CONF-880911--32

Paper submitted for presentation at the 1988 International Reactor Physics Conference, September 18-21, 1988, in Jackson Hole, Wyoming.

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CONF-880911--32

DE89 005865

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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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ABSTRACT

Experiments done in several LMR-type critical assemblies simulated core axial expansion, core radial expansion and bowing, coolant expansion, and control driveline expansion. For the most part new experimental techniques were developed to do these experiments. Calculations of the experiments basically used design-level methods, except when it was necessary to investigate complexities peculiar to the experiments. It was found that these feedback reactivities generally are overpredicted, but the predictions are within 30% of the experimental values.

INTRODUCTION

Current innovative liquid-metal-cooled fast reactor (LMR) designs rely, to a large extent, on expansion and bowing reactivity feedback to avoid core-disruptive accidents.[1] Reactor designers must know how accurate their predictions are for both the magnitude of the material displacements and the reactivity effect of a given displacement. Critical experiments can provide tests to assess the latter. This paper describes such experiments and analyses performed over the last four years at the Zero Power Physics Reactor (ZPPR).

The inherent feedback phenomena included here are core axial expansion, core radial expansion and bowing, coolant density reduction, and control driveline expansion. Radial expansion and bowing are closely related in the sense that they both result in a radial displacement of reactor material. Consequently, to a large degree, both can be addressed in the same experiment, and we will often refer to them as a single entity, radial expansion/bowing. They have received the most attention at ZPPR, partly because radial expansion is the single most important feedback in recent innovative designs, and partly because they are difficult to simulate.[1] There has been substantial emphasis on axial expansion but little has been done with coolant expansion and control driveline expansion.

It is not simple to devise critical experiments that simulate the bowing or expansion displacements that occur in a power reactor. Expansion is characterized by small density changes over a large volume. The ability to mock up such displacements is limited by the fixed dimensions and discrete compositions of the materials that make up a ZPPR critical assembly. Many of the simulations make use of the fact that the target displacements usually constitute first-order perturbations; by introducing discrete but first order perturbations in composition and/or position the essential features of expansion or bowing are simulated. The experimental approaches to this problem have been evolving over the several years of work discussed here.

