CONF-890855--59

Paper to be presented at the 10th International Conference on Structural Mechanics in Reactor Technology to be held August 14-18, 1989 in Anaheim, California.

CONF-890855--59

DE90 002181

THREE-DIMENSIONAL BOWING ANALYSIS OF RADIAL REFLECTOR ASSEMBLIES IN ADVANCED LMRS

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*Work supported by the U.S. Department of Energy, Nuclear Energy Programs under Contract W-31-109-ENG-38.

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INTRODUCTION

The near-core radial shield in some advanced liquid metal fast reactors (LMRs) [1,2] consists of steel reflector assemblies that surround the inner core assemblies followed by shield assemblies that have large volume fraction of boron carbide. The reflector and shield assemblies of these reactors are removable, similar in outer configuration to the inner core assemblies and link the inner assemblies to the outer parts of the core restraint system. An important design goal for these reflector and shield assemblies is to have the longest service life in the core with minimum handling. Extended residence of the reflector assemblies in particular, with the ducts subjected to large neutron flux gradients, could give rise to relatively large differential irradiation-induced swelling strains, duct inelastic deformations and interassembly forces. The purpose of this paper is to assess the effect of extending the residence of reflector assemblies in view of the mechanical design requirements of LMR cores.

Simplified three-dimensional inelastic analyses are performed for a conceptual 900 MWt advanced LMR core that has a limited-free-bowing restraint system and assembly ducts made of a ferritic stainless steel. With all the assemblies in a 30-degree sector of the core simulated, the structural analyses focus on the behavior of the reflector and shield assemblies during a 30-year residence in the core. The design evaluation addresses mainly the reactivity feedback by the bowing and dilation of the core assemblies during unprotected loss-of-flow (LOF) transients and the forces required to withdraw an inner-core assembly during refueling. The negative reactivity feedback contributed by the bowing and dilation of the core assemblies during unprotected LOF transients is a critical element in enhancing the passive safety features in advanced LMR core designs [1].

METHOD OF ANALYSIS

The present analysis method is similar to the method used in Ref. 3, which addressed the bowing reactivity feedback based on time history analyses that covered the equivalent of four years at full power. The present analysis method, however, extends the time history analyses much further so that the effect of irradiation on the reflector and shield assemblies can be evaluated. During these extended time history analyses, approximations are necessary in order to avoid costly detailed calculations of refueling and assembly shuffling schemes. The inner core assemblies which individually have residence time of four years are assumed to remain at an approximate equilibrium condition with fixed neutron fluence for analysis times longer than three years. Maintaining the inner core assemblies at the three-year fluence is considered realistic since the core refueling schedule requires that one fourth of the driver assemblies to be replaced each year. As for the assembly duct wall temperatures, they are assumed to remain at the beginning-of-equillibrium-cycle condition during all full-power steady-state operations. The duct wall temperatures during unprotected LOF transients are derived from the full power temperatures by varying the duct temperatures relative to the support-grid temperature in proportion to the normalized power-to-flow ratio (P/F). All the duct wall temperatures during refueling conditions (P/F=0) are assumed to be at the grid-support temperature of 357°C. The displacement-reactivity-worths of the innner core assemblies are calculated by a refined method which is dacribed in Ref. 4. To determine the amount of the reactivity change as a result of assembly bowing and dilation these displacement worths are multiplied by the corresponding lateral displacements of the assemblies [3].

The NUBOW-3D computer code is used to calculate the bowing and dialtion of the core assemblies and interassembly forces that arise during full power condition and LOF transients. The NUBOW-3D code considers the assemblies in a 30-degree sector of the core. The core assembly configuration and numbering system used in the present analyses are shown in Figure 1. The core restraint system is a limited-free-bowing system [4] with one restraint ring at the top load pad level to control the deformations of the outermost shield assemblies. Some of the core design data that impact the bowing calculations are as follows: the core height is 97 cm, assembly height is 411 cm, assembly duct flat-to-flat is 15 cm, and duct wall thickness is 0.36 cm. Measured from the assembly nozzle-pivot, the elevations of the core midplane, above core load pads, and top load pads are 117, 189, and 368 cm, respectively. In order to assess the effect of the bending stiffness of the reflector assemblies, the NUBOW-3D calculations are performed first with equal bending stiffness for all the core assemblies and then with the stiffness of the reflector assemblies reduced by a factor of ten.

