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THE INFLUENCE OF IRRADIATION AND THERMAL CREEP ON STRESS REDISTRIBUTION IN FUSION BLANKETS

James P. BLANCHARD and Nasr M. GHONIEM

Fusion Engineering and Plasma Physics Program, University of California at Los Angeles,
Los Angeles, California 90024, USA*

Creep processes, due to irradiation and thermal fields, have generally been assumed to relax stresses resulting from the loading of structural components. However, in order to determine failure modes and mechanisms, a global inelastic structural analysis is required. We have recently developed the STAIRE computer code to meet this need. This code is based on a modified beam theory for the self-consistent determination of stresses and deflections in beams of circular cross-section. The work is applied to the lifetime analysis of the Mirror Advanced Reactor Study (MARS) blanket modules. The objective of the present paper is to assess the global (3-dimensional) impact of both irradiation and thermal creep strains on the stresses resulting from thermal and swelling strains.

1. INTRODUCTION

Until recently, structural analysis of fusion components has usually been divorced from radiation effects. Detailed structural models have been used without considerations of radiation induced property changes. On the other hand, estimates of lifetime limits have been performed at a crude level, using simple 1-D models or arbitrary design criteria. The independence and disparity of these two approaches is obviously inconsistent. In order to obtain more reliable end-of-life (EOL) estimates requires a more thorough understanding of the effects of void swelling and thermal and irradiation creep on a 3-D structure. In some cases, the results of a global structural analysis could not be obtained by merely extending the results of a 1-D study.

In this paper, the interplay between swelling and creep is examined through the use of a computer code (STAIRE)[1] developed at UCLA. This code is based on classical beam theory, modified to analyze curved, thin-walled pipes including radiation effects. The basic configuration of these pipes is shown in figure 1.

We show the applicability of this code to fusion blankets by analyzing the blanket modules of the Mirror Advanced Reator Study (MARS) design[2]. This is a major study of a commercial tandem mirror reactor, to establish the feasibility of the mirror concept.

The basic design of the blanket is quite simple. The Li-Pb alloy is fed at 350°C to the HT-9 blanket module through a large coolant header at the top. From there, it flows (in parallel) through the rectangular HT-9 beam structure and the 10-cm-diameter circular HT-9 tube section. The tubes in the front ensure uniform flow in the regions where the neutron heating is the highest, and the rectangular sections are better suited to attain a low void fraction to increase the neutronic energy multiplication factor. At 500°C, the LiPb exits through a large-diameter coolant pipe to a double-walled heat exchanger. The larger pipes are necessary to reduce the MHD pumping power.

2. THEORETICAL BASIS OF STAIRE

The STAIRE code is designed to calculate the stresses and deflections in curved pipes

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with various end conditions. Because the pipes are indeterminate, the stresses and deflections are coupled and must be determined simultaneously. This is accomplished by setting up three equations for the deflections at the end of the pipe in terms of the inelastic strains and the unknown end reactions. For example, the equation for the radial displacement at the end (ΔR) is:

$$\Delta R = -\int w'x\,ds + \int \bar{e}' \sin\theta\,ds + XM \int \frac{x\,ds}{EI} + XF \int \frac{xy\,ds}{EI} + XP \int \frac{y^2 ds}{EI} \quad (1)$$

where

$$w' = \frac{1}{K_{II} I} \int_A (e^c + e^s + \alpha T)\,\xi\,dA \quad (2)$$

and

$$\bar{e}' = \frac{1}{A} \int_A (e^c + e^s + \alpha T)\,dA \quad (3)$$

The quantity w' is the change in curvature due to the inelastic strains and $\bar{e}'$ is the average inelastic strain over the cross-sectional area, A. Equation (1), along with equations for the axial end displacement and end rotation, can be solved for the end reactions, XM, XF, and XP.

