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CO_2 Corrosion and Its Consequences on the Uniform Walled Tubular Burst and Collapse Pressure Rating

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ABSTRACT

This paper presents the effect of uniform corrosion on the burst and collapse pressure rating. The analysis is based on the analytical calculation (API Barlow and Triaxial models) and the finite element method (FEM). Results showed that the FEM analysis validated the analytical models. The FEM modeling is reliable for tubulars that include any type of defect.

1 INTRODUCTION

The NORSOK D-10 tubular design criteria mainly deals with loading and material selection. The design criteria demands that casing shall be of a higher quality to withstand particularly corrosive media in the well such as (H2S, CO2, etc…). Casing shall be designed with respect to realistic load conditions during the life time of the well. The loads shall be corrected for additional loads and effects such as casing wear, bending in a deviated hole sections, temperature, corrosion, plastic formations, reservoir compaction, pressures during completion, workover, and kill operation. [1]

Out of the 75 injection and production wells, the petroleum safety authority's integrity survey report showed that about 39% the integrity problem was associated with tubing. Moreover, failure rate with cement and casing was 11% each [2]. Corrosion is a critical problem among others in the oil and gas industry. According to a nationwide report in the USA, corrosion in the five industrial sectors cost a total of 276$ billion per year [3]. Out of this, in the oil and gas production and manufacturing industry, corrosion problems cost $1.4 billion per year. [3].

During reservoir productivity enhancement jobs such as well acidizing, seawater and CO_2 injection, coil tubing and tubing experience corrosion. Case studies in the North

Sea, Dutch sector, showed that about 25% of CO_2 injection tubulars degraded due to CO_2 pitting [4]. Moreover, the chemistry of geothermal wells contain corrosive gases such as carbon dioxide (60-95%) and hydrogen sulphide (2-15%) [5].

For instance, the NORSOK M056 corrosion rate model prediction for the considered typical input parameters is displayed in **Figure 1**. According to the NORSOK model, the corrosion rate decline for the temperature above 60°C, which is due to the formation of iron carbonate (FeCO3) scale-layer. Iron carbonate precipitates on the steel surface when the concentration of Fe^{2+} and CO_3^{2-} ions exceeds the solubility limit [6]. As a result, $FeCO_3$ film layer will be formed and reduces the corrosion rate by inhibiting the underlying steel from further dissolution [7]. There are also other parameters that influence corrosion rate such as temperature, pH, CO_2 partial pressure, velocity, pressure, shear stress and medium ions. For instance, as displayed in the Figure 1, the 20% glycol reduced the corrosion rate by forming a temporary passive layer on the surface of the tubular. The right concentration and continuous treatment will slow down the corrosion rate and prolong the operational life of a structure. **Figure 2** also illustrates the effect of the 250bar pressure and 0.5bar CO_2 partial pressure for various pH indicating that the lower pH increases the corrosion rate.

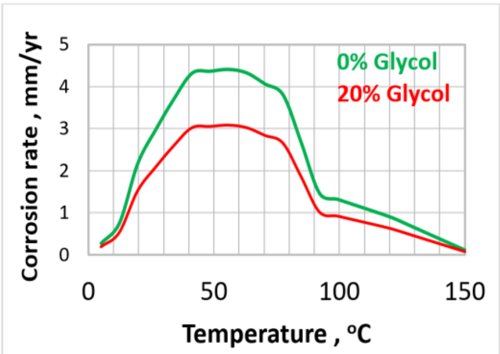


Figure 1: Effect of glycol on corrosion rate

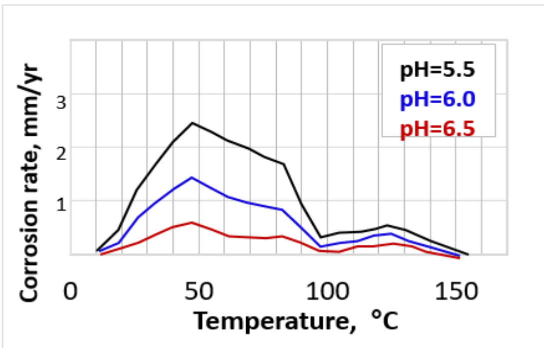


Figure 2: Effect of pH on corrosion rate

The objective of this paper is to evaluate the analytical and the numerical methods for burst and collapse pressure rating of a uniformly worn out tubular.

