Creep Buckling Analyses of Cylindrical HTR-Components

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Summary

In order to prove that creep buckling of the cylindrical gas collector of the prototype nuclear process heat plant due to a pressure loss accident will not occur an instability analysis has been performed.

Applying Hoffs theory, the parameters initial ovality, creep resistance of the material and temperature varying with time have been investigated in detail. In particular the loss of safety potential due to these parameters in comparison with the recommended safety factor of the ASME Code has been quantified.

The analysis has shown that the sensitivity to initial ovality is negligible while the temperature level and creep resistance have an important influence on stability behaviour. Buckling tendency can be avoided by decreasing temperature with time even if the temperature reduction rate is relatively low and the accident recurs. In view of the specified temperature decrease during the accident investigated, the ASME Code load factor seems to be very conservative.

1 Introduction

The pressure loss accident of the secondary circuit is one of the most severe loading conditions which must be investigated for the planned PNP (prototype nuclear process heat) plant.
It must be demonstrated that instability of the intermediate heat exchanger (IHX) and in particular of the cylindrical hot gas collector of the IHX will not occur during this emergency condition. The design paramaters are as follows:

- effective wall thickness of 83 mm
- mean radius 955 mm
- initial temperature 936 °C
- external pressure difference of 40 bars
- Inconel 617 as material

There are a lot of uncertainties which will be investigated in order to show the degree of conservatism with regard to the assumed design factor of 1.5 recommended in ASME-Code Case N47 applied to guard against load-controlled time-dependent creep buckling.
These uncertainties are:

- initial ovality
- creep resistance due to aged conditions
- temperature varying with time

2 Theory of creep buckling of cylindrical tubes under external pressure

This problem has been studied by Hoff / 1 / and Ellington / 2 /. They both used different methods to solve this problem with Hoff applying a Sandwich model and Ellington using a linear stress distribution model.

Hoff made some simplifying assumptions:

a) the shell wall construction is of the ideal sandwich type, that means that bending moments and normal forces are supported by membrane stresses in two concentric cylindrical sheets, while shear is supported without deformation by the core annulus between the sheets;

b) only secondary creep is taken into account, primary creep as well as elastic and plastic deformations are not considered, and

c) the initial as well as all later shapes of the cross section are quasi-elliptically cylindrical.

The cross section is assumed to have some slight initial deviation from circularity which is increased by the creep deformations at an increasing rate with time until the cylinder collapses. Using the creep law of Norton, with the parameters k and n and a biaxial state of stress he developed two separate expressions for the time rate of change of the curvature. If both expressions are made equal there is a differential equation for the change of shape with time:

$$\frac{dt}{\tau} = \frac{dx}{f(x)} \qquad \text{where } f(x) = x + \frac{(n-1)(n-2)}{1^2 . 3^2} x^3 + \frac{(n-1)(n-2)(n-3)(n-4)}{1^2 . 3^2 . 5^2} x^5 + \dots$$

x = dimensionless ovality

$x = 2.\sqrt{3} \quad (\delta . a/h)$

δ = ovality = $\frac{\Delta a}{a}$

h = wall thickness

a = average radius of cylinder

n = creep law exponent

$$\tau^{-1} = 4n\left(\frac{3}{4}\right)^{\frac{n+1}{2}} kp^n \left(\frac{a}{h}\right)^{n+2}$$

k = creep law constant

$$= w_1 e^{-\frac{w_2}{T}}$$

p = external pressure

This leads to a formula for the relation between ovality and time:

$$\frac{t}{\tau} = \int_{x_0}^{x} \frac{dx}{f(x)}$$

It is possible to introduce a time dependent creep law in the form:

$$k(t) = w_1 e^{\frac{-w_2}{T(t)}}$$

Thus the differential equation looks like

$$4n\left(\frac{3}{4}\right)^{\frac{n+1}{2}} \cdot p^n \left(\frac{a}{h}\right)^{n+2} \cdot w_1 \int e^{-\frac{w_2}{T(t)}}\, dt = \int_{x_0}^{x} \frac{dx}{f(x)}$$

The integrals are solved by numerical integration.

Ellington used a variational theorem where stresses and displacements are varied separately. He gave solutions for creep exponents of 1,3 and 5. Glückler / 3 / developed a more general formula for any creep exponents, but with some very complicated mathematical expressions.
Also using the variational theory Schneider / 4 / found an expression that is easier to use:

$$\frac{t}{\tau} = \frac{5p_{cr} - 3p}{3p_{cr}} \; \frac{1}{2} \; \ln\left(\frac{x}{x_0}\right)^2 \frac{\frac{27}{10}(n-1)(n-2)x_0^2 + 1}{\frac{27}{10}(n-1)(n-2)x^2 + 1}$$

$$p_{cr} = \frac{E\, h^3}{4(1-\nu^2)a^3} = \text{critical external pressure}$$

$$x_0 = \frac{1}{1-\frac{p}{p_{cr}}} \frac{\delta a}{h} = \text{dimensionless inital ovality}$$

A comparision between all these methods showed that the theory of Hoff gave the most conservative results (shortest critical time) for the relevant pressure ratio p/p_{cr} (Fig. 1). It must be noticed that this is only valid for very small quotients of p/p_{cr}. Therefore the theory of Hoff was adopted for this investigation.

