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A Design Basis for Geothermal Well Tubulars Subjected to Annular Pressure Buildup from Fluids Trapped in Cement

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ABSTRACT

In geothermal and thermal service wells, the most common source of annular pressure buildup (APB) is trapped fluid pockets in the cement between two tubulars. Such pockets are created due to poor displacement of the drilling fluid during primary cementing. If the fluid pocket is in a cemented section open to formation, the pressure is relieved by leak-off and the inner tubular is safe. If these pockets occur in a pipe-in-pipe cemented section (for example, cemented tieback), they become trapped with no path for relief, and quickly develop pressure when heated during production. The collapse load on the inner string as a result can deform (or fail) the string. Failures from APB-induced collapse of inner strings have been implicated in enough number of wells that this is a major concern of geothermal well designers. A common recourse is careful planning and implementation of the cement operation. The Code of Practice for Deep Geothermal Wells NZS 2403:2015 also suggests a design basis wherein the collapse strength of the inner string is at least 1.2 times the burst strength of the outer string. The implication is that if this design basis is adopted, the outer string bursts (or connections leak), thus providing relief of APB before the inner string collapses. While the rationale appears reasonable, there is no quantitative basis for this recommendation. Besides, the elastic-based API ratings used in this approach are not representative of the limit states of the tubulars.

In the paper, we present a quantitative basis of design for APB loads such that the outer string bursts and relieves APB before the inner string collapses, and investigate the practicability of such a design in typical geothermal wells. An arbitrary fluid pocket is assumed to be present in the cement adjacent to the inner string, surrounded by cement. As pressure increases with temperature, the response of the cement to this local increase in pressure is modeled as a Griffith crack. The initiation and propagation of the crack as a function of increasing pressure are followed until either the inner tubular collapses, or the fluid finds access to the outer tubular and the load is high enough to rupture the outer tubular. The collapse and burst limits in this analysis are based on the limit states described in API TR 5C3 (ISO TR 10400). A number of sensitivities (depth location of fluid pocket, radial location of fluid pocket in the annular gap, cement properties) are studied to characterize the problem. Based on this analysis, the required collapse and burst capacities of the strings and the properties of cement to assure that the outer string bursts (or connections leak) before the inner string collapses are determined. The impact of this method on typical geothermal well architectures is illustrated through examples, and the current New Zealand Standard recommendation is examined in this context. The authors hope that this work provides an approach to design geothermal wells such that the integrity of the production string is maintained when faced with APB from inadvertent fluid pockets in cemented zones.

1. INTRODUCTION

Tubular collapse from annular pressure build-up (APB) in trapped fluid pockets has been reported as a prevalent cause of well failure in geothermal wells (Southon, 2015). In geothermal and thermal service wells, the most common source of APB is trapped fluid pockets in the cement behind a tieback string. Figure 1 shows a typical geothermal well schematic, identifying the region of interest. The depths and sizes of tubulars shown are indicative. As shown, of interest is a trapped fluid pocket (or fluid filled cement void) in the *tieback section* annulus of the well. Trapped fluid pockets can of course occur in other cemented sections, but with access to formation, APB often relieves itself by leaking off into the adjacent formation. However, APB in a trapped fluid pocket as illustrated in Figure 1 cannot relieve itself as the cement is enclosed in steel with no access to the formation. As a result, pressure develops rapidly with heat-up during the first half-cycle (production), and can lead to collapse or an inward bulge of the tieback.

Cement voids and mud channeling have been well studied in the literature. Arguably, cementing literature is concerned more with zonal isolation and the avoidance of cracking, void creation and channeling of cement. Nevertheless, it is valuable to review relevant literature in the context of the current work. Lavrov et al. (2016) and Bentur et al. (1985) have conducted scanning electron microscope examination of laboratory-scale cemented tubulars and show that voids and channels are commonly present at the cement-steel interface. Stresses due to changes in internal pressure and temperature can lead to cracking and fracture of the set cement. Goodwin and Crook (1992) present an excellent experimental study in which they discuss voids and the creation of cracks and channels in cement due to internal pressure and temperature changes. They suggest that thermally induced cracking of cement occurs in the top 1/4th to 2/3rd of the casing, while cracking from internal pressure increase is usually located in the bottom 1/3rd of the casing. Further, Goodwin and Crook (1992) also observe that the cracking is predominantly radial (away from the inner cylinder and towards the outer cylinder). Lavrov et al. conduct a finite element analysis of a cement sheath with voids and note that the voids act as a site for stress concentration and fracture nucleation. Nabipour et al. (2012) also perform finite element analyses of the cement sheath stresses in response to an increase in the internal pressure of the inner casing, and show that the von Mises stresses in the cement can be high enough to cause failure of the cement sheath.

