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Tubing Limits for Burst and Collapse

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Summary

When there is a large pressure differential across the CT wall, especially when combined with a large axial force, you run a risk of a CT failure (burst or collapse). Typically the greatest risk of burst or collapse in a CT job occurs at the wellhead. You can use a mathematical model to determine these limits prior to performing a job to make sure that the operation stays within safe working limits.

A widely accepted model uses the von Mises combined stress to predict tubing burst and collapse limits. You can also take into account helical buckling, maximum expected pressures, diameter growth, and torque.

CT Stresses

A widely accepted method of predicting tubing failure due to pressure and tension limits is based on the von Mises stress. If the von Mises stress exceeds the yield strength of the material, the CT is assumed to fail.

The von Mises stress is a combination of the three principal stresses in CT and the shear stress caused by torque. The three principal stresses are:

- axial stress (σ_a)
- radial stress (σ_r)
- tangential or hoop stress (σ_h)

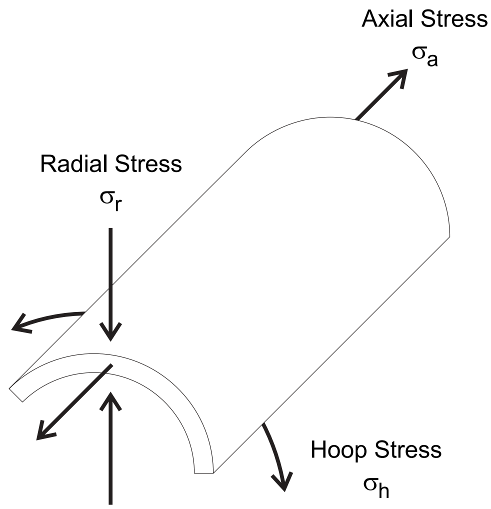

FIGURE 1 Three Principal Stresses

Note that these stresses are determined by the geometry of the CT and the well, as well as three variables:

- internal pressure (P_i)
- external pressure (P_o)
- axial force (tension or compression) (F_a)

Axial Force Definitions

Before axial stress can be defined, two types of axial force must be defined. These are known as the "real force", F_a , and the "effective force", F_e , also known as the "weight". The real force is the actual axial force in the pipe wall, as would be measured by a strain gauge. The effective force is the axial force if the effects of pressure are ignored.

To better understand these forces, consider the following simple example shown in Figure 2.

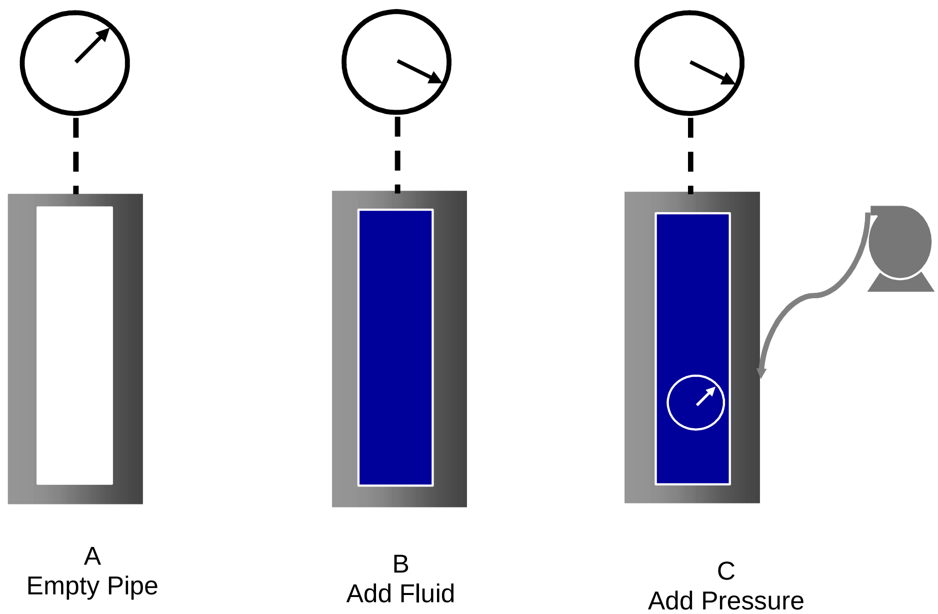

FIGURE 2 Axial Force Example

A closed ended piece of pipe is hung from a scale as is shown in case A. The scale is measuring the weight of the pipe. The real axial force at the top of the pipe is the same as the weight measured by the scale.

