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PIPELINE WALL THICKNESS/DESIGN PRESSURE FORMULATION GIE STUDY, SUPERB PROJECT AND ASME CODES COMPARISON

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ABSTRACT

Design criteria and equations for determining the line pipe wall thickness has been, in the past several years, one of the most important issues with oil and gas transportation companies. Published results of the experimental and analytical studies and safety records of the pipeline operating companies indicate that the present traditional design formulation is conservative and may be revised to reduce pipeline wall thickness safely.

The SUPERB Project was initiated in 1991 and supported by ten major oil and gas companies. A recently published guideline contains, in particular, some recommended design equations for wall thickness determination with a new value of safety (usage) factor using structural reliability and based on calibration methodology.

The goal of Gulf Interstate Engineering's (GIE) study is to develop an accurate, sound analytical solution for determination of the hoop stress due to internal pressure, considering distribution of the radial stresses across the wall and nonlinear property of pipe material. For design purposes we used an elastic, linearly hardening stress-strain diagram, which for this case, was more conservative than an actual stress-strain diagram. The application of a bilinear diagram allows to obtain analytical solution of hoop stress distribution relationship between pressure and strain in the diapason of strains up to the strain that produces yield strength.

More precise equations for determining hoop stress show that maximum hoop stress due to internal pressure is on the pipe external surface, opposite the Lame (linear) solution which gives maximum hoop stress on an internal surface. As well known, the bursting of pipe caused by the internal pressure begins from an external wall surface.

This paper compares reduction of nominal wall thickness using GIE and SUPERB methods to ASME codes for the pipe with the various diameter-to-wall thickness ratios and underthickness tolerances. The comparison shows that results obtained with two different methods are in good coincidence.

Therefore, traditional stress analyses based on performing more accurate calculation considering stress distribution across the wall, nonlinear property of steel, principal, methodology and existing codes design factors may safely reduce the required pipe wall thickness and may be used in the engineering design.

NOMENCLATURE

D = nominal outside diameter
E = longitudinal joint factor according to B31.8
E_o = modulus of elasticity
E_h = hardening modulus
F = design factor according to B31.8
F_g =guaranteed design factor
p = internal pressure
r_i = pipe inside radius
r_o = pipe outside radius
r = radius to any point of wall
S_h = hoop stress
S_{al} = allowable hoop stress
S_{yr} = yield stress
S_u = ultimate tensile stress
S_c = combined stress
T = temperature derating factor according to B31.8
t = nominal wall thickness
tol_g = guaranteed underthickness tolerance, %
tol_c = code specified underthickness tolerance, %
ϵ_c = combined strain
ϵ_{yr} = strain corresponding to yield stress
$\epsilon_{c,al}$ = allowable combined stress

ASME B31.8/B31.4 FORMULATION

Existing method of wall thickness or pressure calculation presented in Codes B31.8 and B31.4 are based on criteria of allowable hoop stress. The B31.8 Code states that "the maximum allowable hoop stress is the maximum hoop stress permitted by this Code for design of piping system."

The criteria for determining wall thickness/design pressure and equations for calculating hoop and allowable hoop stresses according to [1, 2] are

$$S_h \le S_{al}, \quad S_h = \frac{pD}{2t}, \quad S_{al} = S_{ys} FET \qquad (1)$$

The formula for hoop stress, known as the Barlow formula, is based on an assumption that radial and hoop stresses across the pipe wall are constant and on an assumption that section of the pipe is a ring with diameter equal to the nominal outside diameter instead of an annulus. The hoop force in a ring is defined from static condition of equilibrium and hoop stress is calculated for nominal pipe thickness. The underthickness tolerance is taken into account through a design factor. ASME B31.4 as well as B31.8 note that "in setting the values of a design factor, due consideration has been given and allowance has been made for various underthickness tolerances provided for in pipe specification listed and approved for usage in code."

SUPERB PROJECT

The SUPERB Project was initiated in 1991 and is supported by ten major oil and gas companies. An overview of the research programme SUPERB is presented in [3]. A recently published guideline [4] contains, in particular, recommended design equations for the wall thickness determination with a new value of safety (usage) factor, using structural reliability and based on calibration methodology.

The Barlow equation with a mean diameter in the numerator and minimum wall thickness in the denominator was selected to calculate the hoop stress in the design guideline [4].

