METAL SWELLING AND IRRADIATION
CREEP EFFECTS UPON THE FAST TEST REACTOR
CORE COMPONENT PERFORMANCE

R. J. Jackson
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ABSTRACT

An analysis has been performed which predicts the bending distortion in fast reactor core components. It is shown that thermal strains, swelling strains, and irradiation creep strains are all important at some time during the lifetime of these components. It is concluded that irradiation creep greatly ameliorates the bending distortions of these core components.

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INTRODUCTION

Fast neutron-induced swelling and irradiation creep must be considered in the design of the Fast Test Reactor (FTR) which is part of the Fast Flux Test Facility (FFTF). These phenomena are both temperature and fluence dependent.^(1,2,3) In general, this results in swelling gradients whenever there are temperature or flux gradients in a core component. Therefore, consideration must be given to both dilation and distortion of core components exposed to a fast neutron environment. One manifestation of the distortion caused by a transverse swelling gradient is the bending of long, slender core components such as driver fuel assemblies, control rod guide tubes, and closed loops, (Figures 1, 2, and 3). Bending of these components appears to be particularly important during core refueling because of the potential interference from adjacent components.

The magnitude of bending deflection during refueling depends upon the swelling gradient, the temperature gradient during operation, and the amount of stress relaxation which has occurred from irradiation creep. Analyses which consider these phenomena plus the conventional elastic strain have been conducted on each type of core component to predict the potential core component interactions during refueling.

Analysis of the interactions between core components requires simultaneous consideration of all fuel drivers, control rods, closed loops, and reflectors. At present, however, no method is available to undertake such a task. Despite this absence of methods for such analysis, estimations of the interactions can be performed by analyzing the first seven radial positions, as shown in Figure 4, and assuming adjacent ducts in the same row act independently.

Imposed on each FTR core component is a different set of environmental conditions which affect its bending deflections, support loads, stress distribution, and material properties. Because metal swelling increases with increasing time, the bending deflections, support loads, and stress distribution are also time-dependent in addition to the conventional temperature dependency. A finite-element, three-dimensional computer code (BMCRP) is being developed to consider the combined effect of metal swelling and creep upon these time-dependent parameters. The presently available, two-dimensional version of BMCRP, which is called CRASIB (Creep Analysis of Statically Indeterminate Beams), was used for these analyses.

FIGURE 1. Selected Fast Test Reactor Components

FIGURE 2 FTR Driver Fuel Assembly Duct

FIGURE 3. FTR Closed Loop

FIGURE 4. Arrangement of FTR Core

ENVIRONMENT

The axial and radial distributions of neutron flux and metal temperatures in each core component are essential for a calculation of predicted performance.

NEUTRON FLUX

The axial flux distribution and transverse flux gradients used in the deformation analysis are shown in Figures 5 and 6, respectively, for the FIR driver fuels. This same flux distribution was used in the deformation analysis of the closed loops in comparable driver locations. The flux distributions for the Row 4 and Row 7 control rod guide tubes are shown in Figures 7 and 8. These flux distributions were determined by scaling the radial flux distribution in the driver fuel assemblies to account for the flux depression of the poison pins.

The Row 4 control rod was assumed to remain cocked above the core during reactor operation. The Row 7 control rod was fixed with the bottom of the poison section 81.5 in. above the bottom of the core.

Only the flux of neutrons with energies greater than 0.1 MeV were considered, because this achieves the best correlations of swelling data from different reactors.

WALL TEMPERATURES

The axial temperature distribution and transverse temperature gradients for the first six rows of driver fuel assemblies are shown in Figures 9 and 10. The temperature distributions for the control rod guide tubes are shown in Figures 11 and 12. Almost all the energy produced in the control rods is produced in the poison material. This material is located mostly above the core during operations. Therefore, the axial temperature distribution in the walls of the control rod guide tube remains almost constant between the core bottom and the bottom of the poison material.

