based on design margins below the elastic limit are no longer applicable for such scenarios. Therefore, connection evaluation procedures that incorporate post-yield cyclic thermal loading are required to ensure structural integrity and sealability in geothermal applications where such temperature variations can occur.

Existing thermal well casing connection evaluation protocols, such as ISO/PAS 12835, which provides procedures for the assessment of threaded casing connections for thermal well applications with peak operating temperatures between 180°C and 350°C, can form the basis of a connection evaluation program for high-temperature geothermal applications. Although ISO/PAS 12835 was not developed specifically for geothermal applications, the principles and procedures outlined in the protocol can be suitably adapted to evaluate connection performance under geothermal operating conditions.

This paper presents a case study on a customized casing connection evaluation program based on ISO/PAS 12835 procedures for a peak operating temperature of 290°C. The program evaluated the sealability and structural performance of 244.5 mm, 69.9 kg/m and 339.7 mm, 101.2 kg/m grade L80 JFELION™ premium connection designs for a high-temperature geothermal application in Indonesia. Key components of the evaluation program are described, including the material property characterization, finite element analysis (FEA), and full-scale testing. Important considerations for executing the evaluation program are highlighted, and areas for modification and extrapolation of existing casing connection evaluation procedures to develop a fit-for-purpose geothermal casing qualification protocol are introduced.

1. INTRODUCTION

In many geothermal wells, production casing serves as the primary conduit for delivering produced fluids from the reservoir to the surface, and as the well barrier maintaining pressure containment. As most casing failures have occurred at connections (Zahacy 2018), maintaining casing connection integrity is critical to ensure safe and reliable operation of geothermal wells. As such, casing connection designs should be evaluated under load conditions that represent the operating conditions throughout the life of a geothermal well. In particular, the high-temperature conditions in geothermal wells can create severe thermally-induced axial loads that may exceed the yield strength of the casing material. These large, post-yield thermal loads can create significant challenges to the integrity of casing strings and casing connections and should be considered during casing design for geothermal wells.

A fit-for-purpose evaluation program was performed to qualify 244.5 mm, 69.9 kg/m and 339.7 mm, 101.2 kg/m grade L80 JFELION™ premium connection designs for a geothermal application in Indonesia, with a maximum operating temperature of 290°C. Using this evaluation program as a case study, this paper discusses important considerations for casing connection evaluation for geothermal applications.

2. CASING CONNECTIONS IN GEOTHERMAL APPLICATIONS

2.1 Cyclic Thermal Loads

Most geothermal operations produce high-temperature fluids either directly up the production casing barrier envelope (in flowing wells) or up wells with high-temperature production systems (in pumped wells). Casing used in geothermal wells is often exposed to high production fluid and/or reservoir temperatures. Conversely, the same casing may also be exposed to relatively low temperatures during well construction and cementing, water injection, stimulation, or workover operations, resulting in large temperature variations during the life of the well. These temperature variations may induce significant thermal stresses in the well, which has been identified as a primary consideration for geothermal well design (Droessler et al. 2016).

Once a given casing string is cemented in place with a competent cement sheath, the cement constrains thermal expansion and contraction of the casing. With sufficiently large variations in temperature, the thermally-induced axial loads may exceed the yield strength of the casing material and cause plastic deformation.

Figure 1 presents an illustration of the relationship between the thermally-induced axial load and the temperature, with two cycles of constrained thermal expansion (heating) and subsequent constrained thermal contraction (cooling). As shown in the figure, large compressive stress is generated during the first heating phase. As the temperature continues to increase, the axial-compressive stress exceeds the elastic limit of the material and causes plastic deformation in the casing. At the peak temperature, stress relaxation occurs as a result of the strain rate dependency of the material. The subsequent cooling phase results in a decrease of the axial-compressive load, and a further temperature reduction leads to development of axial tension within the casing string. When the temperature reduction is large enough, plastic deformation may also occur in the tensile direction. Multiple thermal cycles are typically expected during the well life due to varying production and workover operations, and the resulting cyclic thermal loads may lead to low-cycle fatigue failure of the casing.

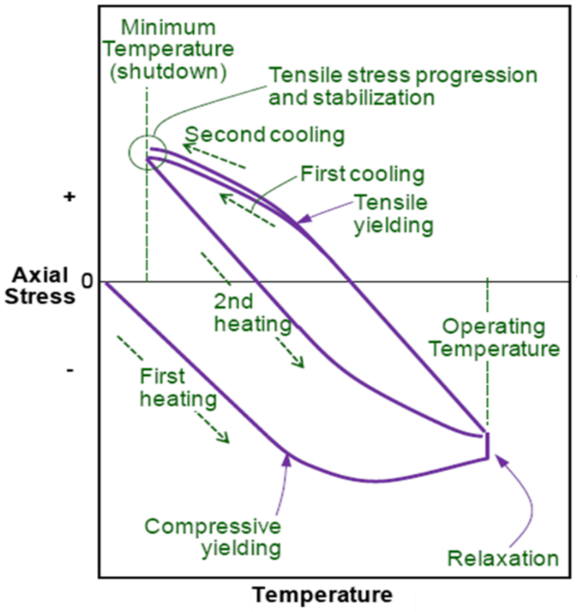


Figure 1: Axial Stress versus Temperature Profile (DACC 2012)

2.2 Strain-based Design

In situations where thermal stresses exceed the yield strength of the casing, conventional stress-based design approaches using the elastic limit as the design criteria are no longer applicable; strain-based approaches that accept limited plastic strains may be more suitable. For example, a design criterion considering an acceptable upper limit of 1.5% total strain in thermal well casing designs has been adopted for many in-situ thermal heavy oil recovery projects in Alberta, which is a province in Western Canada where most of Canada's heavy oil and bitumen reserves are located (Xie 2006). The strain-based design concept also applies to the casing connection performance evaluation for high-temperature geothermal wells where the thermal loads of the conventional connection performance envelope are based on the elastic limit of the pipe body.

Because the post-yield response of the casing material is important in strain-based design, characteristics of the material behaviour in the plastic region need to be considered when applying strain-based design and connection evaluation approaches. Some important considerations include strain localization, stress relaxation, and cyclic strain hardening material behaviour and location in the design.

Strain localization can occur where variations in local factors, such as geometry or material properties, contribute to a non-uniform strain distribution, and can result in mechanical strains in critical locations of the design that are several times higher than the average casing strain (Nowinka et al. 2007; Xie 2008).

The post-yield behaviour of most steel materials shows strain rate dependency (i.e. viscoplasticity), especially at elevated temperatures (Nowinka et al. 2007). Stress relaxation in highly stressed regions at elevated temperature, such as in connection threads and seal regions, can significantly impact the sealability and structural performance of a connection, especially during cooling. Therefore, it is important to characterize such behavior for thermal well design and connection evaluation. In this case study, material property characterization tests were customized with special considerations to capture the strain rate dependency, as described in Section 4.1.