Figure 2 shows the fast neutron flux distribution at the core midplane elevation for assemblies 13 to 21. Assembly 19 is the closest reflector assembly to the core centerline and thus its duct side which faces the inner core is exposed to the highest fast neutron flux. The outer side of the duct, however, is exposed to a much lower flux which is only about one third of the value on the inner side. The duct material of all core assemblies is a ferritic stainless steel characterized by a relatively small irradiation induced swelling [5,6]. Because of lack of test data that show significant material swelling and a clear end of the swelling incubation period, there is presently a large uncertainty in predicting the swelling strains at neutron fluences higher than the fluences reached in the tests. A more recent set of material correlations (HEDL-1984) predicts longer swelling incubation period followed by a much higher swelling rate than predicted by an earlier set of correlations (NSMH-1982). In the present analyses, results will be given for both swelling correlations so that the sensitivity of the results to the material correlations can be assessed. Figure 3 shows the swelling strains predicted by the two swelling correlations as functions of days at full power. Figure 4 shows the corresponding creep strains at a constant stress of 80 MPa as predicted by the two sets of material correlations. Unlike the swelling strains, the creep strains predicted by the two correlations differ only by about 20% for the assumed reflector condition.

Thus differences between the NUBOW results with the two different sets of material correlations are attributed mainly to the difference in the amounts of the swelling strains.

RESULTS

One of the main objectives of the present analyses is to show the effect of the reflector assembly residence time on the amount of the reactivity feedback during an unprotected LOF transient as the P/F increases from 1 to 2. Figure 5 illustrates the negative reactivity feedback as a function of the equivalent full power days (EFPDs) that the reflector and shield assemblies reside in the reactor core. The results are provided for three different cases which delineate the effects of swelling rate and reflector bending stiffness. In each case, the first calculation point represents the result of an LOF transient that occurs very early in the core life, the second point represents an LOF that occurs after 700 EFPDs, and the third point represents an LOF that occurs after 876 EFPDs (the equivalent of three years at full power). The remaining points show the results of LOF transients that occur after extended residence that ranges from 3600 to 8760 EFPDs. The most important conclusion from this figure is that for all the three cases the amount of the reactivity feedback is expected to increase as a result of the extended residence of the reflector assemblies. The inelastic bowing of the reflector assemblies in conjunction with the restraint ring improves the compaction of the driver and blanket assemblies at the load pads and thus generates more outward displacements by these inner assemblies during the transients.

Figures 6 and 7 illustrate two other effects for the extended residence of the reflector assemblies in the core. Figure 6 shows the maximum withdrawal force required to overcome the friction forces acting on an inner core assembly during refueling conditions. These withdrawal friction forces are calculated by summing up all the normal forces that arise on any driver or blanket assembly. A refueling after 876 EFPDs will require less than 8.1 kN to overcome the friction forces on any driver or blaket assembly in all three cases. Extending the reflector residence further, increases the friction forces in Case 1 to a very high and apparently unacceptable level. The forces in Case 2 stabilize at about 15.1 kN as the deflections caused by swelling strains are balanced by deflections due to associated creep strains. The large difference between the results of Cases 1 and 2 illustrate the sensitivity of the withdrawal forces to the swelling strain correlations. The withdrawal forces in Case 3 remain below the forces of the other two cases up to 6300 EFPDs. Beyond this residence time, however, the inelastic (combined swelling and creep) deflections of the reflector assemblies become extremely large, as can be seen in Figure 7. The inelastic deflection of assembly 19 following the swelling incubation period increases at a very sharp rate and in spite of the advantage of lower friction forces, the deflections will become so large that they could adversely affect the neighboring assemblies. It is important to notice that in order to emphasize the effect of the reflector deformations, the present analyses have considered reflectors assemblies that remain in fixed positions during their residence in the core. There are other options, however, that could utilize the mobility of these reflector assemblies to prevent any excessive deformations. For example, in-place 180-degree rotation of these assemblies can be scheduled so that the withdrawal forces and inelastic deformations remain below specified limits and thus longer service life can be attained.

CONCLUSIONS

Simplified three dimensional inelastic analyses are performed for core assemblies of an advanced LMR to study the effect of extended residence of the reflector assemblies on the reactivity feedback during unprotected LOF transients and on the assembly withdrawal forces during refueling. The time history analyses which covered about 30 years of full power operation showed that the bowing reactivity feedback slightly increases in magnitude as a result of improving the compaction of the inner core assemblies by the inelastic bowing of the reflector assemblies. This bowing of the reflector assemblies, however, raises the withdrawal forces of the inner core assemblies during refueling and could limit the service life of the reflectors. The withdrawal forces are found to be sensitive to the swelling strain rate beyond the incubation period and to the relation between this swelling rate and the associated creep strain rate. Reflector assembly designs with small lateral stiffness generally have smaller effect on the inner core assemblies, but the net inelastic deformations of these reflectors are much higher than reflector designs with larger stiffness. It is prefered that reflector designs have a creep deformation rate that becomes equal to the swelling deformation rate at acceptable levels of withdrawal forces and reflector inelastic deformations.

