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Relationship between in-reactor stress relaxation and irradiation creep

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Abstract

Stress relaxation and irradiation creep data are available for 20% CW 316 SS samples fabricated from the same heat of material. The stress relaxation and irradiation creep tests were both performed in bending. The stress relaxation was calculated using an irradiation creep correlation formulated using the irradiation creep data. The calculations were in excellent agreement with the measurements and show that stress relaxation may be calculated using irradiation creep data when the proper methods are used. The methods for this calculation include the use of a transient exponential decay coefficient with a dose rate consistent with the stress relaxation application, the use of irradiation creep coefficients derived from tests with material consistent with the stress relaxation application and the use of irradiation creep data with the same stress state. © 1998 Elsevier Science B.V.

1. Introduction

Reactor core structures are subject to stresses that vary with time, whereas irradiation creep tests are generally performed under constant load. Usually irradiation creep test data are more reliable and are more available than stress relaxation data. Hence, the stress relaxation behavior of reactor structures is usually calculated using irradiation creep data. In applying these constant load irradiation creep test data to structures where the stress varies with time, certain assumptions must be made. For example, are irradiation creep tests performed in uniaxial tension related to stress relaxation in bending? An assessment of the assumptions between stress relaxation and irradiation creep data is required to be able to reliably calculate stress relaxation using irradiation creep data.

Stress relaxation and irradiation creep tests were performed using 20% cold worked (CW) 316 stainless steel (SS) in the Experimental Breeder reactor Number II (EBR-II). These tests were selected for analysis because the tests used the same heat of material and stress state. Irradiation creep tests have shown that the irradiation creep strain is dependent on material chemistry [1]. Hence, any comparison of irradiation creep and stress relaxation ideally should be made with material having the same chemical composition. Irradiation creep and stress relaxation data are available for 20% cold-worked 316 stainless steel. In the case of the stress relaxation test, the reported evaluation [2] indicates that at the lower dose levels, irradiation creep underpredicts the stress relaxation by about 10 to 20%. On the other hand, the stress relaxation data were overpredicted by about 15% for the higher dose level samples. The purpose of this paper is to evaluate the relationship between stress relaxation and irradiation creep, and develop a method which may be used to calculate stress relaxation using irradiation creep data. First, the applicable irradiation tests will be analysed, then the relationship between irradiation creep and stress relaxation will be developed and finally the predicted stress relaxation using an irradiation creep correlation will be compared with actual stress relaxation measurements.

2. Analysis of the irradiation tests

Stress relaxation and irradiation creep tests were performed in bending using samples fabricated with 20% CW

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316 SS using NICE lot material (heat 81581). Uniaxial tensile irradiation creep data were also used for this evaluation, and these samples were fabricated with 20% CW 316 SS using N lot material (heat 87210).

2.1. The H-5 stress relaxation in bending test

A stress relaxation test [2], designated as H-5 by the US DOE National Clad and Duct Materials Development Program (NC/D), was performed in EBR-II. The samples consisted of uniform width beams loaded in four-point bending and were fabricated using 20% CW 316 SS with NICE lot material (heat 81581). The stress relaxation was measured at a temperature of 370°C after two fixed irradiation intervals. The data from the initial irradiation have been reported [2]. Test data at different dose levels was provided by placing the samples in different axial positions (i.e., dose rate variations) and by two different exposure times. The dose levels were determined by the location of the samples, the neutron spectrum and the exposure time. The sample positions were determined from subassembly drawings. The neutron flux values were calculated with the two-dimensional solver routines in the transport code DANTSYS. These evaluations used the ENDF/B-V cross-sections and the sample radial-axial position geometry. The cross-sections were collapsed to a 28 energy group structure using weighting fluxes appropriate for specific regions in the EBR-II core (the fuel, reflector and blanket regions). The 28 group damage cross-sections were collapsed from ENDF/B-VI using the cross section processing code NJOY. The calculated displacement per atom values were determined by multiplying the neutron fluence by the ENDF/B-VI damage cross sections.

The reported stress relaxation was determined by measurement of the beam deflection. The accuracy of these measurements was only ± 10 μm (± 0.0005 in.). Therefore, beams with small deflections are associated with the largest stress relaxation uncertainty. A review of the stress relaxation data showed that the beams with measured deflections < 76 μm exhibited the largest sample-to-sample scatter. As a result, all beams with measured deflections < 76 μm were disregarded. The beams were loaded with initial stresses in the range of 29 to 375 MPa. The measured stress relaxation was independent of the initial stress level. Fig. 1 presents the stress relaxation data for samples with measured deflections > 76 μm. The results show that the stress relaxation (stress relaxation is referred to as the ratio of the instantaneous stress to the initial stress) decreases from a value of about 52% at 0.15 dpa to about 40% at 1.9 dpa.

