ANALYSIS OF THE RESIDUAL STRESS LEVEL IN CASING AND ITS INFLUENCE ON THE COLLAPSE STRENGTH

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1 INTRODUCTION

One of the phenomenons which can decisively affect the reliability of oil well casing is collapse under the effect of external hydrostatic pressure (leading to ovalisation followed by flattening of tubulars). The collapse mechanism differs essentially with the value of the ratio between the outside diameter, *D*, and the wall thickness, *t*, of casing:

- for greater values of this ratio ($D/t > 35$), collapse occurs by means of an elastic flattening, before the tube material reaches its yield strength; in case of elastic collapse of a perfect circular tube, the critical value of the external pressure (the elastic collapse pressure, p_E) can be calculated using the following equation [7]:

$$p_E = \frac{2E}{1-\nu^2} \cdot \frac{1}{D/t^{\,3}}, \tag{1.1}$$

where *E* is Young's elastic modulus, and ν Poisson's coefficient of the casing material;

- for smaller values of the *D*/*t* ratio (under 15...20), collapse will take place in the plastic field; in such case, if considering the thin-wall tubes theory, the critical value of the external pressure (the plastic collapse pressure, p_F) can be calculated as follows [3]:

$$p_F = 2\sigma_c \cdot t/D \tag{1.2}$$

where σ_c is the minimum specified yield strength (SMYS) of the casing material;

- for $D/t = 20...35$, the failure mechanism is much more complex (elastic-plastic collapse); a gradual passage from elastic failure to plastic failure will take place and different calculation methods, detailed in [2], have been proposed in such case by various researchers.

The collapse resistance capacity of casing is importantly affected by some factors, among which the level of residual stress, the pipe geometrical imperfections (mainly its initial ovality), and the pipe material anisotropy. The effect of these factors can be accounted for when assessing the critical value of the external pressure (the collapse pressure, p_c), whatever the failure mechanism, by using the following equation [3]:

$$p_c = k \cdot p_F = k_r \cdot k_\delta \, k_\xi \, p_F \tag{1.3}$$

where $k \leq 1$ is a reduction factor, considering the effect of residual stresses (by means of the coefficient k_r), of initial tube ovality (k_δ), and of initial tube eccentricity (k_ξ).

Residual stress is an important factor affecting the collapse strength of casing and therefore its effect has been studied in various papers [3, 5, 6, 8, 9]. Such stresses are a direct consequence of the operations performed during the manufacturing process of tubulars, mainly rolling, thermal treatment (quenching, normalizing, etc.) and straightening.

The effect of the residual stress level on the collapse pressure value can be assessed using the following equation, developed in [8], to calculate k_r coefficient (from eq. 1.3):

$$k_r = \begin{cases} 1 + 0{,}8\ \sigma_r/\sigma_c \quad \text{if} \quad \sigma_r < 0 \\ \dfrac{2\ \ 1 - 0{,}8 \cdot \sigma_r\ /\ \sigma_c}{1 + \ \ 1 - 2t\ /\ D^2} \quad \text{if} \quad \sigma_r > 0 \end{cases} \qquad (1.4)$$

where σ_r is the level of residual stresses at the inside wall of the tube. The first equation above applies in case yielding develops at the inside wall of the tube (compression at the inside), while the second one applies in case of yielding at the outside wall (traction at the inside).

The effect of a compressive stress ($\sigma_r < 0$) is to cause early yielding on the inside and thus a reduction of wall thickness, while a moderate level of traction stress ($\sigma_r > 0$) on the inside has a positive effect by reducing the value of collapse pressure, p_c.

In such context, the research activities described in this paper aimed to investigate the level of the residual circumferential stresses in seamless tubes for well casing and its variation across the tube thickness, and to evaluate – based on eq. 1.4 above – the influence of such stresses on the critical collapse pressure of casing.

2 DEVELOPMENT OF AN EXPERIMENTAL METHOD FOR THE EVALUATION OF THE RESIDUAL STRESSES IN TUBES FOR CASING

In order to properly determine the actual level of residual circumferential stresses in seamless tubes, an extended research activity has been performed to define the most adequate experimental method, simple, easy to apply, and also accurate.

