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**STRESS RELAXATION ANALYSIS AND IRRADIATION CREEP
AND SWELLING IN PRESSURE TUBES**

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This is a copy of a paper to be presented at the
5th International Conference on Structural Mechanics in Reactor Technology
August 13-17, 1979
Berlin, (West) Germany

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SUMMARY

An analysis is presented of slit width test information on two pressure tubes that had been irradiated in test reactors. The analysis showed that differential swelling stresses and thermal stresses undergo relaxation. The mechanism responsible for the stress relaxation at temperatures less than 700 K was irradiation creep. Irradiation creep in thermal test reactor pressure tubes is evidently greater than it would be at equivalent conditions in fast reactors. The residual stresses observed in the slit width tests varied between 30 and 257 MPa and would act to reduce the operating stresses, thus allowing for increased service life of the tubes as compared with no stress relaxation.

Stresses that result from differential swelling gradients generated through the wall thickness of in-reactor pressure tubes are of practical importance to tube operation and service life. If stress relaxation did not occur the swelling gradients could produce internal stresses which would build up with increased fluence and cause yielding or fracture of the pressure tubes. The mechanisms which induce the stress relaxation are believed to be irradiation creep, cyclic plastic strain, and an effect of stress on swelling. The effect of stress on void swelling was stated by Hayns, Gallagher and Bullough [1] to be important only at temperatures high enough for thermal emission of vacancies. The maximum temperature at which the pressure tubes in this report have operated is 700 K, which is too low for the role of stress on void swelling to have much effect. The cyclic plastic strain is also small, thus irradiation creep should be the principal mechanism for the stress relaxation.

It has been reported that stress relaxation and creep are temperature and time phenomena which are enhanced by the presence of fast neutron flux (through displacement of atoms). For example, Kenfield, Busboom, and Appleby [2] found the addition of a fluence of 2×10^{21} n/cm² $E > 0.1$ MeV at 643 K resulted in 50% relaxation, while the thermal relaxation for the same time and temperature was only 15%. The initial relaxation and creep rate upon introduction into a neutron field are greater than the secondary rates.

The slit tube test was proposed by Pennell [3] to obtain swelling-creep superposition information from irradiated cladding, and applied by Foster, Wolfer, Biancheria, and Boltax [4] and by Flinn, McVay, and Walters [5] to irradiated fuel pin capsules and cladding. Stresses that result from differential swelling gradients generated through the wall thickness of in-reactor pressure tubes have been investigated by Beeston and Burr [6] by stress relaxation analysis of slit width tests on an Engineering Test Reactor (ETR) tube. Additional data and analysis from an Advanced Test Reactor (ATR) tube are included in this report.

2.0 PROCEDURE

2.1 Slit Width Sections

Slit width test sections were machined from two Type 348 stainless steel in-pile tubes. One tube was irradiated in the ETR to a maximum fluence of 3.8×10^{22} n/cm², $E > 1$ MeV (~ 72 dpa) and the other tube to a maximum fluence of 3.2×10^{22} n/cm², $E > 1$ MeV (~ 61 dpa) in the ATR. Before making a slit width test with the irradiated sections of the tubes, a test was conducted on a dummy section of an unirradiated 17-4 PH tube of the same size, heat-treated to simulate the yield strength to verify that the hold down clamps did not introduce any stresses.

A plunge cut (the index cut) was made in the center with sufficient ligament length to restrain the plunge cut section. The index width was then measured and the final cuts

of the ligaments made by moving the tube-fixture unit so that the saw blade did not traverse the index position. The dummy tube section measurements indicated no change from the index measurement.

2.2 Equations

The basic equations involve the relative displacements, δ , of the slit faces, the thermal stress, and the differential swelling stress across the tube wall. The residual stress in the reactor-off ambient condition can be calculated from the change in the slit width. If $\Delta\sigma_R$ is the residual stress, as defined by the stress on the outside (tensile) minus the stress (compressive) on the inside wall of the tube section, then $\Delta\sigma_R$ is given by:

$$\Delta\sigma_R = \frac{2\delta Et}{\pi(1-\nu)D} \quad (1)$$

where δ = slit width change (positive - opens)

E = Young's modulus

ν = Poisson's ratio

D = diameter of tube (average), and

t = wall thickness.

The residual stress in the tube section may thus be calculated from the slit width measurement and compared with the sum of the differential swelling stress and the thermal stress before and after stress relaxation. The differential swelling stress is given by:

$$\Delta\sigma_s = \frac{E}{6(1-\nu)} \left[\left(\frac{\Delta V}{V} \right)_o - \left(\frac{\Delta V}{V} \right)_i \right] \quad (2)$$

where $\left(\frac{\Delta V}{V} \right)$ is the swelling on the outside and inside walls.

The thermal stress is given by:

$$\Delta\sigma_t = -\frac{E \alpha}{(1-\nu)} \Delta T \quad (3)$$

where α = coefficient of thermal expansion, and

ΔT = the temperature difference between the outside and the inside wall.