The temperatures in the closed loop pressure tube were computed using the TAP computer code,⁽²⁾ and are shown in Figure 13. The operating conditions were 4.0 MW test assembly with an 800 °F inlet temperature to the flow tube and a 400 °F rise through the test section. It was assumed that the closed loops had no temperature gradients imposed on them due to the presence of the coolant flowing inside the flow tube.

FIGURE 5. Axial Flux Variation For Driver Fuel Assembly Ducts

FIGURE 6. Transverse Flux Gradient For Driver Fuel Assembly Ducts

FIGURE 7. Axial Flux Variation For
Row 4 and Row 7 Control Rods

FIGURE 8. Transverse Flux Gradient For Row 4 and Row 7 Control Rods

FIGURE 9. Axial Average Temperatures For Driver Fuel Assembly Ducts

FIGURE 10. Transverse Temperature Gradient For Driver Fuel Assembly Ducts

FIGURE 11. Rows 4 and 7 Control Rod
Average Duct Temperatures

FIGURE 12. Transverse Temperature Gradient For Row 4 and Row 7 Control Rods

FIGURE 13 Closed Loop Temperature Variation

IRRADIATION CREEP

Data on irradiation creep^(1,2,3) in austenitic stainless steel clearly indicates a higher creep rate than thermally activated creep in both thermal and fast reactors at temperatures below 700 °F. Stress relaxation enhancement in austenitic stainless steel that has been reported in a thermal reactor indicates an enhancement of both the primary creep or transient irradiation creep and steady-state creep.^(4,5) The irradiation creep data has been fit to an equation of the form

$$\bar{\epsilon}/\bar{\sigma} = K_1 [1 - \exp(-\phi t/K_2)] + K_3 \alpha(\phi t).$$

Where

$\bar{\epsilon}$ = effective strain

$$= \frac{\sqrt{2}}{3} [(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2]^{1/2}$$

$\bar{\sigma}$ = effective stress

$$= \frac{1}{\sqrt{2}} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

α = temperature dependence of irradiation creep

ϕt = fluence, $E > 10^{-10}$ MeV

K_1, K_3 = material constants with units (psi)⁻¹

K_2 = material constant with units, n/cm⁻².

The first term is the transient creep term which approaches the value K_1 asymptotically. The second term is the steady-state creep term which increases linearly with time and stress. The above equation was used to extrapolate to FTR goal fluence of 2×10^{23} n/cm².

METAL SWELLING

Data on metal swelling are reported in References 6, 7, and 8. These data, which cover the temperature range 700 to 1100 °F and the neutron fluence range of 0.05×10^{22} to 7×10^{22} n/cm² (E > 0.1 MeV), were obtained from AISI 304 or 316 SS. Equations of the form

$$\Delta v/v = K \phi t^N \exp [(-Q_1/RT) - (Q_2/RT^2)]$$

$\Delta v/v$ = Volume change, %

K = Material constant, % n⁻¹ cm²

ϕt = Neutron fluence, n cm⁻² (E > 0.1 MeV)

Q_1, Q_2 = Material constant, cal mole⁻¹

R = 1.9872 cal mole⁻¹ °K⁻¹

T = Temp., °K

N = Material constant, dimensionless

have been fit to the data and used in the analysis. This model is used for fluences as high as 2×10^{23} n/cm² (Total), the FTR goal fluence. This assumes that the same swelling mechanisms are continuing to act at the FTR goal fluence of 2×10^{23} n/cm² as are operative at the fluences for which data exists up to 7×10^{22} .

RADIAL DILATATION AND AXIAL LENGTH INCREASE

Determination of radial dilatation and axial length increases resulting from fast neutron-induced metal swelling

is important in determining the performance of the FIR core. Radial dilatation, which is one-half the increase in dimension across the flats, subtracts from the nominal clearance between adjacent core members. This coupled with bending deflections may, in extreme cases, result in duct-to-duct contact at axial locations between support pads. Failure to account for axial length increase due to thermal expansion or swelling can result in axial interference or high axial compressive loads in the duct walls.