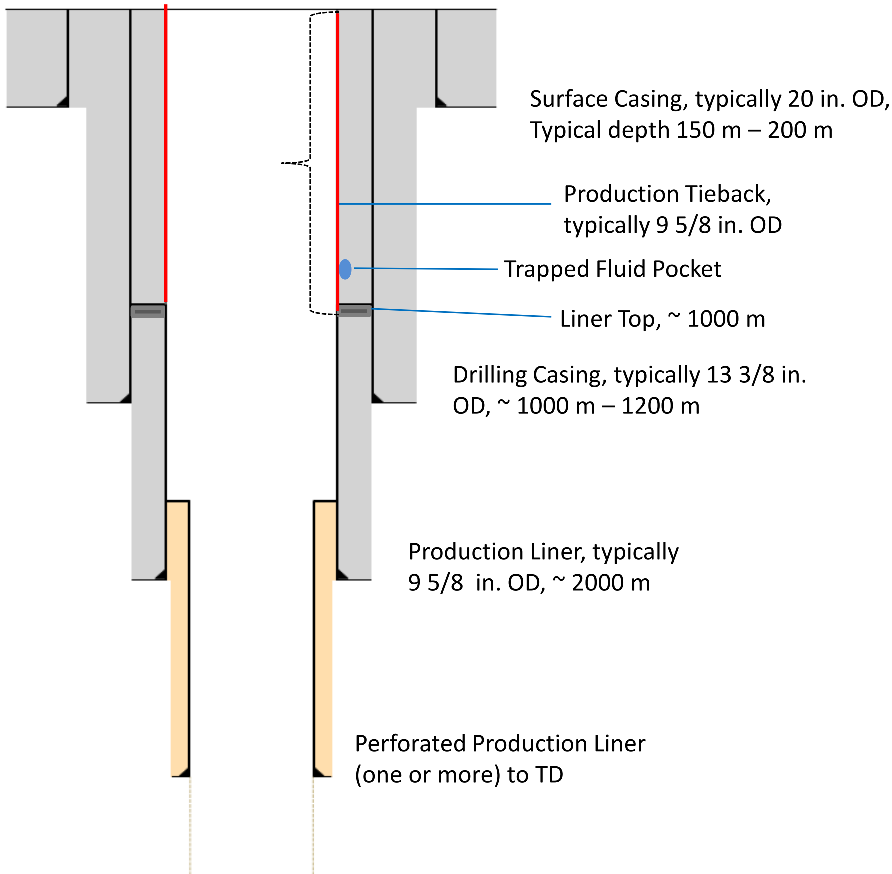

Figure 1: Typical Geothermal Well Schematic, Highlighting Production Tieback as Location of APB

In the design and construction of a geothermal well, this APB load scenario has to be considered, and may even dictate design. However, there are very few options to design against such a load. Suryanarayana, et al. (2020) review APB-induced collapse as a cause of casing failure in geothermal wells, but do not provide a quantitative basis to design against this problem. Common APB mitigation approaches used in deepwater wells (see, for example, Sathuvalli et al., 2017), such as vacuum insulated tubing, rupture disks and syntactic foams are not feasible options for mitigating the type of APB common in geothermal wells. Most mitigation options for geothermal wells therefore center around cementing practices, such as reverse circulation of cement (Kruszewski and Witting, 2018), use of swellable packers (Southon, 2015), inclusion of microspheres in cement slurry to provide APB volumetric relief (Brown et al., 2016), etc. The only tubular design based mitigation is given by the Code of Practice for Deep Geothermal Wells NZS 2403:2015, where it is suggested that the collapse strength of the inner string should be at least 1.2 times the burst strength of the outer string. The rationale behind this suggestion is that APB in trapped fluid pockets will likely crack the cement, and provide a path for the fluid to the outer casing. If the outer casing of the annulus bursts in response before the inner casing collapses, the well is safe. Unfortunately, no quantitative basis for this suggestion is provided. It is not clear if this gap between the collapse rating of the inner casing and burst rating of the outer casing is adequate to assure well integrity, or whether it is practicable in actual geothermal wells.

The objective of this work is to address this gap, and provide a rational and quantitative basis for the design of an annulus in such a way that the outer string bursts and relieves APB before the inner string collapses. An arbitrary void filled with fluid is assumed in the cement, and using fracture mechanics and fracture toughness properties of the cement, the APB magnitude at which a crack will initiate and propagate is calculated. Based on the burst and collapse loads (on the outer and inner casings respectively) that result from this, the minimum gap between the collapse resistance of the inner string and burst resistance of the outer string can be determined. Importantly, rather than use the API performance ratings, collapse and burst limits in this analysis are based on the limit states described in API TR 5C3 (2018). Using these limit states and a Level 4 Reliability Based Design approach (Suryanarayana and Lewis, 2016), the required gap in performance properties is based on ensuring that the probability of burst of the outer casing is an order of magnitude greater than the probability of collapse of the inner casing. It is shown that this gap is a function of the location (by depth) of the trapped fluid pocket, and the properties of the cement. The impact of this method on typical geothermal well architectures is illustrated through an example and sensitivity analyses. The current New Zealand Standard recommendation is examined in this context. Finally, a step-by-step design procedure is presented for use in the design of geothermal wells.