Once the reactions are known, the stresses in the pipe can be determined with the use of simple statics. The moment, M, and axial force, F, at any angle, θ, can be found in terms of the reactions and the axial stress can then be given as:

$$\sigma = \frac{F}{A} + \xi(1 - K_I \xi^2)\left(\frac{M}{K_{II} I} - Ew'\right) - E(e^c + e^s + \alpha T - \bar{e}') \quad (4)$$

where K_I and K_{II} are constants determined by the pipe dimensions.

The pipe deflections are obtained by replacing the end reactions in equation (1) with the forces on the section at which the deflection is calculated and adjusting the coordinates to correspond to that section. This completes the analysis.

3. IRRADIATION AND THERMAL CREEP

Irradiation creep data exists for a limited

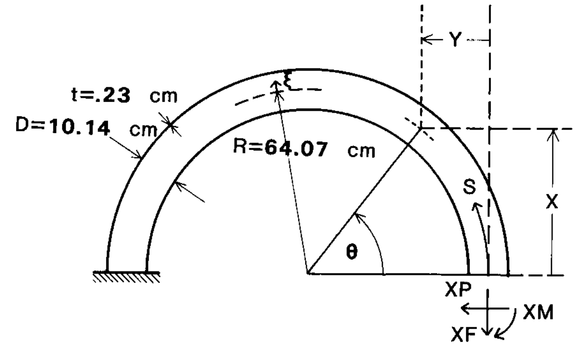

FIGURE 1
configuration of pipe model

number of ferritic alloys. Odette[3] compiled such information, with a suggested correlation of the form:

$$\dot{e}^c_{irr} = A_c \sigma \dot{\delta} \quad (5)$$

where A_c is a constant, σ the applied Von Mises (equivalent) stress, and δ is the irradiation dose. The values of A_c seem to be both temperature and alloy dependent. Values ranging from 7×10^{-7} dpa^{-1} ksi^{-1} to 2×10^{-5} dpa^{-1} ksi^{-1} were reported.

The following equation, developed by Amodeo and Ghoniem[4], was used for thermal creep:

$$\dot{e}^c_{th} = \frac{7.4 \times 10^{-3}}{KT} \exp\left(-\frac{1.23}{KT}\right)(\sigma - \sigma_o)^3 \quad (6)$$

where T is the absolute temperature and σ_o is the temperature dependent back stress.

4. INFLUENCE OF IRRADIATION CREEP

In an indeterminate structure with no applied loads, the stresses result solely from restraint of the inelastic strains, so irradiation creep leads to stress relaxation, rather than an increase in the total strain as in a typical, constant load situation. In contrast, void swelling causes a substantial increase in both stresses and deflections as damage occurs. If both phenomena are considered simultaneously, one can envision the pipe reaching a steady-state, in which the stress increase due to swelling is balanced by the relaxation due to creep. In figure 2, the maximum stress due to swelling alone is seen to increase linearly with time, as the damage is accumulated at a rate of 69 dpa/year. When creep is included in the analysis, the maximum stress exhibits a less rapid increase and it reaches a steady-state value of 41 ksi. This steady-state value is determined by the creep-free elastic strain rate divided by the creep coefficient.

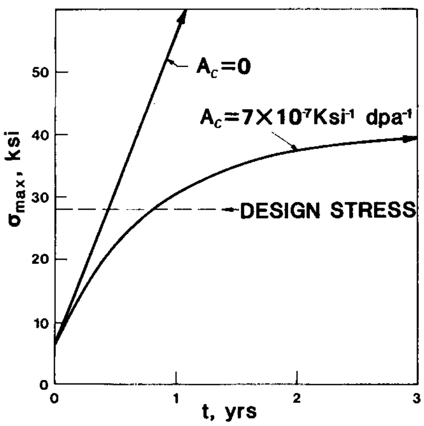

FIGURE 2
maximum stress history with and without irradiation creep

Contrary to what one might expect, the pipe deflections do not change when creep is included, ie. the pipe expanded with time as if the creep coefficient is zero. This can be understood by more closely investigating the distribution of creep strains over the cross section. Because creep is proportional to the local stress and the stress is an odd function over the cross-section, the creep strains are negative on the inner fibers ($\zeta < 0$) and positive on the outer fibers ($\zeta > 0$). As a result, the pipe accomodates creep by decreasing the elastic strains rather than increasing the total strains. In terms of our model, the radial deflections of the clamped pipe are caused by $\bar{e}'$ alone and the creep strains do not contribute significantly to this quantity.