The radial swelling data and radial dilatation for the core components are tabulated in Table 1, at a peak burn-up of 80,000 MWd/MTM for the Row 1 driver fuel (275 days operation).

The axial length increases for selected core components is tabulated in Table 2. The first column lists the thermal expansion above 400 °F reference temperature. The second column lists the sum of the thermal expansion and swelling elongation after 275 days operation.

Driver Fuel Ducts

A graphical representation of the radial dilatation for the six driver fuel assembly ducts is shown in Figure 14. The maximum swelling occurs at approximately 7 in. above the core midplane for the Row 1 driver fuel. This maximum increase amounts to only 0.024 in. at 275 days exposure. As a result, no problem is anticipated in duct-to-duct contact of the driver fuel assembly ducts between support pads because of fast neutron swelling alone.

A potential concern resulting from axial length increase is the possibility of driver duct and instrument probe support interaction. Sufficient clearance must be provided to ensure continued reactor availability to high fuel burnup.

TABLE 1. Swelling and Radial Dilatation
in Selected Core Components

Row	120 Days		208 Days		275 Days	
	Swelling %	Radial Dilatation, in.	Swelling, %	Radial Dilatation, in.	Swelling, %	Radial Dilatation, in.
(DRIVER FUEL ASSEMBLY DUCTS)						
1	0.0238	0.0018	0.565	0.0043	0.904	0.0084
2	0.230	0.0017	0.546	0.0041	0.874	0.0067
3	0.206	0.0016	0.489	0.0037	0.782	0.0060
4	0.161	0.0012	0.382	0.0029	0.610	0.0046
5	0.124	0.0009	0.295	0.0024	0.471	0.0036
6	0.064	0.0005	0.152	0.0012	0.244	0.0019
(CLOSED LOOP PRESSURE TUBE)						
2	0.358	0.0027	0.848	0.0065	1.356	0.0103
4	0.272	0.0021	0.644	0.0049	1.029	0.0078
6	0.117	0.0009	0.277	0.0021	0.442	0.0034
(CONTROL ROD GUIDE TUBES)						
4	0.037	0.0003	0.088	0.0007	0.140	0.0011
7	0.0074	0.0001	0.018	0.0001	0.028	0.0002

TABLE 2. Axial Length Increase of
Core Components

Row	Thermal Expansion, in.	Thermal and Swelling Expansion (275 days), in.
<u>DRIVER FUEL ASSEMBLY DUCTS</u>		
1	0.528	0.749
2	0.524	0.731
3	0.506	0.677
4	0.490	0.619
	0.470	0.552
	0.437	0.466
<u>CLOSED LOOP PRESSURE TUBE</u>		
2	2.027	2.371
4	2.027	2.261
6	2.027	2.092
<u>CONTROL ROD GUIDE TUBE</u>		
4	0.299	0.334
7	0.319	0.323

FIGURE 14. Radial Dilatation for Various Driver Fuel Assembly Ducts

Control Rod Guide Tubes

As noted from the tabulated data, the radial dilatations and duct length increases for the control rods are lower than either the driver fuel assembly ducts or closed loops. This is a consequence of the lower flux and temperatures in the control rod guide tubes.

Closed Loops

The closed loops have the highest swelling values of the three core components analyzed. This is attributed to higher temperatures in the closed loops.

OPERATIONAL DEFLECTIONS

Because of fast neutron-induced dilatation, distortion, and irradiation creep, the clearance in the core region between some core components will be reduced during operation, and structural interaction between core components may occur. Clearance changes cause reactivity and thermal changes. It is necessary to predict the reactivity change in the core with time, in order to ensure that bridging of the core components has not occurred. Bridging with subsequent sudden release could create an uncontrollable reactivity insertion. Also in the case of duct-to-duct interaction, possible component failure or malfunctions may result. Therefore, it is necessary to precisely predict the position of all core components for all operating times.

