LIMITING CONDITIONS FOR STRUCTURAL INTEGRITY OF COMPONENTS UNDER FAST BREEDER REACTOR CORE ENVIRONMENT*

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SUMMARY

Limit analyses of structures generally focus upon the influence of a uniquely defined loading condition or set of conditions upon the integrity of the structure. Components of a fast breeder reactor core may reach the limits of their structural integrity during normal reactor operation as a result of experiencing loads which may be significantly lower than the "limit" loads obtained from limit analyses. The primary reasons for this are (i) the change in the material properties as a function of fast neutron irradiation; (ii) structural deformations resulting from irradiation-induced creep and swelling, and (iii) residual stresses set up in a component as a result of interaction with adjacent structure undergoing differential deformations.

The present study focuses upon the influence of the fast breeder reactor core environment on the resultant useful service life and load carrying capability of core components of the Experimental Breeder Reactor II (EBR-II). Specific examples selected are: (i) the dynamic response of a single hexagonal subassembly can to a potential pressure pulse resulting from a failed fuel element cladding; (ii) interaction between a fuel element cluster and its surrounding subassembly can; (iii) the interaction between adjacent subassemblies, and (iv) the influence of swelling and pressure induced stresses on the grid plenum assembly.

Results of core surveillance efforts, experimental investigations, and analyses completed to date by several EBR-II investigators are presented. The study demonstrates the significance of fast breeder reactor core operating conditions in determining the safe limiting conditions for core structural components.

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1. Introduction

Like other fast test reactors, the Experimental Breeder Reactor-II (EBR-II) was designed and built before the phenomenon of stainless steel swelling was discovered. The structural components of the core may therefore swell, change shape, and otherwise reach the end of their useful life at times and stresses below those originally established by conventional limit load analysis. Such behavior results from the unique combination of thermal, mechanical, chemical and radiation effects that constitute the core environment. Although analytical techniques can not now predict whole core performance, the predominant effects of the environment can be identified and their influence on the structural integrity of individual components can be evaluated. Such evaluations, which are necessary to ensure continued safe operation of EBR-II, are illustrated by the results of investigations on the fuel element clusters, subassembly ducts and grid plenum assembly of the reactor. Each of these components experiences a unique set of loading conditions ranging from the high intensity fast neutron flux at the core center to the low intensity epithermal flux near the grid plenum.

The EBR-II reactor vessel environment is illustrated in Fig. 1. Sodium coolant at 370°C is pumped into the grid plenum assembly at the bottom of the vessel. The sodium rises through the hexagonal array of subassemblies of which the seven central rows form the core. The sodium leaves the top of the vessel at a nominal mixed temperature of 475°C on its way to the intermediate heat exchanger. The entire vessel, pumps, heat exchanger, storage basket, etc. are submerged in the pool of 370°C sodium that is contained in the primary tank. The inserts in Fig. 1 illustrate the neutron flux distributions in the vessel. At the core center the flux is $\sim 2.5 \times 10^{15}$ n/cm^2, of which 85-90% of the neutrons have energies higher than 0.1 MeV.

2. Interactions Between Fuel Elements and Ducts

Differential swelling between wire-wrapped fuel element clusters and subassembly ducts has been observed in EBR-II. Wire-wrapped clusters have generally swollen at a higher rate than their ducts [1]. Consequently, mechanical interference has been encountered during the removal and replacement of ducts on element clusters. This interference causes additional bending stresses in the element cladding and local loads on the duct. When a wire-wrapped cluster swells at a lower rate than its duct, which has occasionally happened in EBR-II [2], the cluster becomes looser with exposure. In this case elements become free to move and vibrate under the action of the flowing sodium. Such vibration has been found to cause local wear of the cladding and the duct.

These interaction loads are localized and cannot be treated in an axisymmetric manner. The influence of the loads must therefore be accounted for with two or three-dimensional models in studying fatigue and fracture resistance of the components [3].