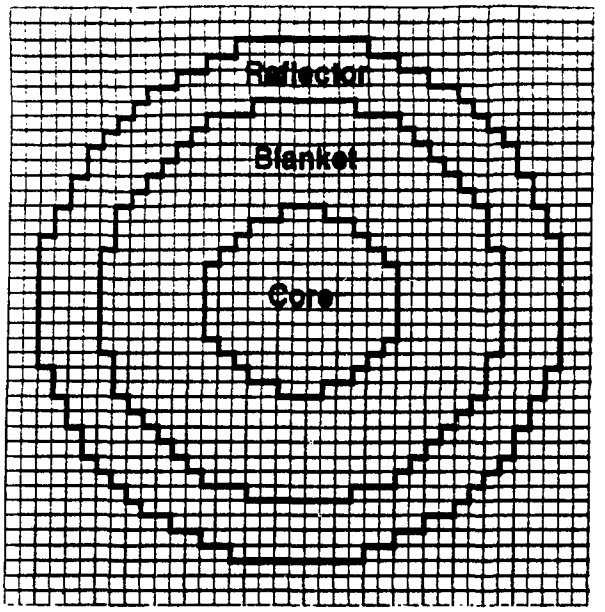

Fig. 1 ZPPR-12 Assembly Interface Diagram

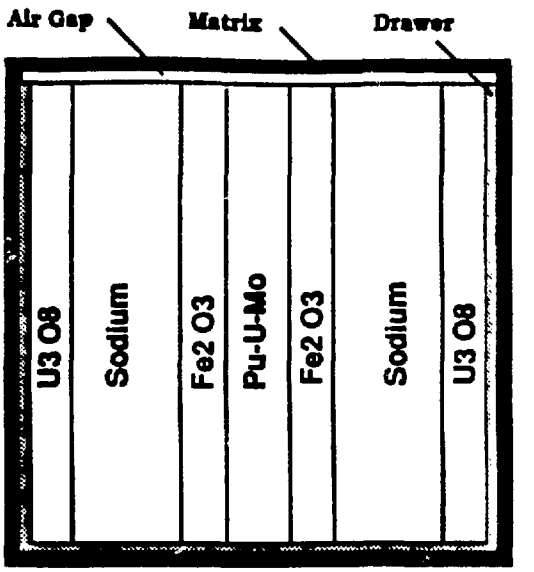

Fig. 2 Typical Core Unit Cell

It is important that the simulation avoid features not present in the feedback phenomenon that cannot be calculated with confidence. Otherwise it is difficult to know how much of the calculational error is related to the phenomenon of interest and how much is due to the peculiarities of the experiment. In fact a number of experiments are considered unsuccessful and are omitted here because they were discovered to violate seriously this requirement.

To understand the simulation techniques described in subsequent sections, some background about how ZPPR critical assemblies are constructed is needed. An XY (radial) slice through a simple assembly is depicted in Fig. 1. Each box represents a 5.5 cm square matrix tube containing a plate-loaded drawer. One drawer is loaded in each half of the split matrix. An axial segment of a matrix tube with its loaded drawer constitutes a unit cell. The XY cross section of such a cell is shown in Fig. 2. The columns in Fig. 2 are 5.08 cm-tall plates of the various materials that comprise a reactor region. Essentially any LMR composition can be matched reasonably well by the homogenized composition of one, or a mix of two, ZPPR unit cells.

The experiments were performed in several different assemblies. These assemblies provided a variety of environments for testing feedback reactivity calculations. ZPPR-13D was a large, loosely coupled, radially heterogeneous assembly with three fuel rings.[2] It had mixed oxide fuel. ZPPR-15 had a two enrichment zone, metal-fueled core of about 330 MWe size.[3] The fissile species was plutonium in Phases A and B, and primarily uranium in Phase D. ZPPR-17A was an axially heterogeneous design of about 700 MWe size.[4] It had mixed oxide fuel.

Two methods were used to determine the reactivity associated with the material motion in these experiments. If the signal is large, a static approach is used in which the subcriticality of the assembly before and after the material motion are measured. The subcriticality is determined by the modified source

multiplication technique.[5] When the signal is small, some kind of oscillator device is used at one matrix location to introduce and remove the material shift cyclically; the reactivity is inferred from the reactor power history using an inverse kinetics algorithm.[6]

Similarly, designers use one of two basic approaches to compute the feedback reactivity. In the k-difference approach the eigenvalues for the reactor with and without the feedback change are computed directly. This is applicable to relatively large changes such as uniform radial expansion. The other approach is to use first order perturbation theory (FOP).

In the FOP approach material reactivities are computed as function of position and this is used to determine the reactivity from moving material. Since only mesh-average reactivities are known, there is an issue of how to deal with motions that are small compared to the mesh spacing. For our standard FOP analysis a linear interpolation approximation is used. It is assumed that the mesh-average reactivity equals the mesh center reactivity and that reactivities vary linearly between mesh centers.

There are a number of features that are common to most or all of the calculations of these experiments. Generally these features match those used by designers at ANL. Using the MC^2-2/SDX processing codes, 21 group cell average cross sections were derived from ENDF/B Version 5.2 data.[7] Calculations of ZPPR-13D core expansion experiments were slightly different in that 28 group cross sections were obtained from Version 4 data. Beta-effective values, used to convert calculated reactivity in delta k/ k units to dollar units, are based on ENDF/B Version 5 delayed neutron data. Assembly eigenvalue calculations were usually done in the finite-difference diffusion theory approximation with an XYZ geometry model and about a 5 cm mesh in each direction. In a few cases (ZPPR-17A and some ZPPR-13D calculations) nodal diffusion theory was used. The node spacing was constrained by geometry considerations to one node per drawer in XY, but the nodes were as large as 15 cm axially.

Cell heterogeneity and neutron streaming are more pronounced in plate critical assemblies than in power reactors. Cell heterogeneity was treated in the cross section processing. Streaming was accounted for by using Benoist diffusion coefficient modifiers.

Some additional critical experiments jargon is used throughout this paper. Worth is used for the reactivity change associated with some perturbation. The measure of calculational accuracy is the C/E, the ratio of calculated to measured values. Diluent refers to all nonfissile constituents of a core composition.

