Core Restraint Analysis of a Large Heterogeneous Free-Flowering Core Design

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SUMMARY

Core restraint performance was conducted on a heterogeneous core with two special design features - the heterogeneous core arrangement and the free-flowing assembly design - which set this core restraint study apart from previous ones.

Three dimensional core restraint analyses were performed with the NUBOW-3D code for a 30° section over the first two operating cycles or 510 full-power days. The analyses provided the time-history of the assembly displacements and of the forces at the contact points of the assemblies. These data were used to assess bending stresses, the compression of the load pads, the alignment of control assemblies with their drive lines and of the fuel handling equipment with the top of the assemblies, the reactivity at various power and cycle conditions, and the amount of friction resisting refueling.

The major results of the core restraint performance study are, (1) the top-end displacements fall within the values used in U.S. designs (e.g. CRBRP), (2) the bowing reactivity coefficient is quite small, although positive. The overall power coefficient is predicted to be negative over most or all of the power range, (3) the forces during refueling are acceptable, and (4) the load pad compression forces are sufficiently low except for the early part of the first cycle when they may produce permanent deformations. If detailed structural analysis should confirm this possibility, three options are available: redesign the ACLP, recalculate the duct wall temperatures which give overly conservative temperature gradients, or modify the operating cycle to take advantage of creep.

The overall conclusion of the study is that the free-flowing design performs quite satisfactorily. These findings are particularly significant because of the greater demands of a heterogeneous core layout on the core restraint performance.
1.0 Introduction

As part of a broader study of large LMFBR designs, EPRI requested an investigation of a 1000 MWe heterogeneous mixed-oxide core with a free-flowering restraint concept which included the analysis of the core restraint performance and the core seismic response [1]. Prior to the investigation for EPRI only a very limited core restraint study of a large heterogeneous core, in which the flux and temperature gradients were treated as parameters, was conducted in the U.S. [2]. Since the free-flowering core had not been selected in previous U.S. LMFBR design, the sole analysis of this type of restraint system was a conceptual study to understand the basic patterns of assembly interactions and to evaluate its advantages and disadvantages vis-a-vis the limited-bow system [3]. The objective of this study was to calculate the core restraint performance of the system, as extensively as the available design information permitted, to identify areas in which design improvement could be made and to assess the potential of the system for incorporation into an LMFBR design.

Core restraint analysis consists of determining the mechanical equilibrium forces and displacements in the core system due to assembly interaction during normal operation. Quantities of particular interest in this analysis are the forces at the load pad contact points during power operation, the total lateral forces during refueling, the top-end misalignment of control assemblies during power operation, the top-end displacements of all assemblies during refueling, and the radial structural component of the power reactivity coefficient.

The analysis was performed with the NUBOW-3D [4] program, an established three-dimensional code which modeled the 86 assemblies in a 30° section of the large heterogeneous core. Geometrical, neutronic and temperature input data were obtained from a companion core analysis study [5]. The NUBOW-3D calculations took into account the changes in duct wall temperatures during the cycles and in the core loading due to refueling between cycles. The key features of the free-flowering restraint system are (1) relatively flexible fuel and blanket assemblies with long inlet nozzles which severely limit free pivoting, (2) a relatively soft above-core-load pad (ACLp) with small gaps between assemblies and a relatively hard top-load pad (TLP) with large gaps and (3) stiff radial reflector assemblies to limit the displacement of the fuel and blanket assemblies due to thermal and swelling-induced bowing. The performance requirements of the core restraint system were not quantified because of the preliminary design status of the interfacing systems; the criteria for evaluating the free-flowering system were based on the criteria from other LMFBRs and the experience from previous studies.

In the following section the calculated performance of the free-flowering system is evaluated at three times during the core lifetime - beginning of life (BOL), end of the first cycle (EO1C) and during the second cycle (BO2C to EO2C). The assessment of the design and the conclusion from the study are presented in Section 3.
2.0 Performance of the Free-Flowering Core Restraint System

2.1 BOL Conditions

The displacement and forces at the BOL full power conditions are given for the ACLP elevation in Fig. 1 and for the TLP elevation in Fig. 2. The interaction pattern seen in the figures is determined by the radial temperature profile of the heterogeneous core, which has a center blanket region, two rows of fuel assemblies, then two rows of blanket, two rows of fuel, and so on. The temperature profile reaches a maximum between two adjacent, high power density fuel assemblies and a minimum between two adjacent, low power density blanket assemblies. The temperature gradients, therefore, cause the tops of the fuel assemblies in adjacent rows to bow away from one another and to contact at the ACLP, while the top of the two adjacent blankets to bow toward each other, i.e., in a buggyspring pattern. The forces are the highest at BOL conditions, a fifth row fuel assembly has a single ACLP contact force of 5274 N with its two inboard neighbors and a six-face load of 17,494 N. The top-end displacement of the control assemblies are acceptably small. The bowing reactivity is positive but small, as seen in Fig. 3a. The positive change with increasing power/flow ratio is primarily caused by the compacting of adjacent fuel assemblies at their ACLP, as discussed above.

2.2 EOIC Conditions

Very little swelling but a lot of irradiation-enhanced creep occur during the first 255 day cycle, so the assemblies become straighter and have very light interaction loads under EOIC, full power conditions. The alignment of control assemblies continues to be acceptable. Removing the temperature gradient produces reverse bowing of the assemblies, which results in the adjacent fuel assemblies moving apart at the ACLP. This effect is seen in the reactivity curve (Fig. 3b) which is negative over most of power/flow range and has a more negative value at zero power because of the larger clearances at lower temperatures. The withdrawal force needed to overcome friction on the most heavily loaded assembly during refueling is 4400 N, an acceptable value.

2.3 Second Cycle Conditions (BO2C, EO1C)

The assemblies which remain in the core after the first cycle begin to bow due to differential duct swelling. The overall effect is similar to that due to thermal bowing at the BOL but the continuing creep significantly reduces the magnitude of the effect. The behavior of the core restraint system, therefore, lies between that at the BOL conditions and that at EO1C conditions. The calculations predict that the alignment of the control assemblies, the forces on the load pads, the bowing reactivity and the refueling forces are all acceptable.
3.0 Assessment of the Free-Flowing System and Conclusion of the Study

The force on the ACLP at BOL conditions is the only performance characteristic which was not clearly acceptable. Structural analysis of the ACLP must be performed to determine whether its capability is exceeded. If so, three options are available: (1) refine the core restraint analysis, particular the duct wall temperatures leading to the strong bowing interactions, (2) re-design the ACLP so it is capable of taking the loads or (3) institute operational procedures, i.e. operate at 75% power until the forces are reduced by creep.

The free-flowing concept looks very promising and should be considered as a strong candidate for the core restraint system in U.S. LMFBR designs. It meets the performance criteria established in this study, except for a one-time force on the ACLP. The design approach has the flexibility to accommodate uncertainties in the analysis, even the large ones associated with the swelling and creep correlations. The final evaluation must include other aspects of core restraint, such as, the seismic response. Within the scope of this study, however, the free-flowing core restraint system was found to meet the functional requirements and to be an attractive candidate for LMFBR designs.

References


Fig. 1. Assembly Displacements and Contact Forces at the ACLP under Full Power, Beginning-of-Life Conditions
Fig. 2. Assembly Displacements and Contact Forces at the TLP under Full Power, Beginning-of-Life Conditions
Fig. 3. Radial Structural Reactivity Effect for the Full Range of Power/Flow Values