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HPHT Well Integrity and Cement Failure

Bomá Wilcox Jr., Babs Oyeneyin, and Sheikh Islam, Robert Gordon University

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Abstract

A petroleum wellbore must have complete zonal isolation to maintain its integrity. This is primarily achieved by the cement sheath barrier that sits between the casing and rock formation. However, effective zonal isolation can be adversely affected by conditions such as high pressures, high temperatures, and high hole angles. These conditions are increasingly popular in deep-water drilling and can compromise the strength and integrity of the cement sheath if not anticipated early.

This paper presents some critical issues and factors that affect well integrity in HPHT wellbores. It also presents an analytical model of the interaction between the casing, cement sheath, and rock formation. This model also contains mathematical relationships for the interfacial pressures at the casing-cement and cement-rock contacts/interfaces. The study was limited to vertical wells as this allowed us, for purposes of symmetry, to analyse the casing-cement-formation relationship as a composite cylinder. The area of the wellbore that was analysed is the pay-zone area where the relationship between the casing, cement and rock formation is represented by a concentric composite cylinder. This paper is part of an on-going research project on well integrity at Robert Gordon University, United Kingdom.

Introduction

Well Integrity is the use of technical, operational and organizational solutions to reduce the risk of any uncontrolled release of formation fluids throughout the life cycle of a petroleum well (Torbergsen et al. 2012; Calosa et al. 2010; Wakama et al. 2004; Ugwu, 2008). Complete zonal isolation of a petroleum wellbore must be attained to maintain integrity and produce economically. Hence, the entire working staff responsible for planning and executing the drilling and completion of wells must proactively identify solutions that would ensure safe life cycle designs (Tobergsen et al., 2012). Unfortunately, well integrity is realistically not always maintained in oil field practice. History has shown some devastating consequences of losing well integrity: Philips Petroleum’s Bravo blowout in 1977, Saga Petroleum’s blowout in 1989, PTT’s Montara oil spill in 2009, and most recently, BP’s Macondo blowout in the Gulf of Mexico in 2010 (Shadravan & Amani, 2012; Torbergsen et al. 2012). Engineers and researchers alike have identified ″poor cement design″ as the primary cause of the aforementioned oil spills (Turley, 2014; Visser, 2011; Shadravan & Amani, 2012; Garg & Gokavarapu, 2012). Cementing operations in high-pressure/high-temperature (HPHT) environments are challenging due to large differential changes in the physical and chemical behaviour of the cement materials. These harsh conditions pose a threat during the well cementing operations and after the cement sheath has set during its life cycle (Yetunde & Ogbonna, 2011; Shadravan & Amani, 2012).

Cement Sheath Barrier

The sole aim of the annular cement sheath is to provide zonal isolation for the entire life-cycle of the petroleum wellbore (Tahmourpour & Griffith, 2007; Yetunde & Ogbonna, 2011; Shadravan & Amani, 2012; Calosa, 2010; Ravi et al. 2008). In order to achieve this aim, the entire annulus must be filled with oil-well cement after removing the drilling fluid or mud. Selecting a particular cement for well operations depends largely on down hole and formation conditions, but it must possess certain features that are required for a solid completion job (Ugwu, 2008; Nelson, 1990). These features include:

- Durability – The cement mixture/slurry must be durable and not decline in strength during the operational phase of the wellbore.
- Optimal Setting Time – An overly reactive slurry will result in the cement mixture setting too quickly, and inadequately reactive slurry will take too long to set. The cement slurry must have an optimal setting time.

As indicated by the aforementioned features, the cement slurry should satisfy the short-term and long-term requirements needed for the life-cycle integrity of the petroleum wellbore. Conventionally, the oil and gas industry has focused on the short-term features and properties that are relevant when the oil-well cement is in the slurry/paste form (Tahmourpour & Griffith, 2007). This procedure is important, but the long-term integrity of the cement depends primarily on the material and mechanical properties of the cement sheath such as Tensile Strength, Young's Modulus, and its resistance to downhole chemical attack (Bosma et al., 1999; Hunter et al., 2007; Tahmourpour & Griffith, 2007; Stiles, 2006). Thoroughly evaluating the properties that affect the long-term integrity of the cement sheath is crucial for designing a cement system that will withstand high temperature and high pressure differentials. Any sort of failure in the cement matrix or sheath could potentially cause the formation of cracks and pathways for the movement of gas to the surface as shown in figure 3 (Yetunde & Ogbonna, 2011; Ravi et al., 2002; Nygaard, R., 2010).

