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THE IMPACT OF SWELLING ON FUSION REACTOR FIRST WALL LIFETIME

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The impact of swelling in 20% cold-worked Type 316 stainless steel on first wall lifetime is assessed for the INTOR, DEMO, and STARFIRE first wall designs. Three separate predictive swelling correlations, two of which are empirically derived from fission reactor data and one which is based upon a theoretical model, have been used. The equations have been incorporated into a code that examines the temperature-stress-strain-radiation effects history of fusion components.

1. INTRODUCTION

A major concern for any first wall is potentially high irradiation swelling that can lead to large dimensional changes, high stress levels, and eventually to failure. The leading candidate for the first wall structural material in near-term fusion reactors is 20% cold-worked Type 316 stainless steel, but at present there are uncertainties in its swelling response under fusion radiation conditions. The purpose of the present work is to compare the predicted swelling response of 20% cold-worked Type 316 stainless steel for the operating conditions specified from the INTOR (International Tokamak Reactor), DEMO (Demonstration Power Reactor), and STARFIRE tokamak reactor design studies.[1-3]

Three swelling equations have been utilized in the study: 1) an empirical fast reactor equation, 2) an empirical HFIR equation, and 3) a theoretical fusion equation. The breeder based equation has been derived from an extensive data base from fast fission reactor experiments where the helium generation rate is low (He (appm)/dpa $\simeq$ 0.6).[4] The HFIR equation is based upon swelling data taken exclusively from experiments in the High Flux Isotope Reactor where the helium generation rate is variable and very high (He/dpa $\simeq$ 60).[5] Finally, a theoretical swelling equation has been used, which predicts swelling for the helium generation rate expected in a fusion reactor (He/dpa $\simeq$ 10).[6,7]

The effect of swelling on first wall behavior has been analyzed with a recently developed one-dimensional computer code.[8,9] The code incorporates the operating parameters from reactor design studies, materials characteristics, and appropriate failure criteria. It calculates the temperature-stress-strain-radiation effects history of the first wall so that synergystic effects between sputtering erosion, swelling, creep, failure, and crack growth can be studied. The code determines the behavior of a plate that is composed of either a single or two different materials. Both radiation creep and radiation induced changes in tensile properties are included in the calculations. The only materials equation that was varied in this study is the swelling response.

2. SWELLING CORRELATIONS

2.1. Breeder induced swelling

The following correlation for stress-free swelling assumes no influence of displacement rate on swelling, although it is known that the incubation period becomes progressively more sensitive to displacement rate and stress above 500°C.[4] For STARFIRE and DEMO studies (< 425°C), these variables can be ignored however.

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This equation can be applied to fusion studies if the influence of helium/dpa ratio is ignored. Some data are available in the 500-700°C regime that agree with this assumption,[10] but no reliable data exist to test this assumption at lower temperatures. This equation is only applicable for steels made to the specification employed for FFTF first core steels.

$$\frac{\Delta V}{V_0}(\%) = R\left[D + \frac{1}{\alpha}\ln\frac{1+\exp[a(\tau_0 - D)]}{1+\exp(\alpha\tau_0)}\right]. \qquad (1)$$

D = total number of atomic displacements in dpa

α = curvature parameter in units of $[\text{dpa}]^{-1}$

τ_0 = stress-free incubation parameter in dpa

T = temperature in units of °C

R = swelling rate parameter in units of %/dpa

$R = 1.0$; $\beta = 0.01\,(T - 500)$

$\alpha = 0.63 \exp[-4.402 \times 10^{-3}(T)]$

$\tau_0 = \exp(4.078 + 0.149\beta + 0.334\beta^2$

The predictions of Eq. 1 are shown in Fig. 1.

2.2 HFIR induced swelling

An equation describing the swelling of 20% cold-worked Type 316 stainless steels irradiated in HFIR has been developed.[11] The data are sparse, particularly at higher fluence, but all samples have been characterized via transmission electron microscopy (TEM).[12,13] Since the microstructural observation revealed complex behavior, the swelling contribution of each cavity component (i.e., matrix voids, precipitate-associated void, matrix bubbles, precipitate-associated bubbles, and grain boundary bubbles) are described by empirical equations having separable temperature- and fluence-dependent behavior. These components were then summed to give the total cavity volume as a function of temperature and fluence. The swelling for the range 50 < T < 700°C and d < 60 dpa, is

$$\frac{\Delta V}{V_0}\% = 0.05\,A\,d\exp(-d^3/B) + C[0.028\,d - 0.36 + 0.36\exp(-0.1\,d)] + E\,\{0.5[0.08\,(d + D) - 2.72] \times (1 + \tanh(0.1\,[d + D - 40]))\} + .035\exp[-0.005\,(d + D - 40)^2] + .033\,d\exp[0.025\,(T - 680)]; \qquad (2)$$

