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1. Introduction

The lack of a large data base for material properties in a prototypical fusion environment complicates the process of component lifetime prediction. A considerable degree of uncertainty is associated with measurements aimed at assessing radiation effects on structural materials. If we consider structural swelling due to neutron displacement damage as an example, we realize the sizable degree of ambiguity in the swelling behavior due to the nature of the irradiation environment. Displacement damage rate, helium generation rate, and helium-to-dpa ratio are just a few of the parameters that influence swelling. Other uncertainties may result from heat-to-heat variations, compositional differences, sample conditions, etc. In view of such a wide range of conditions, a lifetime prediction of a fusion reactor component is best treated as a probabilistic quantity. This is especially true if various phenomena interact in a non-linear fashion.

A sensitivity analysis of a blanket's lifetime can be used to guide future materials testing. If the lifetime is particularly sensitive to a measurable property, such as the creep modulus or the swelling rate, additional testing in that area can be quite valuable to designers. Alternatively, testing of parameters for which uncertainty has little impact on blanket life can be deemphasized. The potential for equipment and manpower savings are obvious.

A useful by-product of a detailed lifetime analysis is a set of scaling functions which contain the dependence of the blanket dimensions. Full-size fusion reactor blanket modules must eventually be tested before commercial fusion is achieved. To reach this goal, however, smaller size modules may have to be used in order to study interactive phenomena at a reasonable cost. An interesting question arises in this regard: Is it possible to preserve the "structural state" of a blanket module when its size is scaled down? In other words: Can the failure of a structure be simulated by a scale model? The scaling functions can be utilized to address these questions.

We have recently developed the 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 semicircular tubular fusion blankets, as described in the MARS design.

We aim to accomplish two objectives in this paper: (1) to establish the sensitivity of lifetime predictions to uncertainties in material properties, and (2) to develop scaling functions for the study of the effects of geometrical dimensions on lifetime determination.

In the following section, we discuss stress and strain limits that determine the structural lifetime. In section 3 we present simple analytical equations for the determination of component lifetime based on swelling, stress or creep strain limits. This is followed by a brief description of the stress analysis model as applied to a mirror fusion reactor blanket. We then proceed to develop methodology for determining the sensitivity of lifetime predictions to material variables in section 5 and scaling relationships in section 6. Section 7 is devoted to the results of the analysis. Conclusions are given in section 8.

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. Strain limits account for impaired performance due to either large deflections or damage which causes fracture or rupture, while stress limits account for a number of failure modes. 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. In this context, the limit is somewhat contrived but it can still be meaningful if considered as a conservative limit. Since it has been argued that irradiation creep is non-damaging [4] and thermal creep rates in HT-9 are low for the temperature at which the MARS blanket operates [5], the actual damage limit could actually be much higher than 1%. Conservative limits are advisable though, until more is known about material failure in a fusion environment.

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 radiation effects. As with the damage limit, the stress limit used in this paper is conservative, although for different reasons. In the ASME Code, thermal stresses (referred to as secondary stresses) have higher allowable levels because they are selflimiting. However, a key deficiency of the Code is the absence of any time-dependent strain that would be analogous to void swelling. Failure due to stresses developed by such a phenomenon will likely be bounded by the well understood primary and secondary stresses considered in the Code, so the conservative primary stress limit has been used because of the uncertainty involved.

Table 1
Stress limits (MPa) for ferritic/martensitic alloys (without irradiation)

Temperature (°C)	$2\frac{1}{4}$Cr–1Mo		HT-9	
	3 years	30 years	3 years	30 years
450	170	170	190	185
475	160	130	180	155
500	130	100	155	130
525	100	80	130	105
550	80	60	105	80

The values in table 1 illustrates stress limits for the two structural materials HT-9 and $2\frac{1}{4}$Cr–1Mo [5]. These limits are determined according to the ASME Boiler and Pressure Vessel Code guidelines for S_{mt}.

3. Lifetime equations

This section presents material behavior equations that are used to model swelling and irradiation creep. In each case these equations are the simplest available, so some potentially significant effects are ignored. The swelling equation, for instance, ignores temperature dependence of the incubation dose and stress dependence of the swelling rate. Also, the irradiation creep rate is assumed to be independent of temperature. These equations do not necessarily reflect the exact material behavior, but they are useful for analyzing the gross effects of material data deficiencies. The analysis can be refined as material behavior is better quantified.

