The Effect of Irradiation Creep, Swelling, Wall Erosion and Embrittlement on the Fatigue Life of a Tokamak First Wall

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THE EFFECT OF IRRADIATION CREEP, SWELLING, WALL EROSION AND EMBRITTLEMENT ON THE FATIGUE LIFE OF A TOKAMAK FIRST WALL

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A lifetime methodology has been developed which couples the long-term stress history for a generic first wall element to a two-dimensional fatigue crack growth calculation, while including, in a self-consistent manner, the detrimental effects of radiation damage. The reduction in fracture toughness due to embrittlement can reduce lifetimes by as much as a factor of 10 by accelerating stage II fatigue crack growth and enhancing the potential for brittle fracture. Swelling and irradiation creep appear not to be life-limiting, and a certain amount of wall erosion is found to enhance first wall lifetimes.

1. INTRODUCTION

In order for the Alloy Development for Irradiation Performance (ADIP) program to successfully improve the lifetime of candidate alloys, it is necessary to identify the critical materials properties and their changes as a result of radiation damage which significantly influence the lifetime of fusion reactor first wall components. Although previous investigators have [1] identified fatigue crack growth as the primary damage mechanism for tokamak reactors, their methods have not properly included the complex synergisms that exist between the structural response and the crack growth processes which are caused by irradiation creep, swelling, embrittlement, and surface erosion.

For this reason, we have developed a comprehensive and self-consistent lifetime analysis methodology, based on a generic first wall section, which can assess and quantify those mechanical and fracture properties and design parameters which impact most severely on the lifetime. Until an irradiation facility becomes available to test these components in an actual fusion environment, this lifetime analysis code can be utilized to analytically study the impact of new materials property correlations and to guide further materials data development. Hopefully, its use will establish a stronger link not only between the Analysis and Evaluation task group and the Correlation Methodology subgroup of DAFS (Damage Analysis and Fundamental Studies task group), but also between fusion materials researchers and fusion reactor design engineers.

The lifetime analysis methodology consists of two sequentially-linked computer codes, TSTRESS and WISECRACK. TSTRESS performs an inelastic stress analysis of a generic thin-walled shell element and computes the long-term stress history which then is used as input for WISECRACK, which simulates the two-dimensional growth of a hypothetical semi-elliptical surface flaw through the wall, ultimately causing "leak-through" or "brittle fracture" failure.

2. REFERENCE DESIGN

The reference first wall design used to illustrate these effects is based on a Westinghouse FW/blanket design [2] consisting of a cylindrical canister 70 cm long with a hemispherical end cap of radius 5 cm. The 6 mm thick 316 stainless steel integral first wall operates at a neutron wall loading of 2 MW/m^2, surface heat flux of 50 W/cm^2, nuclear heating rate of 20 W/cm^3, plasma burn time of 1140 seconds, plasma off time of 60 seconds, 100% availability, and is cooled by helium gas at 6.89 MPa (1000 psi), thereby causing a coolant pressure membrane stress of 27.6 MPA (4 ksi). The wall temperature on the coolant side is fixed at 350°C and gives a maximum structure temperature of 520°C. These conditions give rise to initial stresses during the plasma burn of 434 MPa (63 ksi) on the coolant side and -331 MPa (-48 ksi) on the plasma side. The neutron damage rate is 7 x 10^{-7} dpa/sec and the surface erosion rate is zero because the wall is assumed to be protected from particle fluxes. The reference flaw is a semi-circular surface flaw 1 mm deep located on either side of the wall.

3. STRESS ANALYSIS

The stress analysis was performed by TSTRESS [3], which uses a shell element that represents a critical position on the first wall. The element, shown in Fig. 1, is constrained from bending but not from expansion and effectively models a spherically or cylindrically shaped first wall geometry whose radii of curvature are large when compared to the wall's thickness.