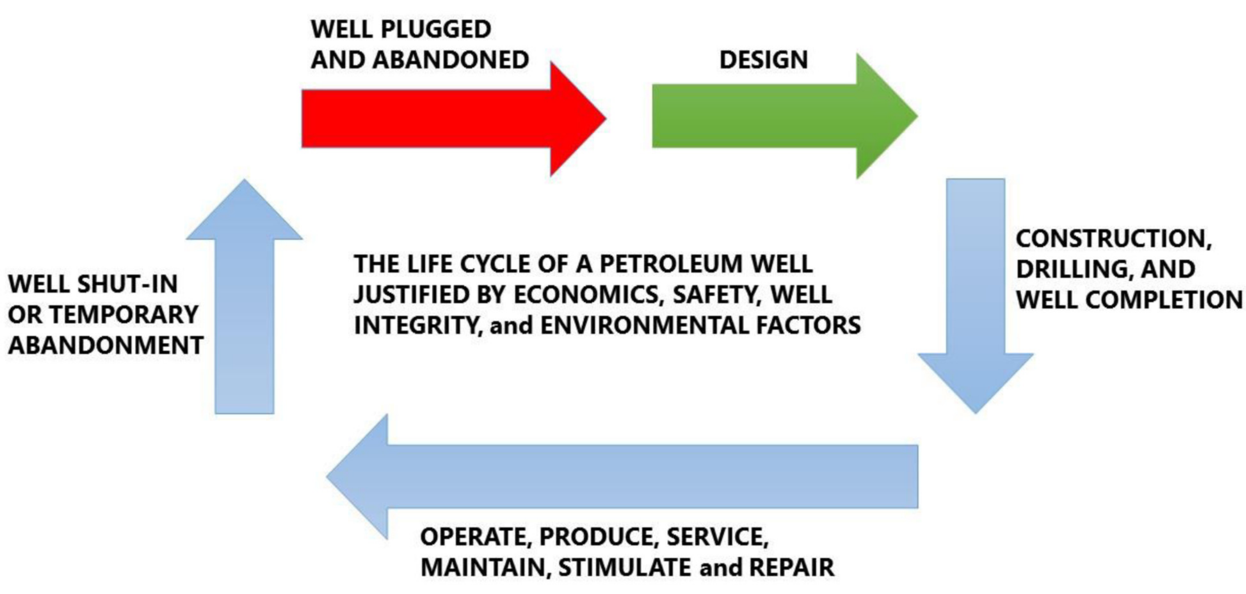

Figure 1—The entire life cycle of a petroleum wellbore. The design stage, signified by the green arrow, marks the beginning of the wellbore's lifecycle, and the red arrow signifies the end of the lifecycle, albeit petroleum wellbores can be re-stimulated long after abandonment (Adapted from Calosa et al., 2010)

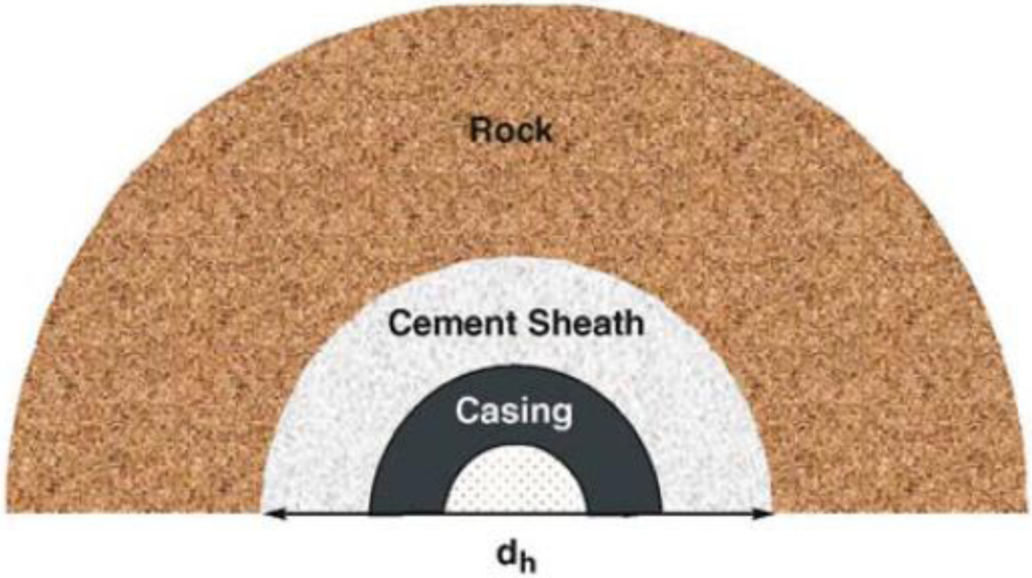

Figure 2—A cross-section of a petroleum wellbore showing the geometrical arrangement of the casing, cement sheath, and rock formation. d_h represents the diameter of the wellbore (Adapted from Tahmourpour & Griffith, 2007)

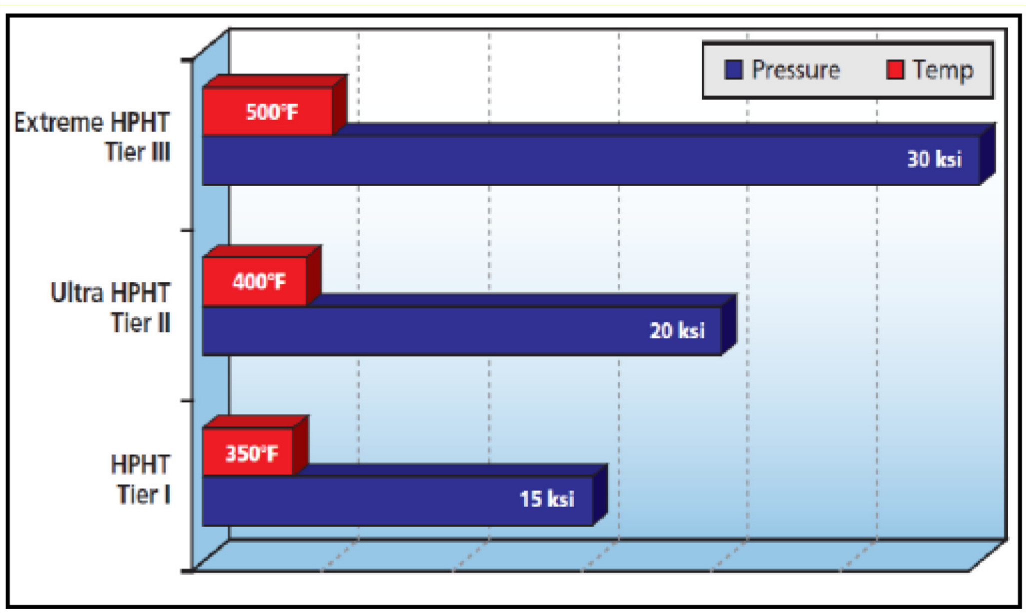

Figure 3—High-Pressure/High-Temperature Tiers (Adapted from Zhaoguang et al., 2012)

The research conducted by Ugwu (2008) shows that oil-well cement fails by three main processes: debonding, radial cracking, and cement plastic deformation. Debonding in the wellbore is usually caused by cement shrinkage which creates a weak bond between either the cement sheath and casing, or the cement sheath and rock formation (see figure 4). In radial cracking, failure is caused by the gradual formation of cracks in the cement sheath due to fatigue loading and constant pressure, as shown in figure 3. Plastic deformation, as the name suggests, is the stage where the cement sheath is permanently deformed under loading and forms a new shape.