Figure 2 shows the simple structural model that was used to analyze element-duct interference [4]. The cladding of the outer fuel elements was assumed to contact the wall of the hexagonal duct at three locations corresponding to the spacer-wire pitch. The compliance of the inner fuel elements was represented by elastic springs at the three locations of contact between the outer elements and their immediate inner neighbors. The influence of the axial load on the bending stresses in a fuel element was neglected. Cladding stress, bending moments, and deflection were obtained as a function of several variables: (i) the axial force exerted on the duct by the disassembly machine, (ii) the friction between the element claddings and the duct wall, (iii) the number of elements in contact with the duct, (iv) the spacer-wire pitch, (v) the lateral stiffness of the element cluster, and (vi) the manner of load distribution and contact between the outer elements and the duct wall.

Figure 3 shows the relationship between support stiffness ($k_{A,B}$,k_C), element deflection ($\delta_{A,B}$,δ_C), and bending stresses ($\sigma_{A,B}$,σ_C) for EBR-II subassembly X062 for two of the loading configurations considered and a disassembly pull force of 2000 lb. The dashed arrows indicate the stiffness and bending stresses that correspond to a 15-mil deflection, that is, the estimated dimensional change in the hexagonal duct.

The problem of flow-induced vibration and consequent wear of fuel element cladding is currently being investigated. Cluster-duct interactions suggest the need to minimize differential growth between clusters and ducts. If this cannot be accomplished in a given subassembly design, the design criteria must change to include interaction conditions.

3. Response of Duct to Internal Pressure Pulse

An important consideration in subassembly duct design is its response to a pressure pulse that may possibly result from the rapid release of fission-product gas from a failed fuel element. Although all fuel element failures to date in EBR-II have been benign, typically pin-holes or hairline crack, the possibility of cladding bursts during transients cannot be precluded. Thus the EBR-II Project has performed numerous pressure pulse tests on subassembly ducts [5,6,7] and is continuing with analytical studies as well as additional testing.

Investigations are being conducted within the fail-safe analysis framework given in Table I. Correlation of the duct test results yielded an empirical relationship between the permanent (ΔD_p) of a duct, and the pressure (P) and volume (V) of fission gas in the fuel element of the following form:

$$\Delta D_p = A + BP^2V^{1/3} \qquad (1)$$

A is a "correlation" parameter and B is a "pressure pulse effectiveness" parameter; the latter accounts for the way gas escapes from the element and the pressure pulse is experienced by the duct. Results of the correlation are shown in Fig. 4 for a number of variables including the type of gas, the cladding and duct material, the presence of internal restriction to gas flow, and whether pre-defected tubes or rupture discs are used to produce the pressure pulse.

Analyses are being conducted using the STRAW code [8] to obtain more accurate descriptions of duct deformation and stresses. A preliminary result is shown in Fig. 5. The CREEP-PLAST code [9], with suitable modifications, is also being used to conduct fracture analyses of the duct.

Duct deformation, with or without the occurrence of fracture, must not impede subassembly removal from the core or the motion of adjacent control or safety rods. A large fracture in an embrittled duct must be avoided since fractured fragments would be difficult to remove from the core. As a precaution, ducts with pressure-pulse protection are being used where appropriate for high burnup subassemblies in EBR-II.

4. Swelling and Bowing of Subassembly Ducts

Limits on the swelling and bending of subassembly ducts in EBR-II are established by evaluating the swelling of stainless steel as a function of operating temperature and flux profiles, the allowable clearances in the reactor, and the limited clearance available in the storage basket.

4.1 Duct Swelling

Subassembly diametral growth (ΔD) in the core is limited by the space between ducts, which is ~0.025-in. In an array of ducts, swelling in one subassembly may be offset partly by lower swelling in other ducts in the array. The allowable swelling for a given duct depends on the number of ducts, their individual ΔD's and the cumulative ΔD. A core-wide surveillance of swelling in experimental subassembly ducts guards against the occurrence of local regions of high swelling in the core. An absolute limit on diametral growth is imposed by a hexagonal opening in the tubes of the subassembly storage basket. Storage and retrieval difficulties were experienced with two subassemblies, X115 and X145 suggesting interference. Result of calculations based on empirical swelling correlations, shown in Fig. 6, indicate that the diametral growth in both subassemblies exceeded the storage basket limit of $\Delta D = 0.04$ inch.