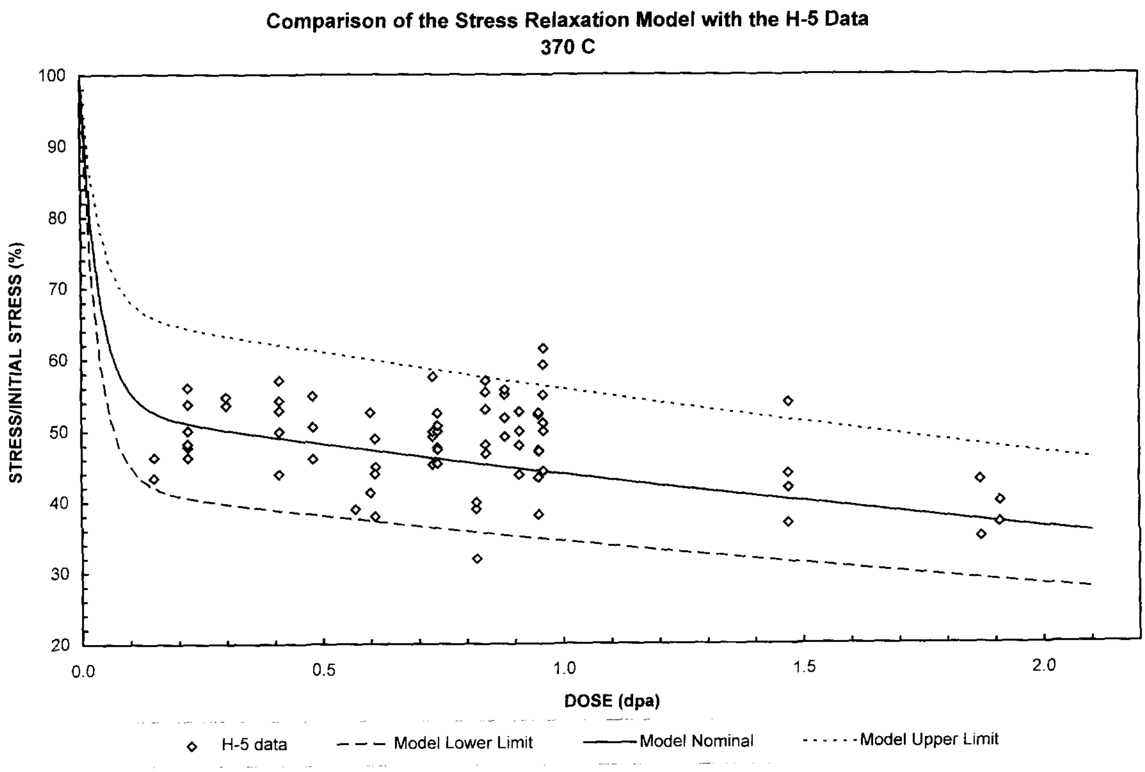

Fig. 1. Comparison of the calculated stress relaxation using an irradiation creep correlation formulated using the C-1 irradiation creep test with the H-5 test stress relaxation data.

2.2. The C-1 irradiation creep in bending test

An irradiation creep in bending test [3–5], designated as C-1 by the NC/D Program, was performed in the EBR-II fast neutron reactor. The beam samples were fabricated using 20% CW 316 SS with NICE lot material (heat 81581). The beam samples included both four-point uniform width and tapered width cantilever beams. The width of the cantilever beams was uniformly tapered such that a uniform bending stress resulted over the entire beam length. The data consist of repetitive strain measurements [3,5] made on the same samples with increasing dose. The displacement dose was calculated based on the beam axial locations at each measurement position and the neutron spectrum. The beam positions were determined from subassembly radiographs for each examination. The displacement dose was calculated by the procedure used for the H-5 test described above.

The beams were loaded with stresses over the range of 156 to 240 MPa for the cantilever beams and 80 to 327 MPa for the uniform beams, respectively. Since irradiation creep is linear with stress [6], the data were analysed as strain divided by stress versus dose. Figs. 2 and 3 present typical examples of the cantilever and four-point beam data, respectively. Irradiation creep, at low temperatures (where thermal creep is small) and low dose levels (where swelling is negligible), may be described by an equation of the form [6]

$$e^{ic} = A_1\sigma[1 - \exp(-A_2 f)] + A_3\sigma f, \qquad (1)$$

where e^{ic} is the irradiation creep strain, σ is the stress, f is the displacement dose and A_1, A_2 and A_3 are material coefficients. The bending samples exhibit all three irradiation creep components (i.e., the initial transient A_1, the steady state rate A_3 and the high dose tertiary component). The transient A_1 coefficient and the steady state rate coefficient A_3 were determined by regression fits to the data of the strain normalized stress versus dose in the linear region as illustrated by the solid lines in Figs. 2 and 3 for all of the beam samples. The tertiary component was neglected because the stress relaxation test data are at very low dose levels (prior to the onset of tertiary irradiation creep). There were a total of 22 four-point and 42 cantilever beam samples.