In case B the piece of pipe is full of fluid. The weight is increased by the weight of the fluid. The real axial force at the top of the pipe is still the same as the weight measured by the scale.

In case C, pressure is applied to the fluid inside the pipe. The weight remains the same as in case B. However, the real axial force in the pipe wall is now increased by the internal pressure multiplied by the cross sectional area. Thus, the weight (also known as the effective force) and the real force are not the same.

The relationship between real and effective force can be written as:

$$F_a = F_e + A_i P_i - A_o P_o \quad \textbf{EQ 1}$$

Effective force, or weight, is important for two reasons:

- The weight indicator on a CT unit measures the weight, not the real force, just as the scale in Eq 1above measures the weight.
- When buckling occurs depends upon the effective force. Thus the helical buckling load is an effective force.

The real force is important because it is the force required to calculate the axial stress, and thus to determine the CT limits.

Axial Stress

The axial stress is caused by the axial force (tension or compression) applied to the CT. When the CT is in tension, the axial stress is the axial force divided by the cross-sectional area:

$$\sigma_a = \frac{F_a}{A} \quad \text{(tension)}$$

EQ 2

If the compressive force exceeds the helical buckling load, the CT forms a helix in the hole. This helix causes an additional axial bending stress in the CT, which must be added to the axial stress.

Note that in a vertical well the helical buckling load is nearly zero. The CT buckles into a helix as soon as the effective force becomes compressive (which is defined as a negative force value). Hercules assumes that the CT is buckled if the effective force is less than zero.

$$\sigma_a = \frac{F_a}{A} + \frac{F_e R r_o}{2I} \quad \text{(compression / helical buckling)}$$

EQ 3

This additional axial bending stress also truncates the elliptical shape of the traditional von Mises limits curve.

Radial Stress

According to Lame's equation, the radial stress at a given location in the CT wall is the stress through the CT wall due to internal and external pressures. The maximum stress always occurs at the inner or the outer surface. Since yielding occurs first at the inner surface, Hercules uses the radial stress at the inner surface in its calculations.

$$\sigma_r = -P_i$$

EQ 4

Hoop Stress

According to Lame's equation, the hoop stress at a given location in the CT wall is the stress around the circumference of the CT due to internal and external pressures. As with the radial stress, the maximum stress always occurs at the inner or the outer surface. Again, because yielding occurs first at the inner surface, Hercules uses the hoop stress at the inner surface in its calculations.

$$\sigma_h = \frac{\left(r_i^2 + r_o^2\right)P_i - 2r_o^2 P_o}{r_o^2 - r_i^2}$$

EQ 5

Torque

In some situations the CT may also be subject to a torque, T. If the torque is significant, then torsion of the CT occurs and causes the associated shear stress, τ, which is given by:

$$\tau = \frac{2Tr}{\pi\left(r_o^4 - r_i^4\right)}$$

EQ 6

The variable r ranges from r_i to r_o, with the greatest shear stress occurring at r_o. Although the radial and hoop stresses are calculated for the inner CT surface, the shear stress is calculated for the outer surface, a more conservative approximation.

The von Mises Yield Condition

The von Mises yield condition is commonly used to describe the yielding of steel under combined states of stress. The initial yield limit is based on the combination of the three principle stresses (axial stress, radial stress, and hoop stress) and the shear stress caused by torque.

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

EQ 7

Note that if there is no torque, the shear stress term drops out of the equation.

The yield limits for CT are calculated by setting the von Mises stress, σ_{vme} to the yield stress, σ_y , for the material.

The Limits Curve

There are four forces which determine the combined stress limits in CT. They are the internal pressure, P_i, external pressure, P_o, the real axial force, F_a, and the torque, T. To simplify the presentation of the limits, the pressure difference P_i - P_o is calculated. A positive differential pressure represents a "Burst" condition. A negative differential pressure represents a "Collapse" condition.

One method of drawing the limit curve is to hold the external pressure constant at zero for the top or Burst half of the plot and hold the internal pressure constant at zero for the bottom or Collapse portion of the plot. The von Mises equation now has only two variables, real axial force and internal pressure for the Burst portion, and external pressure for the Collapse portion. The Weight can also be calculated using Eq 1. Thus, this curve can be drawn versus either the real axial force or the effective axial force (which will be called Weight for the remainder of this document).