TSTRESS calculates the detailed stress distribution through the wall caused by four different sources: membrane loads, N_x and N_y, from coolant pressure; temperature gradients, $T(z)$, through the wall; radiation-induced swelling gradients, $S(z)$, caused by temperature gradients through the wall; and residual stress gradients

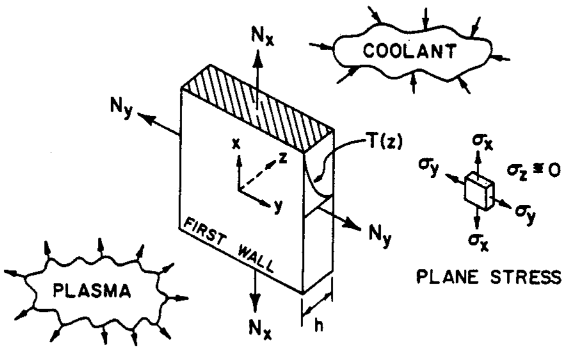

Fig. 1. TSTRESS thin-walled shell element model of a generic first wall section.

caused by a combination of thermal and irradiation creep induced stress relaxation. The Young's modulus, E, thermal expansion coefficient, α, Poisson's ratio, ν, and thermal conductivity, k, are temperature dependent and the wall's thickness, h, is allowed to decrease linearly over time due to surface erosion.

The computation of the time-dependent stress distribution through the wall is based, in principle, on the boundary integral method for inelastic deformation. In the present case, however, the method reduces to a closed-form solution that involves the one-dimensional integration of the inelastic strain components through the thickness. As a result, the stress rate $\dot{\sigma}_x(z)$ can be expressed at any given depth z as a function of the stresses at all other points through the wall. It can be shown [3] that this equation is:

$$\dot{\sigma}_x(z) = \frac{1}{h}\int_0^h \frac{E}{1-\nu}\left(\alpha\dot{T} + \frac{1}{3}\dot{S}\right) dz \qquad (1)$$

$$- \frac{E}{1-\nu}\left(\alpha\dot{T} + \frac{1}{3}\dot{S}\right)$$

$$- \frac{E\psi}{(1-\nu^2)}\left[(2-\nu)\sigma_x - (1-2\nu)\sigma_y\right]$$

$$+ \frac{1}{h}\int_0^h \frac{E\psi}{(1-\nu^2)}\left[(2-\nu)\sigma_x - (1-2\nu)\sigma_y\right] dz \quad .$$

The creep compliance, $\psi(z)$, is defined as the sum of the irradiation and thermal creep rates divided by the von Mises equivalent stress. The swelling rate, $\dot{S}(z)$, and the creep rates are functions of temperatures, stress, and fluence. The correlations for these processes are taken from the Nuclear Systems Materials Handbook. A typical long-term stress history during plasma-ON conditions for the reference design is shown in Fig. 2. During the first year of operation, the initial stresses relax due to irradiation creep. Then, the incubation dose for swelling is reached and differential swelling drives the stresses in the opposite direction. Finally, a steady-state distribution is reached after three years where an equilibrium is established between the buildup of stresses from differential swelling and the relaxation of stresses from creep processes. Wolfer [4] has shown that this saturated stress level is proportional to the ratio of $\dot{S}/\psi$.

The steady state stress distribution through the wall is shown in Fig. 3. The linear stress gradient for plasma-ON conditions is caused by the approximately linear temperature dependence of swelling, within the range of 350°C to 520°C. The fact that surface flaws located on the coolant side are predicted to grow faster than flaws on the plasma side can be easily explained by recognizing that the mean stress level is tensile on the coolant side, but is compressive on the plasma side, therefore retarding the rate of crack growth.

Although Fig. 3 resembles the initial stress distribution at time = 0, this is only fortuitous because no direct connection exists between the two states. The ratio of $\dot{S}/\psi$ that controls the steady state stresses is a function of the average wall temperature, whereas the initial stresses depend only on the temperature gradient. Nevertheless, the general shape of the stress history as shown in Fig. 2 is characteristic of any first wall which experiences simultaneous creep and swelling.

The radiation-induced changes in first wall stresses will affect fatigue crack growth in two ways, as shown in Fig. 4. First, simultaneous irradiation creep and swelling cause the mean stress level to undergo a transient redistribution over time. However, since the cyclic thermal stresses are observed to remain constant

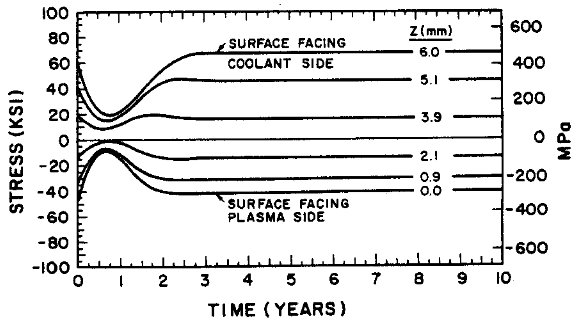

Fig. 2. First wall stresses during plasma-ON conditions for different depths through the wall without surface erosion.

