FEA Modeling for Thermal Well Casing Connection Evaluation Programs

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Abstract*: Thermal recovery methods, such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD), have been widely used in production of heavy oil and bitumen. The cyclic thermal loading with high peak temperatures may cause both the casing string and connections to deform plastically, and therefore given the key role that connections play in the hydraulic and structural integrity of wellbores, they are considered as one of the most critical components in thermal wells. Engineering evaluation programs, such as physical testing and numerical analysis, are often used to ensure adequate structural integrity and sealability of the connections over the full service life of a well. The recently developed ISO/PAS 12835:2013 (2013), also known as the Thermal Well Casing Connection Evaluation Protocol (TWCCEP), specifies connection evaluation conditions and requirements for thermal well applications.*

This paper starts with a review of the evaluation program requirements for thermal well casing connections, and presents Finite Element Analysis (FEA) modeling considerations in support of ISO/PAS 12835:2013 thermal connection qualification programs. The paper covers a few key topics for such FEA modeling, including the structural and material modeling, determination of biased test population, impact of material properties, impact of make-up torque, and the determination of a stiff-length factor for the testing program. The paper also presents the use of FEA modeling to guide the design evaluation and optimization of thermal well casing connections based on an assessment of predicted demand (loading) and capacity (response) relative to performance criteria for sealability. Analysis examples are presented to demonstrate the use of the proposed approaches and methods.

Keywords*: Casing, Collapse, Connection, Constitutive Model, Creep, Design Optimization, Drilling, Elasticity, Experimental Verification, Failure ,Fatigue, Fatigue Life, Low-Cycle Fatigue, Mechanisms, Oil Well, Pipes, Plasticity, Residual Stress, Strain-based Design, Thermal Cycles, Thermal Stress, Wellbore.*

1. Introduction

Thermal recovery methods, such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD), are widely used for the in-situ production of heavy oil and bitumen resources. The CSS recovery process involves injecting high temperature (300ºC to 350ºC) steam into the reservoir, followed by a short soak period to reduce the viscosity of the oil and then production of the heated oil from the same well for a period of time before the cycle is repeated. The SAGD process typically operates with continuous high temperature (200°C to 275°C) high quality steam injection into a dedicated horizontal injection well, along with continuous production of the heated bitumen and condensed steam that drains into a horizontal production well positioned a few metres below the injection well. However, SAGD wells also experience thermal cycles due to various operational and workover events. The cyclic thermal loading with high peak temperatures may cause both the casing string and connections to deform plastically, and potentially fail in thermal wells (Xie 2006).

There are three general classes or types of connections used in oil field casing tubulars: API (American Petroleum Institute) round, API buttress (and oversized buttress) and proprietary premium connections (API 5B 2008, API 5CT 2011). Premium connections are often preferred for thermal well applications based on their generally superior structural and sealability performance (Xie 2009 and Xie et al 2010). Figure 1 shows a schematic of a particular form of premium connection which is commonly used in thermal well applications. It uses a buttress-type thread form to meet the structural requirements of full pipe body capacity and incorporates a metal-to-metal radial seal for enhanced sealability. It also includes a torque shoulder next to the seal region to control make-up, with the shoulder contact providing some degree of additional sealability in some cases.

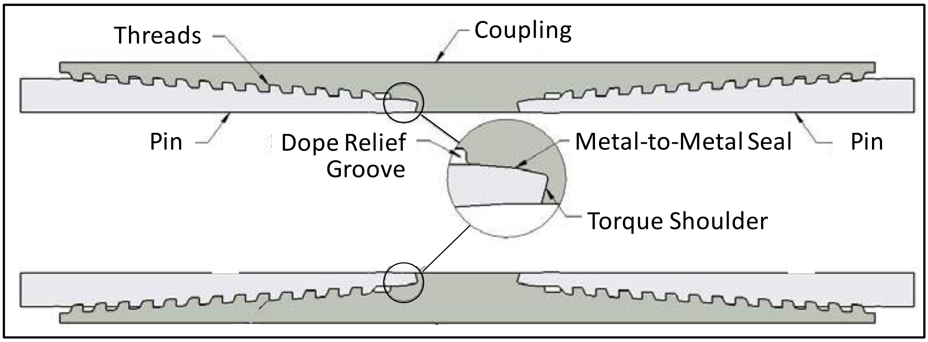

Figure 1 Schematic of a Premium Casing Connection

The threaded connections are viewed to be one of the most critical components of an oil well in terms of maintaining the structural and hydraulic isolation functions of wellbore casing strings. Payne and Schwind (1999) noted that, based on industry estimates, connection failures account for 85% - 95% of all oilfield tubular failures. For thermal well applications in Western Canada, the Canadian Association of Petroleum Producers (CAPP 1992) report noted that more than 80% of the uphole casing failures experienced in thermal wells occurred at connections.

Over the years, industry has established various standards, protocols and guidelines for assessing the sealability and structural performance of casing connections to be used in wellbores for different oilfield applications, including for thermal wells. These connection evaluation programs focus on full-scale physical tests with analytical modeling often used to assess connection performance and to identify connection designs suitable for the intended application. The use of Finite Element Analysis (FEA) has been increasingly incorporated into the connection performance evaluation process.

The recently developed ISO/PAS 12835:2013 (2013) protocol, also known as the Thermal Well Casing Connection Evaluation Protocol (TWCCEP), outlines procedures for evaluating the suitability of threaded casing connections for service in intermediate or production casing strings of thermal recovery wells. The ISO/PAS 12835:2013 defines thermal wells as those with operating temperatures that cyclically vary between minimum values appreciably below 180°C and maximum temperature values that range from 180°C to 350°C, in which these casing strings are cemented and the primary axial loading is thermally-induced and strain-based due to the axial constraint provided by the cement sheath. The overall program includes assessment of the sealability, galling resistance and structural integrity of the candidate connection design under loads typical of both make-up and thermal well service. The protocol sets four Application Severity Levels (ASL) for the testing program which correspond to different upper-bound temperatures and maximum internal pressures, as shown in Table 1.

Table 1 Maximum internal pressure and upper/lower-bound temperature for various ASL (based on ISO/PAS 12835:2013).

Application Severity Level (ASL)	Upper-bound Temperature (°C)	Lower-bound Temperature (°C)	Maximum Internal Pressure (MPa)
Not applicable	180	5	1.0
240	240	5	3.3
290	290	5	7.4
325	325	5	12.1
350	350	5	16.5

ISO/PAS 12835:2013 requires that FEA be used to support the physical testing program in the following tasks:

- Determination of biased test population by establishing:
    - the worst geometric cases for the connection design based on the combinations of pin and coupling dimensional tolerances which display comparatively poorer performance for sealability and contact surface galling resistance, respectively;
    - the impact of material property variations; and
    - the impact of make-up torque variations.
- Determination of high-stiffness length of the test string.

This paper outlines the approach and considerations for conducting FEA modeling in conjunction with the execution of an ISO/PAS 12835:2013 testing program for qualification of a thermal well casing connection. An analysis example of a generic premium connection is also presented to demonstrate the application of the analysis approach.

The paper also presents an approach that can be used to quantitatively assess the connection sealability performance as well as its structural integrity using FEA models. This includes a description of the relationship between metal-to-metal seal seepage rates and seal contact stress/contact length parameters that is used to assess the seal capacity of a premium connection design under the conditions of a thermal connection qualification program. The generic premium connection design introduced above is further evaluated using the proposed sealability demand versus capacity criterion and limit-strain conditions to demonstrate practical use of the approach.

2. FEA Model Considerations

As indicated in Annex A – FEA Modeling Guidelines of ISO/PAS 12835:2013, “it is a challenging task to accurately represent thermal casing connection behavior using numerical methods due to the physical nonlinearities in the system, such as contact, complex geometry and temperature dependent, elastic-plastic material behavior. Due to mathematical complexity and computational limitations, numerical models necessarily are simplified representations of the actual physical system. Model simplifications must be carefully chosen to ensure that all fundamental mechanics are considered.”

This section presents the considerations for the FEA structural, material and load models.

2.1 Structural Modeling

In the structural modeling of premium connections, the following assumptions are typically made:

1. Model length:

   Axial symmetry is generally assumed for threaded-and coupled connection designs such that the connection model employed typically consists of one half of a 12.5 m long full joint of casing pipe body and one half of the made-up coupling, as recommended by ISO/PAS 12835:2013. The coupling center is generally fixed axially, and the pin mid-span point is fixed for the thermal cycle loading analysis. For the ultimate strain loading analysis, the pin mid-span point is assigned a displacement to represent the pipe strain.

