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STRUCTURAL EVALUATION OF FAST REACTOR CORE RESTRAINT WITH IRRADIATION CREEP-SWELLING OPPOSITION EFFECTS

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SUMMARY:

The principal functions of a fast reactor core restraint system are to: control core sub-assembly displacements within limits imposed by reactivity considerations; ensure acceptable sub-assembly insertion and withdrawal loads; limit sub-assembly irradiation induced deformation, maintain the alignment of the sub-assemblies with interfacing internals structures. In passively restrained cores, these requirements are addressed by providing contact or load pads at appropriate locations along the sub-assembly ducts and by precisely locating peripheral support surfaces on surrounding internals structures. Minimization of gaps at load plane elevations permits reactivity, alignment and assembly distortion requirements to be met. However, a degree of free bowing is desirable to partially accommodate residual irradiation induced sub-assembly bowing so that withdrawal loads are kept below prescribed limits.

Permanent bowing of the core sub-assemblies occurs through the action of irradiation creep and swelling in the presence of in-core neutron flux and lateral temperature gradients. Restrained thermal bowing loads are relaxed by irradiation creep. Differential swelling induced bowing generates sub-assembly loads which are opposed and limited by irradiation creep. Uncertainties associated with the sub-assembly duct alloy irradiation creep and swelling characteristics together with core environment and mechanical interaction uncertainties are addressed in core restraint system design evaluations from which load pad gap size conclusions are drawn.

Irradiation creep and swelling design correlations are derived from primary loading in-reactor experiments in which irradiation creep and swelling act in the same direction. When correlation uncertainty bands are applied in core restraint evaluations, significant variability in sub-assembly behavior is predicted. For example, sub-assemblies in the outer core region where neutron flux and duct temperature gradients are significant exhibit bowing responses ranging from a creep dominated outward bow to a swelling dominated inward bow. Furthermore, solutions based on upper bound and lower bound correlation uncertainty combinations are observed to cross-over indicating that such combinations are physically unrealistic in the assessment of creep-swelling opposition effects. In order to obtain realistic upper and lower bound sub-assembly responses, judgement must be applied in the selection of creep-swelling equation uncertainty combinations.

Experimental programs have been defined which will provide the needed basic as well as prototypic creep-swelling opposition data for reference and advanced sub-assembly duct alloys. The first of these is an irradiation of cylindrical capsules subjected to a through-wall temperature gradient. This test which is presently underway in the EBR-II reactor will provide the data needed to refine irradiation creep and swelling correlations and their associated uncertainties when applied to core restraint evaluations. Restrained pin and duct bowing experiments in FFTF have also been defined. These will provide the prototypic data necessary to verify irradiated duct bowing methodology. The results of this experimental program are expected to reduce creep and swelling uncertainties and permit better definition of the design window for load plane gaps.

1. CORE RESTRAINT SYSTEM DESIGN REQUIRMEENTS

1.1 DESIGN CONCEPT

The limited free bow concept is the basis for the core restraint system designs employed in FFTF and CRBRP. This concept is based on passive peripheral restraint of core assemblies while allowing some limited free lateral movement of assemblies between the thermal conditions of refueling and normal power operation. The key objectives of this system design concept are: simplicity in design and the utilization of irradiation creep to offset the effects of duct material swelling. Figure 1 schematically shows the design features and interfaces of the limited free bow core restraint concept. (1)

In the limited free bow core restraint concept, axial (vertical) support of the core sub-assemblies is provided at the assembly inlet nozzles by the inlet modules and the core support plate. Vertical hold-down of the core sub-assemblies against the upward coolant flow is provided by assembly weight and hydraulic balance at the inlet nozzles. Lateral (horizontal) restraint of the core sub-assemblies is provided at three elevations: at the inlet nozzles, at the above core load plane (ACLP), and at the top load plane (TLP). Interassembly loads are transmitted through the load planes to the core formers.