3. Results

First of all the influence of the initial ovality on the critical time was studied. For the initial ovalities of 0.3, 0.6, and 1 % calculations were made for constant temperature conditions Fig. 2 shows the results. By increasing initial ovality from 0.3 to 0.6 and 0.3 to 1.0 % the buckling time reduces by the factor .66 and .41 respectively.

The influence of temperature level on buckling time is well known. As the temperature during the described emergency condition will not be constant, it is interesting to know the effect of temperature decreasing with time on instability. The time dependent creep law factor k(t) was used to develop a temperature-time-function. Fig. 3 shows the results of the following conditions: constant temperature of 936 °C, reduction of 1,5, 10, and 25 K/h. It can be seen that for decreasing temperature the risk of buckling will be essentially diminished as due to inelastic deformation decrease a steady state condition will grow up.

In connection with initial ovality and decreasing temperature discussion repeated secondary pressure loss accidents have been investigated. The duration of each accident was assumed to be 10 hours. For a constant temperature there is no difference between the time dependent ovality curve for a prolonged accident and a repeated accident. See Fig. 4. Fig. 4 also shows the curve for one of the decreasing temperature cases, one can see that each new accident results in approximately the same increment in ovality.

Because of uncertainties of the material's creep behaviour in end-of-life condition, due to aging, carborization and oxidation processes, have also been examined.

A reduction of creep resistance of 20 % leads to a corresponding reduction of buckling time from 3265 h to 573 h which is a factor of about .18. These values were obtained for an external pressure of 40 bars and an initial ovality of .3 % and a time independent temperature level of 936° C. Taking into account again a temperature decrease with time, the instability process will be stopped after some hours.

4. Discussion

The instability analysis has been performed in order to quantify the degree of conservatism given by applying the recommended safety factor of the ASME Code in relation to uncertainties due to initial ovality, material behaviour and temperature (see figure 5).

Concerning initial ovality, no problems are expected as fabrication tolerances are low enough to be covered by an assumed value of 0,3 %. Uncertainties due to circumferential temperature distribution have no important influence on reducing the available safety margin. Evaluations have shown, that a maximum circumferential temperature difference of about 30 °C would not increase the initial ovality by more than 0.1 %.

Creep resistance as well as temperature level have an important influence on stability behaviour of the component. Figure 5 shows, that a reduction of creep resistance of about 35 % or a temperature increase of about 60 °C would consume the whole safety potential. On the other hand, the study has shown very clearly, that buckling tendencies can be completely avoided by decreasing temperature with time even if the temperature reduction rate is relatively low. In view of the specified temperature decrease of the investigated accident, the considered load factor seems to be very conservative.

Creep buckling experiments are being planned to simulate loading conditions and geometry in order to confirm the applied methods as well as the presented theoretical results.

References

/ 1 / Hoff, N. J., Jahsman, W.E., Nachbar, W., "A Study of Creep Collapse of a long Circular Cylindrical Shell Under Uniform External Pressure," J. Aero/Space Sc. 26, No. 10(1959).

/ 2 / Ellington, J. P., "Creep Collapse of Tubes Under External Pressure," DEG Report 162 (R)

/ 3 / Glückler, E., Passig, E. Höchel, J., "Kriechbeulen von Brennelement-Hüllrohren, "Nucl. Eng. Design 7,236-248 (1968)

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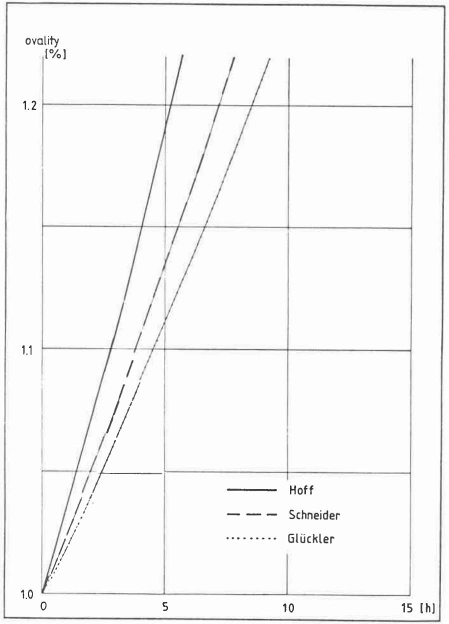

