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API 5C3 Addendum and Casing Collapse Design

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Abstract

Casing is typically a hollow steel pipe set inside of the drilled hole (wellbore) and cemented in place to aid drilling and production operations, such as to prevent contamination of fresh water zones, to isolate different zones that have different pressures, and to seal off high pressure zones from the surface to avoid potential for a blowout. Casing needs to be designed safely and cost-effectively to withstand the possibly exposed loads (pressure, axial load, temperature) during its life in oil and gas well.

American Petroleum Institute (API) has established the industry standards on casing design, and continuously holds work group studies and technical standards conferences to update and improve these industry standards. API TR 5C3 2015 Addendum, which deleted the external pressure equivalent of external pressure and internal pressure, and revised the casing material equivalent yield strength for collapse design, is an update to API TR 5C3 standards “Equations and Calculations for Casing, Tubing, and Line Pipe Used as Casing or Tubing”, to improve casing collapse design in the presence of internal pressure under some collapse load cases, such as cementing, partial void (drilling mud drop or production packer fluid drop), and deepwater WCD (worst case discharge of uncontrolled flow out of the well).

This paper presents tubular mechanic analyses on casing collapse in the presence of internal pressure and casing collapse design examples to help understand and verify the changes made by API TR 5C3 2015 Addendum on casing collapse design, and help correctly apply API TR 5C3 2015 Addendum on casing collapse design in the presence of internal pressure.

Introduction

Casing collapse is a casing failure of losing its circular shape (Fig. 1), under excessive external pressure, which may severely impact the well construction, even including a loss of the well. The mechanism of casing collapse can be complicated, associated with casing circular shape stability loss, or casing material yield, or a combination of the both, depending on casing outside diameter and wall thickness. To prevent casing from collapse, casing needs to be properly designed to have sufficient strength to resist the external pressure possibly exposed to casing during its life in the well application.

Fig. 1 Casing collapse sample (courtesy of SPE 89775-MS)[1]

Due to the complexity of casing collapse mechanism, API (American Petroleum Institute) established the API casing collapse strength (collapse pressure), through a statistical analysis of full-size casing collapse tests data, and specified it in the industry standards API TR 5C3 [2]. The full-size casing collapse tests were conducted under zero internal pressure condition (Fig. 2), and therefore the established API casing collapse strength (collapse pressure) is also the casing external pressure limit at casing collapse, under zero internal pressure condition.

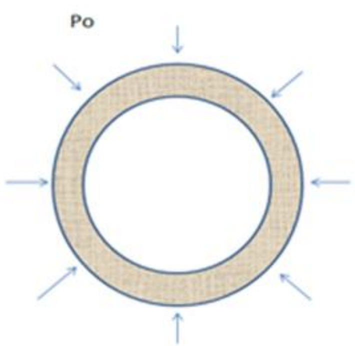


Fig. 2 API full-size casing collapse test condition (zero internal pressure)

Four API casing collapse strength (collapse pressure) equations were established and specified in API TR 5C3 [2], based on the different ranges of casing outside diameter to casing wall thickness ratio (D/t) on the API casing material grades, to define the four types of casing collapse: elastic collapse, transition collapse, plastic collapse, and yield collapse. The following Eq. 1 is the API plastic collapse strength (collapse pressure) equation, for the common range of casing outside diameter to casing wall thickness ratio (D/t) on the API casing material grades:

$$P_p = \sigma_y \left[\frac{A}{\left(\frac{D}{t}\right)} - B \right] - C \tag{1}$$

This API casing plastic collapse strength (collapse pressure) (P_p) is seen proportional to the casing material yield strength (σ_y) and affected by the casing outside diameter to casing wall thickness ratio (D/t). The higher the casing material yield strength (σ_y), the higher the API casing collapse strength (collapse pressure) (P_p), and the larger the casing outside diameter to wall thickness ratio (D/t), the lower the API casing collapse strength (collapse pressure) (P_p). The statistical constants of A, B, and C were determined from the statistical analysis of the full-size casing collapse test data.