2. Axisymmetric solid elements:

   Due to the nearly axisymmetric nature of the structure (i.e. ignoring the small helical angle of the threads) and applied loading (i.e. temperature and pressure), axisymmetric elements are generally used. Although ISO/PAS 12835:2013 suggests that mixed formulation elements with pressure degrees of freedom should be used to accurately predict post-yield behavior, it was found that the general stress/displacement axisymmetric solid elements are sufficient for the connection model for the purposes of the protocol assessments since the plastic deformation in the model is generally limited and localized and therefore such plastic deformation does not affect the overall analysis convergence.

   Note that to assess the behaviour of connections subjected to non-axisymmetric loads, such as those resulting from bending induced by wellbore curvature, casing buckling and formation shear movement, axisymmetric elements with nonlinear asymmetric deformation (e.g. Abaqus CAXA4N elements) can be used (Xie, 2007).

3. Element mesh:

   A very fine element mesh should be used in the thread, seal and shoulder regions, while a relatively coarse mesh can be used in the pipe-body areas (Xie, Dessein and Rong 2015). Figure 2 shows details of the meshes established for the thread and seal areas in the example case of the generic 177.8 mm, 38.7 kg/m connection design considered in this paper. In this example, a mesh size of 0.04 mm /element was used to capture the detail of the distributed contact stress profile within the seal region. In the thread areas, a mesh size of 0.1 mm/element was used for to allow for assessment of the galling potential of the connection design. Note that if the analysis will also be used to assess the potential for thread rupture failure due to high localized stress/strain values in the thread roots areas, further mesh refinement will also likely be required in these areas. This is due to the fact that the stress/strain magnitudes near the thread root surfaces may increase significantly due to the stress/strain localization effects under the test loading conditions (Xie, Fan, Tao and Matthews 2011).

4. Non-linear geometry:

   The non-linear geometry features of the FEA model should be enabled to consider the large-strain behavior in the seal, shoulder, threads and pipe-body, and the large displacements that may result if local axisymmetric buckling occurs in the region of the pin nose of the connection.

5. Contact elements:

   Contact elements should be used between the pin and the coupling components over the thread, seal and shoulder regions. Typically, the coupling surface is defined as the master surface, while the pin surface becomes the slave surface. Modeling of friction on the contact surface is not required for the protocol assessment as per ISO/PAS 12835:2013.

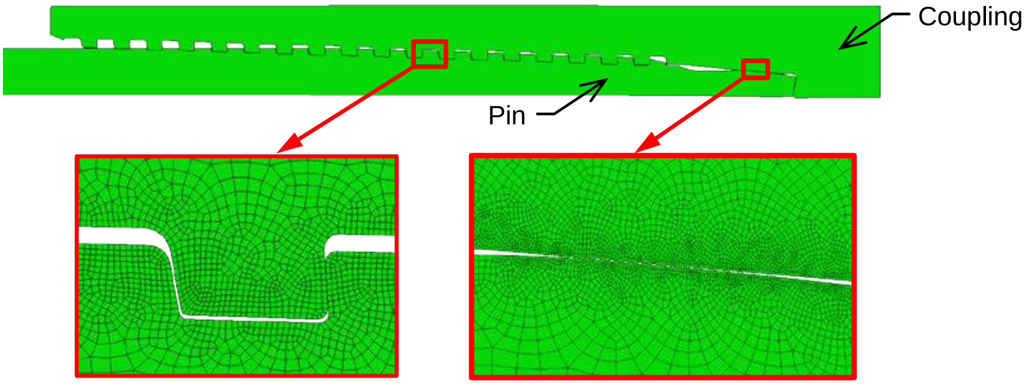

Figure 2 FEA model meshes for thread (left) and seal (right).

2.2 Material Modeling

The base material model, described by ISO/PAS 12835:2013 as the "as-characterized model", is typically developed using an isotropic-hardening constitutive relationship and temperature-dependent material properties based on static axial tensile coupon test results (i.e. material coupon tests conducted at a slow strain rate). The key parameters defining the elastic-plastic material model include the Young's modulus, Poisson's ratio, yield strength, post-yield modulus, and the dependency of these parameters to temperature (Figure 3). A temperature-dependent thermal expansion coefficient is also defined to model the material length and volumetric changes due to temperature variations.

For the analysis cases used to examine the impacts of pin material property variations on the connection performance, three material models are considered for the representative L80 grade tubular steel. Low (minimum) yield and high (maximum) yield material models (Figure 4) were generated by modifying the starting L80 base material model using the API-specified minimum and maximum L80 yield strengths which can be found in API Specification 5CT (2011). The procedure to generate the models is described in ISO/PAS 12835:2013.

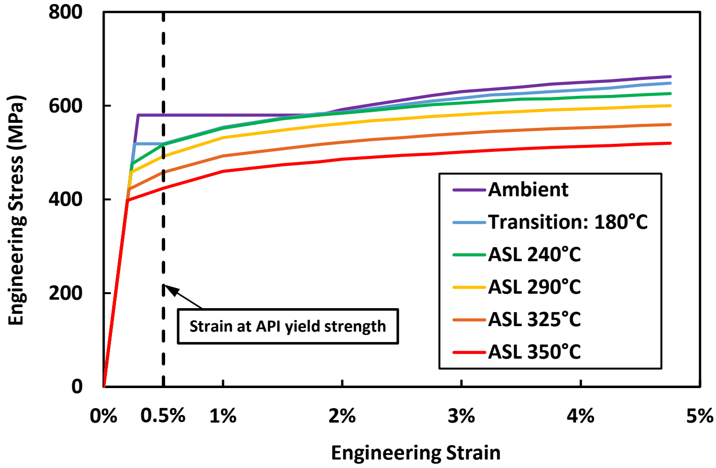

Figure 3 Example of as-characterized monotonic stress-strain curve (based on ISO/PAS 12835:2013)

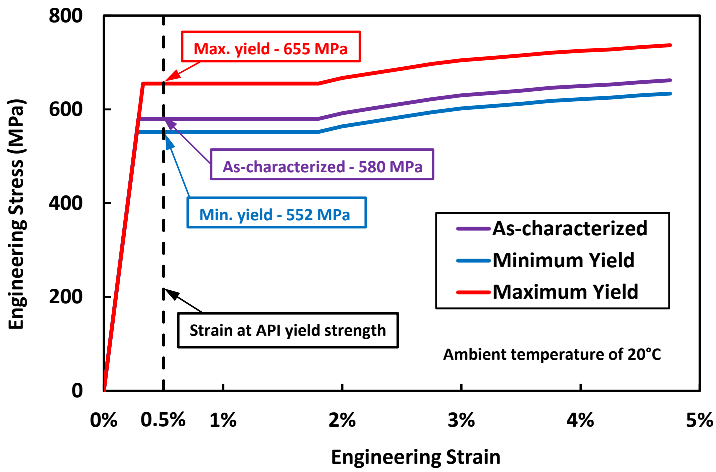

Figure 4 Example of ambient-temperature material properties (based on ISO/PAS 12835:2013)

2.3 Load Modeling

2.3.1 Make-up Condition

Figure 5 shows a schematic representation of the torque-turn response associated with the make-up of a shouldered premium connection which captures the key features of an actual connection make-up operation (Hamilton, Wagg and Roth 2007). The torque-turn make-up response of a premium connection can be characterized by three regions or stages:

1. Engagement of the thread and seal: as the thread and seal portions of the pin and coupling are engaged and made-up, increasing torque is applied to overcome pin-coupling thread interference and friction. This process continues up to a torque value designated as the shoulder torque, T_{sh}, at which point the pin tip comes into contact with the coupling torque shoulder;
2. Engagement of the pin-coupling shoulders: further advancement of the pin into the coupling causes the development of: (1) largely axially-oriented contact forces between the pin and coupling components at the shoulder; (2) largely radial forces at the seal; and (3) both axial and radial reactionary forces at the thread interfaces. These various contact forces result in the development of incremental torque ΔT, with the magnitude dependent on the coupling design as well as the number of incremental turns applied after shouldering, $\Delta turn$; and
3. Release of the applied make-up torque: where the externally applied torque is removed.