Figs. 4 and 5 present the results for the transient (A_1) and steady state rate (A_3) coefficients, respectively, versus temperature. The A_1 coefficient exhibits considerable scatter and is temperature independent over the range of 379 to 465°C. The steady state rate A_3 coefficient is temperature dependent over the same temperature range. The value of A_3 decreases with decreasing temperature. The relatively moderate temperature dependence and beam sample-to-

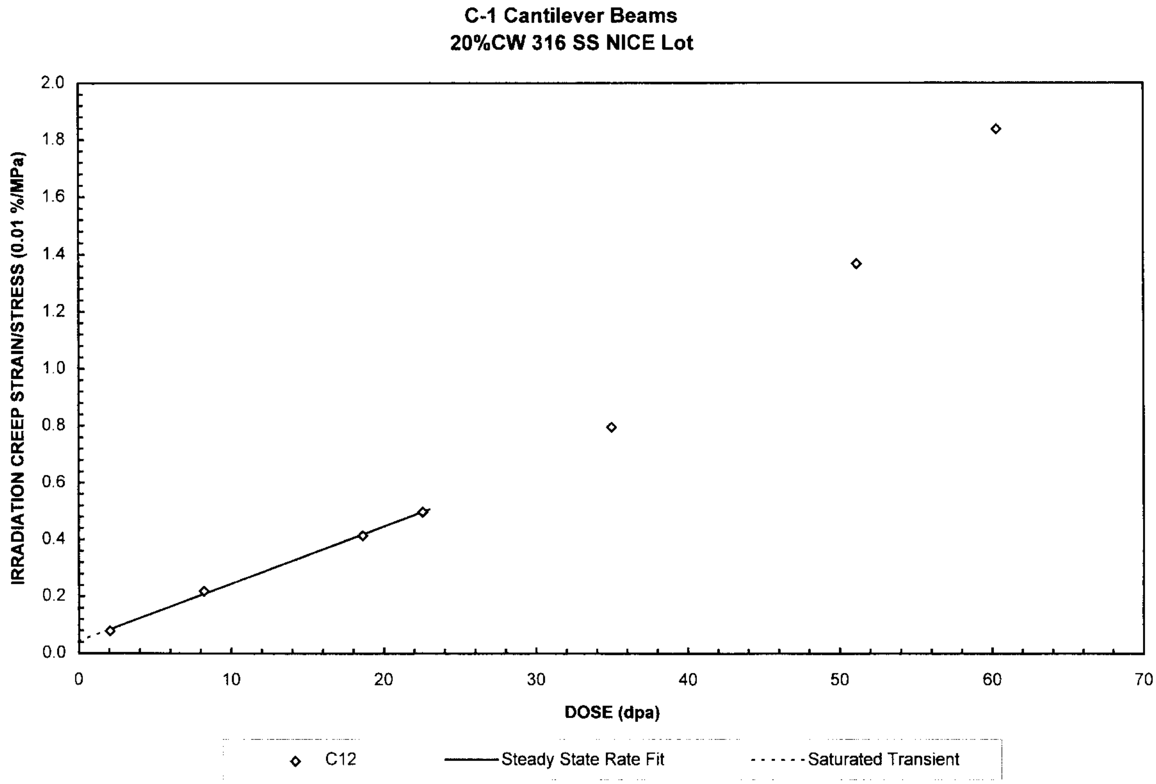

Fig. 2. Irradiation creep strain normalized stress versus dose data and the steady state rate regression fit for cantilever beam sample C12.