CONTROL DRIVELINE EXPANSION

This feedback occurs due to different axial expansion of the core and control driveline in slow transients. In the most recent designs the cores are made to have a minimal reactivity swing over the burnup cycle. Consequently the rod tips are always near the core-blanket interface where the reactivity effect from expansion is relatively small. In earlier reactor designs the control rods were deeply inserted into the core at the beginning of the fuel cycle, leading to a more substantial feedback effect.

Design calculations treat this feedback using a constant reactivity coefficient. Typically the coefficient is determined from the eigenvalue change resulting from inserting the control rod bank one or two centimeters beyond its nominal position. This single coefficient is used for whatever bank motion occurs in the

transient calculations. Two eigenvalue calculations are performed, typically using finite-difference diffusion theory. The mesh spacing is identical in the two calculations. For the experiment analysis we have followed this design procedure.

The experiments were done with a bank of six rods in the second fuel ring of ZPPR-13D. The bank was moved in static measurements in the smallest possible increments, 2.54 cm, in order to provide expansion coefficients that correspond to the design analysis method. Using this increment, the rod bank tips covered the range from 10.16 cm into the blanket to 10.16 cm into the core. Then a few larger steps were used to reach full insertion.

From these data and, in addition, ZPPR operational control rod data, the control worth profile was characterized. The worth gradient (expansion coefficient) was seen to change most rapidly near the core-blanket interface. Consequently about a 10% error would result from using, on one side of the core-blanket interface, the coefficient that corresponds to the other side. For designs where the rod bank is deeply inserted this is not a problem since the coefficient is nearly constant from core center to about 10 cm from the boundary.

Some results are shown in Table I. Because the calculations are very expensive, the only calculated rod tip positions are 0.00, 2.54, 7.62, 10.16 and 91.44 cm, where 0.00 corresponds to the the rod bank tips being at the core-blanket interface. The insertion worths are relative to the bank tips at 0.00 cm. From the insertion worth C/Es it is clear that the calculational error at the core-blanket boundary is different from the error for deeper insertions. Another observation is that the C/E for full insertion is smaller than is typical for full insertion worths in other cores. When this worth was recomputed using nodal transport theory, which reduces the mesh and transport errors, the insertion worth C/E increased almost 4% to 0.935. (This is 4% lower than the C/E from a bank of 12 rods; the difference is due to the azimuthal asymmetry of the rod worth C/Es.)

TABLE I

Control Driveline Expansion Results

Rod Bank Insertion (cm)	2.54	7.62	10.16	91.44
Exp. Insertion Worth (¢)	-6.49 ± 0.20	-25.70 ± 0.38	-37.57 ± 0.48	-662.79 ± 6.36
Insertion Worth C/E	1.066 ± 0.033	0.866 ± 0.013	0.912 ± 0.012	0.897 ± 0.009
Position Change (cm)	0.00 to 2.54	2.54 to 7.62	7.62 to 10.16	
Exp. Expansion Coeff. (¢/cm)	-2.56 ± 0.08	-3.78 ± 0.07	-4.67 ± 0.19	
Expansion Coeff. C/E	1.066 ± 0.033	0.798 ± 0.016	1.011 ± 0.041	

The C/Es for the expansion coefficient vary by about 25%. There is not a uniform C/E trend with distance from the core-blanket boundary, and more data points would be needed to clarify this behavior. It is likey that the C/E variation is related to the inaccuracy of diffusion theory near material boundaries.

A factor to consider in trying to generalize these results for design applications is the extent to which ZPPR-13D is an appropriate testbed. This core was very loosely coupled azimuthally. Consequently many parameters in this assembly, perhaps including these expansion coefficients, are unusually sensitive to methods and modeling errors. It is likely that C/Es from a more typical core would be at least as close to unity as the C/Es found here.

COOLANT EXPANSION

Coolant expansion involves a small sodium density change over a very large volume. An attempt to simulate coolant expansion in one core cell was made in ZPPR-17A. A new device called a plate column oscillator was used to withdraw a column of sodium plates from a cell in the outer core. By doing the same thing to a matched column of empty cladding, the sodium withdrawal reactivity was inferred. The column contained half the cell's sodium.