Duct bending results from both transverse thermal gradients and transverse swelling gradients. If creep occurs, the bending deflections are modified considerably. These effects are shown in Figure 15, which depicts the deflection curve of a Row 6 driver fuel assembly duct at 275 days. Figure 15a is a plot of a deflection curve of the duct which experiences only the thermal strain from the transverse thermal gradients shown in Figure 10. Figure 15b is the corresponding deflection curve for the duct if it were to experience only swelling strains.

FIGURE 15 Comparison of Duct Deflection Curves During Operation

Elastic theory of stress analyses is applicable during load application for both cases depicted in Figures 15a and b. Therefore, the forces, strains, and deflections can be added to show the resultant combined effect of thermal strain and swelling on the duct deflection shown in Figure 15c. When irradiation creep is also considered, so that thermal, swelling, and creep strains are combined, the resulting deflection curve for 275-day operation is shown in Figure 15d. Note that the addition of creep modifies the deflection curve significantly. This is because creep strains almost entirely relax the thermal stress prior to the onset of swelling and greatly relax the swelling strain. Therefore, the end-of-life stresses shown in Figure 15c are never attained if creep is active. In a manner similar to Figure 15, the effects of thermal, swelling, and creep strains are compared in Figure 16, for an unrestrained duct during refueling. The creep occurred while the duct was restrained during operation. Figure 16a shows that the duct returns to its straight configuration after the transverse thermal gradient and the upper two support restraints are removed. Figure 16b shows the deformed shape of the unrestrained duct when experiencing swelling strains only. This deformation occurs because the swelling strains do not unload elastically. Figure 16c, which shows the deflection from the combined effects of thermal and swelling strains, is the sum of deflectors from Figures 16a and b. The resultant deflection from creep, swelling and thermal strains is shown in Figure 16d. The inward deflection results from applying the reverse thermal gradient to the unrestrained duct as illustrated in Figure 17. Figures 17a, b, and c represent reactor startup with a new Row 6 duct. Figure 17a represents the new driver fuel assembly duct inserted into the reactor. The duct is supported near its bottom by the coolant inlet plenum. Figure 17b shows the duct prior to startup, but after restraint forces have been applied. Figure 17c shows the duct deflection curve resulting from the transverse thermal

FIGURES 16. Comparison of Unrestrained Duct Deflection Curves

FIGURE 17. Duct Deflection Comparison

thermal gradient distribution, shown in Figure 10. The restraint forces required to maintain the support locations co-linear are also shown. Note that the applied thermal loading (i.e., the transverse thermal gradient) causes an outward duct deflection in the core region, which is required for safety.

Figures 17d, e, and f, represent a reactor shutdown at 1500 hr operation. This time corresponds with maximum duct deflection. In Figure 17d, it can be noted that the restraint loads are reduced, and the deflections are greater than Figure 17c. Very little swelling has occurred during 1500 hr so these changes are a result of irradiation creep. Figure 17e represents the duct deflection curve after the transverse thermal gradient is removed, i.e., zero power condition, but still restrained.

Because the thermal load causes only elastic strains, Figure 17e is the result of subtracting Figure 17c from Figure 17d. This is the same as applying the reverse thermal gradient to Figure 17d. This causes the upper two restraint forces to reverse in direction. When they are removed, the duct bows inward as shown in Figure 17f. Figures 17g, h, and i represent the deflection curves during an end-of-life reactor shutdown (6600 hr). These deflection curves are somewhat straighter than the 1500 hr shutdown, because metal swelling causes an inward motion in the core region. Similarly to the 1500 hr shutdown, Figure 17h results from applying the reverse thermal gradient to Figure 17g. The resulting unrestrained inward bow shown in Figure 17i, is about $3/4$ of the 1500 hr inward bow. The duct continues to move inward in the core region during operation as swelling continues. At some time, the duct will be almost straight, and then with continued swelling, it will bow inward in the core region. The unrestrained duct would continue to straighten with increased swelling until it started moving outward with swelling. Thus, late in life, the duct forces and deflection curve are determined largely by swelling and thermal

load, i.e., transverse thermal gradient. At operating times before about 1500 hr, the forces and deflection curves are determined largely by irradiation creep and thermal load. At initial startup, the forces and deflection curves are determined entirely by the thermal load.