2 THEORY

This section presents the analytical models used for tubular modeling. These are API burst and triaxial burst/collapse models, which are derived based on thin and thick-walled cylinder theories, respectively.

2.1 API burst

The API burst is derived based on thin-wall cylinder stress theory and the model is also known as Barlow equation [8]:

$$P_y = Tol.\frac{2\sigma_y.t}{OD} \quad 1$$

Where, *t* and OD are the wall thickness and outer diameter and σ_y is the yield strength. The API tolerance (Tol) factor for wall thickness is 0.875[8]. (Tol = 1/SF, Safety factor (SF)=8/7)

2.2 Triaxial models

Consider a thick-walled cylinder subjected to pressures internally and externally. Due to the pressure loading, stresses and deformations will be generated across the wall thickness of the cylinder in the radial, axial and circumferential directions (Eqs.A1-A3). The von Mises failure criteria (Eq.A5) is commonly used to describe the yielding of steel under the combined state of stresses.

2.2.1 Triaxial burst pressure

Tubulars yield when the von Mises stress reaches the yield strength of the material. Applying the von Mises failure criteria and solving for the internal pressure (Pi), the triaxial burst design pressure is given as [9, 10]:

$$P_i = \frac{\beta\sigma_a - 2\sigma_a + 2\beta^2 P_o - \beta P_O \pm \sqrt{-3\beta^2\sigma_a^2 - 6\beta^2\sigma_a P_o - 3\beta^2 P_o^2 + 4(\beta^2 - \beta + 1)\sigma_y^2}}{2(\beta^2 - \beta + 1)} \quad 2$$

The yield stress, σ_y, is replaced by σ_y/SF, P_o is the external pressure, σ_a is the axial stress, β is the geometrical factor, which is given in Appendix A as Eq.A8.

2.2.2 Triaxial collapse pressure

Similarly, the triaxial collapse pressure can be derived by solving for the external pressure as [9, 10]:

$$P_o = \frac{-\sigma_a + 2\beta.P_i - P_i \pm \sqrt{-3\sigma_a^2 - 6\sigma_a P_i - 3P_i^2 + 4\sigma_y^2}}{2\beta} \quad 3$$

3 Finite Element Method Modeling

During acid injection or when the tubing surface is uniformly exposed to corrosive gas such as CO_2, the corrosive protective passive layer of the inner tube will be removed. As a result, the surface will be anodic and releases electrons continuously. The inner surface of the tube will be therefore be reduced uniformly. ABAQUS/CAE is a well-known structural engineering design and analysis tool. The simulation of uniform wear effect on tubular collapse and burst rating is conducted by ABAQUS/CAE, which is basically using the numerical technique called Finite Element Method (FEM). The following section presents the FEM simulation results of the effect of 5-50% wall thickness reduction on the burst/collapse derating pressure.

3.1 Simulation setup

The main objective of the FEM simulation study is to compare and verify the analytical models (Eqs.1-3).

Material properties: T-95 production tubing is analyzed in this paper. It is widely used along with L-80 tubing. **Table 1** shows the mechanical properties and the geometry of the tube.

Table 1: T-95 Tubular data

Parameters	Value
OD-diameter	4.00 in
ID-diameter	3.548 in
Yield strength	95000 psi
Young's modulus	$30x10^6$ psi
Poisson's ratio	0.25

Boundary condition: As previously mentioned, pressure and temperature loadings will cause tubular deformation in the axial, circumferential and radial directions. Therefore, the boundary condition is assumed to be free at the top and the bottom end of the string.