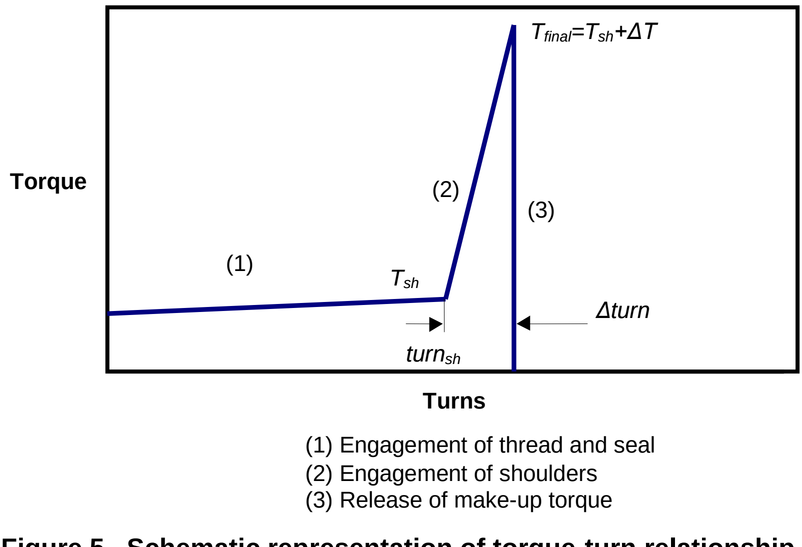

Figure 5. Schematic representation of torque-turn relationship.

Accordingly, the torque-turn relationship for such connections can be characterized by the following four key parameters:

T_{sh} = torque value at shouldering;

T_{final} = final torque after shouldering, which is the sum of the torque at shouldering, T_{sh}, and the incremental torque, ΔT, post shouldering;

$turn_{sh}$ = total turns to shoulder engagement; and

$\Delta turn$ = turn increment from shoulder engagement to the release of the applied torque.

The values of these four parameters vary with the size, weight and grade of the tubular and the connection design. However, in practice, these make-up parameters are often controlled to ensure they stay within the acceptable ranges prescribed by the manufacturer to ensure proper make-up of the specific connection design (i.e. engagement for load transfer and sealability).

ISO/PAS 12835:2013 does not specify the details for how the connection make-up should be modeled. Modelling of the make-up as a static loading condition makes the inherent assumption that a premium connection is made up at a very slow strain rate (i.e. strain-rate independent), and therefore use of the static yield strength properties is adequate for developing the material constitutive model. The make-up loading, however, actually occurs very rapidly (e.g. in the range of 4 to 7 RPM (rotations per minute)) and therefore it is more appropriate that strain-rate dependent material properties be used to capture the response (Xie 2011). For either analysis approach (static or strain-rate dependent), the make-up torque effects on the connection can be modeled by analyzing the interference fit in the thread, seal and shoulder regions, in at least two distinct steps:

1. interference fit in the threads and seal; and
2. interference fit in the shoulder.

Note that although Figure 5 shows three load steps during the connection make-up, the third step (i.e. release of torque) can be ignored in the static loading analysis, assuming the normal contact stress conditions between pin and coupling components remain unchanged after the second step.

The magnitude of the interference imposed in the threads and seal areas correspond to the dimensions and tolerances of the specific connection design, as detailed in the manufacturer's drawings and specifications. The shoulder interference should be calculated based on the geometry of the connection torque shoulder and thread profile and the turn increment ($\Delta turn$) applied after the shoulder torque position:

$$I_{sh} = pitch \times \Delta turn \qquad (1)$$

where pitch is the average distance between neighbouring threads of the pin and coupling for the specific connection design. Note that the above equation assumes that the axial pin displacement corresponding to the incremental turn value (and associated incremental torque) is fully accommodated by interference at the shoulder interface (i.e. the response within the thread profile is neglected). In support of this assumption, it is noted that the results from a number of parametric finite element analyses completed previously by the lead author for similar connection designs suggest that the pin and box twist angles that develop over the thread and seal regions in response to the applied make-up torque and representative friction values will be insignificant compared to the typical incremental turn values.

The determination of the incremental turn amount ($\Delta turn$) is a critical step in the make-up analysis. As illustrated in Figure 5, the shoulder make-up can be defined by three parameters: the torque value at shouldering (T_{sh}), the final torque after shouldering (T_{final}), and the incremental turns after shouldering ($\Delta turn$). It is recommended that nominal values for these three parameters be obtained for a particular connection candidate through review and analysis of make-up test data from a number of representative samples in order to determine the incremental turn value used in the analysis. It has been found that attempts to reduce the independent parameters, for example through the use of an effective friction coefficient applied to the thread, seal and shoulder regions during make-up, often leads to an inappropriate prediction of the shoulder interference.

As such, the recommended procedure to determine an appropriate incremental turn value is as follows:

1. If physical make-up torque-turn data is available for the candidate connection design, determine the average shouldering torque (T_{sh}) and the average slope of the torque-turn curve after shouldering (i.e. the slope over stage 2 in Figure 5) based on a regression analysis of the make-up test results; and
2. Determine the incremental turn amount ($\Delta turn$) based on the average values established for the shouldering torque and torque-turn slope along with the final make-up torque value to be considered in the analysis of the candidate connection design. Typically a manufacturer can provide the optimal, minimum and maximum torque values which they prescribe for make-up of the connection.

Using this procedure, the incremental turn values corresponding to each of these three torque thresholds can be obtained.

In the event that there is no make-up torque-turn data available for the connection design, approximate incremental turn values can be determined for the different make-up torque thresholds by referring to published data for connections of similar design, size, weight and material, or through parametric FEA. Parametric FEA can be used to establish the relationship between the normalized resultant torque (i.e. with the assumption of a 1.0 friction coefficient) and the shoulder interference (i.e. incremental turn), which is expected to be linear when the torque value is low. The maximum allowable incremental turn value can be determined as the load point corresponding to the limited residual incremental turn upon the removal of the applied loading. The torque at the maximum allowable incremental turn can be considered as the maximum torque value. Subsequently, the incremental turns corresponding to the prescribed optimal and minimum torque thresholds can be established on a proportionality basis.

2.3.2 Thermal Cycle Operating Conditions

For each ASL listed in Table 1, the temperature and internal pressure are applied to the numerical model in six load steps. Figure 2 shows an example of the load path for the six load steps for ASL-290.

In implementing the FEA for this type of connection assessment, the temperature change can be defined as a nodal variable to the entire connection model while the internal pressure loading is applied over the entire ID surface of the pin and coupling, the pin and coupling shoulder surfaces, and the pin and coupling seal surfaces from the shoulder up to the point where the maximum contact stress is anticipated from the design.

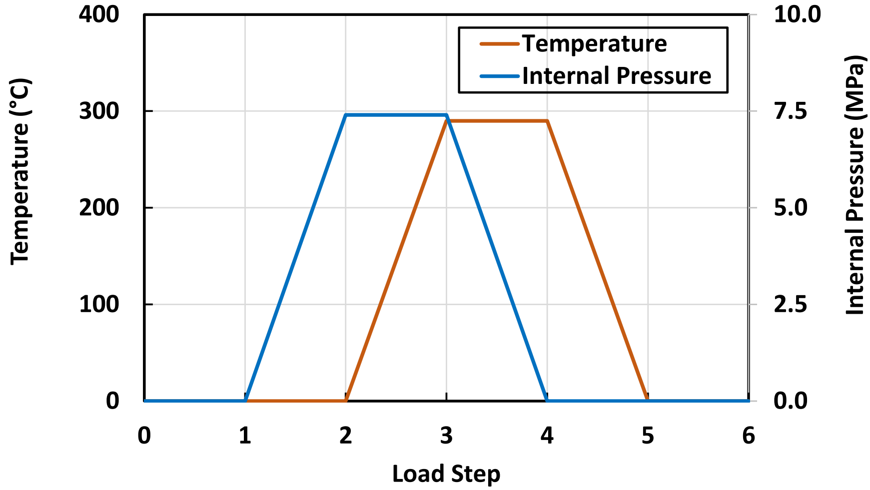

Figure 6 Example of applied load path profile for ASL-290.

3. Evaluation Criteria

FEA evaluation of a premium connection design for a thermal well application requires the use of appropriate criteria for acceptable sealability, structural integrity and galling performance. These criteria are outlined in the following section.

3.1 Evaluation Criterion for Sealability

As noted above and illustrated in Figure 6 for ASL-290, the temperature and internal pressure are applied to the connection model in six load steps. For the sealability evaluation, the following three load steps are generally considered most critical:

- After make-up (Load Step 0): prior to the application of internal pressure and temperature;
- After application of the upper-bound temperature (Load Step 3): with the axially-confined model under maximum compression loading at the maximum operating temperature; and
- After application of the lower-bound temperature (Load Step 6): with the axially-confined model under maximum tension loading at the end of the thermal cycle.