Driver Fuel Ducts

The outer (Rows 5 and 6) driver fuel assembly ducts have more thermal distortion than the interior ducts due to the higher transverse thermal gradients imposed upon them. Figure 18 indicates the steady-state thermal profile of Row 6 driver fuel duct at reactor startup. This corresponds to Figure 17c. The bending stress in the ducts at reactor startup depends on their location in the core, being greatest in the outer rows.

Figure 19 shows the maximum core deflection and maximum stress as a function of time. The deflection increases from the initial thermal deflection to a maximum, then decreases with time. Until this maximum point is reached, the predominate deflection mechanism is that of irradiation creep. Irradiation creep strain is a function of the stress state, temperature, and the fluence. The high thermal gradient imposed on the Row 6 driver duct causes it to experience a high, thermally induced bending stress. This high stress causes the duct material to creep significantly, reducing the stress and increasing the deflection as shown in Figure 19. Later in life, the predominating deflection mechanism is that of fast neutron-induced metal swelling. The Row 6 drive has imposed on it a high flux gradient which results in differential swelling between the hot side and cold side of the duct. This differential swelling causes the duct to move inward towards the core center. Thus, although irradiation creep is still operative, the effects of swelling are predicted to slightly dominate.

The maximum deflection (6) of any driver fuel duct occurs in the Row 6 position and was calculated to be 0.042 in. in

FIGURE 18 Row 6 Driver Fuel Assembly Duct Deflection at Initial Startup

FIGURE 19 Row 6, Maximum In-Core Displacement and Stress

the core region. A tabulation of these deflections in the driver fuel ducts, closed loops, and control rods: as a function of time, are tabulated in Table 3. Positive numbers represent inward deflections.

As noted, the driver fuel assembly duct deflection in the core regions (i.e., 53 in. above the duct bottom) are in the same directions for all rows. Since there is an initial nominal clearance between ducts of 0.140 in. duct-to-duct contact between the support locations is predicted not to occur.

Closed Loops

Initially, the closed loop pressure tubes are in a stress-free state if provisions are made for axial expansion and no transverse temperature gradients exist. As noted earlier, irradiation creep is a function of the member's stress magnitude, and since the closed loops are essentially stress-free until after metal swelling occurs, the primary deflection mechanism is that of fast neutron-induced swelling. Since irradiation creep is small compared with swelling, the difference in swelling between the two opposite sides of the duct causes the closed loops to deflect inward in the active core region. This is opposite in direction to the adjacent driver ducts. As a result, the initial clearance is steadily being reduced due to the opposite deflections and radial dilatation of the closed loops and driver fuels.

The worst possible condition occurs between a Row 5 driver and a future Row 6 closed loop. The total inward movement of the closed loop duct wall is 77.17 mils (66.97 deflection, plus 10.2 radial dilatation). The total outward movement of the Row 5 driver fuel is 22.49 mils. Based on a nominal clearance of 140 mils, there remains a net clearance of 40.34 mils.

Based on the above, it is predicted that no interaction will occur between closed loops and driver fuels during operation at least up to 275 days.