Cyclic strain hardening represents strengthening of the steel through plastic deformation, wherein the material yield strength increases with repeated load cycles. Although cyclic strain hardening can contribute to reduced material ductility and material degradation, it can also serve as a favorable feature for thermal casing design by increasing resistance to strain localization and other deformations (Xie 2008).

2.3 Casing Connections

There are three general types of casing connections used in geothermal applications: premium, semi-premium, and American Petroleum Institute (API) buttress designs. API round connections, including short-threaded and coupled (STC) and long-threaded and coupled (LTC) designs, are another type of connection popular for oil and gas applications. However, they do not provide adequate axial load carrying capacity for most geothermal applications and are more susceptible to thread jump-out and jump-in failures compared to other connection designs (Xie and Tao 2010).

API buttress connections (BTC) utilize a trapezoidal thread form and have the potential to provide adequate structural capacity; however, they typically have limited sealing capacity as they rely on thread compound to seal the helical gap between the threads. Many thread compounds degrade at elevated temperatures, potentially compromising the reliability of the seal in geothermal operation conditions. BTC have been shown to leak under thermal well conditions above 200°C (Maruyama et al. 1990), in part due to their reliance on thread compounds for connection sealability.

Semi-premium connections utilize proprietary thread profiles that provide adequate structural capacity, but they lack a dedicated radial metal-to-metal seal (and the contact force between the pin faces of a semi-premium connection can unload during cooling, thereby removing any seal capacity at that location).

Several premium connection designs that utilize a radial metal-to-metal seal have been shown to maintain sealability at elevated temperatures up to 350°C (Maruyama et al. 1990; Xie and Tao 2010) and have been recommended where gas-tight seals are required (Torres 2014). In thermal recovery and geothermal wells, leakage of wellbore fluids may contribute to issues such as degradation of cement integrity, weakening of water-sensitive formations, and compromised casing and/or connection integrity due to corrosion and/or erosion. To prevent such damage and failures that can result from connection leakage, Alberta’s Industry Recommended Practice (IRP) 3 specifically recommends using qualified premium connections for production casing strings (DACC 2012).

3. GEOTHERMAL CONNECTION EVALUATION

3.1 Connection Evaluation Procedures

Prevalent connection evaluation procedures include ISO 13679 and API RP 5C5 for applications with temperatures up to 180°C, and the Thermal Well Casing Connection Evaluation Protocol (TWCCEP) for applications between 180°C and 350°C (Merliahmad et al. 2015).

The intentions of ISO 13679 and API RP 5C5 are to evaluate connections under stress-based load conditions within the triaxial yield or collapse limits of the pipe body. However, near-yield loading has been shown to produce localized plastic deformation at stresses below the measured material yield strength, particularly at elevated temperatures where the stress-strain curve typically becomes rounded (Nowinka et al. 2017). While the most recent release of ISO 13679 considers these near-yield loading effects, the procedures do not consider thermally-induced loads or the post-yield thermal-mechanical behaviour of the material and are therefore not representative of loading conditions experienced in high-temperature thermal wells.

Originally developed as a joint industry project consisting of thermal well operators and connection manufacturers, the TWCCEP was adopted by the International Standards Organization (ISO) as a Publicly Available Specification (PAS) in 2013. The protocol is not an international standard as per the definitions of ISO, but it is in the process of undergoing updates based on feedback from a wide range of industry experts, such as premium connection manufacturers, thermal oil recovery operators, qualified test labs, and (more recently) geothermal operators. As use of ISO/PAS 12835 expands globally, it is anticipated that it will eventually become the international standard to evaluate casing connection performance for thermal applications (including geothermal).

ISO/PAS 12835 provides procedures for the assessment of threaded casing connections for service in thermal recovery wells with operating temperatures up to 350°C. This assessment includes the galling resistance, structural integrity and sealability of the connections under typical assembly and service loads in thermal recovery wells through a combination of finite element analysis (FEA) and full-scale experimental testing. Essential to the assessment philosophy of ISO/PAS 12835 is evaluation within a strain-based design framework, where applied axial loads and strains are driven by constrained thermal expansion and contraction, typically exceeding the traditional elastic connection design envelope.

3.2 ISO/PAS 12835 Evaluation Scope

An ISO/PAS 12835 evaluation program consists of three main components: determination of a biased test population, test specimen procurement and full-scale tests.

Determination of biased test population consists of material property characterization and specimen configuration analysis. The objective of the material property characterization is to determine reference thermo-mechanical properties by conducting material coupon tests at room and elevated temperature conditions. The results of the material property characterization are used as inputs for the subsequent identification of the biased test population using FEA evaluation and for determining some of the load step conditions for full-scale tests. Specimen configuration analysis consists of parametric FEA evaluation to identify the worst-case combinations of connection tolerance geometry, material yield strength range and make-up torques for subsequent test specimen procurement and assembly.

The full-scale testing phase of an ISO/PAS 12835 evaluation program consists of the galling resistance, thermal cycle, and limit-strain tests, as well as an optional bending evaluation test. The galling resistance test subjects four connection specimens to multiple make-up and break-out cycles to assess the connection’s ability to withstand galling. The subsequent thermal cycle test evaluates the structural integrity and sealability of four connection specimens under cyclic thermal loading representing the application conditions of the target thermal well application. The limit-strain test (generally tested to failure) assesses the connection’s structural integrity and sealability under strain localization conditions that exceed the strains induced by constrained thermal expansion and contraction.

The thermal cycle test is intended to simulate the cyclic thermal load conditions in a given well, as depicted in Figure 1. During the test, axial displacement of the test specimen is restrained as the test temperature is adjusted, resulting in corresponding temperature-driven axial loads. Internal pressure is applied according to the pressure-temperature relationship for saturated steam, and gas seepage past the seals of the connections is measured and compared with the seepage rate thresholds specified in the protocol, which are

1 mL/min and 10 mL/min for high- and low-temperature holds, respectively. Since achieving sealability thresholds tends to be more challenging for larger diameter connections (with larger diameter-to-thickness ratios), the protocol provides an option to scale the seepage rate thresholds according to the casing diameter relative to 177.8 mm casing. An example of the stress (left) and mechanical strain (right) induced by thermal expansion and contraction of the casing, along with the associated load path of the test program, are presented in Figure 2.