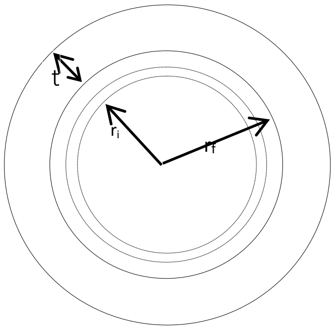
Loading: The tube is loaded externally with a constant pressure, which is due to completion fluid. For burst load rating, the internal pressure was increased until the von Mises stress in the tubing reaches the yield strength. The pressures determined through the simulation process is used to limit the loads over the well's operational life such as production, shut-in, well injection, bullheading and well stimulation can be mentioned. Likewise, for collapse load rating, the external pressure due to gas lift and annulus pressure testing was increased until the von Mises stress reaches the yield strength while keeping the internal pressure constant.

3.2 Simulation results and discussion

This section presents the comparison between the analytical (API Barlow, Triaxial burst and collapse) models with the FEM modeling. Finally, the consequence of uniform tubular corrosion on production tube working loads with respect to the safe design window will be simulated with WellCatTM/Landmark.

3.2.1 Comparison of analytical API Barlow and FEM modeling

The first base case design illustrates the whole process of the modeling and the comparisons conducted in this paper. For this, the API Barlow's equation (Eq. 1) is compared with the FEM approach. Since the API model is derived based on the uniform wall thickness of a tube, the wall thickness of the tube is removed from the initial radius, r_i to the final radius r_f , which is until 50% of the wall thickness has been removed (See **Figure 3**). **Figure 4** displays the von Mises stress field in the tube loaded internally with 3500psi. **Figure 5** shows the burst de-rating pressures simulation results. As shown, the FEM nearly captures the API burst model (Eq.1) calculated result. The base case simulation clearly shows the trustworthy of the FEM result and the applicability of the API model for a uniformly worn tubular.



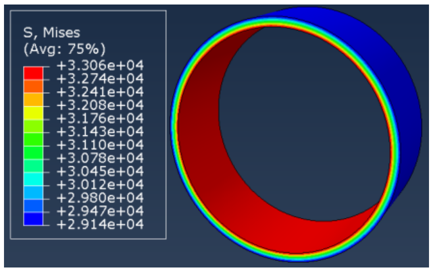


Figure 3 Inner surface uniformly removed tube **Figure 4: von Mises stress field**

