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# Creep of Thick-Walled Cylinders Based on Torsion Creep Data for 0.18 Percent Carbon Steel at 400° C

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## ABSTRACT

The possible advantages of using torsion creep data in preference to constant load tension creep data in the analysis of cylinders creeping under a constant internal pressure are considered. Presented is a résumé of the various theories that have been proposed including a modified Bailey solution that allows for wall thinning.

Experimental creep data for torsion, constant load tension, and pressure tests on thick-walled cylinders are presented. The various theories proposed have been computed, and the theoretical curves are compared with the experimental data.

It is concluded that torsion creep data are of a more fundamental nature than constant load tension data where the stress is varying. From the observation that axial creep in cylinders is negligibly small, it is concluded that shear creep data is of greater relevance in cylinder analysis than constant load tension creep data. It is also concluded that for the magnitude of creep strains involved in this experimental work due account must be taken of the effect of wall thinning of a thick-walled cylinder subjected to creep. The most consistent agreement between theory and experiment was obtained using isochronous shear stress-strain data.

## NOMENCLATURE

| | |
|---|---|
| $\sigma_\theta, \sigma_r, \sigma_z$ | circumferential, radial, and axial stresses |
| $\sigma_r', \sigma_\theta', \sigma_z'$ | circumferential, radial, and axial stress deviations |
| $\epsilon_\theta, \epsilon_r, \epsilon_z$ | corresponding strains |
| $\dot\epsilon_\theta, \dot\epsilon_r, \dot\epsilon_z$ | corresponding strain rates |
| $\tau$ | shear stress |
| $\gamma$ | shear strain |
| $p$ | internal pressure |
| $t$ | time |
| B | material constant |
| $n$ | stress index |
| $m$ | time index |
| $J_2$ | second stress invariant $\left(= \frac{1}{6}\left\{\Sigma(\sigma_1 - \sigma_2)^2\right\}\right)$ |
| $r$ | radius |
| $a$ | initial inside radius |
| $b$ | initial outside radius |
| $K$ | diameter ratio $(= b/a)$ |
| $E$ | Young's modulus |
| $\mu$ | Poisson's ratio |

## INTRODUCTION

There is a considerable amount of evidence to support the use of torsion creep data in preference to the conventional constant load tension creep data for the creep design of thick-walled closed-ended cylinders containing high internal pressures. Most theoretical investigations to date have used tension data, but the authors have shown [1] that there is a considerable error involved with this form of data even at quite moderate strains due to the increase of stress that accompanies the changing cross-sectional area of the test specimens. In the same paper, they have also discussed the experimental advantages and disadvantages in torsion creep testing over tension creep testing.

Under plastic or creep conditions the state of stress in the walls of a thick-walled cylinder, subjected to internal pressure, is one of a pure shear stress with a superimposed hydrostatic stress. Experimental evidence of this is that the axial strain in such a vessel, if not zero, is certainly of negligible magnitude compared with the circumferential strain. Figure 1 shows a scouting creep test that has been carried out on an EN 25 steel cylinder with a test pressure of 26 ton-ft/in.$^2$ at 350° and it is seen that the axial strain is of a negligible proportion. Consequently, if the hydrostatic stress has no significant effect on creep, as seems probable, then pure shear stress data can be applied directly to the design of cylinders. If constant load tension creep data are used, it is necessary to derive constant stress creep data. One is immediately faced with the problem of deciding upon an effective stress criterion instrumental in causing creep, in order to correlate the uniaxial data with the complex stress system in a thick-walled cylinder, e.g., von Mises or Tresca criteria.

The object of this paper is to report torsion, constant load tension, and cylinder creep data obtained for a 0.18 percent C steel at 400°C and to attempt to correlate the experimental cylinder data with the torsion creep data using various theoretical approaches. For comparison purposes, the cylinder data will also be correlated with the tension data using the Bailey theory described later.

## THEORETICAL ANALYSES

This section deals with the various theories that the authors have to date used for the prediction of creep in thick-walled cylinders.

The three principal deviatoric stresses in a cylinder wall are

$$\sigma'_\theta = \sigma_\theta - \left(\frac{\sigma_\theta + \sigma_r + \sigma_z}{3}\right)$$

$$\sigma'_r = \sigma_r - \left(\frac{\sigma_\theta + \sigma_r + \sigma_z}{3}\right) \tag{1}$$

$$\sigma'_z = \sigma_z - \left(\frac{\sigma_\theta + \sigma_r + \sigma_z}{3}\right)$$

On the assumption of zero axial strain, then the axial deviatoric stress is zero:

$$\sigma'_z = \sigma_z - \left(\frac{\sigma_\theta + \sigma_r + \sigma_z}{3}\right) = 0$$

Thus,

$$\sigma_z = \frac{\sigma_\theta + \sigma_r}{2} \tag{2}$$

Substituting this into Eqs. (1) gives

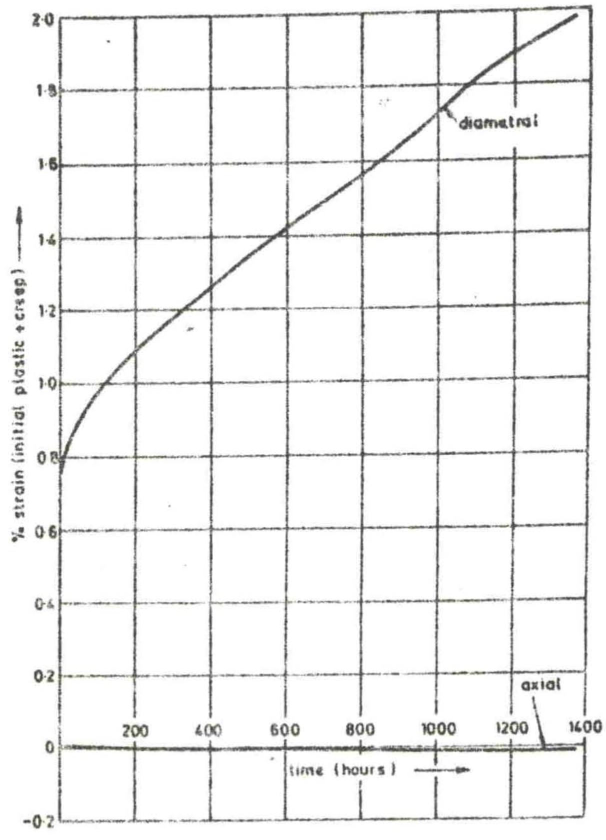


FIG. 1 PRESSURE CREEP TEST ON EN 25 STEEL CYLINDER (K=1.67), TEST PRESSURE 26 tonf/in$^2$, TEST TEMPERATURE 350°C

$$\sigma'_\theta = \frac{\sigma_\theta - \sigma_r}{2} = \tau \qquad (3)$$

$$\sigma'_r = -\frac{\sigma_\theta - \sigma_r}{2} = -\tau$$

Thus, the equivalent shear stress in a thick-walled cylinder is given by $\tau = (\sigma_\theta - \sigma_r)/2$.

To analyze the unsteady creep behavior of a thick-walled cylinder, three independent conditions must be satisfied throughout the cylinder wall.

(1) Equilibrium of Forces

*Radial equilibrium as defined by Lamé's equation:*

$$\sigma_\theta - \sigma_r = r\,\frac{d\sigma_r}{dr} \qquad (4)$$

*Axial equilibrium:*

$$\int_a^b 2\pi r\sigma_z dr = \pi p a^2$$

However, if zero axial creep is assumed, it is easy to show that if Lamé's equation is satisfied then axial equilibrium is automatically satisfied.

(2) Compatibility of strains

$$\epsilon_r - \epsilon_\theta = r\,\frac{d\epsilon_\theta}{dr} \qquad (5)$$

(3) Stress-Strain-Time Relationship for Material

## THE BAILEY THEORY

In 1951, Bailey [2] produced a theory for the primary creep behavior of thick-walled cylinders under internal pressure. In this he neglected elastic strains and assumed zero axial creep; he also ignored wall thinning. Consequently, the Bailey theory predicts a stress distribution that is constant with respect to time. The expressions used for the creep strain rates in the tangential, radial, and axial directions are of the following form:

$$\dot{\epsilon}_\theta = F(J_2)\,\sigma'_\theta\, t^{m-1}$$

$$\dot{\epsilon}_r = F(J_2)\,\sigma'_r\, t^{m-1} \qquad (6)$$

$$\dot{\epsilon}_z = F(J_2)\,\sigma'_z\, t^{m-1} = 0$$

where $F(J_2)$ is a simple power function of the second stress invariant $J_2$.