2. DEVELOPMENT OF BASIS OF DESIGN

2.1 Problem Description

Consider a cemented annulus enclosed within steel tubulars on the inside and the outside, with a wellhead above, and a liner top below (Figure 2). This corresponds to the tieback annulus in Figure 1. Outside the outer annulus, there is a cemented pipe-in-pipe section above, and formation below the previous casing shoe. A fluid filled void, of initial volume *V*, is assumed to be present at the steel-cement interface of the inner casing, just above the liner top. Without loss of generality, the pocket is idealized as a small bounded arc section around the inner casing. Further, for simplicity, we assume that the cement is isotropic, with initial stress state characterized by mix water density ($Sh_{min} = Sh_{max} = S_v$ = water hydrostatic pressure, where Sh_{min} and Sh_{max} are the minimum and maximum horizontal stresses at a given location, and S_v is the vertical "overburden" stress at the same location). A longitudinal defect or initial crack, of depth *a,* is assumed to exist in the cement (as shown in the figure).

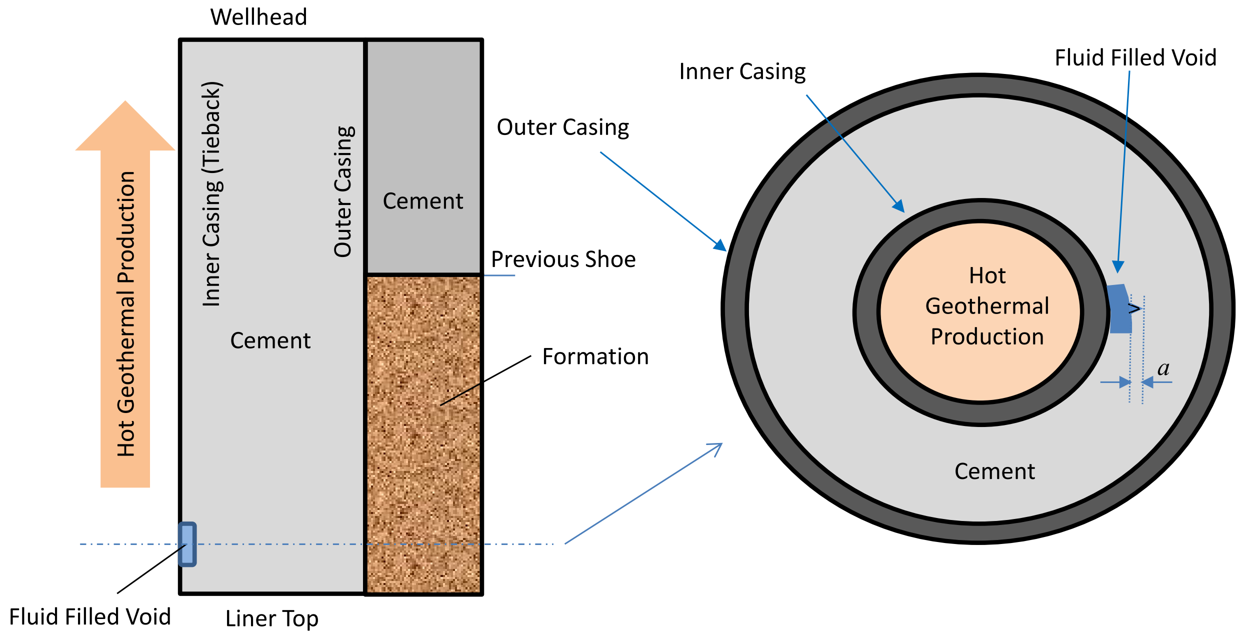

Figure 2: Schematic Depicting the Problem

The inner casing is exposed to flowing geothermal brine, and hence to an increase in its temperature. As the temperature of the inner casing (and hence the trapped fluid pocket) increase, the pressure in the trapped pocket also increases, creating a collapse load on the inner casing. Eventually, the pressure may reach a magnitude where the cement fractures, creating a flow path to the outer casing, and causing a burst load on the outer casing. The design basis of interest is to ensure that when the burst load reaches the rupture limit of the outer casing, the collapse resistance of the inner casing is adequate to withstand the resulting collapse load on it. Usually, the outer (surface or intermediate) casing strength selection is based on the loads during normal drilling, production and other operational loads. Therefore it is a given in the problem. The design process then seeks to select the collapse strength of the inner string such that the outer casing bursts (or outer casing connections leak) before inner casing collapses, and finally check that the selected inner casing has adequate strength to withstand all other loads.