For the physical qualification test program, the ISO/PAS 12835:2013 protocol recommends a minimum reportable seepage rate of 0.06 mL/min., and stipulates sealability criteria consisting of maximum seepage rates of 1 mL/min. and 10 mL/min, respectively, during periods of peak axisymmetric compression and tension load conditions (these correspond to the upper and lower bound temperature conditions considered in the connection analyses).

For establishing the relative ranking of the various specimen configurations based on sealability performance (as described further below), ISO/PAS 12835:2013 requires use of the seal contact intensity parameter f_s, defined as the integration of the seal contact stress σ over the effective seal length LES (see Eqn. 2). This seal contact intensity parameter has been used in previous studies to evaluate the sealability performance of premium connections (Xie 2007 and 2009).

$$f_s = \int_{L_{ES}} \sigma \, dx \qquad (2)$$

Note that one of the shortcomings of this sealabiltiy criterion is that it does not relate the seal contact intensity value to actual seepage rates of such metal-to-metal seals. In an effort to address this need, Xie, Matthews and Hamilton (2016) developed an empirically-based model that correlates seepage rates for different metal-to-metal seal configurations to contact stress. As shown in the equation below, the proposed empirical model relates the seal contact stress and seal length to the differential pressure, seepage rate and tubular diameter as follows:

$$\sigma^n L = A\, D^k Q^m P \qquad (3)$$

where σ is the contact stress, L is the seal length, D is the tubular diameter at the seal region, Q is the seepage rate, P is the differential pressure, and A, k, m and n are model fitting parameters.

To account for the variations that typically exist in the contact stress levels over the seal surface area of an actual premium connection (e.g., Hamilton et al 2007) and to relate the above variables to the ability of a connection design to provide a certain level of sealability, a variable called Sealing Capacity (S_C) was subsequently defined as follows:

$$S_C = \int_L \sigma^n(l)\, dl \qquad (4)$$

Similarly, to represent the parameters corresponding to the loading and performance conditions relevant to the subject connection design, another variable called Sealing Demand (S_D) was defined as:

$$S_D = A\, D^k Q^m P \qquad (5)$$

With these two newly introduced variables, a minimum sealing criterion was expressed as:

$$S_C \geq S_D \qquad (6)$$

This limit-state condition for sealability is thus captured by: (i) the Sealing Capacity (S_C) variable, which represents the leakage resistance as estimated based on the FEA-obtained seal contact stress profile within the connection design, taking into consideration both the magnitude of the contact stresses and the axial length of the contact stress on the seal; and (ii) the Sealing Demand (S_D) variable, which represents the leakage activation potential and which is a function of the differential pressure, the tubular diameter and the leakage limit threshold. Note that the minimum sealing criterion presented by Equation (6) can also be used for conducting sealing reliability assessments which require the use of such a limit state function expressed in terms of design capacity and service load demand.

Based on calibration to test data, Xie, Matthews and Hamilton (2016) proposed two sets of the values for the coefficients that can be used to calculate both SC and SD, as shown in Table 2. The coefficient values labelled "Best-Fit" were derived through a calibration exercise that considered the full set of test results. The coefficient values labelled "Proposed Limit" are the values suggested for use in completing connection sealability evaluations based on Equation (6). The proposed criterion was supported by further metal-to-metal seal tests with considerations of impacts of surface roughness and thread compounds (Xie and Matthews 2017).

Table 2 Values of key parameters for calculating sealing capacity and demand

Parameter	Values for Best-Fit	Values for Proposed Limit	Unit
A	6.91	7.88	MPa^{n-1} mm^{1-k} $(mL/min)^{-m}$
K	0.8	0.8	~
m	-0.0333	-0.0333	~
n	1.557	1.557	~

3.2 Evaluation Criterion for Structural Integrity

For thermal well applications, due to the demanding load conditions, casing connections are typically required to have an ultimate strength that exceeds the pipe-body yield strength (e.g. IRP 03, DACC 2012). For ISO/PAS 12835:2013, limit-strain tests are required for the candidate connection test specimens following completion of the thermal cycle loading and sealability tests. The tensile strain threshold (i.e. the minimum tensile pipe strain below which the connection needs to maintain structural integrity) adopted by ISO/PAS 12835:2013 is the greater of: (1) five times the free axial expansion strain that would be induced by temperature excursions between the lower-bound temperature (e.g. 5°C) and the upper-bound temperature of the selected ASL; or (2) 3% global pipe body strain.

Depending on the connection design and service environment, the structural failure modes for premium connections in thermal wells include: thread jump-out; thread jump-in (for connection designs without a torque shoulder); thread rupture; pipe buckling; fatigue and corrosion-influenced cracking and parting; and pipe necking (Xie 2009 and Xie et al 2011). Depending on the anticipated tubular and connection failure mode, the structural integrity evaluation criterion can be different. The following are considered as practical approaches for structural integrity evaluation of thermal well premium connections:

- Thread jump-out:

  Thread jump-out can be observed as a loss of contact and axial translation between the previously engaged threads. This condition will also be characterized by a sudden change in the axial loading carrying capacity of the connection (e.g. discontinuous load-displacement relationship or, with complete thread jump-out, a total loss of force).

- Thread rupture:

  The principal tensile strain values in the thread root areas typically serve as an indicator of thread rupture occurrence. Another more practical way to assess the rupture potential is to compare the localized plastic strain levels in the thread roots areas to an appropriate critical strain limit.

- Pipe buckling:

It is often suggested that the pin nose may be subject to pipe buckling as it is loaded with increasingly high compressive forces during make-up and the subsequent thermal cycle heating phase. In a connection analysis, axisymmetric buckling of the pin will be reflected by a sudden increase in the radial displacements during loading.

- Pipe necking:

  Provided that a suitable plasticity model is used, the onset of pipe necking (i.e. a significant reduction in pin or pipe body wall thickness) would be indicated in an analysis as a decrease in the load from a peak value.

3.3 Galling Susceptibility Assessment

As indicated in ISO/PAS 12835:2013, the candidate connection geometry cases that display the highest peak contact stresses between the pin and box components, either within the threads or in the seal, should be identified as the worst-case galling specimen configurations.
However, while this requirement is generally suitable to use for establishing galling potential in the seal, the use of peak contact stresses has been found to be unreliable in terms of identifying worst-case specimen configurations for thread region galling susceptibility. This can be attributed to: (1) the typical lack of significant variation in the peak contact stress values in the thread region between the geometric cases; and (2) the high sensitivity of the results to the mesh density. Therefore, it is recommended that the total contact force on an individual thread be used to determine the most susceptible thread galling specimen geometry (Tao and Xie 2013).

4. Determination of Biased Test Populations

As noted above (in Section 1), ISO/PAS 12835:2013 requires the use of FEA to assist in establishing specimen geometries and other key parameters for conducting the physical connection qualification test program. One of the key FEA roles is the determination of the biased test population, ensuring the physical test specimens represent the worst geometry cases for leakage and galling susceptibility, respectively, taking into account the impacts of material property and make-up torque variations.

This section presents an analysis example case for a generic premium connection design to demonstrate the FEA approach and show the general response of such connections to thermal well loading conditions. Note that the FEA work presented in this section focuses on connection sealability since experience has shown that this is generally the most challenging criteria for a connection design to successfully meet under thermal connection qualification conditions.

4.1 Nominal Case Study

A generic premium connection design for a 177.8 mm, 38.7 kg/m L80 grade casing string is analyzed here to demonstrate the use of the FEA approach described above. As shown in Figure 2, the basic features of this generic connection are common to many commercially available premium connections used in thermal wells, including the buttress-type thread form, a metal-to-metal radial seal and a torque shoulder. This connection design uses 4 TPI (Threads Per Inch), with 16 total threads including 7 imperfect threads and 9 complete threads over the threaded region of the pin. The seal is assumed to be 10 mm long, and the shoulder angle is assumed to be 10°. The L80 grade tubular material is assumed to have the Young's modulus of 200,000 MPa, Poisson's ratio of 0.3, and a yield strength at the ambient temperature of 580 MPa. An incremental turn of 0.035 was assumed for the nominal make-up condition.