Fig. 1 comparison of different methods to evaluate buckling time

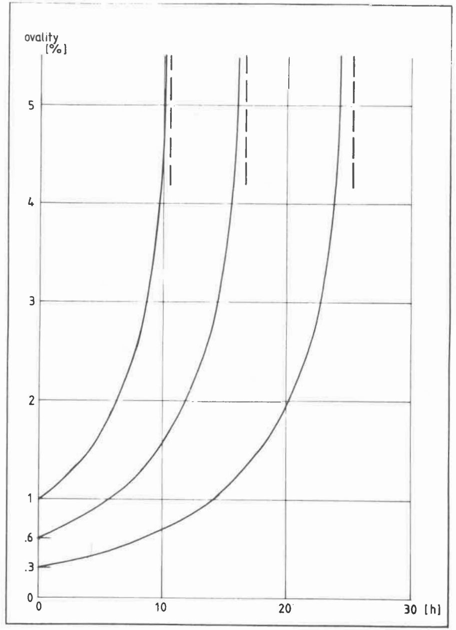

Fig. 2 influence of the initial ovality on the increase of ovality with time

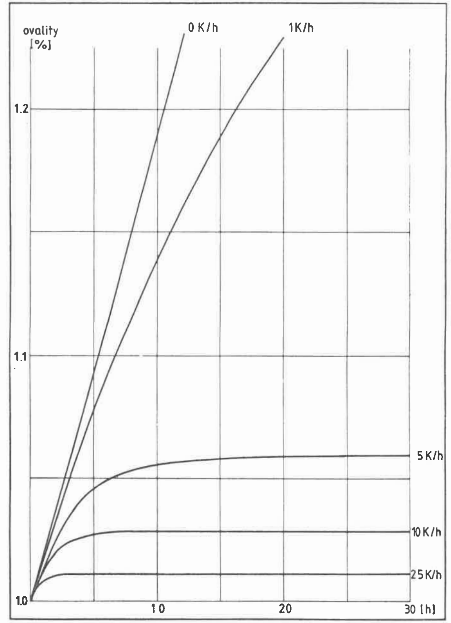

Fig. 3 influence of temperature reduction with time on the ovality

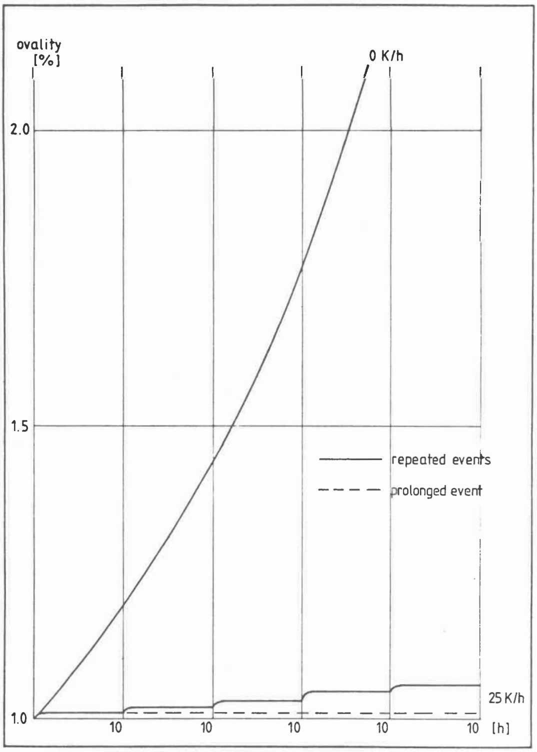

Fig. 4 repeated accidents lasting 10 h in comparison to a prolonged accident

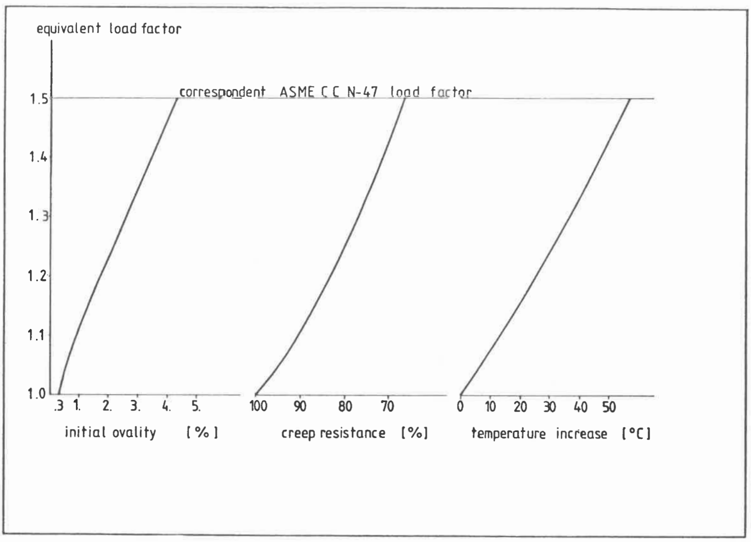

Fig. 5 safety region of the time dependend load controlled buckling factors, recommended by ASME-Code Cases N47, due to initial ovality, creep resistance and temperature increase