**TABLE 3. FTR Core Component Deflections
During Operation, (Positive
Deflection is inward)**

Row	Inches above duct Bottom	DUCT DEFLECTION, IN.				
		0 hr	1000 hr	3000 hr	5000 hr	6600 hr
(DRIVER FUEL ASSEMBLY DUCTS)						
1	53	-0.0021	-0.0036	-0.0027	-0.0024	-0.0023
1	118	+0.0018	+0.0029	+0.0027	+0.0025	+0.0023
2	53	-0.0039	-0.0069	-0.0050	-0.0047	-0.0048
2	118	+0.0028	+0.0052	+0.0046	+0.0040	+0.0035
3	53	-0.0067	-0.0112	-0.0082	-0.0072	-0.0073
3	118	+0.0047	+0.0085	+0.0075	+0.0062	+0.0052
4	53	-0.0087	-0.0149	-0.0112	-0.0094	-0.0090
4	118	+0.0051	+0.0102	+0.0092	+0.0079	+0.0068
5	53	-0.0176	-0.0318	-0.0265	-0.0212	-0.0188
5	118	+0.0127	+0.0233	+0.0225	+0.0205	+0.0188
6	53	-0.0272	-0.0475	-0.0441	-0.0037	-0.0322
6	118	+0.0194	+0.0346	+0.356	+0.0034	+0.0322
(CLOSED LOOPS)						
2	53	0	+0.0013	+0.0056	+0.0100	+0.0131
2	118	0	-0.0005	-0.0020	-0.0034	-0.0042
2	300	0	+0.0016	+0.0065	+0.0110	+0.0138
4	53	0	+0.0031	+0.0146	+0.0252	+0.0340
4	118	0	-0.0011	-0.0050	-0.0087	-0.0114
4	300	0	+0.0036	+0.0162	+0.0283	+0.0370
(CONTROL ROD GUIDE TUBES)						
4	53	-0.0008	-0.0008	-0.0003	+0.0008	-0.0013
4	118	+0.0013	+0.0014	+0.0012	+0.0011	+0.0010
7	53	-0.0254	-0.0290	-0.0265	-0.0241	-0.0222
7	118	+0.0141	+0.0171	+0.0208	+0.0205	+0.0202

REFUELING

During refueling, it is necessary to remove core components such as driver fuel assembly ducts, control rod guide tubes, closed loops, and reflectors from the core without damaging the neighboring components.

Unrestrained ducts are bowed after creep or swelling, as shown in Figure 20. This figure depicts the relationship between duct deflection curves for a radial row of driver fuel assembly ducts if each duct were supported at the inlet plenum only. Obviously, they would interact at the top because a Row 6 duct top cannot be closer to the core center than a Row 5 duct top. Therefore, the ducts must push against each other at the top and come to some equilibrium location such as shown in Figure 21.

Figure 21 was drawn assuming the lattice spacing in the inlet plenum core plate is the same during refueling and during reactor operation. The dimensional changes occurring in the core plate and in the ducts when going from full to zero power will modify the duct equilibrium locations slightly, but Figure 21 represents reasonably well the interactions which will exist during refueling. This indicates that the ducts will still make contact at the top support pad. This will require smooth transitions in section geometry at the support pads in order to avoid damage during refueling.

Figure 22 shows the refueling deflections of a radial row of ducts with driver fuel assembly ducts in Rows 1, 2, 3, 5 and 6. Row 4 is occupied by a closed loop. Obviously, interaction has occurred at the top of the driver fuel assembly ducts and at the above core support pad location between rows 1, 2, 3, and 4. The opposite deflection of the closed loop to that of the driver fuel assembly ducts indicates that special arrangements may be required when refueling adjacent to a closed loop.

Figures 23 and 24 show, respectively, the unrestrained and the refueling deflection curves for a radial row of ducts with

FIGURE 20. Unrestrained Driver Fuel Duct Deflections, 275 Days

FIGURE 21 Refueling Deflections of Driver Ducts, 275 Day

FIGURE 22. Refueling Deflections of Driver Ducts and Row 4 Closed Loop, 275 Days

FIGURE 23. Unrestrained Duct Deflections of Drivers Ducts with Rows 4 and 7 Control Rods

FIGURE 24. Refueling Deflections of Driver Ducts with Rows 4 and 7 Control Rods

control rods in Rows 4 and 7. All other rows are occupied by driver fuel assembly ducts. Here, also, interaction occurs at all duct tops with interaction between some rows at the above core support pad location.