ACKNOWLEDGEMENT

The author thanks Y. Orechwa and D. C. Wade for their encouragement to initiate this work and for their review of the paper. The author also thanks T. J. Moran for the many discussions about the subject.

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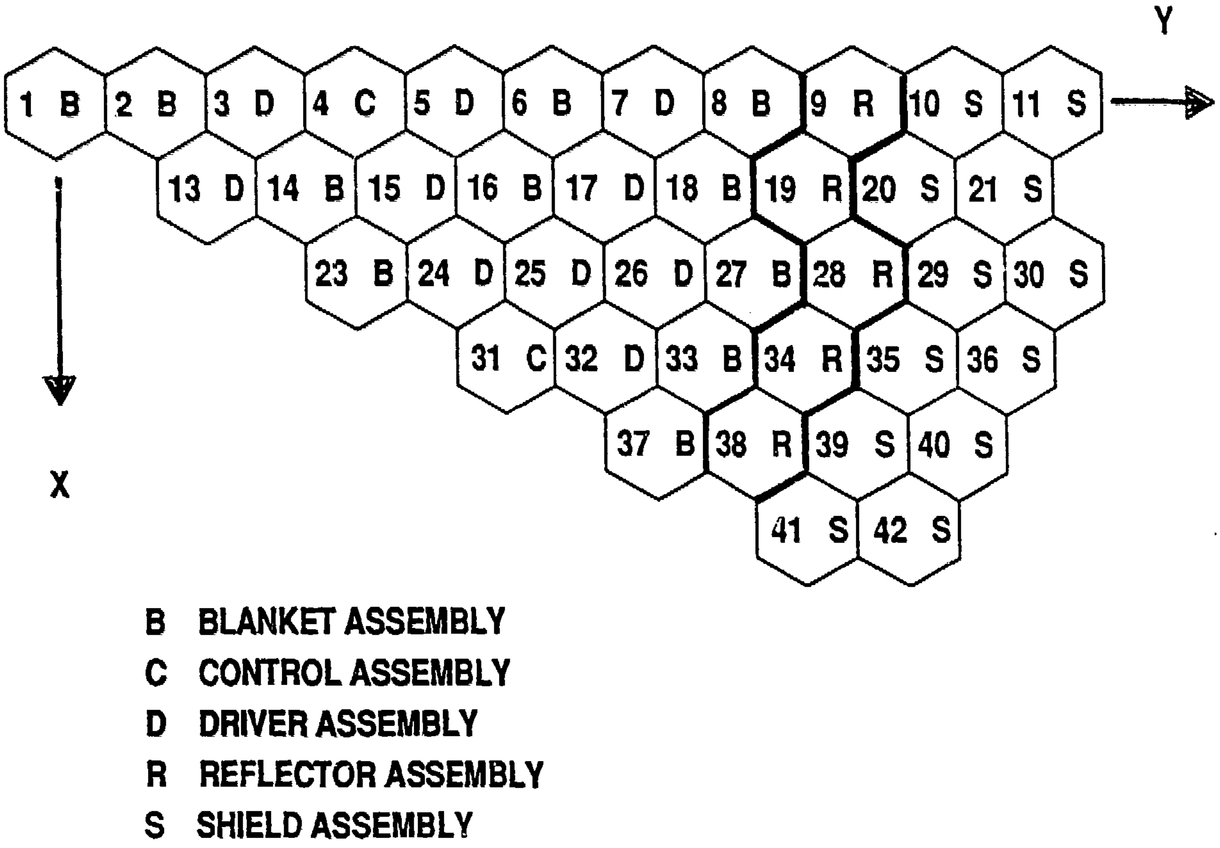

Fig. 1. 30-Degree Sector of the LMR Core Showing Assembly Configuration and Numbering System