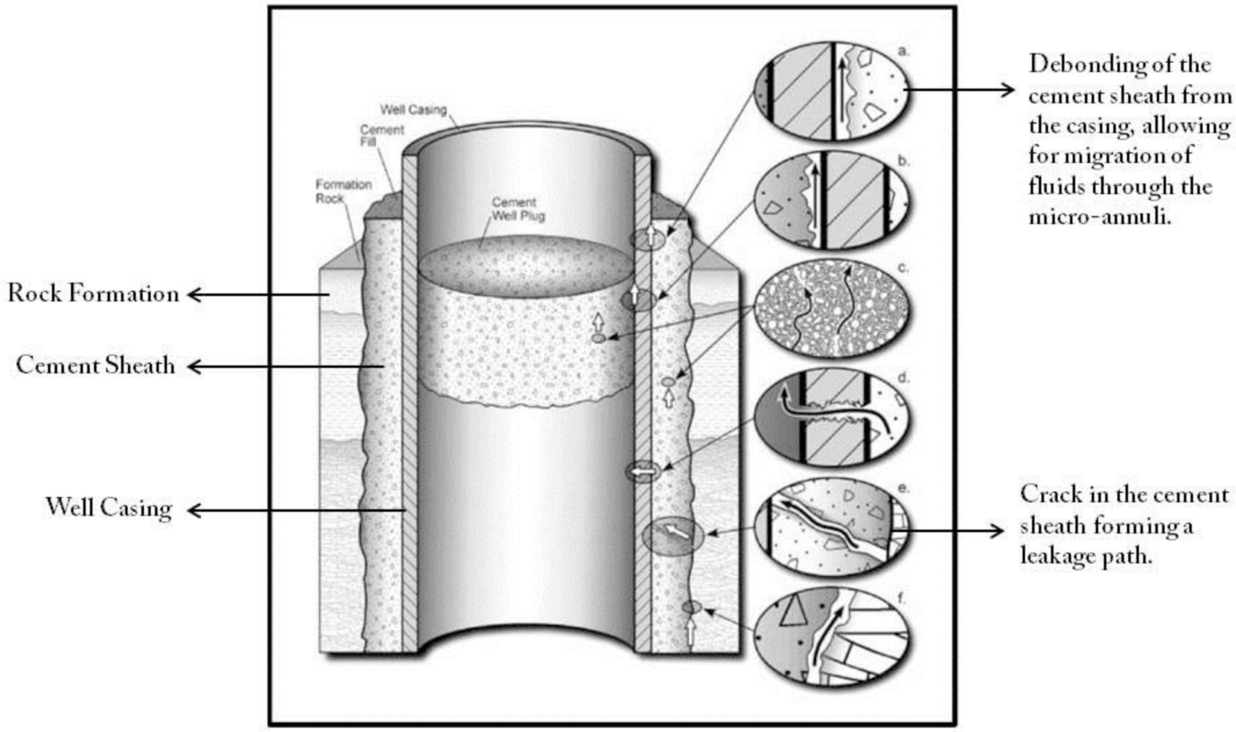

Figure 4—Possible leakage paths in a cased wellbore. The enlarged picture, *a*, shows debonding of the cement sheath from the casing, thereby creating a leakage path for the potential migration of fluids to the surface. The enlarged picture, *e*, shows a crack in the cement sheath which could adversely affect the integrity of the cement sheath (Adapted from Nygaard, 2010)

After well cementing, if there is no immediate migration of petroleum fluids to the surface, then it is most likely that the short-term properties shown in table 1 have been well designed (Bosma et al., 1999). Although, research shows that the stresses caused by high differentials in pressure and temperature during later operational phases, such as stimulation and production, cause a reduction and eventual decline in the integrity of the cement sheath. As shown in figure 1, the life-cycle of an oil and gas well can be divided into two major phases that are important for the integrity of the cement sheath.

Table 1—Short-term and long-term properties required for a cement sheath sealant (Adapted from Bosma et al., 1999)

No.	Short-Term Properties: The Fluidic State	Long Term Properties: Solid Cement Sheath
1	Environmentally acceptable and approved for use.	Thermally stable under downhole conditions of pressure and temperature.
2	Has the required density.	Should be easily detected by conventional logging techniques.
3	Can be pumped through the drill string or coiled tubing.	Repel attacks from downhole chemicals.
4	It should be mixable at the surface.	Should possess the right mechanical properties to withstand stresses from various downhole operations and provide zonal isolation for the life of the well.
5	Non-settling under static and dynamic conditions.	
6	Zero free water.	
7	Desired thickening time.	
8	Desired fluid loss.	
9	Desired strength development.	
10	100% placement in the annulus.	
11	Resist fluid influx.	

i. The Well Construction Phase:
   - Drilling
   - Cementing
   - Completion

During the well construction phase, the stresses around the wellbore will change often due to the unsteady gravity of the fluids inside the wellbore. This will affect the resultant stresses in the cement sheath.

ii. The Later Operational Phase:
   - Depletion
   - HPHT operation
   - Water and steam injection
   - Production
   - Fracturing, etc.

During the Later Operational Phase, the naturally developing stresses alongside other planned interventions will greatly affect the integrity of the cement sheath. In order to avoid well integrity problems, realistic extremes in well operation should be properly defined (Hunter and Kinnaird, 2007; Edgley et al., 2005; Bosma, 1999). The goal is to develop a pressure-tight vessel design for each and every well.

Technical Issues

Effect of High Temperature and High Pressure

High temperatures affect the rheological features of the cement slurry and reduce the thickening time of the slurry, thereby causing the cement sheath to set quicker (Shadravan and Amani, 2012; Yetunde & Ogbonna, 2011). Important features such as the Bottomhole Circulating Temperature (temperature at which the cement mixture is pumped into the wellbore), Yield Viscosity, and the Plastic Viscosity often decline with an increase in temperature. If the pressure is not accurately anticipated, the casing and cement sheath may not be able to withstand the pressure from the rock formation, leading to a total collapse of the wellbore (Shaughnessy & Helweg, 2002).