If, however, torsion creep data is used that can be represented by an expression of the form

$$\gamma = B\tau^n t^m \qquad (7)$$

then Eqs. (6) are not necessary and the Bailey theory becomes much simpler, with the conditions to be satisfied being

$$\sigma_\theta - \sigma_r = 2\tau = r\,\frac{d\sigma_r}{dr}$$

$$\epsilon_\theta - \epsilon_r = \gamma = -r\,\frac{d\gamma}{dr} \qquad (8)$$

$$\gamma = B\tau^n t^m$$

Combination of Eqs. (8) leads to the following expression for the equivalent shear stress at any radius r, viz.

$$\tau = \frac{p}{n(K^{2/n} - 1)}\,\frac{(b)^{2/n}}{(r)} \qquad (9)$$

and the shear strain

$$\gamma = B\left\{\frac{p}{n(K^{2/n}-1)}\right\}^n \frac{(b)^2}{(r)}\, t^m$$

from which the circumferential strain at the outside diameter is

$$\epsilon_{\theta_b} = \gamma_{b/2} = \frac{B}{2}\left[\frac{p}{n(K^{2/n}-1)}\right]^n t^m \qquad (10)$$

## THEORY OF JOHNSON, HENDERSON, AND KHAN

This theory [3] takes into account the effect of elastic strains in the creep of a thick-walled cylinder, and the general expression for the strains is of the form

$$\dot{\epsilon}_\theta = F(J_2)\,\sigma'_\theta\, t^{m-1} + \frac{1}{E}\,\frac{d}{dt}\,\sigma_\theta - \mu(\sigma_r + \sigma_z) \qquad (11)$$

Use of these expressions gives a stress system that is changing with time. However, Larke and Parker [4] have shown that even with this basic difference the strains at the outside surface and the bore as predicted by Bailey and Johnson et al. are identical. Hence, if one is interested purely in strains, there is no need to get involved with the much more complex mathematical theory of Johnson et al.

## MEAN-DIAMETER THEORY

An elementary way of estimating the creep strain occurring in a thick-walled cylinder is to treat it as being thin-walled and to calculate the equivalent shear stress at the mean diameter. This is essentially the same approach as that of Soderberg [5], except that he considered only steady-state or secondary creep and used tension creep data.

The shear stress in a thin-walled cylinder is given by

$$\tau = \frac{p(a+b)}{4(b-a)} = \frac{p}{4}\left(\frac{K+1}{K-1}\right) \tag{12}$$

The shear strain $\gamma$ in a thin cylinder is half the circumferential strain, and thus, if a single torsion creep test is run at a shear stress given by Eq. (12), the circumferential creep strain at the mean diameter of a thick-walled cylinder will be given approximately by

$$\epsilon_{\theta_m} = \gamma/2 \tag{13}$$

Assuming constancy of volume and zero axial creep, the strain at the outside surface is, therefore,

$$\epsilon_{\theta_b} = \frac{\epsilon_{\theta_m}}{\left(1+\dfrac{b-a}{a+b}\right)^2} = \frac{\epsilon_{\theta_m}(K+1)^2}{4} \tag{14}$$

Clearly, this theory is a gross oversimplification of the problem. However, Coffin et al. [6] have shown that there is a radius in the cylinder wall where the effective stress or the second stress invariant $J_2$ remains sensibly constant, and this has been proposed independently by Marriott and Leckie [7]. Consequently, a single creep test such as this effective stress should be adequate to predict the creep of a thick-walled vessel. The mean-diameter formula might consequently be expected to give results of the right order of magnitude; if so, it could provide a simple rule for the use of designers.

## STRAIN-HARDENING METHOD ALLOWING FOR EFFECT OF WALL THINNING ON CREEP OF THICK-WALLED CYLINDER

The theories examined earlier have ignored the effect of wall thinning on the creep behavior of a thick-walled cylinder. For bore strains as small as 1 percent in a cylinder of diameter ratio 2, this effect can be considerable. In this section the simple Bailey theory is adapted, using a strain-hardening method to allow for these changes in dimensions.

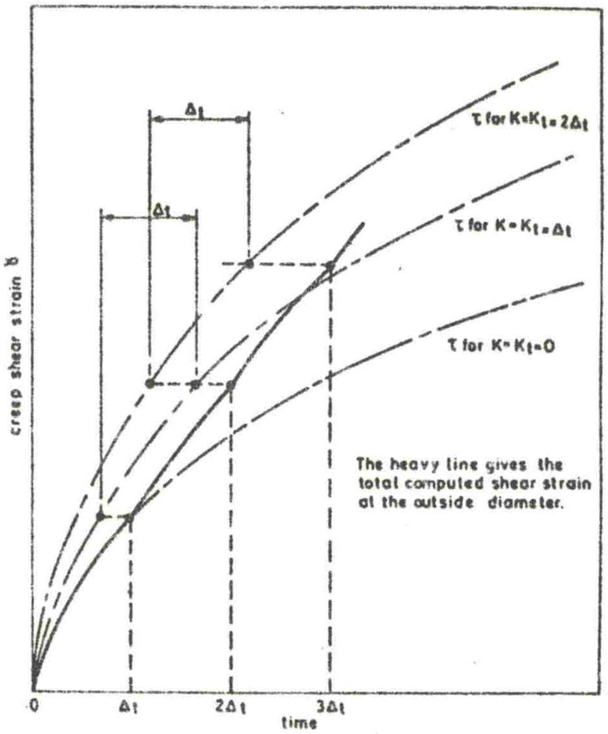


FIG. 2 EXAGGERATED DIAGRAM TO ILLUSTRATE STRAIN-HARDENING METHOD USED TO PREDICT CREEP OF THICK-WALLED CYLINDER

Considering a cylinder with diameter ratio $K' = (b'/a')$, the shear stress at the outer surface is from Eq. (9)

$$\tau = \frac{p}{n\left[(K')^{2/n} - 1\right]} \tag{15}$$

where the dash refers to current dimensions as opposed to original dimensions. Clearly, as the cylinder expands due to creep, because the bore material is strained very much more than the material at the outside surface, the diameter ratio will be gradually reduced. Equation (15), therefore, predicts a continual increase of shear stress at the outer diameter. The technique employed to deal with this varying stress is to consider it as remaining constant for small intervals of time and then increasing stepwise to a new value at the end of each interval. Reference to Fig. 2 will explain the procedure used to predict the creep strain occurring in the cylinder.

For greater accuracy, when there is considerable initial plastic deformation, as in the present experimental work, it is necessary to start at zero time with the actual dimensions of the cylinder immediately after pressurization. The initial dimensions can be found by the method, based on torsion data, suggested by Manning [6] or later by Crossland [8], which is described in the following section. Hence, the shear stress at the outer surface for the first interval of time $\Delta t$ is

$$\tau_1 = \frac{p}{n\left(K_{t=o}^{2/n} - 1\right)} \tag{16}$$

If it is assumed that any constant shear stress creep curve can be represented by an expression of the form of Eq. (7), then the increment of creep shear strain at the outer surface of the cylinder for a stress $\tau_1$, acting for time, $\Delta t$ is

$$\Delta\gamma_{b_1} = B\,\tau_1{}^n(\Delta t)^m \tag{17}$$

After this interval the new dimensions of the cylinder are calculated. Assuming $\Delta\gamma_{b_1}$ to be small (this can be assumed by making the time increment small enough) then the increment of circumferential strain at the outer surface is

$$\Delta\epsilon_{\theta_{b_1}} = \Delta\gamma_{b_1} \tag{18}$$

Also, for constancy of volume with zero axial creep, the relationship between the strain at the bore and the outer diameter is

$$\Delta\epsilon_{\theta_{a_1}} = K_{t=o}^2\,(\Delta\epsilon_{\theta_{b_1}}) \tag{19}$$

Therefore,

$$b_{t=\Delta t} = b_{t=o}\left(1 + \Delta\epsilon_{\theta_{b_1}}\right)$$

$$a_{t=\Delta t} = a_{t=o}\left[1 + K_{t=o}^2\,(\Delta\epsilon_{\theta_{b_1}})\right] \tag{20}$$