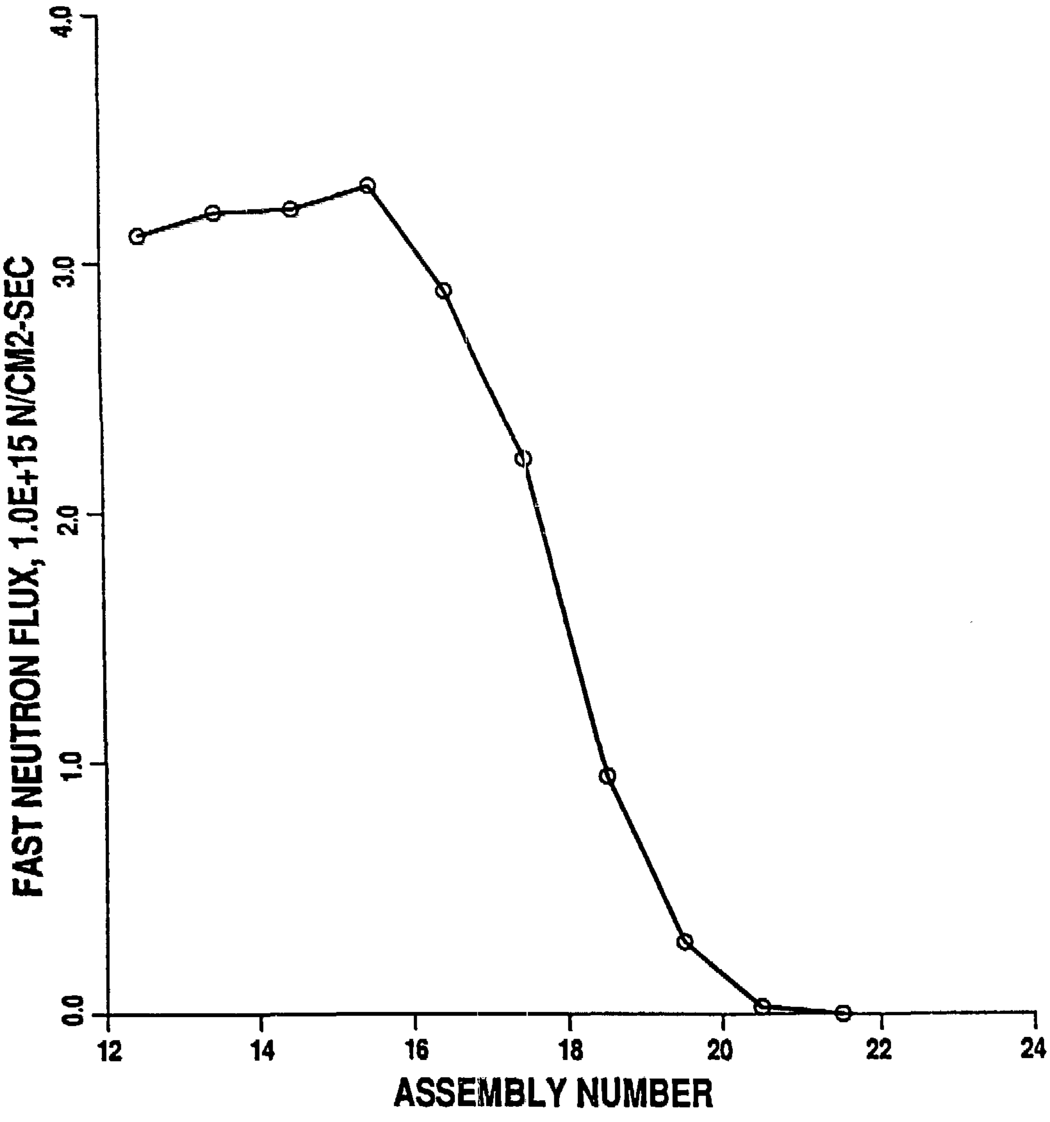

Fig. 2. Fast Neutron Flux Distribution at Core Midplane Elevation

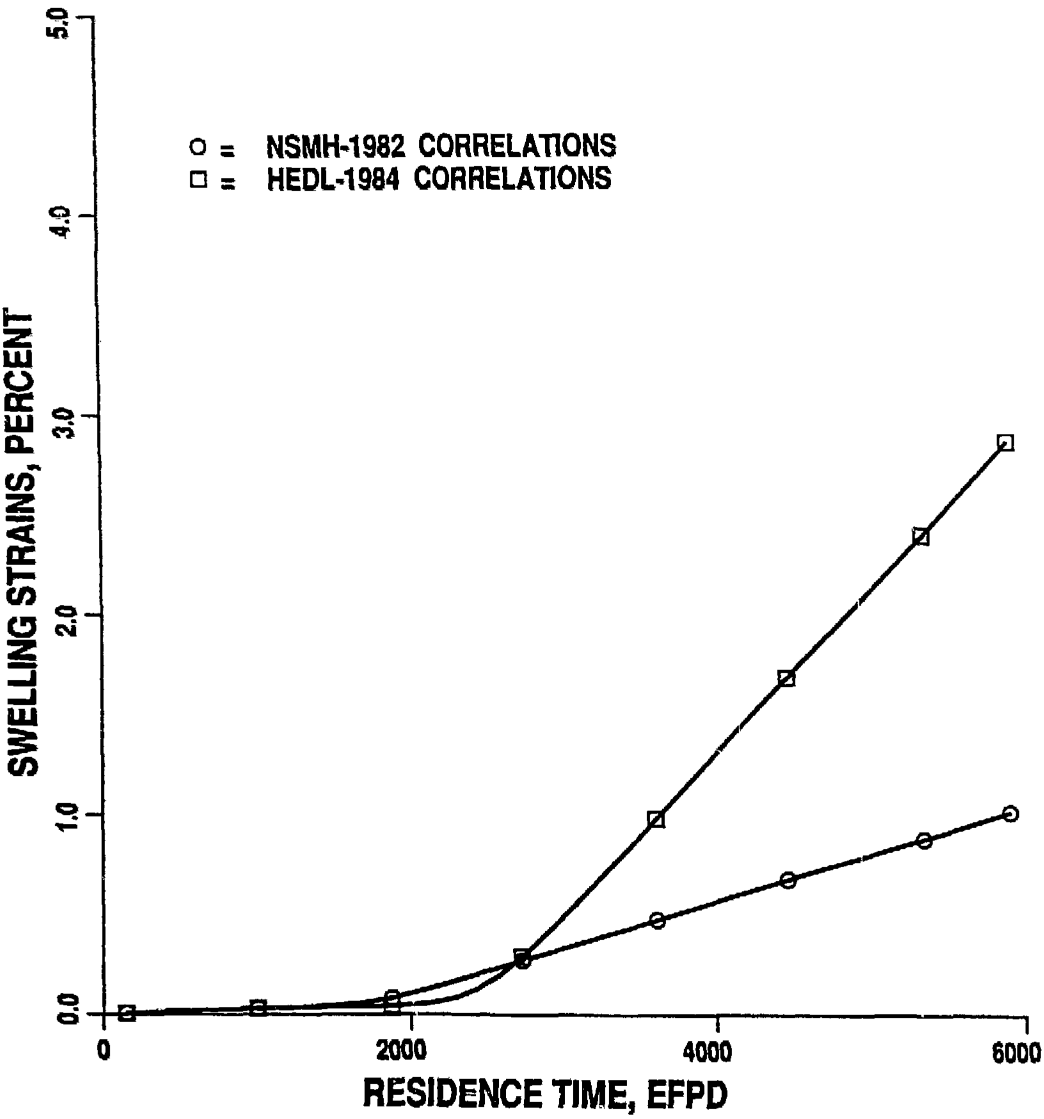

Fig. 3. Swelling Strains at Fast Neutron Flux of 0.942 × 10^{15} n/cm^2-s and Temperature of 400°C as Predicted by Two Sets of Material Correlations