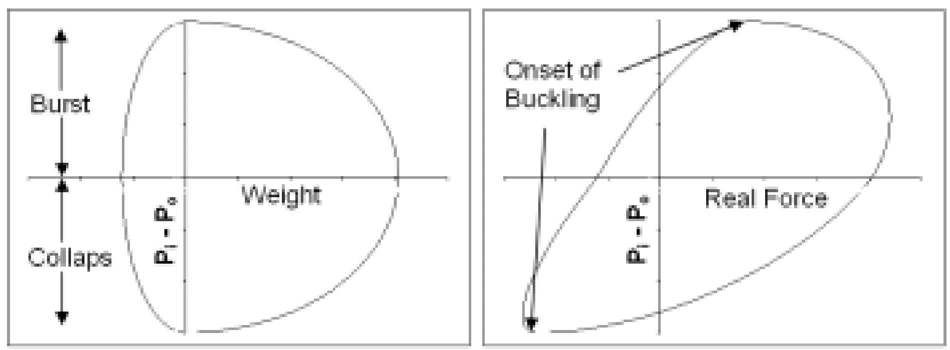

FIGURE 3 Single Limit Curves with External Pressure Constant at Zero

The resulting plots of pressure difference versus axial force are elliptical. In the Weight case, the ellipse is horizontal. In the Real Force case, the ellipse is inclined somewhat. The left side of the ellipse is truncated, due to the helical buckling stress. For the Weight case, the helical buckling begins at the Y axis, when the Weight becomes negative. For the Real Force case, the onset of buckling occurs at the maximum and minimum pressure difference points.

Maximum Pressure Considerations

Drawing the limits curve for a constant external (Burst case) or internal (Collapse case) pressure only shows the limits for that pressure. However, pressures do not stay constant throughout the CT job. To form a limits curve that addresses a range of pressures, one can create a composite of multiple limits curves.

First, a limit curve is drawn as in Figure 3, holding the external pressure at zero for the Burst case and the internal pressure zero for the collapse case. A second limit curve is drawn holding these same two pressures to their expected maximum values. The resulting set of limits curves are shown in Figure 4.

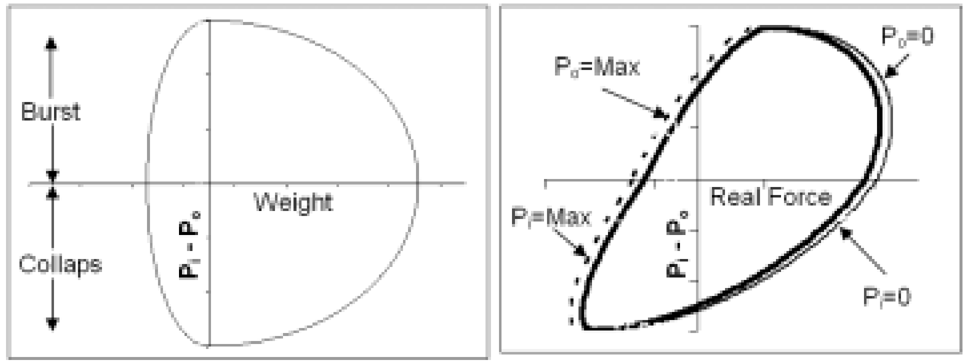

FIGURE 4 Limit Curve for Zero and Maximum

The inner most (closest to the origin) portion of these 2 curves in the Real Force plot, shown as a thick black line in Figure 4, is the limit curve produced by Hercules. Note that this limit curve no longer represents the true yield limit of the CT. Rather, it represents a conservative combination of the actual limits.

Note that the curve of the limit versus Weight is exactly the same for 0 and maximum pressure. Thus absolute pressure does not affect the CT limits when considered with respect to weight.

Diameter Growth Considerations

Depending upon the application, CT may have a tendency to increase in diameter during its life. This change in geometry changes the stresses, and thus the limits. In previous versions of Hercules, the user was able to input a percentage growth factor, and this increased diameter was taken into consideration. However, this caused confusion amongst the users, and often included diameter growth greater than was really seen in the field. For this reason the diameter growth parameter has been removed. If there is significant diameter growth and associated wall thinning, the user must input the correct diameter and wall thickness into Hercules.