Mechanical Properties of Sealant

The cement sheath sealant has to fulfill a number of pertinent functions in the oil well such as supporting the casing and sealing up the annulus. In general, reducing the Young's modulus or increasing the Poisson's ratio of the cement will cause a decrease in the stresses induced in the cement sheath, and subsequently reduce the risk of failure (James and Boukhelifa, 2006). Conventionally, the oil and gas industry has focused on the short-term properties that are applicable when the cement is still in slurry/paste form. This approach is necessary for good cement-slurry mixing and placement, but the long-term integrity of the cement sheath depends primarily its mechanical and material properties such as Young's modulus, tensile strength and resistance to chemical attack downhole (Tahmourpour and Griffith, 2007).

Gas Migration

The changes caused by temperature and pressure differentials cause cracks to form in the cement sheath which form a pathway for the migration of gas to the surface, thereby compromising the integrity of the cement sheath (Yetunde and Ogbonna, 2011; Shadravan and Amani, 2012). Research conducted by Al-Yami et al. (2009) shows that approximately eighty percent of wells in the Gulf of Mexico have gas transmitted to the surface through their cement sheaths at some point during their life cycle, and the migration of gas represents twenty-five percent of the primary cementing failures. The hydrostatic pressure of the cement sheath and mud column must be high enough to prevent fluids and gas from entering the wellbore's annulus, but not too high as it can fracture the rock formation and cause further damage (Cesaroni et al., 1981). Research conducted by Gonzalo et al. (2005) shows that the gel strength of the cement slurry directly affects the distribution of the hydrostatic pressure in the annular column, with a higher gel strength lowering the ability to transmit hydrostatic pressure in the annulus.

High Hole Angles

The eccentricity of the casing is a direct function of the hole/wellbore angle, the number of centralizers used in the well development phase, and the geometry of the wellbore (Zhaoguang et al., 2012). A higher wellbore inclination angle (hole angle) often leads to higher eccentricity of the casing (Ferda et al., 2004). When a casing is not well centered in the wellbore, the fluid will flow along the wider path rather than on the narrow side as shown in figure 5. This results in a partial velocity distribution and the displaced fluids may circumvent the slow-moving drilling mud on the narrower side (Zhaoguang et al., 2012).

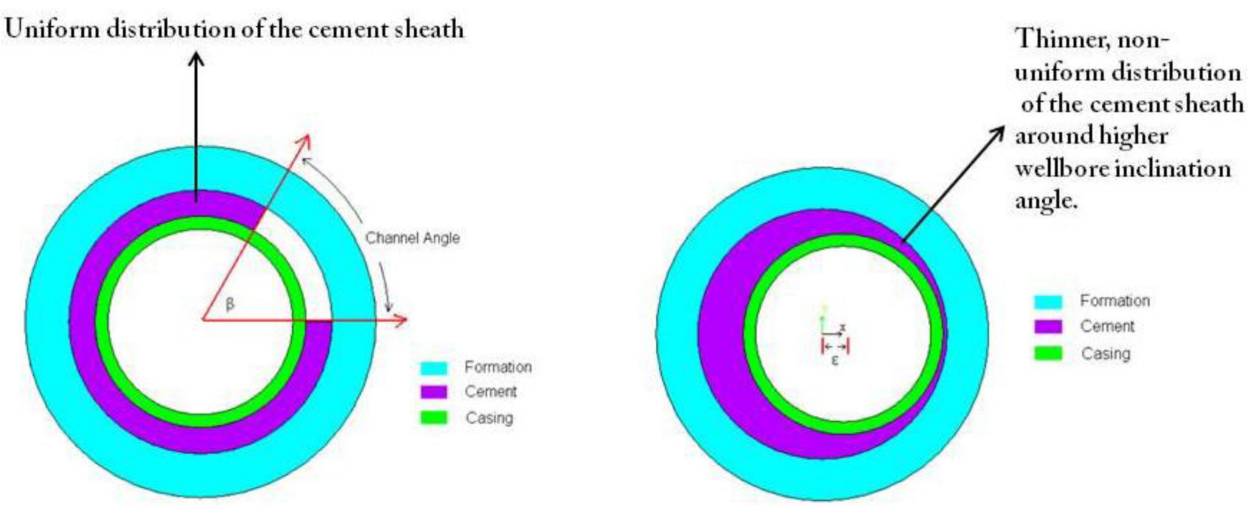

Figure 5—The first figure shows a concentric arrangement of the casing, cement sheath and rock formation, while the second figure shows an eccentric arrangement of the casing, cement sheath and rock formation. In the concentric arrangement, the cement sheath is uniformly distributed between the casing and rock formation while in the eccentric arrangement, the distribution of the cement sheath is uneven around the section with a higher hole angle (Adapted from Zhaoguang et al. 2012)

Analytical Model

This section shows an analytical model of the interaction between the casing, cement sheath, and rock formation. This model also contains mathematical relationships for the integrity of the cement sheath at the casing-cement and cement-rock contacts/interfaces. The study was limited to vertical wells as this allowed us, for purposes of symmetry, to analyse the casing-cement-formation relationship as a composite cylinder (see figure 7). If we consider the stress state of an element within the cement sheath, the element is subjected to a triaxial stress state and the entire cement sealant can be regarded as being subject to a triaxial stress state. In order to facilitate the analytical modelling of the casing-cement-formation interaction, the following assumptions were made:

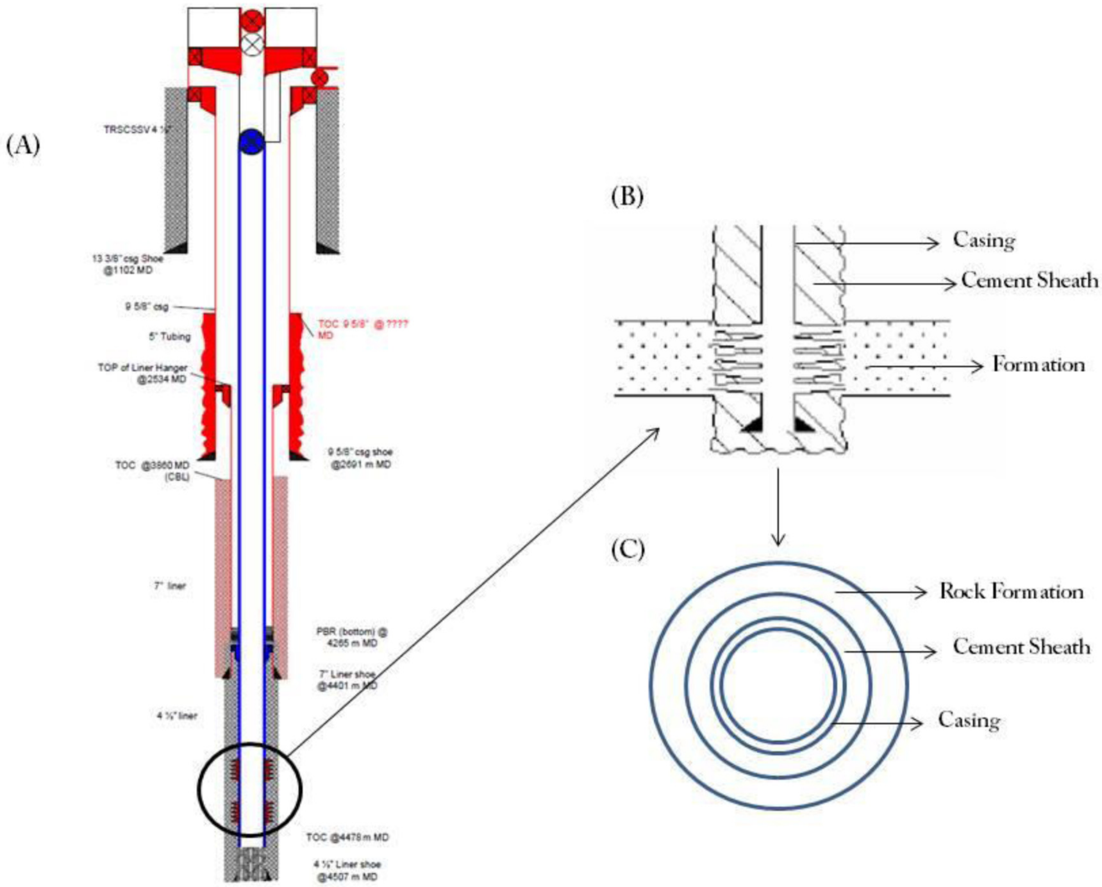

Figure 6—(a) Schematic of a vertical wellbore. The vertical wellbore has a measured depth of 4,507m (b) Enlarged view of the cased wellbore around the payzone. (c) Simplified schematic of the casing-cement-formation interaction (the plan view) represented by a composite cylinder

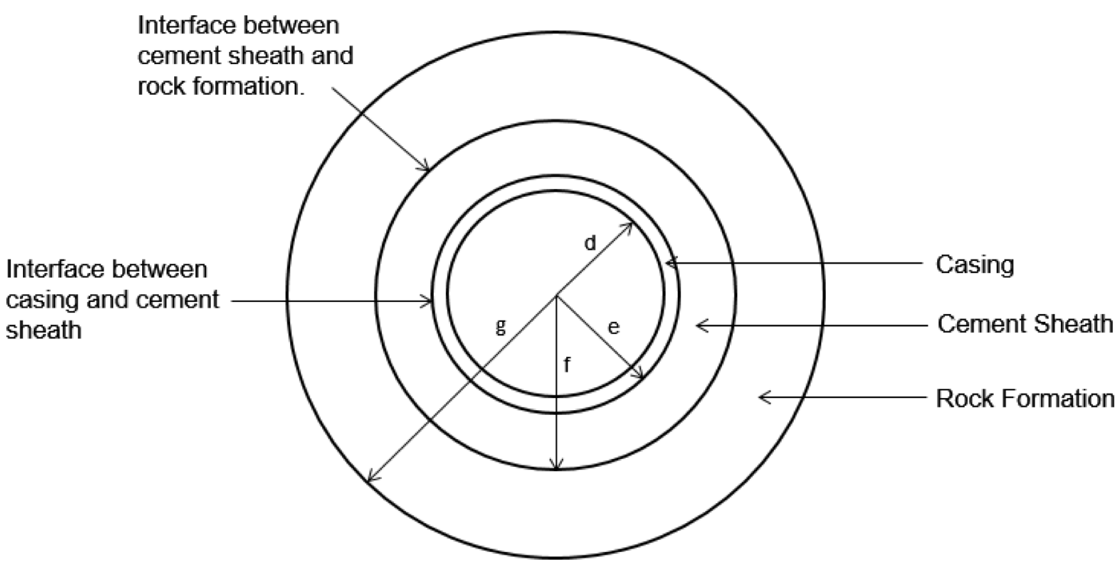

Figure 7—Schematic (plan view) of the casing-cement-formation relationship in a petroleum wellbore. The casing is represented by a thin-walled pressure vessel, while the cement sheath and rock formation are represented by thick-walled pressure vessels. The interfaces between the casing, cement and rock formation are bonded without any discontinuities

- The casing is modelled as a thin-walled cylindrical pressure vessel (as the ratio of the thickness to inner diameter of a casing cylinder is usually less than 0.05).
- The cement sheath and the rock formation are both modelled as thick-walled cylindrical pressure vessels.
- Assuming axisymmetry, the lateral principal stresses are both equal.
- We assume that before the borehole was drilled, the state of stress was uniform.
- We assume that the interfaces between the casing, cement and rock formation as shown in figure 7 are well bonded without any gaps, making the radial stresses the same across the boundary.
- Plane strain assumption – the axial/longitudinal strain is assumed to be negligible due to large depths.
- We assumed a homogenous state of stress in the axisymmetric setup making the hoop strain equal equivalent to the radial strain.

The hoop stress, σ_H, in a thin-walled cylindrical pressure vessel is given by:

$$\sigma_H = \frac{pa}{t} \quad (1)$$

The hoop stress, σ_H, in a thick-walled cylindrical pressure vessel is given by:

$$\sigma_H = \frac{pa^2(r^2 + b^2)}{r^2(b^2 - a^2)} \quad (2)$$

The longitudinal strain, σ_L, in a thin-walled cylindrical pressure vessel is given by:

$$\sigma_L = \frac{pa}{2t} \quad (3)$$

The longitudinal strain, σ_L, in a thick-walled cylindrical pressure vessel is given by:

$$\sigma_L = \frac{pa^2}{b^2 - a^2} \quad (4)$$

Where *a* represents the inner radius, *b* represents the outer radius, *r* represents the radial position where the stress is to be found, and *t* represents the wall thickness.