Buildup of sub-assembly bowing induced by irradiation swelling is limited by using irradiation creep to offset the effects of swelling. The core formers restrain bowing of the core sub-assemblies and thereby generate the sub-assembly duct stresses that permit irradiation creep to offset the effects of swelling. Sub-assembly restraint loads are relieved at refueling by allowing limited freedom of movement as the temperature gradients associated with power production are removed.

1.2 CORE RESTRAINT SYSTEM FUNCTIONAL REQUIREMENTS

To achieve both thermal and breeding performance goals, the fuel and blanket sub-assemblies are hexagonally shaped and arranged in a closely packed array. Performance incentives dictate minimal duct and interassembly gap thicknesses.

Sub-assembly-to-sub-assembly power to flow variations, particularly between the fuel and radial blanket regions, result in significant lateral duct thermal gradients within and above the reactor core zone. These gradients cause the assemblies to bow and contact one another. Assembly bowing motions, particularly in the reactor zone, affect the reactivity balance of the operating reactor. The synergistic action of the thermal and flux gradients within the reactor core zone results in an additional duct bowing component associated with material swelling. Irradiation creep affects the residual bowing patterns because of its action in reducing duct stresses induced by thermal gradients.

Consideration of the above environmental factors plus the need to satisfy performance, operational, and safety goals leads to the definition of the following functional requirements for the core restraint system:

a. Control core motion within the limits imposed by reactivity considerations.
b. Limit interassembly loads on core assemblies to acceptable levels for both normal operating and abnormal events.
c. Limit core assembly insertion and withdrawal loads to acceptable levels.
d. Maintain core assembly alignment within requirements imposed by the control assembly driveline and the refueling grapple.
e. Limit core assembly irradiation induced bowing distortions to acceptable levels.

In order to demonstrate satisfaction of these requirements a quantitative understanding of irradiation creep and swelling interactions along the sub-assembly duct is required.

2. IRRADIATION INDUCED SUB-ASSEMBLY BOWING

2.1 SINGLE SUB-ASSEMBLY MODEL

Single sub-assembly models are useful to evaluate irradiation creep and swelling equations under prototypic conditions. The single sub-assembly model considered here is based on the limited free bow concept. Lateral restraints are provided at the inlet nozzle, ACLP, and TLP as shown in Figure 1. This restraint is representative of core restraint systems in which free thermal bowing is limited and irradiation creep is utilized to counteract swelling.

The characteristic response of an outer core sub-assembly swelling is shown in Figure 2 (2). During power operation, the assembly is subjected to cross duct temperature and flux gradients. The temperature gradients induce stresses in the restrained duct. The initial response to irradiation is creep relaxation which causes the unrestrained isothermal bow shapes shown at 6750 hours in Figure 2. Because of the temperature and flux dependence of swelling, swelling strains act in the opposite direction to creep. The effect of swelling increases with fluence as shown by bow shapes for 13140 hours and 19710 hours in Figure 2.

2.2 IRRADIATION CREEP AND SWELLING EQUATIONS (3)

The swelling equation for CW316SS is characterized by a negligible swelling region at low fluence and a steady state swelling region at high fluence. The integral form of the swelling equation is expressed as the local fractional change in volume.

$$\text{Fractional volume change} = \frac{\Delta V}{V_o} = (0.01)\, R(\phi t + \frac{1}{\alpha} \mathrm{Ln}\, \{\frac{1 + \exp\,(\alpha(\tau-\phi t))}{1 + \exp\,(\alpha\tau)}\})$$

In this equation ϕt denotes the fast fluence. At low fluences, $\phi t < \tau$, swelling is negligible while at high fluences, $\phi t > \tau$, swelling is proportional to the rate constant R. R is typically a complex function of temperature. However, in the temperature range of interest in sub-assembly bowing, R increases monotonically with temperature. The parameter α establishes the transition between low fluence and high fluence swelling.