API casing collapse strength (collapse pressure) is therefore defined as the external pressure limit at casing collapse under zero internal pressure condition, since:

1. API casing collapse strength (collapse pressure) is established based on the statistical analysis of full-size casing collapse tests data from zero internal pressure test condition;
2. Zero internal pressure condition (full void casing) represents the worst casing collapse loading (no internal pressure to help resist external pressure);

However, casing collapse design may also be conducted under some collapse load conditions where the internal pressure is present, such as under the cementing and WCD (worst case discharge of uncontrolled flow out of a deepwater well) conditions, in order to achieve a safe and effective design. For casing collapse design in the presence of internal pressure, is the casing collapse strength (collapse pressure) kept the same or changed?

API TR 5C3[2] then defined an external pressure equivalent (P_{ci}) of external pressure and internal pressure (Eq. 2), as the external pressure limit at casing collapse when internal pressure is present. This external pressure equivalent (P_{ci}) is an increase of the casing collapse strength (collapse pressure) (P_c) under zero internal pressure condition by a prorated internal pressure $(1 – 2t/D)P_i$, to represent a reinforcement of internal pressure (P_i) to casing collapse strength (collapse pressure). Note this prorated internal pressure is less than the internal pressure P_i, and the thicker the casing wall, the less the prorated internal pressure $(1 – 2t/D)P_i$.

$$P_{ci} = P_c + (1 – 2t/D)\, P_i \tag{2}$$

where Pc is the API casing collapse strength (collapse pressure) under zero internal pressure condition, which can be reduced by casing axial tension, based on the casing material equivalent yield strength (Eq. 3). Note that Eq. 3 is only applicable to the “axial tension” condition (σ_a) > 0.

$$\sigma_{ye} = \left(\sqrt{1 - \frac{3}{4}\left(\frac{\sigma_a}{\sigma_y}\right)^2} - \frac{1}{2}\left(\frac{\sigma_a}{\sigma_y}\right) \right) \sigma_y \qquad (\sigma_a > 0) \tag{3}$$

Casing Collapse Pressure in the Presence of Internal Pressure

API TR 5C3 2015 Addendum [3] made changes on casing collapse design in the presence of internal pressure, by deleting the external pressure equivalent equation (Eq. 2), and adding the internal pressure (P_i) to the casing axial stress in calculating the casing material equivalent yield strength (σ_{ye}), as shown in Eq. 4. Note that Eq. 4 is only applicable to the “effective axial tension” condition ($P_i + \sigma_a$) > 0.

$$\sigma_{ye} = \left(\sqrt{1 - \frac{3}{4}\left(\frac{p_i + \sigma_a}{\sigma_y}\right)^2} - \frac{1}{2}\left(\frac{p_i + \sigma_a}{\sigma_y}\right) \right) \sigma_y \qquad (P_i + \sigma_a) > 0 \tag{4}$$

The changes made by API TR 5C3 2015 Addendum on casing collapse design can help improve casing collapse design in the presence of casing internal pressure, with resulting in a higher casing collapse safety factor or allowing using a lighter weight or lower grade of casing, as discussed later in details.

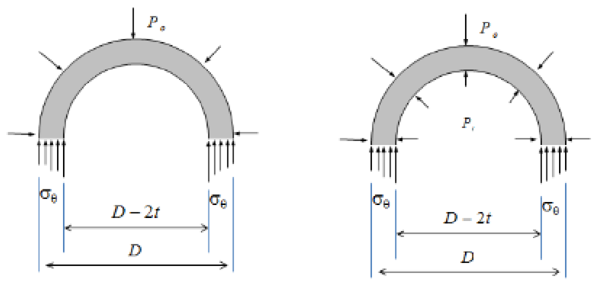
To help understand the changes made by API TR 5C3 2015 Addendum, let us first review how the external pressure equivalent (P_{ci}) of external pressure and internal pressure is derived and defined. From a 2-dimensional casing half-ring hoop stress model (Fig. 3), we can easily derive the total casing hoop compressive stress integration $2\int \sigma_\theta dt$, to balance with the casing external and internal pressures, for the two cases: Case (a) “Zero internal pressure” (Eq. 5) and Case (b) “with internal pressure” (Eq. 6):

(a) Zero internal pressure:

$$2\int \sigma_\theta dt = P_o D \tag{5}$$

(b) With internal pressure:

$$2\int \sigma_\theta dt = P_o D - P_i(D-2t) \qquad (6)$$



(a) Zero internal pressure (b) With internal pressure

Fig. 3 2-dimensional casing half-ring hoop stress model

For Case (a) "Zero internal pressure condition", dividing the total casing hoop compressive stress integration by casing outside diameter, it gives the external pressure (P_o) (Eq. 7), which represents the casing collapse strength (collapse pressure) when the external pressure reaches its limit at casing collapse. For Case (b) "With internal pressure", dividing the total casing hoop compressive stress integration by casing outside diameter, it gives a prorated differential pressure [P_o - (1 – 2t/D)P_i] (Eq. 8), which is considered as a combining "external pressure" with internal pressure being converted to casing outside diameter and represents the same casing collapse strength (collapse pressure) under zero internal pressure condition when the external pressure reaches its limit at casing collapse.