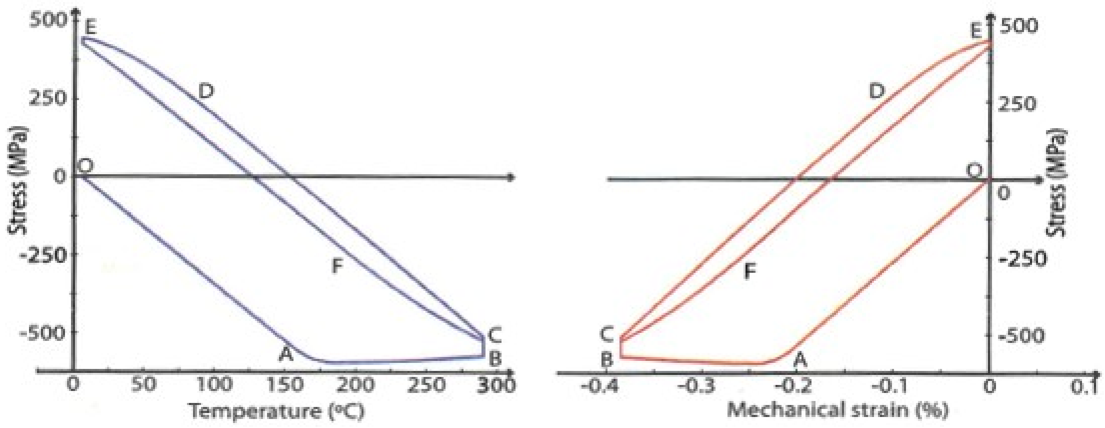


Figure 2: Load Path Examples with Axial Stress versus Temperature (left) and Strain (right) (ISO 2013)

In addition to the thermally-induced axial loads, ISO/PAS 12835 specifies mechanical strain compensations to address practical test execution considerations (e.g. cooling below ambient test conditions) and measurement uncertainties.

3.3 Applicability to Geothermal

Although ISO/PAS 12835 was originally developed for thermal oil recovery wells in Canada, many of the principles and procedures outlined in the protocol may be directly applied or adapted to geothermal operating conditions.

Because the ISO/PAS 12835 assessment procedures were developed within a strain-based design framework where applied loads are driven by temperature, the severity of the load conditions that connections are subjected to depend on the operating temperatures of the application. The maximum operating temperature of the intended application corresponds to the Application Severity Level (ASL) upper-bound temperature, which can be selected by the party that commissions the evaluation program. ASLs defined in ISO/PAS 12835 are listed in Table 1.

Application Severity Level (ASL)	Maximum operating temperature	Lower-bound temperature	Upper-bound temperature
(°C)			
N/A	180		180
240	181 to 240	5	240
290	241 to 290	5	290
325	291 to 325	5	325
350	326 to 350	5	350

Table 1: ISO/PAS 12835 Application Severity Levels (ISO 2013)

The severity of temperature-driven load conditions is a function of the difference between the upper- and lower-bound temperatures of the thermal cycle test. ISO/PAS 12835 assumes a constant lower-bound temperature for all ALSs of 5°C, which is considered a suitable lower temperature for thermal wells in colder climates such as Canada. As many geothermal operations are located in regions with warmer climates where the minimum ground temperature is consistently higher than 5°C, this lower-bound temperature could be reconsidered to ensure that the test conditions are representative of the target application, particularly at the higher ASLs where the greater temperature differential would result in greater induced strains that may exceed field conditions. Alternatively, the evaluator may choose to stick with the lower-bound temperature of 5°C to ensure conservative evaluation conditions or for a geothermal application where the lower-bound temperature conditions are unknown. To minimize deviations from ISO/PAS 12835 procedures and ensure conservative evaluation conditions, the fit-for-purpose evaluation of the JFELION premium connections utilized the ISO/PAS 12835-specified lower-bound temperature of 5°C.

The test procedure prescribed in ISO/PAS 12835 may be considered representative of many geothermal well conditions where intermediate and/or production casing strings are cemented in place at relatively low temperatures (e.g. near surface) and subsequently exposed to high-temperature production conditions. An alternative load path could be considered for other geothermal wells where the starting condition for constrained thermal expansion and/or contraction is at some elevated temperature. For example, a casing string cemented at a relatively deep location within an injection well could be constrained at a temperature near the reservoir temperature. Subsequent fluid injection from the surface, presumably at a relatively low temperature and high flow rate, could cool the casing string towards the injection temperature, generating significant axial-tensile loads from the constrained thermal contraction.

Depending on the operating plans for the geothermal wells being designed, the expected load path should be considered to ensure the connection evaluation program is representative of the most severe loading conditions expected during the life of the wells.

In addition to cyclic thermal conditions, supplementary elements could be added to the evaluation program to investigate performance limits of the casing connections and to replicate other load conditions associated with geothermal well failures. For example, high external pressure due to pressurization of trapped annular fluid, as described by Maruyama et al. (1990) and Torres (2014), may compromise connection integrity. Test components based on modified API RP 5C5 Test Series A or other procedures could be considered for evaluating the external pressure resistance of connections under such scenarios. As drilling of deviated Enhanced Geothermal System (EGS) wells becomes more common, or to consider the potential impact of geomechanical loads, evaluation procedures that include bending loads, such as the ISO/PAS 12835 bend test or API RP 5C5 Test Series B, could also be considered.

4. EVALUATION PROGRAM CASE STUDY: JFELION PREMIUM CONNECTION DESIGN

4.1 Material Property Characterization

The material property characterization was conducted with a series of tensile coupon tests to obtain the temperature-dependent stress-strain response of the L80 material for the pin and coupling components of the connection, as per ISO/PAS 12835. All tests were performed under strain-controlled mode at a strain rate of 0.1% per minute up to 5.5% strain, followed by displacement-controlled mode to specimen failure.

Test coupon specimens were held for one hour at each of the constant strain values of approximately 0.5%, 1.5%, 3.5% and 5.0% to determine the amount of stress relaxation at these strain intervals. Figure 3 shows an example of the stress relaxation curve at 290°C. An exponential regression function was used to fit the stress relaxation curve to estimate the asymptotical value (i.e. the static stress). The estimated static stress values, along with the post-relaxation stress values at the four constant strain intervals, were then fitted using Needleman's curve (Needleman 1975) to obtain a continuous static stress-strain curve, as shown in Figure 4. Note that the elastic portion of the static stress-strain curve is unchanged.

The derived static stress-strain curves were used to define constitutive models for the FEA of the connection design. Using static stress-strain curves is generally accepted to closely represent the material response of casing in geothermal wells where the thermal loads are typically sustained over an extended period of time (i.e. months or years).