Hence,

$$K_{t=\Delta t} = \frac{(b)}{(a)}_{t=\Delta t} \tag{21}$$

This new value of diameter ratio gives the shear stress $\tau_2$, which is considered constant for the next interval of time. To apply the strain-hardening theory, the time at which a creep test run at a shear stress of $\tau_2$ attains a shear strain of $\Delta\gamma_{b_1}$ must now be evaluated from Eq. (7), and this is equal to $(\Delta\gamma_{b_1}/B\tau_2{}^n)^{\frac{1}{m}}$. The additional creep strain occurring over the next interval $\Delta t$ is thus

$$\Delta\gamma_{b_2} = B\tau_2^n\left\{\left[\frac{(\Delta\gamma_{b_1})}{(B\tau_2{}^n)}\right]^{\frac{1}{m}} + \Delta t\right\}^m - \Delta\gamma_{b_1} \tag{22}$$

and the new dimensions are accordingly

$$b_{t=2\Delta t} = b_{\Delta t}\left(1 + \frac{\Delta\gamma_{b_2}}{2}\right)$$

$$a_{t=2\Delta t} = a_{\Delta t}\left[1 + K_{t=\Delta t}^2\left(\frac{\Delta\gamma_{b_2}}{2}\right)\right] \tag{23}$$

hence,

$$K_{t=2\Delta t} = \frac{(b)}{(a)}_{t=2\Delta t} \tag{24}$$

The shear stress $\tau_3$ is then found and the time for a constant shear stress creep test at $\tau_3$ to reach a total shear strain of

$$\Sigma(\Delta\gamma_b) = \Delta\gamma_{b_1} + \Delta\gamma_{b_2} \tag{25}$$

is calculated. The procedure can be continued in this manner for as long as desired. As the creep rate falls off the increment of time can be increased without loss of accuracy. The engineer's or nominal diametral strain at any time $t$ is found simply by the relationship

$$\epsilon_{\theta_{b_t}} = \frac{b_t - b}{b} \tag{26}$$

where $b$ refers to the original outer radius of the cylinder before it is pressurized.

## CREEP OF THICK-WALLED CYLINDERS USING ISOCHRONOUS SHEAR STRESS-STRAIN CURVES

For the plastic deformation of metallic thick-walled cylinders at room temperature, where little if any creep takes place, Crossland [8] has suggested a method of predicting the pressure-expansion curve based on torsion data. This method, which is

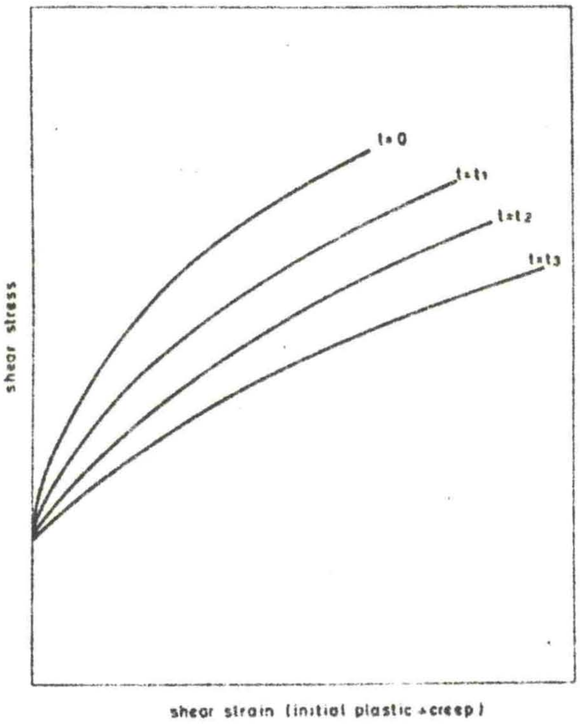


FIG. 3 HYPOTHETICAL ISOCHRONOUS SHEAR STRESS-SHEAR STRAIN CURVES DRAWN FROM TORSION CREEP CURVES

basically that proposed by Manning [9] allows for the dimensional changes associated with large strains. In this section, the approach is extended for use with time-dependent conditions

From a family of torsion creep curves, which include the initial plastic shear strains, a series of imaginary shear stress-shear strain curves can be constructed for various times. Figure 3 shows a hypothetical set of some such curves. If it is assumed that, no matter how the shear stress in a cylinder wall may vary with time, at a given time there is a unique relationship between stress and strain, then it is possible , using the Crossland or Manning type of analysis, to predict a series of isochronous pressure-expansion curves for a thick-walled cylinder of any desire diameter ratio. Hypothetical pressure expansion curves for different times are shown in Fig. 4. From these the diametral creep curves of cylinders with different internal pressures are deduced easily. The horizontal line AB in Fig. 4 for a particular pressure gives the initial plastic strain at time $t = 0$, while BC, BD, etc. give the creep strains at times $t_1$, $t_2$, etc.

Similar approaches to this have been suggested by Coffin, Shepler, and Cherniak [6] and by Parker [10], but both these do not make any allowance for dimensional changes.

## TESTING MACHINES AND MATERIAL

The torsion creep specimens used for this work were of thin-walled tubular form with a bore diameter of 0.750 in. and a wall thickness of 0.050 in. Shear strain was measured on a 5-in. parallel gauge length. The thick-walled cylinders had a diameter ratio of 2 with the outer diameter 2 in., and the tension creep specimens were of the standard N.P.L. design with an initial cross-sectional area of 0.1 in.$^2$ and a 2-in. gauge length. The testing machines have all been fully described in Refs. [1], [11], and [12], respectively, so no further details will be given here.

The material, a wrought carbon steel, was supplied by English Steel Corporation Ltd. in the form of a bar 15 in. in diameter and 74 in. in length. This had been trepanned from the center of a large forging for a chemical reaction vessel. Before delivery, English Steel Corporation Ltd. performed ultrasonic tests on the material, as well as sulphur-printing the end faces to check for segregation. As a result of these tests, some defective material was removed

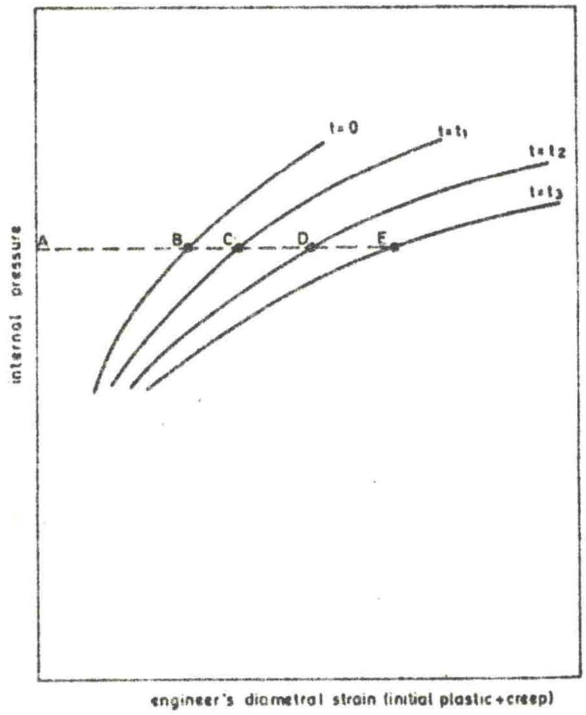


FIG. 4 HYPOTHETICAL ISOCHRONOUS PRESSURE-EXPANSION CURVES FOR THICK-WALLED CYLINDER

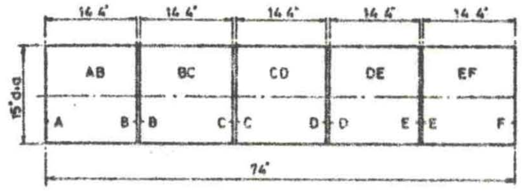


FIG. 5(a) INITIAL CUTTING DIAGRAM

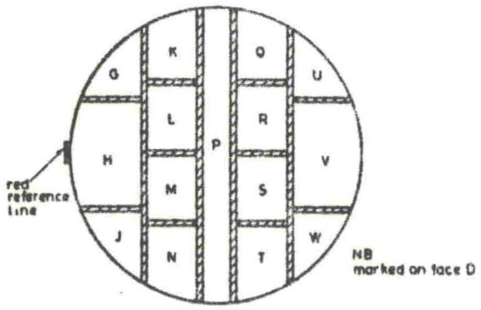


FIG. 5(b) CUTTING DIAGRAM FOR SECTION DE

from each end. The material was originally rather coarse grained, and the suppliers gave the entire core a refining heat treatment in a vacuum. This consisted of heating slowly to 610°C, soaking for 1 h at this temperature, and then cooling, still within the vacuum, over a period of about 18 h.