The length growth (ΔL) of a subassembly in EBR-II is limited by the clearance between the subassembly holddown fingers in the reactor cover and the top of the subassemblies. An initial limit was established from the nominal dimensions of the reactor vessel, cover and core. The clearance at operating conditions was 0.465 ± 0.390 inch (or a minimum of 0.075 inch), including the tolerance on nominal subassembly length of ±0.070 inch. Length increases of subassemblies were measured in-core by bottoming the gripper onto a subassembly and recording the gripper shroud height. A comparison of measured and calculated length increases is shown in Fig. 7. No length increases greater than ~0.25 inch have been measured, which suggests subassemblies contact the holddown fingers at this value. Interference loads may then cause plastic deformation of the fixture at the top of a subassembly. In laboratory tests, the load necessary to cause plastic deformation of the slot in the fixture was found to be lower than the buckling load of the holddown finger [6].

In-reactor interference tests also were performed on high-fluence subassemblies with the wide-bladed gripper of the fuel handling machine. Interference was confirmed for two subassemblies where partial closure of the slot had resulted from pressure contact with the holddown finger. An axial growth limit (ΔL) of 0.20 inch was consequently established for current subassemblies in EBR-II.

4.2 Duct Bowing

Subassembly bowing may influence core neutronics during reactor operation and can cause structural damage during subassembly removal and storage. Bowing may be induced in the core by radial thermal gradients or by a swelling gradient across the duct. Handling difficulties due to bowing were experienced in EBR-II with an experimental subassembly that contained a large-diameter nickel rod specimen [10]. Alignment difficulties were encountered with the holddown assembly and although the subassembly was easily removed from the core, a greater than normal force was required to retrieve the subassembly from the storage basket. Thus, subassembly bow may be more limiting on operations in the storage basket than in the core.

An analysis was conducted to determine the amount of bow that can be accommodated in the storage basket without mechanical interaction. The clearances at the hexagonal guide collar and with the bore of an individual tube, and the angle between a bar that orients the subassembly in the tube and the direction of bow were the three factors that were found to govern the amount of bow which can be accommodated without mechanical interaction. The allowable bow on a subassembly for insertion into the storage basket is shown in Fig 8. The bowed subassembly which experienced interference is also shown.

5. Grid Plenum Assembly

The EBR-II grid plenum assembly has basically two functions: to distribute sodium evenly to the core, and to position all subassemblies and ensure their mechanical stability. Proper positioning of the subassemblies is achieved by the close fitting of the lower section of the subassemblies (lower adapters) through holes in two 4-inch thick plates that form the upper and lower bounds of the high pressure plenum (Fig. 9). Because of the low flux and temperature in the vicinity of the grid plenum assembly, radiation damage to this component had been discounted until recently. However, because of the small clearances between the lower adapters and the grid plate holes, changes in the grid plate dimensions need to be considered.

The combination of swelling, coolant pressure and subassembly weight leads to some transverse displacements of the grid plates. The overall effect on the coupled grid plates is a relative radial displacement of the two sets of holes and a tilting of the hole centerlines.

Swelling in the grid plates today and to 1985 was estimated from flux calculations and empirical swelling correlations [9] assuming a 56% plant factor for future operation of EBR-II. The volume changes shown in Fig. 10 were used to perform a gross area stress analysis of the plenum assembly [10]. Figure 11 shows the relative displacements between the upper and lower plates for 1973, 1979 and 1985. The dashed line represents the effective misalignment of the holes with lateral deformation of the plates taken into account. This lateral deformation is not uniform and results in a slight tilt of the axes of the holes. These displacements reduce the clearances available suggesting the possibility of interference in the near future. Additional reduction in clearance as a result of swelling of the adapters, is very small.

Because the grid plenum assembly is an irreplaceable reactor component its functional integrity determines the useful life of EBR-II. A plan to gauge the grid plate alignment has been implemented. In addition the diameter of the lower adapters are being reduced to offset the projected lose of clearance. The effect of swelling induced stresses and irradiation-induced changes in the fracture properties of the material on grid plenum stability integrity and performance are currently under study.

6. Concluding Remarks

The key structural component of EBR-II is the grid plenum that positions subassemblies in the core. The useful life of the grid plenum may be limited by differential deformation of the upper and lower grid plates due to swelling which is currently being measured and evaluated. If high stresses are associated with this deformation, the possibility of crack propagation between the locating holes must be considered. Whereas such cracks may not cause significant flow disruption, the reduced stiffness of the structure could cause increased deformations.