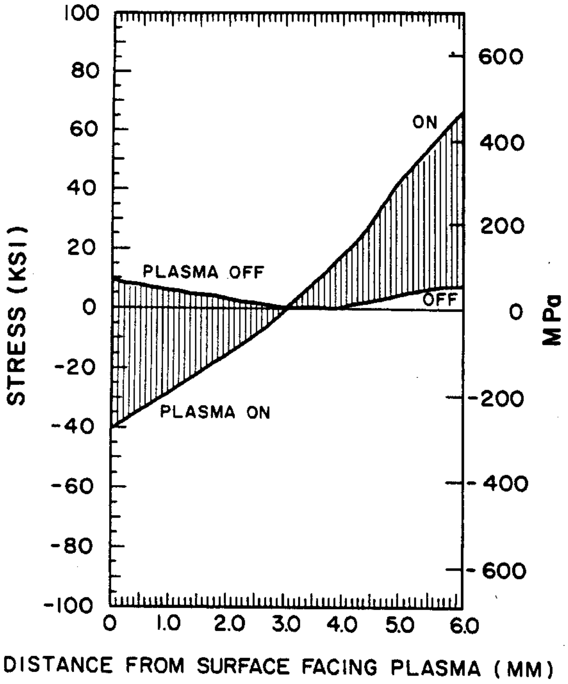

Fig. 3. Steady state stress distribution through the first wall without erosion.

for all time, the irradiation effects only influence the R-Ratio for crack growth, and not the driving force for crack propagation, $\Delta\sigma_{thermal}$.

TSTRESS was also used to study the synergistic effects of surface erosion caused by sputtering or vaporization of an unprotected first wall. Figure 5 shows the long-term history of stresses on the coolant side for the reference design subjected to an erosion rate of 0.82 mm/FPY (Full Power Year). Four different regimes of behavior can be identified. Stages I and II are essentially identical to the example of zero erosion rate shown in Fig. 4. However, in stage III a steady state distribution is never reached because the thermal stresses are constantly decreasing due to the reduction in the temperature difference, ΔT, across the wall. Eventually in stage IV, the increase in coolant pressure membrane stress $PR/2h$, will dominate over the decrease in thermal stress, and ultimately cause gross yielding or fracture.

4. CRACK GROWTH ANALYSIS

Although standard fatigue crack propagation codes are available in the literature, the unique environment in a tokamak reactor motivated us to develop a more sophisticated program: WISECRACK (Wisconsin Semi-Elliptical Crack Growth Code). Based on linear elastic fracture mechanics, WISECRACK includes the following unique features: long-term stress history from TSTRESS; two-dimensional growth of surface flaws; bending stress intensity factors; correction for short cracks; wall thinning and crack erosion effects; and temperature, R-Ratio, threshold ΔK, and embrittlement effects on the fatigue crack growth rate, da/dN.

A two-dimensional crack growth model is necessary when thermal stresses dominate, because of the linear stress gradient. Fig. 6 illustrates a typical two-dimensional growth pattern predicted by WISECRACK. Because the stresses are highest at the surface, the initially semicircular flaw grows faster along the surface "c" than through the thickness "a", eventually causing a leak-through failure after 621,000 cycles of normal operation.

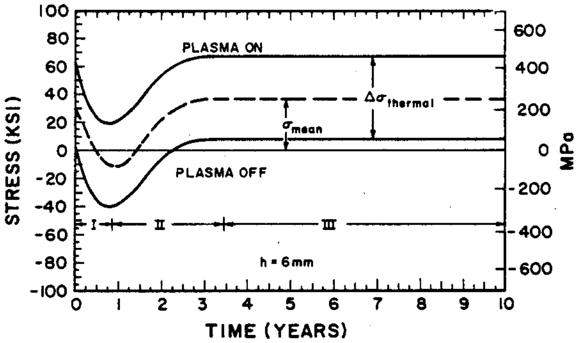

Fig. 4. Plasma-ON/OFF stresses on the coolant side; reference design without surface erosion.

