

SUBASSEMBLY BOWING EXPERIENCE IN EBR-II

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SUMMARY

Subassembly bowing in an LMFBR can affect core neutronics, subassembly handling, and possibly create a potential safety hazard if the phenomenon can not be characterized and predicted. Bowing may be induced by thermal gradients, differential swelling, and/or intersubassembly loading. Neutronic variations, such as long or short term power-reactivity-decrement (PRD) variations, can be indicators of a bowing problem. But, because of other influences on the PRD it is very difficult to isolate the affect of bowing. As a result, subassembly bowing was not considered a problem in EBR-II until subassembly handling problems occurred.

A typical handling problem, caused by top end deflection of the bowed subassembly, is centering of the subassembly removal mechanism over the subassembly. Another problem is excess loads of up to 375 kg that have been required to remove bowed subassemblies from their grid position. This latter problem is due in part, to the magnitude of bow and subassembly stiffness in addition to the overall subassembly cluster tightness caused by duct swelling and/or the occurrence of multiple bowing. Observed interferences in storing a bowed subassembly in the storage basket can be used as a qualitative gauge for bowing magnitude. In EBR-II a storage basket tube can accomodate a subassembly bow of 2.3 to 3.1 mm depending on the position in the basket.

All of the bowed type 304 stainless steel subassemblies that created handling difficulties were given a post-irradiation examination. Damage that may have been caused by interference loading was found to be limited to surface scratches. The measured bow of these subassemblies range from 1.9 mm for a fueled subassembly to 5.7 mm for a neutron-source-rod thimble.

Correlation of the in-core bowing phenomena with the bowing data base required both an axial and radial thermal and flux characterization, consideration of the subassembly design, interpretation of swelling and creep behavior and a simple workable model that could incorporate these factors. A thermal hydraulics code, "CLUSTER" was used to calculate the operating temperatures at sixty radial locations for each of nineteen axial sections along the hex duct.

For this analysis a simple beam method was used with postulated radial restraint bounds in simulating intersubassembly loading. The results of this analysis showed that the bow, at a neutron fluence of $>2.7 \times 10^{22}$ n/cm², $E > 0.1$ MeV, in these structurally varying subassemblies was highly thermal gradient dependent. This is due to the fact that both differential swelling and the thermal gradients that induce bowing were appreciably compensated by irradiation enhanced creep. The restraint loads were found to be sufficiently high to cause creep relaxation of the thermal and differential swelling stresses.

Subassembly bowing can be accurately predicted. However, the accuracy is limited to the characterization of the operating core environment and the irradiation enhanced creep and swelling behavior of the material.

1.0 Introduction

Subassembly bowing large enough to cause minor handling problems were first observed at EBR-II shortly after its conversion to an irradiation facility in 1965. Several designs of subassembly were then used to accommodate different types of fueled and structural experiments. This variability in design caused, and still causes a rather heterogeneous core with respect to subassembly stiffness and temperature gradients. Post-irradiation bow on subassemblies has always been greater than any lack of straightness before irradiation.

Subassembly bow measured after irradiation is the product of a complex combination of temperature and neutron dose gradients in-reactor, as well as the result of the subassembly design and inter-subassembly mechanical interactions (which control the dynamic effects of swelling and radiation-enhanced creep). Unfortunately, none of the computer codes developed to model bowing in large clusters or uniform LMFBR cores can be applied with confidence to the EBR-II core, because of its unique and varying mixture of different subassemblies. For this reason, each bowed subassembly has been considered separately in an attempt to determine what factors dominate in causing bow.

2.0 Bowing Experience

Difficulty in discharging an irradiated subassembly at EBR-II is often the first indication that it has bowed in-reactor. Operators experience difficulty either in locating the handling tool onto the top of a subassembly or in having to apply greater than normal forces to insert or remove it from the core and storage basket. The following paragraphs describe five of the bowed subassembly and the handling problems they caused. Throughout, bow is defined as the maximum deflection of the axis of a hexagonal subassembly duct from a line connecting the top and bottom of the duct. For clarity, Fig. 1 shows the major components of a typical EBR-II subassembly. Table I lists the moment of inertia (I), the section modulus (Z), the irradiation dose in dpa, and the measured and calculated bow for the five subassemblies.