The maximum permissible hoop stress depends on specific minimum yield stress and specific minimum ultimate tensile strength

$$S_h = \frac{p(D - t_{min})}{2t_{min}} \qquad S_h \le \min[\eta_y S_{ys}, \eta_u S_{ut}] \qquad (2)$$

The values for usage (safety) design factors for operating pipelines in midline zones are $\eta_y = 0.83$ and $\eta = 0.75$. The pipeline in the middle zones can be compared with the pipeline with a hoop stress design factor of 0.72 according to B31.8.

From equation (2) and values for usage (safety) design factors follows that if the yield to the ultimate stress ratio is not higher than 0.9 the design wall thickness depends on specific minimum yield stress.

It should be noted that SUPERB Project guideline also proposed other criterions, which are not a subject of this paper.

GIE STUDY

As distinguished from the above studies, which used Barlow's formula for hoop stress determination, the Lame's solution [5] is based on linear property of pipe material (linear relation between stress and strain) and considers the distribution of hoop and radial stresses across the wall. According to this solution the maximum hoop and combined stresses take place on the inner surface. It is well known that burst of the pipe caused by the internal pressure begins on the external surface of the pipe wall.

Therefore, the goal of GIE study is to develop an accurate analytical solution for determining the hoop stress considering distribution of the radial stresses across the wall and nonlinear property of pipe material.

An elastic, linearly hardening stress-strain diagram is being used in this study for design purposes. This diagram is simpler and more conservative than actual stress-strain, and may be described by following equations

$$S_c = E_o \epsilon_c \qquad if \;\; S_c \le S_p \qquad (3)$$

$$S_c = (1 - E_h/E_o) S_p + E_h \epsilon_c \qquad if \;\; S_p > S_c \ge S_{ys} \qquad (4)$$

The proposed equation for calculating hardening modulus is based on the assumptions that stress limit proportionality S_p is equal to 70% of yield strength and linear hardening lasts up to yield stress

$$E_h = 0.3 S_{ys} / (e_{ys} - 0.7 S_{ys} / E_o) \qquad (5)$$

In elastic range of stresses, the maximum hoop and combined stresses due to internal pressure take place in the internal surface [5]. With internal pressure being increased above the value, which produces combined stress on the inner surface of pipe equal to the proportional limit, the area of the wall nearest the inner surface is in plastic condition. We designate this area as r_p.

The following equations, based on the above-described model of steel and on method described in [6], allow determination of:

- internal pressure that produces plastic area between r_i and r_p

$$p = (1 - k)\frac{S_p}{2}\ln\frac{r_p^2}{r_i^2} + \frac{S_p}{2}[k(\frac{r_p^2}{r_i^2} - 1) + 1 - \frac{r_p^2}{r_o^2}] \qquad (6)$$

- hoop stress distribution across the wall when plastic zone radius reaches outside radius

$$S_h = (1 - k)S_p(1 + \ln\frac{r}{r_o}) + k\frac{S_p}{2}(1 + \frac{r_o^2}{r^2}) \qquad (7)$$

Where $k = E_h / E_o$ = ratio of hardening to elastic moduli.

Figure 1 shows the value of pressure versus plastic zone radius according to the equation (6). Figure 2 represents hoop stress distribution due to internal pressure, which is function of a plastic zone radius. The lower line represents the solution for case, when plastic zone radius is equal to an inside radius, i.e., an elastic, a linear solution. The upper line represents the solution for case, when the plastic zone radius is equal to an outside radius, i.e., plastic solution. For the linear model of steel the maximum hoop stress is on an inner surface of pipe. For the plastic model of steel the maximum hoop stress is on an external surface. The latter solution is in qualitative agreement with the experiments, which show that bursting of pipe from the internal pressure starts on the external surface of the pipe wall.

According to [1] the maximum allowable hoop stress is the maximum hoop stress permitted by the Code for design of piping system. To comply with the Code requirements, the allowable design pressure versus allowable hoop stress may be calculated as

$$p_{des} = \frac{S_{al}}{2}[(1-k)\ln\frac{D^2}{(D-2t)^2} + k(\frac{D^2}{(D-2t)^2} - 1)] \qquad (8)$$

The equation (8) takes into account the distribution of stress across the pipe wall, nonlinear property of pipe steel, and main principal and methodology of the codes. This method, which considers nonlinear property of pipe material, is closer to the limit state design concepts than the traditional method.