However, equations 1-4 do not account for the interfacial (contact) pressures that exist at the casing-cement and cement-formation interfaces. Hence, both instances were analysed separately to develop relationships for the stresses and strains on the cement sheath, and the pressures at the interfaces.

Casing-Cement Analysis

In a typical HPHT petroleum wellbore, as shown in figure. . ., the hydrostatic wellbore pressure (inner pressure) acting on the inner walls of the casing, in addition to the rise in temperature, will cause a linear expansion of the casing as shown in figure 8. The cement sheath will resist the expansion of the casing thereby leading to the formation of an interfacial contact pressure.

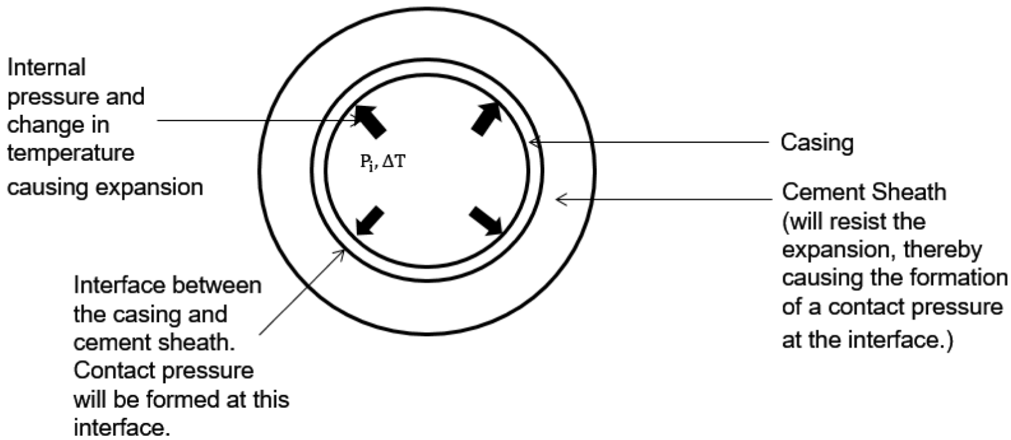

Figure 8—In the casing-sealant schematic under consideration, the internal pressure, *P_i*, and the increase in temperature, *ΔT*, acting on the inner walls of the casing will both cause a radial expansion of the casing. The cement sheath will resist this expansion thereby leading to the formation of pressure at the casing-sealant interface

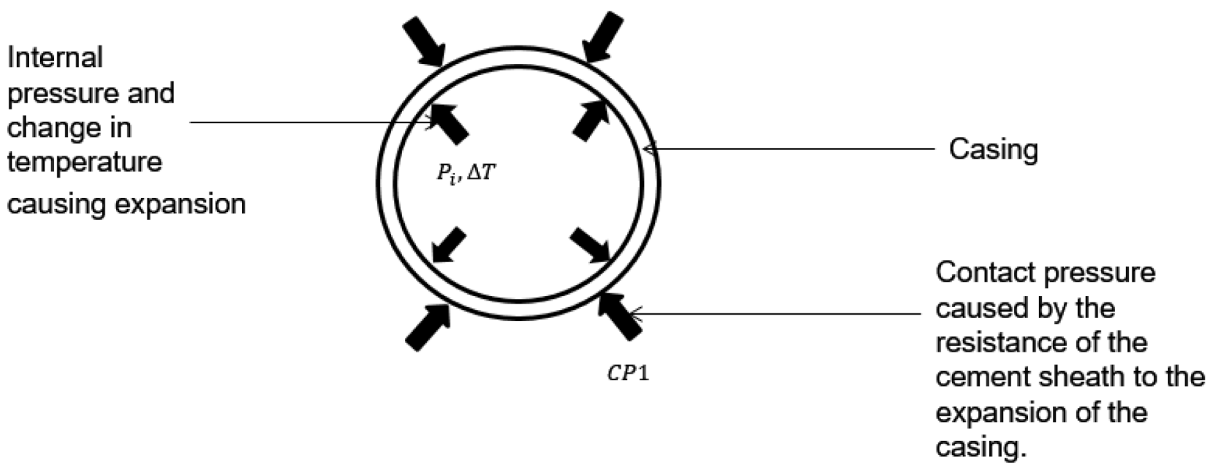

Figure 9—A schematic of the casing under consideration. The contact pressure formed at the casing-cement interface is denoted *CP_1*. This interfacial pressure is created by the resistance of the cement sheath to the radial expansion of the casing

The casing's hoop strain, ε_H, is given by:

$$\varepsilon_H = \frac{1}{E}(\sigma_H - v\sigma_L) \tag{5}$$

Adding the linear expansion of the casing due to high-temperature differentials;

$$\varepsilon_H = \frac{1}{E}(\sigma_H - v\sigma_L) + \alpha\Delta T \tag{6}$$

Where E represents the elastic modulus, σ_H represents the hoop stress, v represents the poisson's ratio, σ_L represents the axial strain, ΔT represents the increase in temperature, and α represents the coefficient of thermal expansion.

Similarly, the casing's longitudinal (axial) strain is given by:

$$\varepsilon_L = \frac{1}{E}(\sigma_L - v\sigma_H) + \alpha\Delta T \tag{7}$$

In huge depths, the longitudinal strain can be considered negligible, i.e. ε_L is approximately 0.

$$\varepsilon_L = 0 = \frac{1}{E}(\sigma_L - v\sigma_H) + \alpha\Delta T \tag{8}$$

$$\sigma_L = v\sigma_H - E\alpha\Delta T \tag{9}$$

Substituting equation 9 (longitudinal stress in casing) into equation 5 (hoop strain in casing);

$$\varepsilon_H = \frac{1}{E}\left(\sigma_H - v(\sigma_H - E\alpha\Delta T)\right) \tag{10}$$

$$\varepsilon_H = \frac{1}{E}(\sigma_H - v\sigma_H + vE\alpha\Delta T)$$

In homogenous materials, the hoop strain is equivalent to the radial strain. The radial strain in the casing is given by:

$$\varepsilon_R = \frac{r}{E}(\sigma_H - v\sigma_H + vE\alpha\Delta T) \tag{11}$$

The mathematical relationship for the hoop stress in the casing, based on the thin-walled cylindrical geometry, is given by;

$$\sigma_H = \frac{pd}{2t} = \frac{pr}{t} \tag{12}$$

Where r represents the casing's internal radius, p represents the internal pressure in the casing, and t represents the casing's thickness.