The first major difficulty was encountered with an experimental subassembly that contained a 52-mm diameter nickel-200 solid rod in a standard duct. This row 7 subassembly exhibited some signs of bowing when removed from the core, but in order to remove it from the storage basket the load limit of the handling mechanism had to be overridden. The bow was 3.3 mm, which according to calculated clearances, should not have caused a major problem through interference in the storage basket. The primary difference between this subassembly and a standard one was its high rigidity, however, which would create a higher removal resistance if interference occurred. The cause of bow was from differential swelling in the nickel rod.⁽¹⁾

Two Type 304 stainless steel reflector subassemblies (from row 8 and row 10) showed higher than normal core and storage basket handling loads but less than the limit; they were bowed 1.8 mm and 5.1 mm respectively (see Table I and Figure 2). These subassemblies were designed with standard hardware but contained stacked hexagonal blocks of stainless steel. These reflector blocks were <0.24 m long with rounded ends and with 1.3 mm radial clearance, which allowed for considerable freedom of movement. Postirradiation examination indicated that the reflector blocks did not influence bowing. Another subassembly, which was designed to accommodate a pressure pulse, contained a thick-walled tube welded into a standard duct. This row 6 subassembly caused a core interference problem while attempting to insert a new

control rod thimble in an adjacent position. Postirradiation examination indicated a 1.9 mm bow. This bow was not large by comparison to some subassemblies, but was twice that of other subassemblies with the same design (see Table I for parameters).

In only one case has the bowing of a subassembly, in this instance a source-storage thimble in row 8 of the reactor, been severe enough that its removal from the core required overriding the design load limit (2.2 KN). Based in part on the assumption that radiation-enhanced creep would appreciably relax the thermal and swelling-induced bow while at power, permanent bow was calculated to be about 5 mm. The method of calculation is given in the next section. It was further estimated that the required removal load could be as high as 3.7 KN. The thimble was removed with a special removal adapter at a 3.1 KN load. Because of its known stiffness ($I = 6.66 \times 10^5 \text{ mm}^4$) the thimble was not inserted in the storage basket.

The important fact about these bowed subassemblies was that the residual bow appeared to be independent of design. However, the design stiffness plays a major roll in the degree that it affects reactor operations.

3.0 Analysis

Two assumptions were made in separately analyzing the permanent bow of the four Type 304 stainless steel in Table I; first, that residual bow was the response of the subassembly duct to the temperature environment at full power; second, that the subassemblies were bound by semi-rigid neighbors, i.e. radial movement was limited to the design clearance (0.6 mm) at full power. The second assumption is somewhat debatable but probably reasonable because near neighbors are inherently more rigid due to their second neighbor support.

One of the major problems in bow analysis is establishing the core environment with confidence. In EBR-II the flux gradient is established before and after each reactor run at four section points for each subassembly; temperature gradients are not as well characterized. For this analysis a thermal hydraulics code, "CLUSTER",⁽²⁾ was specially used to calculate temperatures at sixty radial locations for each of nineteen axial locations along a subassembly duct. This code assesses the subassembly and its six immediate neighbors as to radial heat transfer. One or more of the six neighbors to a particular subassembly are often exchanged with another subassembly having a different operating temperature; this substitution can increase uncertainty in bowing analysis. The subassemblies considered here had no or very few neighbor change-outs during their life. Figure 3 illustrates the thermal and flux gradient for the four Type 304 stainless steel subassemblies analyzed. Also, included in this figure are the gradient and bowing directions with respect to each other.

With the thermal gradient established the resultant stress conditions were determined from elementary beam theory. The gradient was assumed to increase linearly over the axial length of the core. Table I lists the calculated full beam deflections due to this temperature rise (ΔT) for four Type 304 stainless steel subassemblies. Note, the similar magnitude of the residual bow. By applying to radial movement limit assumption the peak outer fiber stresses ranged from 15 to 70 MPa for a 0.5 and 2.5 mm bow respectively. These stresses are expected to be the driving force for irradiation enhanced creep strain.

The swelling (ΔS) contribution to bowing is a function of the dose, temperature gradient and stress state. In order to assess the maximum effect of swelling on bow, the following relationship for isotropic differential swelling was used:⁽³⁾

$$\Delta S = S_1 - S_2$$

$$S_1 = 1.76 \left(f_1 - 3.4 \tanh \frac{f_1}{3.4} \right) \left[\exp^{-a(T_1 - 480)^2} \right],$$

where ΔS = in the differential swelling, f_1 = fluence in units of 10^{22} cm^{-2} ($\text{dpa} \sim 5 \times 10^{-22} f$), $a = 1.60 \times 10^{-4} \text{ } ^\circ\text{C}^{-2}$ and T_1 = temperature. The potential swelling contribution is listed in Table I in the ΔS column. In the two cases where 30 and 40 mm bow was predicted the effect of swelling clearly did not materialize - either due to the effect of stress on swelling, or, more likely, due to the relief of differential swelling by irradiation-enhanced creep. Even when comparing the calculated and measured values of residual bow (see Table I) the amount of bow clearly correlates well if the subassemblies are assumed to be stress relieved at full power, residual bow being representative of the negative thermal gradient.