Assume that the hardening modulus is equal to zero, i.e., nonlinear property of steel is described by elastic, idealized plastic stress-strain diagram, known as Prandtl diagram. Then, the equation (8) for the case $k = 0$ is in qualitative agreement with equation (35a) paragraph K304.1.2 of ASME B31.3 [7], which is used for designing wall thickness of straight pipe under high internal pressure, and second equation paragraph AD-201 of ASME Section VIII, Division 2 [8], which is used for designing wall thickness of cylindrical shells.

Some remarks to the hoop stress design factor F, established by ASME Codes. This factor is a complicated parameter that considers dimensional tolerance, variables of properties, failure statistic of pipelines, probability, reliability, cost of rehabilitation, and public safety. Therefore, our next study relates to the hoop stress design factor considering only underthickness tolerance. This tolerance may be less than Code specified. If guaranteed underthickness tolerance is less than the codes specify, the design factor may be increased and the guaranteed design factor can be calculated by equation

$$F_g = F\frac{1 + tol_g/100}{1 + tol_c/100} \qquad (9)$$

Equation (9) is represented by Figure 3.

By using the value of F_g calculated in equation (9), to determine the allowable stress by last formula in equation (1), the equation (8) allows determining design pressure or design wall thickness based on criteria of allowable hoop stress.

<u>**The method to use allowable strains criteria is being proposed.**</u>

When plastic zone radius reaches outside radius, the maximum combined strain is on an internal surface and the value of combined strain for this pressure is equal to

$$\epsilon_{c,max} = \frac{S_p}{E_o}\frac{r_o^2}{r_i^2} \qquad (10)$$

If allowable combined strain is less or equal to maximum combined strain, calculated by equation (10), then the plastic zone radius is determined by equation

$$r_p^2 = \frac{\epsilon_{c,al}}{S_p/E_o} r_i^2 \qquad (11)$$

Substituting this value in equation (6) the allowable design pressure versus allowable combined strain may be found.

If allowable combined strain is more than maximum combined strain calculated by equation (10), then it is possible to increase the pipeline internal pressure above the value, calculated by equation (8), to the value that produce combined strain on the inner surface equal to allowable. Then combined strain distribution will be

$$\epsilon_c = \epsilon_{c,al}\frac{r_i^2}{r^2} \qquad (12)$$

Considering equation (12), equation (4) may be rewritten as

$$S_c = (1-k)S_p + E_h\epsilon_{c,al}\frac{r_i^2}{r^2} \qquad (13)$$

Substituting equation (13), as Tresca combined stress, in static condition of equilibrium [6] the differential equation is obtained. The solution of this equation, considering boundary condition, is distribution across the wall of radial and hoop stresses. Then, the allowable pressure corresponding to allowable strain is

$$p_{al} = (1-k)\frac{S_p}{2}\ln\frac{r_o^2}{r_i^2} + \frac{E_h}{2}\epsilon_{c,al}(1 - \frac{r_i^2}{r_o^2}) \qquad (14)$$

It should be noted that according to our definition of hardening modulus (equation 5), this solution is correct only for allowable strain up to the strain required to produce yield strength (0.5% for API 5L)

Figure 4 presents allowable pressure versus allowable combined strain (total and plastic) according to equations (11), (6) and (14). Last point on these curves is pressure that produces plastic combined strain equal to 0.1%.

The presented example assumes 28" diameter, 0.375" wall thickness, and steel grade X-70 pipe. The calculations show that the allowable plastic combined strain equal to 0.1% allows to increase allowable pressure by 11% compared with the pressure, that produce hoop stress equal to allowable hoop stress established by Codes [1,2] for the pipeline with design factor equal to 0.72.

Establishing the value of allowable strain due to pressure is a very complicated task. The additional criteria of allowable strain will be important and timely when steel grade X-80 and higher strength pipe is used.

COMPARISON

The results of calculations according to the GIE study and the SUPERB Project [4] were compared with equations in B31.8 and B31.4 codes.

A design factor of 0.72 was assumed for calculations using ASME codes and GIE proposed equations. The usage (safety) design factor of 0.83 for yield criteria, which corresponds to ASME Code conditions, was used in SUPERB Project equations. Both GIE and SUPERB studies propose to use the underthickness tolerance guaranteed by manufacturers, instead of Codes specified tolerance, for wall thickness calculations.

The following tables present a comparison of the SUPERB and GIE methods with pressure and wall thickness calculated by B31.8. Tolerance of -8% means the guaranteed tolerance for a pipe diameter not larger than 20" (Codes specified tolerance is -12.5%). Tolerance -12.5% means that guaranteed and specified tolerances are equal.