(a) No internal pressure:

$$\frac{2}{D}\int \sigma_\theta dt = P_o \qquad (7)$$

(b) With internal pressure:

$$\frac{2}{D}\int \sigma_\theta dt = P_o - P_i\left(1-\frac{2t}{D}\right) \qquad (8)$$

By denoting the external pressure (P_o) in Eq. 8 as the external pressure limit at casing collapse in the presence of internal pressure, called the external pressure equivalent (P_{ci}) of external pressure and internal pressure, and replacing the total casing hoop compressive stress integration divided by casing outside diameter $\frac{2}{D}\int \sigma_\theta dt$ by the casing collapse pressure (P_c) under zero internal pressure condition, Eq. 8 can be rearranged to define the external pressure equivalent (P_{ci}) of external pressure and internal pressure (Eq. 2):

$$P_{ci} = P_c + (1 - 2t/D)\, P_i \qquad (2)$$

The external pressure equivalent (P_{ci}) of external pressure and internal pressure is seen derived and defined as the external pressure limit at casing collapse or a new "casing collapse strength (collapse pressure)" with internal pressure inside casing. It is an increase of the casing collapse pressure (P_c) under zero internal pressure condition by the prorated internal pressure (1 – 2t/D)P_i. Note this prorated internal pressure (1 – 2t/D)P_i is less than the internal pressure (P_i), and the larger the ratio of casing wall to casing outside diameter (the thicker wall or the smaller outside diameter), the smaller the prorated internal pressure (1 – 2t/D)P_i.

As the external pressure equivalent (P_{ci}) of external pressure and internal pressure is defined as the external pressure limit at casing collapse with the internal pressure inside casing, it seems reasonably to calculate the casing collapse safety factor by comparing with the actual external pressure, i.e. to calculate the casing collapse safety factor by the ratio of the external pressure equivalent (Pci) as the external pressure limit at casing collapse to the actual external pressure:

$$SF_{c1} = P_{ci} / P_o = [P_c + (1 - 2t/D)\, P_i] / P_o \qquad (9)$$

However, as the prorated differential pressure [P_o – (1-2t/D)P_i] is considered as the combining "external pressure" with internal pressure being converted to casing outside diameter from Eq. 8, it seems also reasonably to calculate the casing collapse safety factor by comparing with the casing collapse strength (collapse pressure) pressure (Pc) under zero internal pressure condition, i.e. to calculate the casing collapse safety factor by the ratio of the casing collapse pressure (Pc) under zero internal pressure condition to the prorated differential pressure [P_o – (1-2t/D)P_i]:

$$SF_{c2} = P_c / [P_o - (1 - 2t/D)\, P_i] \qquad (10)$$

These two calculations of casing collapse safety factor do not result in the same value, as clearly shown in the following Example 1, and thus a reasonable question arises: which calculation would be correct? In fact, none of them is correct, as they are both based on the definition of the external pressure equivalent (P_{ci}) of external pressure and internal pressure from the 2-dimensional casing half-ring hoop stress model, which does not correctly describe the casing collapse status under a 3-dimesional stresses status.

Example 1: 7" 29# (t = 0.408") L80 casing, P_c = 7020 psi, P_o = 10020 psi, P_i = 3000 psi, and axial compressive stress - 3000 psi. Calculate casing collapse safety factor by Eqs. 9 and 10.