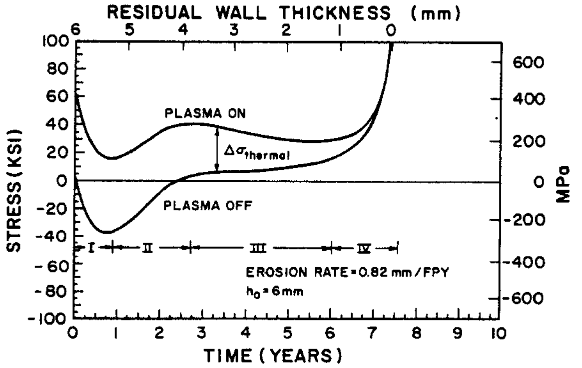

Fig. 5. Plasma-ON/OFF stresses on the coolant side; reference design with surface erosion.

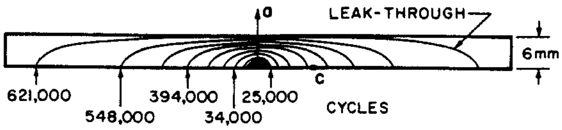

Fig. 6. Two-dimensional flaw growth pattern predicted by WISECRACK for the reference design.

The method of solution used by WISECRACK begins by computing the stress intensity factor, K, at both locations "a" and "c" along the crack front, assuming a superposition of bending and membrane loads according to

$$K_{a,c} = (M_m \sigma_m + M_b \sigma_b) \sqrt{\frac{\pi a}{Q}} \qquad (2)$$

where σ_m = membrane stress, σ_b = bending stress, M_m = membrane correction factor, M_b = bending correction factor, and $Q = 1 + 1.464\ (a/c)^{1.65}$. The stresses σ_m and σ_b are derived from a linearization technique which is applied to the actual nonlinear stress distribution $\sigma_x(z)$. The correction factors, M_m and M_b, have been computed by Newman and Raju [5], and are functions of the position along the crack front (a or c), the flaw aspect ratio, a/c, and the dimensionless depth through the wall, a/h. The fatigue crack growth rates in each direction, da/dN and dc/dN, are functions only of the cyclic stress intensity factor, $\Delta K = K(ON) - K(OFF)$ at each location. However, da/dN and dc/dN are coupled together by the dependence of the correction factors on the flaw aspect ratio, a/c. WISECRACK then solves these two coupled equations for the crack advance in both directions by using a fourth-order Runge-Kutta numerical method using automatic step size control for efficiency.

WISECRACK uses two different models for the fatigue crack growth rate. Traditionally, the Paris equation has been used to model stage II growth. However, in order to correctly model stages I, II, and III as well, the code also uses the more general Modified Forman equation, as originally proposed by Sperr [6]:

$$\frac{da}{dN} = \frac{c\lambda^m \left[f\Delta K - \Delta K_{th}\right]^n}{K_{Ic} - \lambda f \Delta K} \qquad (3)$$

where $\Delta K = K_{max} - K_{min}$, $\lambda = 1/(1 - R)$, $R = K_{min}/K_{max}$ (R-Ratio), K_{Ic} = plane strain fracture toughness, ΔK_{th} = threshold ΔK, and $f = E(T_o)/E(T)$. This equation accounts for both the threshold in ΔK below which negligible crack growth occurs and also the acceleration in stage III when ΔK approaches the static fracture toughness. For 316 stainless steel the constants are: C = 3.122E-6 mm/cycle, $K_{Ic} = 150$ MPa $\sqrt{m}$, $\Delta K_{th} = 5.4(1 - 0.9R)$ for $R > 0$ and $\Delta K_{th} = 5.4(1 - 0.2R)$ for $R < 0$, $m = 0.5$ and $n = 2.95$. Both models include temperature effects through the modulus correction factor, f, and are applicable to inert environments such as helium, sodium or vacuum. Neither model considers hydrogen effects, creep-crack growth or crack retardation/overload effects, however. For short cracks, e.g., $a \lesssim 0.5$ mm, a correction must be made by adding the constant $\ell = 0.064$ mm to the crack size to effectively account for the breakdown in continuum mechanics for these very small dimensions, as recommended by El-Haddad, Smith and Topper [7].

