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**CORE RESTRAINT PERFORMANCE
OF LARGE HETEROGENEOUS REFERENCE CORES**

by

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June 1977

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ABSTRACT

A preliminary study of the core restraint performance of heterogeneous cores was performed as part of the Large Heterogeneous Reference Core Study (LHRCS). The objective of the core restraint portion of the study is to identify the key features of heterogeneous cores which play an important role in setting the trends for their core restraint performance. The analysis is not carried to the point where absolute evaluations of the core restraint performance of heterogeneous cores are stated. This objective, which is less than that of a complete core restraint analysis, is nonetheless consistent with the scope of LHRCS, the available flux and temperature data for heterogeneous cores and the resources allotted for the work. The performance is based on satisfying four functional requirements: (1) to provide assembly alignment for control rod insertion and fuel handling; (2) to permit fuel handling within allowable insertion and withdrawal forces; (3) to maintain the core reactivity (from radial motion) within specified limits during normal and off-normal conditions; and (4) to prevent extensive duct-to-duct contact throughout the core.

Six generic cases were selected to represent the range of core arrangements whose features greatly influence core restraint performance. Case 1 is a reference homogeneous core with temperature gradients only near the fuel-blanket interface. Case 2 is also a reference homogeneous core, but has fictitious opposing temperature gradients within the fuel region. Cases 3 and 4 are tightly-coupled heterogeneous cores with fuel and blanket in the center region, respectively. Cases 5 and 6 are loosely-coupled heterogeneous cores with fuel (Case 5) and blanket (Case 6) in the center region.

The analyses of these cores were carried out with the NUBOW-2D Inelastic code in which all assemblies in a row are represented as a single beam. Although this representation is a very simplified one for a truly three-dimensional problem, NUBOW-2D Inelastic is well suited for the objective of this study.

The flux distribution for the homogeneous core was assumed to be a cosine function in the fuel region and a exponential one in the blanket region. Estimated perturbation factors were applied to the homogeneous flux distribution in a consistent manner to obtain the flux distribution for the heterogeneous cores. The magnitude of the temperature gradient in the fuel region of the heterogeneous cores was 100°F; the direction of the gradient was the same as the local flux gradient.

In regard to alignment and radial displacement features of core restraint performance, there is not a significant difference between homogeneous and heterogeneous cores. The force level in some heterogeneous cores is higher than in the references homogeneous case. However, an acceptable force level can probably be achieved, although the performance of these cores in some other areas may be somewhat degraded in the process.

The most important relative difference in the performance of homogeneous and heterogeneous cores is the extent of duct-to-duct contact in the core region. Three of the four heterogeneous cores have substantial duct-to-duct contact while neither of the homogeneous cores do. This performance characteristic of heterogeneous cores appear to be inherent in their design and not amenable to change by core modifications, etc. The features producing duct-to-duct contact should be kept in mind in the initial stages of laying out heterogeneous cores, and detailed core restraint analysis (i.e., 3-D) should be employed to investigate their core restraint performance in preliminary design studies.

1.0 INTRODUCTION

This report presents a preliminary evaluation of the core restraint performance of large heterogeneous cores with reference (CRBRP) core assemblies. The work was performed as part of a multi-organization study which investigated many facets of heterogeneous cores. The preliminary evaluation was based on a set of "generic" homogeneous and heterogeneous core arrangements, which were chosen to compare the relative performance of homogeneous and various types of heterogeneous cores. The core restraint performance of various cores is compared on the basis of meeting the functional requirements. The generally accepted functional requirements of a core restraint system are: (1) to provide assembly alignment for control rod insertion and fuel handling; (2) to permit fuel handling within allowable insertion and withdrawal forces; (3) to maintain the core reactivity (from radial motion) within specified limits during normal and off-normal conditions; and (4) to prevent extensive duct-to-duct contact throughout the core. In this preliminary study quantitative values are not given for the functional requirements. Rather, the core restraint performance of the different cores was evaluated on a relative basis.

Core restraint performance was recognized early in the Large Heterogeneous Reference Core Study (LHRCS) as a potential problem. Core restraint systems are basically required because of assembly interactions. Experience has shown that greater assembly interactions place greater demands on the core restraint system in meeting its functional requirements. Some heterogeneous cores may have greater assembly interaction than corresponding homogeneous cores because a larger number of assemblies are in a flux and temperature gradients. Core restraint performance is quite sensitive to the core design features and environment. Few general rules exist with which the performance of one core can be used to predict that of another core. In fact, seemingly small changes in core designs have produced an effect opposite from the one expected. Thus the results of this study should not be considered sufficient to evaluate the core restraint performance of all heterogeneous cores, but rather to identify the key features and environmental conditions which play an important role in determining the performance. Detailed calculations would then be required to verify the core restraint design of a particular core.

