# CHARACTERISTICS OF IRRADIATION CREEP IN THE FIRST WALL OF A FUSION REACTOR*

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A number of significant differences in the irradiation environment of a fusion reactor are expected with respect to the fission reactor irradiation environment. These differences are expected to affect the characteristics of irradiation creep in the fusion reactor. Special conditions of importance are identified as the (1) large number of defects produced per pka, (2) high helium production rate, (3) cyclic operation, (4) unique stress histories, and (5) low temperature operations. Existing experimental data from the fission reactor environment is analyzed to shed light on irradiation creep under fusion conditions. Theoretical considerations are used to deduce additional characteristics of irradiation creep in the fusion reactor environment for which no experimental data are available.

## 1. INTRODUCTION

Irradiation creep is the plastic deformation of a material under stress that is caused by damage from incident high energy particles. Creep rates under real or simulated reactor conditions have been measured along with the dependence of these rates on material and reactor parameters. Theoretical models of irradiation creep have been developed to understand the phenomenon and to guide further experiments in this area. The importance of irradiation creep has been apparent to designers of fission reactors for a number of years. However, because no fusion reactor exists, the characteristics of irradiation creep in a fusion environment are unknown. The purpose of this paper is (1) to consider the existing body of knowledge for fission reactor applications to help anticipate where possible the characteristics of irradiation creep in the fusion environment and (2) to indicate the further theoretical and experimental research deemed to be most important. A more extensive report on this subject containing a more complete background on irradiation creep is available [1].

## 2. SPECIAL IRRADIATION CONDITIONS FOR FUSION REACTORS

There are many proposed designs for fusion energy systems. We have identified five special irradiation conditions that are common to many, and are different from conditions in fission reactors.

### 2.1 Larger Number of Defects Produced per Incident Neutron

All fusion reactors, except for a few special futuristic designs, produce heat from the reaction of tritium with deuterium. This reaction produces an α-particle with 3.5 MeV and a neutron with 14.1 MeV. The α-paricle is stopped in the surface of the first wall, but the neutron penetrates the bulk, producing cascades of point defects initiated by primary knock-on atoms (PKA) in much the same fashion as do fission-produced neutrons. The damage differs, however, because the neutron energy spectrum is very different. The comparison is shown in Fig. 1 for typical fission and fusion spectra [2,3]. The shaded area shows the much higher fraction of high energy neutrons found in a fusion spectrum. These higher energy neutrons produce higher energy PKA's with over 60% of the damage resulting from PKA's having E > 100 keV [3,4]. This compares with less than 10% for fission spectra. However, the total number of defects produced per incident neutron [5] is much greater for the high energy fusion reactor PKA's.

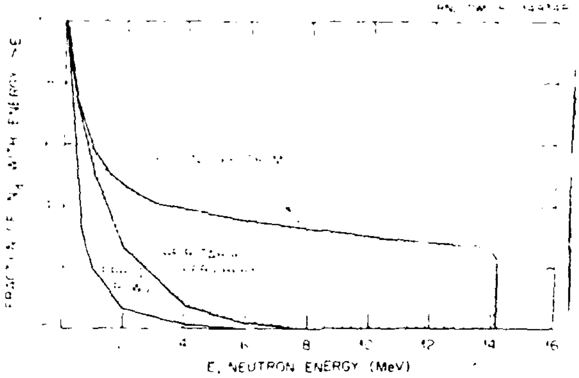

Fig. 1: The fraction of $N_d$ with energy greater than E versus E for typical fusion and fission reactors. $N_d$ is the flux of neutrons with E > 0.1 MeV.

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## 2.2 High Helium Production

Another consequence of the higher energy neutron spectrum is that the production of He per dpa is greater. This difference is easily seen using Fig. 2 where the He production per dpa is plotted for a number of fission and fusion reactors. The values plotted for fusion reactors are for a neutron wall loading of 1 MW/m$^2$. Some designs call for values near this one but others support values as high as 7.3 MW/m$^2$ [6]. Differences in ductility, swelling, and precipitation phenomena have been observed [7] with high helium content. A significant effect on the irradiation creep rate to swelling rate ratio is expected from theory.