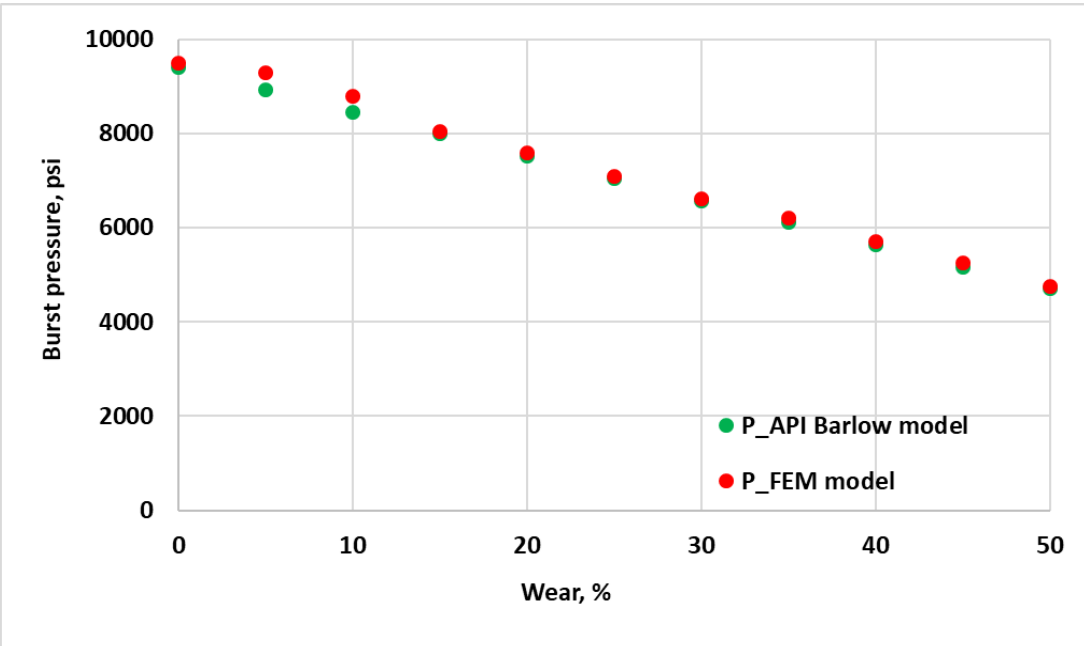


Figure 5: Comparisons between burst de-rating API Barlow and EFM modeling.

3.2.2 Comparison of analytical Burst Triaxial, API and FEM modeling

To evaluate the triaxial burst model (Eq. 2) and the API (Eq.1), the external pressure and axial stress were assumed to be neglected. **Figure 6** shows the FEM and the analytical models prediction with about 4% deviation, where the wear depth is between 0 – 15% and less than 1% deviation for the wear depth in the range of 20%-50%. In general, the result shows good agreement between the analytical and the numerical model results.

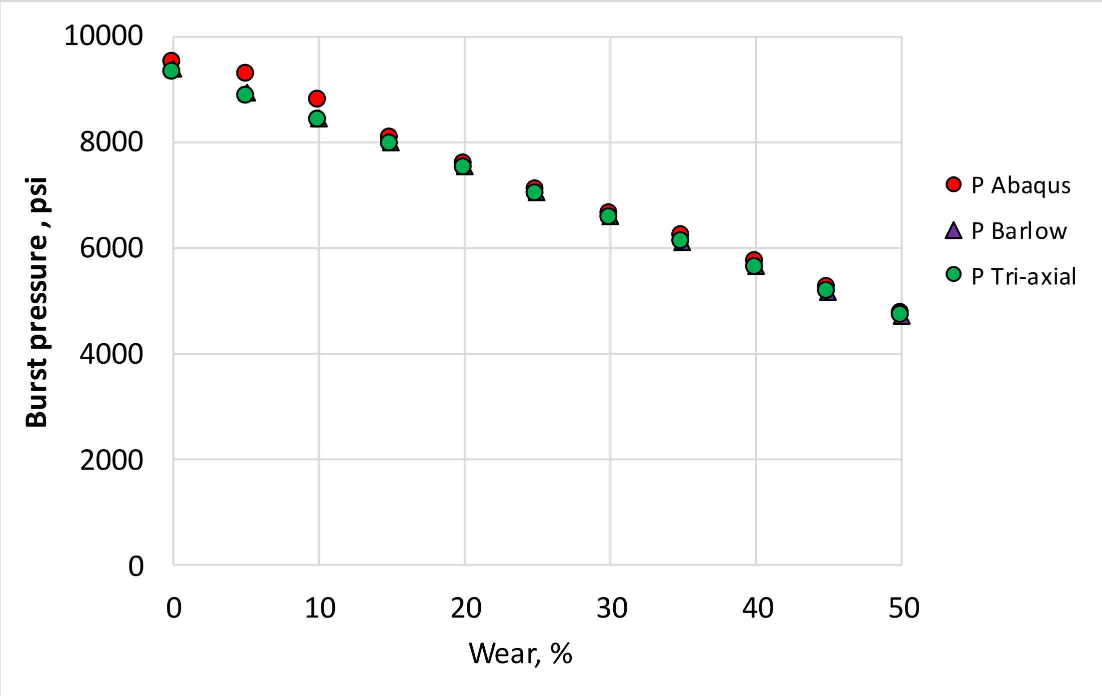


Figure 6: Simulation vs. theoretical burst de-rated pressures.