After analysing various methods, we reached the conclusion that the most suited one for measuring residual stresses which do not vary circumferentially is the slit ring method, described in [4]. In this procedure, a ring with the height equal to h is cut from the tube (with the outside diameter D_e, the inside diameter D_i, and the wall thickness t) and then slit axially (fig. 1). The movement across the slit gives a measure of the residual stress; an opening of the ring indicates compressive stress on the inside wall ($\sigma_r < 0$). Various values have been proposed for the ring height, h, ranging between 51 mm (2 in) [9] and 10 mm [4].

In order to define the most adequate calculation method to assess the residual stress level, given the measured opening of the ring, Δa, or the variation of the outside diameter of the ring, several selected methods have been investigated. Their results were compared with the results of experimental tests performed to determine the actual stress level in the ring

– both at the inside and outside walls – by means of strain gauges, placed as per figure 1.

The first calculation method considered was proposed by Lari [4], based on the straight beams theory. This method, neglecting the effect of the axial force, *N*, and bending moment, *M*, developed in the slit zone (see fig. 2), recommends the following equation:

$$\sigma_r = 2{,}77 \cdot E \cdot t \cdot \frac{\Delta a}{\pi \cdot D^2}. \qquad (2.1)$$

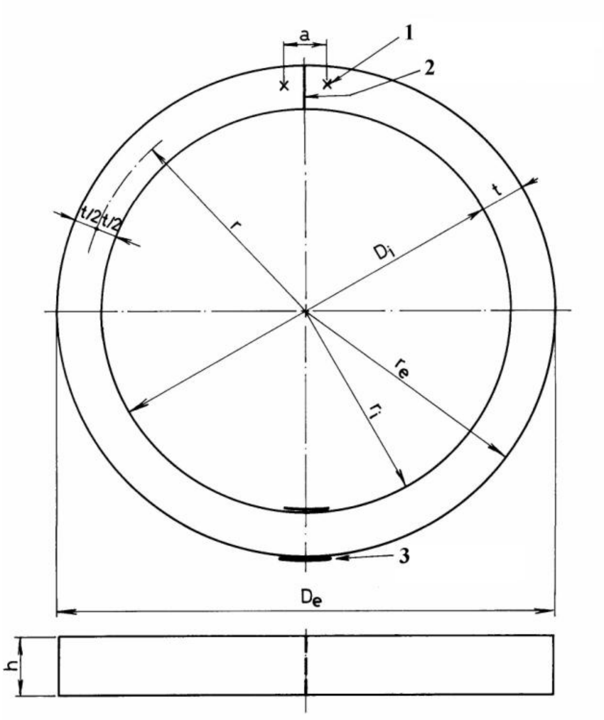

Figure 1 - Ring Specimen Geometry:
1 – marks on the ring; 2 – slit zone; 3 – strain gauges

The second method considered has been developed by the authors of the present paper using the slender beams theory. If considering the relative displacement, δ, and relative rotation, φ, between the two sides of the slit (fig. 2), the following equations can be written:

$$3\,\pi r^2 \cdot N + 2\,\pi r^2 \cdot M = E\,I'' \cdot \delta \quad ,$$
$$2\,\pi r^2 \cdot N + 2\,\pi r \cdot M = E\,I'' \cdot \varphi, \qquad (2.2)$$

where *r* is the average radius of the ring, and *I”* is the modified inertia moment, given by:

$$I'' = \frac{1}{\frac{1}{h \cdot t \cdot r^2} + \frac{1}{I'}},$$

$$I' = \frac{h \cdot t^3}{12}\left[1 - \frac{3}{20}\left(\frac{t}{r}\right)^2 + \frac{3}{112}\left(\frac{t}{r}\right)^4\right]. \tag{2.3}$$

The values of *N* and *M* will be determined by solving equations 2.2 above, given δ and φ – calculated based on accurate measures of distances *a* and *b* from figure 2. Then, the stress values at the gauges (see fig. 1), respectively at the outside and at the inside of the ring specimen, can be calculated as follows:

$$\sigma_{r,ext} = \frac{N}{h \cdot t} - \frac{M}{h \cdot t \cdot r} - \frac{M}{I'} \cdot \frac{t}{2} \cdot \frac{r}{r + 0.5 \cdot t},$$

$$\sigma_{r,\text{int}} = \frac{N}{h \cdot t} - \frac{M}{h \cdot t \cdot r} + \frac{M}{I'} \cdot \frac{t}{2} \cdot \frac{r}{r - 0.5 \cdot t}. \tag{2.4}$$

