Sensitivity Analysis for Lifetime Prediction of Fusion Structures

J.P. Blanchard, N. Ghoniem
University of California, School of Engineering and Applied Science,
6288 Boelter Hall, Los Angeles, California 90024, U.S.A.

ABSTRACT

The sensitivity of lifetime predictions for fusion reactor blanket structures is investigated by applying the Monte Carlo numerical technique. A structural computer code, STAIRE, which has been developed for the analysis of mirror fusion blankets is used for the prediction of structural lifetime. Uncertainties in material variables are treated as probabilistic input to the STAIRE code. Irradiation Creep rates are shown to be sufficient for relaxation of swelling stresses under the majority of conditions. An engineering swelling limit, which is dependent on blanket geometry, is shown to be an important failure criterion. In the case of HT-9, it appears that the blanket structure lifetime could be several hundred displacements per atom.

1. INTRODUCTION

A considerable degree of uncertainty is associated with measurements aimed at assessing radiation effects on structural materials. In view of such a wide range of ambiguities, lifetime predictions of fusion reactor components are best treated as probabilistic quantities. This is especially true if various phenomena interact in a non-linear fashion.

Recently, we have developed a computer code, STAIRE, for the determination of blanket structural response in mirror fusion reactors [1]. The model has been applied to the analysis of the MARS [2] blanket modules. The significant features of this work are the inclusion of radiation swelling and creep, as well as thermal creep. With this in hand, it is possible to perform a complete structural analysis of semi-circular, tubular fusion blankets, as described in the MARS design. In this paper, we seek to establish the sensitivity of lifetime predictions to uncertainties in material properties.

2. STRESS AND STRAIN LIMITS

After performing a thorough stress analysis, the structure's life is determined by imposing limits on either the strain or stress. Excessive deformation can account for impaired performance due to either large deflections or damage which causes fracture or rupture. In this paper, limits of 10% swelling (excessive deformation) and 1% total creep strain (damage) are considered. The creep limit is based on guidelines in the ASME code [3], despite the fact that the code doesn't treat irradiation creep explicitly.

Stress limits, such as those in the ASME code, attempt to account for a number of possible failure mechanisms, including tensile instability and creep rupture. Again, the present analysis employs stress limits suggested by the ASME code, although these limits do not explicitly include irradiation effects.

3. LIFETIME EQUATIONS

3.1 Swelling Limit

If one assumes that the swelling rate in a material is independent of the stress state, the lifetime can be easily determined. In general, the swelling rate depends on the hydrostatic stress [4], but this effect is assumed to be small. The volumetric swelling, $\frac{\Delta V}{V}$, is generally given by an equation of the form:

$$S(T) = \frac{\Delta V}{V} = \dot{S}(T)(\delta-\delta_I) \qquad (1)$$

where δ is the dose in displacements per atom (dpa), δ_I is the incubation dose, and $\dot{S}(T)$ is the swelling rate at a given temperature, T. The lifetime (in dpa) due to a swelling limit, $S_{\ell im}$, is then given by:

$$\delta_L^S(T) = \frac{S_{\ell im}}{\dot{S}} + \delta_I \qquad (2)$$

$S_{\ell im}$ is a predetermined engineering swelling limit, which is design-dependent.

3.2 Creep Limit

Commonly, irradiation creep is modeled according to: [5]

$$\dot{e}^c = A\,\delta\sigma \qquad (3)$$

where $\dot{e}^c$ is the creep rate, $A\delta$ is the creep compliance (MPa^{-1}) and σ is the effective stress. Using modified beam theory, which applies to the MARS blanket, one finds the following equation for the local stress in the blanket pipes [1].

$$\sigma = \begin{cases} \sigma_0 \exp(-\delta/\Delta) & \delta<\delta_I \\ \sigma_0 \exp(-\delta/\Delta) + \dot{\sigma}\Delta\{1-\exp[-(\delta-\delta_I)/\Delta]\} & \delta>\delta_I \end{cases} \qquad (4)$$

where σ_0 is the thermal stress, $\dot{\sigma}$ is the creep-free rate of stress increase (MPa/dpa), δ_I is the incubation dose, and Δ is a relaxation parameter given by $\Delta = 1/AE$, where E is Young's Modulus. Equation (4) features an exponential decay of the thermal stress and an exponential approach of the local stress to a steady-state value: $\dot{\sigma}\Delta$.

Integrating equation (3) and assuming that the lifetime is much greater than the incubation dose, one finds

$$\delta_L^c = \delta_I + \Delta + (E\varepsilon_{\ell im}^c - \sigma_0)/\dot{\sigma} \qquad (5)$$

where $\varepsilon_{\ell im}^c$ is a pre-supposed creep limit. Hence, for a given material, the creep life depends only upon σ_0 and $\dot{\sigma}$, which are design dependent.