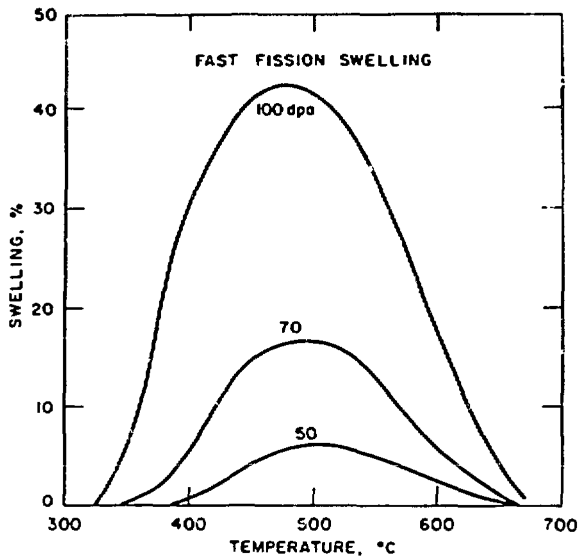

FIGURE 1
Predicted swelling based upon breeder data.

d = atomic displacements, dpa,

T = temperature (°C),

$A = \exp[-6.94 \times 10^{-5}(T - 250)^2]$,

$B = \exp(26 - 0.039\,T)$,

$C = 0.7\exp[-0.001\,(T - 380)^2]$,

$D = 0.041\,T - 15.3$,

$E = 0.5\,\{1 + \tanh[0.02\,(T - 100)]\}$.

The predicted swelling for HFIR condition is shown in Fig. 2. The data, also plotted in Fig. 2, incorporate temperature and fluence corrections recommended recently.[14-16] The corrections result in a 75°C increase in the previously reported swelling equation. Equation (2) has been fitted to HFIR data on the DO heat of CW 316.

2.3 Theoretical prediction of swelling

As a complement to the data-based swelling design equations, predictions of a rate theory model of swelling have been used to develop three additional equations. These are based on modifications of the model after its calibration using fission reactor data.[6,7] The model was calibrated using a set of swelling data from the

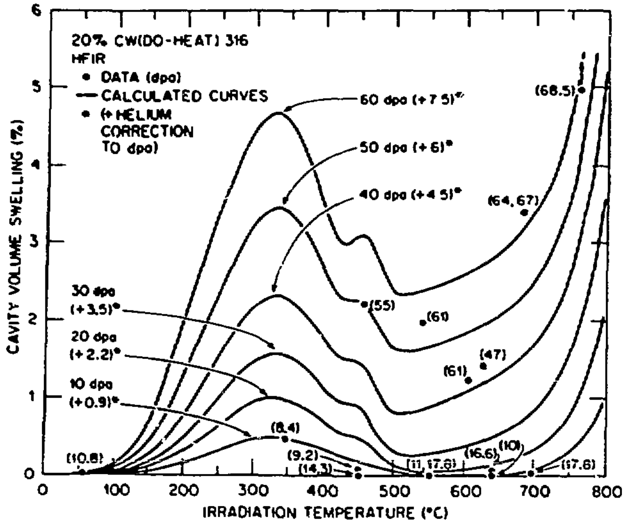

FIGURE 2
Predicted swelling in HFIR (numbers in parenthesis reflect recent dpa corrections).

FFTF first core steels.[17] The calibration of the model has been previously described elsewhere in more detail.[6,18]

Below 600°C and 100 dpa, the predicted swelling is

$$\frac{\Delta V}{V}(\%) = A(T)(d-\tau(T)) - B(T)(d-\tau(T))^a \quad (3)$$

for $d > \tau$, where T is the irradiation temperature (°C), d is the dose (dpa) and A, B, and τ are temperature dependent parameters. A value of the exponent a = 1.25 provides the best overall fit for the swelling curves.

Three values for the parameter p, 0.2, 0.5, and 0.8, have been used, corresponding to low, intermediate and high cavity densities, respectively. (p is an exponent in the helium cavity density equation.) For the p = 0.2 which has been used for the comparison study, the parameters are:

$$A(T) = 1.285 \exp\left[\frac{-(T-500)^2}{8100}\right] + 0.8 \exp\left[\frac{-(T-615)^2}{500}\right] + 0.09 \exp\left[\frac{-(T-380)^2}{2000}\right] \quad (4a)$$

$$B(T) = 0.225 \exp\left[\frac{-(T-500)^2}{5300}\right] \quad (4b)$$

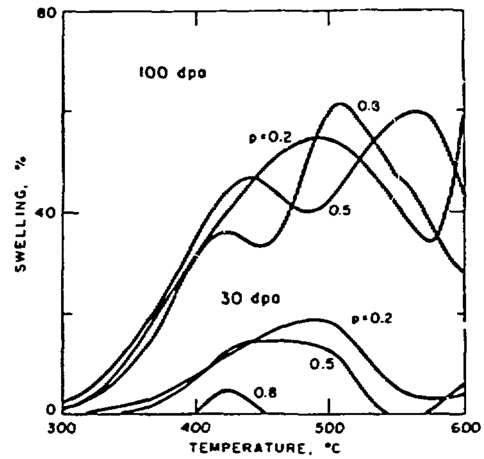

FIGURE 3
Theoretically predicted swelling.