2.2 Cement Fracture and Critical APB

The annular pressure buildup in a closed, constrained volume is proportional to the increase in temperature of the trapped fluid. Assuming no container expansion, the annular pressure buildup ΔP can be estimated by

$$\Delta P_{APB} = B\beta\Delta T \tag{1}$$

where B is the bulk modulus of the fluid, β is the volumetric thermal expansion coefficient of the fluid, and ΔT is the increase in temperature. Note that the APB is independent of the initial volume, as it is a function of volumetric strain. It is dependent only on the fluid properties and the average increase in fluid temperature. The bulk modulus B of fluids is a function of temperature and pressure, and is not a constant. In the region of interest, the bulk modulus of water can be approximated as a constant, equal to 300,000 psi. The volumetric thermal expansion coefficient β is also a function of temperature. For water, at 68°F (20°C), this is about 0.00012/°F (0.00022/°C). At higher temperatures, the value of β increases (by a factor of 5 or 6 at temperatures in excess of 300°F). In this work, we use 0.00012/°F.

As the pressure increases, a Mode 1 opening stress (hoop stress) is imposed on the crack. The hoop stress can be calculated using Lame's equations, but a reasonable and conservative estimate can be obtained using the Barlow equation,

$$\sigma_h = \frac{\Delta P\, OD_{IC}}{2t_{cem}} \tag{2}$$

where OD_{IC} is the outer diameter of the inner casing, and t_{cem} is the thickness of the cement sheath.

The stress intensity K_I at the crack tip from Mode 1 loading, from Griffith's law, can then be calculated as

$$K_1 = \gamma\, \sigma_h \sqrt{\pi a} \tag{3}$$

In Eq. (3), γ is a geometric shape factor, with values usually close to unity. For the purposes of this work, we assume that $\gamma = 1$. Substituting Eq. (2) in Eq. (3), the stress intensity, in terms of the APB, is

$$K_1 = \frac{\Delta P\, OD_{IC}}{2\,t_{cem}} \sqrt{\pi a} \tag{4}$$

For cement fracture, the stress intensity should equal the fracture toughness of cement,

$$K_1 = K_{1C} \tag{5}$$

where K_{IC} is the fracture toughness of cement. The APB at which this occurs is referred to as *critical APB* in this work. From Eq. (4) and Eq. (5), the critical APB can be easily calculated:

$$Critical\ \ APB = \frac{K_{1C}}{\sqrt{\pi a}} \frac{2\,t_{cem}}{OD_{IC}} \tag{6}$$

Limited data is available in the literature on the fracture toughness of cements used in well construction. Thomas, et al. (2012) report the fracture toughness of high temperature cements in oil wells. The cement investigated in this work is a high silica (35% by weight) cement typical of those used in geothermal wells. The fracture toughness was measured using a microscratch tester, and fracture toughness is reported for a range of curing time and temperature values. The reported values ranged from 2.55 MPa √m to 4.1 MPa √m (2.32-3.74 ksi √in). These values are higher than those reported by Mazloom and Saleh (2018), who conducted tests on notched-beam concrete specimens in an effort to study the effect of the water-to-cement ratio on fracture toughness. They also provide a correlation to calculate the fracture toughness of concrete based on its unconstrained compressive strength. The fracture toughness increased with reducing water-to-cement ratios, and ranged from 20-40 MPa √mm (0.63 to 1.26 MPa √m, 0.58 to 1.15 ksi √in). In order to cover the range of expectation, we consider fracture toughness ranging from 0.5 ksi √in to 5 ksi √in in this work. In general, properly selected and mixed geothermal cements can be expected to be at the higher range of fracture toughness, as they typically have higher ductility than standard well cements.

For an assumed initial crack depth, given well configuration, and knowing the fracture toughness of cement, Equation (6) can be used to calculate the *critical APB*. When *critical APB* is reached, the cement fractures, and creates a flow path to the outer casing. The temperature at which the *critical APB* is reached can be calculated using Eq. (1). Given the high producing temperatures typical of geothermal wells, *critical APB* can be expected to be always reached during production.

2.3 Loads on Casings and Failure APB

Recalling that APB is incremental, the internal pressure on the outer casing is the APB plus existing hydrostatic pressure. The external pressure is the pore pressure in the exposed formation (or, if the void is located shallower, the hydrostatic pressure of the cement mix-water[1]). The difference between these two pressures is the burst load on the outer casing. Depending upon the pore pressure at the depth of the void, when *critical APB* is reached, the corresponding burst load on the outer casing may not be adequate to rupture the casing.

The inner casing meanwhile experiences a collapse load. In geothermal wells, the pressure of the hot flowing brine at shallower depths can be quite low, particularly if the brine flashes to steam within the wellbore at or below the depth of location of the void. For design, it is both conservative and prudent to assume zero internal pressure in the inner casing to calculate the collapse load. Thus, the collapse load on the inner casing is simply the APB plus the existing hydrostatic pressure in the cement at this depth. In order to satisfy our design criterion, the minimum collapse rating of the inner casing should meet or exceed the collapse load when critical APB is reached. This defines one bound of the required collapse strength of the inner casing.