The effect of stress relaxation on the differential swelling stress is to reduce it from the maximum to zero, but when a differential swelling stress is present it always moves the slit width (at test) in the same direction. The effect of stress relaxation on the thermal stress is to reduce it from the maximum to zero at power but in the reactor-off condition the thermal stress may be reversed after stress relaxation so that the slit width (at test) may open or closed depending on the amount of stress relaxation.

The relative displacement of the slit width due to the calculated swelling only may be calculated and compared with the measured value in direction and magnitude. The

displacement, δ_s , is given by:

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$$\delta_s = - \frac{\pi D (1+\nu)}{6 \ln \frac{r_o}{r_i}} \left[\left(\frac{\Delta V}{V} \right)_o - \left(\frac{\Delta V}{V} \right)_i \right] \quad (4)$$

where r_o = the tube outside radius

and r_i = the tube inside radius,

since $T_o > T_i$ with the reactor at power, any residual stress from swelling will tend to close the slit width.

3.0 RESULTS

3.1 Slit Width Measurements and Stress Calculations

The slit width measurements were made with gage indicators to an estimate of ± 0.3 mm. The data, including the fluence for each tube section, are given in Table I. The slit width in each case opened as indicated by the positive sign. The residual stress, $\Delta\sigma_R$, is calculated by eq. (1) and is given in Table I. Calculated and given in the table are the differential swelling stress, eq. (2), thermal stress, eq. (3), and the slit width to be expected from swelling only, eq. (4). In eq. (2) and (4) the swelling at the outside wall (the higher temperature) was taken as twice the measured value for the irradiated fluence, and the swelling at the inside wall was taken as negligible because of the low swelling temperatures involved (< 650 K). As seen in Table I from the direction of the slit width displacement (opening versus closing from swelling only) and the magnitude of the residual stress and thermal stress, the thermal stress is nearly completely relaxed and reverses upon reactor cooldown to open the slit width. Stated in terms of the stresses, the residual stress is equal to the algebraic sum of the differential swelling stress plus the thermal stress or $\Delta\sigma_R = \Delta\sigma_s + \Delta\sigma_t$, and as seen from Figure 1, the differential swelling stress must approach zero and the thermal stress be reversed upon reactor cooldown to open the slit width. The reactor-on thermal stress was calculated for the power conditions that existed for the last fluence addition of 1.44×10^{21} , $E > 0.1$ MeV (1.4 dpa).

It should be noted in Table I that the slit opening in the low fluence tube section irradiated out of the core region must be due to fabrication stresses which have not been relaxed. The thermal stress at the time of the slit width test would be negligible.

3.2 Density and Swelling

The immersion density of slices from the tube sections was measured using water with Photoflo as a wetting agent. Densification calculated according to the correlation for Types 316 stainless steel of Garner, Bates, and Gilbert [7] is small ($\frac{\Delta\rho}{\rho_0} = 0.04\%$). The ferrite content of an ETR irradiated sample was measured with a Ferrit-Messser instrument as 0.1% (also small). Metallography indicated the presence of the austenitic phase and small amounts of carbides. The swelling is thus taken as equal to the density change, $\Delta\rho/\rho_i$. The values are given in Table II.

3.3 Irradiation Creep and Cyclic Plastic Strain

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The total creep in the tubes was measured with a bore gage as a change in diameter. The creep due to densification and swelling is small (~ 0.0007), and the metal temperature is below the thermal creep range, hence the total creep is given in Table II as the irradiation creep.

The cyclic plastic strain accumulation due to thermal ratcheting in a similarly constructed and operating tube was calculated by Beeston and Burr [6] to be less than 0.08%. The FW-HEDL computer Code R1045 program was used in the calculation. The program performs a cyclic elastic-plastic-creep analysis of an infinitely long thick-walled cylinder subject to pressure loads at the inner and outer surfaces, to axial loads, and to a radial thermal gradient through the tube wall. Additionally the program includes the effects of irradiation-induced creep and swelling. It seems certain from operating experience, and from the results of the slit-tube tests presented in this paper, that residual stresses are affected by the irradiation creep in in-pile tubes operating with a mean metal temperature range of 583 to 698 K.

3.4 Irradiation History of ATR Tube

The irradiation history of the ATR tube was such that generally for the first period of its life it operated at higher wall temperatures than for successive periods, see Table III. In the last period it generally operated at the lowest wall temperatures and for the shortest period of time (1.4 dpa). These periods include a number of reactor cycles.

4.0 Discussion

The slit width measurement has indicated that an effective mechanism has operated to relax the differential swelling stress and the thermal stress in the wall of the in-pile tubes in the reactor core. That mechanism has been indicated to be irradiation creep for the range of temperatures involved.