Figure 5 shows the manner in which the material was cut up. All the tests reported in this paper were performed on material from section DE at a test temperature of 400°C. Also shown is the way this section was further cut up.

Chemical analysis was carried out on four samples taken from pieces J, M, R, and U. Table 1 shows the results of these analyses.

Microscopic examination of the grain structure in both the longitudinal and transverse directions showed that the grains were orientated randomly, which suggested a minimum of anisotropy and difference in directional properties.

## TEST PROGRAM

The creep tests at 400°C on section DE of the steel have in general not exceeded 3,000 h. Eight torsion creep tests have been completed at shear stresses ranging from 6.5 to 10.5 ton-ft/in.$^2$, while another test at a shear stress of 11 ton-ft/in.$^2$ is still in progress. To date, six tension creep tests covering the nominal stress range 12 to 17 ton-ft/in.$^2$ have been taken to 3,000 h. Finally, seven pressure creep tests on cylinders are reported, with internal pressures ranging from 8 to 13 ton-ft/in.$^2$. Tables 2, 3, and 4 show details of these tests. Included in the tables are the initial plastic strains associated with each stress or pressure level. Because of the difficulty of measuring the instantaneous strain at the moment of loading, the initial plastic strain is taken as the nonelastic strain that occurs up to 1 min from the instant the test load or pressure is applied.

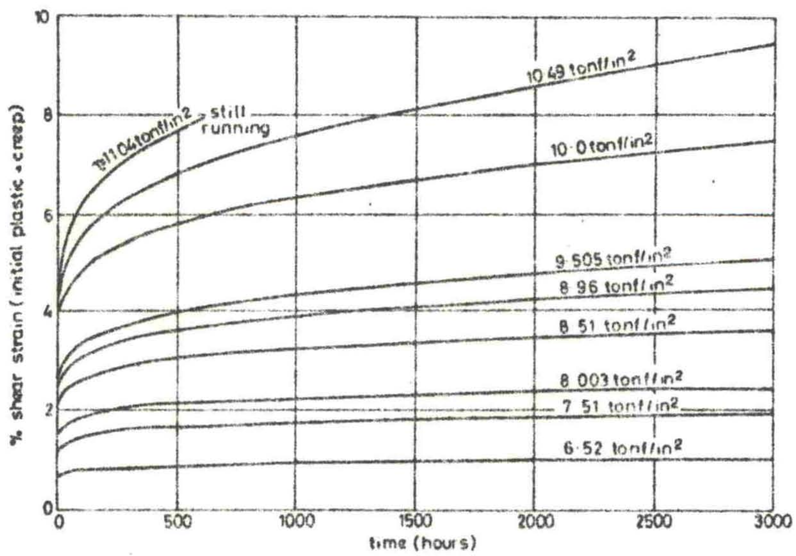


FIG. 6 TORSION CREEP CURVES FOR 0.18 PERCENT CARBON STEEL AT 400°C

*Table 1.*

| Element | Composition by Weight (%) Specimen Number | | | |
|---|---|---|---|---|
| | J1/3A | M1/1A | R1/3A | U1/3A |
| Carbon | 0.17 | 0.17 | 0.17 | 0.18 |
| Sulphur | 0.029 | 0.025 | 0.019 | 0.020 |
| Phosphorus | 0.023 | 0.020 | 0.019 | 0.021 |
| Silicon | 0.27 | 0.26 | 0.25 | 0.26 |
| Manganese | 0.71 | 0.72 | 0.69 | 0.69 |

*Table 2. Torsion Creep Results*

Test Temperature 400°C

| Shear-Stress (ton-f/in.$^2$) | Specimen No. | Initial Plastic Shear Strain (%) |
|---|---|---|
| 6.52 | G1/1/DE | 0.594 |
| 7.51 | W1/1/DE | 1.074 |
| 8.00 | M1/3/DE | 1.382 |
| 8.51 | R1/2/DE | 1.910 |
| 8.96 | J1/1/DE | 2.275 |
| 9.51 | U1/1/DE | 2.395 |
| 10.00 | M1/2/DE | 3.403 |
| 10.49 | R1/1/DE | 3.722 |
| 11.04 | P1/3/DE* | 4.041 |

*Still running.

*Table 3. Tension Creep Results*

Test Temperature 400°C

| Stress (ton-f/in.$^2$) | Specimen No. | Initial Plastic Strain (%) |
|---|---|---|
| 12 | M2/5/DE | 0.588 |
| 13 | M2/1/DE | 0.838 |
| 14 | M2/3/DE | 1.051 |
| 15 | M2/2/DE | 1.320 |
| 16 | M2/4/DE | 1.656 |
| 17 | M2/6/DE | 1.935 |

*Table 4. Pressure Creep Results*

Test Temperature 400°C

| Pressure (ton-f/in.$^2$) | Specimen No. | Initial Plastic Strain (%) |
|---|---|---|
| 8 | K/DE | 0.112 |
| 9 | L/DE | 0.220 |
| 10 | T/DE | 0.322 |
| 11 | N/DE | 0.461 |
| 11.5 | S/DE | 0.557 |
| 12 | H/DE | 0.678 |
| 13 | V/DE | 0.796 |

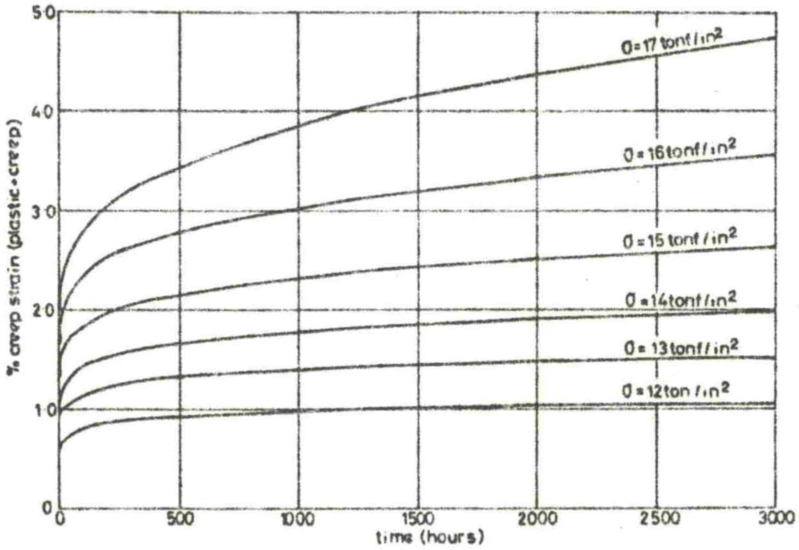


FIG. 7 EXPERIMENTAL TENSION CREEP CURVES FOR 0.18 PERCENT CARBON STEEL AT 400°C

Thereafter, all the time-dependent strain is taken as creep strain. The results of the torsion creep tests are plotted in Fig. 6, the tension in Fig. 7, and the cylinder creep tests in Fig. 8. They are plotted as total strain (i.e., initial plastic + creep) vs. time. Experimental points are not shown as in every case they lay on the smooth curves drawn. It should be noted that the reason for the slight variation in increment of shear stress between each torsion creep test was due to the critical dependence of stress on wall thickness and to the necessity of allowing for the oxide layer formed in the thin-walled tubes.

## DISCUSSION AND CORRELATION OF RESULTS

There was some experimental scatter between the curves from one stress level to another, especially in the torsion creep tests, and inasmuch as the torsion data were to form the basis of most of the correlation work, it was deemed necessary, before analyzing it, to eliminate this scatter. This was done by cross-plotting from the torsion creep curves, shear stress-strain curves for various values of time, or what are termed isochronous curves. Smooth curves were drawn through the resulting points and to assist in this it was found helpful to plot the initial curve ($t$=0) using not only the initial plastic shear strain values but also values taken during the complete loading-up procedure for each test. Some of the isochronous stress-strain curves obtained in the above manner are shown in Fig. 9. From these it was a simple matter to redraw the modified torsion creep curves shown in Fig. 10 with creep shear strain plotted versus time. The shear stresses in the modified curves were chosen with an equal increment of 0.5 tonf/in.$^2$ between each, which shows another advantage of drawing isochronous curves.