The radial stress will vary from zero at the outside surface to a value that is equal to the internal pressure, P_i. Substituting equation 12 (hoop stress in casing) into equation 11 (radial strain in the casing);

$$\varepsilon_R = \frac{r}{E}\left(\frac{pr}{t} - v\left(\frac{pr}{t}\right) + vE\alpha\Delta T\right) \tag{13}$$

At the casing's internal radius, when $r = d$, equation 13 (radial strain in the casing) can be re-written as;

$$\varepsilon_R = \frac{d}{E}\left(\frac{pd}{t} - v\left(\frac{pd}{t}\right) + vE\alpha\Delta T\right) \tag{14}$$

At the casing's outer radius, when $r = e$ (the interface between the casing and cement sheath), equation 13 can be re-written as;

$$\varepsilon_R = \frac{e}{E}\left(\frac{pe}{t} - v\left(\frac{pe}{t}\right) + vE\alpha\Delta T\right) \tag{15}$$

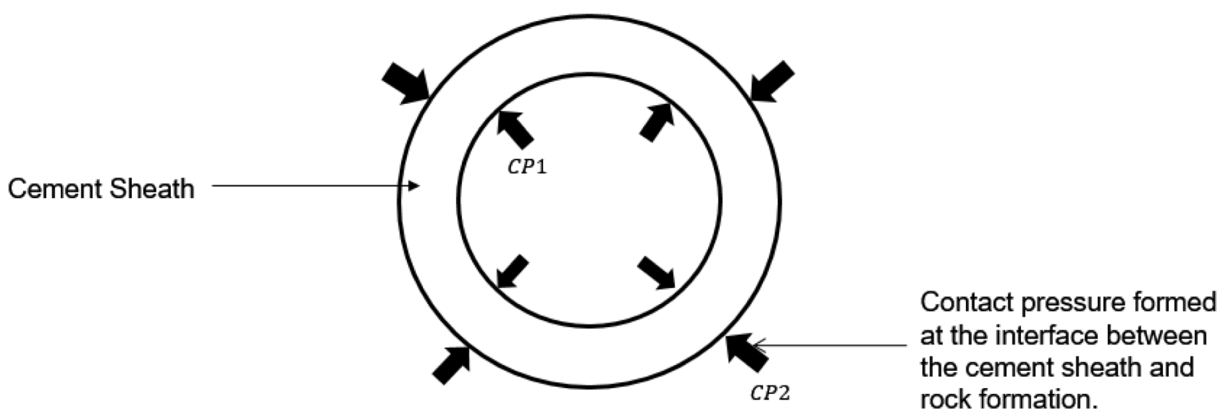

Figure 10—A schematic of the cement sheath under consideration. The contact pressure formed at the cement-formation interface is denoted CP_2

Analysing the cement sheath as a thick-walled cylinder, the hoop stress in the cement sheath is given by;

$$\sigma_H = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2 (P_o - P_i)}{r^2 (r_o^2 - r_i^2)} \tag{16}$$

Inputting r_i as e, r_o as f, P_i as CP_1, and P_o as CP_2 into equation 16;

$$\sigma_H = \frac{CP_1 e^2 - CP_2 f^2}{f^2 - e^2} - \frac{e^2 f^2 (CP_2 - CP_1)}{r^2 (f^2 - e^2)} \tag{17}$$

The radial stress, σ_R, at a point in the cylindrical cement sheath is given by;

$$\sigma_R = \frac{CP_1 e^2 - CP_2 f^2}{f^2 - e^2} + \frac{e^2 f^2 (CP_2 - CP_1)}{r^2 (f^2 - e^2)} \tag{18}$$

At the internal radius of the cement sheath, where $r = e$, equation 17 (hoop stress in the cement sheath) and equation 18 (radial stress in the cement sheath) can both be re-written as;

$$\sigma_R = \frac{CP_1 (e^2 - f^2)}{f^2 - e^2} = -CP_1 \tag{19}$$

$$\sigma_H = \frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2} \tag{20}$$

Substituting equation 20 (hoop stress in the cement sheath) into equation 11 (radial strain formula)

$$\varepsilon_R = \frac{r}{E}\left[\frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2} - v\left(\frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2}\right) + vE\alpha\Delta T\right] \tag{21}$$

Equations 21 and 13 are both radial expansion formulas and can be equated to each other;

$$\varepsilon_R = \frac{r}{E}(\frac{Pr}{t} - v\left(\frac{Pr}{t}\right) + vE\alpha\Delta T) = \frac{r}{E}[\frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2} - v\left(\frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2}\right) + vE\alpha\Delta T] \tag{22}$$

Simplifying equation 22 further;

$$\frac{Pr}{t} - v\left(\frac{Pr}{t}\right) = 1 - v\left(\frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2}\right) \tag{23}$$

$$\frac{Pr}{t} = \left(\frac{CP_1 (e^2 + f^2) - 2CP_2 f^2}{f^2 - e^2}\right) \tag{24}$$

$$Prf^2 - Pre^2 = CP_1 t(e^2 + f^2) - 2CP_2 f^2 \tag{25}$$

Writing equation 25 in terms of the contact pressures, CP_1 and CP_2.

$$XCP_1 + YCP_2 = Z \tag{26}$$

Where,

$$X = t(e^2 + f^2) \tag{27}$$

$$Y = -2f^2 \tag{28}$$

$$Z = Prf^2 - Pre^2 \tag{29}$$

Cement-Formation Analysis

In similar fashion, the interaction between the cement sheath and rock formation produces a contact pressure, CP_2, at the interface. The cement sheath and rock formation are both analysed as thick-walled cylinders. The hoop stress on the cement sheath, at the cement-formation interface, is given by:

$$\sigma_H = \frac{CP_1 e^2 - CP_2 f^2}{f^2 - e^2} - \frac{e^2 f^2 (CP_2 - CP_1)}{r^2 (f^2 - e^2)} \tag{30}$$

Where CP_1 represents the internal pressure on the cement sheath, CP_2 represents the external pressure on the cement sheath (contact pressure at the cement-formation interaction), e represents the internal radius of the cement sheath, and f represents the external radius of the cement sheath.