5. DAMAGE GRADIENT EFFECTS

The previous analysis has been performed under the assumption that the damage rate (69 dpa) was uniform everywhere in the pipe. In reality, 3-D neutronics Monte Carlo calculations in the MARS study found that the damage rate at the back of the pipe is about half that at the front[2]. This affects the results in two ways. First, the swelling is taken to be a linear function of the dose, so it decreases with major radius. Second, the irradiation creep shows similar behavior, because it is proportional to the dose rate.

Figure 3 exhibits the deleterious effects of a damage gradient on the stress distribution in the pipe. Although the overall damage in the pipe has decreased, the maximum stress actually increases due to the overall decrease in the creep coefficient. Fortunately, the stress at the welds (θ = 0), which will likely be the pipes' weakest points, decreases by a small amount.

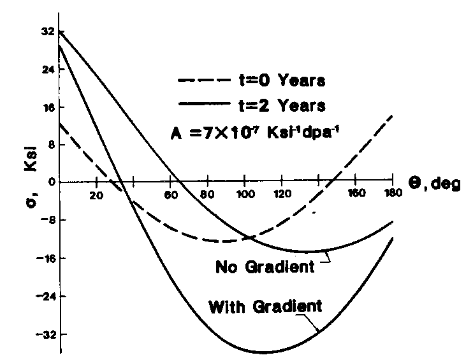

FIGURE 3
effect of damage gradient on stress distribution

6. THERMAL CREEP

From the available HT-9 data, it appears that at temperatures near or below 500°C, thermal creep can be neglected if the stress levels are below about 40 ksi. Because the structure temperatures in the MARS blanket are limited to about 500°C by the compatibility of the LiPb coolant with HT-9 and the stresses are maintained below 30 ksi, the previous analyses will not be substantially affected by thermal creep.

In order to assess the structural response to the temperature and non-linear stress dependences of thermal creep, we will consider an illustrative case in which the inlet and outlet coolant temperatures will be 450°C and 550°C respectively. Irradiation creep will be neglected here, so the diminished stress relief will enhance the thermal creep deformations. The assumed coolant temperatures might be seen in a blanket for which the designer attempts to avoid the ductile-to-brittle transition temperature (DBTT) of HT-9 and also keep the structure temperature away from the peak swelling temperature of 425°C.

The effect of thermal creep on the stress distribution in the pipe is shown in figure 4. The stress is redistributed by the deformation, increasing in some places and decreasing in others. This non-uniform effect results from the temperature dependence and non-linear stress dependence of the creep law. In the case of irradiation creep, the creep rate is linear in the stress and is unaffected by temperature over the range used, so the relaxation process occurs uniformly and the shape of the stress distributions is unchanged.

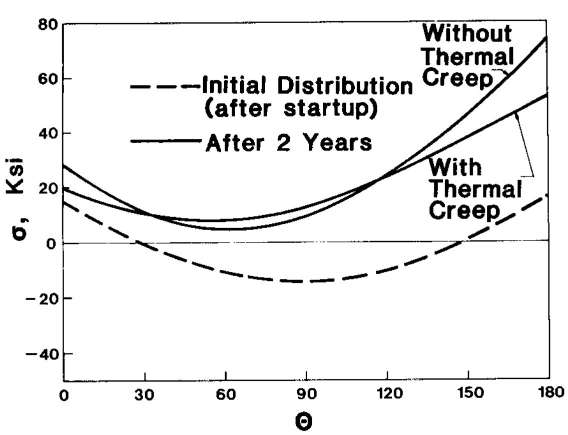

FIGURE 4
effect of thermal creep on stress distribution

Although thermal creep appears to have increased the blanket lifetime by decreasing the stresses at the welds, the increased deformation due to creep strains must also be considered as a cause of failure. If we impose a limit of one percent on the accumulated creep strains (as seen in the ASME Boiler and Pressure Vessel code), the life would be limited to less than three years by thermal creep alone. A limit of one percent on the total permanent strain would decrease the lifetime to below two years and the inclusion of irradiation creep will further increase the permanent strain. Apparently, operating the blanket in this high temperature range is not beneficial because of the onset of thermal creep.