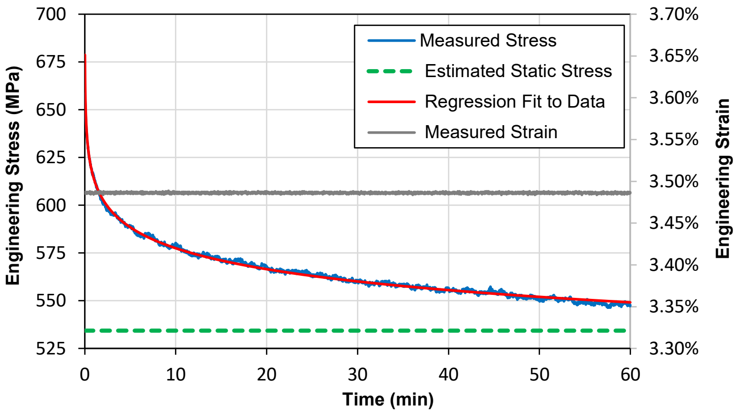


Figure 3: Estimation of the Static Stress from the Stress Relaxation Curve (290°C)

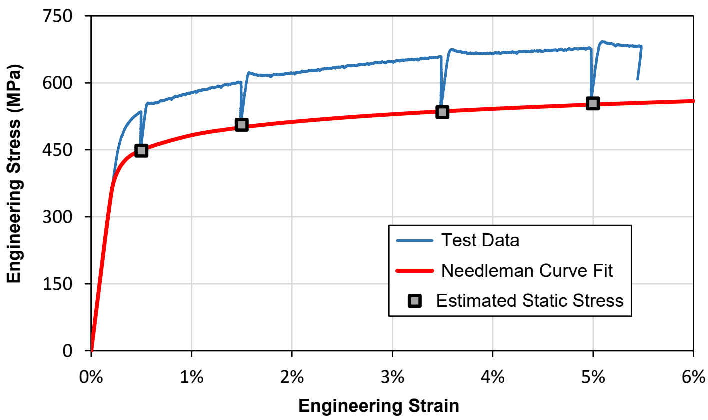


Figure 4: Development of the Static Stress-strain Curve (290°C)

4.2 Finite Element Analysis

ISO/PAS 12835 requires the use of FEA to determine the biased test population of the connection specimens for full-scale laboratory testing, which includes the worst-cases for galling susceptibility and sealability performance. As specified in ISO/PAS 12835, variations of connection manufacturing tolerances (i.e. interference in seal and threads, threads taper) were modelled using parametric FEA to determine the worst-case geometry configurations for both galling and sealability test specimens. In addition, FEA was also used to evaluate the impact of variation in material properties (yield strength within the allowable production range) and final make-up torque (manufacturer-specified range) on the connection response. The analysis results were then used with the ISO/PAS 12835 specifications to determine the appropriate target yield strength and final make-up torque for the connection specimens in the full-scale sealability tests.

Since the load conditions were primarily axisymmetric (i.e. make-up, thermal loading, uniform internal pressure), the casing connection was modelled as an axisymmetric structure by ignoring the spiral feature of the threads. The axisymmetric model allowed the details of the connection geometry to be considered, while also maximizing the computational efficiency. Figure 5 presents an example of the connection FEA model developed using the commercial program Abaqus®. Non-linear responses, such as large deformation, material plasticity, contact interaction and temperature dependency, were considered in the FEA model. With the assumption of the axial symmetry in the geometry and loading at the center planes of the pin and coupling, the connection model consisted of one-half of the casing pipe body and one-half of the coupling of a Range 3 casing joint (12.5 m/41 ft long) as per the modelling requirement described in ISO/PAS 12835. Four-node linear quadrilateral axisymmetric solid elements were used in the FEA model. The connection was modelled with high mesh density in the critical regions, including connection threads, seal and torque shoulder regions. Relatively low mesh density was used in other regions, such as pipe body and coupling. A mesh sensitivity study was performed to ensure accuracy and convergence of the analysis results.

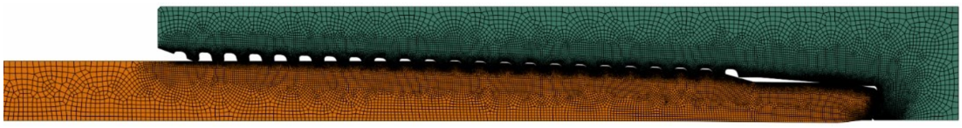


Figure 5: Connection FEA Model Mesh

There are currently no industry-accepted criteria for sealability evaluation of premium casing connections based on analytical methods. ISO/PAS 12835 specifies using the seal contact stress intensity, defined in Equation 1, to evaluate the relative ranking of the various specimen configurations in terms of their sealability. The seal contact stress intensity is the integration of the seal contact stress (σ_c) over the axial length of the metal-to-metal seal region, as illustrated by the blue region shown in Figure 6. The seal contact stress intensity has been used in previous studies to evaluate the sealability performance of premium connections (Xie and Tao 2010, Tao and Xie 2013, Xie et al. 2017).

$$f_s = \int_{L_{ES}} \sigma_c dx \tag{1}$$

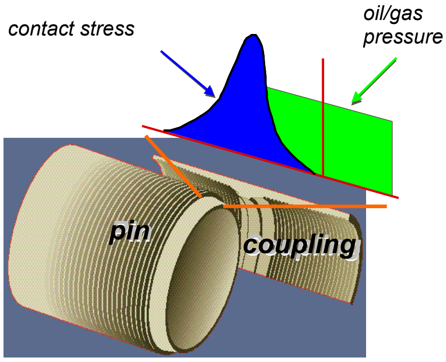
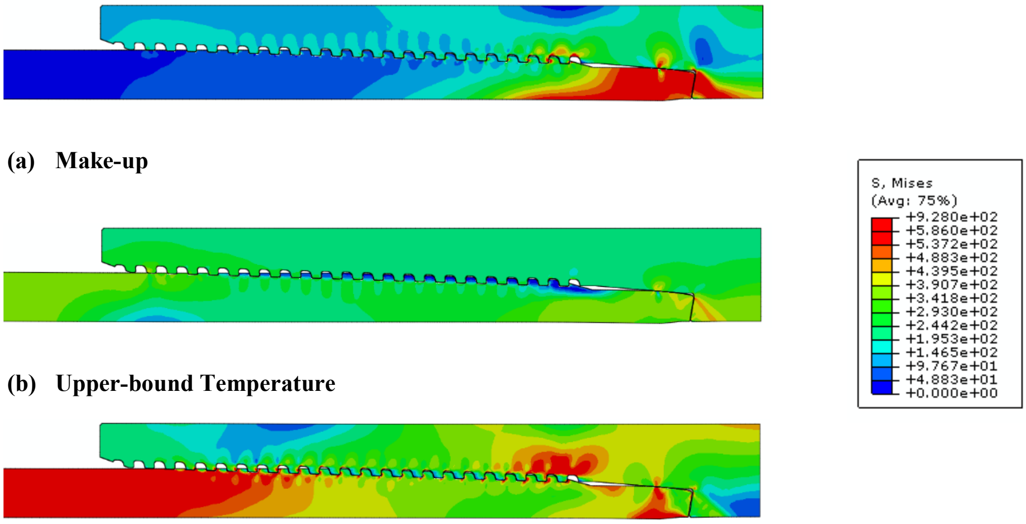


Figure 6: Illustration of Seal Contact Stress in a Premium Connection

Most of the analysis included load steps with either one make-up or two make-ups (one make-up and break-out followed by a final make-up) followed by one thermal cycle. For a few cases that considered the maximum seal interference for determination of galling test specimens, only make-up analysis was conducted.

