

Analysis of Casing Connections Subjected to Thermal Cycle Loading

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Production of heavy oil and bitumen, which is increasing around the world as conventional oil resources are depleted, often uses thermal well technologies such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD). Casing connections are one of the most critical components in thermal wells. Historically, the literature shows that over 80% of reported uphole casing failures experienced in thermal wells occurred at connections. Typical connection failure mechanisms include structural damages, such as parting, thread rupture, and shoulder plasticity, and serviceability damages, such as leakage. One of the critical load conditions causing casing and casing connection failures is the thermal cycle loading, with high peak temperatures typically in excess of 200°C, which can cause the well casing and casing connections to deform plastically.

There are generally three types of connections used in intermediate or production casing of thermal wells: API (American Petroleum Institute) round, API buttress and proprietary premium connections. This paper presents finite element analysis of these three types of casing connections subjected to thermal cycle loading. Based on analysis results, this paper demonstrates that the premium connection, which has a metal-to-metal seal region, is the most suitable of these three connection designs for the use in thermal wells, in terms of structural integrity and sealability. This paper also presents recommendations for casing connection design for successful service in thermal well applications.

Keywords: Casing, Connection, Cyclic Steam Stimulation (CSS), Sealing, Steam Assisted Gravity Drainage (SAGD), Strength, Structural Integrity, Thermal Cycles, Thermal Wells.

1. Introduction

Thermal well technologies, such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD), have been widely used in the production of heavy oil and bitumen. Their use continues to increase as the worldwide production of oil continues to evolve from depleting conventional light oil to more viscous heavy oil and bitumen resources. In the CSS recovery process, high pressure, high temperature steam (330°C-350°C) is injected into the reservoir, followed by a soaking period to allow the thermal energy of the injected steam to disperse into the reservoir, heat the oil and thereby significantly reduce its viscosity, and the heated oil is then produced to the surface from the same well. The SAGD process typically utilizes two parallel horizontal wells positioned above one another and spaced several meters apart. High temperature steam (200°C -275°C) is continuously injected into the upper injection well to heat the reservoir. The hot fluids produced (oil, condensate and formation water) then drain into the lower production well by gravity and are produced to surface by natural steam lift or various artificial lift

techniques. Shutdowns due to facility disruptions or wellbore services, such as to replace failed artificial lift systems, and the associated cooling and reheating on restart result in cyclic thermal loading in SAGD wells.

The casing strings in thermal wells typically consist of many steel casing joints (usually 10 - 13 m in length) joined by threaded connections and are cemented over the entire wellbore length to provide structural support and hydraulic isolation to the wellbore, and as such the casing strings and in particular the casing connections are one of the most critical components in thermal wells (Xie, 2006). 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) reported that more than 80% of the uphole casing failures experienced in thermal wells occurred at connections, and the recently published casing failure occurrence data for thermal operations in Alberta (i.e. since 2000) suggests this trend has continued.

In thermal wells, investigation indicates that a large portion of these casing string and connection failures can be attributed to the severe loading conditions of these applications. A common feature for thermal wells is the cyclic thermal loading with high peak temperatures that may result in high thermally-induced stresses, which typically exceed the elastic limit of the material and cause the casing and connection to deform plastically. In addition, curvature loading resulting from casing buckling and formation shear movement is also a critical load condition for thermal well casing and casing connection integrity (Smith, 2001). Connection fatigue failures can also occur during casing installation rotations and during thermal cycles. Therefore, ensuring adequate structural integrity and sealability of the connections over the full service life of a thermal well is a significant challenge. Proper casing design, including material selection and connection design, plays an important role in achieving the long term structural and hydraulic integrity and minimizing the risk of casing failure in these applications.

This paper presents discussions on design requirements for casing connections in thermal wells. There are three basic types of casing connections used in oil wells: standard API (American Petroleum Institute) round, API buttress (and oversized buttress) and proprietary premium connections. This paper focuses on the finite element analyses of these three types of connections subjected to thermal cycle loading representative of CSS well operating conditions. The analysis results provide a comparative assessment of their relative structural integrity and sealability performance under thermal cycle loading conditions representative of these applications.

2. Connection design requirements

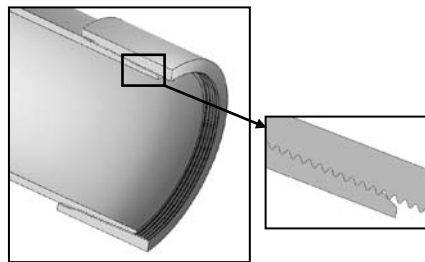
Two of the primary functions of casing connections are adequate structural integrity and hydraulic integrity or sealability. Various guidelines for connection designs have been established by industry over the years. For example, the Alberta Industry Recommended Practice (IRP, 2002) outlines the following general recommendations for casing connections in thermal wells:

- The connections should have a joint axial load carrying capacity greater than, or equal to, the pipe body yield strength;
- The casing connections should provide adequate sealing under the anticipated thermal operating conditions; and

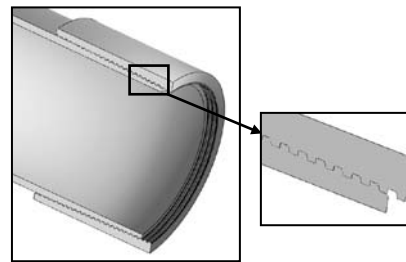
- The selection of a suitable thread compound is an integral part of casing connection design and should be properly matched with the type of connection selected.