A creep strain (ϵ) relationship developed from stressed specimens of Type 304 stainless steel irradiated at 400°C is ⁽⁴⁾

$$\epsilon = B\sigma f + D\sigma S$$

where σ is the stress (Pa), f is the dose (dpa), $B = 1.43 \times 10^{-12} \text{ Pa}^{-1} \text{ dpa}^{-1}$ and $D = 1.80 \times 10^{-9} \text{ Pa}^{-1}$. The residence (dose) required to achieve the strain necessary to relax the stress due to thermal and swelling gradients was calculated and found to be much less than their respective end of life dose. Figure 4 illustrates the creep strain that can be achieved as a function of stress for two different dose levels, 5 and 15 dpa.

4.0 Conclusions

In-reactor bowing of subassemblies has caused some handling difficulties at EBR-II, the extent of the problem increasing with the subassembly stiffness. Analysis of four particular bowed subassemblies with respect to their core environment and structural design has indicated that residual bow is primarily the result of radiation-enhanced creep during irradiation.

References

- [1] STRAIN, R. V., RUTHER, W. E., "Results of Irradiation of Nickel-Reflectors Test Subassemblies", ANL/EBR-044, August 1971.
- [2] CHANG, L. K., "CLUSTER, a Computer Code for Predicting Temperature Within a Cluster of Seven Subassemblies", ANL-RDP-33, October 1974.
- [3] FLINN, J. E., "Empirical Swelling Description for Anneal Types 304L and 304 Stainless Steel", ANL-RDP-43, September 1975.
- [4] McVAY, G., private communication, ANL, February 1977.

TABLE I

	I, mm^4	Z, mm^3	DOSE, dpa	Bow, mm		
				Residual	ΔT	ΔS
Row 8 Reflector	9.13×10^4	3.14×10^3	11.6	+1.8	-2.0	-00.5
Row 10 Reflector	9.07×10^4	2.70×10^3	9.7	+5.1	-5.1	+02.5
Experimental Reflector	4.50×10^5	1.68×10^4	7.0	+3.3	-	-
Source Thimble	6.66×10^5	1.97×10^4	31.0	-5.7	+5.3	+40.6
Experimental Subassembly	1.11×10^5	7.2×10^3	37.4	-1.9	+1.5	+30.5

* + = Bowed toward core center.

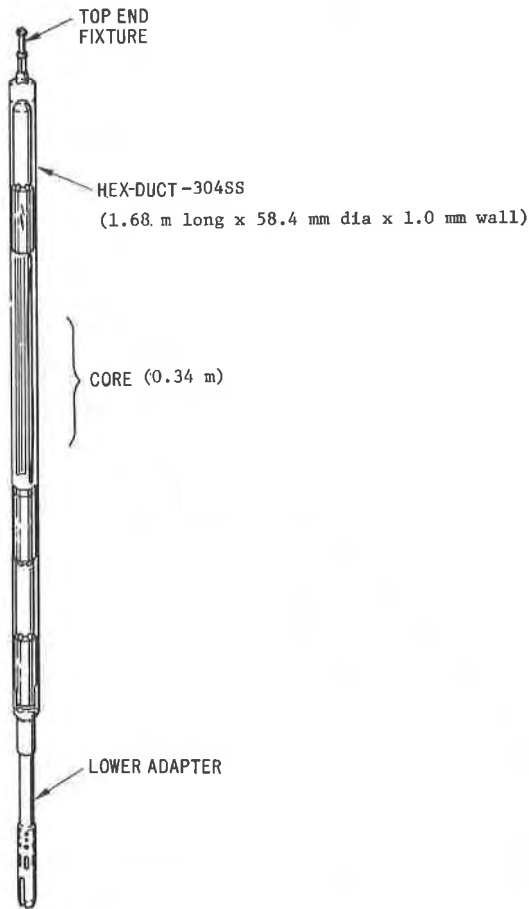


Figure 1. Schematic of an EBR-II Subassembly.

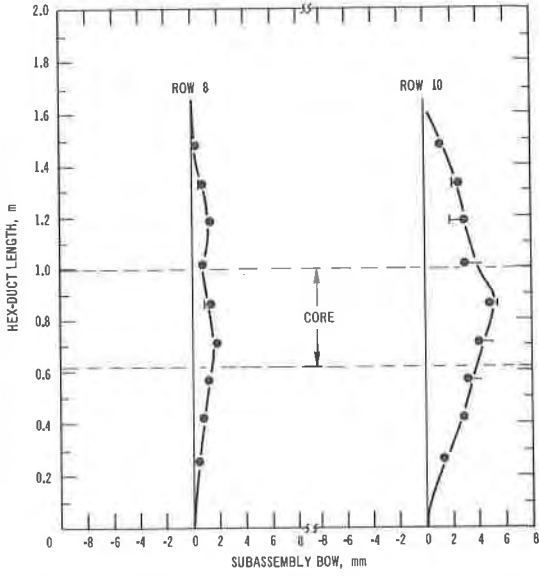


Figure 2. Measured Hex-duct Bow of Two 304 Stainless Steel Reflector Subassemblies.