Detailed information, particularly flux and temperature distributions throughout the life of a core, are essential for core restraint analysis. This information is available only after rather extensive neutronic, thermal hydraulic and mechanical analysis of a reference core. However, temperature and flux distributions from the various LHRCS designs were not expected to be available on a timely basis. It was decided, therefore, to emphasize core restraint analysis of "generic" types of homogeneous and heterogeneous cores, and at the end of the study, to analyze LHRCS designs for which input data were available. The "generic" cases were selected to encompass various types of cores under study, i.e., loosely- vs. tightly-coupled and blanket vs. fuel in the center. Flux and temperature distributions were assumed using the experience gained from previous studies of homogeneous and heterogeneous cores.

A set of temperature and flux distributions from one participant of the LHRCS was received in the latter stage of this core restraint study and a preliminary analysis was performed.

The analytical method is discussed in Section 2.0. The discussion of the generic cases is given in Section 3.0 and that of the one LHRCS design is presented in Section 4.0. Overall conclusions from the study are found in Section 5.0.

2.0 DESCRIPTION OF ANALYTICAL METHODS

2.1 General Considerations

The limitation on both the scope of the study and the input data available dictates that the core restraint analysis be performed with a two-dimensional model. Three-dimensional core restraint analysis requires very detailed input information and the use of significantly large amounts of computer time to examine a single operating cycle for each core design. Two-dimensional core restraint analysis requires considerably less input (two-dimensional temperature and fluxes) and, relatively short running times. However, there are definite limitations to two-dimensional analysis. Two-dimensional analysis assumes that all assemblies within a row behave in an identical manner; that is, they are assumed to be exposed to the same temperatures and fluxes on their duct walls and to be replaced with fresh elements at the same time. These conditions are found only in the most idealized cores, and definitely not in a heterogeneous core.

In interpreting the results from the two-dimensional calculations the values of the forces, the displacement of the assemblies, etc., must be thought of as "global" quantities for a row, rather than as quantities describing any individual assembly. With this proviso in mind, two-dimensional analysis was selected as very appropriate for a core restraint study to identify key features and relative performance characteristics of broad classes of core designs. The NUBOW-2D Inelastic Code⁽¹⁾ was used to analyze all the cases in this study.

2.2 Description of the NUBOW-2D Inelastic Code

The NUBOW-2D Inelastic Code performs a two-dimensional analysis of fast reactor core systems subjected to assembly bowing due to thermal and neutron irradiation effects. The code calculates the mechanical equilibrium configuration of the core, treating the assembly ducts as beam members. In the two-dimensional code, the core is modeled as a single row of interacting core assemblies in which each member of the row represents a hexagonal ring of assemblies in the actual core. Restraints at the outer boundary of the core are permitted to complete the mechanical systems. Each assembly (beam) may have up to six contact

points and up to six support locations. The bowing due to thermal effects is calculated from the values of the duct wall temperatures. Bowing due to inelastic effects is calculated from the fluxes and stress-strain state of the ducts.

The input quantities consist of the geometrical and mechanical description of the assemblies, the temperature and flux distributions in the core, the temperature change during a rise to power, and a fuel management scheme. Material properties, such as swelling and creep correlations, and control parameters complete the input data.

The inelastic calculation begins at zero power conditions for the first cycle of the core. The equilibrium configuration is calculated at specified power level intervals up to full power. Equilibrium configurations are then calculated at given time intervals during the operating cycle. At each time interval, the increment of inelastic strains is determined from swelling and creep correlations and added to that calculated at the previous time interval. The new values of total strain are used to give the free deflection of the assemblies. The mechanical equilibrium of the assemblies is then determined, giving a new value for the forces and stresses in each duct wall. At the end of the operating cycle, the power is reduced to the zero value, a fuel management operation is performed and the calculation of the next operating cycle begins.

The output quantities consist of printed input data, calculated geometrical thermal and material data, the clearances between the assemblies, thermal deflections and forces at equilibrium, the free-bow shape of the assemblies and the average displacement of the active core zone.

The two-dimensional nature of the calculation must be kept in mind when interpreting the results of the calculations. Global features such as the reactivity changes are usually calculated fairly accurately with a two-dimensional representation. However, the forces and displacements should not be interpreted as those actually occurring to individual assemblies in a three-dimensional system. Rather, the relative trends in these quantities should be considered in comparing one core restraint performance with another. Experience with three-dimensional calculations has shown that the forces on assemblies may be much higher or much lower than those calculated in a two-dimensional analysis.

However, two-dimensional calculations are very useful in investigating core design features, operating modes, fuel management schemes, etc. The value of the forces given in the output refers to the total force on all surfaces of all assemblies in a row. Thus, the value of the force on Row 15 is very large while the force on an individual assembly may be relatively small.