The casing connections of oil country tubular goods (OCTG) can be classified into three types: API round, API buttress (and oversized buttress), and proprietary premium connections. These connections, the general forms of which are shown in Figure 1, have the following features:

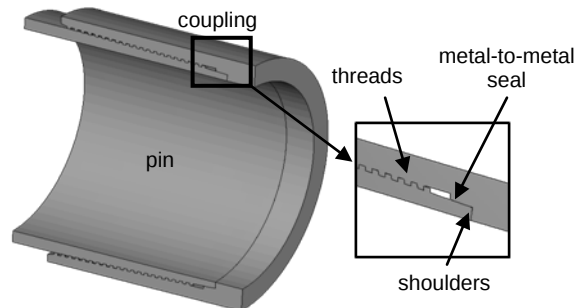
- API round threads are of two forms: API long threaded and coupled (LTC) and short threaded and coupled (STC). The sloped profile and tolerance of the API round thread design, in conjunction with the appropriate thread compound, provide the structural and sealing capabilities of these connections (Figure 1a).
- API buttress threaded and coupled connections (BTC) have a more square thread profile which provides the structural function and some degree of sealability (i.e. by the combination of the action of a thread compound and the helical leak path of the buttress thread section) (Figure 1b).
- Premium connections typically use buttress-type threads for the structural function and a metal-to-metal radial contact seal section for sealability. Many premium connections also include an axial metal-to-metal shoulder next to the seal region of the pipe body and coupling design to control makeup and, in some designs, to gain additional sealability. Figure 1c shows a generic premium connection which employs buttress threads, a metal-to-metal radial seal and a pin-to-coupling shoulder.



(a) API round thread connection



(b) API buttress thread connection



(c) A generic premium connection

Figure 1. Schematics of (a) an API round thread connection; (b) an API buttress thread connection; and (c) a generic premium connection

3. Finite element model

3.1 Modeling of casing connections

The analysis examples presented in this paper consider a 177.8 mm outer diameter (OD), 34.2 kg/m weight, Grade 80 steel alloy casing material with API STC, API BTC and generic premium connection designs. As shown in Figure 2, an axially symmetric section including one half of a connection and one half of a typical casing joint (e.g. 10 m in length) were considered in the model. A finite element model of the half coupling and casing section was created using axisymmetric solid elements CAX4 in Abaqus. The geometries of API STC and BTC connections were developed based on nominal dimensions as per API Specifications 5CT (2005) and 5B (2008). The generic premium connection model included the basic features common to the premium connections currently used in thermal well applications (e.g. buttress threads, axial torque shoulders, and radial metal-to-metal seals) such that the analysis results were representative of such connections. Note that the generic premium connection model presented here should not be taken as being representative of any specific commercially available connection product. It is also important to note, however, that premium connection designs must be modeled based on the proprietary design details of the connection.

This paper focuses on simulating the response of the connections under axisymmetric loading, such as makeup, axial tensile and compressive loading, and thermal cycle loading representative of CSS well operating conditions (e.g. thermal cycle with peak temperature of 350°C). In the analyses, symmetric boundary conditions were assumed for both ends of the models, and the casing OD was constrained radially to represent radial confinement provided by the cement sheath and formation surrounding the casing. For 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).

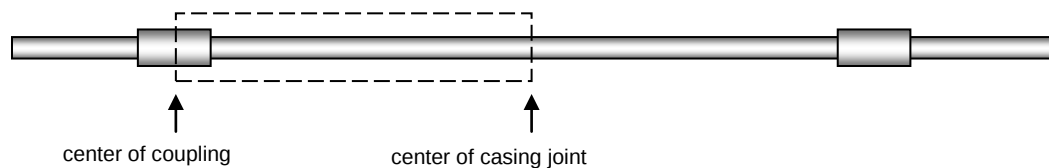


Figure 2. Section of coupling and casing pipe body modeled

3.2 Modeling of casing materials

The Grade 80 (i.e. nominal minimum yield strength of 80 ksi (552 MPa)) material of casing connection (i.e. pipe body and coupling) response was modeled using an elastic-plastic, combined kinematic hardening constitutive relationship. The initial yield stress at room temperature was assumed to be 570 MPa, which is representative of such commercial Grade 80 casing materials, and the Young's modulus was assumed to be 200 GPa. The material model also takes into consideration of temperature- and time-dependence effects. These modeling considerations were

required to capture material property variations with temperature, stress relaxation behavior and Bauschinger effect (i.e. reduced yield stress upon load reversal after plastic deformation has occurred during the initial loading) (Dowling, 1998). Additional discussions of the material modeling approach for thermal cycle loading analysis were presented by Xie (2008b).

3.3 Modeling of loading conditions

The following is a brief description of three loading conditions that each of the connection designs was analyzed.