The column can be withdrawn axially any desired distance, and by using a sufficiently small withdrawal, the perturbation, like true coolant expansion, would be first order. Unfortunately, a widthdrawal of at least 5 cm was needed to get adequate experimental precision. The signal for this withdrawal was just 0.0135 cents (±6.2%), however, and even the largest withdrawal, 30 cm, was only a 0.0543 cent (± 1.4%) perturbation.

Different levels of sophistication were tried in analyzing this experiment. Using our standard FOP method, a C/E of 1.41 was obtained. This C/E is an average for withdrawals ranging from 5 to 30 cm. Although the perturbations were too small to cause a global flux change, the disruption of the intracell flux could be significant. Accordingly, we computed cell average cross sections for both the unperturbed and perturbed cell configurations. Both of these cross section calculations used the same group- and region-dependent bucklings from the reference eigenvalue solution to account for the fact that the experiment was surrounded by a normal core. Applying these cross sections reduced the average C/E to 1.32. Finally, a factor was applied to correct for the fact that flux-weighted cross sections do not account properly for cell heterogeneity in an adjoint flux calculation.[8] With this factor, the C/E was reduced further, to 1.10. Both of these corrections account for phenomena that are much more important in a ZPPR assembly than in a power reactor. It would be useful to try a fixed-source approach, as was done for the ZPPR-15A fuel shifting experiment (see below), which is a less approximate way of accounting for both of these effects. Accounting for the adjoint error caused by using flux weighting in the energy collapse of cross sections should produce an additional improvement in the C/E.[9]

It must be kept in mind that this experiment provides just one data point. It is well known, both from traditional sodium voiding experiments and from small-sample worth measurements, that the C/E can be expected to vary strongly with position in the core as well as with reactor type. There is a wealth of large volume sodium voiding data but, unfortunately, its applicability to coolant expansion is limited because these voidings were major perturbations.

RADIAL EXPANSION/BOWING

Uniform Expansion

In uniform radial expansion there is a small decrease in the core density and a corresponding increase in core radius. The single most important component of this change is the displacement of fissile material. With the main focus on this component, an attempt was made to simulate uniform radial expansion in ZPPR-13D. The idea was to take fuel plate columns from a few interior core cells and use them to convert a few radial blanket cells at the core-blanket interface into core cells. This did produce the desired fissile material motion but also resulted in untypical diluent changes. (In the interior there was a loss of Fe and a small gain of uranium and oxygen; at the core edge there was a larger loss of uranium and oxygen, and a gain of sodium and iron.)

The design method for determining the uniform radial expansion coefficient is to compute directly the eigenvalues for the normal and expanded configurations. We used the same approach to analyze this experiment. Nodal diffusion theory was used and the resulting C/E is 1.048 ± 0.015.

Fuel Shifting

In the fuel shifting experiments there was motion of fuel alone, and the motion occurred within a core cell. By modifying a cell to include a column of empty fuel cladding, and then interchanging the clad fuel and empty cladding columns, radial motion of just the fuel was achieved. This experiment was done three times, each in a different ZPPR-15 configuration. It was always done in a core cell adjacent to the radial blanket, using the drawer oscillator technique.[10]

The C/E results obtained with our standard analysis are 1.06 ±0.01 for ZPPR-15A, 1.33 ±0.01 for ZPPR-15B and 1.42 ±0.02 for ZPPR-15D. The fuel in ZPPR-15A and ZPPR-15B was a plutonium-uranium-molyldenium metal alloy (28% Pu and 69% depleted uranium). In ZPPR-15D it was uranium metal enriched to 93%.

All-Plate Shifting

In this scheme plate columns of a cell were rearranged such that most of the cell moved radially a small distance. To achieve this it was necessary to move a narrow, low worth section of the cell a much larger distance in the opposite direction. As an illustration, imagine that in Fig. 2 the plate column at the right edge of the cell was removed, the remaining columns were shifted to the right and then the removed column was installed at the left edge. This kind of experiment was done in three different assemblies. Our standard FOP analysis method was used to obtain the C/Es in this subsection.