Table 1. The percent increase of the design pressure using SUPERB and GIE equations compared with B31.8

Tolerance $(t_{min}-t)/t$	$D/t = 20$		$D/t = 30$		$D/t = 40$		$D/t = 50$		$D/t = 60$	
	SUP	GIE	SUP	GIE	SUP	GIE	SUP	GIE	SUP	GIE
- 8%	11.2	13.7	9.4	10.6	8.6	9.2	8.0	8.3	7.7	7.8
- 12.5%	5.5	8.1	3.9	5.2	3.1	3.9	2.7	3.0	2.4	2.5

Table 2. The percent reduction of the nominal wall thickness using SUPERB and GIE equations compared with B31.8

Tolerance $(t_{min}-t)/t$	$D/t = 20$		$D/t = 30$		$D/t = 40$		$D/t = 50$		$D/t = 60$	
	SUP	GIE	SUP	GIE	SUP	GIE	SUP	GIE	SUP	GIE
- 8%	-9.6	-11.2	-8.4	-9.1	-7.7	-8.1	-7.3	-7.5	-7.1	-7.1
- 12.5%	-5.0	-7.0	-3.7	-4.7	-3.0	-3.6	-2.6	-2.9	-2.3	-2.4

It should be noted that the reduction in wall thickness is calculated relatively to nominal wall thickness, instead of minimum wall thickness, as in Table 6 [4].

Figures 5 and 6 present graphic results of Tables 1 and 2. The comparison shows that results obtained with two different methods are in good coincidence.

The SUPERB Project guideline also includes the hoop stress criteria for ultimate check. The allowable hoop stress for midline zones is equal to 75% of ultimate tensile strength. The allowable pressure for SUPERB Project ultimate strength requirements will be 1693 psig, when calculated for pipe 28" diameter, 0.375" wall thickness and steel grade X-70.

According to GIE model of steel, stress-strain diagram, described by equations (3) and (4), for stress equal to 75% of ultimate tensile strength the combined strain will be 0.369%. Then, for this value of strain the allowable pressure according equation (14) will be 1652 psig for the same pipe. The difference is only approximately 2.5%.

CONCLUSION

The GIE study for determining the hoop stress considers not only distribution of hoop and radial stresses across the wall, but also considers nonlinear property of pipe steel. The method allows more accurate, than existing code equation,.determination of maximum hoop stress due internal pressure. This may result in an increase of design pressure or reduction of the wall thickness up to 9%, depending on steel grade and internal pressure.

The GIE study also includes possible reduction of wall thickness when manufacturer's underthickness tolerance is guaranteed less than Codes specified.

The subject GIE method applies basic principal and methodology of ASME B31.4 and B31.8 codes for allowable hoop stress and, therefore after industry approval, may be used in design practice.

Comparison of the GIE and SUPERB methods shows that results are in good coincidence, and therefore the traditional method may serve as a basis to modify Codes B31.8 and B31.4 wall thickness/pressure formulation.

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7. ASME B31.3, "Chemical Plant and Petroleum Refinery Piping."
8. ASME, Boiler and Pressure Vessel Code, Section VIII, Division 2, Part AD, "Design Requirements."