Connection makeup

The initial state of the three models of the connections was obtained by engaging the threaded casing pin end into the coupling to the nominal makeup position by resolving overclosure interference between the threads of the pin and box, as well as in the radial seal and axial shoulder regions for the premium connection. The connection makeup was assumed to occur at a low ambient temperature of 20°C. This load scenario simulates connection makeup in the fabrication facility and in the field.

Axial loadings

For assessment of the structural capacities of the three connection designs, axial tensile and compressive loads were applied along the axis of the connection models after makeup. This load scenario was used to assess the relative structural and sealing capacities of different types of connections.

Thermal cycles

To investigate the performance of the three connections under loading conditions representative of a CSS operation, the thermal cycle loading was simulated by subjecting the connection models to temperature variations equivalent to one thermal cycle. Through this thermal cycle loading, the ends of the model were constrained axially to represent the casing cemented to the formation in the wellbore. Note that multiple cyclic loading analysis may also be conducted with a suitable casing material model (Xie, 2008b).

To model a single thermal cycle, the temperature of the casing joint and coupling was gradually increased from the initial temperature, here assumed to be 20°C, to the maximum operating temperature, assumed here for the CSS scenarios to be 350°C.

To illustrate the key features of the thermal cycle loading, Figure 3 presents the relationship between the casing axial stress and temperature for the Grade 80 casing pipe-body over the temperature cycle from 20°C to 350°C and back to 20°C. The thermal cycle consists of three loading stages:

1. The “Heating” load stage occurs as the temperature increases from the initial value of 20°C to the peak temperature of 350°C. Since the casing string is constrained axially (e.g. cemented), axial compressive stress develops which ultimately exceed the material yield capacity in compression, in this case at a temperature of approximately 210°C;
2. The “Hot-hold” stage is where the temperature is held at the peak value for a period of time (e.g. hours or days). Stress relaxation occurs with a significant reduction in axial compressive stress; and

3. The “Cooling” load stage occurs when the temperature is decreased from the peak “hot-hold” value of 350°C, to the initial ambient temperature of 20°C, causing the constrained casing to contract and the axial load to gradually change from compressive to tensile loading. In high temperature applications, such as CSS operations, and depending on the properties of the material and the peak temperature range, the casing pipe body material could reach yield in tension at the end of a thermal cycle, as shown in Figure 3.

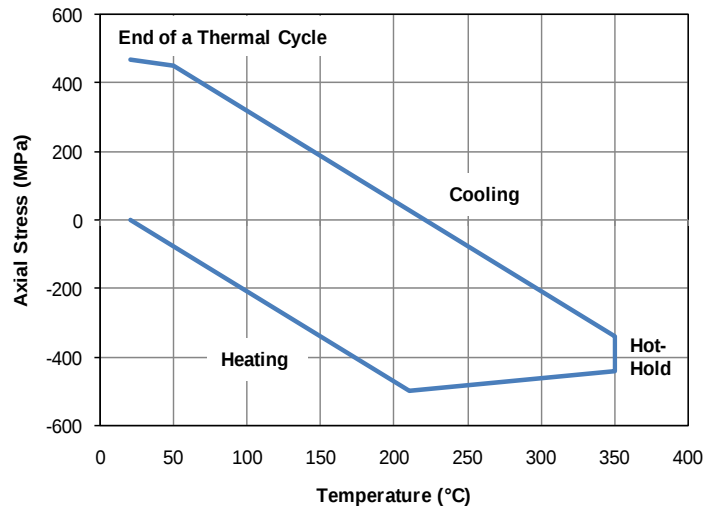


Figure 3. Axial stress and temperature relationship for a Grade 80 casing string under thermal cycle loading from 20°C to 350°C

4. Analysis results

The following section describes the results of the axial loading and the thermal cycle loading scenarios on the three connection designs. The makeup loading results are not presented in detail since this loading scenario was merely completed to obtain the initial conditions for the axial and thermal load scenarios.

4.1 API STC and API BTC connections under axial loading

Structural capacities

The structural response of the API STC and BTC connections under axial loading scenarios was assessed by applying the tensile and compressive loads along the axis of the connection models after makeup. Figure 4 presents the axial force response to average axial strain within the API STC and BTC connections under tensile load. The analysis results show that the BTC connection has axial load carrying capacity greater than the pipe body yield strength. The STC connection, however, shows lower axial load carrying capacity than the yield strength mainly due to reduced cross section of the unengaged thread section of the pin. Initiation of thread jump-out was predicted under a relatively low axial tensile load (i.e. less than half of the pipe body yield load).

Note that thread jump-out is a potential connection failure mechanism which occurs when threads on the pin jump over one or more thread grooves of the coupling axially outward under axial tensile loading. This is in contrast to thread jump-in which occurs when threads on the pin of a connection jump by one or more thread grooves axially inward relative to the coupling under compressive loading. As the tensile load increases beyond the jump-out initiation, separation of the flanks between coupling and pin threads becomes significant, as shown in Figure 5.