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 [6], but this effect is assumed to be small. The volumetric swelling $\Delta V/V$ is given by an equation of the form:

$$S(T)=\frac{\Delta V}{V}=\dot{S}(T)(\delta-\delta_{I}), \tag{1}$$

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_{lim} is then given by:

$$\delta_L^S(T) = \frac{S_{\text{lim}}}{\dot{S}} + \delta_I, \tag{2}$$

where S_{lim} is a predetermined engineering swelling limit, which is design dependent. For the MARS design [2], the average swelling is about 2/3 of the peak swelling, due to the predicted temperature variations in the swelling rate [1], so one must be careful to specify whether the peak or average swelling is life limiting.

3.2. Creep limit

Commonly, irradiation creep is modeled according to [7]:

$$\dot{e}^c = C\dot{\delta}\sigma, \tag{3}$$

where $\dot{e}^c$ is the creep strain rate (s^{-1}), $C\dot{\delta}$ is the creep compliance ($MPa^{-1}\ s^{-1}$) 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].

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

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

$$\Delta = 1/CE, \tag{5}$$

where E is Young's Modulus. Eq. (4) features an exponential decay of the thermal stress and an exponential approach of the local stress to a steady-state value of $\dot{\sigma}\Delta$.

Integrating eq. (3) with eq. (4) and assuming that the lifetime is much greater than the incubation dose (which seems to be valid for ferritic steels), one finds

$$\delta_L^c = \delta_I + \Delta + (E\epsilon_{\text{lim}}^c - \sigma_0)/\dot{\sigma}, \tag{6}$$

where ϵ_{lim}^c is a pre-determined 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 eq. (4). Assuming $\delta_L^\sigma \geqslant \delta_I$, one finds

$$\delta_L^\sigma = -\Delta \ln\left[\frac{\sigma_{\text{lim}} - \dot{\sigma}\Delta}{\sigma_0 - \dot{\sigma}\Delta \exp(\delta_I/\Delta)}\right], \tag{7}$$

where σ_{lim} is the stress limit. In deriving this equation, the quantity in brackets was assumed to be positive.

4. Model description

The investigation in this paper is generic and can be applied to any irradiated structure once a stress analysis approach has been adopted. To give specific conclusions, however, we will apply the structural code STAIRE [1]. This computer code has been developed by a modification of beam and arch theory to include inelastic radiation strains. The method has been successfully applied to the MARS [2] blanket configuration. For the reader's benefit, we include in this section a brief description of the method and its application to the MARS study.

Fig. 1 shows one pipe of the MARS blanket. In our model, we treat the pipe as an indeterminate beam of a hollow cross section. Because the pipes are indeterminate, the stress and deflections are coupled and must be simultaneously found 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:

$$\Delta R = -\int w'x\, ds + \int \bar{e}' \sin\theta\, ds + XM\int \frac{x\, ds}{EI} + XF\int \frac{xy\, ds}{EI} + XP\int \frac{y^2\, ds}{EI}, \tag{8}$$

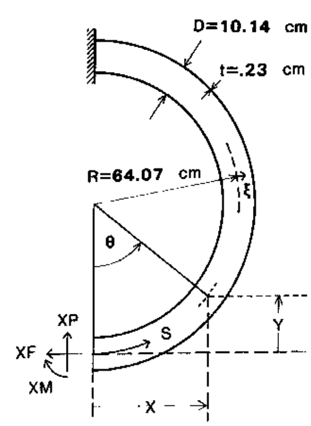

Fig. 1. Model used for analysis of the MARS coolant pipes.

where

$$w' = \frac{1}{K_{II} I} \int_A \left(e^c + \frac{\Delta V}{3V} + \alpha T \right) \xi \, dA, \tag{9}$$

and

$$\bar{e}' = \frac{1}{A} \int_A \left(e^c + \frac{\Delta V}{3V} + \alpha T \right) dA. \tag{10}$$

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. Combining eq. (8) with equations for the axial end displacement and end rotation, the system 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. The axial stress is then given by:

$$\sigma = \frac{F}{A} + \xi\left(1 - K_I \xi^2\right)\left(\frac{M}{K_{II} I} - E w'\right) - E\left(e^c + \frac{\Delta V}{3V} + \alpha T - \bar{e}'\right), \tag{11}$$

where K_I and K_{II} are constants determined by the pipe dimensions. ξ is the distance from the neutral axis at a given cross section, I the moment of inertia, e^c is the creep strain, $\Delta V/3V$ is the swelling strain, α is the coefficient of thermal expansion, and E is Young's Modulus. For further details of the method, the reader should consult ref. [1].