As important as the grid plenum behavior is the performance of the subassembly ducts in EBR-II. Duct performance is governed by interaction with the fuel element a duct contains, the adjacent subassemblies, the grid plenum, the subassembly holddown fingers, and finally, after removal from the core, with the storage basket. These interactions are being evaluated against the changing loading environment of EBR-II and the corresponding changes in material properties.

The performance of a fuel element cladding will be modified by local interaction stresses between elements and between an element cluster and the hexagonal duct of a subassembly, particularly if flaws or defects exist in the cladding [3]. Premature cladding failure may result in a pressure pulse that deforms or fractures the duct. Ducts should therefore be designed to maintain sufficient structural integrity to allow subassembly retrieval from the core and unimpeded motion of adjacent control rods. Some irradiation tests may require additional protection against pressure pulses on the duct.

The usefulness of the storage basket in EBR-II is governed by its ability to contain irradiated subassemblies. Available clearance in the basket limits the deformation which may be permitted for a subassembly. Forced insertion, or retrieval of a deformed subassembly into the basket can result in damage to the basket as well as the subassembly.

In conclusion, this study demonstrates the interactions between several structural elements in the core of a fast breeder reactor in addition to their individual responses to the core environment. Structural integrity and limit analyses of core components should include these interactions. Current efforts at EBR-II are directed towards further evaluation of these interactions.

7. Acknowledgments

The authors are indebted to several members of the EBR-II Project who were involved in the studies summarized in this paper. In particular, thanks are due to J. F. Koenig, L. K. Chang and S. Srinivas for the use of unpublished test data and analysis results.

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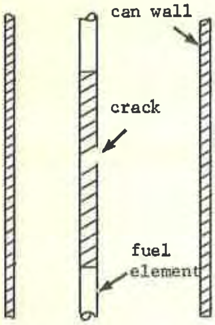
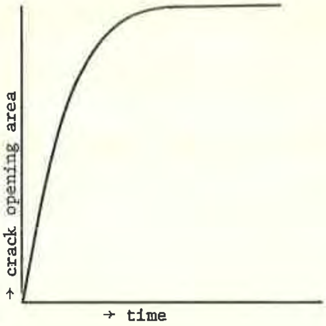
TABLE I. Ingredients of Duct Fail-safe Analysis



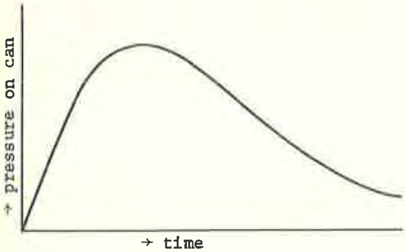
A. FUEL-ELEMENT SAFE-LIVES

Pin failure time, location and mode; determined by service experience, tests and analyses.



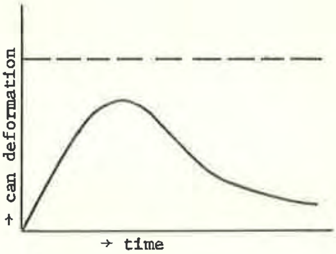
B. FUEL-ELEMENT FAIL-SAFETY AND FRACTURE MECHANICS

Rate of crack opening and crack opening area; determined by service experience, tests and analyses.



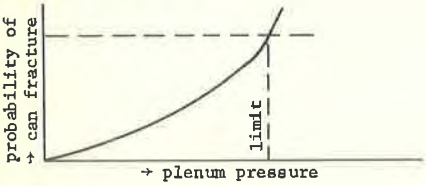
C. PRESSURE PULSE CHARACTERISTICS

Influence of crack location, orientation, opening area; surrounding pins; fluid media; determined by service experience, tests and analyses.



C. DUCT DEFORMATION

Determined by service experience tests and analyses. Parametric studies using STRAW and CREEP-PLAST codes. Materials property data.



E. DUCT FRACTURE

Determined by tests and fracture mechanics analyses.