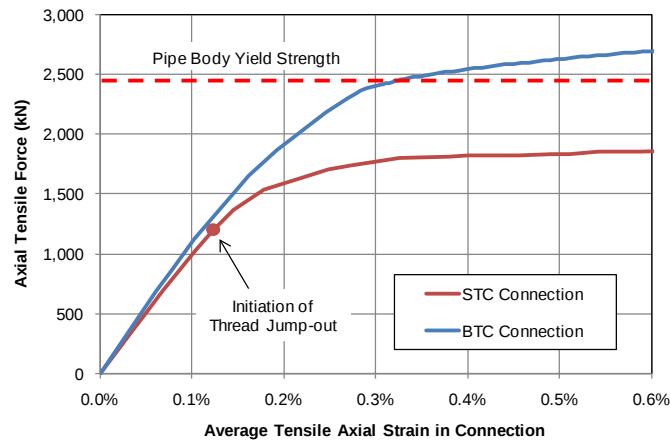


Figure 4. Axial force vs average axial strain of 177.8 mm, 34.2 kg/m Grade 80 API STC and BTC connections under tensile loading

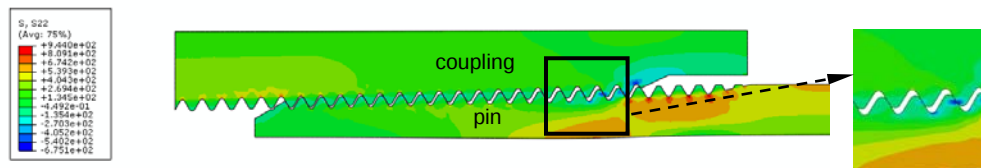


Figure 5. Axial stress (MPa) of a 177.8 mm, 34.2 kg/m Grade 80 API STC connection under tensile loading (showing development of thread jump-out)

Figure 6 presents the axial force response of the API STC and BTC connections under compressive loading. The analysis results show that BTC connection also provides higher axial load carrying capacity than the pipe body yield strength under compressive loading. For the STC connection, the compressive load carrying capacity was shown to be lower than pipe body yield strength. Initiation of thread jump-in was observed under an axial load level significantly below the pipe body yield load. Due to the taper angle of the pitch line of the STC connection threads in the pin and coupling, the results show that thread jump-in requires a higher applied load (or energy) than that required for thread jump-out under tensile loading. Figure 7 shows the deformation in the STC connection with development of thread jump-in evident by the inward deformation within the unengaged thread region of the pin portion of the connection.

Based on the analysis results of this illustrative example, the API STC connection with the assumed Grade 80 material properties did not satisfy the suggested guidelines of the Alberta IRP that the connections should have a joint axial load carrying capacity greater than or equal to the pipe body yield strength. On the other hand, the analyzed API BTC connection (i.e. with the same casing pipe body and material grade) showed sufficient axial load carrying capacity to satisfy the Alberta IRP guidelines.

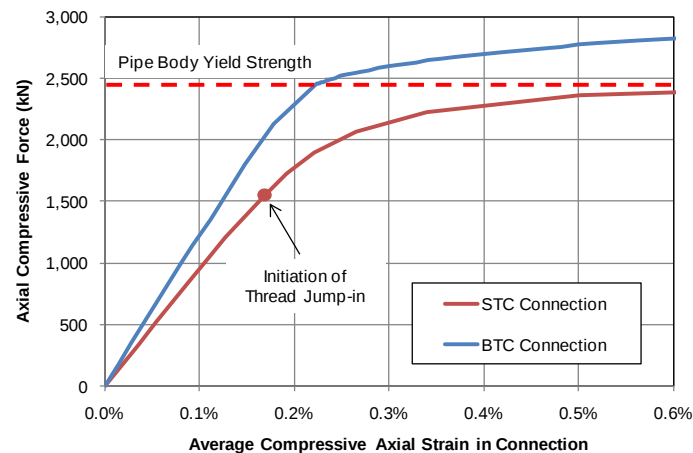


Figure 6. Axial force vs average axial strain of 177.8 mm, 34.2 kg/m Grade 80 API STC and BTC connections under compressive loading

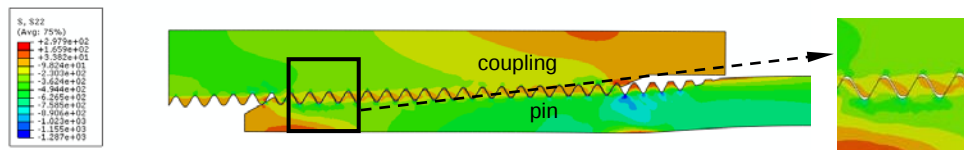


Figure 7. Axial stress (MPa) of a 177.8 mm, 34.2 kg/m Grade 80 API STC connection under compressive loading (showing development of thread jump-in)

4.2 API STC and API BTC connections under thermal cycle loading

Structural capacities

Figures 8a and 8b present the axial stress distribution for the API STC connection after makeup at room temperature (i.e. 20°C) and after axially constrained thermal loading to 350°C, respectively. Figure 8b shows the development of thread jump-in and excessive plastic deformation in the critical section of the unengaged threads of the pin. Figure 9 presents the axial stress distributions for an API BTC connection after makeup and during thermal cycle loading over the same temperature range. The analysis shows that the API BTC connection maintained structural integrity during the imposed thermal cycle, and no thread jump-in or jump-out was observed for the modeled API BTC connection.