The connection make-up analysis was performed by resolving dimensional interferences between the pin and the coupling components in the threads, seal and torque shoulder regions. Various torque shoulder interference values were applied in the model to simulate the variation of the final make-up torque condition. The amount of torque shoulder interference applied in the model was calibrated based on actual connection make-up torque-turn curves. Thermal cycle loading was applied by specifying the temperature variation over the entire connection model. Since both the coupling and pin ends of the model were fixed axially to simulate the cement constraint, axial loads were generated as a result of constrained thermal expansion and contraction. The saturated steam pressure was applied on the inner surfaces of the pipe body, connection pin and the coupling. Since ISO/PAS 12835 requires that a groove be cut to bypass the torque shoulder in the physical test, the internal pressure was extended through the torque shoulder to the seal region. The load sequence in the analysis followed the specification of the FEA modelling guideline in ISO/PAS 12835.

Figure 7 shows an example of the effective stress distribution of the connection from the FEA results at several key load steps. Note that the upper-bound temperature is defined as the load point of peak temperature with maximum internal pressure, and the lower-bound temperature is defined as the load point at the end of the thermal cycle. Upon connection make-up, high stresses were developed within the seal and torque shoulder regions, while the pipe body stress was zero. At the upper-bound temperature, the stresses within the seal and torque shoulder decreased as a result of material strength reduction at elevated temperature. High stresses developed within the pipe body due to constrained thermal expansion upon temperature increase. At the lower-bound temperature, the stresses in the seal and torque shoulder regions increased again, but at a relatively lower level than the make-up condition due to the plastic deformation that developed within these regions at the peak temperature. Since the axial-compressive load was large enough to cause the pipe body stress to exceed the yield limit, axial-compressive plastic strain developed within the pipe body, which in turn resulted in high tension along the pipe body upon constrained cooling. Also, a general trend of decreasing seal contact stress intensity over the thermal cycle was observed. The seal contact stress intensity values at both the upper-bound temperature and lower-bound temperature were used to rank the connection specimen configurations examined in the parametric analysis. The worst-case sealability specimen configurations were identified following the procedures described in ISO/PAS 12835.



(a) Make-up

(b) Upper-bound Temperature

(c) Lower-bound Temperature

Figure 7: Effective Stress Distribution of the Premium Connection Over One Thermal Cycle

4.3 Full-scale Test Program

A fit-for-purpose test program was conducted for the worst-case geometries identified from the FEA evaluation based on the galling resistance and thermal cycle test procedures.

<u>4.3.1 Test Specimen Procurement</u>

Casing and coupling stock for the test specimens were manufactured and supplied by JFE Steel Corporation. The seamless casing was manufactured using a Mannesmann piercing mill process, and quenched and tempered to achieve the physical properties as per API Specification 5CT requirements for grade L80.

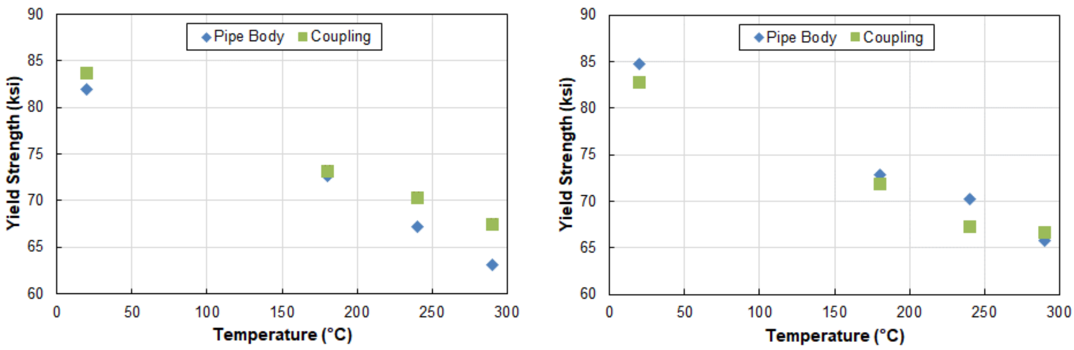


Figure 8: 244.5 mm (left) and 339.7 mm (right) Material Yield Strength Verification Results

The FEA results were used with the ISO/PAS 12835 specifications to determine the appropriate target yield strength and final make-up torque for the connection specimens in the full-scale sealability tests. The yield strengths of the supplied casing and coupling stock were subsequently verified to match the requirements for the biased test population, as determined by the FEA evaluation. Yield strength properties of the casing and coupling stock were tested at 25°C, 180°C, 240°C and 290°C, and the results are shown in Figure 8.

The connections were threaded in accordance with the biased test population requirements determined by the FEA evaluation, as well as JFE's technical requirements. Two specimens were manufactured for each size with tolerances identified by the FEA for worst-case sealability in compression and tension (both cases were the same configuration). Inspection of the connections using speciality gauges was conducted to ensure the precise tolerances were met, and the resulting specimen interference results are provided in Tables 2 and 3. The thread taper was also manufactured in accordance with the biased test population requirements with a slow pin and fast box.

Configuration	Connection Number	Pin Interference		Box Interference		Combined Interference	
		Thread	Seal	Thread	Seal	Thread	Seal
High-low	1A	93.8%	10.0%	112.5%	5.0%	103.1%	7.5%
	1B	87.5%	0.0%	87.5%	5.0%	87.5%	2.5%
High-low	2A	81.3%	10.0%	81.3%	0.0%	81.3%	5.0%
	2B	100.0%	10.0%	81.3%	5.0%	90.6%	7.5%

Table 2: 244.5 mm Connection Interference Results

Configuration	Connection Number	Pin Interference		Box Interference		Combined Interference	
		Thread	Seal	Thread	Seal	Thread	Seal
High-low	1A	81.3%	10.7%	87.5%	0.0%	83.3%	5.8%
	1B	106.3%	17.9%	87.5%	-4.2%	100.0%	7.7%
High-low	2A	87.5%	17.9%	75.0%	12.5%	83.3%	15.4%
	2B	106.3%	14.3%	75.0%	8.3%	95.8%	11.5%

Table 3: 339.7 mm Connection Interference Results

4.3.2 Galling Resistance Test

The galling resistance test consisted of two make-up and break-out cycles of one connection specimen of each size, based on ISO/PAS 12835 procedures, followed by a final make-up of each connection specimen. Connection specimen make-ups and break-outs were completed using vertically-oriented hydraulic power tongs with integrated backups. No galling damage, defined in ISO/PAS 12835 as "cold welding of contacting material surfaces followed by tearing of metal during subsequent sliding," was observed following any of the break-outs. All pin shoulder seals were disabled by filing a small (approximately 0.8mm deep) groove on each pin tip, as per ISO/PAS 12835 requirements, before final make-up. Each final make-up was performed to the maximum make-up torque identified by the FEA evaluation as the worst-case condition for sealability.