In ZPPR-13D most of the cell shifted 0.95 cm radially outward while a clad sodium column plus an iron oxide column shifted 4.13 cm inward. The zone of shifted cells eventually spanned the width of the outermost fuel ring, but the shifting occurred in steps. The C/E is 1.17 ± 0.09 for shifting near the center of the ring, 1.33 ± 0.07 for shifting cells at the outer edge of the ring, and 1.18 ± 0.06 for shifting in the entire zone.

In ZPPR-15B the drawer oscillator was used for all-plate shifting in the same core edge cell where the fuel shifting was done. Most of the cell shifted 0.95 cm radially inward while a clad sodium column plus a stainless steel column shifted 4.13 cm outward. The C/E for this measurement is 1.16 ± 0.01.

In ZPPR-17A the shifting occurred in a zone of cells that spanned much of the radial extent of the outer core. To make the shift look as much as possible like bowing, the only material moving counter to the rest of the cell was a 0.64 cm-wide clad sodium column. The C/E for this experiment is 1.14 ± 0.04.

Bowing Oscillator

In order to simulate bowing more closely than is possible with the plate shifting technique, the bowing oscillator was devised. With the bowing oscillator the entire drawer with its plate contents is raised and lowered the distance allowed by the cooling air gap that is always present above a drawer (see Fig. 2). The displacement is about 0.13 cm, which is in the range of bowing motion, whereas the motion is much greater with plate shifting. The displacement of interstitial sodium counter to the main cell motion is missing with the bowing

oscillator, but the unwanted counter motion of other diluents (steel cladding at a minimum) that occurs with plate shifting is avoided.

The bowing oscillator was used one cell away from the edge of the ZPPR-17A core. Using our standard FOP analysis gives a C/E of 1.34 ± 0.05.

ISSUES IN EXPANSION/BOWING EXPERIMENTS

The C/Es from the radial expansion/bowing experiments have a wide range of values and are quite far from unity in a few cases. A number of issues that could contribute to this situation, or that affect the applicability of the C/Es to power reactors, have been investigated.

Proximity to Core/Blanket Boundary

In a power reactor the core subassemblies adjacent to the radial blanket often make the largest contribution to radial expansion/bowing feedback. However, there are two reasons why the edge cell of a ZPPR core is not the best location for these experiments. One is that the most important location, the place where the worth gradient is maximum, is usually at the second or third drawer in from the core boundary. (The width of a subassembly is more than twice the width of a ZPPR cell.) The more important reason is that the edge cell location presents difficulties - both experimental and calculational - that are not typical of the rest of the core.

Strongly nonuniform worth gradients have been observed experimentally at the core edge. In an edge cell location in ZPPR-15D a bundle of 47% enriched uranium oxide pins was shifted and tilted in various ways. Comparing the worths of these motions it was inferred that the worth gradient varied by 33% over a distance of less than 1 cm. This is an extreme case (the gradient variations were exacerbated by composition and geometry mismatches with the rest of the core) but still it indicates the existence of a difficult situation. Experimentally this means that even small material position uncertainties can translate into sizeable worth uncertainties; this has not been included in the quoted uncertainties. To calculate this kind of worth variation may require more sophisticated methods than are practical for design work.

The ZPPR-13D all-plate shifting results demonstrate that calculational accuracy degrades at the core edge cell. Recall that shifting in all the cells across the width of the fuel ring has a C/E of 1.18 while shifting in just the edge cells has a C/E of 1.33.

Core Nonuniformities

Except for depletion effects, the composition is uniform within a given region of a power reactor. In order to match this composition well on average, there is usually a mixture of single-fuel-column (SFC) and double-fuel-column (DFC) cell types in a ZPPR core. Unfortunately this mixture leads to worth gradient variations not present in a power reactor. The only case where a zone of just one cell type (DFC) was created for the experiment was ZPPR-13D all-plate shifting.

Calculations for the ZPPR-17A all-plate shifting experiment provide an illustration of this. For the fissile material the magnitude of the material worth gradient is about 10% higher in a DFC cell than in a corresponding SFC cell. For diluent materials the gradient magnitude is much lower in a DFC cell, e.g. about a factor of 2 lower for clad sodium.