5. Uncertainty analysis

5.1. Monte Carlo technique

Because the irradiated behavior of many ferritic steels is essentially unknown, 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. Then the response is also random and its distribution about an average indicates its sensitivity to a particular input or groups of inputs.

There are two basic methods for inserting random variables into a structural model. The first, which is termed linear statistical analysis [8], uses a truncated Taylor's series expansion to create a relationship between the input variables and the random response. The drawback of this method is that it only yields limited information about the response function [8].

The second method is a Monte Carlo technique [8], which is ideal for use with an existing computer code. In essence, the method simulates an experiment by generating a random number to represent the uncertainty in each input parameter and then calculates 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. This method is generally more favored than the Taylor's series approach because it yields the complete response function, regardless of the degree of non-linearity in the relationship between input and output. The Monte Carlo method will be used here for the above reasons and because it adapts very well to use with the STAIRE computer code.

5.2. Input representation

In representing a random input or output, one assigns to it a probability density function $p(z)$, where $p(z)\,dz$ is defined as the probability that a variable exists between z and $(z + dz)$. In addition, one can also consider the cumulative probability distribution functions $P(z)$, which gives the probability that the variable will have a value less than or equal to z.

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

To define these functions, an average and standard deviation must be supplied. For the three random input

Table 2
Baseline parameters of MARS blanket and average material parameters

$R = 64$ cm	$\alpha = 11.3 \times 10^{-6}$ °C^{-1}
$r = 5$ cm	$C = 7.25 \times 10^{-7}$ MPa^{-1} dpa^{-1}
$\tau = 0.25$ cm	$\dot{S} = 0.03\%$/dpa
$T_{in} - T_{ref} = 320$ °C	$\delta_I = 90$ dpa
$T_{out} - T_{ref} = 470$ °C	$\epsilon^c_{lim} = 0.01$
$\Delta T = -30$ °C	$\sigma_{lim} = 180$ MPa
$d = 0$	$S_{lim} = 10\%$ (average)
$E = 180$ GPa	–

variables, the standard deviation is chosen to be 10% of the average values given in table 2.

6. Scaling relationships

For a given set of design limits and material parameters, the lifetime depends only on $\dot{\sigma}$ and σ_0, which are geometry dependent. As shown in fig. 1, the MARS coolant pipes are semi-circular, with the baseline dimensions as given in table 2. For simplicity, the temperature difference over the cross section, i.,e., the difference between the shield-side and plasma-side temperatures, is assumed to be independent of θ.

In order to allow maximum flexibility in using the lifetime equations generated in section 3, relationships are developed for σ_0 and $\dot{\sigma}$ in terms of four key parameters. First, the stresses are given in terms of the temperature difference ΔT and the radial header translation d, which is the radial distance traveled by one end of the pipe relative to the other. If the pipes are rigidly attached to a fixed header, then no translation is allowed and $d = 0$. On the other hand, thermal expansion is better accomodated by a less rigid connection at the header. Allowing some radial header motion then, can relieve the stresses and increase the blanket life. In this model, d is positive inward so a negative value will reduce the stresses.

The second set of equations gives the stress parameters σ_0 and $\dot{\sigma}$ in terms of geometric quantities r, t, and R.

Using equations developed previously [1], the maximum thermal stress $\sigma_{0,\mathrm{MAX}}$ (in MPA), is found to be

$$\sigma_{0,\mathrm{MAX}} = 103.3 + 0.745\,\Delta T + 187.3\,d, \tag{12}$$

assuming all parameters other than ΔT (in K) and d (in cm) are constant. varying R, r, and t, and keeping ΔT and d constant, one also finds

$$\sigma_{0,\mathrm{MAX}} = 2372\,w\left[\frac{0.355 + 1.2(u/w)^2}{1 + 1.2(u/w)^2}\right], \tag{13}$$

where $u = t/r$ and $w = r/R$. According to eq. (13), $\sigma_{0,\mathrm{MAX}}$ depends only on the ratios of pipe dimensions, so if a scale model preserves these ratios and the temperatures, the initial stress will be preserved.