4.3.3 Thermal Cycle Test

A full-scale thermal cycle test was completed on 244.5 mm and 339.7 mm test strings, each consisting of two connection specimens, in accordance with ISO/PAS 12835 test procedures, including application of the mechanical strain compensations, where applicable. The thermal cycle test was completed to ASL-290 with an upper-bound temperature of 290°C. Although the intended application in Indonesia was expected to have a minimum ground temperature above the lower-bound temperature of 5°C defined in ISO/PAS 12335, this lower-bound temperature was adopted to ensure worst-case conditions were simulated in the thermal cycle test, and to maintain conformity with ISO/PAS 12835 test procedures.

A load frame was used to react the thermally-induced axial loads generated in the specimen strings. Heat was applied with electrical resistance heating pads and controlled using an automated temperature control system based on feedback from an array of over 50 thermocouples attached along the length of each test string. Internal pressure was applied using nitrogen gas and controlled using an automated control system, which matched the pressure to the saturated steam pressure at the test temperature, where applicable. Connection seepage was collected through holes drilled into the dope relief groove of each coupling and measured by the amount of water displaced from inverted burettes, as described in ISO/PAS 12835. Figure 9 shows an instrumented and insulated specimen test string installed in the load frame.

The relationship between temperature and the resulting axial load and strain is evident in Figure 10, which presents the average specimen string temperature, applied axial load, and average axial strain for the duration of the thermal cycle test conducted on the 244.5 mm test specimen. Although not shown, the load-cycle response for the 339.7 mm test displayed a similar profile.

Important elements of the thermal cycle test data plot are annotated and identified as follows:

1. Cycle 0 (Load Steps 0.1 to 0.9) including elastic loading to establish the zero-strain reference;
2. 24-hour bake-out hold (Load Step 1.3) where stress relaxation can be observed by the decrease in axial load;
3. Application of ISO/PAS 12835 strain compensation prior to the low-cycle temperature hold;
4. First low-cycle temperature hold (Load Step 1.8) under axial-tensile stress;
5. Cyclic strain hardening as indicated by the increase in the measured axial-tensile loads as the cycles progress; and
6. Residual compressive strain at zero load and pressure.