When the *critical APB* is reached and the resulting burst load on the outer casing is not adequate to rupture it, the fluid continues to respond to increase in temperature. If no other cracks form, or the volume created by such cracks is negligibly small, the pressure

[1] Goodwin and Crook (1992) point out that cement-column pressure after setting can vary between 2 pounds per gallon (ppg) to the pore pressure of the surrounding formation. In practice, most design engineers assume that within steel-enclosed cement, the pressure is the hydrostatic pressure of the mix water, and in cement exposed to formation, the pressure is the pore pressure of the formation at that depth.

continues to rise, until it reaches the rupture limit of the outer casing. This is the "*failure APB*". The collapse load on the inner casing when the *failure APB* is reached defines a second bound on the collapse rating of the inner casing.

Failure APB may also be calculated directly from the known properties of the outer casing. Depending upon the properties of the outer casing, fracture toughness of cement, and external pressure on the outer casing, *failure APB* may be lower or higher than the *critical APB*. If the *failure APB* is higher, it dictates the collapse design of the inner casing. If, on the other hand, *critical APB* is higher, it dictates the collapse design of the casing. In the latter case, as soon as *critical APB* is reached and the cement fractures, creating access to the outer casing, it will rupture. In what follows, we discuss different ways of calculating *failure APB*.

2.4 Criteria for Ensuring Inner Casing Safety in Collapse

We now turn out attention to the determination of when the outer casing bursts (or ruptures). In doing so, it is important to remember that the API Burst (or API Minimum Internal Yield Pressure) does not represent the rupture limit of the pipe. The API Burst is an important performance property used in working stress design of well tubulars. Specifically, API Burst is the magnitude of burst load at which the stress in a thin-walled open ended cylinder reaches yield at its ID, according to the von Mises criterion. Therefore, when the load reaches this value, pipe rupture is not imminent. Ductile rupture of pipe is discussed in detail in API TR 5C3 (2018). The Klever-Stewart Ductile Rupture limit in API TR 5C3 is more representative of pipe rupture behavior. Therefore, *failure APB* should be based on this limit, rather than the API Burst of the outer pipe.

The collapse strength of the inner casing should be selected such that it meets or exceeds the dictating collapse load discussed earlier. For this, the API Collapse equation may be used, with a design factor of unity (this is the common practice in collapse design). Alternatively, the Klever Generalized Tamano collapse limit equation in API TR 5C3 may also be used.

Given the uncertainties in the material and geometric properties of the tubulars, it is more appropriate to use a probabilistic approach to determine when the outer casing ruptures. Reliability-based design (RBD) is a commonly used approach to determine the probability of failure of load bearing structures. RBD and its application to tubular design is discussed at length in API TR 5C3 (2018). Suryanarayana and Lewis (2016) present a detailed description of how Level 4 RBD may be used in survival design of tubulars. In Level 4 RBD, the load is deterministic, based on conservative load estimation methods, and resistance is stochastic, using the limit state based on statistical data describing the uncertainty in each underlying strength defining parameter (material or geometric properties of the tubular). This approach is most suitable to the current problem. Since we seek to preferentially rupture the outer casing, a target probability of burst failure of 10^{-1} or greater is reasonable. In most failure analyses, failure is said to be imminent when the probability of failure is greater than or equal to 10^{-1}. This is what we use in this work to determine the *failure APB.*

The collapse strength of the inner casing may also be selected using the RBD approach as discussed above. However, as discussed in API TR 5C3, the Target Reliability Level of the API Collapse equation is such that with a design factor of unity, the probability of failure in collapse is around $10^{-2.3}$. Therefore, it may be inferred that complying with a design factor of unity using API collapse assures a probability of collapse failure of the inner casing of $10^{-2.3}$ or lower. This is also at least one order of magnitude higher than the probability of burst failure of the outer casing, thus satisfying our stated design criterion. As a result, a deterministic basis for the selection of the inner casing collapse strength may be adequate, thus simplifying the design process.

In the next section, the above design basis and approach are illustrated using an example.

3. ILLUSTRATIVE EXAMPLE

3.1. Data and Assumptions

As an example, we consider a typical geothermal well annulus, with 13 3/8 in., 68 ppf, K55 outer casing, and a 9 5/8 in., 47 ppf, L80 inner casing. This is a common pairing used in many geothermal wells. The key parameters for these strings are summarized in Table 1 below. Further, let us assume that the fluid filled void is at a depth of 3,000 ft (liner top depth) in the cement in the annulus. At this depth, the cement behind the outer casing is exposed to formation, implying that the external pressure on the outer casing for load calculations is the pore pressure at this depth. For calculation of loads on the outer and inner casing, let us assume that the hydrostatic pressure in the cement column is based on fresh water (8.33 ppg, 1 SG). Further, let us assume that the pore pressure in the formation at this depth is 8.5 ppg equivalent (1.02 SG equivalent), or 1,326 psi (9.14 MPa).