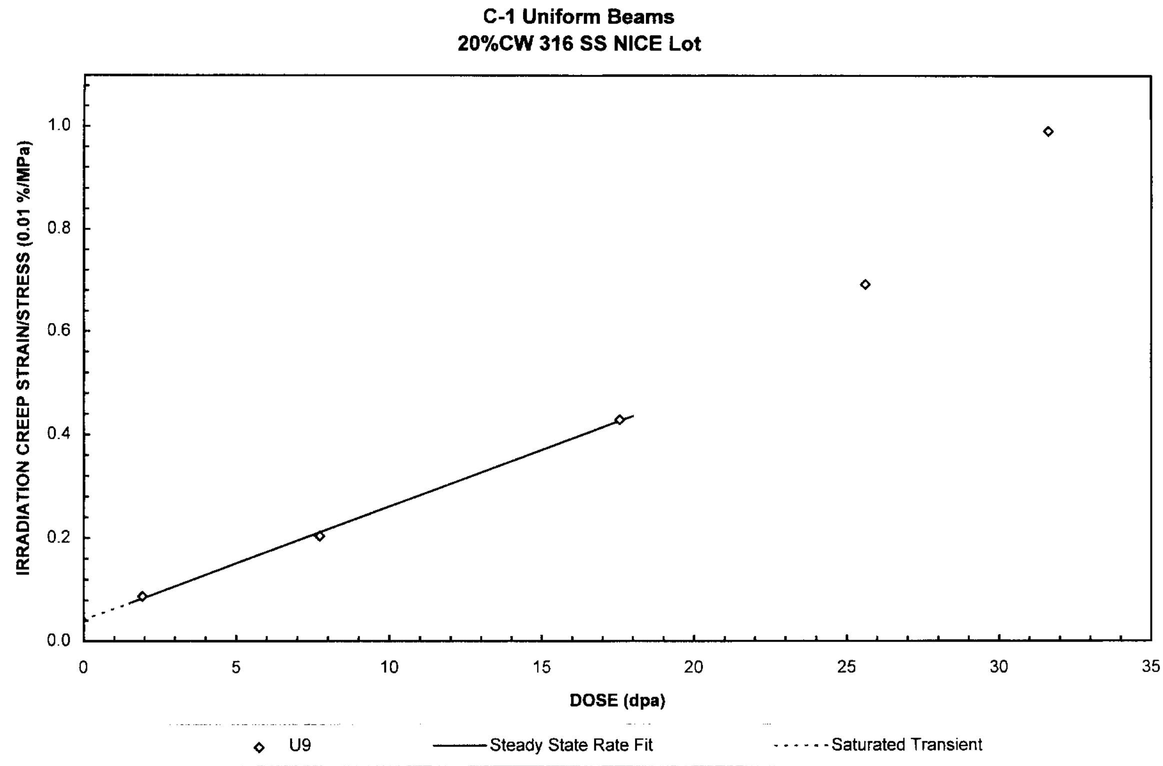

Fig. 3. Irradiation creep strain normalized stress versus dose data and the steady state rate regression fit for four-point uniform beam sample U1.

sample data scatter explain why the temperature dependence of the steady state rate was not previously observed. The steady state rate decrease is only a factor of 1.5 from 465 to 379°C. The line presented in Fig. 5 is a regression fit to the steady state rate data. The cantilever beams with applied stresses below 156 MPa were neglected because of the inaccuracies associated with very small irradiation creep strains.

2.3. The uniaxial tensile irradiation creep tests

Uniaxial tensile irradiation creep tests [7,8] have been performed in two reactors using a facility that measured the strain during neutron irradiation. One test was performed in EBR-II using 20% CW 316 SS N lot material (heat 87210) at 454°C [7]. The data consist of repetitive strain measurements made on one uniaxial sample during neutron irradiation. After 2.2×10^6 s, the strain measurement instrumentation became inoperable. Several higher dose strain measurements were made by pressure cycling and by post test measurement. The neutron flux (and fluence) was determined by post test analysis of foil dosimeters located in the test assembly. The flux (and fluence) were converted to dose rate (and dose) by multiplying the ratio of dose rate to flux. The ratio of dpa/s to flux was calculated as described above for the H-5 test. The resulting irradiation creep coefficients were calculated by this study to be: $A_1 = 3.88 \times 10^{-4}$%/MPa, $A_2 =$ 4.3/dpa and $A_3 = 9.53 \times 10^{-5}$%/MPa dpa.

A second set of uniaxial tests was performed in the K reactor [8]. The tests were performed using three solution annealed (SA) 304 SS and one 20% CW 316 SS N lot sample, respectively. The data consist of repetitive strain measurements made during neutron irradiation. The results are presented in Fig. 6. Since irradiation creep is linear in stress [6], the data were analyzed as strain divided by stress versus dose. The SA 304 SS data do not exhibit a strong temperature dependence over this temperature range. The 20% CW 316 SS test was performed at 370°C. The dose levels were calculated using the reported seven-group energy flux spectrum [9] and the displacement cross sections from the ENDF/B-VI file. Fig. 6 shows the test results. Strain data are available for SA 304 SS in the transient region for temperatures between 175 and 200°C. The SA 304 SS tests were performed in the temperature interval from 175 to 370°C. The strain measurements for SA 304 SS show that the duration of the transient component is not very temperature dependent over the temperature range from 175 to 370°C. Although the strain measurements of the 20% CW 316 SS sample were only made for a short dose interval in the steady state rate region, measurements show that the duration of the transient component is