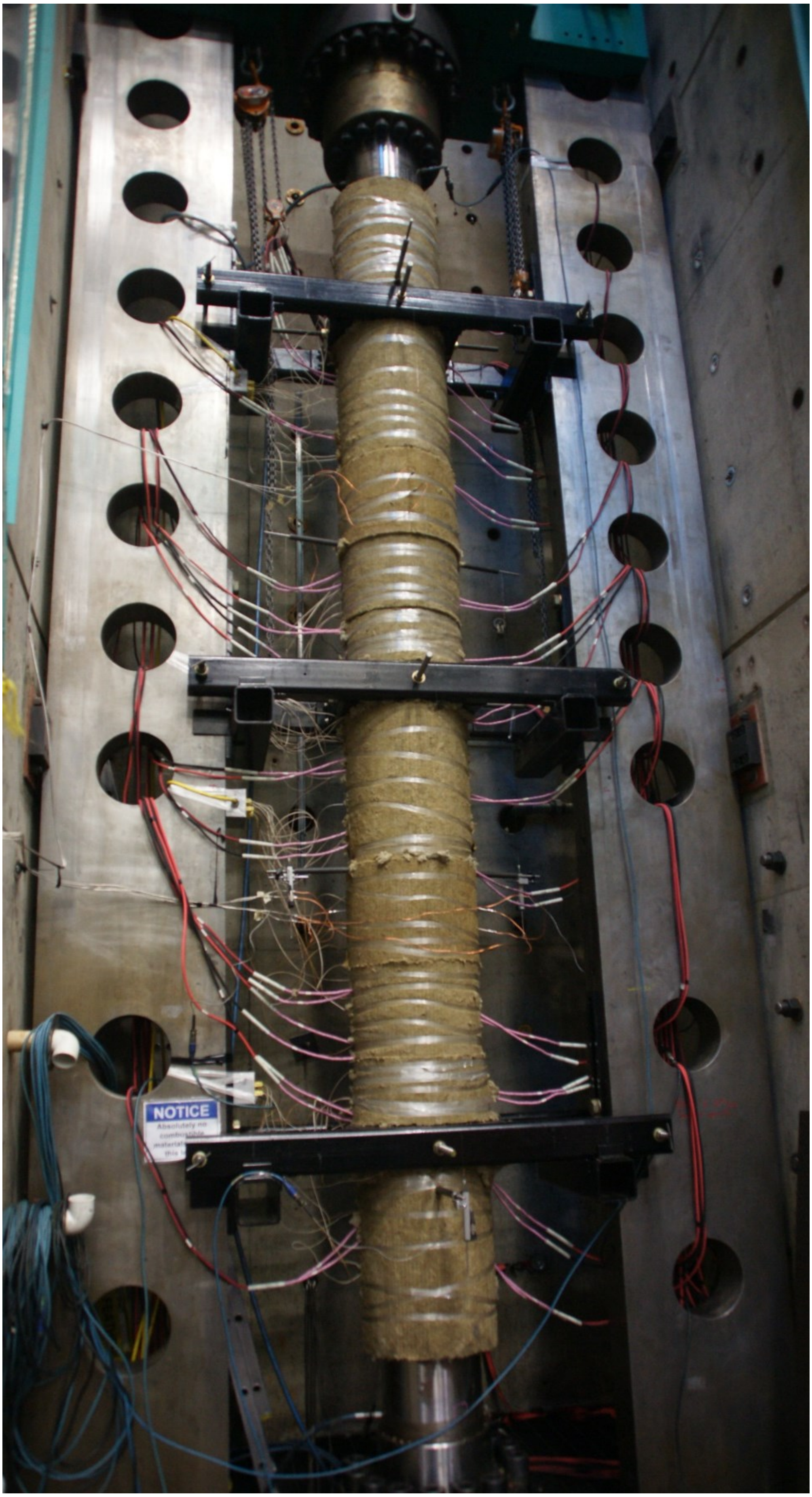


Figure 9: Thermal Cycle Test Setup

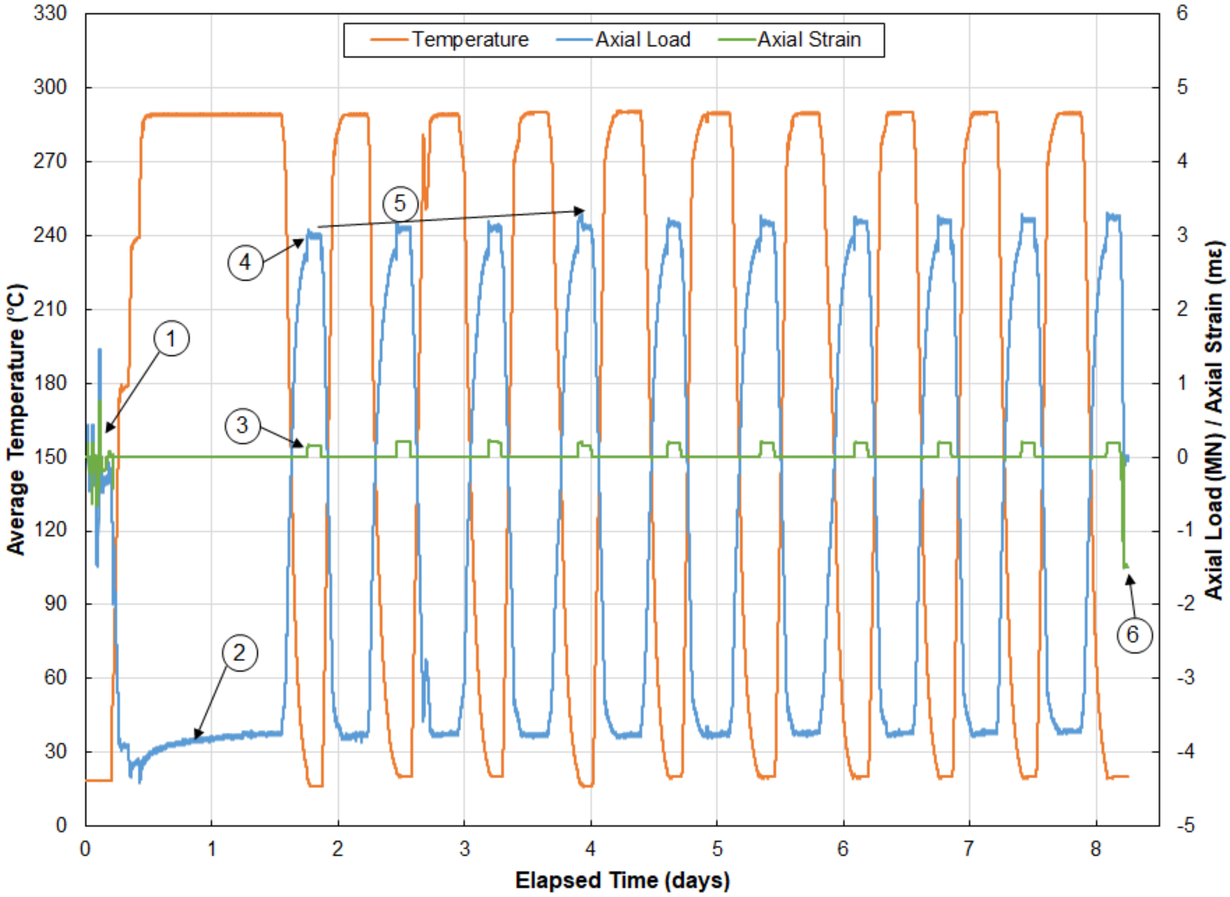


Figure 10: 244.5 mm Thermal Cycle Test Data

During the initial 24-hour bake-out hold (2), the applied axial load gradually reduced as axial strain was held at zero and the temperature was held at 290°C, indicating stress relaxation of the casing material was occurring. The stress relaxation was observed to be most pronounced near the beginning of the hold period, similar to the behaviour observed during the material characterization tests, as discussed in Section 4.1. As the temperature was reduced towards ambient conditions, Figure 10 shows that axial-tensile stress was generated from constrained thermal contraction of the test string. As the thermal cycles progressed, peak axial-tensile loads increased (5), representing cyclic strain hardening behavior, as discussed in Section 2. At the end of the test program (6), applied axial load and internal pressure were reduced to zero, and the resulting residual axial-compressive strain in the specimen string could be observed.

To better visualize the relationship between axial load and temperature, Figure 11 plots the applied axial load against the average temperature of the 244.5 mm test string for the 10 thermal cycles of the test program.

Important elements of the plot are identified as follows:

1. Elastic loading to establish the zero-strain reference;
2. Initial heat-up resulting in elastic thermal compressive stress;
3. Continued heating resulting in yielding and plastic deformation;
4. Stress relaxation during the 24-hour bake-out;
5. Cooling cycles resulting in increasing axial-tensile stress;
6. ISO/PAS 12835 tensile strain compensation; and
7. Subsequent heating cycles resulting in increasing axial-compressive stress.

The linear relationship between axial load and temperature (2) represents the elastic thermal stresses generated from constrained thermal expansion of the casing material during the initial heat-up. The thermally-induced axial stress in this elastic region can be characterized by the elastic modulus and thermal expansion coefficient of the material, as given by Equation 2:

$$\sigma_T = E \cdot CTE_a \cdot \Delta T \tag{2}$$

where σ_T, E, CTE_a, ΔT are the thermally-induced axial stress, elastic modulus, average coefficient of thermal expansion, and change in temperature, respectively. Although the material properties are temperature-dependent, the coefficient of thermal expansion roughly represents the slope of the initial heat-up curve (2) shown in Figure 11.