Applying Safety Factors

The limits curve calculated by the von Mises yield condition represents where the CT would begin to yield. Although combining two limits curves for 0 and maximum pressure does introduce a small safety margin, more is desirable.

Hercules uses safety factors to produce a “working limits” curve with a larger safety margin. It multiplies the limits curve by safety factors to obtain a working limits curve. There are different safety factors for burst and for collapse. The safety factor for collapse should be more conservative to account for ovality. (During its life, CT becomes somewhat oval due to bending on the reel and over the gooseneck. Increased ovality increases the likelihood of collapse. However, the von Mises stress does not take ovality into account.)

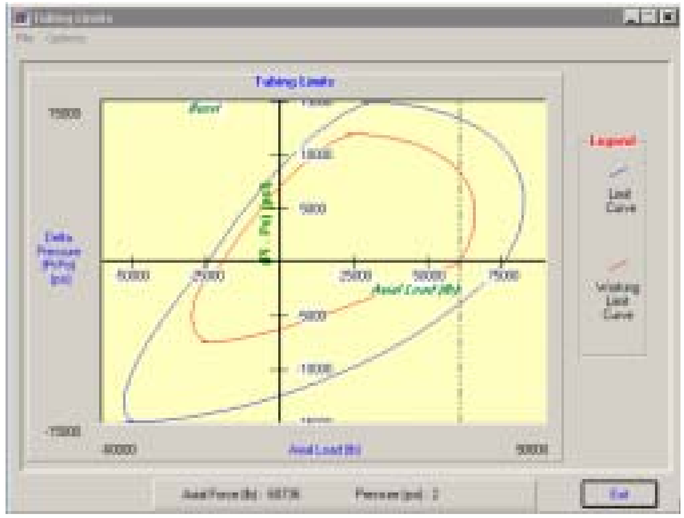

FIGURE 5 Hercules Limit and Working Limit Curves versus Real Axial Force

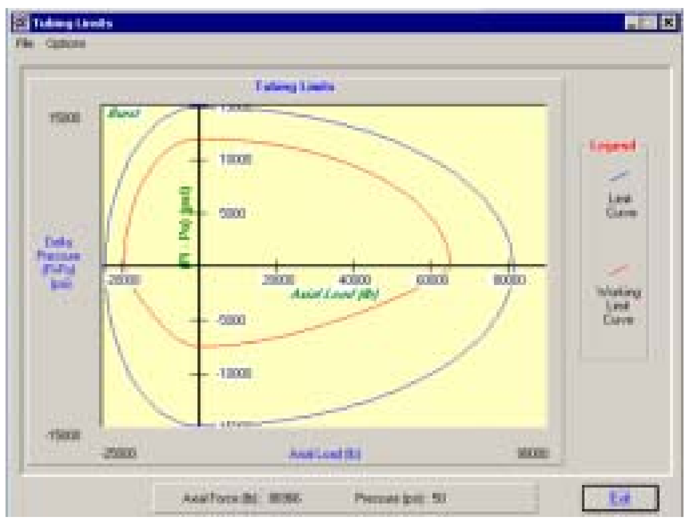

FIGURE 6 Hercules Limit and Working Limit Curves versus Effective Axial Force (Weight)

Nomenclature

A = cross sectional area of the CT material

F_e = effective axial force

F_a = axial force on CT (positive for tension, negative for compression)

I = moment of intertia of CT section

P_i = internal pressure inside the CT

P_o = external pressure outside the CT

R = radial clearance between the CT and the hole (hole radius - r_o)

r_o = radius from the center of the CT section to the outside of the wall

r_i = radius from the center of the CT section to the inside of the wall

T = torque

σ_a = axial stress

σ_h = hoop or tangential stress

σ_r = radial stress

σ_y = yield stress

σ_{vme} = von Mises stress

τ = shear stress caused by torque

References

1. Newman, K.: "Coiled Tubing Pressure and Tension Limits," SPE paper 23131, Proceedings from Offshore Europe 91, Aberdeen, September 1991.

2. Newman, K., “Coiled Tubing Forces and Stresses Modelling Improvements”, 2nd ICoTA/SPE European CT Roundtable, October 1995.

3. McSpadden, A., Newman, K., “Modified CT Limits Analysis for Practical Well Intervention Design”, SPE/ICoTA CT Conference & Exhibition, April 2002.

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