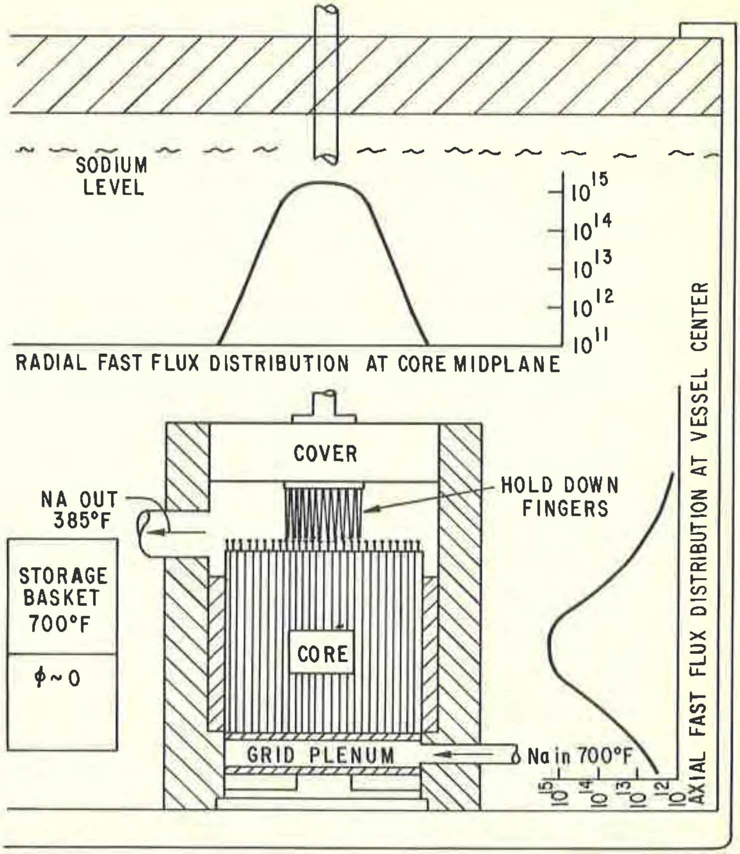


Fig. 1. Operating Environment of EBR-II Reactor Vessel.

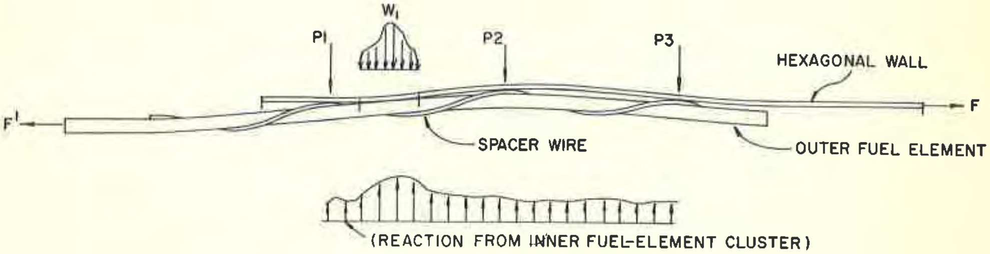


Fig. 2. Interference Loads Between Fuel Element and Duct.

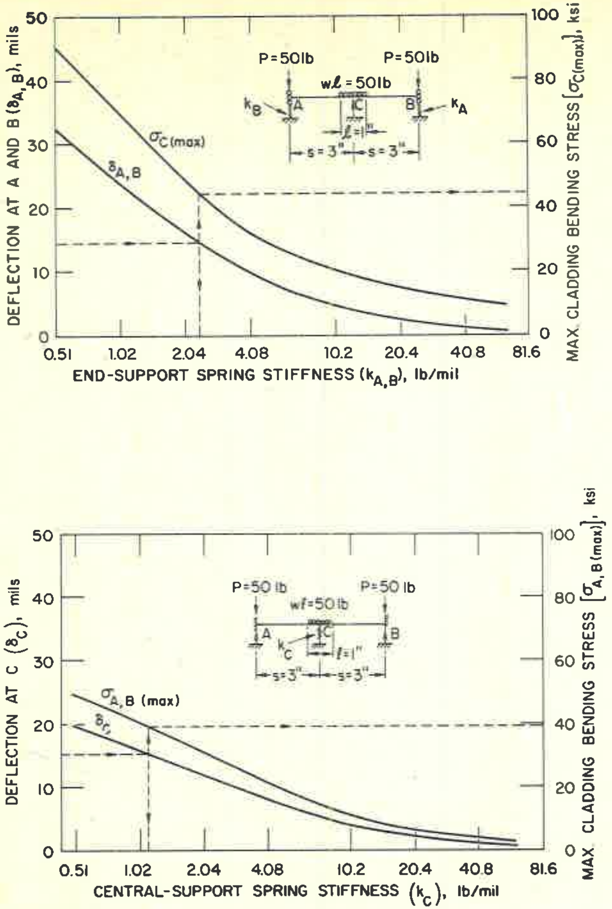


Fig. 3. Influence of Spring Stiffness on Fuel Element Reflections and Cladding Bending: End Support and Center Support.