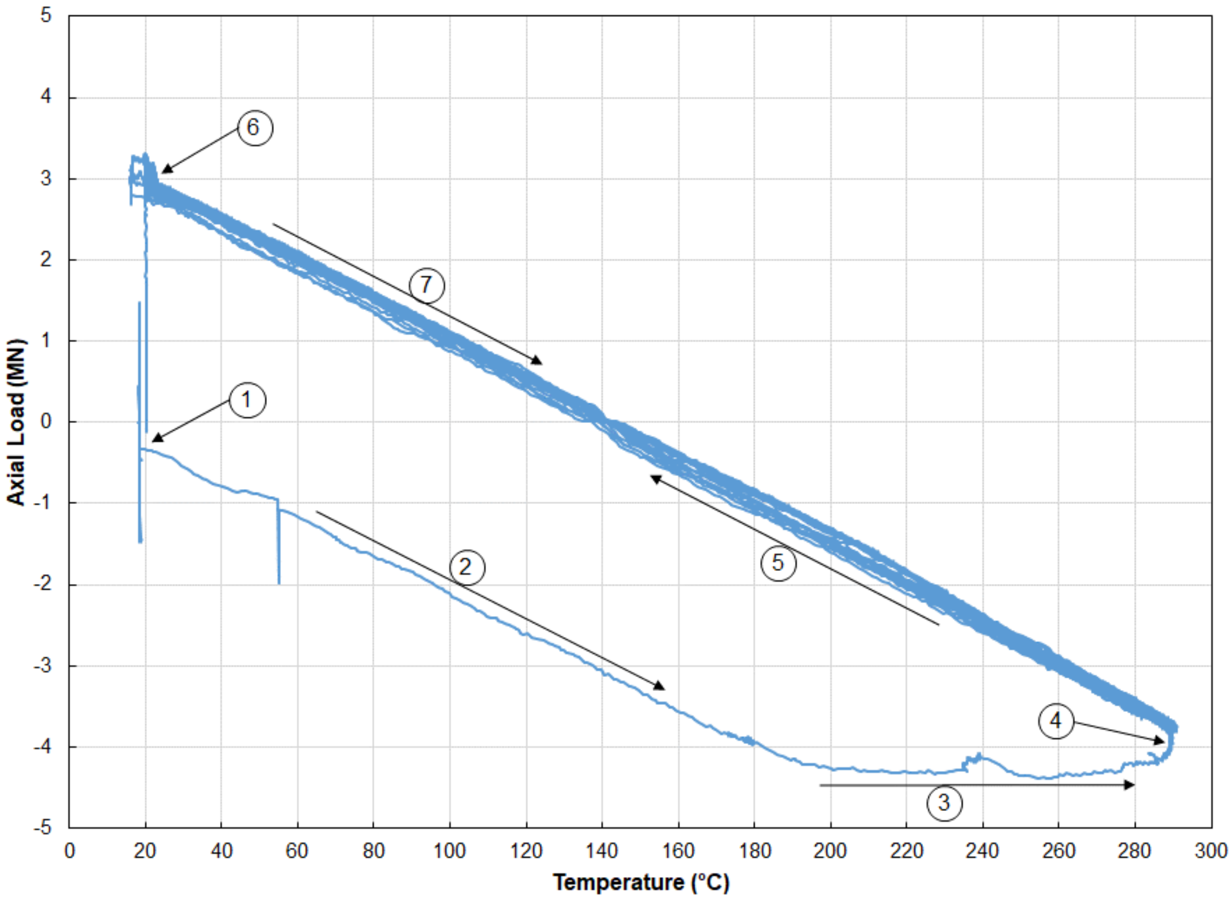


Figure 11: 244.5 mm Thermal Cycle Test Data

As the thermal stresses approached the yield strength of the casing (which is also a temperature-dependent property), plastic deformation of the casing was observed (3) as increasing thermally-induced axial-compressive strain no longer resulted in significant increases in axial stress as per Equation 1.

The similarity of Figure 11 to the axial stress versus temperature diagram presented earlier in Figures 1 and 2 is noted. In addition, the post-yield behavior observed during the full-scale thermal cycle test is similar to the behavior of the material coupons during the elevated temperature material characterization tests, as described in Section 4.

No structural failure of either the 244.5 mm or 339.7 mm test specimens was observed during either test program, and the average measured seepage rates were below the threshold seepage rates defined in ISO/PAS 12835 for each connection size. Based on the results of this fit-for-purpose evaluation program, both the 244.5 mm, 69.9 kg/m and the 339.7 mm, 101.2 kg/m grade L80 JFE LION premium connection designs met the threshold performance requirements of ISO/PAS 12835 in the thermal cycle test to ASL-290. However, as IOS/PAS 12835 requires four connection specimens to be subjected to the thermal cycle test, and since only two connection specimens were tested in this modified program, additional testing would be required to fully assess the connection designs in accordance with ISO/PAS 12835 requirements.

5. DISCUSSION

Strain-based design approaches have been applied to thermal enhanced oil recovery operations in Canada for well over a decade (Nowinka et al. 2007). Although New Zealand's code of practice for deep geothermal wells (NZS 2403-2015) references Alberta's IRP 3 and ISO/PAS 12835, these strain-based concepts are not as commonly considered within the broader geothermal industry. Given that casing connections are a critical element in ensuring geothermal well integrity, casing connections selected for use in geothermal wells should be evaluated based on procedures that consider the post-yield thermal-mechanical behaviour of the material.

Recognizing the costs associated with full-scale testing on each connection design, activities are underway to advance approaches using FEA to interpolate existing evaluation results to qualify connection designs of different size, weight or material grade (Nowinka and Dall'Acqua 2016). Furthermore, research is being conducted to better understand the mechanisms governing seepage in premium casing connections and establish a sealability criterion for use in combination with FEA evaluation of premium connection designs (Xie et al. 2016, Xie and Mathews 2017, Xie et al. 2017). Combined with connection evaluation procedures such as ISO/PAS 12835, these advances offer the potential for more cost-effective and widespread evaluation of casing connection designs used in geothermal wells.

Successful performance of casing connections evaluated to ISO/PAS 12385 at 350°C is uncommon as the associated loads (i.e. thermally-induced strains and saturated steam pressures) increase in a non-linear manner. However, as higher-temperature geothermal resources are produced, including recent activities associated with developing EGS and supercritical geothermal wells with conditions above 374°C, evaluation procedures beyond 350°C may need to be established. Further research is warranted for selection of casing materials and connection designs to ensure long-term well integrity, which will be required for economic success of such high-consequence geothermal applications. Methods to predict reliability and key factors, such as those discussed by Zahacy 2018, should be considered, as well as fit-for-purpose strain-based design and evaluation procedures for geothermal wells.

6. CONCLUSIONS

A case study involving a fit-for-purpose evaluation of two different sizes of a premium connection design has been presented to highlight important considerations of connection evaluation for geothermal applications. Based on the results of this case study and associated discussion, the following conclusions are drawn:

- Geothermal wells are generally subject to large temperature variations, potentially imposing significant post-yield thermal stresses on the casing strings, and such loading conditions should be addressed during well design and casing connection evaluation programs.
- A strain-based design framework that considers cyclic thermal loads and post-yield material properties appears to be more suitable than traditional stress-based design approaches.
- Casing connection evaluation procedures based on strain-based design approaches, such as ISO/PAS 123835, provide a suitable basis for evaluating the structural and sealability performance of casing connection designs for service in high-temperature geothermal operating conditions.

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