3.0 DISCUSSION OF GENERIC CASES

3.1 Rationale for Case Selection

Six core arrangements were selected to perform the generic study of core restraint performance of heterogeneous cores. Each core consisted of reference fuel, blanket and reflector assemblies. The arrangements of the assemblies were selected to give the key features which affect the core restraint performance. The six generic cases described in Table I consists of two homogeneous cores, two tightly-coupled heterogeneous cores and two loosely-coupled heterogeneous cores. The first case, the homogeneous core, is comprised of nine rows of fuel assemblies followed by three rows of blanket assemblies and finally three rows of reflector assemblies. Case 2 is identical to Case 1 except for the temperature gradients as will be discussed below. Case 3 is a tightly-coupled heterogeneous core with fuel in the center, while Case 4 is a tightly-coupled core with blanket assemblies in the center. Cases 5 and 6 are loosely-coupled cores with fuel in the center of Case 5 and blanket in the center of Case 6. A tightly-coupled core is defined as one having a single row of internal blanket separated by fuel, while a loosely-coupled core has two rows of internal blanket. As will be seen later, the distinction with respect to core restraint performance is between a single row of internal blanket assemblies and a multi-row of internal blankets. The terms "loosely" and "tightly" coupled were adopted because of their use in the neutronic studies of heterogeneous cores, but the neutronic coupling has no direct bearing on their core restraint performance.

3.2 Description of Input Data

The flux distribution for the homogeneous cores (Cases 1 and 2) were taken from a chopped cosine distribution in the core; and an exponential distribution in the blanket, fitted to centerline flux and the core-blanket interface flux of the reference (CRBRP) core. The flux distributions for the heterogeneous cores (Cases 3-6) were obtained by multiplying the homogeneous flux distribution by local perturbation factors. These perturbation factors were estimated for various arrangements of fuel and blanket assemblies by examining many flux distributions obtained from previous heterogeneous core studies. From a variety of beginning-of-life and end-of-life flux distributions, perturbation factors were

estimated for mid-life conditions. Although no claim is made for the accuracy of these perturbation factors, they were applied in a uniform and consistent manner for all the heterogeneous cases, thus preserving the ability to make relative evaluations of the performances. Radial flux distributions used in the six generic cases are presented in Figs. 1-3.

The direction of the temperature gradients depends directly on the flux distribution in the region around the assembly. The magnitude of the temperature gradient is somewhat arbitrarily taken. In Case 1 the outermost fuel has a typical temperature gradient of 100°F, while the neighboring fuel (inboard) and blanket (outboard) assemblies have a 50°F gradient. All other assemblies are assumed to have no temperature gradient. In Case 2, the temperature gradient alternates from -50° to +50°F for Rows 2 through 7. The purpose of this fictitious case is to investigate opposing temperature gradients within the core without the effect of a perturbed flux distribution, which is present in a heterogeneous core. The values of a temperature gradient for the fuel and inner blanket assemblies in Cases 3 through 6 are either -100° or +100°F depending upon the direction flux gradient in the region of the assembly. The first row of radial blankets is always assumed to have a temperature gradient of 50°F while all other radial blanket and reflector assemblies have no temperature gradient. The values of the temperature gradients for the six cases is given in Table I.

The length of an operating cycle is 250 days. At the end of each cycle, one-half of the fuel and internal blankets (for heterogeneous cores) are replaced with fresh assemblies. The radial blankets are removed after six cycles. The fuel management scheme for the first four cycles is given in Tables II-V for the generic cases. The order in which the fuel and blanket assemblies are replaced is unique only for Case 4. In this case, the calculations were performed with two fuel management schemes which differ only in which half of the assemblies are removed at the end of the first cycle.

3.3 Presentation of Results

As discussed in the Introduction, the Core Restraint Performance is judged on four performance quantities: (1) force level during operation and refueling; (2) alignment of the top-end of assemblies; (3) reactivity changes with change in power level; and (4) assembly interaction away from the load pads (normal contact points). The results presented in this section for the six generic cases

deal directly with these four quantities so that the relative core restraint performance of these cases may be evaluated in the following section.

The results of core restraint analysis are presented in the following forms. The maximum contact force (assembly at core center) under full power conditions at the end of each operating cycle is given in Table VI for the six generic cases. Also presented in the table are the maximum top-end deflection due to free-bow of the assemblies in the six cases at the end of each of the first three operating cycles. The lack of data on the reactivity worth of fuel assembly motion prevents a tabulation of the reactivity change with power level for the six cases. In lieu of these data, Table VII presents the change of radial position of the outer two rows of fuel assemblies at the end of each operating cycle for the six cases. The last two rows of fuel assemblies were selected because their motion historically contributes a very large fraction of the reactivity effects of bowing. Although these numbers are not sufficient to give a value to the reactivity effect, they do indicate at least whether the bowing coefficient would be negative or positive.

Figures 4 through 6 show the time-history of the force on the center assembly from beginning of life to 750 days of full power operation. Figures 7 through 9 give the same data for the force on the restraint ring. Since these values represent the total force on the 84 assemblies in the outer ring, the force level on each assembly is small relative to the center assembly. The forces on the restraint ring are included, not because they represent a design limit but rather because they are more indicative of the average force throughout the core than is the force on the center assembly. The equilibrium assembly configurations are plotted for full power conditions at the end of each operating cycle for the six generic cases in Figures 10 through 30. In viewing these figures, one must always keep in mind that the scale in the radial direction is many times smaller than that in the axial direction. Thus, an assembly appearing in these figures to be greatly distorted would be barely distinguishable from a straight assembly.