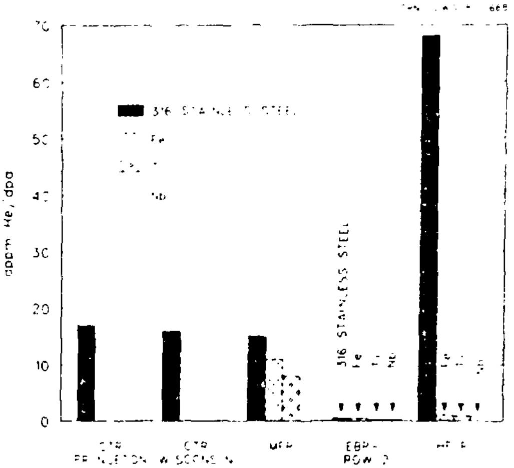

Fig. 2: Plot of He production as a function of damage rate for several tokamak fusion and fission reactors [2,3].

## 2.3 Cyclic Operation

The planned D-T plasma burn in various fusion reactors continues for times from 10 s to 6000 s [8]. Some of the more recent designs [9] plan on a continuous plasma burn. Two fusion devices that may be built in the near term, and which will ignite a D-T plasma, are the Fusion Engineering Device (FED) and the International Tokamak Reactor (INTOR). Both of these devices are planned to have burn times >100 s with recycle times of about half of that [10,11]. In addition to the pulsed nature of most fusion devices, a number of unplanned plasma disruptions are expected to occur.

The consequences of the cyclic operation, either planned or unplanned, are that the first wall will experience cycles in temperature, particle flux, and stress.

## 2.4 Unique Stress Histories

The stress state in the first wall is complex and changes with time — both during the burn cycles and also during the lifetime of the material. Harkness and Cramer [12] give description of the expected effects. The stresses are large, as high as 400 MPa during a plasma disruption, and will change by perhaps 250 MPa during a burn cycle. Four primary sources of stress in the first wall have been identified. There is typically a temperature gradient between the coolant and plasma sides of the wall of from 80 to 200°C (1 cm wall with 1 MW/m$^2$ flux loading). This temperature gradient results in thermal stresses and also differential swelling stresses. Initially these stresses may be as high as 150 MPa. The pressure of the coolant results in significant stresses. If water is the chosen coolant, typically these stresses are about 13.7 MPa. During plasma disruptions, changes in torodial stress of ~150 Mpa are expected with rapid oscillations. These stresses will be highest in the region of plasma discharge. Because of the sudden high particle flux there will be large initial thermal stresses during start-up. The value reported is 72 MPa for 316 stainless steel under a 1 MW/m$^2$ wall loading.

Some additional stress will also result from turbulence in the coolant and, if ferromagnetic materials are used, from induced magnetic forces. During the operation of the reactor these stresses will be relaxed through irradiation and thermal creep in the material. This creep lowers the stresses during the burn cycle but it also causes an increase in the opposite signed stress during the dwell period. This stress reversal is not generally experienced in fission reactor systems or in material irradiation experiments. For this reason very little is known about irradiation creep under compressive stress. Understanding swelling under stress is also important as there appears to be significant differences in the observed behavior [13, 14]. An accompanying effect is expected in irradiation creep behavior.

## 2.5 The First Wall May be Operated at Low Temperatures

In early designs there were plans to operate the reactors in the same temperature range as that planned for fast breeder reactors, i.e., between 400 and 550°C. The most recent plans as reflected in the designs for Starfire [9] and FED [10] show maximum first wall temperatures of 320°C. This temperature is below the temperature for most fission reactor data. There are some experimental results, to be discussed in the next section, that suggest that both irradiation induced swelling and creep behave differently at lower temperatures.