It can be seen from Figs. 6, 7, and 8 that there was no significant evidence, up to 3,000 h, of tertiary creep, or more specifically an increase of strain rate, in any of the tests so far conducted.

The creep constants in Eq. 7 were then found from the modified torsion creep curves [1] and the following expression was then taken to represent the data:

$$\gamma = 6.74 \times 10^{-8}\, \tau^{4.70}\, t^{0.313} \tag{27}$$

Figure 11 compares the curves predicted by Eq. (27) with the modified experimental ones. A reasonable fit has been achieved for the majority of stress levels, and at worst the deviation for any curve is 10 percent at 3,000 h.

The tension data was also processed in a similar way and the expression found to fit these curves was

$$\epsilon = 9.12 \times 10^{-9}\, \sigma^{4.5}\, t^{0.25} \tag{28}$$

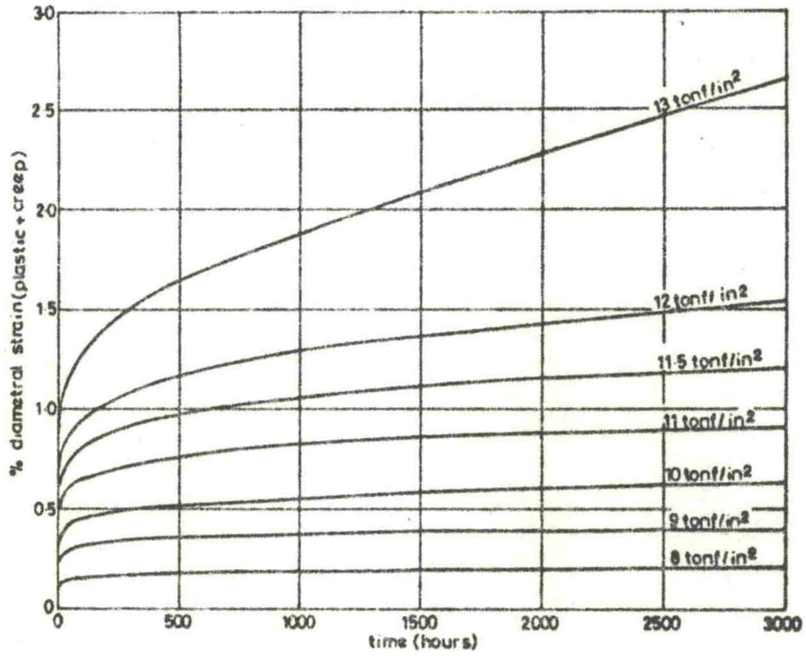


FIG. 8 EXPERIMENTAL PRESSURE CREEP CURVES FOR CYLINDERS (K=2) (0.18 PERCENT CARBON STEEL AT 400°C)

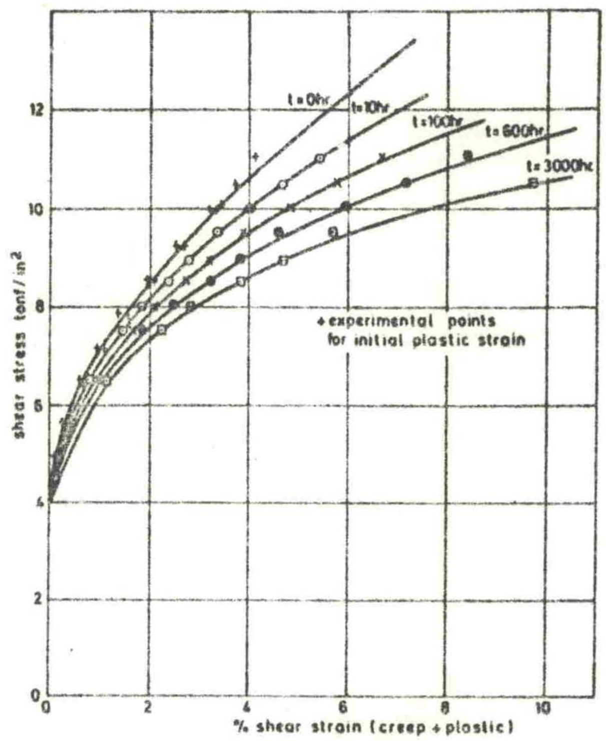


FIG. 9 TYPICAL ISOCHRONOUS CURVES DRAWN FROM TORSION CREEP RESULTS (0.18 PERCENT CARBON STEEL AT 400°C)

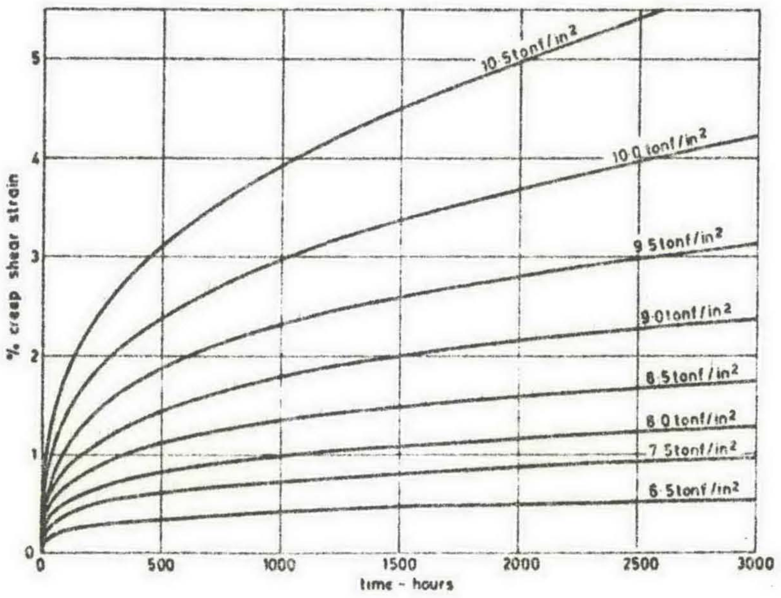


FIG. 10 MODIFIED TORSION CREEP CURVES (0.18 PERCENT CARBON STEEL AT 400°C)

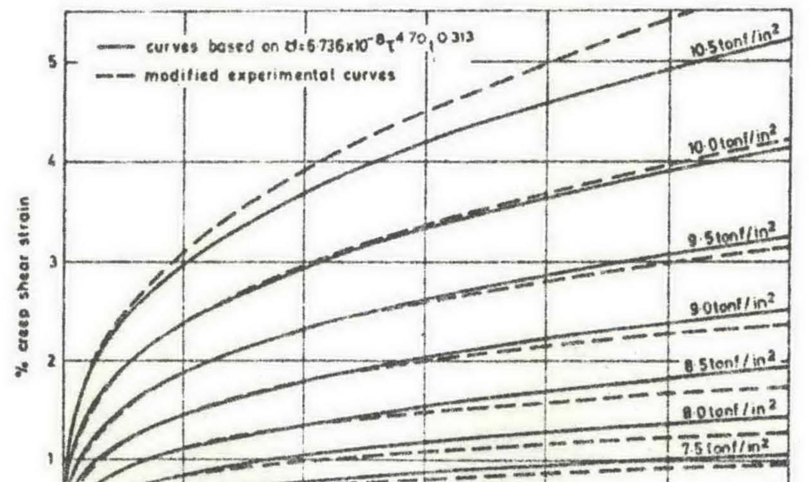


FIG. 11 COMPARISON OF PREDICTED TORSION CREEP CURVES WITH THE MODIFIED EXPERIMENTAL CURVES (0.18 PERCENT CARBON STEEL AT 400°C)

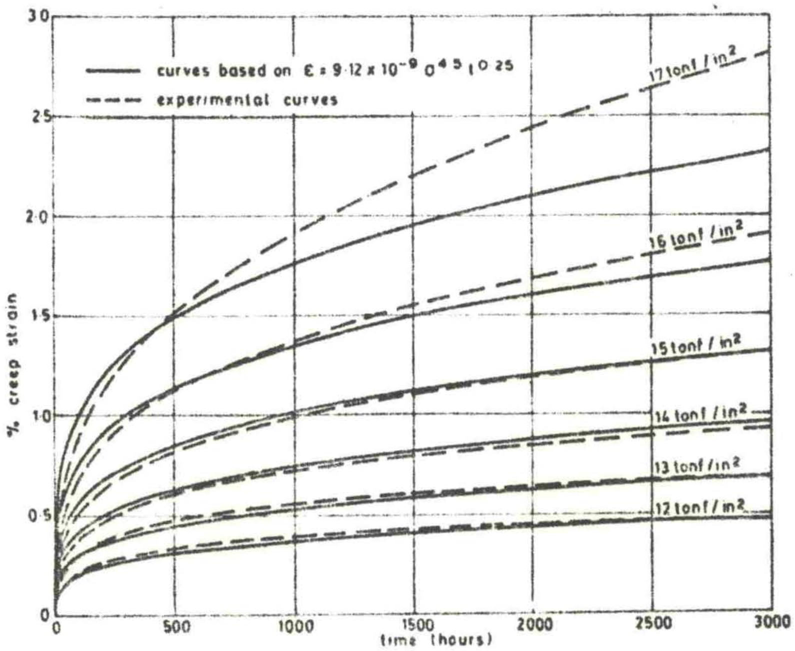


FIG. 12 COMPARISON OF PREDICTED TENSION CREEP CURVES WITH EXPERIMENTAL CURVES (0.18 PERCENT CARBON STEEL AT 400°C)

Figure 12 shows the comparison between the experimental tension creep curves and those predicted by Eq. (28). Here the fit is very good apart from the 17 ton-f/in.$^2$ stress level. This suggests that a different set of constants may be required for this stress and higher.