Table 1. Parameters Describing Inner and Outer Casing

Parameter	Units	Inner Casing	Outer Casing
OD	In.	9.625	13.375
Wt	lbf/ft	47.0	68.0
ID	In.	8.681	12.415
Nom. Wall	in	0.472	0.480
D/t		20.39	27.86
Yield	ksi	80	55
API Burst	psi	6,870	3,450
API Coll*	psi	4,750	1,950

* With no axial tension

In order to calculate the *critical APB*, we need to make an assumption regarding pre-existing crack depth. This is typically represented as percent of cement sheath thickness. A reasonable assumption is 5% of the cement sheath thickness. The cement sheath thickness in this case is 1.395 in., giving an initial crack depth of 0.070 in (1.78 mm) for a "5% crack".

3.2. *Critical APB* and Casing Loads

The *critical APB* and the increase in temperature are listed for some typical cement fracture toughness in Table 2. For the typical geothermal production temperatures, it can be expected that *critical APB* will always be reached, or in other words, the cement will always fracture at a void if a preexisting crack is present. The loads are calculated as described in section 2.3.

Table 2. Critical APB, ΔT and Loads as a Function of Cement Toughness*

	Cement fracture		Loads on Casing	
K_{IC} ksi-in.$^{0.5}$	Critical APB psi	ΔT ^{0}F	OC, Burst psi	IC, Coll psi
0.5	310	8.6	283	1609
2.0	1,238	34.4	1,211	2,537
5.0	3,096	86	3,069	4,395

*Initial Crack Depth = 5% of cement sheath thickness = 0.070 in (1.78 mm)

3.3. Design Check Based on API Performance Properties

As noted earlier, one rule used in the design for trapped fluid APB is to ensure that the collapse strength of the inner string is 1.2 times the burst strength of the outer string. Using the API performance properties for the two strings from Table 1, the ratio for the presently selected tubulars is 1.38, higher than the recommendation. We now check if this is adequate, based solely on the API performance properties.

As Table 2 shows, even at the highest fracture toughness considered, the API Burst strength of the outer string is higher than the *critical APB.* If we interpret *failure APB* as the APB at which the burst load equals the API Burst[2] , we need a burst load of 3,450 psi, which implies a *failure APB* of 3,477 psi. The temperature corresponding to this APB is 96.6°F, assuming that there is neither container expansion nor relief of APB from cracks and channels. At this APB, the collapse load is calculated to be 4,776 psi. This is just slightly higher than the API Collapse rating of the inner casing (Collapse Safety Factor = 0.99). Note that we have performed this design check ignoring axial forces (which is conservative, since the axial forces and stresses in a heated cemented pipe are compressive), and without derating the yield for temperature (which is non-conservative, as the load is accompanied by an increase in temperature). Nevertheless, we may deem this acceptable (If the pore pressure at this depth is slightly lower, if the void were slightly shallower, or the internal pressure of the inner casing is non-zero, the SF would have been higher than 1.0). Therefore, if we use the API performance properties as the basis for design, we would accept that the current design is adequate.

3.4. Design Check Based on Limit States and Reliability-Based Design

Recall that API Burst is not representative of the rupture limit of the pipe. Therefore, rupture is not imminent when burst load reaches this value. It is possible to calculate a design rupture limit based on the Klever Stewart design equation for rupture (API TR 5C3, 2018). Assuming a preexisting defect of 12.5% of casing wall (for K55, assuming API 5CT SR1 specification, API 5CT, 2018), and using the Klever-Stewart design equation, the deterministic limit state design value (in the absence of axial force and without temperature deration) is 4,110 psi. This corresponds to a *failure APB* of 3,756 psi, and a corresponding collapse load of 5,055 psi. This collapse load is higher than the API collapse strength of the inner casing. Thus, deterministic limit state design is showing that the inner casing is not adequate to satisfy our criterion of "outer casing rupture before inner casing collapse", even though the design check using API performance properties suggested otherwise.

We now turn to the application of RBD for our design check. To do this, we need the statistical distributions of the strength defining parameters in the Klever Stewart Limit State equation. These can be obtained from Annex F of API TR 5C3, manufacturer data, or receiving inspection of the actual pipe. Table 3 shows the statistical parameters used for the 13 3/8 in., 68 ppf, K55 casing in this paper. The table uses data from API TR 5C3. Reasonable assumptions are made about the distribution of ultimate tensile strength and minimum wall thickness, as these are not available in API TR 5C3. More representative distributions can be used in actual cases by obtaining data from the manufacturer, or performing receiving inspection.

[2] As discussed earlier, API Burst is not representative of the rupture limit of the pipe. Nevertheless, we pretend this is the case for purposes of illustration.