## 3. EXISTING CREEP DATA OF SPECIAL RELEVANCE TO FUSION SYSTEMS

Below we describe results which bear on the special conditions of fusion reactors. For a more complete review of earlier work we refer the reader to previously published review articles [15-19]. *Before proceeding, however, it is* important to point out that the existing data is rather heavily concentrated on stainless steels and zirconium alloys. Some measurements have been made on other materials such as Nimonic 80A and pure Ni, but the results are not as complete. However, several widely different classes of materials are projected for active research toward possible use in fusion reactor first walls [20]. These classes include many different materials. It is important to realize, therefore, that the paucity of experimental data applicable to materials for fusion reactor applications stems not only from the lack of *appropriate irradiation environment*, but also from lack of extensive experience on these alloy types under irradiation conditions in general.

There have been a number of attempts to determine the effect of spectrum on irradiation creep, and the results *reported are somewhat* contradictory. Walters et al. [21] observed that for some long pressurized tubes, the flux varied a factor of 60 over the length while the average neutron energy went from 0.077 MeV to 0.61 MeV. The observed deformation scales exactly with dose indicating no effect of average neutron energy. *Foster and Boltax* [22] arrived at a different conclusion by analysis of creep results on identical heats of material which were creep tested in different reactors using the same measurement technique. Using displacement cross sections for comparison, they found steady-state irradiation creep coefficients to be *a factor of 2.5 larger* in mixed spectrum than in fast neutron irradiations. This *observation* would be consistent with additional hardening from the high energy neutron cascades. Another explanation may be that there is more in-cascade recombination in the larger cascades of the fast reactor giving rise to a smaller free point defect *production rate* per unit displacement rate.

For fusion reactors which operate in a pulsed mode, the temperature, stress, and defect production will be cyclic. A temperature change of 40 to 100°C appears to have little effect on the measured creep rate [23] of 20% cold-worked stainless steel. The samples continue to creep at much *the same rate as* they had at the original irradiation temperatures. These creep tests were conducted near 500°C, however, and this result may only reflect the weak temperature sensitivity for irradiation creep rate near this temperature. A change in applied stress [24], on the other hand, appears to cause immediate transient creep that is independent of prior stress history. This transient strain is believed to involve thermal processes because it does not appear if can be are annealed for 50 h at the new stress in the absence of irradiation.

Recently, creep has been measured in samples *undergoing a gradual temperature decrease* [25]. In 20% cold-worked AISI 316 cladding, larger creep deformations have been measured in those samples that have undergone a temperature decrease. If this increased strain is not a reversible transient, cyclic operation could result in substantial increased strain.

In a study of creep of loaded helices made from cold-worked austenitic stainless steels, Lewthwaite and Mosedale [26] reported that the strain per unit dose increases with decreasing dose rate. We have replotted, in Fig. 3, the normalized creep strain per dpa from ref. [26] *against the inverse square root of the damage* rate. This type of plot is suggested by theoretical considerations as will be discussed in the next section. This dependence on dose rate will result in lower creep strain in pulsed systems than in continuous systems under the same average dose rate. The dose rate during irradiation in the pulsed system will be *higher* and the creep strain lower.

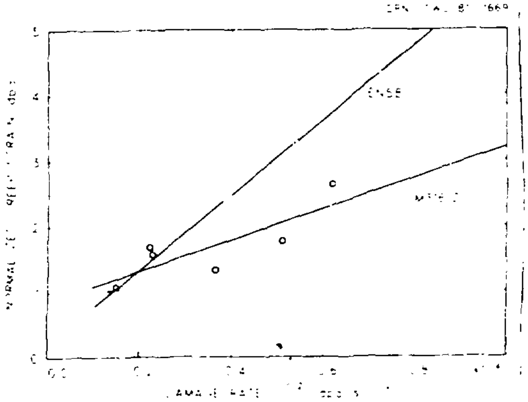

Fig. 3: The normalized creep strain per dpa plotted against the square root of the damage rate for two austenitic stainless steel. The data are replotted from ref. [26].