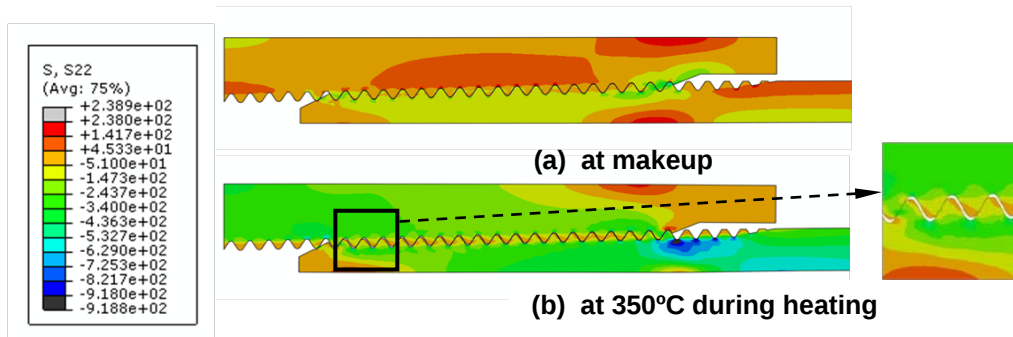


Figure 8. Axial stress (MPa) of a 177.8 mm, 34.2 kg/m Grade 80 API STC connection subjected to thermal loading

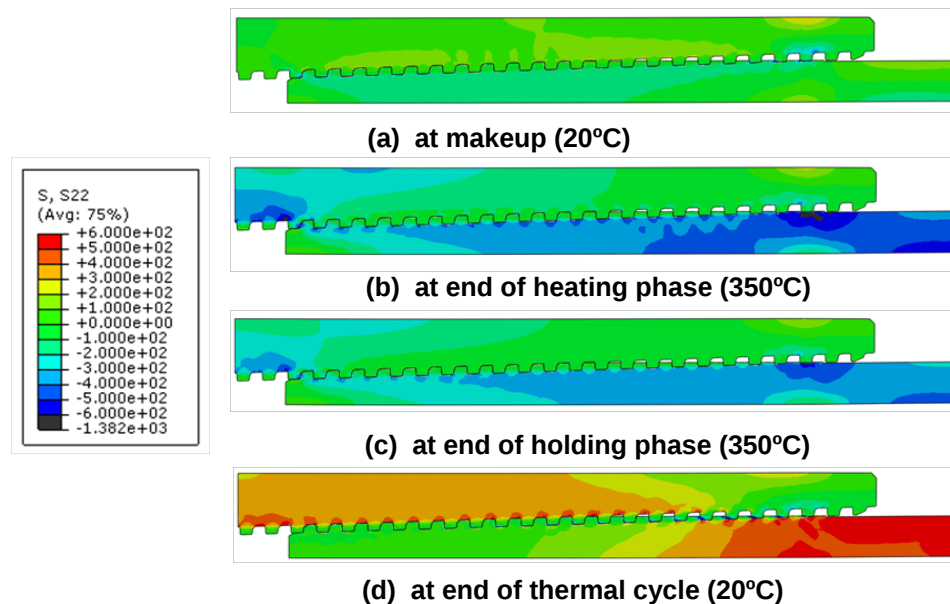
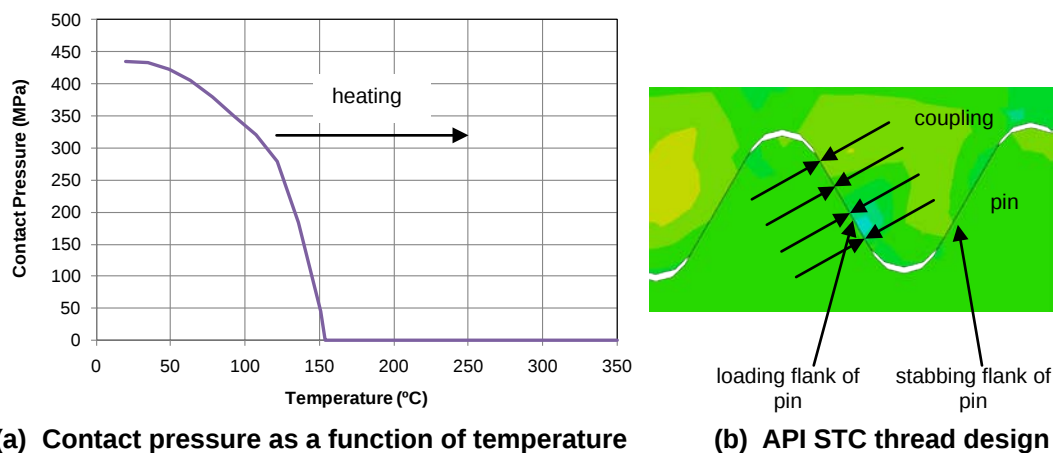


Figure 9 Axial stress (MPa) of a 177.8 mm, 34.2 kg/m Grade 80 API BTC connection subjected to thermal cycle loading