3.3 Stress Limit

The stress-limited life is easily obtained from equation (4). Assuming $\delta_L^\sigma > \delta_I$, one finds

$$\delta_L^\sigma = -\Delta \ln \left\{ \frac{[\sigma_{\ell im} - \dot{\sigma}\Delta]}{[\sigma_0 - \dot{\sigma}\Delta \exp(\delta_I/\Delta)]} \right\} \tag{6}$$

where $\sigma_{\ell im}$ is the stress limit. In deriving this equation, the quantity in brackets was assumed to be positive.

4. UNCERTAINTY ANALYSIS

Because the irradiated behavior of many ferritic steels is not well characterized, an investigation of the response of a first wall to changes in the material parameters is useful for addressing the relative importance of these unknowns. If the blanket life calculation is not sensitive to variations in a given parameter, then precise knowledge of the value of that parameter is relatively unimportant and testing should be focused elsewhere. These types of evaluations can be made by considering material parameters as random input, with a probability distribution centered about some average value. The response, then, is also random and its distribution about an average indicates its sensitivity to a particular input or groups of inputs.

The Monte Carlo method [6] simulates an experiment by generating a random number to represent the uncertainty in each input parameter and then calculating the corresponding parameter according to an assumed distribution function. The structural response to these inputs is then calculated. After repeating this process many times, a response distribution is obtained.

In this paper, the variables $\dot{\sigma}$, δ_I and $\dot{S}$ will be treated as random. For comparison purposes, all three will be characterized by normal probability density functions.

5. RESULTS

Given the lifetime criteria from equations 2, 5 and 6, the lifetime is the lowest of $\delta_L{}^s$, $\delta_L{}^c$ and $\delta_L{}^\sigma$. The following results will consider the stress limit along with *either* of the strain limits, so the effects of creep and swelling can be accounted for separately. After calculating values for σ_0 (81 MPa) and $\dot{\sigma}$ (5.6 MPa/dpa), the lifetime can be plotted in terms of $\dot{S}$, as seen in figure 1. The 15% peak swelling limit, which leads to a deflection at the pipe's center of approximately 4.4 cm, is the most conservative of the three limits, but the allowable swelling may be lower in other designs.

The importance of the stress limit depends on the relative creep and swelling rates. If the swelling rate is high, the stress will increase rapidly and the stress limit will quickly be reached. On the other hand, a relatively high creep rate will relax the stress leading to a steady state stress below the limit. In this case, the stress limit is inconsequential. As shown in figure 1, a creep rate of $7.3\text{x}10^{-7}$ MPa^{-1} dpa^{-1} leads to a creep-limited life for any value of $\dot{S}$ in the range expected for ferritic steels. A creep rate of $1.6\text{x}10^{-7}$ MPa^{-1} dpa^{-1}, though, does invoke the stress limit, leading to rather short lives for swelling rates above .03%/dpa.

To investigate the impact of the creep/swelling ratio, one can plot curves of constant life in S-A space. Figure 2 shows a typical plot for δ_L = 420 dpa. For a given material, the creep/swelling ratio can be represented by a straight line from the origin and the lifetime is determined by the intersection with the constant-life curve. As seen, the creep/swelling ratio must be above 1790 MPa to invoke the stress limit. Using data gathered by Gelles and Puigh [7], the creep/swelling ratio of a typical ferritic steel is approximately 500 MPa, so the stress limit will not likely be important for the MARS blanket. The design would have to be more highly constrained, increasing $\dot{\sigma}$, before the steady state stress exceeded the stress limit.

The failure criteria used in the analysis can significantly impact the blanket life. Figure (3) gives the lifetime distribution for the swelling and creep limits. The stress limit is not significant because the creep coefficient, A, is relatively high and the stresses are correspondingly low. The distribution functions are of similiar shape, but the swelling-limited curve is shifted almost two hundred dpa up the scale. Notice that the results of the Monte Carlo simulations are smoothed in Figure (3) for clarity.

The stress limit enters the picture as the average creep coefficient is decreased. If $\bar{A}$ is lowered to $1.6\text{x}10^{-7}$ MPa^{-1} dpa^{-1}, the lifetime distribution becomes more complex because the stress limit leads to "failures" at 150 to 400 dpa. When stress limits are reached early in life, the strain limits only affect the remaining blankets, ie., there is no interaction between the criteria. These features are displayed in figure (4); for the higher average creep coefficient, about half the blankets reach the design limit before 200 dpa.

6. CONCLUSIONS

It is shown in this paper that an analogue Monte Carlo technique can successfully be coupled to a deterministic inelastic structural analysis code. Such a strategy allows investigations of the influence of material property uncertainty propagation on the prediction of structural failure. The need for such a technique is particularly important in fusion reactor applications, since prototypical testing environments are non-existent, and that radiation effects on material properties are uncertain. The following are conclusions of the present work which apply to the structural material HT-9 in a Mirror Fusion Reactor:

(1) Irradiation creep and swelling rates of HT-9 indicate that chances are small for overstressing a MARS-type blanket due to swelling.