3.2.3 Comparison of analytical triaxial collapse vs FEM modeling

Tubulars fail by collapse when the differential pressure between the external and internal pressure exceeds the collapse rating of the tubing. Depending on the OD/t ratio, four modes of tubular collapse are given in API 5C3 [8]. In the oil and gas wells, tubulars may collapse due to the annular pressure build-up, which are associated with packer leak, production tubing leak, annular pressure testing, or artificial lift operation. During the life of a well, it is important to predict the collapse rating differential pressure with respect to the geometry of the tubular and temperature effect as well.
Similar to the burst case, the analytical triaxial collapse model (Eq.3) was assessed. For this, the FEM modeling assumes a constant internal production fluid pressure and we increased the external pressure until tubular fails by collapse. Based on the reservoir pressure and hydrocarbon density, the internal pressure at the gas lift depth was calculated being 3758psi.

Figure 7 displays the results obtained from the triaxial collapse model (Eq. 3) and the FEM simulation. The collapse derating pressure reduces linearly as wear depth increases. As shown, the analytical collapse model prediction is nearly equal to the FEM result. This indicates again the reliability of the FEM modeling approach as well as the validity of the analytical models. One can also observe that the trend and the deviation of the analytical collapse and burst pressures from the FEM result are quite similar.

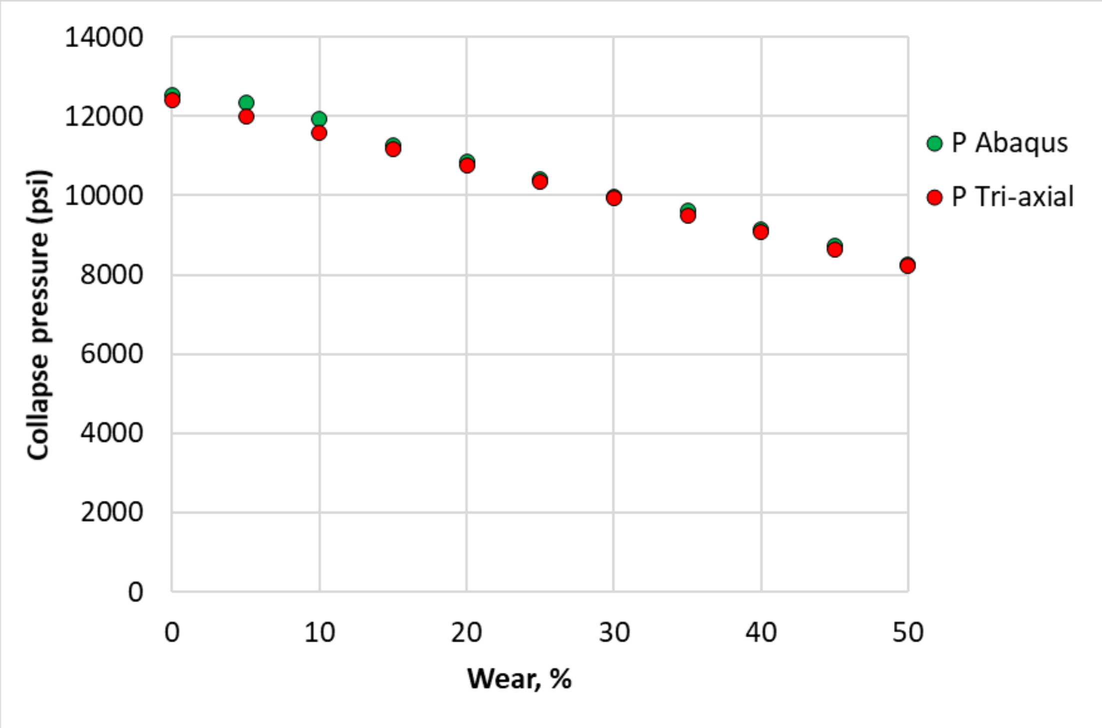


Figure 7: Simulation vs. theoretical collapse de-rated pressures

3.3 The consequence of wall thickness reduction

For the evaluation of tubular wall thickness reduction with respect to design limits, a production tube exposed to different operational loads is considered. The loads are bullheading, pressure test tubing, pressure test annulus, production (early, steady state & late), shut-in (short & long) and pump kill fluid. **Figure 8** shows the operational loading on the unworn tube and all the loads are bounded within the safe operational window. On the other hand, assuming that the wall thickness of the tube is reduced by 20%, the narrowed down operational window is displayed in **Figure 9**. As shown, three of the loading cross the design limit and resulting in tubular burst/collapse failures. The simulation result suggests that during the life of a well, it is important to monitor the condition of tubing and perform re-design calculation based on the type and the severity of tubular damage. For an irregularly shaped damages, FEM based burst and collapse derated pressure determination is more reliable. The commercial software considers uniform wall thickness cylinder only.