Figures 7 and 8 present the axial and radial stress contour plots, respectively, for the generic connection following make-up (Load Step 0), at the upper-bound temperature (Load Step 3) and at the lower-bound temperature (Load Step 6). As shown in Figure 7, both the connection and the pipe-body are subjected to significant axial compressive loading at the upper-bound temperature as a result of the constrained thermal expansion during heating. On the other hand, the connection experiences high axial tensile loading at the lower-bound temperature due to the material contraction during cooling. As shown in Figure 8, high radial compressive stress is present on the seal surface at make-up, suggesting there is a high contact stress between the pin and coupling as discussed further below.

Figure 9 presents the seal contact stress distributions determined for the generic connection at make-up, at the upper-bound temperature and at the lower-bound temperature. The magnitude of the contact stress profile exhibits a reduction at the upper-bound temperature relative to make-up, while both the magnitude and the length of the contact stress profile are notably reduced at the low-bound temperature.

Figure 10 presents the change in seal contact intensity versus temperature for the nominal (N) dimensional geometry (G) case (GN) of the generic connection design, calculated using Equation (2) over the seal region where the model was subjected to a full thermal cycle per ASL-290 and ASL-350 conditions. These results clearly show that the seal contact intensity can vary significantly over a thermal cycle and that the changes are different depending on the magnitude of the temperature differential applied. Note that the figure also shows that the seal contact intensity values may approach similar lower-bound levels at the end of a thermal cycle (Load Step 6) despite the significant difference in temperature range between the two ASL conditions.

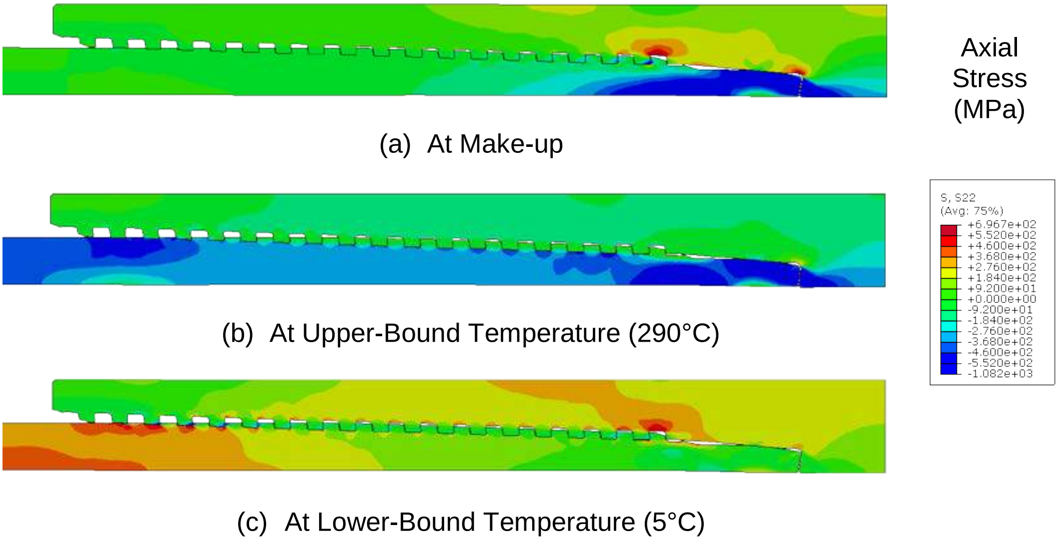

Figure 7 Axial stress over a thermal cycle for nominal generic connection under ASL-290.

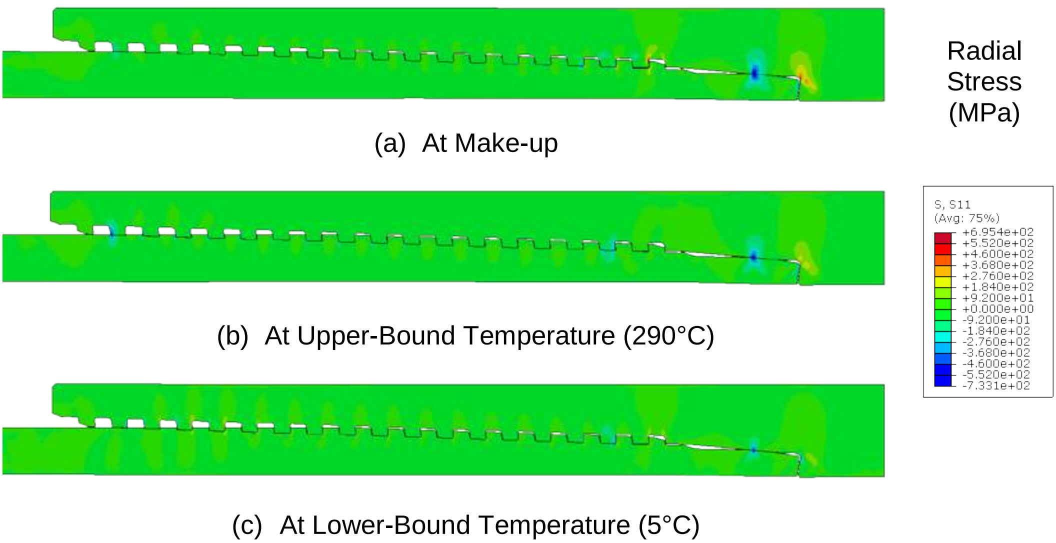

Figure 8 Radial stress over a thermal cycle for nominal generic connection under ASL-290.

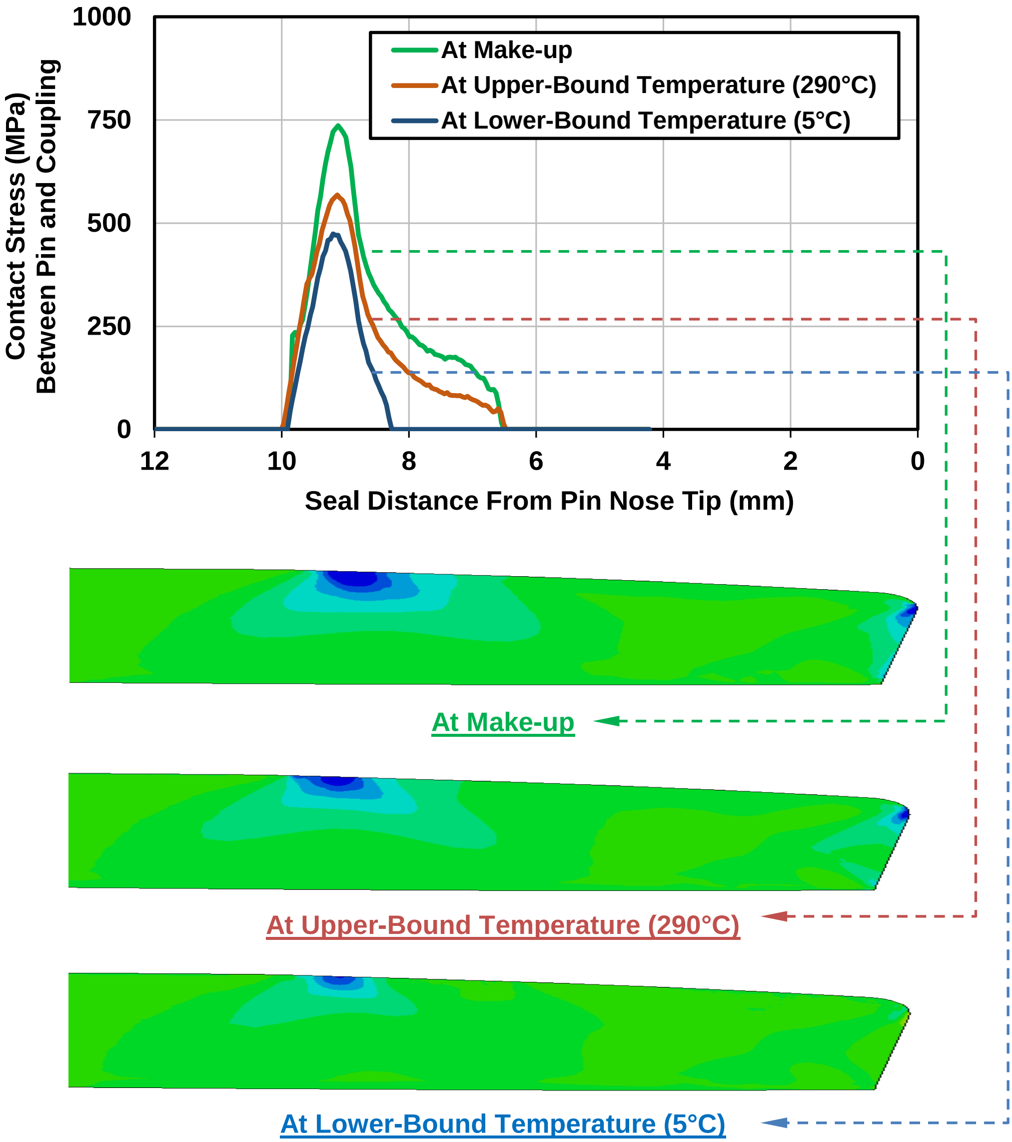

Figure 9 Seal contact stress at make-up, upper-bound temperature and lower-bound temperature for nominal generic connection under ASL-290. (Contour plots show the radial stress with blue in compression)