$$\tau(T) = 5.88 + 23.5 \exp\left[\frac{-(T-250)^2}{7250}\right] + \tau'(T) \quad (4c)$$

$$\tau'(T) = \begin{cases} 0, & T < 490^0C \\ 18.6\left[1.0-\exp\left(\frac{-(T-490)^2}{2000}\right)\right], & T > 490^0C \end{cases}$$

Predicted swelling is presented in Fig. 3.

3. REACTOR PARAMETERS

The design and operating parameters for the three first walls are given in Table 1. The INTOR first wall is composed entirely of 20% cold-worked Type 316 stainless steel, whereas the DEMO and STARFIRE first walls are clad with beryllium. The beryllium has a porosity of 30% which is assumed to prevent helium bubble swelling. The initial temperature distribution is shown in Fig. 4. (Note that the plasma side surface is at the origin of the x axis.) Peak temperatures of the stainless steel for INTOR, DEMO, and STARFIRE are 225, 375, and 415°C.

4. SWELLING RESULTS

Peak swelling values are shown in Fig. 5 for STARFIRE. The theoretical equation predicts the highest swelling, and the fast fission equation exhibits the greatest time dependence in

Table 1. Design and Operating Conditions for FED/INTOR, DEMO, and STARFIRE First Walls

Parameter	FED/INTOR	DEMO	STARFIRE
Material	20% CW Type 316 SS	Be (70% TD) on 20% CW Type 316 SS	Be (70% TD) on 20% CW Type 316 SS
Thickness	12 mm	2 mm (Be) 4 mm (SS)	1 mm (Be) 1.5 mm (SS)
Coolant Temperature	90°C	300°C	300°C
Surface Heat Flux	.11 MW/m^2	.25 MW/m^2	.85 MW/m^2
Neutron Wall Load	1.3 MW/m^2	2.1 MW/m^2	3.5 MW/m^2
Availability	50%	50%	75%
Lifetime Goal	10 y	10 y	6 y
Lifetime Cycles	7×10^5	250	230
Lifetime Fluence	52 dpa	84 dpa	173 dpa
Burn Time (s)	200	6×10^5	6×10^5
Dwell Time (s)	40	3.6×10^3	3.6×10^3
Down Periods/Year	6	2	2
Stress Condition	Free to expand but not bend	Free to expand but not bend	Free to expand but not bend
Primary Stress Level	0 MPa	50 MPa	50 MPa
Erosion Rate	3×10^{-11} m/s	1×10^{-11} m/s	7×10^{-12} m/s

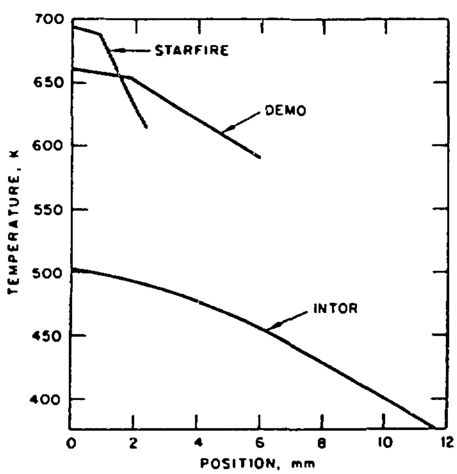

FIGURE 4
First wall temperature distributions (plasma side surface located at zero of x-axis).

swelling rates, with a long incubation period followed by rapid swelling. The swelling behavior in DEMO follows the same pattern shown in Fig. 5 for STARFIRE. The lifetimes, assuming a maximum allowable swelling of 5%, are predicted to be less than the desired lifetimes indicated in the design studies.[2,3] The lifetime in DEMO varies from 3.25 to 7.5 y, and the lifetime in STARFIRE varies from 0.6 to 2.5 y. For INTOR conditions, only the HFIR equation predicts any swelling (0.8%) after 10 y of operation.