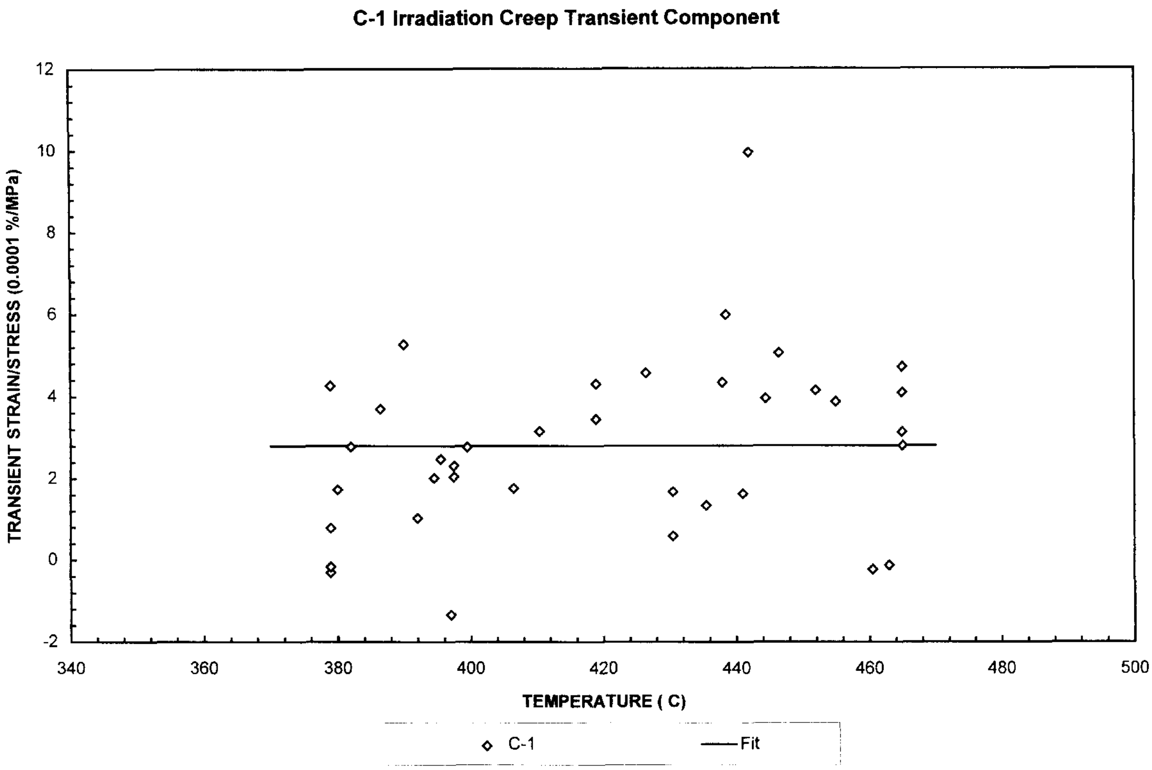

Fig. 4. The transient irradiation creep component A_1 coefficients versus temperature determined from the C-1 irradiation creep test.

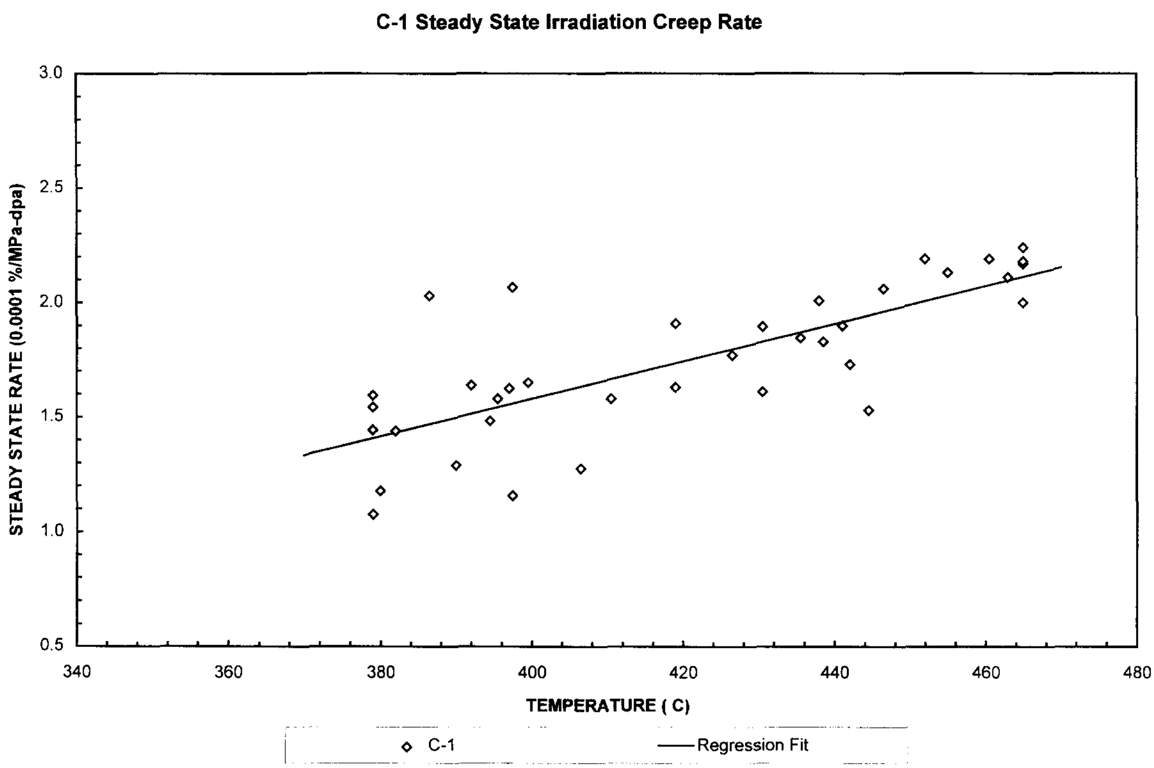

Fig. 5. The steady state rate irradiation creep component A_3 coefficients versus temperature determined from the C-1 irradiation creep test.