There have been at least three recent experiments reported on creep of a variety of materials at relatively low temperatures. Causey et al. [27] reported in-reactor stress relaxation of bent beams of 11 different materials at 67 and 300°C. In all but one of the cases reported the creep rate at 67°C was greater than or equal to that at 300°C. Another observation [28] of an inverse temperature dependence *was made in an instrumented*, tension, in-reactor creep machine on a sample of 20% cold worked EN58B (type AISI 321) stainless steel. The creep rate increased a factor of 4 as the temperature decreased from 450 to 400°C. Paxton et al. [29,30] also observed an inverse temperature dependence in two precipitation hardening materials crept at temperatures from 540 to 605°C. These materials also showed a simultaneous decrease in swelling for the increase in temperature.

Some fusion designs have suggested using ferritic stainless steels for the first wall. Paxton et al. [29,30] reported that ferritic steel containing 12% Cr is as resistant as the best of the austenitic steels they studied in the temperature range from 540 to 605°C. At lower temperatures, 400—550°C, Erler et al. [31] reported that void swelling was confined to the σ-phase particles formed during some heat treatments. The accompanying creep rate was very low with very few measurements of creep greater than 0.2% for irradiation out to 150 dpa. The creep behavior of ferritic steel DIN 1.6770 (2.2 Cr, 1.0 Mo, 0.8 Ni) has also been measured using a resonant cavity apparatus [32]. For irradiations *out to a fluence of 4.5 dpa and* stress to 200 MPa at 400°C, the creep rate was less than 2.2E-11 s$^{-1}$. At 500°C and 100 MPa the strain rate increases with time (like tertiary creep) and is about five times as fast as a typical austenitic stainless steel. Continuation of the 400°C sample at 500°C reproduced the same result. The 500°C result is about ten times as fast as thermal creep in the same material but shows the same general behavior.

## 4. THEORY

The theoretical framework that has been developed to understand irradiation creep can be called on to provide guidance in the fusion reactor regime. Much can be done in this area especially where there is already some experimental information. For example, in further theoretical research into the temperature dependence of irradiation creep the experimental findings of significant creep rates at low temperatures will be of great importance. However, in the present section we do not concentrate on the findings in the previous experimental section. At this time we believe that it is of greater importance to identify the main characteristics of irradiation creep in the fusion reactor. In the present section we extract from the theory complementary findings that are not suggested by the available data in the fission reactor regime.

Several mechanisms of irradiation creep have been proposed. The possible interaction of irradiation creep with swelling has also been explored. A recent conference can be cited as a reasonably up to date source of information [33]. The expanded version of the present paper outlines the essential aspects of the theory of irradiation creep and swelling [1]. We call on this background to evaluate aspects associated with fusion reactors.

One statement that can be made based on a knowledge of the theory is that the ratio of the creep rate to the swelling rate in a fusion reactor may be quite different from that in a fission reactor. This ratio and its derivative with respect to temperature, in part, determine the level of stress in the first wall and its evolution with time. The ratio is useful in reactor design to establish first wall behavior.

The theoretical basis for the statement can be described briefly. Consider for simplicity a situation where stress induced preferred absorption (SIPA) is the dominant mechanism of irradiation creep. It has been shown that the creep rate by this mechanism can be expressed as [34]

$$\dot{\epsilon} = \frac{2}{9}\,\Omega L \Delta Z_i^d\, D_i C_i \quad . \tag{1}$$

Here $\Omega$ = atomic volume,
$L$ = dislocation density,
$\Delta Z_i^d$ = difference in capture efficiencies for interstitials of aligned and non-aligned dislocations,
$D_i$ = interstitial diffusion coefficient,
$C_i$ = free interstitial concentration/unit volume.

The cavity growth rate is

$$\frac{dr_c}{dt} = \frac{\Omega}{r_c}\left(Z_v^c D_v C_v - Z_i^c D_c C_i\right) \quad , \tag{2}$$

Here the new terms are
$r_c$ = cavity radius
$Z_v^c$, $Z_i^c$ = capture efficiency of cavities for vacancies, interstitials,
$C_v$ = vacancy concentration,
$D_v$ = vacancy diffusion coefficient.