DUCT ROTATION

To reduce the swelling induced deflection, it has been suggested that the partially burned up fuel assembly ducts be rotated 180° during reactor down time. If the ameliorating effect of irradiation creep did not occur, this duct rotation would be very helpful. However, because the ducts remain much straighter because of creep, duct rotation is not necessary. In addition, duct rotation increases the restraint loads imposed on the support pads during the start-up on a partially burned-up duct. This is shown in Figure 25 for a Row 6 driver fuel assembly duct at 1500 hr. Figures 25a, b, and c represent a pseudo start-up with the duct nonrotated. Figures 25d, e, and f represent a pseudo start-up of a duct which has been rotated 180° . Figure 25a shows the unrestrained duct deflection at 1500 hr. Figure 24b indicates the duct deflection which would occur if the thermal load were applied without applying the radial restraint forces. In this case, the thermal load would cause the duct to bow slightly outward. To bring the support pads colinear, the duct top must be pushed inward at the top with a 255 lb force, as shown in Figure 25c.

If the duct were rotated 180° , the unrestrained and unloaded duct would bow outward at the top. Now the thermal load would cause additional outward bow, a force significantly greater than 255 lb would have to be applied at the duct top to bring the support pads colinear. The force required at the above core support pad for colinearity is also increased by duct rotation.

The magnitude of these forces at 275 days operation can be determined by considering that subsequent to removing the

FIGURE 25 Effect of Duct Rotation During Restart

thermal load a constrained Row 6 driver fuel assembly duct will have a profile as indicated in Figure 26 (Figure 17h). When the reactor is restarted and brought to full power, there is again imposed on each component axial and transverse temperature loads. By reversing the Row 6 driver duct restraint loads and deflections after 275 days' operation and then superimposing the initial thermal loads and deflections (Figure 17c) reactor restart with duct rotation can be simulated. At reactor restart, Figure 27, the restraint loads are increased in excess of the thermal loads by an amount equal to the deformation loads, i.e., the loads from Figure 17h. Therefore, duct rotation is not recommended.

FUEL SHUFFLING

Fuel shuffling, (i.e., moving partially burned fuel assemblies toward the core center), is predicted to reduce the restraint loads. This is a result of the lower thermal load on the inner ducts. However, the benefits gained must be balanced against the potential handling damage to these relatively brittle ducts. The resulting lower restraint forces on Row 6 duct moved to a Row 5 position are shown in Figure 28. Figure 29 shows the required restraint force at the above core support location as a function of time. Also shown is the change in this restraint force, resulting from duct rotation and for fuel shuffling from a Row 6 to a Row 5 location.

FIGURE 26. Row 5 Driver Fuel Assembly Duct Deflection after 275 Days (6600 hr) After Thermal Unload

FIGURE 27. Superposition of a Reversed Row 6 Driver Profile After 275 Days Operation and Startup Thermal Profile for a Row 6 Driver Duct

FIGURE 28. Superposition of Row 6 Restrained and Row 5 Thermal Deflections and Forces to Simulate Shuffling a Row 6 Duct into a Row 5 Location

FIGURE 29. Reaction Load Versus Time with Comparison of Rotation and Shuffling Loads

CONCLUSIONS

- It is necessary to consider the effects of thermal strain, fast neutron-induced metal swelling, and irradiation creep to predict the forces and displacements in fast breeder reactor core components.
- Thermal strain is the significant parameter during reactor start-up or shut down.
- Irradiation creep is the significant parameter early in life of a core component.
- The competing effects of irradiation creep and metal swelling are the significant parameters late in the life of core components. Irradiation creep is predicted to greatly ameliorate the duct bending effects of metal swelling.
- The minimum restraint forces occur after irradiation creep has been effective in reducing the thermal stresses but before metal swelling becomes significant. For the conditions analyzed here, this corresponds to about 1500 hr operating life.
- Duct rotation is not recommended because the resulting restraint loads are higher.

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