σ_a = - 3000 psi

σ_{ye} = 80,000 psi (no reduction of casing material yield strength by Eq. 3, on casing axial compression)

P_c = 7020 psi (no reduction of casing collapse strength/collapse pressure, on casing axial compression)

$P_{ci} = P_c + (1 - 2t/D)P_i$ = 7020 + (1 – 2*0.408/7)*3000 = 9670 psi

$SF_{c1} = P_{ci} / P_o = 9670/10020 = 0.965$

$SF_{c2} = P_c / [P_o - (1 – 2t/D)P_i] = 7020 / [10020 – (1 – 2*0.408/7)*3000] = 0.953$

Based on an API work group study with a specially designed full-size casing collapse test with internal pressure inside casing, [4] API TR 5C3 2015 Addendum [3] was developed to make changes on casing collapse design in presence of internal pressure, by deleting the external pressure equivalent equation (Eq. 2), and adding the internal pressure (P_i) to the casing axial stress in calculating the casing material equivalent yield strength (σ_{ye}) in Eq. 4. With API TR 5C3 2015 Addendum, casing collapse safety factor in the presence of internal pressure is then calculated as the ratio of casing collapse pressure (Pc) under zero internal pressure condition to the differential pressure ($P_o – P_i$), which is considered as the casing collapse loading:

$$SF_c = P_c / (P_o - P_i) \qquad (11)$$

Example 2 (rework Example 1): 7” 29# (t = 0.408”) L80 casing, P_c = 7020 psi, P_i = 3000 psi, P_o = 10020 psi, and an axial compressive stress -3000 psi. Calculate casing collapse safety factor by API TR 5C3 2015 Addendum, using Eq. 11.

σ_a = - 3000 psi

σ_{ye} = 80,000 psi (no reduction of casing material yield strength by Eq. 4, on ($P_i + \sigma_a$) = < 0)

Pc = 7020 psi (no reduction of casing collapse strength/collapse pressure, on ($P_i + \sigma_a$) = < 0)

$SF_c = P_c / (P_o – P_i) = 7020/(10200 – 3000) = 1.00$

For the same casing pressures and axial compressive load in Example 1 and Example 2, the casing collapse safety factor (1.00) calculated in Example 2 by following API TR 5C3 2015 Addendum (using Eq. 11) is higher than those (0.953 or 0.965) calculated in Example 1 without API TR 5C3 2015 Addendum (using Eqs. 9 and 10). This indicates that API TR 5C3 2015 Addendum can help improve the casing collapse design in the presence of internal pressure, by resulting in a higher collapse safety factor. The higher casing collapse safety factor is simply achieved by the use of the differential pressure ($P_o – P_i$) as the casing collapse loading, rather than the larger prorated differential pressure [$P_o – (1-2t/D)P_i$].

The following tubular mechanic analysis on casing collapse in the presence of internal pressure will help understand and verify the changes on casing collapse design made by API TR 5C3 2015 Addendum, and confirm the differential pressure ($P_o – P_i$) as the casing collapse loading. From the 3-dimensional casing cylinder triaxial stresses model in Fig. 3, it shows that the external pressure and internal pressure on a casing segment at the “Original” case (a) can be converted into a differential pressure ($P_o – P_i$) acting outside of casing with zero internal pressure, with a “fictitious” axial tensile stress equal to the internal pressure (P_i), on the casing segment at the “Modeling result” case (c). This conversion is supported by the “equivalent” traxial stresses concept, as the “Original” case (a), the “Equivalent” case (b), and the “Modeling result” case (c) are all equivalent in terms of triaxial stresses status. The “Modeling result” case (c) is equivalent to the “Original” case (a), as the “Modeling result” case (c) is simply resulted from subtracting an “internal pressure” (P_i) around the casing segment at the “Original” case (a). This subtraction is actually subtracting an equal compressive principle stress of value P_i or adding an equal tensile principle stress of value P_i ($\Delta\sigma_1 = \Delta\sigma_2 = \Delta\sigma_3 = P_i$) in the casing segment, by a triaxial stresses analysis.

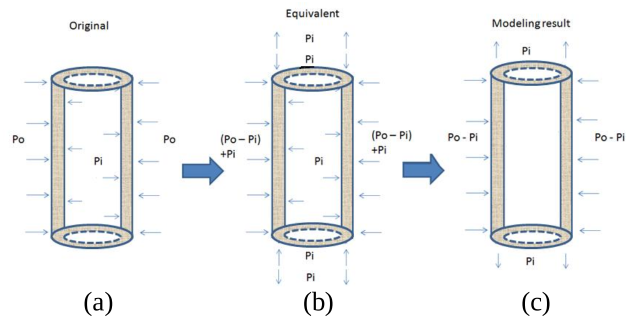


Fig. 3 3-dimensional casing cylinder triaxial stresses model (courtesy of SPE 166200-MS)[4]