The torsion creep data was correlated with the tension data using the von Mises flow rule and in one case allowing for the changing stress in the constant load tension data and in the other ignoring it [1]. Figure 13 gives the results of this, and it is seen that there is a marked difference between theories even at the 12 ton-f/in.$^2$ stress level. Therefore, it is clear that any correlation between thick-walled cylinder creep and constant load tension creep can be only approximate.

Using the Crossland theory [7], the initial plastic torsion data has been used to predict the pressure initial expansion curve for a cylinder with $k$ ratio = 2. The prediction is compared with the experimental data obtained in the loading up of the pressure creep tests in Fig. 14. An excellent correlation has been achieved. The isochronous pressure expansion curves obtained from the torsion data times up to 3,000 h are shown in Fig. 15. Figures 16 to 22 show each of the experimental creep curves for the thick-walled cylinders compared with the curves predicted by the various theories, i.e.,

(1) simple Bailey using torsion creep data,

(2) simple Bailey using tension creep data,

(3) mean diameter theory using torsion creep data,

(4) modified Bailey taking account of wall thinning and using torsion creep data, and

(5) isochronous theory using torsion data.

In every case the simple Bailey theory using torsion creep data is the lowest of the theoretical predictions and becomes steadily worse as the test pressure is higher. The simple Bailey theory using tension creep data is higher than that using torsion, as is to be expected because the actual stresses in the tension tests are greater than the nominal values.

For the 8 ton-f/in.$^2$ pressure creep test the mean diameter theory overestimates the strain, but as the test pressure level increases, it is seen that the effect of wall thinning overtakes this effect, and the prediction becomes steadily worse. Nevertheless, at the lower pressures this simple theory gives a reasonable prediction.

The modified Bailey theory using torsion creep data is a big improvement over the simple Bailey theory and shows clearly that for the present magnitude of strains the effect of wall thinning is considerable. At the lowest pressure, the effect is quite

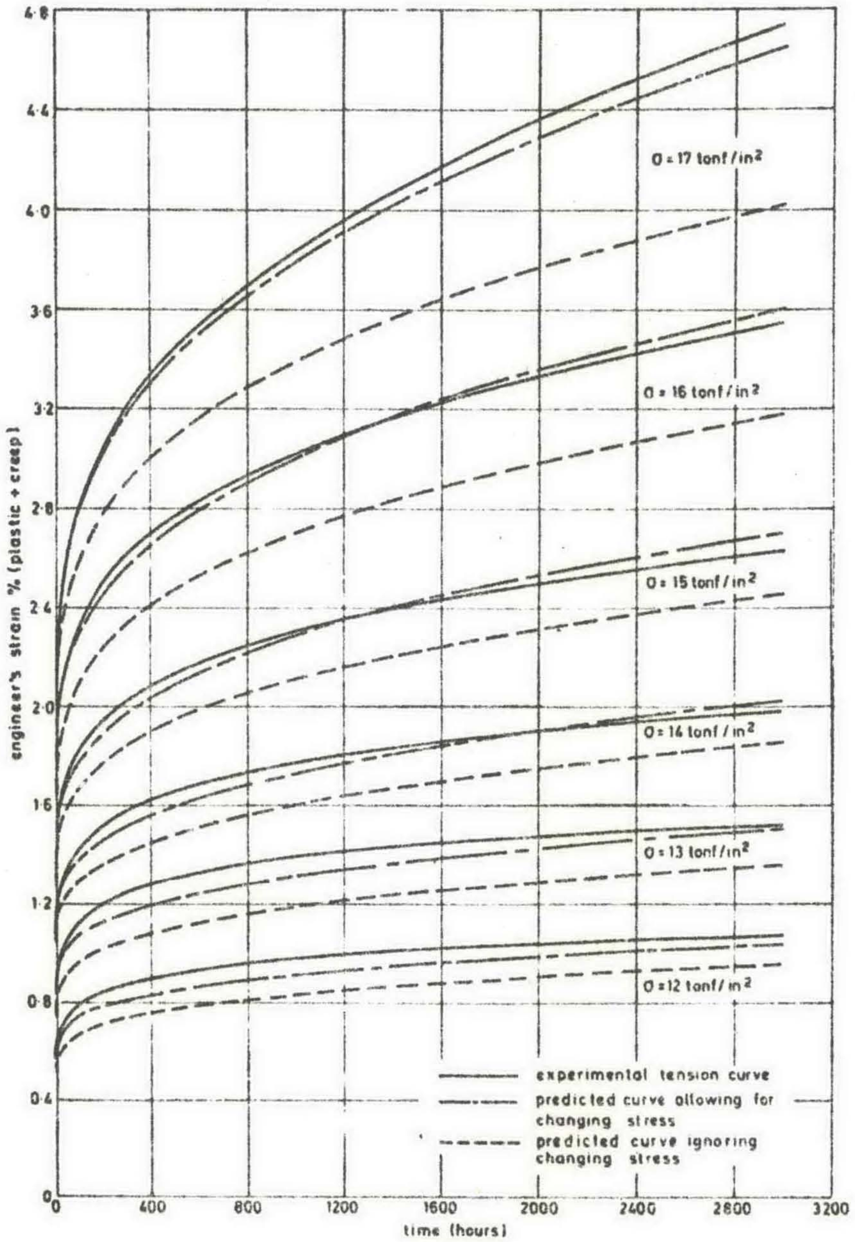


FIG. 13 COMPARISON OF EXPERIMENTAL TENSION CREEP CURVES WITH THOSE PREDICTED FROM TORSION CREEP DATA ON BASIS OF VON MISES FLOW RULE (0.18 PERCENT CARBON STEEL AT 400°C)

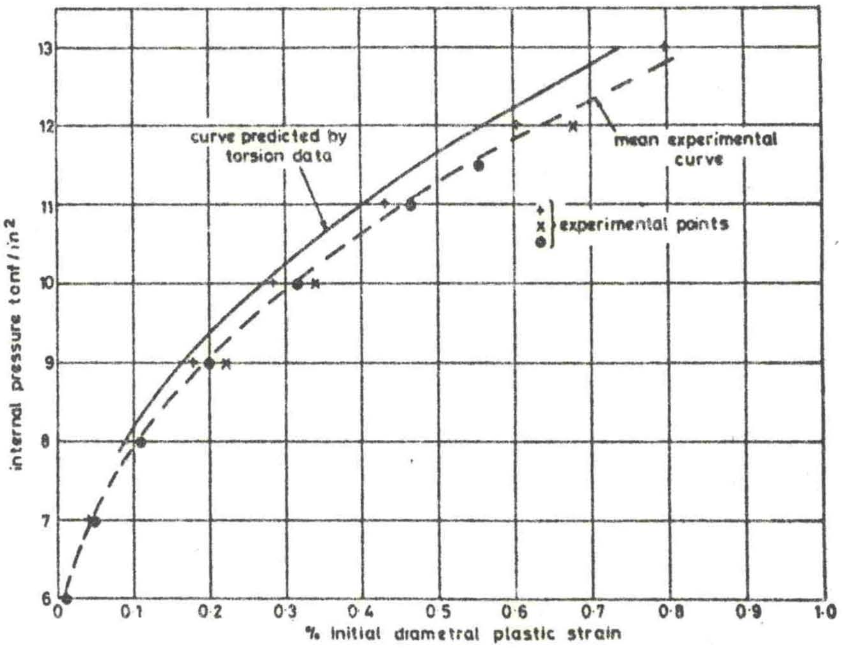


FIG. 14 COMPARISON OF PREDICTED AND EXPERIMENTAL INITIAL PRESSURE-EXPANSION CURVES (0.18 PERCENT CARBON STEEL AT 400°C)