3.4 Discussion of Results

a) Alignment of Assemblies

The alignment of assemblies for the six cases may be seen in Figures 10 through 30 which plot the equilibrium configuration of the assemblies in the core restraint system. Top-end alignment does not appear to be a critical factor for

these core arrangements within the reference core restraint system. The reference core restraint system is a fairly tight system in which only 15 mils (cold clearance) exists between each assembly and 120 mils exists between the outer assembly and the core restraint ring at the TLP. Thus, for all the cases, the top-end alignment meets the typical requirements for control rods (.35-.40") and for fuel handling ($\sim 1"$).

b) Radial Motion in the Core Zone

There are no clear trends in the radial core displacement with an increase from zero to full power for the six cases. In the homogeneous cores (Cases 1 and 2), the radial motion of the outer two rows of assembly is consistently inward in going from zero to full power for the three cycle conditions. This suggests a positive reactivity change due to bowing; however these calculations are not sufficient to make any conclusion as to the reactivity coefficient of bowing. The radial motion characteristics of the heterogeneous core appear to be more favorable than those of the homogeneous core. For the four cases (Case 3 through 6), the radial motion is either outward, indicating a negative reactivity effect, or inward but of a smaller magnitude than for the homogeneous cases at the three operating conditions.

c) Force Levels at the Load Pads

The discussion of the force levels will begin with a general discussion based on the results presented in Table VI. Then the time-history of the forces for the homogeneous case will be presented and finally a discussion of the time-history of the forces for each of the heterogeneous cases will be given.

The forces given in Table VI at the end of each of the first three cycles shows a substantial variation among the six cases. However, as further examination of the results will show, the maximum force on the center assembly is not significantly different among these cases and does not appear to eliminate any core configuration at this time. Although Cases 3 and 5 do exhibit higher forces after 500 days of operations, the magnitude of the forces could be reduced by some minor changes in the operational mode of the reactor. There is a direct correlation between the force level and the maximum top-end free-bow, as will be discussed later in this section.

The time-histories of the forces for Cases 1 and 2 (homogeneous cores) are shown in Figs. 4 and 7. It is most useful to understand these time-histories, since the basic phenomena producing the time behavior of the forces can be more easily obtained by interpreting the results for these relatively simple cases. During the first cycle (0-250 days) the force level decreases because of creep relaxation of the forces arising from interaction of thermally bowed assemblies. During this cycle the fluence level on all assemblies is below the threshold for swelling. Thus, assembly interaction due to differentially swelled assemblies plays no role. One-half of the assemblies are replaced at 250 days. In these cases the force level is virtually unchanged by the refueling because the assemblies removed at the end of 250 days are almost as straight as the new ones. At approximately 350-400 days, irradiation-induced swelling begins to have a very pronounced effect. The assemblies at the fuel-blanket boundary have reached the fluence threshold for swelling, and differential swelling between the inboard and outboard duct walls results in large bowing of these assemblies. The forces build up more rapidly than they can be relaxed by creep effects. At 500 days those assemblies with a two-cycle residence time (those having undergone significant swelling) are removed and are replaced with straight assemblies, thus reducing the force level at the completion of refueling. During the initial portion of the third cycle the forces are reduced again due to creep but begin to increase about half way through the third cycle from the swelling of the assemblies which are in the core for their second cycle. The force levels at the end of the third cycle are significantly below those seen at the end of the second cycle and the forces are expected to remain at about the 2000 lb. level as the reactor operation continues into additional cycles. Although variations in the forces are expected during the cycle, a quasi equilibrium between the effects of irradiation-induced creep and swelling is established and results in a maximum force at about the 2000 lb. level. The forces in the homogeneous core arrangement are due primarily to the large swelling-induced bowing of the assemblies in the outer fuel rows. The effect of the thermal-gradients is seen only at the beginning of the first cycle and soon disappears due to creep relaxation in the first cycle and due to domination by swelling-induced bowing in subsequent cycles. The temperatures within the inter-core region of Case 2 act against the transmission of the forces from the outer row of fuel assemblies

to the center assembly, as is seen from the low force levels in the first cycle. The top of the second assembly contacts the top of the center assembly, while the third assembly bows outward and the fourth assembly bows inward resulting in a top-end contact between the two. These pairs of assemblies (1-2 and 3-4) act as a spring. The inward forces arising from the assemblies in the outer core region is taken up, in part, by the compression of these spring-like configurations of the assemblies in the inner core region. This effect will also be seen in the heterogeneous cores.

Before discussing the individual heterogeneous arrangements, two general observations are made in regard to the force level for the heterogeneous cores. The force levels are higher for those core arrangements with fuel in the center than those arrangements with blanket assemblies in the center. The reason for the higher forces stems from the force loading pattern that is set up in the array of assemblies, as discussed below. The second observation is that loosely-coupled heterogeneous cores have a larger number of flux and temperature gradients across their assemblies, and thus tend to have larger swelling and temperature bows and, in turn, greater assembly interactions. These two observations will be seen in the discussion of individual cases, and additional explanation will be provided for the reasons producing these situations.