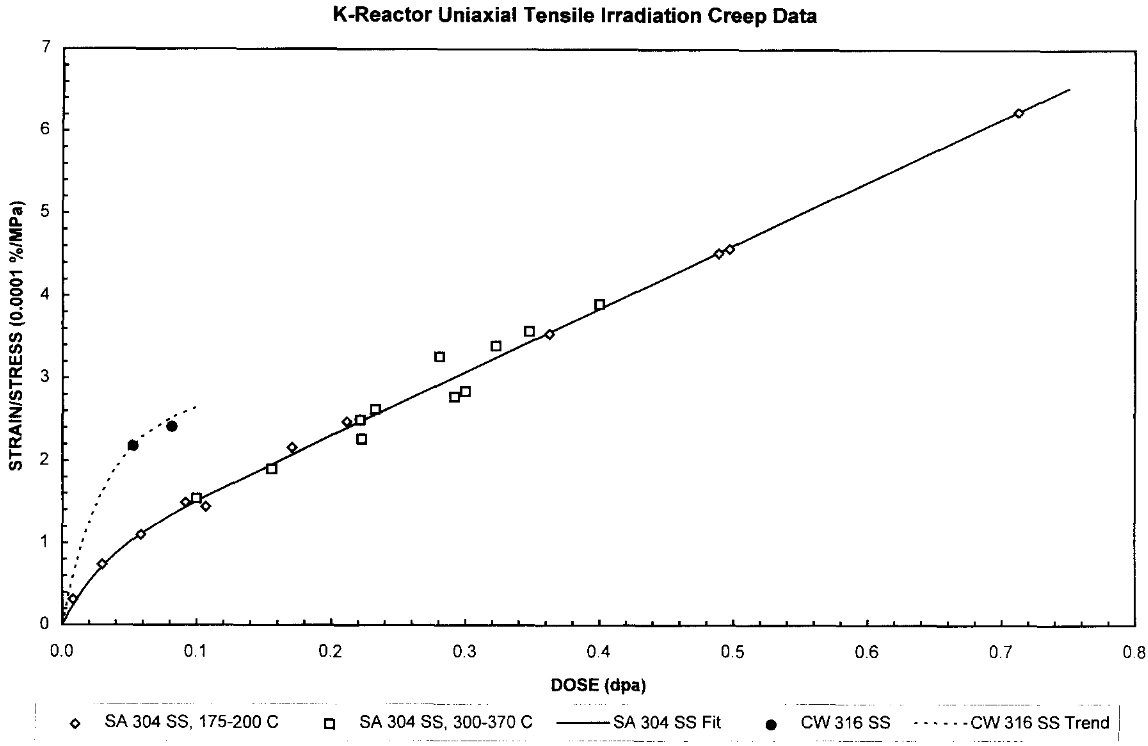

Fig. 6. Uniaxial tensile irradiation creep data measured in the K reactor.

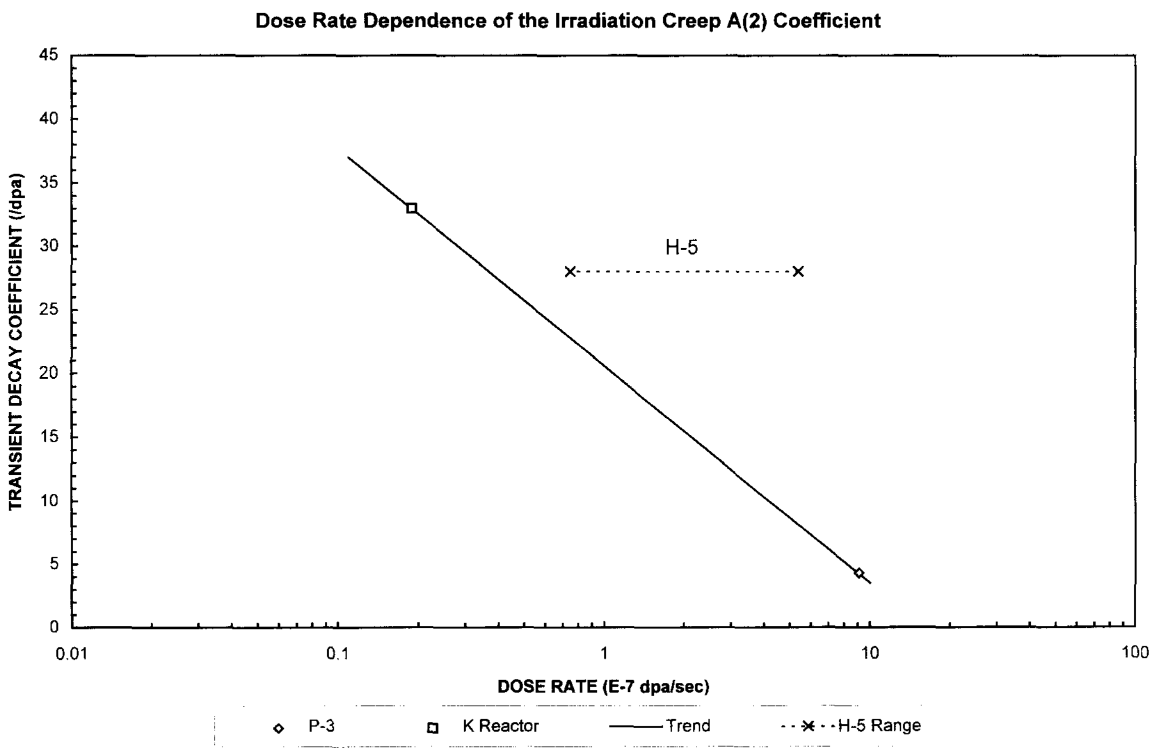

Fig. 7. Dose rate dependence of the irradiation creep transient component A_2 coefficient.

similar for 20% CW 316 SS and SA 304 SS. As a result, the A_2 coefficient, evaluated with the SA 304 SS data, was considered to be representative of 20% CW 316 SS.