Because the swelling equation used previously [1] was a highly nonlinear function of temperature, equations for $\dot{\sigma}$ could not be derived analytically. Using the STAIRE code to determine the increase in the local stress due to a constant swelling rate $\dot{S}$, values of $\dot{\sigma}$ for various values of w, u, and R were generated. These data points were fit to equations similar to eqs. (12) and (13) with a least-squares fitting routine. The results (in MPa/%) are:

$$K = 65.6 - 3.97\,\Delta T, \tag{14}$$

and

$$K = 103 + 332\,u + w\left[74.5 + \frac{9.52 \times 10^{-3}}{u^3} \times \left(\frac{0.355 + 201\,u^2}{1 + 201\,u^2}\right)\right], \tag{15}$$

where

$$\dot{\sigma} = K\dot{S}. \tag{16}$$

7. Results

7.1. Lifetime predictions

Given the lifetime criteria from eqs. (2), (6), and (7), the lifetime is the lowest of δ_L^s, δ_L^c, and δ_L^σ. 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 choosing values for σ_0 (81 MPa) and K (185 MPa/%), the lifetime can be plotted in terms of $\dot{S}$, as seen in fig. 2. 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.

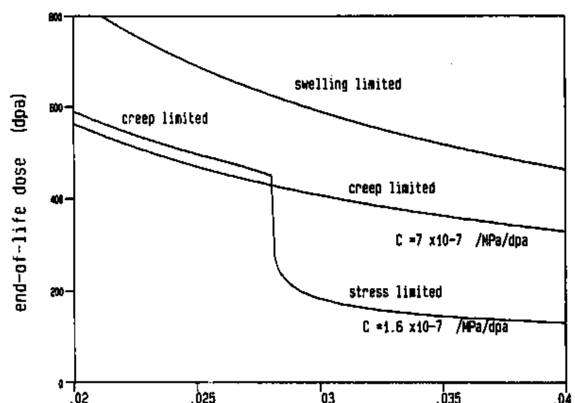

Fig. 2. Lifetime as a function of swelling rate for the swelling limit and for the creep and stress limits at two different creep rates.

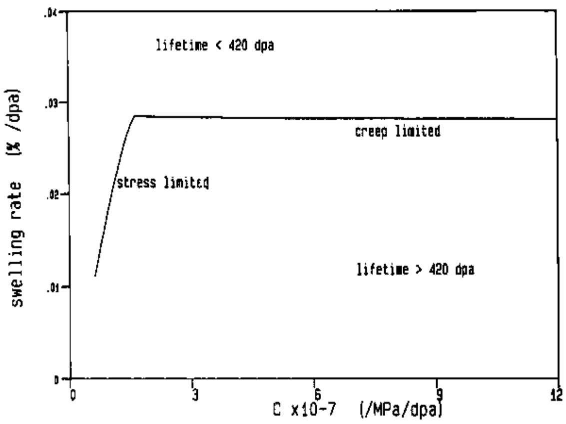

Fig. 3. Constant-life curve assuming stress and creep damage limits are operative.

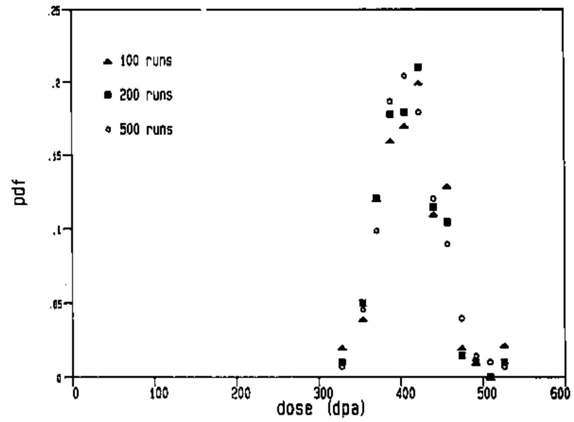

Fig. 4. Probability density function for three different numbers of Monte Carlo histories.