The time-history for Case 3 is given in Figures 5 and 7. During the first 250 day cycle, Case 3 behaves somewhat similar to Case 1. However, during the next cycle a very high force level is created, primarily due to the bowing the fifth assembly from differential swelling. The force level during the third cycle varies between 2000 and 3000 lbs. on the central assembly and is expected to remain in that order of magnitude during subsequent cycles. The force level for Case 3 is characterized by assemblies (Row 5, Row 8) which are in both a high flux and a high flux gradient field. These assemblies tend to bow outward at the top causing an inward transmission of the force at the ACLP. The force loading pattern characterized by fuel in the center facilitates the transmission of the forces from Rows 5 or 8 to the center assembly. Since the force level above a 3000 lb. center assembly is due primarily to the bowing of the fifth assembly (2nd cycle), a small modification to the fuel management scheme in the second cycle would reduce the maximum force to about a 3000 lb. level.

Although the forces for Case 3 are higher than for other cases except for Case 5, the force level does not eliminate Case 3 from consideration at this time.

Case 4 is characterized by a small number of flux and temperature gradients across the assembly ducts. It is additionally characterized by a blanket loading in the center which reduces the transmission of forces from the outer core region towards the center. The time-history of the force, as shown in Figures 6 and 8, shows a common behavior during the first and second cycles. An unusual feature is the increase in forces upon refueling at the end of the second cycle with fresh elements. The reason for higher forces upon refueling with straight assemblies is the following: during the first two cycles of operation, creep relaxation dominates over swelling. Thus, the assemblies removed from the reactor at the end of the second cycle are bowed in a direction opposite to that produced from thermal and flux gradients across the duct during power operation. As the temperature gradients are imposed on assemblies with a reverse free-bow, they actually become straighter at full power than at refueling conditions. Thus, replacing the assemblies with a reverse free-bow with straight assemblies actually results in greater interactions of the assemblies during initial full power operations. It should be realized however, that the level of the forces are quite low, so this increase of force is not a serious problem.

Case 5 is quite similar to Case 3 in its time-history of force on the center assembly (Figs. 5 and 9). The force level at the beginning of operation is the highest of all cases and arises from the large number of temperature gradients throughout the core. Shortly after the start of the second cycle, irradiation-induced swelling causes large bowing of the assemblies, particularly in Row 6 which is exposed to both a high flux and a high flux gradient across its duct. Since the sixth assembly bows outward at the TLP and inward at the ACLP, the forces from its interaction are transmitted inward along the ACLP, a situation which results in high forces on the center assembly. The replacement of the assembly in Row 6 with a fresh assembly reduces a force level at 500 days. The time-history of force in the third cycle is characterized by the reduction in the initial part due to creep relaxation and an increase in the latter part due to the initiation of swelling bow of the assemblies with two cycles of residence time.

Case 6 is quite similar to Case 4. The forces on the center assembly are slightly higher at the beginning of operation due to the larger number of temperature gradients, as seen in Figures 6 and 9. However, the blanket loading in the center reduces the force level well below that as seen in Cases 3 and 5. Again, an increase in forces upon refueling at 500 days is due to the replacement of assemblies with a reversed bow with straight assemblies. Changes in the loading pattern during the third cycle results in virtually no force on the center assembly.

d) Duct Interaction at Non-load Pad Regions

The last performance quantity to be discussed is that of duct contact at other than the load pads. Of particular concern is duct-to-duct contact in the core region where the duct has lost its ductility due to the high irradiation. A small relative movement of the assemblies (i.e., an OBE) may result in a brittle failure of the duct in the core region, an event which assembly designers usually intend to exclude from accident analysis. Duct interaction may be seen from the equilibrium core configuration plots (Figures 10 through 30). The distance between the vertical dashed lines represents the distance between ducts in the non-load pad regions. Thus, when one solid line intersects another, the ducts would be in contact at that point. The homogeneous cores (Cases 1 and 2) do not have any problem with duct interference since they all tend to bow in the same direction. However, several cases of duct-to-duct contact are seen for the heterogeneous cores, i.e., Case 3 at 750 days, Case 5 at 250 days, 500 days and 750 days and Case 6 at 500 days. Duct-to-duct contact can be expected in cores with large flux gradients across assemblies in the inner core regions, particularly in cases where adjacent assemblies have flux gradients in the opposite direction. The existence of flux gradients within the core region is characteristic of loosely-coupled heterogeneous cores and thus duct-to-duct contact may be expected in these types of core arrangements. Tightly-coupled cores may avoid duct-to-duct contact if the core is arranged with alternate rows of fuel and blanket assemblies.

e) Summary of the Results

The study showed the core restraint performance of heterogeneous cores was approximately the same as that of homogeneous cores in regard to assembly alignment and radial displacement of the core. The force level for two heterogeneous cores was substantially higher than the homogeneous, but may be reduced by

appropriate fuel management, which may also degrade other performance quantities, e.g., burnup. Heterogeneous cores do exhibit decidedly poor performance with respect to duct-to-duct contact in the core region. This feature of many heterogeneous arrangements appears to be inherent and no corrective measures are apparent presently.