The effects of rapid swelling to induce stresses and cracking have also been analyzed. An example of swelling induced stresses is shown in Fig. 6 for DEMO conditions. Initially, during the burn, the Be cladding is under a tensile stress, the stainless steel at the Be interface is under a compressive stress, and the stainless steel at the coolant interface is under a tensile stress. The initial stress distribution is largely a consequence of the lower thermal expansion in Be compared with stainless steel. After about 1 y of operation, the stresses have relaxed during the burn cycle as a result of radiation creep. After swelling begins following the incubation period (t = 6 y), the stress distribution is altered. Swelling in the steel is predicted to be greatest at the Be interface. The resultant stresses in the steel are predicted to be compressive in the high swelling regions and tensile in the low swelling regions. The equilibrium stress distribution

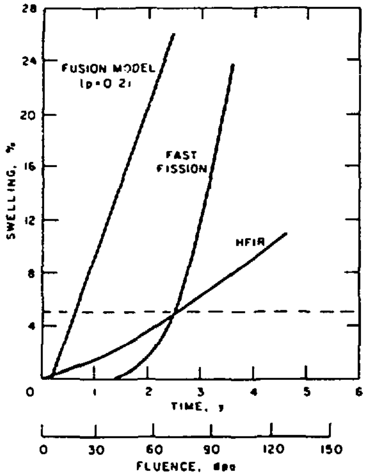

FIGURE 5
Peak swelling predicted for STARFIRE first wall.

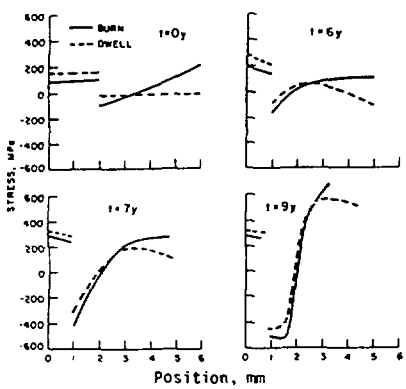

FIGURE 6
DEMO first wall stresses using breeder equation.

is the one which allows the entire first wall to expand uniformly with a combination of swelling and radiation creep. As the swelling rate increases with time, the stress gradient through the stainless steel also increases until the yield stress of the stainless steel is exceeded at t = 9 y. During this time, the Be cladding, which is assumed not to swell, is placed under a large tensile stress. The combination of high tensile stress and cyclic operation is predicted to cause cracking in the Be after 6.9 y of operation. Fatigue crack initation is predicted in the stainless steel at the coolant interface after ~ 9 y of operation.

The stress gradient through the first wall is dependent on the swelling rate gradient as shown in Fig. 7 for the theoretically predicted swelling in STARFIRE. The temperature dependent swelling rate varies from ~ 34%/y (~ 1%/dpa) at the Be interface to ~ 4%/y (~ 0.12%/dpa) at the coolant interface. The stresses vary from ~ 400 MPa (compressive) at the Be interface to ~ 450 MPa (tensile) at the coolant interface. Although the stress gradient is high, the results shown in Fig. 7 indicate that radiation creep can accommodate large swelling gradients.

These calculations are subject to several uncertainties. First, the radiation creep equation has been kept the same for all cases studied. Second, there is evidence that the degree of swelling depends on the stresses that are present.[19] Third, swelling is also expected to depend upon the damage rate. The swelling equa-

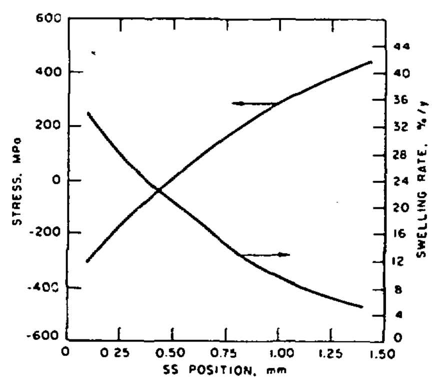

FIGURE 7
Stress and swelling gradients predicted through the STARFIRE first wall (t = 0.75 y), for the theoretical equation.

tions are assumed to be independent of the previous two variables. Finally, there are design related uncertainties, such as the constraint of the first wall and its detailed geometry.

5. CONCLUSIONS

(1) Swelling does not appear to be a concern for low temperature (≲ 300°C) conditions expected in INTOR, regardless of which equation is employed.
(2) The most likely first wall operating temperature is ~ 400°C for power reactors. The temperature regime of interest is ~ 300-550°C.
(3) High values for swelling are predicted at elevated temperatures predicted in DEMO and STARFIRE. For all cases investigated, the swelling is unacceptably high for economic operation. An advanced alloy, like PCA, would be needed for these devices to meet the desired lifetime goals.
(4) The theoretical equation predicts the highest values of swelling for the STARFIRE conditions. Significant differences in swelling between the equations are predicted at fluence levels of only ~ 20 dpa.
(5) Radiation creep is expected to accommodate relatively high swelling gradients (≲ 30%/y) and to maintain the stresses at acceptable levels.
(6) The major problem associated with swelling is expected to be the gross dimensional changes. Additional design work is required to define the allowable limits for dimensional changes.

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