7. LIFETIME PREDICTION

Because of the uncertainties in the material properties and modeling of any structural analysis, the most realistic result is a frequency of failure, rather than an absolute failure time. In the context of this paper, we will illustrate this method by focusing on irradiation creep. We predict the failure frequency using an assumed probability of occurrence for the creep compliance, A_c. The EOL criterion will vary, depending on the extent of the analysis.

In figure 5, the EOL is shown for a design stress limit of 28 ksi[5] and two different strain limits. Apparently, the lifetime will be primarily strain limited and the failure will occur by loss of structural integrity or rupture.

In order to determine the frequency of failure, we will use the more conservative limit of 2% permanent strain and assume that A_c has an equal probability of occurrence anywhere in the measured range of the available data[3] and no probability outside that range. A more realistic assumption might be some type of normal distribution, but a uniform occurrence will be adequate for demonstration purposes. Figure 6 shows that, under the assumed operating condi-

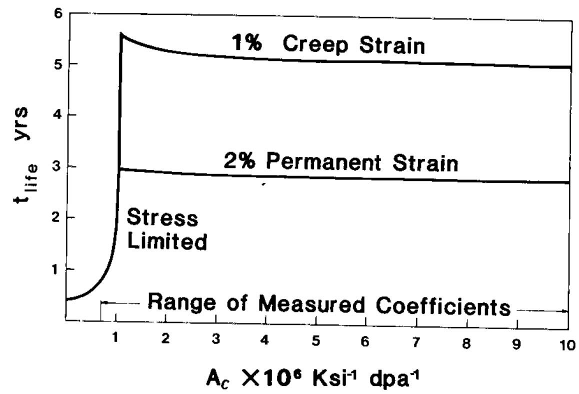

FIGURE 5
end of life for assumed failure criteria

tions, over 90% of the coolant pipes in the MARS blanket should survive nearly three years. The abrupt change in the predicted frequency at about 2.8 years is due to the fact that the vast majority of the pipes will be in the strain limited region, where the EOL is nearly independent of A_c .

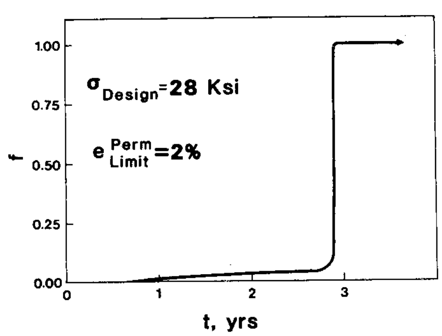

FIGURE 6
frequency of failure for uniform A_c distribution

8. SUMMARY AND CONCLUSIONS

Although void swelling can cause very large stresses in a structure, irradiation creep may relieve these stresses to a level that will allow an adequate lifetime for a fusion component. The stress levels in a well designed pipe will reach a steady-state value below the design stress, but this does not lead to infinite life. The swelling and creep will continue, despite the steady stress, and failure occurs because of excessive deformation.

To narrow down the prediction of a component's failure point, statistical methods can be used to calculate the probability of failure. With the use of some reasonable, simplifying assumptions, the probability of any pipe lasting about 2.8 years in the MARS blanket was found to be about 0.95. Obviously, the failure frequency will vary widely for different EOL limits or parameter distributions. More work is needed to quantify the effects of statistical uncertainties and alternate design equations such as the recently suggested bilinear swelling behavior for HT-9 including an incubation dose.

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