The concentrations $C_v$ and $C_i$ are functions of the point defect generation rate, the strengths of the various sinks in the microstructure, and the coefficient of point defect recombination. Here we take cavities and dislocations as the dominant sinks. $C_v$ and $C_i$ are known [see for example ref. 35] and can be substituted in Eqs. (1) and (2) above. Taking the ratio of Eq. (1) to Eq. (2) we obtain [36].

$$\frac{\dot{\epsilon}}{\frac{\Delta \dot{V}}{V}} = \frac{2}{9}\,\frac{\Delta Z_i^d}{Z_v^c Z_i^d - Z_i^c Z_v^d}\left(Z_v^c + \frac{Z_v^d L}{4\pi r_c N_c}\right) \tag{3}$$

where $Z_i^d$ and $Z_v^d$ are the capture efficiencies of dislocations for vacancies and interstitials, and $N_c$ is cavity density. This expression shows, as expected physically, that the creep rate to swelling rate ratio is a strong function of the ratio of dislocation density to cavity density sink strength.

Figure 4 is a plot of Eq. (3), showing the ratio of the strain rate normalized by $\Delta Z_i$ to the swelling rate, against the number of cavities, for several dislocation densities. The important practical result is that the creep rate to swelling rate ratio varies significantly over the range of cavity density from $10^{20}$ m$^{-3}$ to $10^{22}$ m$^{-3}$. This is the range typical of cavity densities in irradiated materials.

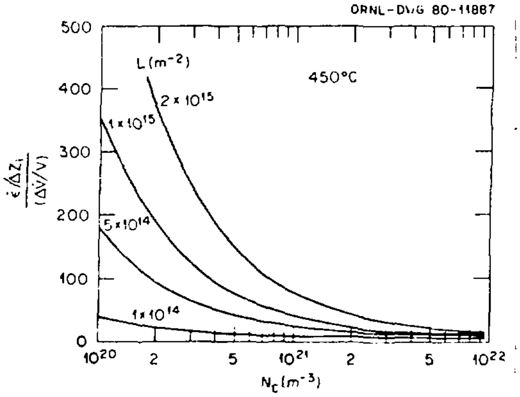

Fig. 4: The ratio of the strain rate normalized by $\Delta Z_i^d$ to the swelling rate versus cavity *density for several different* dislocation densities.

Experience has shown, that under high helium generation rates cavities may occur at higher density than at low helium generation rates. The fusion reactor helium generation rate is *more than an order of magnitude* higher than the fission reactor generation rate. Therefore, it might be expected that the cavity density in a fusion reactor material would be higher. Fig. 4 then would give an indication of the sensitivity of the creep rate to swelling rate ratio to the environment. Of course the microstructure in both environments *is dose and temperature* dependent so that Fig. 4 represents a snapshot for particular conditions. Nevertheless, the wide variability of the ratio should serve as a note of caution against taking the creep rate to swelling rate ratio for particular fission reactor conditions for application to fusion reactors.

Equation (1) is the basis for replotting the results of Lewthwaite and Mosedale in Fig. 3. It has been shown previously [35] that the concentration $C_i$ is proportional to the square root of the dose rate where mutual recombination is the dominant mode of loss of vacancies and interstitials. At low temperature, where vacancy mobility is low, recombination is often the dominant mode of loss. The data of Lewthwaite and Mosedale falls into this temperature regime. Not having the precise microstructural information available it is not possible to state unequivocally that recombination is the dominant mode of loss, but this is likely. The theory then offers an explanation of the increasing strain per dpa with decreasing dose rate. In the limit where $\dot{\epsilon} \propto (\text{dose rate})^{1/2}$ we get $\dot{\epsilon}/\text{dpa} \propto (\text{dose rate})^{-1/2}$. Figure 3 of the previous section plots the data of Lewthwaite and Mosedale on this type of plot for two out of their set of many different materials. The materials shown in Fig. 3 were selected as one showing good agreement with the (dose rate)$^{-1/2}$ law and one showing scatter.