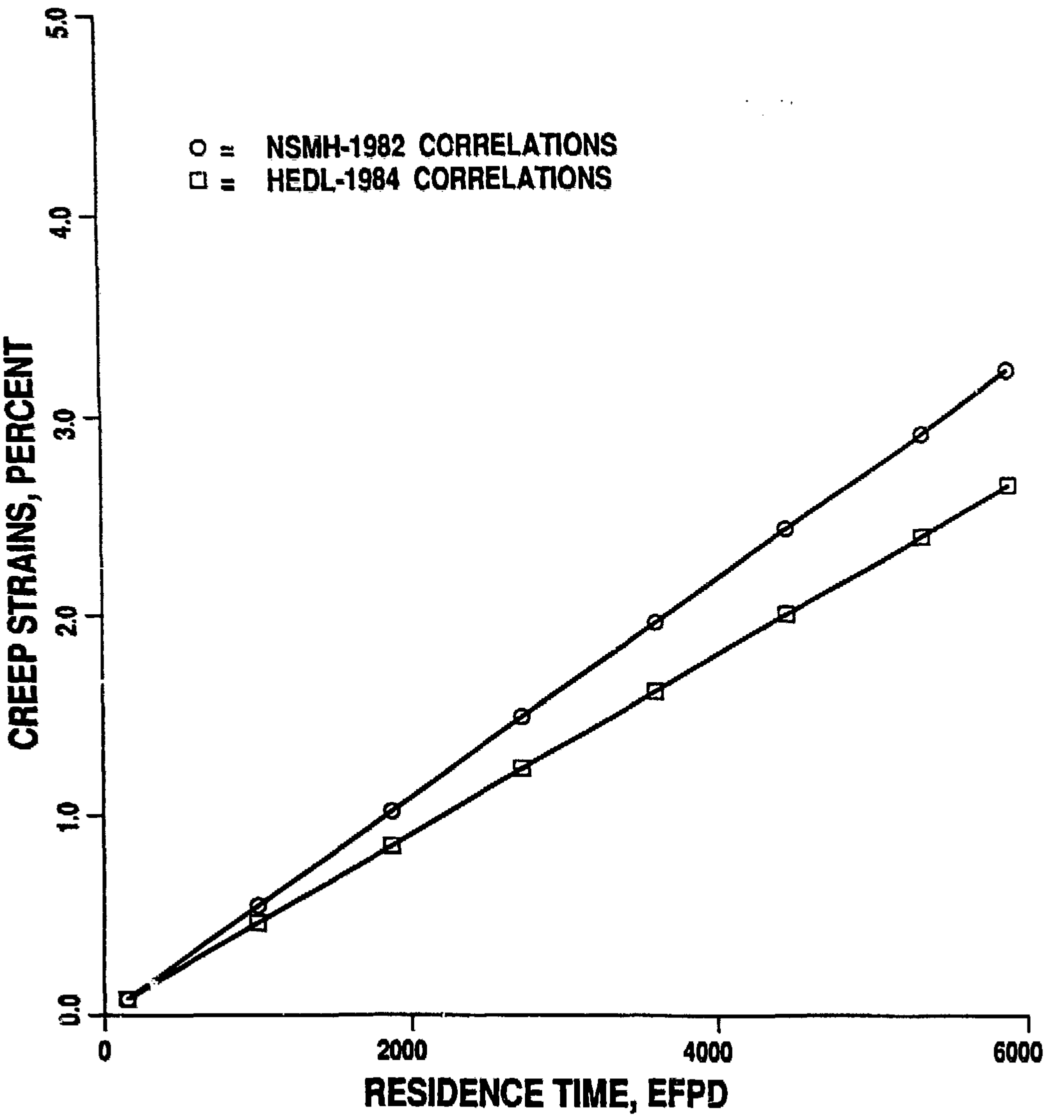

Fig. 4. Creep Strains at Fast Neutron Flux of $0.942 \times 10^{15} n/cm^2$-s, Temperature of 400°C and Stress of 80 MPa as Predicted by Two Sets of Material Correlations