Table 3. Statistical Distribution of Strength Defining Parameters, 13.375 in., 68 ppf, K55

Parameter	Mean	SD	Source
Outer Diameter (in)	13.454	0.0244	API TR 5C3 (2018)
Average Wall Thickness (in)	0.483	0.0125	API TR 5C3 (2018)
Minimum Wall Thickness (in)	0.460	0.0125	Assumed based on average wall
Temp. Derated Yield Strength (psi)	66,549	4.7851	API TR 5C3 (2018)
Tensile Strength (psi)	104,880	4.7851	Assumption, based on yield distribution
Crack Depth	12.5	0.0125	Assumed
Burst Equation Error	1.008	0.0252	API TR 5C3 (2018)

The commercial program *StrinGnosis* is used to calculate the probability of failure of the casing for a given (deterministic) burst load (Level 4 RBD)[3]. A burst load of 4,830 psi is required to obtain a 10^{-1} probability of burst failure. This is higher than the load calculated using deterministic limit state design, which was 4,110 psi. The *failure APB* to reach this burst load is 4,857 psi, and the corresponding collapse load is 6,176 psi. This is much greater than the API collapse strength of the current inner casing, meaning that our design criterion is not satisfied, and the inner casing is likely to collapse before the outer casing ruptures.

3.5. Upgrading the Inner Casing Based on RBD

The conclusion from the above discussion is that the design as it stands (9 5/8 in., 47 ppf, L80) is not adequate to satisfy the RBD design criterion to assure that burst of outer casing occurs before collapse of inner casing. One choice for upgrade of the inner casing is to increase its weight to 53.5 ppf. This does not compromise the drift (8 ½ in.) for drilling the next hole section. With this upgrade, the collapse strength of the inner casing is now 6,620 psi. The collapse load, calculated in the previous sub-section, is 6,176 psi. This gives us an API Collapse safety factor > 1, and correspondingly, an expected probability of collapse failure of less than $10^{-2.3}$, which satisfies the design criterion. We can confirm this with a numerical check of the probability of collapse failure of the 9 5/8 in., 53.5 ppf, L80 inner casing with a collapse load of 6,176 psi. The probability of failure in collapse, calculated using *StrinGnosis,* is $10^{-2.5}$. Thus, with the upgraded inner casing and the original 13 3/8 in. casing, we have shown that the probability of outer casing rupture is 10^{-1}, while the probability of inner casing collapse is $10^{-2.5}$. This means that that the outer casing is very likely to burst before the inner casing collapses, satisfying our stated design criterion.

3.6. Impact of Initial Crack Depth in Cement Sheath

In the preceding analysis, we have assumed an initial crack depth equal to 5% of the cement sheath thickness. A reduced crack depth will result in a higher *critical APB.* Results for a 2% (0.028 in, 0.71 mm) initial crack depth are shown in Table 4 below. The depth of the void is the same as before, at 3,000 ft. As can be seen, the *critical APB* is higher in all cases. For all but the highest cement fracture toughness, the *critical APB* is lower than the *failure APB*. But for the highest fracture toughness (5 ksi √in, 5.5 MPa √m), the *critical APB* is now 4,896 psi, *higher than* the *failure APB* of 4,857 psi. This means that in this case, *critical APB* dictates the collapse design of the inner casing, and the corresponding collapse load is 6,195 psi. The upgraded 9 5/8 in., 53.5 ppf, L80 casing is still adequate for this load, and satisfies our design criterion. The result also shows that the design can tolerate an even smaller initial crack depth.

Table 4. Critical APB and Casing Loads with Reduced Crack Depth*

	Cement fracture		Loads on Casing	
K_{1C} ksi-in$^{0.5}$	Critical APB psi	ΔT °F	OC, Burst psi	IC, Coll psi
0.5	490	13.6	463	1,789
2.0	1,962	54.5	1,935	3,261
5.0	4,896	136	4,869	6,195

*Crack depth is 2% of cement sheath thickness, 0.028 in. (0.71 mm)

3.7. Summary of Results

Key results from the preceding sections are summarized in Table 5. All of the results are for a void depth of 3,000 ft, with the previously discussed assumptions of internal pressure in the inner casing, cement column pressure, and external pressure outside the outer casing. The outer casing is assumed to be 13 3/8 in., 68 ppf, K55. The summary illustrates how fracture toughness, initial crack depth, and method of calculating the burst load causing rupture of the outer casing can impact the design results.

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[3] Alternatively, the probability of failure can be calculated using the methods described in Suryanarayana and Lewis (2016). This work presents a detailed, step-by-step procedure to calculate probability of failure for a deterministic load and stochastic resistance based on limit states (Level 4 RBD).

Table 5. Summary of Key Results from the Example

K1C Ksi-in.$^{0.5}$	Initial Crack Depth in.	Critical APB psi	Failure APB psi	Dictating Loads OC Burst psi	Dictating Loads IC Coll psi	Method of Calculating Load to Fail Outer Casing in Rupture
0.5 - 5	0.07	310 - 3,096	3,477	3,450	4,776	API performance properties
			3,756	4,110	5,055	Deterministic Limit State Design
			4,857	4,830	6,176	Level 4 RBD with OC Burst POF = 10^{-1}
2	0.028	1,962	4,857	4,830	6,176	Level 4 RBD with OC Burst POF = 10^{-1}
5	0.028	4,896	4,857	4,869	6,195	Burst load corresponding to critical APB

3.8. Impact of Void Location

The analysis so far assumes a void at the steel-cement interface of the inner casing. This is a common location of the void (Lavrov, et al., 2016). However, the design approach applies without loss of generality to any radial location of the void, since the *critical APB*, which is a function only of the cement properties. If the *critical APB* is lower than the *failure APB*, a flow path is always created connecting the two casing strings before the outer casing bursts, regardless of the radial location of the void. If the *failure* APB is greater than the *critical APB,* radial locations closer to or at the wall of the outer casing could result in its burst without affecting the collapse load on the inner casing. However, this cannot be counted on in design.