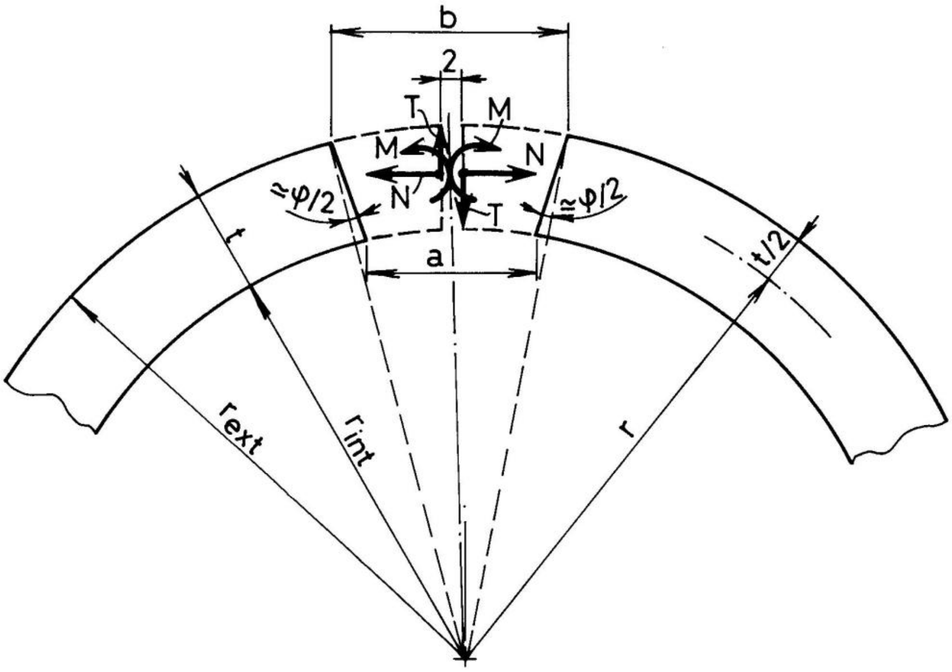

Figure 2 - Sectional Efforts in the Ring Specimen after Splitting

The method above has been applied firstly considering the calculated value for the relative rotation, φ, and then assuming $\varphi \equiv 0$, due to the fact that such rotation is mostly the effect of a radial displacement of the two sides of the slit and not the effect of residual stress.

The third method considered has been developed by NKK Corporation [6] and is based on the following equation, considering the variation of the outside diameter of the ring:

$$\sigma_r = \frac{E}{1-\nu^2} \cdot t \cdot \left(\frac{1}{D_o} - \frac{1}{D_1} \right), \qquad (2.5)$$

where D_o is the initial outside diameter, and D_1 is the outside diameter after sectioning, measured in a direction perpendicular to the one of the slit. If $D_1 > D_o$, the circumferential residual stress at the inside of the tube is compressive ($\sigma_r < 0$).

Equation 2.5 is a particular case of the equation developed by Sachs, based on the elasticity theory, in order to assess the residual stress inside the tube wall at a given distance, x, from the outside surface of the tube:

$$\sigma_r(x) = \frac{E}{1-\nu^2} \cdot (t-2x) \cdot \frac{D_1 - D_o}{D_1 \cdot D_o}. \qquad (2.6)$$

Finally, the calculation method proposed by Verner [9] which uses the equation below has also been considered:

$$\sigma_r = 0{,}889 \cdot \frac{\Delta a}{t} \cdot E \cdot \left(\frac{D}{t} - 1 \right)^{-2}. \qquad (2.7)$$

The characteristics of the five ring specimens used to determine the residual stress by means of strain gauges are summarised in Table 1, together with the test results. All specimens were cut from seamless tubes made of N80 steel (SMYS value – 552 MPa). Table 2 compares the residual stress values at the outside of the specimens, obtained as test results, with the ones calculated by using the four methods presented above.