Sealing integrity

In addition to the structural capacity guideline, the Alberta IRP (2002) also indicates that the casing connections should provide adequate sealing under the anticipated thermal operating conditions. For API round connections, the sealing capacity usually depends on three factors: (1) contact pressure between threads of the coupling and pin; (2) the geometry of the leakage path (i.e. the length and cross-section area), and (3) the property of the thread compound occupying in the leakage path. After connection makeup, contact is established on both the stabbing flank and

the loading flank of the round threads of the pin (Figure 10b). As noted by Teodoriu (2009), if the contact pressure is higher than the pressure to be sealed, the only potential leak paths in API round connections are the spiral paths between the thread crests and roots. Figure 10a presents the average contact stress on the loading flank next to the entry plane as a function of temperature for the API STC connection. As shown in Figure 10a, as the STC connection was heated, the contact pressure decreased with increasing temperature and eventually dropped to zero at around 153°C, leading to loss of contact pressure between the threads. However, due to the combined effects and variability in material properties and connection tolerances, it is important to note that finite element analysis is not generally sufficient on its own to determine the seal performance of API round thread connections, and physical testing should be used in conjunction with numerical simulation to assess the connection sealing performance.



(a) Contact pressure as a function of temperature

(b) API STC thread design

Figure 10. Predicted contact pressure on the critical loading flank as a function of temperature for a 177.8 mm, 34.2 kg/m Grade 80 API STC connection

In contrast to API round connections, according to API specification 5B (2008), the API buttress threads leave a nominal 0.025 mm (0.001") gap between the thread flanks of the coupling and the pin for 177.8 mm (7") connections. The thread manufacturing tolerance allowed for 177.8 mm (7") API buttress connections is 0 to -0.076 mm (-0.003") for both pin and coupling threads along the axial direction of the connection. Therefore, the maximum gap between the threads of the pin and coupling can be as large as 0.178 mm (0.007"). Therefore, the sealing performance of the API buttress connection relies on the combined effects of contact pressure between the threads, the leakage path geometry and the thread compound properties. As indicated in the Alberta IRP (2002), API buttress connections require a high concentration of solids in a high temperature thermal lubricating compound to improve sealability once the connection is made-up. The solids and lubricant fill gaps in the pin-box thread form that otherwise might allow fluids to seep through the connection. Full-scale testing has confirmed that, in most cases, a buttress connection does not provide the same degree of seal integrity as does a premium connection. In some cases, buttress connection specimens have exhibited leakage rates several orders of magnitude higher than premium connections under the same conditions (Maruyama, 1990). For these considerations,

buttress connections are often considered not suitable for the demanding conditions of the intermediate or production casing strings in high-temperature thermal well applications.

4.3 Premium connection under thermal cycle loading

Structural capacities

Premium connections are commonly designed to have the buttress type threads for structural capacity and a metal-to-metal seal section for sealing. Therefore, one would expect premium connections to have similar load carrying capacity to that of API buttress connections and should therefore, have sufficient structural capacity for thermal well applications.

Figure 11 presents the axial stress contours for a generic premium connection at makeup, and at the end of the hot-hold and cooling stages of a thermal cycle. The red color represents areas with high tensile stress and the blue color is for areas with high compressive stress. As shown in this figure, regions of the connection are subjected to high compressive loading (blue color) at makeup and during the hot-hold period due to connection shoulder engagement and material thermal expansion, respectively, and to high tensile stress (orange to red color) as it is cooled down due to material thermal contraction. For many premium connections, thermal cycle loading does not cause a significant structural concern in the thread roots due to the generally low magnitude of the associated plastic strains. However, under such conditions, the excessive compressive loading on the pin/coupling shoulders may cause some concerns for structural failure as these regions may be subjected to excessive shear deformations. Note that the plastic strain value in the torque shoulder regions can be significantly larger during heating as compared to that at makeup.

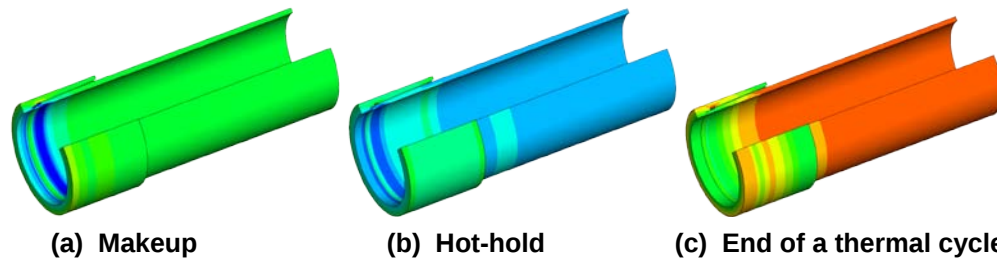


Figure 11. Axial stress distribution of a generic premium connection subjected to thermal loading

Sealing integrity

The sealing capacity for a premium connection is generally provided by the metal-to-metal contact stress over the effective seal region (Xie, 2009), as shown in Figure 12. Since the purpose of the examples presented in this paper is to demonstrate typical connection deformation mechanisms, connection seal contact forces are presented on a relative performance scale to that of the connection makeup condition. Figure 13 shows the variation in the seal contact intensity (integration of the seal contact stress profile over the effective seal length) of the generic premium connection from make-up through the thermal cycle. The figure shows that the seal contact intensity (i.e. relative to makeup) varies during the thermal cycle, with a significant reduction of about 38% during the hot-hold period as a result of the stress relaxation of the material. At the

end of the thermal cycle, the seal contact intensity was further reduced to only about 42% as compared to that of the made-up condition, due to the effect of thermal tensile loading. Note that the seal contact stress must be significantly higher than the oil/gas/steam pressure in order to maintain sealability.