The importance of the stress limit depends on the relative creep and swelling rates. If the creep rate is low, 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, thus rendering the stress limit inconsequential. As shown in fig. 2, a creep rate of 7.3×10^{-7} MPa^{-1} dpa^{-1} leads to a creep-limited life for any value of $\dot{S}$ in the range expected for ferritic steels. However, a creep rate of 1.6×10^{-7} MPa^{-1} dpa^{-1} does invoke the stress limit, leading to rather short lives for swelling rates above 0.03%/dpa.

To investigate the impact of the swelling/creep ratio, one can plot curves of constant life in swelling-creep space. Fig. 3 shows a typical plot for $\delta_L = 420$ dpa. For a given material, the swelling/creep ratio ($\dot{S}/C$) can be represented by a straight line from the origin and the lifetime (and the relevant limit) is determined by the intersection with the constant-life curve. A seen, the ratio must be above 1790 MPa to invoke the stress limit. Using data gathered by Gelles and Puigh [9], the swelling/creep 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 (thereby increasing K) before the steady-state stress exceeded the stress limit.

7.2. Monte Carlo results

Because the Monte Carlo method is a sampling process, its accuracy of representation improves as the number of samples or trial runs is increased. Unfortunately, the cost increases with the number of samples, so one must choose a count that is sufficiently accurate and yet affordable. Fig. 4 shows the probability density function (pdf) for the blanket life, assuming that C, δ_I, and $\dot{S}$ are all variable. As seen, the result does not converge to a single function as the number of samples increases, so it is not apparent that even 1000 runs are sufficient for the analysis.

The cumulative distribution function (cdf), on the other hand, integrates out many of the variations inherent in the density function so less samples are necessary for the same accuracy. This is evident in fig. 5, which shows the distribution function of the blanket life for the same three random inputs. Apparently, even 100 samples would be sufficient for most analyses. The effects of sample size on the accuracy of results can be established [10], but this is outside the scope of the present study.

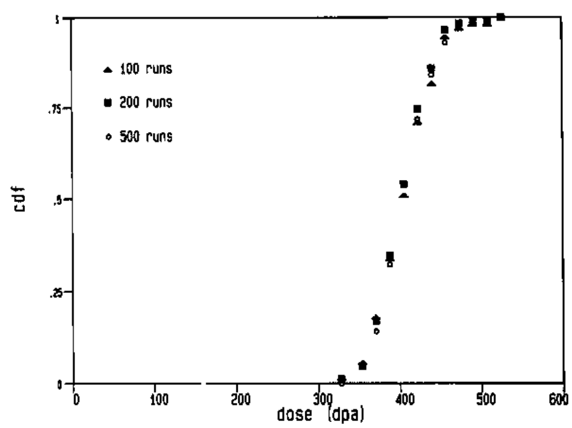

Fig. 5. Cumulative distribution function for three different numbers of Monte Carlo histories.

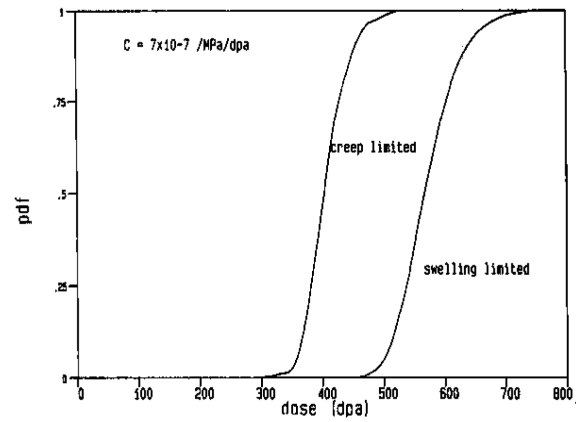

Fig. 6. Cumulative failure probability for $C = 7\times10^{-7}$ MPa^{-1} dpa^{-1}.

The failure criteria used in the analysis can significantly impact the blanket life. Fig. 6 gives the lifetime distribution for the swelling and creep limits. The stress limit is not significant because the creep coefficient C is relatively high and the stresses are correspondingly low. The distribution functions are of similar shape but the swelling-limited curve is shifted almost 200 dpa up the scale. Notice that the results of the Monte Carlo simulations are smoothed in figs. 5–7 for clarity.