Based on this equivalent conversion from “Original” case (a) to “Modeling result” case (c), it clearly confirms that the differential pressure ($P_o – P_i$) represents the casing collapse loading, when combining the external pressure and internal pressure together, with a “fictitious” axial tensile stress equal to the value of internal pressure (P_i) being added at the same time. It supports the changes made by API TR 5C3 2015 Addendum on deleting the equivalent external pressure equation (Eq. 2), as the differential pressure ($P_o – P_i$) is casing collapse loading, and adding the value of internal pressure to axial tensile stress in calculating casing material equivalent yield strength (σ_{ye}) in Eq. 4.

Casing Collapse Design Applications in the Presence of Internal Pressure

Casing collapse design in the presence of internal pressure is needed on some collapse load cases, where casing internal pressure is present or does not need to be set zero, to achieve an effective and safe design. Those casing collapse load cases include but not limited to the followings:

1. Cementing
2. Partial void (mud drop in drilling or packer fluid drop in production)
3. Deepwater WCD (worst case discharge)

By correctly following API TR 5C3 2015 Addendum, casing collapse design in the presence of internal pressure can be improved by achieving a higher casing collapse safety factor or allowing a lighter weight / lower grade of casing. This will help avoid an over-design on casing collapse in the presence of internal pressure. The following example of surface casing collapse design on cementing load case is used to further illustrate how to follow API 5C3 2015 Addendum to perform casing collapse design in the presence of internal pressure and what would be expected if not following API TR 5C3 2015 Addendum.

Example 3: 13 3/8" 54.5# (t = 0.38") J55 casing (P_c = 1130 psi) set to 2500 ft in a vertical on-land well, cement slurry density 16 ppg returning to surface, displacement fluid density 8.5 ppg, and a float collar at bottom of the casing. Perform casing collapse design for the cementing load case with a casing collapse design factor 1.15.

Calculate and plot the casing internal and external pressures and axial load for the cementing load case, as shown in Fig. 4:

Casing cross-section area = 3.14159/4*[(13.375^2) – (12.615^2)]

= 15.51 in.^{2}

Casing external pressure at surface = 0 psi,

Casing external pressure at bottom = 0.052*16*2500 = 2080 psi

Casing internal pressure at surface = 0 psi,

Casing internal pressure at bottom = 0.052*8.5*2500 = 1105 psi

Highest collapse loading ($P_o – P_i$) at bottom = 2080 – 1105

= 975 psi

Casing axial load at bottom = - 2080*3.14159/4*(13.375^2) + 1105*3.14159/4*(12.615^2) = - 154,130 lb (compressive)

Casing axial stress at bottom = - 154,130 / 15.51

= - 9935 psi (compressive)

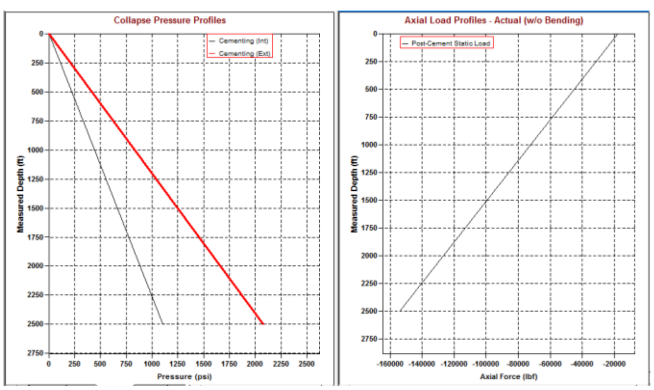


Fig. 4 Casing internal and external pressures and axial load on cementing (Example 3).

The highest casing collapse loading (max. differential pressure Po - Pi) is 975 psi at the bottom of casing for the cementing load case, as the external pressure is higher by the heavier density of cementing slurry and the internal pressure is lower by the lighter density of displacement fluid; and the casing axial stress corresponding to the highest casing collapse loading at the bottom of casing is a large compressive (negative) axial stress - 9935 psi.