4.0 LHRCS DESIGN CASE

4.1 System Description

A loosely-coupled heterogeneous reactor and a homogeneous reactor with the configuration corresponding to the first iteration design of the ANL-AP cores⁽²⁾ were studied. The loosely-coupled core consists of three fuel zones alternating with three internal blanket zones (with a blanket region at the core center) plus a radial blanket and a row of reflector assemblies. The homogeneous reactor has 16 rows of fuel assemblies, three rows of outer radial blanket and one row of reflector. The core layout is given in Figures 31 and 32 for the homogeneous and heterogeneous cores, respectively. The assembly design, including dimensions, moments of inertia, contact stiffnesses and position of the support and load pads were taken to be the same as those of the CRBR. The fast flux distributions were taken from R-Z geometry data provided by the ANL-AP Division, and imposed upon a radial row of assemblies. This was recognized to be only an approximation, but was determined by the limitations inherent to the two-dimensional structural analysis code used. The relative flux distributions are given in Figures 33-35 for the homogeneous and heterogeneous cores. The temperature distributions presented in Table VIII were provided by ANL-AP.

4.2 Discussion of the Results

Table IX lists the maximum contact forces and pre-bow for the two ANL-AP cores under consideration; the results for the heterogeneous core are obtained with both the beginning-of-life and end-of-equilibrium-cycle fluxes. A refueling scheme was adopted whereby one-half of the fuel and internal blanket assemblies in each row were replaced with fresh ones every 250 days of operation. The maximum forces occur at the core center row in the homogeneous reactor and at Rows 4 to 6 in the loosely-coupled one. It is seen that the heterogeneous core experiences forces which are comparable to those of the homogeneous reactor at the beginning of operation. At the end of the equilibrium cycle, however the heterogeneous core layout results in lower forces, usually ~ 500 lbs., compared with ~ 1100 lbs. for the homogeneous core. In general, the ANL-AP cores appear to be under less severe load conditions than the six generic cores studied earlier and described above, as shown by a comparison of Tables VI and IX. This can

be attributed, in part, to the smaller temperature gradients obtained in the AP cores. The only exception is that of the generic Case IV, which exhibits the lowest forces, in spite of large thermal gradients at core/blanket interfaces. This seems to suggest again that a suitable arrangement of the blanket zones may be an effective way of reducing the mechanical loading of the assemblies even in the face of severe thermal conditions.

The equilibrium core configurations under full power conditions at the end of three successive cycles are presented in Figures 36-38 for the homogeneous core, in Figures 39-41 for the heterogeneous core (BOL) and in Figures 42-44 for the heterogeneous core (EQEC). The loading patterns are similar to those of its counterpart in the generic cases, i.e., homogeneous- Case 1 and heterogeneous- Case 6. The free-bow distortion of the assemblies in the ANL-AP cores is not as large as in the generic cases so the force level is lower and duct-to-duct contact is absent.

5.0 CONCLUSION

The generic cases selected in this study contained the key features of the homogeneous and various heterogeneous core arrangements which are important in determining core restraint performance. The scoping-type of two-dimensional analyses using estimated fluxes and temperature data provided relative performance characteristics of homogeneous and heterogeneous cores. The two types of core performed approximately the same in regards to assembly alignment and radial displacement of the core zone. Some heterogeneous arrangements exhibit higher force levels, although not sufficiently higher to drop them from further consideration. Most heterogeneous cores were calculated to have extensive duct-to-duct contact in the core region. Maintaining the present core design criterion of no contact would be a severe handicap for many heterogeneous core arrangements.

The analysis of the LHRCS design provided by ANL-AP confirmed the general performance of one arrangement of heterogeneous core. The assembly interactions were somewhat less than expected, probably due to highly uniform temperature data provided.

6.0 REFERENCES

1. B. K. Cha and G. A. McLennan, "NUBOW-2D Inelastic: A Fortran Program for Static Two-dimensional Structural Analysis of Bowed Reactor Cores, Including Effects of Irradiation Creep and Swelling," ANL-77-45.
2. Private Communications, W. P. Barthold to J. F. de Paz, April, 1977.

TABLE I Assembly Arrangement (F = Fuel, B = Blanket, R = Reflector) and Temperature Gradients (Positive for Outward Thermal Bowing) for the Six Generic Cases

<u>Case/Row</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>15</u>
1	F	F	F	F	F	F	F	F	F	B	B	B	R	R	R
$\Delta T =$	0	0	0	0	0	0	0	50	100	50	0	0	0	0	0
2	F	F	F	F	F	F	F	F	F	B	B	B	R	R	R
$\Delta T =$	0	-50	50	-50	50	-50	50	50	100	50	0	0	0	0	0
3	F	F	B	F	F	B	F	F	B	F	B	B	B	R	R
$\Delta T =$	0	100	0	-100	100	0	-100	100	0	100	50	0	0	0	0
4	B	B	F	B	F	B	F	B	F	F	B	B	R	R	R
$\Delta T =$	0	-100	0	0	0	0	0	0	-100	100	50	0	0	0	0
5	F	F	B	B	F	F	B	B	F	F	B	B	R	R	R
$\Delta T =$	0	100	100	-100	-100	100	100	-100	-100	100	50	0	0	0	0
6	B	B	F	F	B	B	F	F	F	B	B	B	R	R	R
$\Delta T =$	0	-100	-100	100	100	-100	-100	0	100	50	0	0	0	0	0