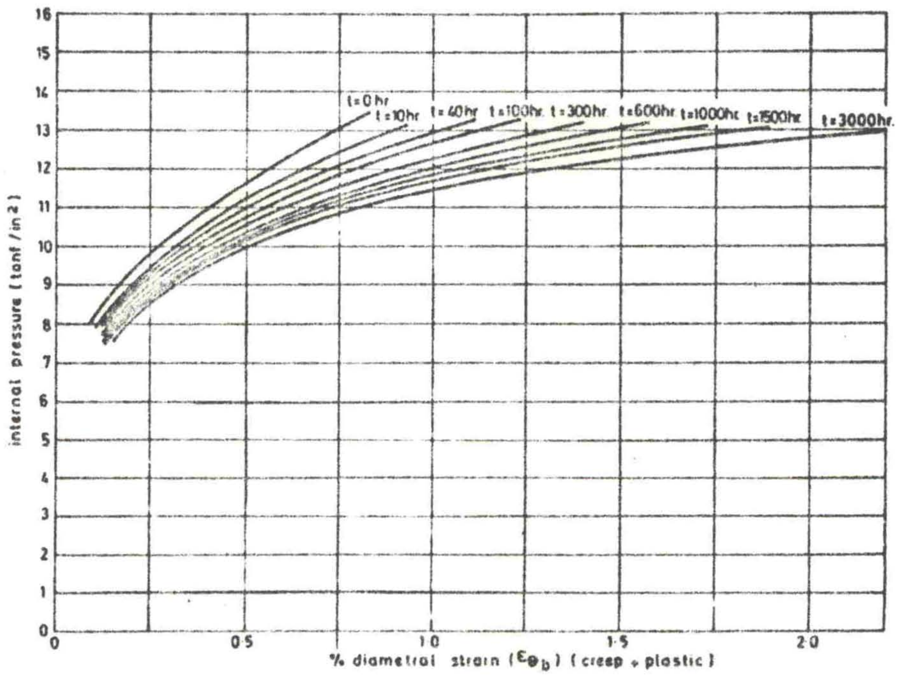


FIG. 15 ISOCHRONOUS PRESSURE-EXPANSION CURVES PREDICTED BY TORSION CREEP DATA (0.18 PERCENT CARBON STEEL AT 400°C)

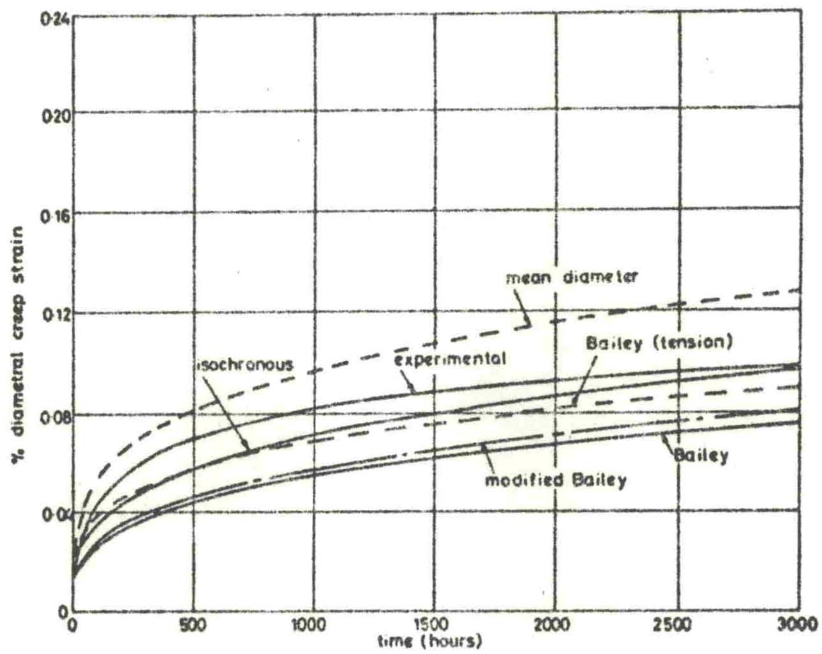


FIG. 16 COMPARISON OF EXPERIMENTAL AND THEORETICAL CREEP CURVES FOR CYLINDER (K=2) WITH 8.0 ton-f/in.$^2$ INTERNAL PRESSURE (0.18 PERCENT CARBON STEEL AT 400°C)

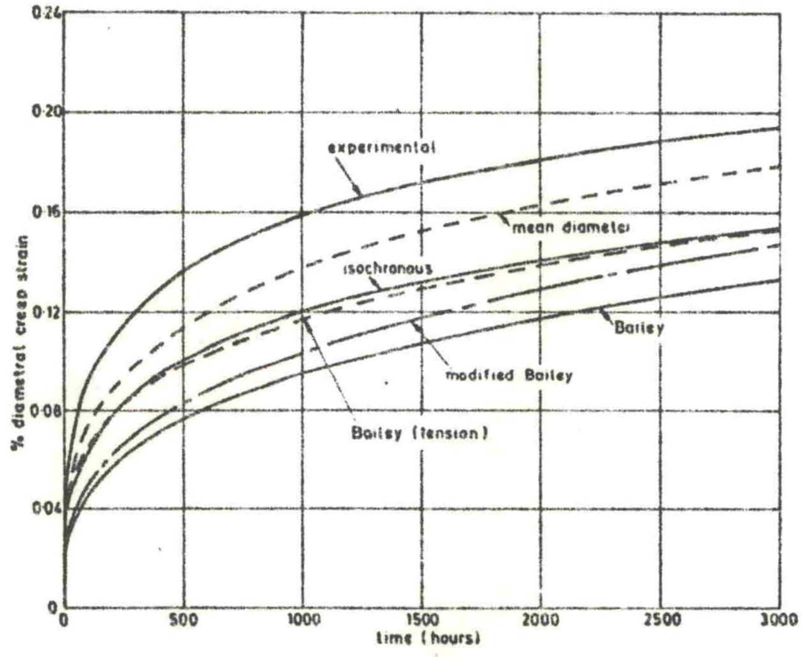


FIG. 17 COMPARISON OF EXPERIMENTAL AND THEORETICAL PRESSURE CREEP CURVES FOR CYLINDER (K=2) WITH 9 ton-f/in.$^2$ INTERNAL PRESSURE (0.18 PERCENT CARBON STEEL AT 400°C)

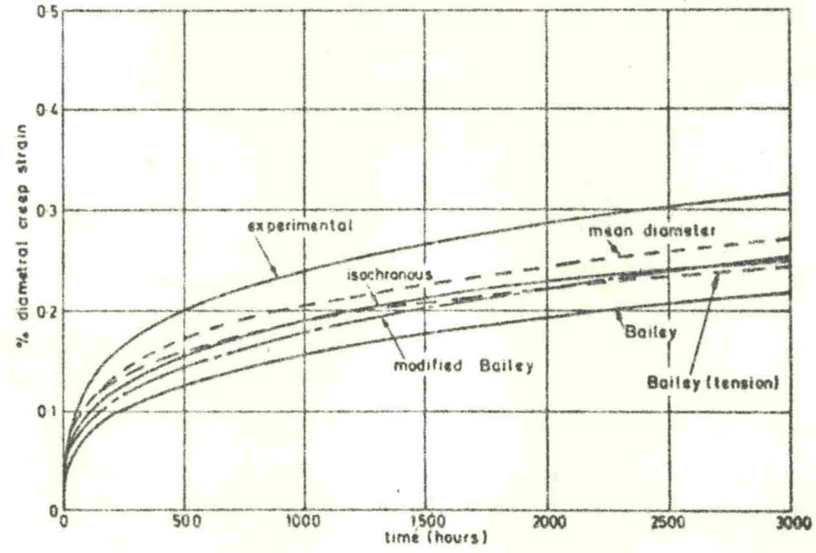


FIG. 18 COMPARISON OF EXPERIMENTAL AND THEORETICAL CREEP CURVES FOR CYLINDER (K=2) WITH INTERNAL PRESSURE 10 ton-f/in.$^2$ (0.18 PERCENT CARBON STEEL AT 400°C)