The stress limit enters the picture as the average creep coefficient is decreased. If the average value of C is lowered to 1.6×10^{-7} MPa^{-1} dpa^{-1}, the lifetime distribution becomes more complex because the stress limit leads to end-of-life at 150 to 400 dpa. When stress limits are reached early in life, the strain limits only affect the remaining blankets, i.e., there is no interaction between the criteria. These features are displayed in fig. 7, which differs from fig. 6 only in the average value of C. For the higher average creep coefficient, the frequency of failure is essentially zero below about 320 dpa.

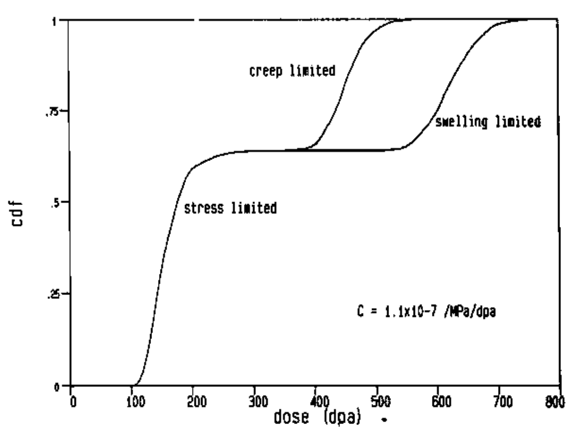

Fig. 7. Cumulative failure probability for $C = 1.6\times10^{-7}$ MPa^{-1}dpa^{-1}.

8. 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 radiation effects on material properties are uncertain. The following are conclusions of the present work, which specifically apply to the structural material HT-9 in a mirror fusion reactor:

(1) When considering the buildup of stresses caused by swelling, the stress limit is potentially the most severe of the three lifetime criteria used in this paper.
(2) For ferritic steels, the creep rate seems high enough to relax the swelling stresses and the stress limit is relatively unimportant.
(3) The strain limit is life-limiting in all cases analyzed.
(4) A lifetime of several hundred dpa is highly probable for a ferritic steel blanket in mirror fusion reactors.

These conclusions suggest that future material testing of ferritic alloys should consider irradiation creep, to a degree. Once it has been shown that the creep rates of ferritic steels are high enough to relieve swelling stresses before significant buildup occurs, the actual value of the creep rate is unimportant. This is because the accumulated creep strain is driven by the amount of swelling strain it must offset, rather than by the creep rate. When the creep rate is large, the accumulated creep is very nearly equal to the accumulated swelling strain (with opposite sign). Hence, accurate knowledge of the swelling behavior of a material is more important than precise radiation creep data for reliable lifetime estimates.

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References

[1] J.P. Blanchard and N.M. Ghoniem, Inelastic structural analysis of the MARS tandem mirror reactor, Nucl. Engrg. Des./Fusion 2 (1985) 19.

[2] B.G. Logan 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, The American Society of Mechanical Engineers, New York, NY (1977).

[4] R.F. Mattas, Fusion component lifetime analysis, Argonne National Laboratory Report ANL/FPP/TM-160 (1980).

[5] R.J. Amodeo and N.M. Ghoniem, Constitutive design equations for thermal deformation of HT-9, J. Nucl. Mater. 122 (1984) 91.

[6] W. Wolfer, M. Ashkin and A. Boltax, Creep and swelling deformation in structural materials during fast-neutron irradiation, ASTM STP-570, American Society for Testing and Materials, (1976).

[7] D. Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements, Technical Information Center, TIC-26711-P1, U.S. Department of Energy (1976) 590.

[8] G. Hart, Uncertainty Analysis, Loads, and Safety in Structural Engineering (Prentice Hall, Inc., Englewood Cliffs, NJ 1982) 65–82.

[9] D. Gelles and R. Puigh, Evaluation of ferritic alloy Fe–$2\frac{1}{4}$Cr–1Mo after neutron irradiation – irradiation creep and swelling, Hanford Engineering Development Laboratory Report HEDL-7405 (1983).

[10] L.L. Carter and E.D. Cashwell, Particle transport simulation with the Monte Carlo method, Los Alamos National Laboratory Report TID-26607 (1975).