At the cement-formation interface, where radius = f,

$$\sigma_H = \frac{CP_1 e^2 - CP_2 f^2 - e^2 f^2 (CP_2 - CP_1)}{f^2 (f^2 - e^2)} \tag{31}$$

The radial expansion in the cement sheath at the cement-formation interface is obtained by substituting equation 31 (hoop stress on the cement sheath at the cement-formation interface) into equation 11 (the radial strain equation).

$$\varepsilon_R = \frac{f}{E}[((1 - v)\left(\frac{CP_1 e^2 - CP_2 f^2 - e^2 f^2 (CP_2 - CP_1)}{f^2 (f^2 - e^2)}\right) + vE\alpha\Delta T)] \tag{32}$$

The relationship for the hoop stress in the rock formation at the cement-formation interface is given by:

$$\sigma_H = \frac{CP_2 f^2 - F_p g^2}{g^2 - f^2} - \frac{f^2 g^2 (F_p - CP_2)}{f^2 (g^2 - f^2)} \tag{33}$$

Where f represents the internal radius of the rock formation, g represents the outer radius of the rock formation, CP_2 represents the rock formation's internal pressure, F_p represents the formation pressure. This was determined at the cement-formation interaction, at $r = f$.

The radial stress in the rock formation is given by:

$$\sigma_R = \frac{CP_2 f^2 - F_p g^2}{g^2 - f^2} + \frac{g^2 (F_p - CP_2)}{g^2 - f^2} \tag{34}$$

$$\sigma_R = \frac{CP_2 f^2 - CP_2 g^2}{g^2 - f^2} \tag{35}$$

$$\sigma_R = -CP_2 \tag{36}$$

The radial expansion in the rock formation, at the cement-formation interface, can be determined by substituting the hoop stress (equation 33) into the radial strain formula (equation 11);

$$\varepsilon_R = \frac{f}{E}\left[(1 - v)\left(\frac{CP_2 (f^2 + g^2) - 2F_p g^2}{g^2 - f^2}\right) + vE\alpha\Delta T\right] \tag{37}$$

Equations 37 and 32 are both relationships for the radial strain at the cement-formation interface, they can be equated and simplified further to obtain relationships for the contact pressures;

$$\frac{f}{E}\left[(1-v)\left(\frac{CP_1e^2 - CP_2f^2 - e^2f^2(CP_2 - CP_1)}{f^2(f^2-e^2)}\right) + vE\alpha\Delta T\right] \tag{38}$$
$$= \frac{f}{E}\left[(1-v)\left(\frac{CP_2f^2 + CP_2g^2 - 2F_pg^2}{g^2-f^2}\right) + vE\alpha\Delta T\right]$$

Simplifying equation 38 further;

$$\frac{CP_1e^2 - CP_2f^2 - e^2f^2CP_2 + CP_1e^2f^2}{f^2(f^2-e^2)} = \frac{CP_2f^2 + CP_2g^2 - 2F_pg^2}{g^2-f^2} \tag{39}$$

Arranging equation 39 in terms of the contact pressures;

$$GCP_1 + HCP_2 = I \tag{40}$$

$$G = e^2g^2 + e^2f^2g^2 - e^2f^2 - e^2f^4 \tag{41}$$

$$H = f^6 + g^2f^4 - 2e^2f^4 + f^2g^2 - f^4 \tag{42}$$

$$I = 2F_pg^2f^4 - 2F_pg^2e^2f^2 \tag{43}$$

In order to obtain mathematical relationships for the interfacial (contact) pressures, CP_1 and CP_2, equations 40 and 26 are solved simultaneously to obtain the following equations;

$$CP_1 = \frac{ZH - YI}{HX - YG} \tag{44}$$

$$CP_2 = \frac{IX - GZ}{HX - YG} \tag{45}$$

Conclusively, the stresses on the cement sheath (hoop and radial) can be calculated using equations 17 and 18 respectively, while the contact pressures can be determined using equations 27 – 29 and 41 – 45.

Conclusions

The model presented in this paper has the potential to be used for cement sheath analysis. It can be used to determine the stresses on the cement sheath and the contact pressures at the casing-cement and cement-formation interfaces in a vertical (concentric) wellbore setup. The area of the wellbore that was used for the mathematical analysis is the pay-zone area where the relationship between the casing, cement and rock formation was represented by a concentric composite cylinder. Even though it has not been verified, it is currently showing promise and is being fully developed in-house at Robert Gordon University, United Kingdom. Plans are underway to extend the model to other parts of the wellbore with multi-cylinder setups and higher hole angles.

Further Work

In the near future, the analytical model presented in this paper will be verified with results from finite-element simulations, analytical results from open literature, and live well data. Also, the model will be extended to include the effects of casing eccentricity in high-angle wellbores, and model the behaviour of the cement sheath in other parts of the wellbore with multi-cylinder setups.

Nomenclature

a = Inner radius of cylindrical pressure vessel
b = Outer radius of cylindrical pressure vessel

d = Casing's internal radius
e = Casing's external radius
f = Rock formation's internal radius
g = Rock formation's external radius
r = Radial position where stress is to be found
HPHT = High-Pressure/High-Temperature
$\boldsymbol{\sigma}_H$ = Hoop/Circumferential Stress, *N/m²*
$\boldsymbol{\sigma}_L$ = Longitudinal/Axial Stress, *N/m²*
P_i = Internal Pressure, *psi*
ΔT = Change in temperature, *°F*
CP_1 = Interfacial pressure at casing-cement interface, *psi*
CP_2 = Interfacial pressure at the cement-formation interface, *psi*
ε_H = Hoop Strain
E = Elastic Modulus, N/m^2
v = Poisson's ratio
α = Co-efficient of thermal expansion, $°C^{-1}$

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