Table 1 - Main Characteristics of the Ring Specimens and Measured Values

Ring No.	Effective Tube Outside Diameter	Effective Tube Wall Thickness	Measured Geometrical Characteristics (before and after slitting the ring)				Strain at Gauge
	D	t	D_o	D_1	δ	φ	ε
	mm	mm	mm	mm	mm	rad	μm/m
1	140.0	9.5	139.69	140.25	2.569	0.016	240
2	140.0	9.5	139.93	140.51	1.710	0.061	210
3	136.8	7.9	136.62	138.12	4.127	0.038	650
4	140.0	8.0	139.75	142.12	6.734	0.061	1050
5	140.0	8.7	139.87	140.14	1.030	0.014	140

Table 2 - Calculated and Experimental Values for the Circumferential Residual Stress at the Outside Wall of the Ring Specimens (in MPa)

Ring No.	Calculated with eq. 2.1	Calculated with eqs. 2.2-2.4		Calculated	Calculated	Test
		$\varphi \neq 0$	$\varphi \equiv 0$	with eq. 2.7	with eq. 2.5	Result
1	230.5	189.6	187.4	261.0	64.0	50.4
2	205.8	- 700.8	167.3	233.0	64.7	44.1
3	346.4	- 185.3	276.5	384.0	144.9	136.5
4	545.9	- 289.1	435.4	604.4	224.7	220.5
5	93.7	- 111.3	75.4	104.8	27.6	29.4

It can be concluded that the method proposed by NKK and based on eq. 2.5 is the most accurate as it gives values very close to the test results for all specimens investigated (see Table 2). This method has been used during all tests described in the next section.

Experimental studies have also been performed by using strain gauges to determine the influence of the height, *h*, of the ring specimens on the results of the residual stress assessment. After investigating ring specimens with various values of the height (h = 10, 20, 50 mm), cut from the same tube, no influence of *h* on the results has been observed.

3 TEST RESULTS FOR RESIDUAL STRESSES IN TUBES FOR CASING

The level of circumferential residual stress has been investigated using specimens cut from seamless tubes for casing with the nominal outside diameter D = 139,7 mm, made of N80 steel (SMYS = 552 MPa). Ten specimens have been tested using the method defined in the previous section: five specimens have been taken from tubes before being subject to the thermal treatment (normalizing), and five specimens have been taken from tubes after being normalized and straightened.

The results are reported in Table 3 for specimens cut before thermal treatment and in Table 4 for specimens normalized and straightened. In all cases, the residual stress values refer to the outside wall and were found to be positive; therefore, the residual stresses at the inside wall are compressive which has negative effects on the collapse resistance of casing.

Based on the test results reported, the medium (σ_{med}), maximum (σ_{max}), and minimum (σ_{min}) values of the residual circumferential stress have been calculated and are respectively:

- before thermal treatment: σ_{med} = 30.06 MPa; σ_{max} = 40.5 MPa; σ_{min} = 22.85 MPa;
- after normalizing and straightening: σ_{med} = 131.68 MPa; σ_{max} = 204.7 MPa; σ_{min} = 47.5 MPa.

Table 3 - Test Results for Tube Specimens before Thermal Treatment

Spec. No.	Ring No.	Measured Geometrical Characteristics (before and after slitting the ring)			Circumferential Residual Stress Values	
		Effective W.T., t	D_o	D_1	for each ring	Medium for specimen
		mm	mm	mm	MPa	MPa
I	1	8.5	140.73	141.02	29.34	33.16
	2		140.58	140.90	32.43	
	3		140.65	141.05	40.48	
	4		140.93	141.24	30.40	
II	5	8.7	140.71	141.05	34.39	29.73
	6		141.13	141.40	27.16	
	7		139.87	140.14	27.65	
III	8	8.7	141.21	141.56	35.15	29.18
	9		140.91	141.20	29.26	
	10		141.15	141.38	23.14	
IV	11	8.8	141.10	141.38	28.43	28.43
V	12	9.0	141.47	141.69	22.85	22.85

Table 4 - Test Results for Tube Specimens after Normalizing and Straightening

Spec. No.	Ring No.	Measured Geometrical Characteristics (before and after slitting the ring)			Circumferential Residual Stress Values	
		Effective W.T., t	D_o	D_1	for each ring	Medium for specimen
		mm	mm	mm	MPa	MPa
VI	13	8.5	140.67	142.27	156.82	181.73
	14		140.48	142.57	204.69	
	15		140.75	142.63	183.69	
VII	16	8.4	140.53	141.01	47.51	96.64
	17		140.75	142.46	167.28	
	18		140.48	141.66	116.31	
	19		140.82	141.39	55.44	
VIII	20	8.5	140.89	142.92	197.90	160.18
	21		140.80	142.81	196.08	
	22		140.78	141.66	86.55	
IX	23	8.2	140.94	141.78	79.48	79.48
X	24	8.5	140.58	141.75	88.46	88.46