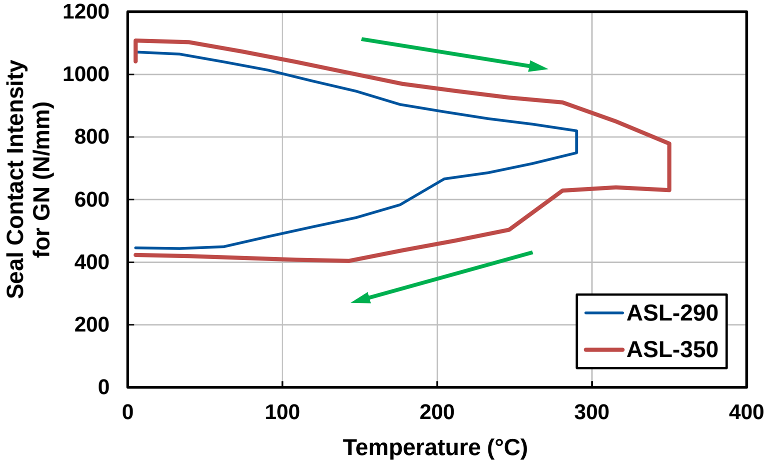

Figure 10 Seal contact intensity vs. temperature for nominal case.

4.2 Determination of Worst Case Geometry Configuration

This section outlines the use of FEA to assist in the determination of worst case specimen geometry configurations per ISO/PAS 12835:2013. Table 3 presents eight (8) geometry cases (G1 to G8) described by ISO/PAS 12835:2013 where each of these geometric cases has a specified limit value for the seal interference, thread interference, and pin and coupling tapers.

Cases G1 to G4 are the geometry configurations with minimum seal interference which are used to determine the worst case configurations with respect to sealability. These four cases are analyzed through make-up and one thermal cycle, and the seal contact intensity results are ranked and used to determine the worst case (i.e. the lowest seal contact intensity) at the upper-bound and lower-bound temperatures. The case with the lowest seal contact intensity at the upper-bound temperature is selected as the worst case geometry for sealing in compression (WSC), while the case with the lowest seal contact intensity at the lower-bound temperature is chosen as the worst case geometry for sealing in tension (WST).

Cases G5 to G8 represent the geometry configurations evaluated for maximum seal interference. These cases, along with Cases G1 to G4, are used to determine the worst case geometry configurations for galling. Note that for the galling evaluation, only the make-up loading condition must be analyzed. The case with the highest contact stress condition in the seal is selected as the worst case geometry for seal galling (WGS), and the case with the highest contact stress condition in the threads is labeled as the worst case geometry for thread galling (WGT). Since this paper focuses on the evaluation of connection sealability, the analysis results related to galling potential of the generic connection are not included.

Table 3 Geometry case definition.

Geometry Case	Severity ranking		Seal	Thread		
	Sealability	Galling	Interference	Interference	Pin Taper	Coupling Taper
G1	Make-up + 1 cycle	Make-up	L	L	L	H
G2			L	L	H	L
G3			L	H	L	H
G4			L	H	H	L
G5	N/A		H	L	L	H
G6			H	L	H	L
G7			H	H	L	H
G8			H	H	H	L

- L=Lower-bound; H=Upper-bound

Figures 11 and 12 summarize the seal contact intensity values established for the nominal geometry case (GN) and the sealability geometry Cases G1 to G4, under ASL-290 and ASL-350 conditions, respectively. The cases producing the lowest seal contact intensity values at both the upper-bound and lower-bound temperature conditions are highlighted by red circles in the figures. As shown, for this generic connection design, geometry case G1 was found to be the worst case for sealability in both tension (WST) and compression (WSC) under both ASL conditions.

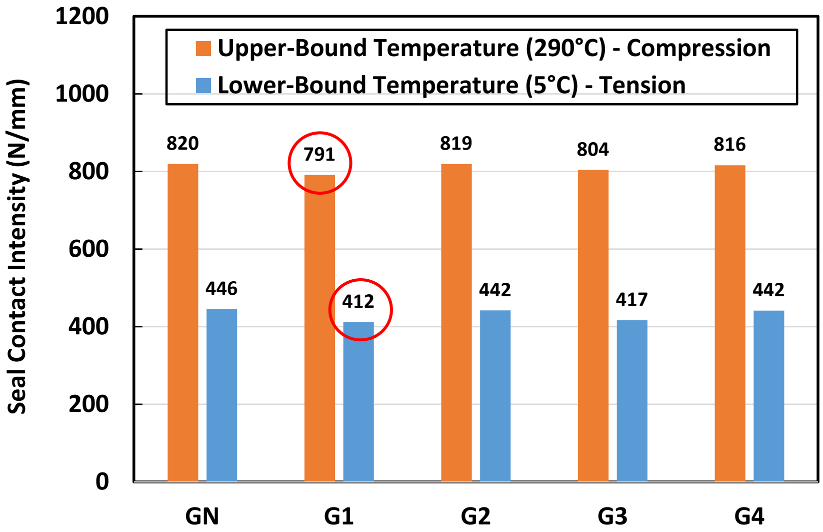

Figure 11 Seal contact intensity for various geometry cases for the generic connection with ASL-290.

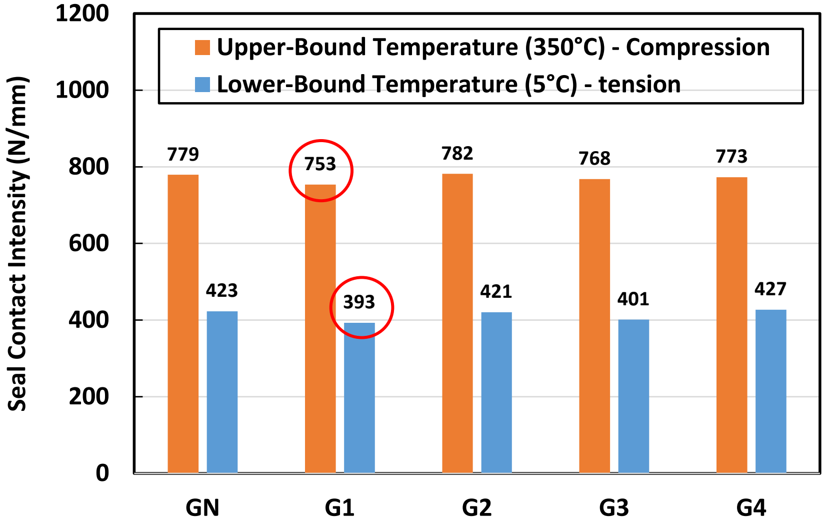

Figure 12 Seal contact intensity for various geometry cases for the generic connection with ASL-350.

4.3 Determination of Material Property Variation Impact

In addition to the assessment of geometric effects, ISO/PAS 12835:2013 requires that FEA be used to determine the impact that a specified range of material property variations has on connection sealability. While determination of the impacts of variations in pin material yield strength is mandatory, similar analysis of variations in the coupling material yield strength remains optional. For this illustrative example, an assessment of material property variations was performed for the worst case configurations for sealability in both tension (WST) and compression (WSC) using the material models corresponding to the maximum and minimum API yield strengths (Figure 4). The severity ranking of the material impact cases was based on the variance of the respective seal contact intensity values as calculated using the following equation:

$$Variance = 2(Highest - Lowest)/(Highest + Lowest) \quad (7)$$

ISO/PAS 12835:2013 stipulates that if the maximum variance is: (i) less than 15%, the selection of the pin material is not restricted; (ii) if the maximum variance is between 15% and 30%, the selection of the pin material shall be restricted to either the lower or upper half of the range allowed for the yield strength by production specifications, corresponding to the lower seal contact intensity; and (iii) if the maximum variance is larger than 30%, the selection of the pin material shall be restricted to the one-third of the range allowed for the yield strength by production specifications, corresponding to the lower seal contact intensity..