The effect of irradiation history on the stress relaxation has been that the last period most affects the slit width test measurement. The final residual stress acts in the direction of a reversed thermal stress to open the slit width and is of smaller magnitude than the thermal stress. The ratio of the final residual stress to the reversed thermal stress of the last period is 0.25. As mentioned previously, Kenfield et al [2] have shown that the total in-reactor relaxation after a peak fluence of 2×10^{21} n/cm², E > 0.1 MeV at 643 K is $\sim 50\%$. The mean metal wall temperature of the final period is about 612 K, hence the relaxation of 25% in this period is consistent. Foster et al [4] point out that the development of the residual stress with time will depend upon the irradiation creep rate. If the differential swelling rate changes with time faster than the irradiation creep rate, the on-power residual stress will build up. At the irradiation conditions of these tubes the total creep and, as indicated, the irradiation creep rate were much

An interesting increase in the irradiation creep appears to occur in thermal reactor irradiation when compared with fast reactor irradiation at equivalent conditions. If the creep equation, as given by Boltax, Foster, Weiner, and Biancheria [8], is

$$\frac{\epsilon}{\sigma} = C\phi t + DS \quad (5)$$

where ϵ = the effective creep strain

σ = the effective stress

t = the fast fluence

S = the fractional swelling

and C and D are constants,

then the value of the constant, C , was noted by Beeston and Burr [6] and by Foster, Weiner and Boltax [9] to be a factor of about 2.5 times greater for thermal reactor than for fast reactor irradiation. Beeston et al [6] attributed the increase to an effect of flux spectrum and gave some transmission electron microscopy (TEM) photographs and data to indicate that the effect was associated with the density of interstitial and vacancy loops. No voids could be detected, and no difference in TEM samples from the inner wall, mid-wall and outer wall could be detected. The loops disappeared after annealing at 1047 K for one hour and air cooling (AC).

Although the temperature range in which these tubes operated is low (600-700 K) so that the swelling is small, the relaxation of the differential swelling stresses has resulted in a 50% reduction of the operating stresses. This reduction allows an increased service lifetime for the tubes.

5.0 Conclusions

1. From the slit width test information, it was shown that the differential swelling stresses and the thermal stress were mostly relaxed.
2. The mechanism responsible for the stress relaxation was indicated to be irradiation creep, which is greater for thermal reactor irradiation than for fast reactor irradiation at temperatures < 700 K.
3. The final irradiation period has more effect than previous irradiation periods on the values obtained in the slit width test, if the exposure of that period is greater than $1.4 \times 10^{22} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$.
4. Residual stresses were observed that varied between 30 and 257 MPa.
5. The operating stresses will be less because of the stress relaxation that has occurred, thus allowing for increased service life of the tubes as compared with no stress relaxation.

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TABLE I

SLIT WIDTH MEASUREMENTS AND STRESS CALCULATIONS

Position	Fluence 10^{22} n/cm^2 $E > 1 \text{ MeV}$	Approximate Displacements per atom	Slit Width Opening mm	Residual Stress Eq. (1) $\Delta\sigma_R$ MPa	Differential Swelling Stress Eq. (2) $\Delta\sigma_s$ MPa	Reactor-on Thermal Stress Eq. (3) $\Delta\sigma_t$ MPa	Calculated Slit Width From Swelling Only mm
ETR-ring	3.4	65	+1.30	257.1	202.0	295.8	-1.02
ATR-1	0.00022		+0.13	25.2	82.7	-57.0	-0.42
ATR-4	2.81(max)	53	+0.20	40.4	174.4	158.6	-0.89
ATR-5	2.77(max)	53	+0.20	40.4	165.5	158.6	-0.84
ATR-6	2.06(max)	39	+0.15	30.3	156.5	110.1	-0.79

TABLE II

DENSITY, SWELLING, AND CREEP

Position	Fluence 10^{22} n/cm^2 $E > 1 \text{ MeV}$	Density g/cm	Swelling $\frac{\Delta V}{V}$	Diameter Change ΔD	Irradiation Creep E_i %
Base	0	7.9360	--	--	--
ETR	3.8	7.9182	0.0022	0.018	0.84
ETR-Ring	3.4	7.912	0.0030	0.015	0.71
ETR-Ring Annealed 1047 K 1 hr. AC	3.4	7.916	0.0025	--	--
ATR-1	0.0002	7.929	0.0009	0.000	0.00
ATR-4	2.81	7.9208	0.0019	0.037	1.74
ATR-5	2.77	--	0.0018 (est)	0.036	1.69
ATR-6	2.06	7.9222	0.0017	0.025	1.17

TABLE III

IRRADIATION HISTORY OF ATR TUBE

Period	Fluence 10^{22} n/cm^2 E > 0.1 MeV	Displacement per atom dpa	Wall Temperatures, K		Thermal Stress MPa
			OD	ID	
1	2.65	26	696	618	400
2	0.96	10	668	603	321
3	2.40	24	648	599	241
4	0.144	1.4	628	596	158.6

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Fig. 1 Schematic stress relations.