The lowest casing collapse safety factor of the 13 3/8" surface casing for the cementing load case, corresponding to the highest casing collapse loading at the bottom of casing, is calculated as:

σ_a = - 9935 psi

$P_i + \sigma_a$ = 1105 - 9935 = - 8830 psi

σ_{ye} = 55,000 psi (no reduction of casing material equivalent yield strength, for ($P_i + \sigma_a$) < 0)

P_c = 1130 psi (no reduction of casing collapse pressure, for (P_i + σ_a) < 0)

SF_c = Pc / ($P_o – P_i$) = 1130 / (2080 - 1105) = 1.16 > 1.15

The 13 3/8" 54.5# (t = 0.38") J55 casing is therefore satisfactory to the casing collapse design safety factor requirement (collapse safety factor > = collapse design factor) for the cementing load case, as the calculated lowest collapse safety factor 1.16 is higher than the specified collapse design factor 1.15, with following API TR 5C3 2015 Addendum.

If the casing collapse design would be performed by not following API TR 5C3 2015 Addendum, the 13 3/8" 54.5# (t = 0.38") J55 casing would not be satisfactory to the casing collapse design factor requirement (collapse safety factor >= collapse design factor) for the cementing load case, as the calculated lowest collapse safety factor would be 1.04 or 1.09, lower than the specified collapse design factor 1.15, as shown below:

σ_a = - 9935 psi

σ_{ye} = 55,000 psi (no reduction of casing material equivalent yield strength, for (σ_a) < 0)

P_c = 1130 psi (no reduction of casing collapse pressure, for (σ_a) < 0)

$P_{ci} = P_c + (1 – 2t/D) P_i$ = 1130 + (1 –2*0.38/13.375)*1105
= 2172 psi

$SF_{c1} = P_{ci} / P_o$ = 2172 / 2080 = 1.04 < 1.15

$SF_{c2} = P_c / [P_o - (1 – 2t/D) P_i]$ = 1130 / [2080 – (1 – 2*0.38 / 13.375)*1105] = 1.09 < 1.15

A heavier weight (such as 61#) or higher grade (such as N80) would have to be used instead of the 13 3/8" 54.5# (t = 0.38") J55 casing, when not following API TR 5C3 2015 Addendum, in order to achieve a collapse safety factor larger or equal to the specified collapse design factor 1.15. That would be an over-design on casing collapse which would likely increase the casing cost and time/work to locate a heavier weight or higher grade of 13 3/8" casing if not presently available.

Conclusions

1. API TR 5C3 2015 Addendum made the change on casing collapse design in the presence of internal pressure (deleting the external pressure equivalent of external pressure and internal pressure, and adding internal pressure to casing axial stress in calculating casing material equivalent yield strength) and helps improve casing collapse design by resulting in a higher casing collapse safety factor;
2. The tubular mechanic analysis of casing collapse in the presence of internal pressure, with the equivalent conversion of external pressure and internal pressure into the differential pressure using the 3-dimensional casing cylinder triaxial stresses model, is presented to help understand and verify the change made by API TR 5C3 2015 Addendum;
3. The differential pressure (P_o – P_i) is confirmed as the collapse loading in the presence of internal pressure, through the tubular mechanic analysis using the 3-dimensional casing cylinder triaxial stresses model, and shall be used in casing collapse design to calculate the casing collapse safety factor;
4. The prorated differential pressure [P_o - (1 – 2t/D) P_i], based on the 2-dimentional hoop stress model which does not correctly describe the casing collapse status under a 3-dimesional stresses status, shall not be used in calculating casing collapse safety factor in the presence of internal pressure. Otherwise, an over-design on casing collapse (to use a heavier weight or higher grade of casing) would be expected.

Acknowledgments

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Nomenclature

D : *Casing outside diameter, in.*
P_c : *Casing collapse strength (collapse pressure), psi*
P_{ci} : *Casing external pressure equivalent, psi*
P_i : *Casing internal pressure, psi*
P_o : *Casing external pressure, psi*
P_p: *Casing plastic collapse pressure, psi*
SF_c : *Casing collapse safety factor*
SF_{c1} : *Casing collapse safety factor*
SF_{c2} : *Casing collapse safety factor*
t : *Casing nominal wall thickness, in.*
σ_a : *Casing axial stress, psi*
σ_y: *Casing material yield strength, psi*
σ_{ye}: *Casing material equivalent yield strength for collapse calculation, psi*
σ_θ : *Casing hoop stress, psi*

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