(2) Since irradiation creep is assumed to be a non-damaging form of plastic deformation, structural failure will most likely be due to excessive swelling.

(3) The present MARS-blanket design, unlike Tokamak blankets, benefits from a low surface heat load, low surface erosion rate, and minimal geometric constraints. These factors combine to give a possible structural lifetime of several hundred displacements per atom.

ACKNOWLEDGEMENT

The research was performed under appointment of J. Blanchard to the Magnetic Fusion Energy Technology Fellowship program administered by Oak Ridge Associated Universities for the U.S. Department of Energy. The support of the U.S. department of Energy through research contract #DE-AT03-80ER52061 Mod. No. A012 with the University of California is appreciated.

REFERENCES

/ 1 / Blanchard, J.P. and Ghoniem, N.M., "Inelastic Structural Analysis of the MARS Tandem Mirror Reactor," Nuclear Engineering and Design/Fusion, January (1985).

/ 2 / Logan, B.G., et al., "Mirror Advanced Reactor Study Interim Design Report," Lawrence Livermore National Laboratory Report UCRL-53333, April (1983).

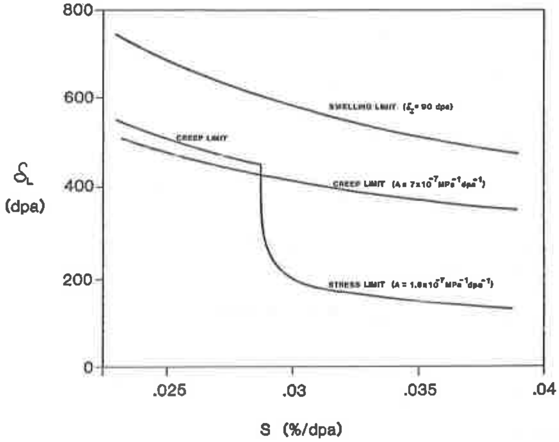
/ 3 / ASME Boiler and Pressure Vessel Code, Sections I, II, and III, and Code Case 1592, "Class I Components in Elevated Temperature Service," (1977).

/ 4 / Wolfer, W., Ashkin, M. and Boltax, A., "Creep and Swelling Deformation in Structural Materials During Fast-Neutron Irradiation," ASTM STP-570 (1976).

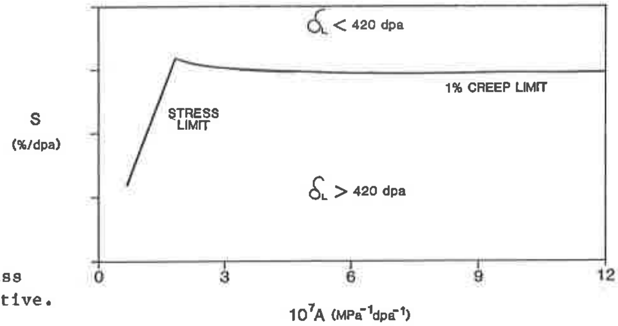
/ 5 / Olander, D., Fundamental Aspects of Nuclear Reactor Fuel Elements, Technical Information Center, U.S. Department of Energy, (1976).

/ 6 / Hart, G., Uncertainty Analysis, Loads, and Safety in Structural Engineering, Prentice Hall, Inc., Englewood Cliffs, NJ (1982).

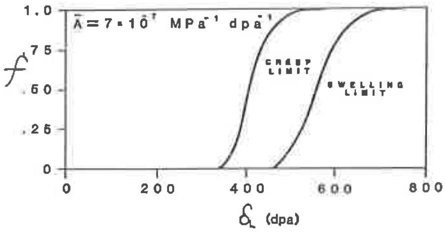
/ 7 / Gelles, D. and Puigh, R., "Evaluation of Ferritic Alloy Fe-2 $1/4$ Cr-$1M_0$ After Neutron Irradiation-Irradiation Creep and Swelling," HEDL-7405 (1983).



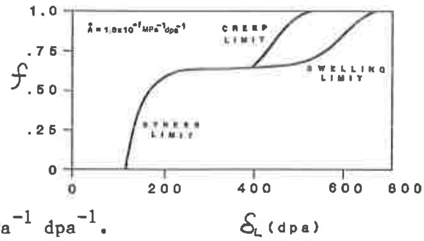
1. Lifetime as a function of swelling rate for three different end-of-life criteria.



2. Constant-life curve assuming stress and creep damage limits are operative.



3. Cumulative failure probability for $\bar{A} = 7\times10^{-7}$ MPa^{-1} dpa^{-1}.



4. Cumulative failure probability for $\bar{A} = 1.6\times10^{-7}$ MPa^{-1} dpa^{-1}.