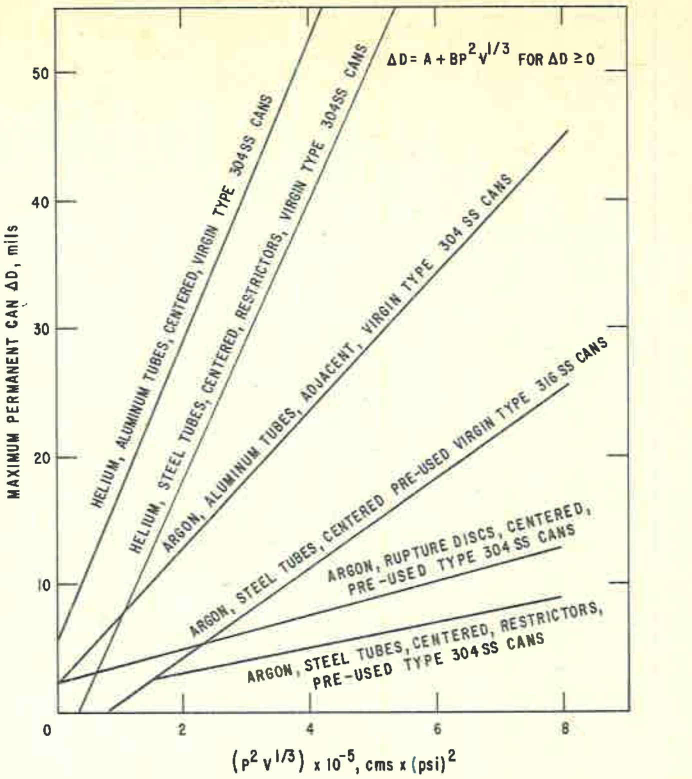


Fig. 4. Empirical Correlations of Duct Deformation Under Various Test Conditions.

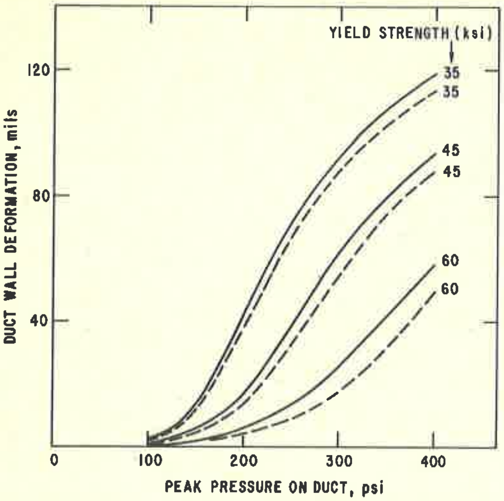


Fig. 5. Influence of Yield Strength on Duct Deformation for Two Loading Rates.

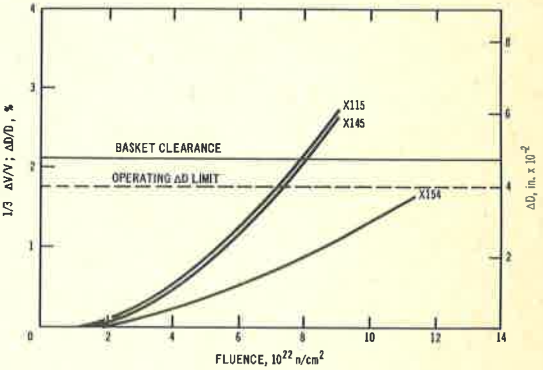


Fig. 6. Diametral Growth of Three Experimental Subassemblies.