A new possibility leading to irradiation creep has been proposed recently. It depends upon the fluctuations in point defect concentration caused by the point defect production in cascades described by the cascade diffusion theory of Mansur, Coghlan, and Brailsford [37]. This possibility is outside the scope of the rate theory described above. The idea is that even if there were no net flow of interstitials to dislocations, i.e., no swelling, and no net flow of interstitials or vacancies to favorably oriented dislocations, i.e., no preferred absorption, there could still be climb-glide creep. *Over a short enough time* increment there is always an imbalance of the flux of vacancies and interstitials to a segment of dislocation. This is because of the discrete nature of point defect production and because of the large difference in diffusion speeds of vacancies and interstitials.

The primary knock-on atoms producing cascades in fusion reactors are expected to be typically more than an order of magnitude more energetic than in fast fission reactors [4]. This increased energy makes the time dependent point defect concentrations at an arbitrary reference point *more variable* than in a fission reactor. For example, we find that the variance of the fluctuations in vacancy concentrations is roughly three times larger for 250 KeV cascades than for the 10 KeV cascades at 500°C, [38].

We show that these cascade induced fluctuations do *indeed produce dislocation unpinning* and creep [38]. The creep rate by this mechanism is found to be larger for the cascades typical of fusion reactors than for the cascades typical of fission reactors.

## 5. DISCUSSION AND CONCLUSIONS

In each of the five special fusion irradiation conditions we identify, there are reasons why the creep behavior may be different in fusion systems. Consider the higher energy neutrons for example. Theory indicates several basic reasons. An increase in the rate at which dislocations climb over small obstacles may result from the cascade effect. This increase would lead to an increase in the creep rate were nothing else to change. Increased neutron energy also increases the He production, which in turn may affect the bubble density. Bubbles are sinks for mobile defects as well as obstacles for gliding dislocations. Both effects decrease creep rate. Experimental data [22] shows a slower creep rate in a neutron spectrum of higher energy. But the comparison was in stainless steel which will have quite different He-production rates for the different neutron spectra as well as different damage energy spectra.

Increased He production can affect the creep rate in another way. Maziasz et al. [39] have reported that the addition of large amounts of He alter the structure, morphology, and phases distribution in irradiated AISI 316 stainless steel. Theoretical work shows that virtually any change in the microstructure effects swelling and creep [40]. McVay et al. [41] have shown that carbide precipitation enhances the creep rate during irradiation. The point defect concentrations are a function of the defect sink structure which includes the precipitates. An increase in interstitial concentration increases creep rate. Also, the particles will be formed from alloy elements which may trap interstitials. If these atoms are removed from solution, the creep rate will increase. These effects must be weighed quantitatively against the fact that the precipitates that form may pin dislocations.

Similar arguments can be found for each of the five special irradiation conditions. For this reason it is not possible to say what their effect on the creep rate will be without quantitative evaluation. This research should include careful microstructure characterization with accurate creep measurements. We feel that it is important to include creep specimens in material testing experiments in fusion reactors as soon as possible. Our present findings suggest that there is a great deal more to learn. In particular, it is important to establish whether irradiation creep is important in limiting the lifetime of the first wall.

In this paper we find several areas where understanding of irradiation creep is incomplete for fusion applications.

1. The fusion reactor irradiation environment is expected to be different from fission reactor environments in at least five ways: more defects per incident neutron; higher He/dpa ratio; cyclic operation (in most designs); a complex stress state; and a lower operating temperature.

2. Study of available experimental data suggests that several of the different conditions will lead to different creep behavior.

3. Creep resulting from cascade-induced point defect concentration fluctuations is increased in the fusion environment.

4. Theory shows that the creep rate to swelling rate ratios characteristic of fission reactors may not be directly applicable in predicting creep behavior for fusion applications.

5. More research is needed in many areas, but specifically more measurements of irradiation creep at low temperatures (50—300°C), creep under cyclic irradiation, temperature, and stress. More work to understand the effect of He on creep interaction is needed. Materials studies in fusion reactor environment should be carried out as soon as possible.

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