It can be seen that the residual stress level is considerably greater (about 4.4 times on average) after normalizing and straightening. As a consequence, the residual stress in casing is mainly the effect of thermal treatment and straightening operations

In addition, for six specimens (three not subject to thermal treatment and three normalized and straightened), the variation of the residual circumferential stress across the tube thickness has been investigated. To that purpose, eight rings have been cut from each of these specimens and their thickness has been reduced with various values (between 1 and 4 mm) by machining four of them at the inside and the other four at the outside, as shown in figure 3. The value of the residual stress was obtained in each case by using eq. 2.5.

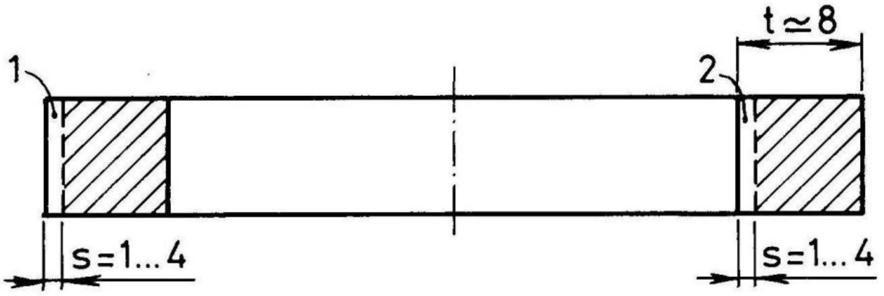

Figure 3 - Ring Specimen Used to Investigate Residual Stress Variation:
1, 2 – material stratum machined at the outside (1) or at the inside (2) of the specimen

The results of this investigation are summarised in figure 4 for the specimens not subject to thermal treatment and in figure 5 for specimens normalized and straightened.