TABLE II Residence Times (in operating cycles) of Assemblies
at the End of the First Four Cycles in Cases 1 and 2

Row	(Residence Time (# of cycles))			
	EOC1	EOC2	EOC3	EOC4
1	1	2	1	2
2	1	1	2	1
3	1	2	1	2
4	1	1	2	1
5	1	2	1	2
6	1	1	2	1
7	1	2	1	2
8	1	1	2	1
9	1	2	1	2
10	1	2	1	2
11	1	2	3	4
12	1	1	3	4

TABLE III Residence Times (in operating cycles) of Assemblies
at the End of the First Four Cycles for Case 3

Row	Residence Time (# of cycles)			
	EOC1	EOC2	EOC3	EOC4
1	1	2	1	2
2	1	1	2	1
3	1	2	1	2
4	1	1	2	1
5	1	2	1	2
6	1	1	2	1
7	1	2	1	2
8	1	1	2	1
9	1	2	1	2
10	1	1	2	1
11	1	2	1	2
12	1	2	3	1
13	1	2	3	1

TABLE IV Residence Times (in operating cycles) of Assemblies
of the End of the First Four Cycles for Cases 4a and 4b

Row	Residence Time (# of cycles)							
	Case 4a				Case 4b			
	EOC1	EOC2	EOC3	EOC4	EOC1	EOC2	EOC3	EOC4
1	1	1	2	1	1	1	2	1
2	1	2	1	2	1	2	1	2
3	1	1	2	1	1	1	2	1
4	1	2	1	2	1	2	1	2
5	1	1	2	1	1	2	1	2
6	1	2	1	2	1	1	2	1
7	1	1	2	1	1	1	2	1
8	1	2	1	2	1	2	1	2
9	1	1	2	1	1	2	1	2
10	1	2	1	2	1	1	2	1
11	1	2	1	2	1	2	1	2
12	1	2	3	1	1	2	3	1
13	1	2	3	1	1	2	3	1

TABLE V Residence Time (in operating cycles) of Assemblies
at the End of the First Four Cycles in Cases 5 and 6

Row	Residence Time (# of cycles)			
	EOC1	EOC2	EOC3	EOC4
1	1	1	2	1
2	1	2	1	2
3	1	1	2	1
4	1	2	1	2
5	1	1	2	1
6	1	2	1	2
7	1	1	2	1
8	1	2	1	2
9	1	1	2	1
10	1	2	1	2
11	1	2	1	2
12	1	2	3	1
13	1	2	3	1

TABLE VI Maximum Contact Forces and Top-end Free-bow at the End of the First Three Cycles for the Six Generic Cases

Case	Max. Contact Force (lbs.)			Top-end Free-bow (in)*		
	EOC1	EOC2	EOC3	EOC1	EOC2	EOC3
1	135	2693	1921	-0.388	0.405	0.621
2	120	3343	1703	0.520	0.838	0.951
3	412	4742	3199	0.876	0.857	1.192
4a	151	404	226	0.769	0.742	0.777
4b	151	413	230	0.769	0.618	0.756
5	719	5992	1743	0.913	1.235	-1.046
6	170	356	706	0.854	1.134	-1.080

* A negative number signifies an inward direction.

TABLE VII Average Radial Displacement of Assemblies
in Outer Two Fuel Rows Upon an Increase
from Zero to Full Power at the End of the
First Three Cycles for the Six Generic Cases

Case	Average Displacement (in)*		
	EOC1	EOC2	EOC3
1	-.0736	-.1057	-.0495
2	-.0119	-.1969	-.0803
3	-.0625	.0337	.0367
4a	.0106	-.0347	.0078
4b	.0106	.0086	-.0516
5	.0219	.1924	.0476
6	-.0512	-.0472	+.0039

* A negative value signifies inward displacement.

TABLE VIII Assembly Exit Temperatures and Across-flat ΔT
for the ANL-AP Homogeneous and Heterogeneous
(BOC) Cores.