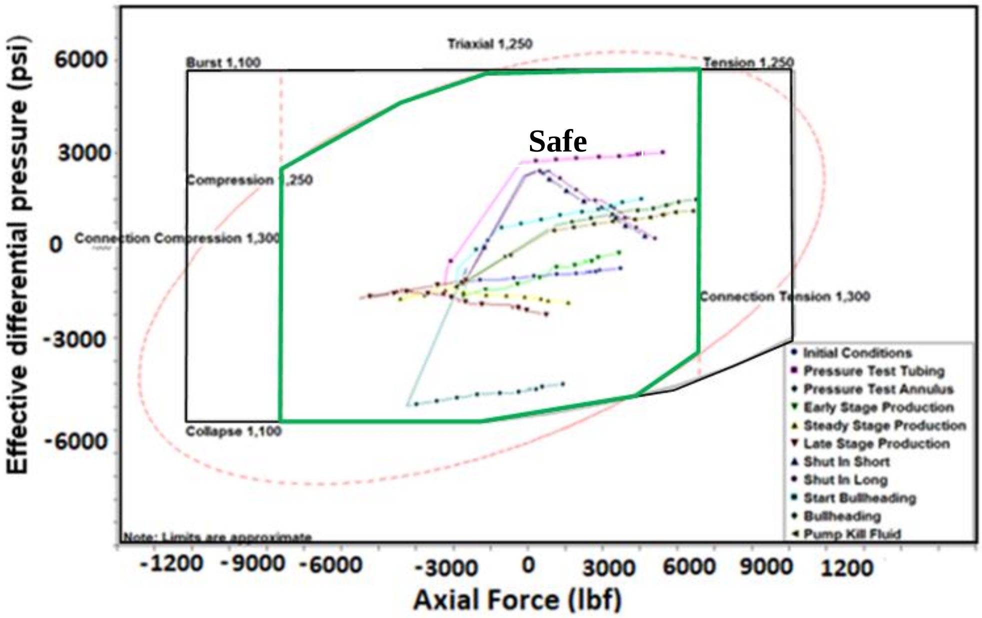


Figure 8: All loading within the safe design limit (green curve) for unworn tube

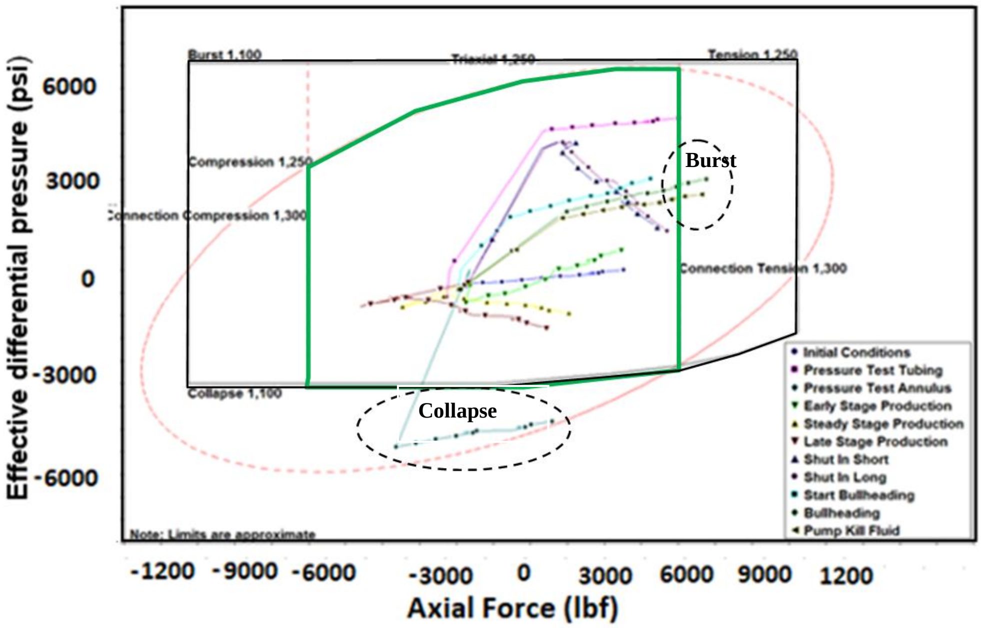


Figure 9: Three loads crossing design limit for tubing with 20% worn out

4 SUMMARY

To avoid or minimize the risk of tubular failure, it is important to precisely predict the load carrying capacity of the tubular during the operational life time of a well. In this paper, the analytical burst and collapse calculation results are compared with the finite element method. Results showed that:

- The tubular burst and collapse strength decrease linearly as the wall thickness decreases uniformly.
- The API Barlow and the triaxial burst models prediction are nearly the same as the FEM result for the assumption that the axial stress and the external pressure are not considered. However, one may get different answer in the presence of these.
- The triaxial collapse and the FEM results are nearly equal.

The analysis presented in this paper indicates the trustworthy of the FEM modeling approach, which can be used for any type of tubular damage.

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APPENDIX A

A1: Theory of thick walled cylinder

A cylinder is said to be thick-walled if the wall thickness, *t*, is greater than 1/10th of the inner radius (r_i). Otherwise, it is a thin-walled. Assume a thick-walled pipe is pressurized internally and externally with P_i and P_o, respectively. In the absence of temperature loading, the stresses in the wall thickness can be given as [9, 10]:

Radial stress $$\sigma_r = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2}(p_i - p_o) \qquad \text{A1}$$

Hoop stress: $$\sigma_h = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2}(p_i - p_o) \qquad \text{A2}$$

Axial stress: Open – Closed end $$\sigma_a = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} \qquad \text{A3}$$

A2: von Mises failure criteria

The von Mises failure criteria is based on maximum distortional energy theory.

$$\sigma_{VME} = \sqrt{\frac{1}{2}\left\{(\sigma_h - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + (\sigma_a - \sigma_h)^2\right\} + 3\tau^2} \qquad \text{A4}$$

The von Mises failure criteria is given as: [9, 10]

$\sigma_{vme} = \sigma_y/SF$ A5

A3: Triaxial burst and collapse solutions

Since the von Mises stress is maximum at the inner wall, from Eq. A1, the radial stress at the inner wall is given as: [9, 10]

$$\sigma_r = -P_i \qquad \text{A6}$$

From Eq. A2, the hoop stress at the inner wall is given as:

$$\sigma_h = (\beta - 1)P_i - \beta P_o \qquad \text{A7}$$

Where, β is geometrical factor and given in terms of the inner diameter (d_i) and the outer diameter (d_o) of a cylinder as: [9, 10]

$$\beta = \frac{2d_o^2}{d_o^2 - d_i^2} \qquad \text{A8}$$

In the absence of torsional stress, inserting stresses (A6 and A7) in Eq. A5 and solving for inner pressure (Tri-axial burst) and for the outer pressure (Tri-axial collapse) are given in main paper as Eq. 2 and Eq. 3, respectively.