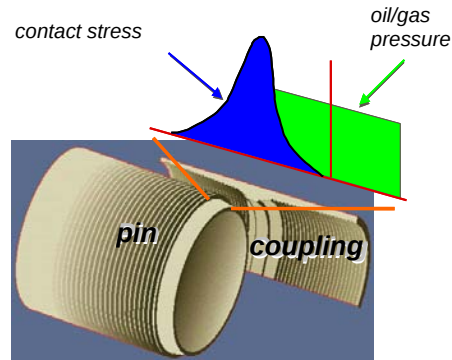


Figure 12. Illustration of seal contact stress in a premium connection

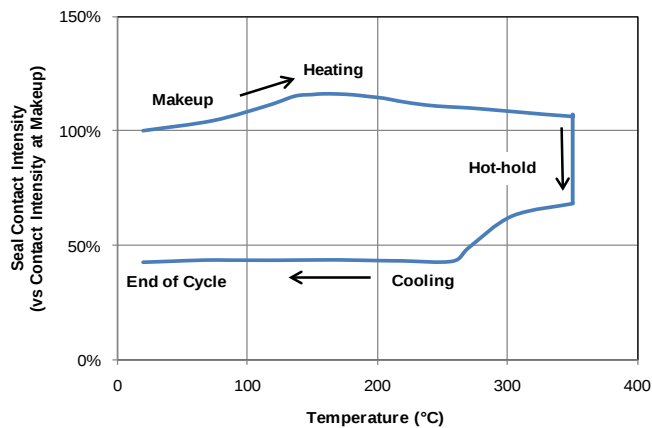


Figure 13. Changing of seal contact intensity for a 177.8 mm, 34.2 kg/m Grade 80 generic premium connection over a thermal cycle

Based on the analysis of the Grade 80 generic premium connection, the results indicate that while the considered thermal cycle loading did not appear to cause a significant concern for the structural performance in threads of this generic premium connection design over the make-up and thermal cycle considered, an over-loaded shoulder condition could potentially cause structural damage in the shoulder region of the connection. The results also show that the premium connection sealing capacity can change significantly over thermal cycle loading. It has been shown that significant reduction in seal contact intensity can occur due to stress relaxation during the hot-hold stage, and due to axial tensile loading introduced during cooling. As such, the results of this analysis show that the seal contact condition is generally at its lowest and most critical value at the end of a thermal cycle in such high temperature application.

It is important to reiterate that the specific behavior of a connection is a function of its design, manufacturing (tolerance), make-up and load history. Therefore, each connection and load scenario must be evaluated for the conditions of the application.

5. Material impacts on connection performance

The numerical evaluation of connection performance in a thermal well application is often challenging because the long-term material behavior is affected by the load and environmental history, which may also be influenced by the cyclic high temperature effects, plastic deformations, and fatigue loading conditions in thermal wells. One important issue raised by Xie (2008a) is that the casing design should take into consideration the potential effects of material degradation in thermal wells. Xie suggested that the effects of strain-hardening, strain-ageing, and corrosion can contribute to material degradation over thermal cycles. These effects are discussed further below with reference to their impact on connection performance in thermal wells.

5.1 Strain-hardening

Strain-hardening (also often termed “cold working”) of steel materials is the strengthening resulting from an increase in the material’s dislocation density by plastic deformation. Material strain-hardening often results in some beneficial effects for casing and liner designs in thermal well completions, as it generally increases casing/liner resistance to strain localization, buckling and shear deformation. In addition, strain-hardening is also favourable in terms of reducing localized plastic strain accumulation in connection threads. Xie (2008a) demonstrated the relationship between plastic strain and temperature for both the casing pipe body and premium connection thread root during a thermal cycle, as shown in Figure 14. It is interesting to note that the development of plastic strain in the connection thread root approaches a plateau value soon after the pipe body reaches yield during both the heating and cooling periods. Yield of the casing pipe body significantly reduces the severity of strain localization in the connection threads and therefore allows incremental plastic strain to be more evenly distributed throughout the casing string. A higher strain-hardening rate would lead to less plastic strain accumulation in the thread root before the pipe body yields and, as a result, would reduce the failure potential in the thread region of the connection. The Alberta IRP (2002) indicates that the Y/T (yield strength to tensile strength) ratio of casing material should be less than or equal to 0.9 for the intermediate or production casing to ensure that the API buttress and premium connections have sufficient structural capacities for application in high temperature thermal wells.

The development of strain-hardening, however, often causes a reduction in the material’s ductility, and that may cause the material to be more susceptible to different forms of corrosion. Physical coupon tests have shown that there is more than 10% reduction in material ductility as a result of strain-hardening induced in the specimen from one thermal cycle (Xie, 2008a). However, the tests also show that such reductions appear to stabilize with further cycles. The reduction in material ductility due to strain-hardening is not typically considered to be the primary reason for casing failures since the main impact of strain-hardening on ductility occurs during the first thermal cycle. Experience has nevertheless shown that most thermal well failures tend to occur after several thermal cycles (Wu, 2008), suggesting that further investigation of the potential impacts that mechanisms such as strain-hardening might have on casing failures appears to be warranted.