Row	Homogeneous Core		Heterogeneous Core (BOC)	
	Exit Ass'y °F	Max. ΔT	Exit Ass'y °F	Max. ΔT
1	709	0	675 682	0
2	978	- 2	710	- 8
3	974	4	744	-20
4	979	- 1	1005	-43
5	980	- 3	980	-15
6	980	1	985	1
7	978	5	739	19
8	974	1	723	34
9	965	1	955	-22
10	953	8	993	-28
11	948	4	1007	- 3
12	959	7	984	4
13	970	22	713	43
14	947	7	732	27
15	896	25	969	-30
16	863	35	958	-32
17	759	56	1017	- 2
18	654	4	968	- 4
19	659	4	722	43
20	649	3	722	40
21			659	30
22				10

TABLE IX Maximum Contact Forces and Top-end
Free-bow at the End of the First Three
Cycles for Three Cores in the LHRCS

Type of Core	Max. Contact Force (lbs.)			Top-end Free-bow (in)*		
	EOC1	EOC2	EOC3	EOC1	EOC2	EOC3
Homogeneous	89	429	1104	0.141	0.697	0.894
Heterogeneous BOL	90	322	449	0.186	-0.496	-0.868
Heterogeneous EOEL	66	345	489	0.356	-0.388	-0.578

* A negative value signifies an inward bow.

Fig. 1 Radial Flux Distribution for Cases 1 and 2.

Fig. 2 Radial Flux Distribution for Cases 3 and 4.

Fig. 3 Radial Flux Distribution for Cases 5 and 6.

Fig. 4 Time-history of the Force on Center Assembly for Cases 1 and 2.

Fig. 5 Time-history of Forces on Center Assembly for Cases 3 and 5.

Fig. 6 Time-history of Forces on Center Assembly for Cases 4a, 4b and 6.

Fig. 7 Time-history of Forces on the Restraint Ring for Cases 1, 2 and 3.

Fig. 8 Time-history of Forces on the Restraint Ring for Cases 4a and 4b.

Fig. 9 Time-history of Forces in Restraint Ring for Cases 5 and 6.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 10 Equilibrium Core Configuration at 250 Days for Case 1.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 11 Equilibrium Core Configuration at 500 Days for Case 1.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 12 Equilibrium Core Configuration at 750 Days for Case 1.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 13 Equilibrium Core Configuration at 250 Days for Case 2.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 14 Equilibrium Core Configuration at 500 Days for Case 2.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 15 Equilibrium Core Configuration at 750 Days for Case 2.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 16 Equilibrium Core Configuration at 250 Days for Case 3.

CCRE CONFIGURATION AT 500.0 DAYS

Fig. 17 Equilibrium Core Configuration at 500 Days for Case 3.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 18 Equilibrium Core Configuration at 750 Days for Case 3.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 19 Equilibrium Core Configuration at 250 Days for Case 4a.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 20 Equilibrium Core Configuration at 500 Days for Case 4a.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 21 Equilibrium Core Configuration at 750 Days for Case 4a.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 22 Equilibrium Core Configuration at 250 Days for Case 4b.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 23 Equilibrium Core Configuration at 500 Days for Case 4b.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 24 Equilibrium Core Configuration at 750 Days for Case 4b.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 25 Equilibrium Core Configuration at 250 Days for Case 5.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 26 Equilibrium Core Configuration at 500 Days for Case 5.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 27 Equilibrium Core Configuration at 750 Days for Case 5.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 28 Equilibrium Core Configuration at 250 Days for Case 6.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 29 Equilibrium Core Configuration at 500 Days for Case 6.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 30 Equilibrium Core Configuration at 750 Days for Case 6.

Fig. 31 Core Layout of ANL-AP Large Homogeneous Core.

Fig. 32 Core Layout of ANL-AP Loosely-Coupled Heterogeneous Core.

Fig. 33 Relative Radial Flux Distribution for ANL-AP
Homogeneous Core (Level II, EOEC).

Fig. 34 Relative Radial Flux Distribution for ANL-AP Heterogeneous Core (Level II, BOL).

Fig. 35 Relative Radial Flux Distribution for ANL-AP Heterogeneous Core (Level II, EOEC).

CORE CONFIGURATION AT 250.0 DAYS

Fig. 36 Equilibrium Core Configuration at 250 Days for Homogeneous Core.

CORE CONFIGURATION AT 500.0 DAYS

Fig. 37 Equilibrium Core Configuration at 500 Days for Homogeneous Core.

CORE CONFIGURATION AT 750.0 DAYS

Fig. 38 Equilibrium Core Configuration at 750 Days for Homogeneous Core.

CORE CONFIGURATION AT 250.0 DAYS

Fig. 39 Equilibrium Core Configuration at 250 Days for Heterogeneous Core (BOL).

CORE CONFIGURATION AT 500.0 DAYS

Fig. 40 Equilibrium Core Configuration at 500 Days for Heterogeneous Core (BOL).

CORE CONFIGURATION AT 750.0 DAYS

Fig. 41 Equilibrium Core Configuration at 750 Days for Heterogeneous Core (BOL).

CORE CONFIGURATION AT 250.0 DAYS

Fig. 42 Equilibrium Core Configuration at 250 Days for Heterogeneous Core (EOEC).

CORE CONFIGURATION AT 500.0 DAYS

Fig. 43. Equilibrium Core Configuration at 500 Days for Heterogeneous Core (EOEC).

CORE CONFIGURATION AT 750.0 DAYS

Fig. 44 Equilibrium Core Configuration at 750 Days for Heterogeneous Core (EOEC).