Fig. 7 presents the results for the A_2 coefficient versus dose rate for 20% CW 316 SS. The limited data indicate that the A_2 coefficient decreases with increasing dose rate. The A_2 versus log dose rate dependence was assumed to be linear versus logarithmic (additional uniaxial irradiation creep test data are necessary to confirm this assumption). The horizontal dashed line denotes the dose rate variation of the beam samples in the H-5 test. Note that the available A_2 coefficient data envelope the dose rates of the H-5 samples.

3. Relationship between irradiation creep and stress relaxation

The relationship between stress relaxation and irradiation creep may be developed by considering the stress relaxation test. In a stress relaxation test, the strain is maintained constant and the stress decreases with increasing time. In equation form

$$e^{e} + e^{ic} = \text{constant}, \tag{2}$$

where e^{e} is the elastic strain and e^{ic} is the irradiation creep strain. Differentiation with respect to time results in

$$\mathrm{d}e^{e}/\mathrm{d}t + \mathrm{d}e^{ic}/\mathrm{d}t = 0. \tag{3}$$

The elastic strain may be obtained by differentiating the elastic strain equation

$$e^{e} = \sigma/E, \qquad \mathrm{d}e^{e}/\mathrm{d}t = (1/E)\,\mathrm{d}\sigma/\mathrm{d}t, \tag{4}$$

where σ is the stress and E is the elastic modulus. Differentiating Eq. (1) with respect to time and assuming that the inelastic stress rate is negligible results in

$$\mathrm{d}e^{ic}/\mathrm{d}t = \sigma[A_1 A_2 \exp(-A_2 f) + C]\,\mathrm{d}f/\mathrm{d}t. \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (3) results in

$$(1/E)(1/\sigma)\,\mathrm{d}\sigma/\mathrm{d}t = -[A_1 A_2 \exp(-A_2 f)\,\mathrm{d}f + A_3\,\mathrm{d}f]. \tag{6}$$

Eq. (6) may be solved in closed form. Integrating results in

$$\sigma/\sigma_0 = \exp\{-E[A_1(1-\exp(-A_2 f)) + A_3 f]\}. \tag{7}$$

Eq. (7) shows that the stress relaxation is exponentially dependent on the elastic modulus E, the irradiation creep coefficients A_1, A_2 and A_3, and the displacement dose. Hence, any uncertainty in the irradiation creep coefficients or the dose results in an exponential uncertainty.

4. Discussion

Fig. 1 presents a comparison of the predicted stress relaxation using Eq. (7) and the measured stress relaxation. The irradiation creep A_1 and A_3 coefficients were evalu-

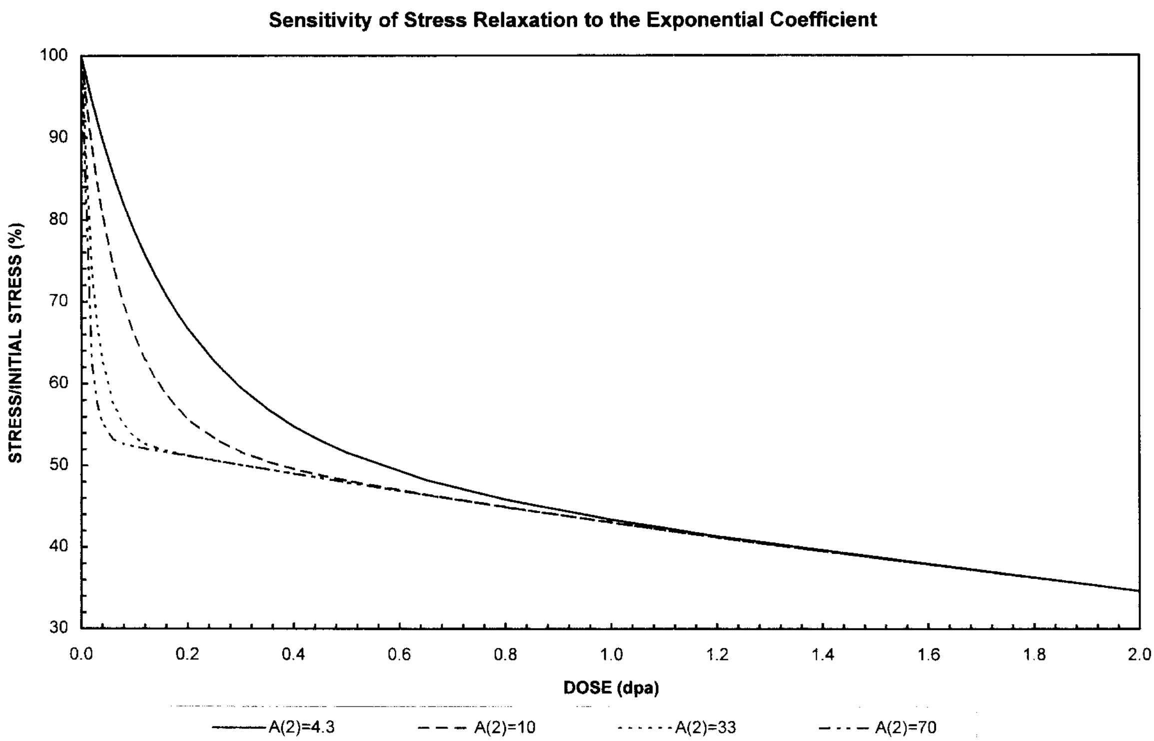

Fig. 8. Sensitivity of the calculated stress relaxation to the irradiation creep transient A_2 component coefficient.