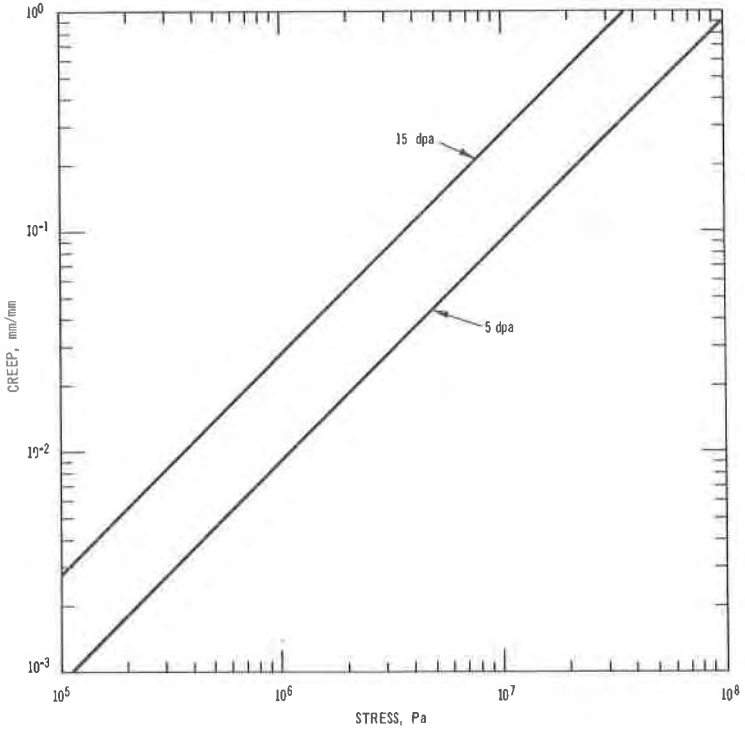
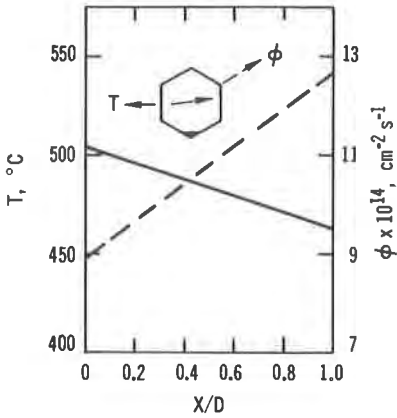
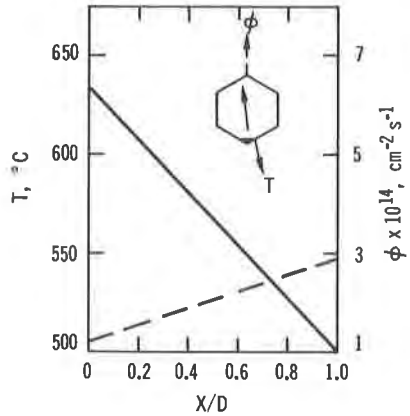


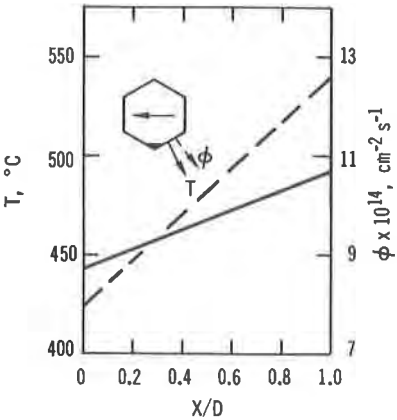
Figure 4. Irradiation-enhanced Creep Strain Versus Stress for 304 Stainless Steel at 400°C.



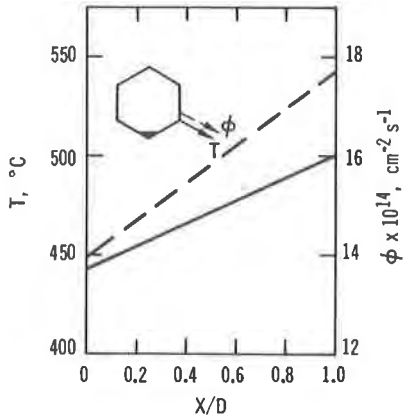
ROW 8 REFLECTOR



ROW 10 REFLECTOR



EXPERIMENTAL



SOURCE STORAGE THIMBLE

Figure 3. Radial Temperature and Flux Gradients and Relative Directions of Gradients and Bow of Four 304 Stainless Steel Subassemblies.