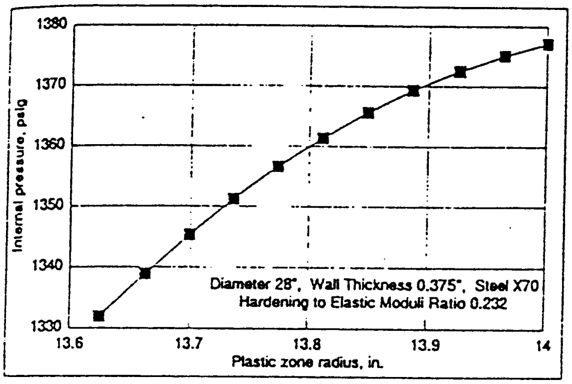

Figure 1 - Pressure Vs. Plastic Zone Radius
Elastic, Linearly Hardening Model

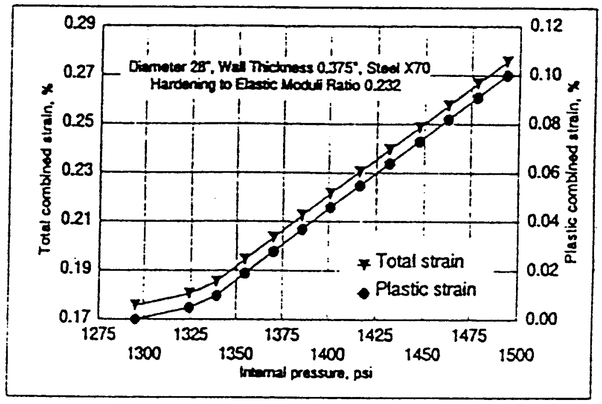

Figure 4 - Combined Strain Vs. Internal Pressure

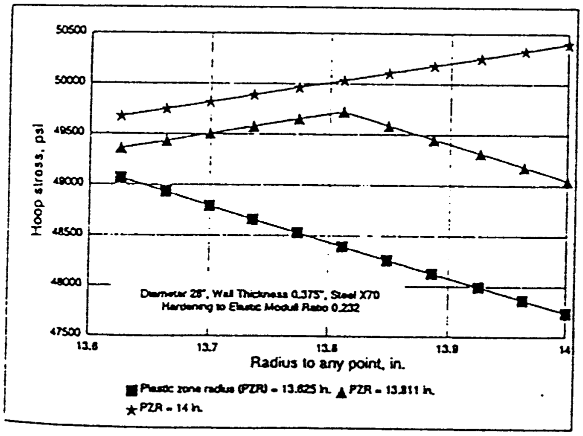

Figure 2 - Hoop Stress Distribution
Elastic, Linearly Hardening Model

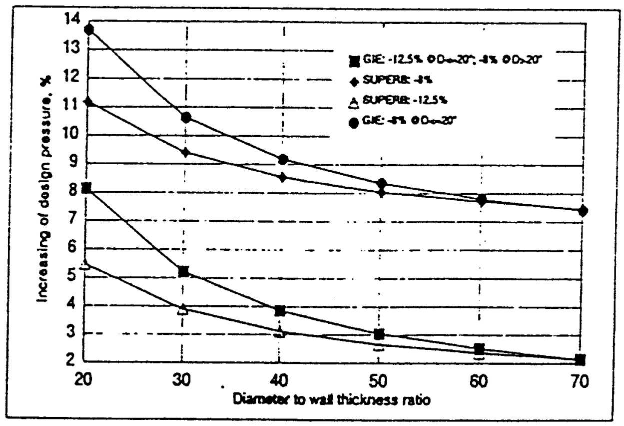

Figure 5 - Comparision of New Formulations to B31.8

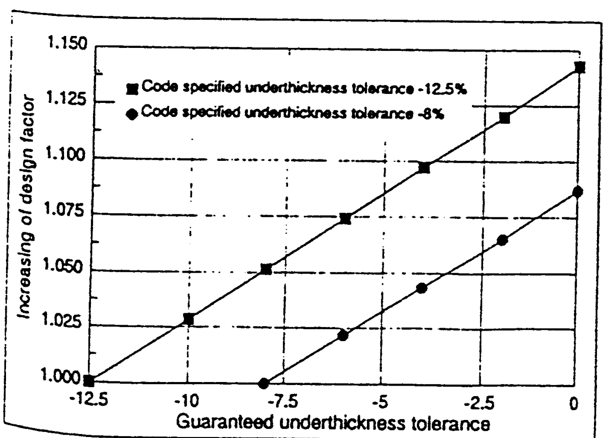

Figure 3 - Design Factor Vs. Underthickness Tolerance

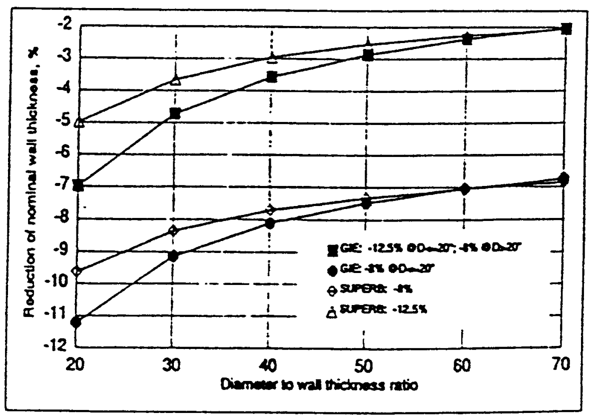

Figure 6 - Comparision of New Formulations to B31.8