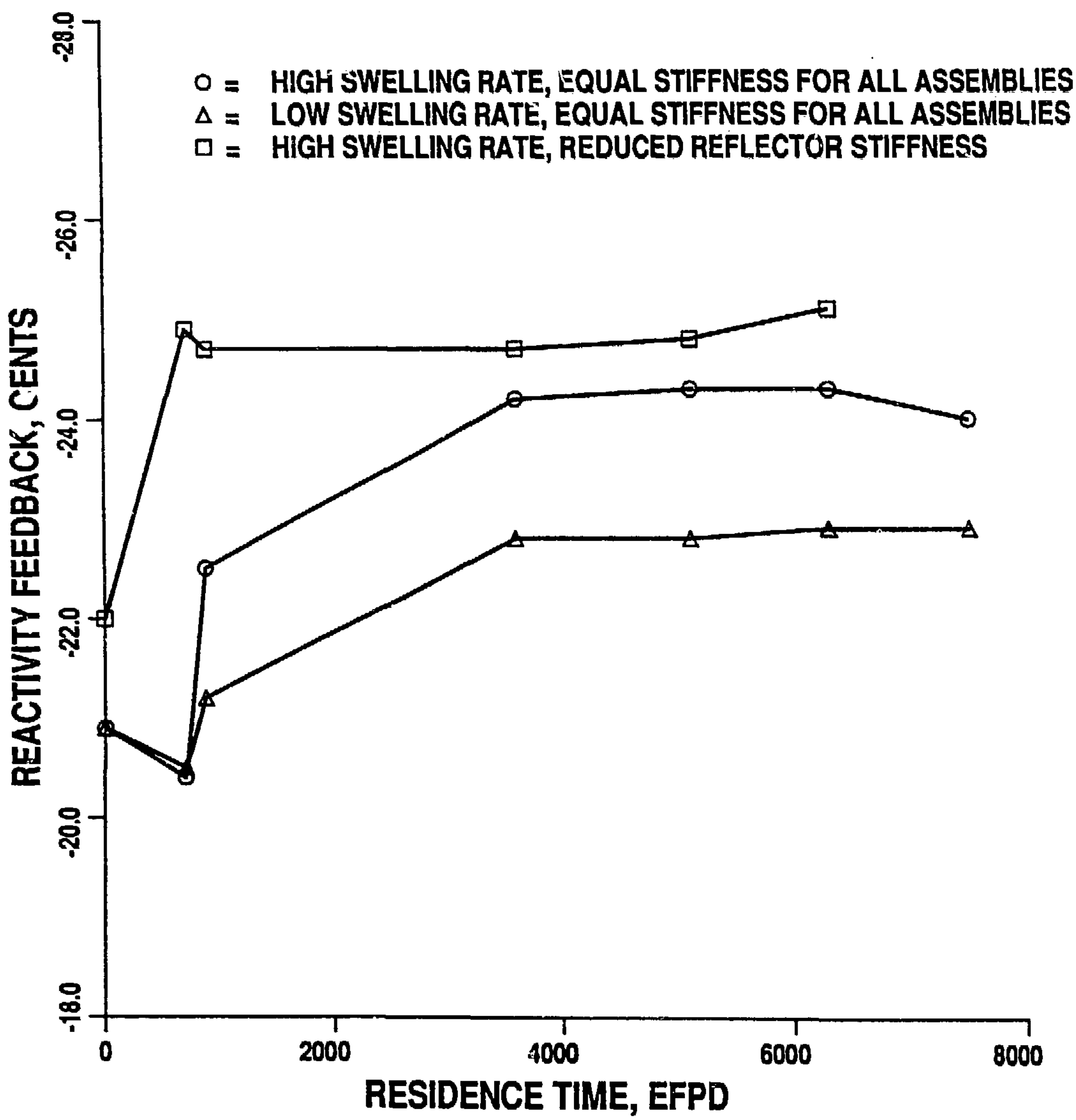

Fig. 5. Negative Reactivity Feedback by Bowing and Dilation of Core Assemblies During Unprotected LOF Transients as Function of Reflector Residence in Core