Figure 13 presents the severity ranking of the WSC and WST geometric cases based on pin-material yield strength variance for the generic connection under ASL-290 and ASL-350 conditions. As shown, the lower-bound temperature results exhibit the maximum variance in seal contact intensity values, at 25.1% for ASL-290, and 26.2% for ASL-350. Therefore, based on these results and the noted guidelines, the selection of the pin material for this illustrative example connection design would be restricted to lower half of the manufacturer's allowable yield strength range in both the WSC and WST cases.

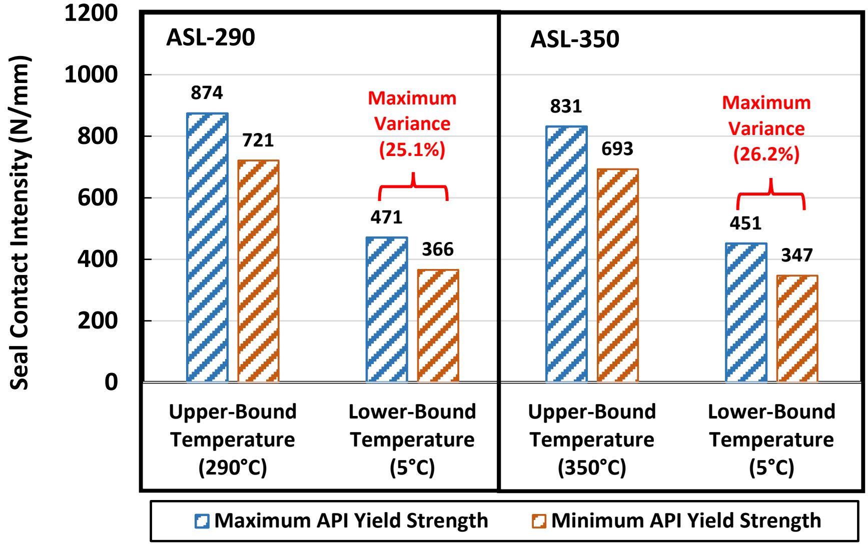

Figure 13 Severity ranking based on pin material yield strength variance.

4.4 Determination of Make-up Torques

ISO/PAS 12835:2013 requires that FEA be conducted to select target torque values for the final make-up of the candidate connection specimens designated for the sealability qualification tests. The objective of this analysis is to identify the torque values from the allowable range specified by the connection manufacturer which result in the lowest contact stress intensity in the seal region. This approach is taken so that the sealability tests are based on realistic but conservative scenarios with respect to connection make-up.

In the make-up torque assessments, the seal contact intensity at the lower-bound temperature (i.e. at the end of thermal cycle) should be considered for the WST case, while the results for the upper-bound temperature condition should be used for the WSC case.

4.5 Determination of Strain Compensation Factors

ISO/PAS 12835:2013 also notes that FEA may be used as one approach to determine the strain compensation factors which are required to account for impacts arising from differences in the lengths of the specimen used in the laboratory tests relative to actual tubular joint lengths in the field. ISO/PAS 12835:2013 proposes a methodology wherein the "stiff length", defined as the axial length of the connection region which has a higher axial stiffness relative to the pipe body, is taken into account in determining the amount of mechanical strain compensation to be applied in the lab tests to replicate the effects of the longer field joints. (See Annex B of ISO/PAS 12835:2013).

A simplified FEA model using one-dimensional or beam elements can be used to determine the “stiff-length” by matching its axial stress in the pipe-body with that in the connection model at the end of a thermal cycle.

5. FEA-Based Evaluation for Premium Connections

This section presents an FEA-based approach that can be used to quantitatively evaluate both the sealability performance and structural integrity of premium connections under thermal well loading conditions. The approach may be used to effectively screen different candidate connection designs to identify the most promising configurations and/or tolerances, and therefore may be quite helpful to manufacturers as part of a pre-test assessment completed prior to undertaking a full connection qualification program. Ultimately, to formally qualify a connection design to a selected ASL, the test protocol must be conducted to validate the numerical analysis results and to verify the manufactured product can satisfy the prescribed performance criteria.

5.1 Sealability Evaluation

The capacity versus demand limit-state approach and sealability criterion proposed by Xie, Matthews and Hamilton (2016) (see Section 3.1) were used to complete the generic connection sealability evaluation.

Figure 14 presents the sealing capacity of the G1 connection geometry (calculated using Equation 4) as a function of temperature under both the ASL-290 and ASL-350 conditions. Similar to the seal contact intensity response established for the nominal geometry GN shown in Figure 6, the results presented in Figure 14 show that the sealing capacity of the connection also varies significantly over the thermal cycle, with the lowest values coinciding with the lower-bound temperature condition.

Figure 15 presents a summary of the sealing capacity and sealing demand values (calculated using Equations 4 and 5, respectively) at the upper-bound and lower-bound temperatures for the ASL-290 and ASL-350 conditions. Consistent with the profiles shown in Figure 14, the sealing capacity at the lower-bound temperature is lower than the capacity at the upper-bound temperature under both ASL conditions. Note that the calculated sealing demand at the lower-bound temperature is slightly lower than the value at the upper-bound temperature in both cases due to the different allowable seepage rates of 10 versus 1 ml/min specified by ISO/PAS 12835:2013 for the respective conditions.

The analysis results also show that the sealing capacity values determined for the ASL-290 conditions are significantly higher (about 4.9 times and 2.6 times, respectively) than the sealing demand values at both the upper-bound and lower-bound temperatures. This finding suggests that the generic connection (and in fact the worst case for sealability in compression and tension, G1, for this connection design) has the potential to satisfy the sealability requirements of the ISO/PAS 12835:2013 qualification test program if tested to the ASL-290 conditions. On the other hand, the results for the ALS-350 condition show that the lower-bound temperature sealing capacity of 8.4 m-MPa$^{1.557}$ is only approximately 10% higher than the corresponding sealing demand of 7.6 m-MPa$^{1.557}$ (i.e. a higher demand value due to the higher internal pressure for the ALS-350 condition). This suggests that the probability of the generic connection meeting the ISO/PAS 12835:2013 sealability criteria is significantly reduced if tested to the ASL-350 conditions. This example demonstrates that the more severe ASL-350 loading conditions represent a much greater challenge for the connection design to deliver adequate sealability in such a thermal qualification program.

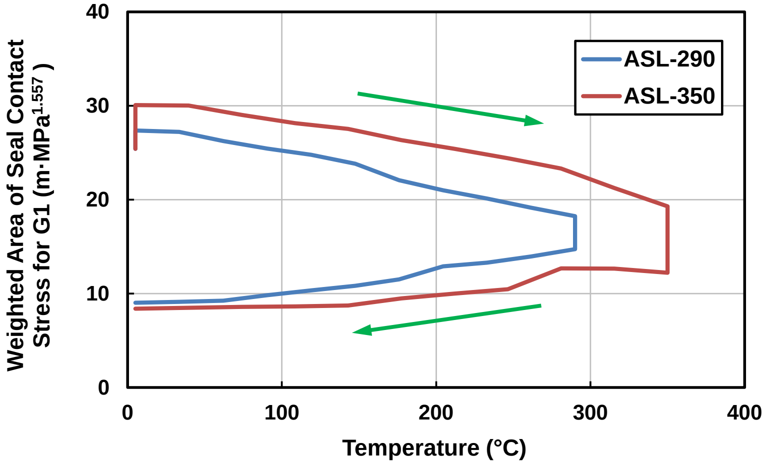

Figure 14 Sealing capacity vs. temperature for geometry case G1.

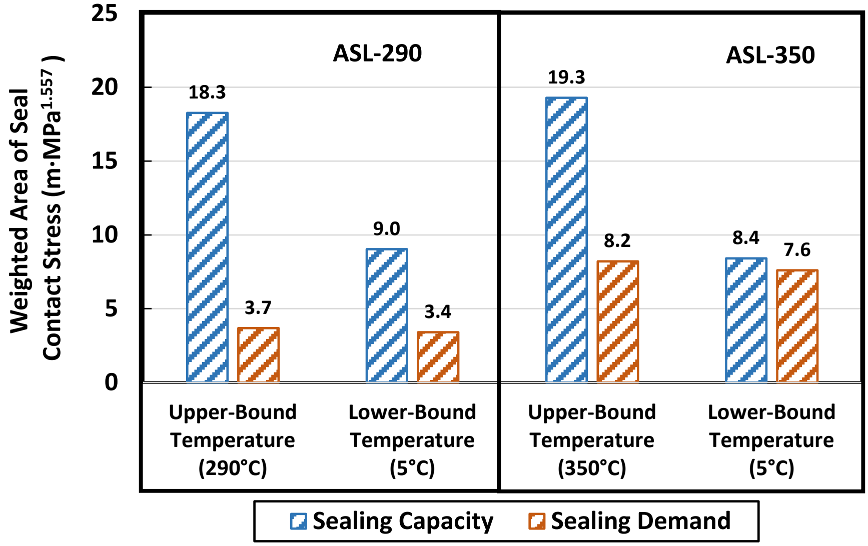

Figure 15 Sealing capacity vs. sealing demand for geometry case G1.