The design approach described can be applied at any depth of location of the void. In the present analysis, the void is just above the liner top. This is the most conservative location of the void, since the external pressure on the outer casing, and hence the *failure APB,* increases with depth. Besides, as noted earlier, Goodwin and Crook (1992) indicate that the upper ½ to 2/3rd of the cement sheath is already cracked due to thermal stresses. One concern may be location of the void shallower than the previous casing depth, since the cement outside the outer casing is not exposed to formation at such a location. However, the design basis still holds, since the cement outside the outer casing immediately fractures after rupture of the outer casing, and will find a path to the shoe or the next outer casing, which typically has an even lower rupture capacity than the outer casing of the tieback annulus.

4. RECOMMENDED DESIGN APPROACH

The design approach described here can be summarized as follows.

1. Select depth of void. At this depth, calculate the *critical APB* using an assumed cement fracture toughness and initial crack depth (recommended values are 2.5 ksi √in and 5% of cement sheath thickness respectively, but other values may be used based on additional data).
2. Estimate the external pressure outside the outer casing (recommended value is pore pressure), hydrostatic pressure in the cement column (recommended value is mix water hydrostatic) and internal pressure in the inner casing (recommended value is zero psi). With these values, calculate the burst and collapse loads on the outer and inner casing respectively.
3. Using the Klever-Stewart Rupture Limit and Level 4 RBD, calculate the required burst load on the outer casing such that the probability of rupture is 10^{-1} or greater. Calculate the APB required to achieve this burst load. This is the *failure APB.* Calculate the collapse load corresponding to this *failure APB.*
4. Use the higher of the two collapse loads calculated (in Step 2 and Step 3) to select the required collapse strength of the inner casing, based on API collapse strength and a design factor of 1.0 (this usually implies a probability of collapse failure of about $10^{-2.3}$). The selection of inner casing can also be based on explicit calculation of the probability of collapse failure using the Klever Generalized Tamano limit state and Level 4 RBD. The target probability of failure in that case should be ≤ 10^{-2}, to ensure that the probability of outer string burst is an order of magnitude higher than the probability of inner string collapse.

5. CONCLUSIONS

In this work, we address the problem of tieback collapse from APB in a fluid pocket trapped in the cement behind the tieback, and present a quantitative basis of design for APB load such that the outer string bursts and relieves APB before the inner string collapses. A fracture mechanics based approach has been used to determine the *critical APB* at which the cement fractures. Using API TR 5C3 limit states and a Level 4 reliability-based design approach (with deterministic load and stochastic resistance), the *failure APB* is determined as the APB at which the probability of failure of the outer casing is ≥ 10^{-1} (imminent failure criterion). It is shown that the dictating collapse load on the inner casing is the one corresponding to the higher of the *critical APB* or the *failure APB.* The inner string collapse strength is then selected to be higher than this dictating load. An example is presented to illustrate the application of the method, and sensitivity analyses are presented to investigate the effect of parameter variations.

The key conclusions from this work are:

- Maintaining a ratio of 1.2 (or indeed any other prescribed ratio) between the API Collapse rating of the inner string and the API Burst rating of the outer string is not an adequate basis of design. This is because the API Burst is not representative of the rupture limit of the outer casing.

- A more appropriate basis for design is to use a probabilistic design (Level 4 RBD) with the design approach presented in this work. Using this design approach, for an example case where the ratio of API Collapse of inner casing to API Burst of outer casing was 1.38, it is shown that the inner casing collapse strength is not adequate to assure burst of the outer casing before collapse of the inner casing.
- Further, using the proposed design approach, it is shown that a practicable upgrade to the inner casing satisfies the probabilistic design criterion, thus assuring outer casing burst before inner casing collapse.
- Fracture toughness of cement and the initial crack depth have an impact on the *critical APB*. However, sensitivity analyses presented here show that within the range of expected values, the approach still results in a practicable design outcome.
- In general, application of this approach requires more intimate understanding of the properties of materials used in the well, and may imply changes in design selections as the APB load design affects selection of both the outer and inner strings. It should be noted that the application of the design approach presented in this work may sometimes lead to infeasible choices for the outer or inner string. In such cases, the recourse is to ensure good cementing.
- It should be noted in closing that this is but one load condition in geothermal well design, and a complete design should include consideration of other loads, in particular thermal cycling loads (Suryanarayana and Krishnamurthy, 2018).

The authors hope that this work provides a much-needed basis for design to combat APB-induced collapse of tiebacks in geothermal wells, and contributes to improving the integrity of geothermal wells.

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