The irradiation creep equation is characterized by three terms:

Effective Fractional Creep Strain/Effective Stress =

$$\overline{\varepsilon}/\overline{\sigma} = A\,(1-\exp(-\phi t/\tau_{tr}) + DR\phi t\,(1- \frac{\Omega}{\phi t}\,G\,(\phi t)) + B_o\phi t$$

where

$$G(\phi t) = 1-\exp\,(-\phi t/\Omega)$$

The first term represents the transient creep effect which contributes only at very low fluence. Note that $\tau_{tr} \ll \tau$, the swelling equation incubation parameter. The third term is the steady state irradiation creep effect. The second term is the most dominant in reactor assembly bowing analyses and is proportional to swelling ($R\phi t$) at high fluences through the swelling effect on creep parameter D. The quantity in the bracket of the second term is a smooth (exponential) transition function which is negligible at low fluence and approaches unity at $\phi t \simeq 3\Omega$. For CW316SS, $\Omega \simeq \tau$.

On the basis of data obtained from primary loading experiments, the following uncertainty levels have been established:

	Min. Creep Min. Swelling	Max. Creep Max. Swell
B_o	$.9\ B_o^*$	$1.1\ B_o^*$
DR	.28 DR*	2.08 DR*
Ω	$.3\ \Omega^*$	$1.7\ \Omega^*$
τ	$1.3\tau^*$	$.7\tau^*$
R	.7R*	$\sim$1.3R*

where the asterisk denotes the nominal parameter value.

2.3 SUB-ASSEMBLY BOWING RESPONSES

Figure 2 illustrates the variability in the bowing responses for an outer core sub-assembly when the uncertainties defined in Section 2.2 are applied. At low fluence (6570 hours) the response is irradiation creep dominant. However, at intermediate and high fluences the response varies significantly between creep and swelling dominance. If the solution were permitted to proceed to still higher fluences, the min/min reponses would eventually cross over the max/max responses. This is observed more clearly in inner core sub-assembly responses within the forecast fluence range. Because of the excessive solution variability and crossover when uncertainties are applied, experiments have been proposed in which irradiation creep and swelling act in opposition as expected prototypically.

3.0 CREEP-SWELLING OPPOSITION TESTING

3.1 SLIT TUBE TEST

The slit tube test is used to determine the basic interaction characteristics of irradiation creep and swelling equations when acting in opposition. As shown in Figure 3 (4), the capsule tubing is subjected to a through wall temperature gradient. As a result of thermal expansion, stress gradients are induced in the tubing wall. The initial response to irradiation is a creep relaxation of this stress. After the swelling incubation period (τ), differential swelling strains increase the stress gradient through the wall. This continues until at high fluences equilibrium is reached between the swelling and creep rates and a constant stress gradient is maintained.

When the capsule is removed from the thermal and flux environment and axially slit, the change in slit width, can be used as a measure of the competing creep and swelling processes which influence the through wall residual stress gradient. This is illustrated in Figure 4 (2). Irradiation creep results in an initial decrease of slit width. When swelling occurs it causes an increase in the slit width.

When the min/min and max/max uncertainties are applied to predict the slit tube gap width change, the crossover of the response is clearly illustrated. Shown for comparison are min/max and max/min responses which do not crossover but bound the nominal solution. Although the latter solutions properly bound the nominal response, the present correlations which are derived from primary loading experiments do not provide guidance for a min/max or max/min selection. For this reason a creep-swelling opposition test of the type illustrated in Figure 3 has been designed for insertion into the EBR-II reactor. On the basis of pretest analyses, the maximum uncertainty in the slit width gap is expected to be one mil. This would represent a substantial improvement over uncertainties in currently used correlations.

3.2 OTHER TESTING

Additional testing has been proposed or defined which will permit better definition of sub-assembly responses in the limited free bow core restraint concept. One such test is the pin bowing test which has been proposed for FFTF. In this test, the pin or tube is axially supported at various elevations within the test vehicle typical of the limited free bow concept load planes. A lateral temperature difference is established across the pin to initiate the bowing process and the pin bow displacement is measured at each out of reactor interim. The advantage of this test is that it provides bowing displacement data for a simpler geometry and a less uncertain environment than can be obtained from actual sub-assembly bowing measurements. However, measurements on the latter are also being examined in order to assess the accuracy of creep-swelling opposition analysis in core restraint methodology.