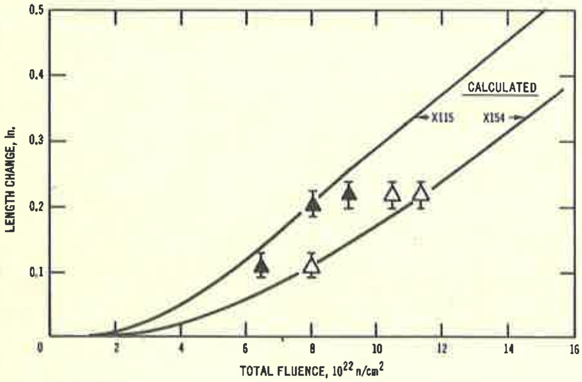


Fig. 7. Measured and Calculated Length Growth of Two Experimental Subassemblies.

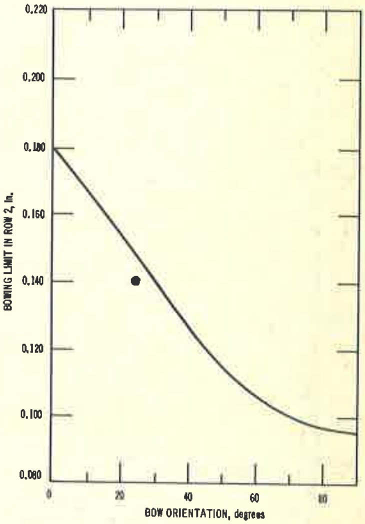


Fig. 8. Storage Basket Clearance for Bowed Subassemblies.

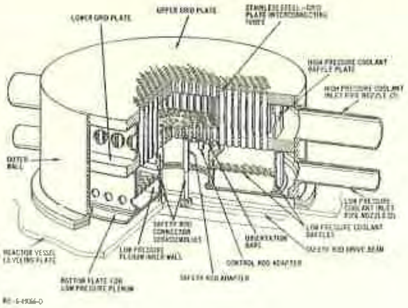


Fig. 9. Reactor Vessel Grid Plenum Assembly.

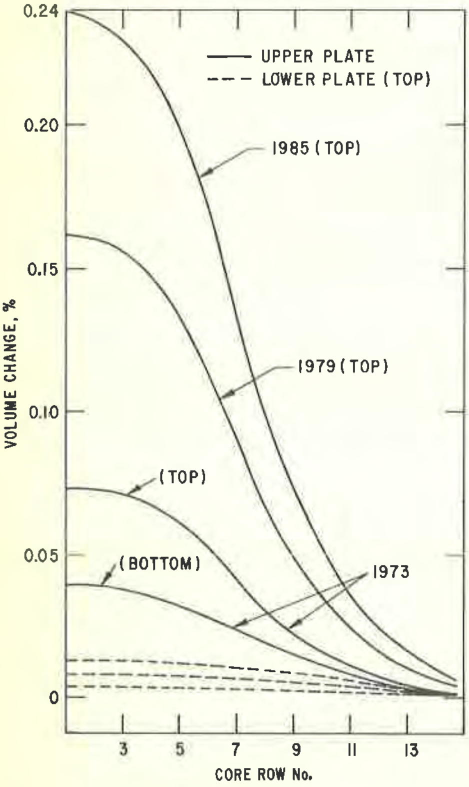


Fig. 10. Radial Distribution of Swelling in EBR-II Grid Plates (No Restraints).

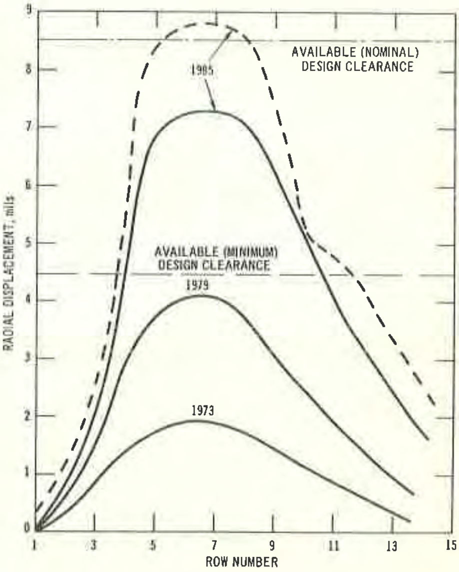


Fig. 11. Radial Displacement of Upper Grid Plate Relative to Lower Grid Plate.