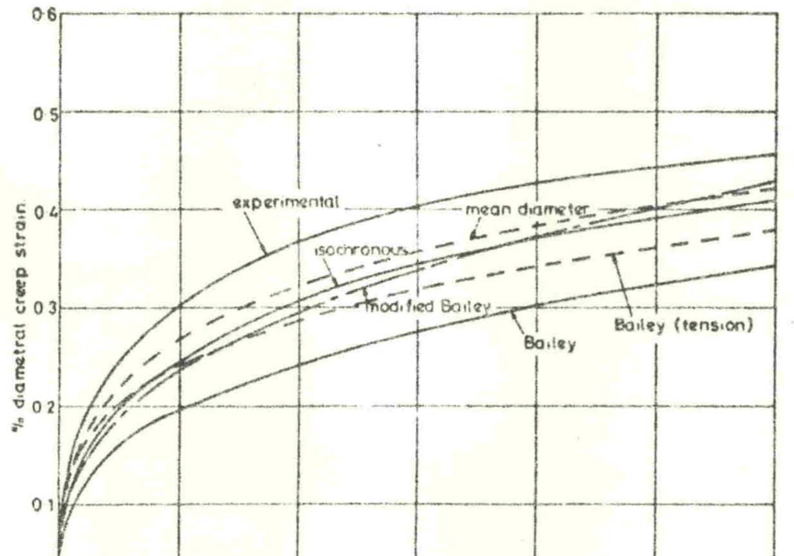


FIG. 19 COMPARISON OF EXPERIMENTAL AND THEORETICAL CREEP CURVES FOR CYLINDER (K=2) WITH INTERNAL PRESSURE 11 ton-f/in.$^2$ (0.18 PERCENT CARBON STEEL AT 400°C)

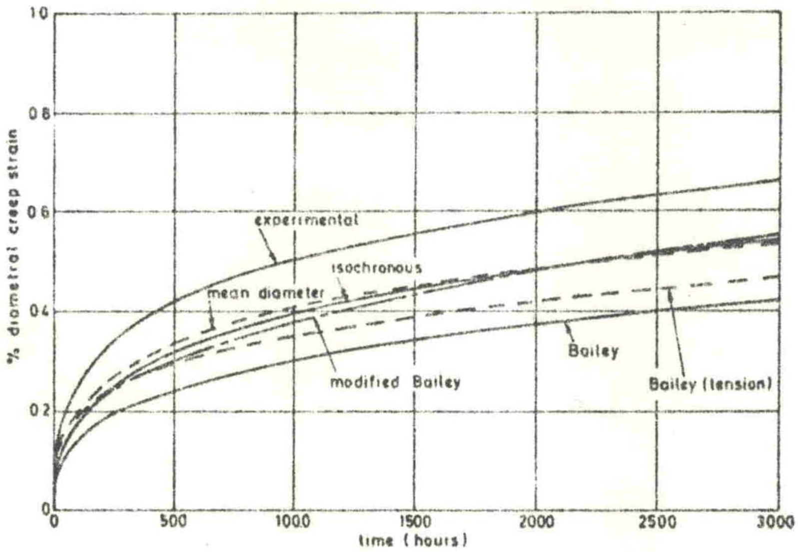


FIG. 20 COMPARISON OF EXPERIMENTAL AND THEORETICAL CREEP CURVES FOR CYLINDER (K=2) WITH INTERNAL PRESSURE 11.5 ton-f/in.$^2$ (0.18 PERCENT CARBON STEEL AT 400°C)

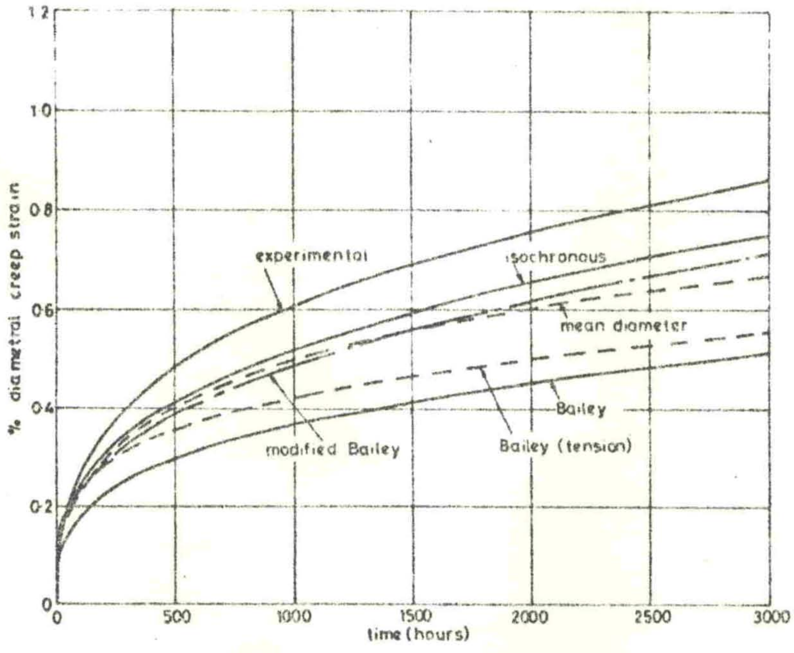


FIG. 21 COMPARISON OF EXPERIMENTAL AND THEORETICAL CREEP CURVES FOR CYLINDER (K=2) WITH INTERNAL PRESSURE 12 ton-f/in.$^2$ (0.18 PERCENT CARBON STEEL AT 400°C)

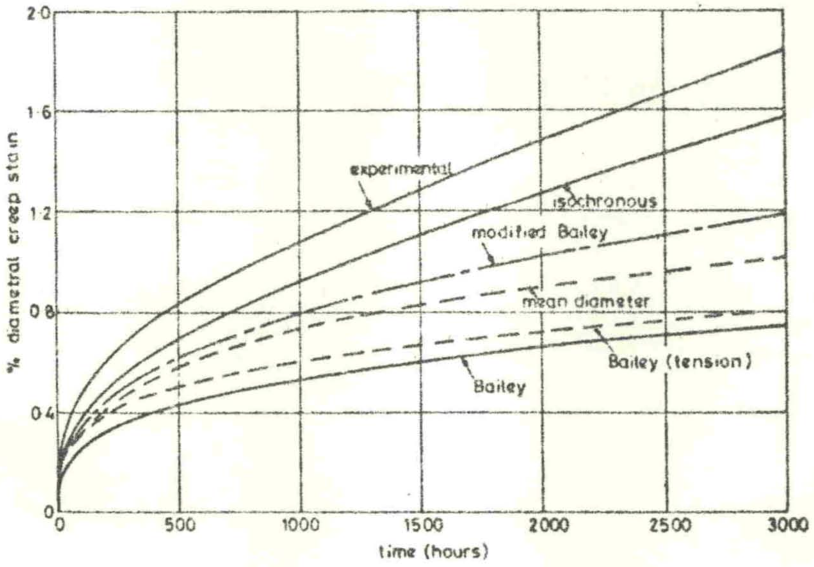


FIG. 22 COMPARISON OF EXPERIMENTAL AND THEORETICAL CREEP CURVES FOR CYLINDER (K=2) WITH INTERNAL PRESSURE 13 ton-f/in.$^2$ (0.18 PERCENT CARBON STEEL AT 400°C)

small, but it steadily increases until for the 13 ton-f/in.$^2$ pressure test there is a factor of 1.6 in the strains at 3,000 h between the two theories.

The isochronous approach gives the most consistent prediction of diametral strain over all the theories for this particular material always being within 20 percent of the experimental value. However, it must be realized that the assumption of a shear stress associated with a particular strain at any given time cannot be exactly correct if the stresses are varying with time, and it may be that this theory may not be as good for another material or for cylinders with a larger $k$ ratio.

## CONCLUSIONS

It would seem that, with the correlation between torsion creep and constant load tension creep data and also with the experimentally observed fact that the axial creep strain in a pressurized thick-walled cylinder is zero, that torsion creep data is more fundamental for designing cylindrical vessels under creep conditions.

It can be concluded that for the magnitude of creep strains involved in the experimental work reported in this paper, account must be taken of wall thinning of a thick-walled cylinder undergoing creep.


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