4.0 CONCLUSIONS

In order to demonstrate satisfaction of the functional requirements for a passively restrained core restraint concept a quantitative understanding of irradiation creep-swelling interaction in sub-assembly bowing is required. Creep and swelling correlations based on primary loading experiments do not provide data sufficiently accurate for use in secondary loading applications such as sub-assembly bowing. Experiments which will provide data on creep and swelling acting in opposition are currently in progress in EBR-II and are planned for FFTF.

REFERENCES

(1) Clinch River Breeder Reactor Plant Technical Review, CRBRP-PMC 76-06 (Fall, 1976).

(2) Core Restraint Development Quarterly Progress Report for Period Ending August 31, 1978, WARD-CR-3045-25.

(3) Nuclear Systems Material Handbook, TID-26666.

(4) Core Restraint Development Quarterly Progress Report for Period Ending May 31, 1978, WARD-CR-3045-23.

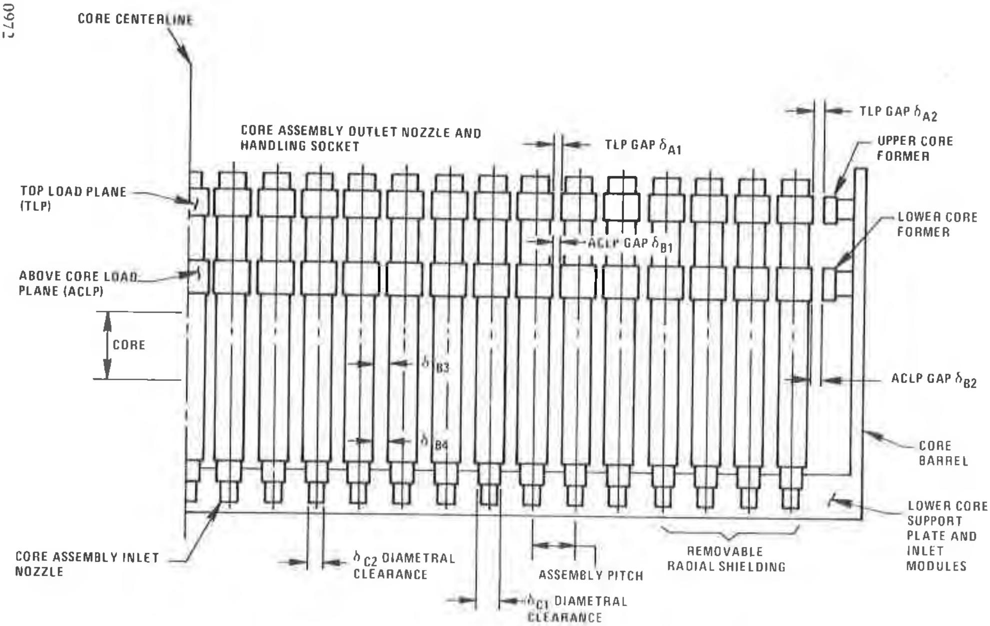

FIGURE 1 LIMITED FREE BOW CORE RESTRAINT SYSTEM

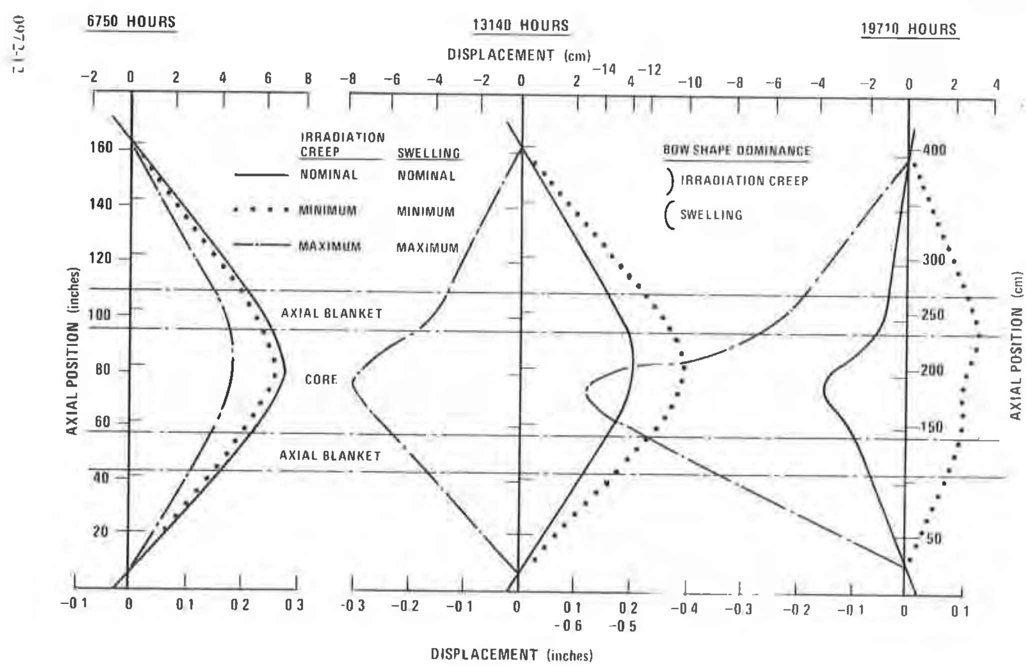

FIGURE 2 OUTER CORE FUEL SUB-ASSEMBLY IRRADIATED FREE BOW SHAPES

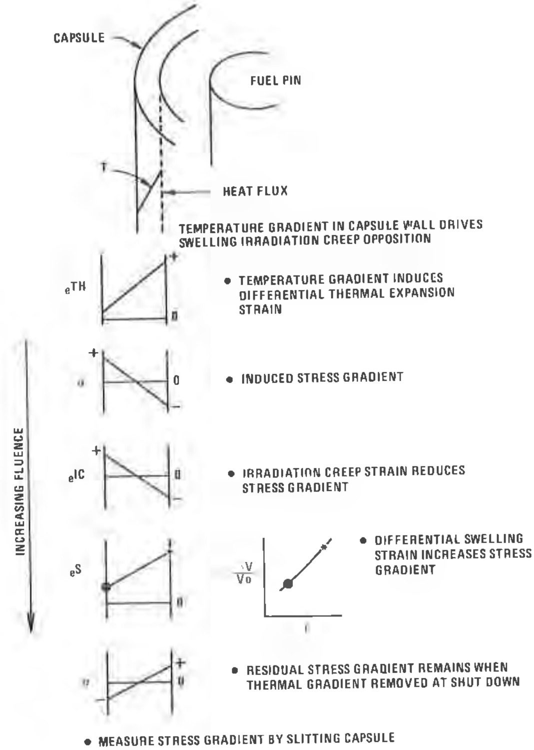

FIGURE 3 FACTORS AFFECTING THE RESIDUAL STRESS IN THE SLIT TUBE TEST CAPSULE

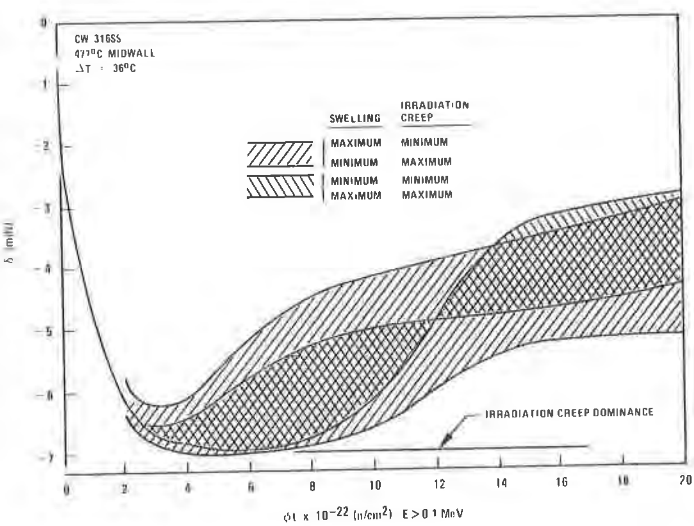

FIGURE 4 SLIT TUBE GAP BEHAVIOR