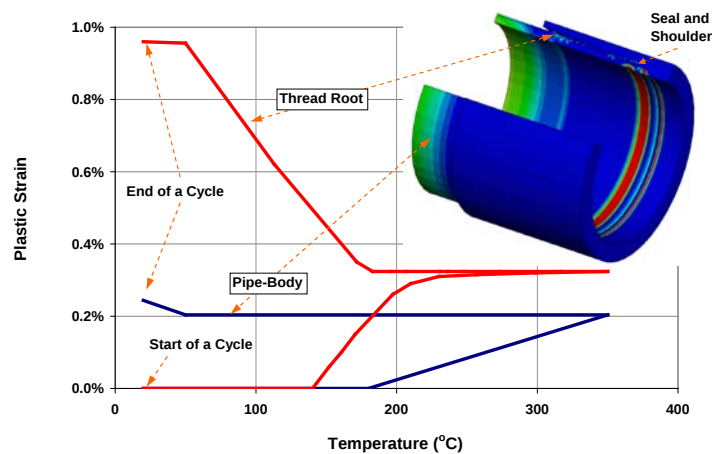


Figure 14. Relationship between plastic strain and temperature for casing pipe body and a premium connection thread root (including plastic strain contour for connection - red represents high plastic strain) (Xie, 2008a)

5.2 Strain-ageing

Strain-ageing for carbon steels mainly involves the interaction of dislocations with interstitial elements, such as carbon and nitrogen, or interstitial-substitutional solute pairs. This interaction stabilizes mobile dislocations and therefore an incrementally larger stress is required to continue to move the dislocations to result in incremental plastic deformations (Xie, 2008a). Usually, a slow strain rate and a relatively high temperature (150 – 250°C) are required to achieve strain-ageing of casing materials, both of which tend to exist in many thermal wells. Strain-ageing can cause a significant reduction in material ductility, and therefore may impact the connection performance.

Xie (2008a) suggested that, given the nature of strain-ageing, it can be postulated that casing material strain-ageing may occur in thermal wells, especially in CSS wells where the cooling phase may occur over a relatively long time period (e.g. several weeks or months during the production stage). As was shown in the finite element analysis of the generic premium connection subjected to thermal cycle loading, the connection thread roots can start to yield at around 150-200°C during the cooling phase. Therefore, it is possible that material strain-ageing may occur in areas of high strain, such as in the thread roots of casing connections. Development of strain ageing may significantly reduce the casing material ductility, and consequently reduces the connection capacity to sustain thermal loads.

5.3 Corrosion

Connection performance may also be significantly affected by a number of possible material corrosion mechanisms. Thermal wells are often exposed to corrosive environments, including carbon dioxide (CO₂) and hydrogen sulfide (H₂S) generated by aqua-thermolysis of the heavy oil in the presence of water at high temperatures. The severe loading conditions present during thermal operation will likely increase the casing material's susceptibility to corrosion induced

degradation, such as stress corrosion cracking (SCC). As noted by Xie (2008a), further study is required to define the impact of material corrosion and the combined and potentially synergistic effects of the temperature variations, plastic deformation and corrosion on connection performance in thermal wells.

6. Conclusions

This paper presents an overview on a number of key connection design requirements for thermal well applications, in particular related to those of the main roles of the connections in maintaining the structural and hydraulic integrity of the wells. Based on the finite element analysis of three types of connections (i.e. API round, API buttress and a generic premium connection), this paper demonstrated the relative structural and seal performance of these connections under thermal cycle loading conditions representative to typical high temperature thermal well (e.g. CSS) applications. Note this paper focused on connection performance under thermal cycle loading. It is important to note that, in addition to thermal loading, curvature loading resulting from wellbore curvature, casing buckling and formation shear movement can also contribute to casing connection failures in thermal wells, and should also be considered.

Based on discussions and analyses presented in this paper, the following conclusions and recommendations are made:

- API round thread connections, such as the STC and LTC designs, do not provide adequate axial load carrying capacity which is recommended to be greater than pipe body yield strength according to industry guidelines such as the Alberta IRP (2002). Therefore, they are generally not suitable connection designs for most of high temperature thermal well applications.
- API buttress connection appears to have sufficient structural capacity for intermediate or production casing of many thermal well applications. However, the API buttress connections rely on thread compound to provide sealing which may not be sufficient under thermal well conditions. Therefore, API buttress connections are generally not recommended for the intermediate or production casing of most of high temperature thermal well applications.
- Premium connections usually provide both sufficient structural capacity and sealability for the conditions of most of high temperature thermal well operations (e.g. up to 350°C). Therefore, they are generally preferred for the intermediate or production casing in thermal wells. However, a combination of both suitable and representative physical and numerical evaluation (or qualification) programs are generally required to properly assess the structural and sealability performance of premium connections in such demanding conditions as those of CSS and SAGD applications.
- Further investigation is necessary to expand the understanding of material degradation effects on the long term connection performance in thermal well applications, such as strain-hardening, strain-ageing and corrosion.

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