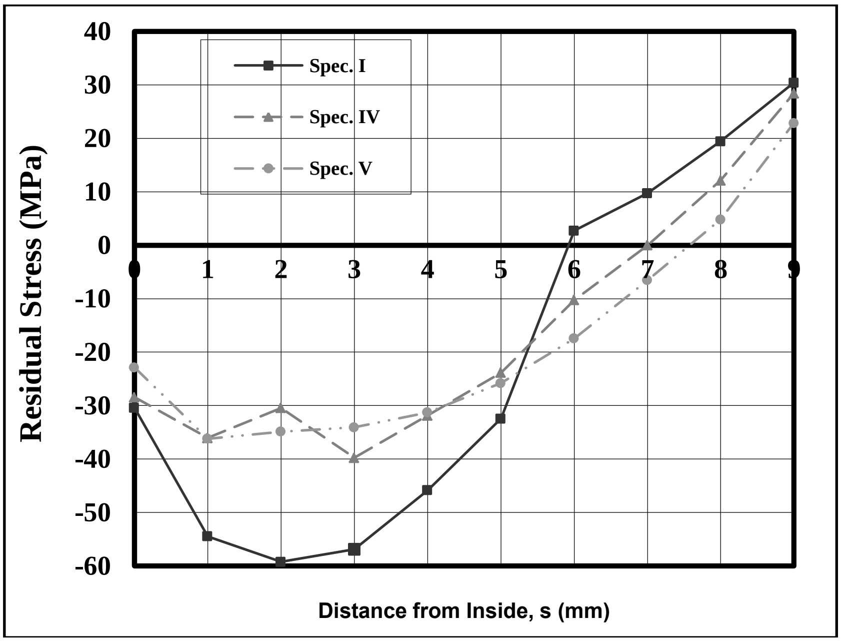

Figure 4 - Residual Stress Variation before Normalizing and Straightening

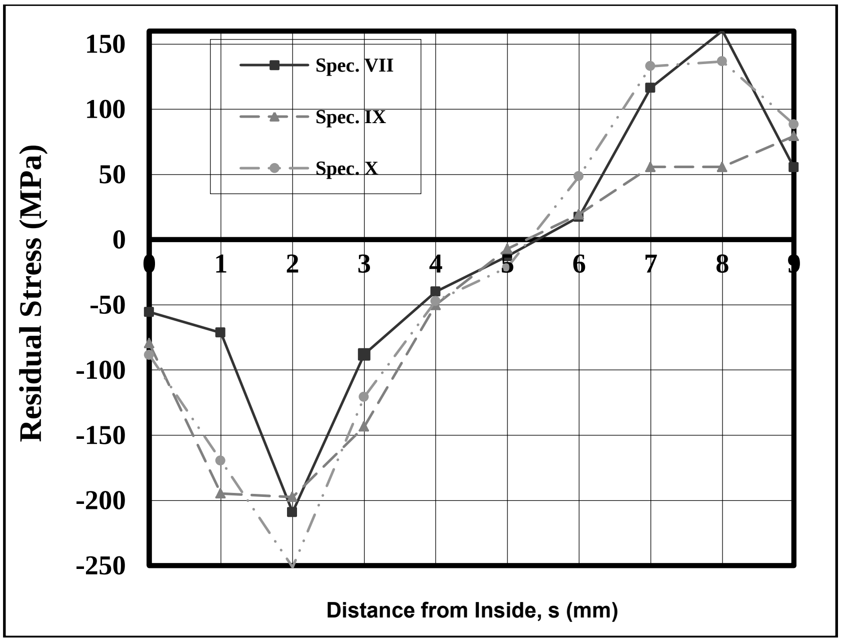

Figure 5 - Residual Stress Variation after Normalizing and Straightening

These results show that the residual stress values are not uniformly distributed across the tubes thickness, the maximum value being reached at about 2-3 mm from the inside wall. Such value corresponds to a compressive stress and is about 45 MPa for the specimens not subjected to thermal treatment and about 220 MPa for the specimens normalized and straightened. This last value is important, corresponding to about 40% of SMYS of the specimens' material.

Finally, an evaluation of the effect of the residual stress upon the value of the collapse pressure of casing was performed based on eq. 1.4 and the results of the test performed.

If considering the average value of the residual circumferential stress of casing (corresponding to specimens subjected to thermal treatment and straightening operations), i.e. 132 MPa (compression stress), eq. 1.4 shows a reduction with 17.3% of the collapse pressure value with respect to a tube without residual stresses. However, if the maximum value obtained during the tests performed is taken into account (250 MPa for specimen X – fig. 5) such reduction becomes important (about 33%).

4 CONCLUSIONS

– The experimental results described in this paper aimed at investigating the level of residual circumferential stresses in seamless tubes for well casing, its variation across the tube thickness, and its influence on the collapse resistance.

– The most adequate (simple, easy to apply, and accurate) method to determine the actual value of residual circumferential stresses in tubes for casing was found to be the slit ring method combined with NKK calculation method (eq. 2.5) for assessing the stress level at the inside wall.

– The test results showed for all specimens that the residual stress is positive (traction) at the outside wall of casing and negative (compression) at the inside, corresponding to the most unfavourable situation from the point of view of the collapse resistance.

– The residual stress values are about 4.4 times (on average) greater in tubes normalized and straightened with respect to the tubes not yet subjected to thermal treatment; therefore, the main source of these residual stresses in casing are the thermal treatment and the straightening operation.

– The residual stresses are not uniformly distributed across the tube thickness, the maximum value being a compressive stress reached at about 2-3 mm from the inside wall; such value is about 220 MPa (about 40% of SMYS of the specimens' material) for tubes normalized and straightened.

– The average value of the circumferential residual stress in casing after normalizing and straightening is about 132 MPa – corresponding to a reduction of about 17.3% of the collapse resistance – while the maximum value is about 250 MPa – corresponding to an important reduction of about 33% of such resistance.

ABSTRACT

The collapse resistance of casing is influenced by many factors, among which the level of residual stresses is an essential one. This paper presents the results of research activities aimed to determine such stress level in seamless tube specimens made of grade N80 steel.

These activities included: the selection – based on experimental and theoretical studies – of the most adequate method to determine the residual circumferential stresses in tubes for well casing; a series of experimental tests to define the level of such residual stresses and its variation across the tube thickness; finally, an evaluation of the influence of such stresses upon the value of the collapse pressure of casing.

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