5.2 Structural Integrity Evaluation

To evaluate the response of the generic connection design under loading simulating the ISO/PAS 12835:2013 limit-strain test, the FEA model for the WSC/WST (G1) geometry case was analyzed under tensile displacement-controlled loading applied following completion of a thermal cycle analysis to ASL-290 conditions. Figure 16 shows the predicted axial tensile force vs. pipe strain response of the connection. The axial tensile force starts at 1780 kN which corresponds to the resultant axial force in the connection model at the end of the thermal cycle. As the pipe strain approaches 0.11%, the axial tensile force begins to plateau - this corresponds to the point where the pipe body has fully yielded. As additional displacement is applied to the model and the pipe strain reaches ~1.3%, the tensile force starts to increase in response to strain-hardening of the pipe body material. The positive slope continues as the pipe strain is extended to 4.8% in the analysis, which is significantly beyond the 3% global pipe body strain stipulated for this test in ISO/PAS 12835:2013.

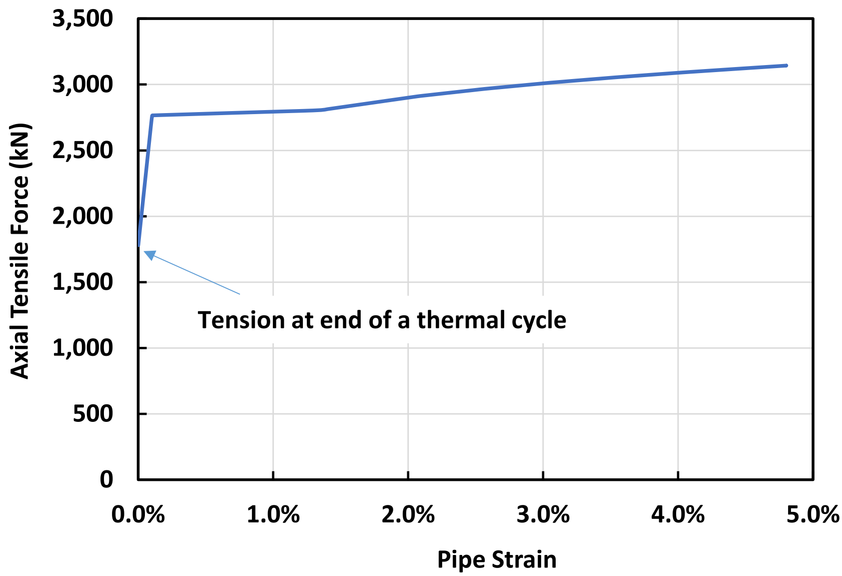

Figure 16 Axial force for Case G1 subjected to increasing tensile strain following ASL-290 thermal cycle loading.

The analysis shows that the connection design does not experience thread jump-out, pipe buckling and pipe necking at pipe body tensile strains up to 4.8%. However, as shown in Figure 17, very high plastic strain levels develop in the thread region near the coupling face at 3% pipe strain. Figure 18 shows the change in plastic strain in the pipe body and in the thread roots of the first, second, third and fourth threads from the coupling face with the application of increasing tensile pipe strain. Note that the development of maximum localized plastic strain levels in these threads migrates progressively from the threads near the coupling face toward the threads located closer to the coupling center, suggesting the more engaged threads pick up more axial loading as the global pipe strain increases. Nonetheless, at 3% pipe strain, the peak localized plastic strain in the threads remains below 10% which is less than the fracture strain limit for the ductile L80 material. Therefore, the connection design appears to have limited thread rupture potential at a global pipe strain of 3%.

In summary, the analysis demonstrates that the generic connection likely has adequate structural integrity to withstand the ISO/PAS 12835:2013 limit-strain test requirements.

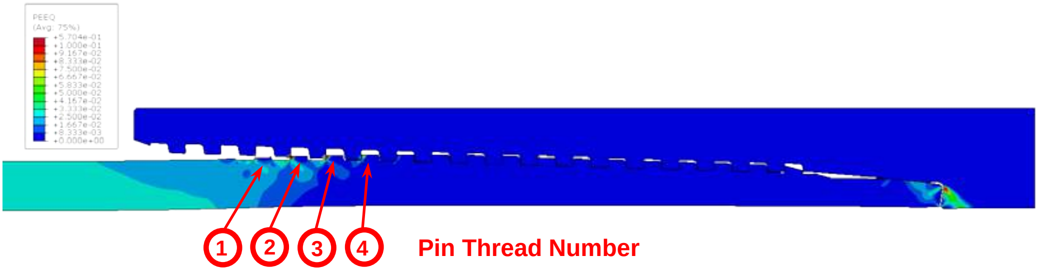

Figure 17 Contour plot of plastic strain for Case G1 subjected to 3% pipe strain following ASL-290 thermal cycle loading.

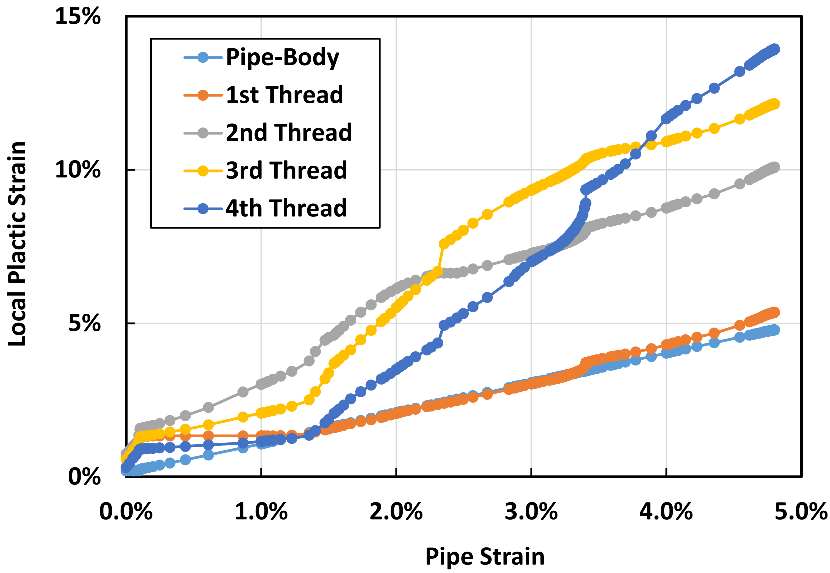

Figure 18 Plastic strains in the pipe-body and pin threads for Case G1 subjected to increasing tensile strain following ASL-290 thermal cycle loading.

6. Summary

This paper describes the application of FEA modeling and analysis as an integral requirement in the execution of a premium connection qualification program following the ISO/PAS 12835:2013 (2013) protocol, and provides an outline of the related modeling assumptions. The work presented includes a review of the sealability criterion and a description of the FEA model considerations involved in completing quantitative sealability evaluations. A full suite of analyses was conducted on a generic connection design to demonstrate the use of the proposed approach.

The paper also presented a framework for completing FEA-based quantitative evaluations of both connection sealability and structural integrity to assist in assessing tubular connection performance per ISO/PAS 12835:2013 as a precursor to testing. The work presented in the paper demonstrated the utility of the proposed approach for evaluating the potential of a connection design (including different tolerances) to satisfy both the sealability and structural performance requirements of such a qualification program based on loading conditions corresponding to a specified ASL. It should be noted that given the large number of factors that can potentially influence connection sealability, a physical test program is necessary to validate the results of such FEA-based quantitative assessments and to formally qualify the connection design.

Reliability Based Design & Assessment (RBDA) is being increasingly used to determine the safety of downhole tubulars and completion equipment (Xie and Hassanein 2012 and Xie et al 2015). In terms of tubular connections, the FEA-based evaluation methodology presented herein can be used in conjunction with RBDA to quantify the probability of acceptable performance being achieved with respect to both the sealing and structural integrity as functions of several key design parameters, including connection geometry and tolerances, material mechanical properties, and make-up and operational conditions.

7. Acknowledgement

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