ated with the C-1 bending test data. Since the steady state rate A_3 coefficient is temperature dependent, the C-1 A_3 coefficients for each beam were normalized to 370°C, which is the irradiation temperature of the H-5 stress relaxation test. The upper and lower limits indicated in the legend of Fig. 1 represent 95% confidence intervals for the A_1 and A_3 coefficients. Unfortunately, the C-1 strain measurements were all performed in the steady state irradiation creep rate region. No measurements were performed in the transient region. As a result, the A_2 coefficients were determined using the uniaxial tensile irradiation creep tests. The value of A_2 depends on the dose rate as illustrated by Fig. 7. Fig. 7 also shows the dose rate interval in the H-5 stress relaxation test. Sensitivity calculations using the nominal A_1 and A_3 coefficients derived from the C-1 test showed that the H-5 beam samples in the lowest dose rate positions are in the transient irradiation creep component region. This sensitivity is illustrated by Fig. 8. The sensitivity calculations with different values of A_2 show that the duration of the transient region associated with the EBR-II uniaxial irradiation creep test (i.e., $A_2 = 4.3/\text{dpa}$) extends to about 0.6 dpa, whereas the transient region duration only extends to about 0.1 dpa for the K reactor (i.e., $A_2 = 33/\text{dpa}$). Hence, the A_2 coefficient associated with the lowest dose rate for H-5 was used for the stress relaxation calculations.

Fig. 1 shows that the predicted stress relaxation using the irradiation creep bending test data are in excellent agreement with the measured stress relaxation. This excellent agreement confirms the methods used to calculate stress relaxation using irradiation creep data. These methods include the use of a transient exponential decay coefficient with a dose rate consistent with the stress relaxation application, the use of irradiation creep coefficients derived from tests with material consistent with the stress relaxation application, the use of irradiation creep data with the same stress state and the requirement that only the elastic stress rate varies. Kenfield et al. [2], previously reported limited agreement between the predicted and measured stress relaxation. This discrepancy is attributed to the irradiation creep model [10] used by Kenfield et al. [2] for the calculations. The transient component A_2 coefficient was based on the EBR-II uniaxial tensile data and not on the dose rate of the H-5 stress relaxation samples. The evaluation was performed for the first irradiation period (note that the data in Fig. 1 include all the test data). The measured stress relaxation after the first irradiation period (a maximum dose of 0.95 dpa), was about 50%. At the low dose levels of about 0.15 to 0.30 dpa, the stress relaxation was underpredicted by about 10 to 20%. The underprediction of the low dose stress relaxation data is due to the use of the A_2 coefficient associated with the EBR-II uniaxial test. The EBR-II uniaxial irradiation creep test was performed at a relatively high dose rate of 9.1×10^{-7} dpa/s in comparison with the minimum dose rate for H-5 of 7.5×10^{-8} dpa/s. The A_2 coefficient value used for the stress relaxation calculations by Kenfield et al. [2] was 3.9/dpa. Fig. 8 shows that an A_2 value of 3.9/dpa will underpredict the stress relaxation relative to the value of 23/dpa used by this study.

In the case of the comparison between the predicted stress relaxation and the measured stress relaxation, Kenfield et al. [2] state that the calculated stress relaxation values are in agreement with the measurements, but that this represents an overprediction because out-of-reactor stress relaxation tests showed about 15% stress relaxation. This evaluation by Kenfield et al. [2] is incorrect for the following reasons. The observed thermal stress relaxation is due to thermal creep. Thermal creep strain calculations were performed using an equation formulated with samples fabricated with 20% CW 316 SS N lot material [11]. The calculations were performed at 370°C for the H-5 samples with the maximum applied stress of 375 MPa (54 ksi). The calculations show that a small amount of thermal creep strain occurs by the time of the initial examination (0.0046%), and that no appreciable increase in the strain occurs by the time of the final examination (0.0053%). Hence, the very small thermal creep strain which occurs will be included in the transient irradiation creep coefficient A_1 determined for the C-1 bending samples. Therefore, this small thermal creep strain effect is already included in the stress relaxation calculation.

5. Conclusions

The results and discussion presented above show that stress relaxation may be calculated using irradiation creep data. The methods for this calculation include the use of a transient exponential decay coefficient with a dose rate consistent with the stress relaxation application, the use of irradiation creep coefficients derived from tests with material consistent with the stress relaxation application and the use of irradiation creep data with the same stress state.

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