Wall thinning due to surface erosion affects crack propagation in three different ways: through the stress history provided by TSTRESS, through the dependence of the stress intensity factor on a/h, and through crack erosion. The latter occurs when a flaw located on the plasma side of the first wall is eroded away by sputtering, and may be obliterated completely if the erosion rate exceeds the crack's growth rate. Experimental tests are needed to verify this last assumption.

The Modified Forman equation was used to study the impact that radiation embrittlement would have on the fatigue crack growth rate. Wolfer and Jones [8] have recently predicted fracture toughness levels of as low as 10-40 MPa $\sqrt{m}$ after 10-20 dpa of neutron damage. Using these numbers, the Modified Forman equation predicts an acceleration in da/dN caused when the asymptote for fast fracture $\Delta K \rightarrow K_{Ic}$ drops with fluence, as illustrated in Fig. 7. These predictions do not contradict existing data for 316 SS because only low damage levels, $\lesssim 5$ dpa, have been tested.

WISECRACK currently does not model any effects of irradiation on the threshold ΔK, as indicated in Fig. 7. However, by considering data by Priddle [9] on the effect of yield strength on ΔK_{th} it may be inferred that neutron irradiation damage will shift the threshold downwards, within the first 10-20 dpa, as the yield strength increases.

5. LIFETIME PREDICTIONS

Although the accuracy of any one prediction may be questioned because of uncertainties in the data for irradiated materials properties, the lifetime methodology we have developed is useful for studying in a generic manner: the sensitivity to model-assumptions; the effect of design variables; and the overall effects of radiation damage. Furthermore, it allows identification of: critical materials properties; and any unknown synergistic effects. In the following, we present examples of such a study.

Table 1 indicates that a two-dimensional growth model always gives a shorter lifetime than a one-dimensional model, by factors of 2 to 4. This results from a comparison of the maximum stress intensity factor at the tip of the crack, which is greater for a long thin (two-dimension-

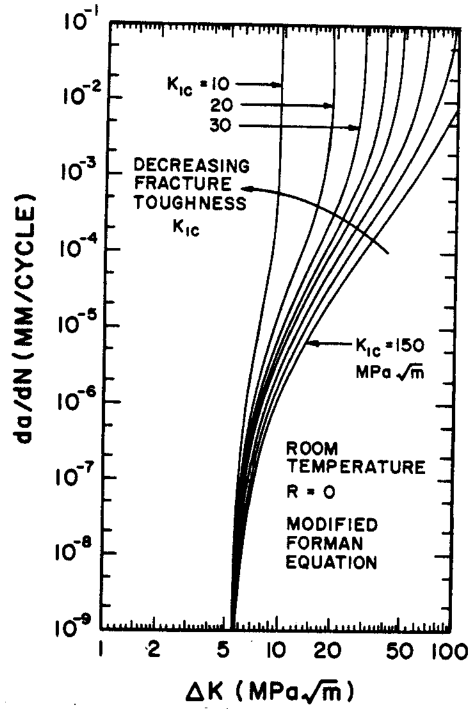

Fig. 7. Effect of radiation-induced embrittlement on fatigue crack growth for 316 SS.

al) crack than for a semi-circular (one-dimensional) flaw of the same depth "a". Likewise, a comparison of the two different equations for fatigue crack growth rate reveals that the more general Modified Forman equation predicts lifetimes of factors 3 less than the traditional Paris equation, when radiation effects are included. Without irradiation, the same comparison shows only a small effect of including a threshold in da/dN. Overall, the sensitivity to model assumptons appears to be quite large.

Figure 8 shows that by increasing the wall thickness and, hence thermal stress, this results in a dramatic reduction in lifetime, with or without irradiation effects. This is caused by ΔK being proportional to $\Delta\sigma_{thermal}$; and since the crack growth rate is proportional to ΔK^4, the fatigue life, N_f, goes as $N_f \sim 1/(\Delta\sigma_{th})^4$.

Figure 8 also demonstrates the detrimental effect that irradiation has on lifetime, over a wide range of stresses and temperatures. Primarily, this is caused by the reduction in fraction toughness with fluence which both accelerates stage II crack growth and also increases the potential for brittle fracture conditions to occur.

The effect of surface erosion on lifetime has been investigated parametrically. For flaws located on the coolant side, the results shown in Fig. 9 indicate that some amount of erosion is beneficial and gives longer lifetimes. This can be explained since the reduction in cyclic thermal stresses (see Fig. 5) caused by wall thinning increases life due to $N_f \sim 1/(\Delta\sigma_{th})^4$. Too much erosion, however, will cause leak-through before brittle fracture occurs. Flaws on the plasma side on the wall usually do not grow fast enough and are soon obliterated.