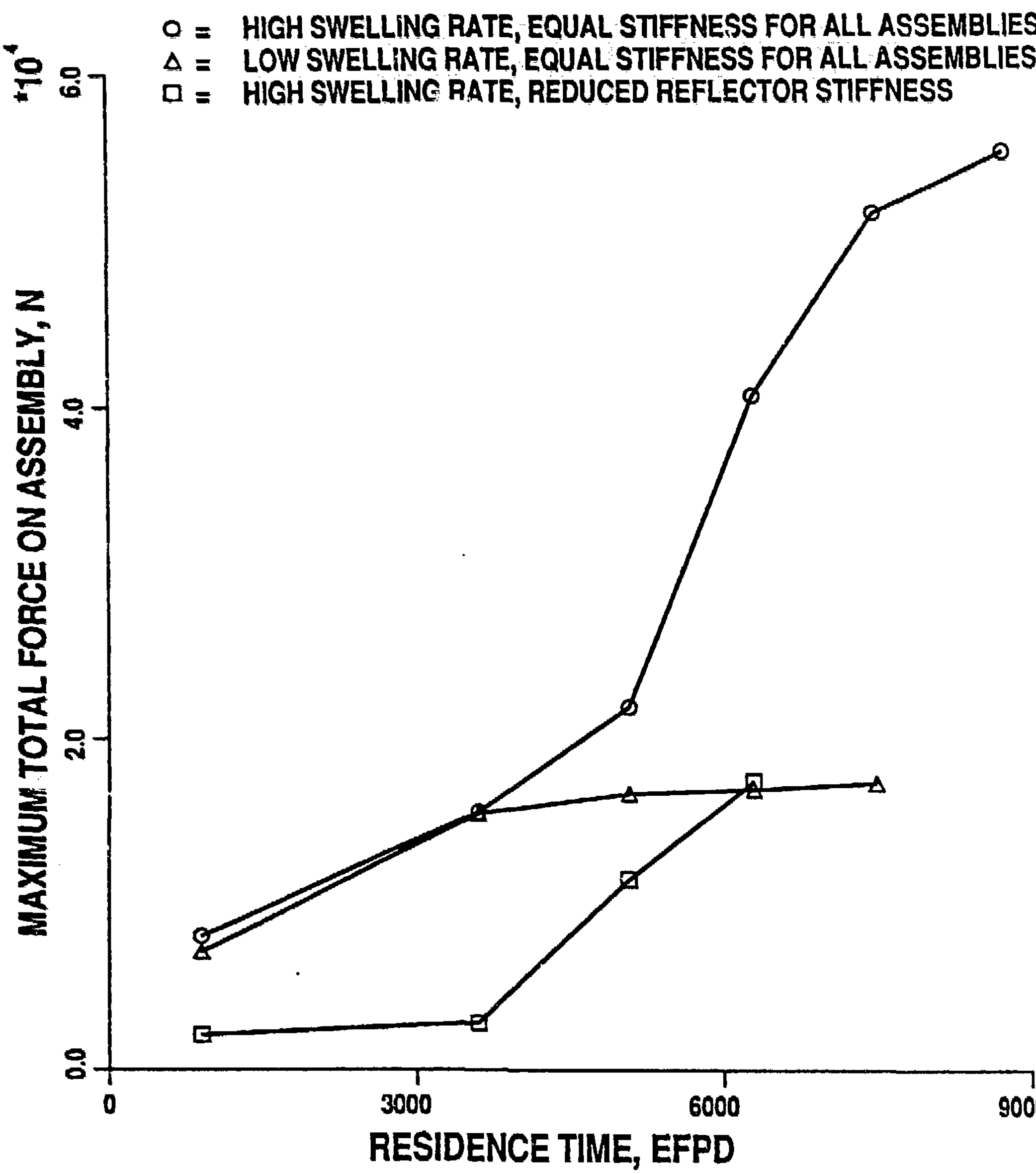

Fig. 6. Maximum Friction Force on Any Inner Assembly during Refueling as Function of Reflector Residence in Core

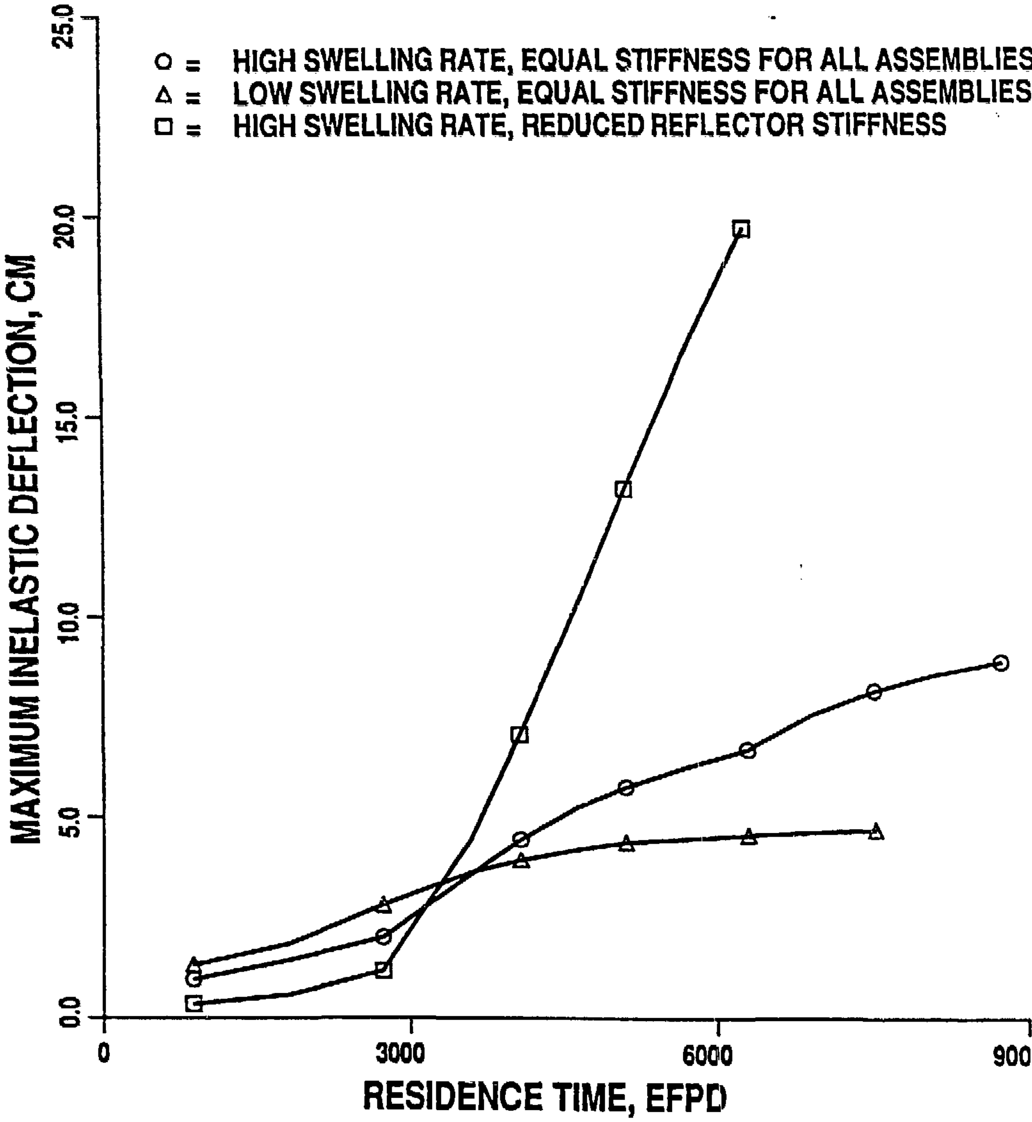

Fig. 7. Maximum Inelastic Deflection of Assembly 19 as Function of Reflector Residence in Core