6. CONCLUSIONS

1. The stresses in a protected first wall undergo a redistribution over time from an initial to a final steady state, whose level is controlled by the ratio of swelling rate to creep compliance.

2. This stress redistribution affects primarily the mean stress level, but does not change the cyclic thermal stresses (for a protected wall).

3. Irradiation creep and swelling appear not to affect the lifetime directly. Only when $\dot{S}/\psi$ becomes large will crack growth be influenced via the R-Ratio (mean stress) effect.

4. The long-term stress history of an unprotected, eroding wall displays four regimes of behavior related to the competition between decreasing thermal stresses and increasing coolant pressure membrane stresses.

5. Fatigue crack propagation is a life-limiting process in tokamak reactors.

6. Under normal operating conditions, a surface flaw located on the coolant side gives the shortest lifetime.

7. Two-dimensional flaw growth models give shorter lifetimes than one-dimensional models.

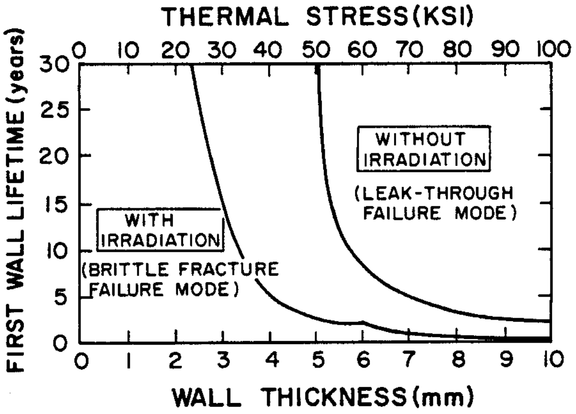

Fig. 8. Effect of wall thickness on lifetime.

Table I. Sensitivity of Lifetime to Model Assumptions for Reference First Wall Design

da/dN Equation		Crack Growth Model		Lifetime* (years)	
Modified Forman	Paris	Two-Dimensional	One-Dimensional	With Irradiation	Without Irradiation
X		X		2.0 (BF)	8.5 (LT)
X			X	4.6 (BF)	30+
	X	X		5.9 (BF)	8.8 (LT)
	X		X	22.8 (BF)	30+

note: 30+ means life > 30 years BF = brittle fracture LT = leak-through *flaw on coolant side

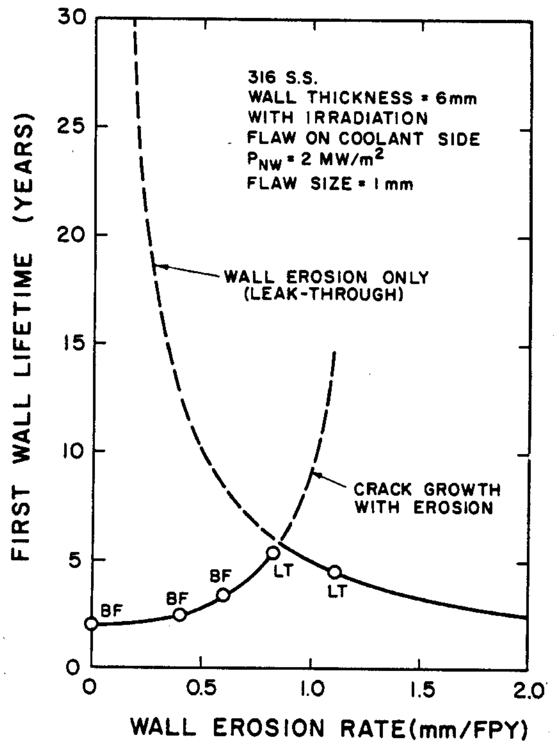

Fig. 9. Effect of surface erosion on lifetime.

8. Neutron irradiation can reduce lifetimes, when compared to no irradiation, by a factor of ten. This is caused by the reduction in fracture toughness which, in turn, accelerates stage II fatigue crack growth and enhances the potential for brittle fracture.

9. A complex synergism exists between the structural response and crack propagation when surface erosion takes place.

10. A certain amount of wall erosion will enhance lifetime.

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