The large difference in fuel shifting C/E between ZPPR-15A and ZPPR-15B is probably related to differences in the cell type-induced gradients combined with the core edge location. The two cores were very similar except for a partial Zr-for-stainless steel substitution in the inner core, which should be unimportant here, and a different SFC-DFC arrangement near the core edge. The edge cell type for the experiments in fact was SFC in ZPPR-15A and DFC in ZPPR-15B. The difference between the measured fuel shifting worths, scaled to the same displacement is about 30%, but the calculated worth gradients differ by only 13%.

Local Flux Change

Our standard FOP analysis assumes that there is no flux change induced by the material motion. Such a small perturbation is unlikely to produce a substantial global flux shift but a flux change in the shifting cell is more probable. This is another issue that is more important in the experiments than in the power reactor, since the cell disturbance is greater in the experiments.

The in-cell flux distribution is implicit in the cell average cross sections. Accordingly, for the ZPPR-17A plate shifting, we accounted for the local flux change by computing cell average cross sections for both the pre-shift and post-shift cells. When this cross section change is included the C/E drops 17% to 0.97.

An experiment was done in ZPPR-13D to confirm that cell heterogeneity changes accompanying all-plate shifting is not a severe problem. The idea was to do, in the presence of small gradients, the same kind of plate shifting as was done in the strong gradients of the outer fuel ring. In the small gradient case, the cell heterogeneity effect would be a much larger fraction of the total signal. Thus a large C/E difference between these cases would indicate a heterogeneity-related problem. The small gradient cases was done at the center of the middle fuel ring. It has a C/E of 1.04 ±0.11, which is only one standard deviation from the corresponding outer fuel ring result (1.17±0.09).

Approximating Worth Gradients

In our standard FOP calculations the linear interpolation (LI) approximation was used to infer worth gradients from the mesh-average worths. For some of the experiments we have tried other approximations.

A new approximation being used by designers to compute bowing reactivity is the CTHS (corrected triangular homogenization scheme) method of Finck, which we will refer to as linear extrapolation (LE).[11] LE is very similar to LI, the difference being that in LE, for a pair of mesh cells, the linear variation between mesh centers is extrapolated to the edges of the mesh cells. Although it would give different values near the cell edge, depending on which mesh cells are paired, this ambiguity is avoided by treating the 6 triangles associated with a hexagonal subassembly as a set; opposing triangles are paired. The motivation for using this approximation is that it is simpler to implement than LI, since only the mesh cells of the moving subassembly are involved and not any neighbors. In applying LE to the experiments where material shifting occurs within a cell, the appropriate pair of meshes is formed by dividing the core unit cell into two mesh intervals in the direction of motion.

The CTHS method replaces an older scheme, THS, at the heart of which is a piecewise constant (PC) approximation.[11] (The THS also includes a cumbersome flux recalculation, but this correction is of secondary importance compared to the implicit PC approximation.) The PC approximation treats worths as constant within a mesh volume, i.e., a histogram shape is assumed.

As just alluded to, the accuracy of these approximations depends on the mesh size. Both the mesh and gradient approximations are needed for a complete description of the method. We do this by combining the gradient approximation abbreviation with a mesh identifier, FC for full cell and HC for half cell, e.g. FCLI. Recall that FCLI was used in our standard FOP calculations. The experiments provide less of a challenge for these approximations than do power reactor calculations in the sense that the mesh spacing is smaller for a given approximation in the experiment. (ZPPR cell width is 5.5 cm while a subassembly is about 15 cm across.)

The accuracy of these methods was compared using the ZPPR-17A experiments. The results are shown in Table II. The plate shifting C/Es there include the correction for the cell heterogeneity change discussed in the previous subsection. (The cell's heterogeneity does not change in the bowing oscillator experiment.) There is about a 3% improvement in the accuracy of the LI approximation when the mesh spacing is halved. The LI and LE predictions are almost the same for the plate shifting and this is what would be expected for power reactors. The 5% difference observed for the bowing oscillator experiment is a manifestation of gradient fluctuations caused by the SFC-DFC nonuniformity of the ZPPR core. (The bowing was in a single cell, but the mix of SFC and DFC cells involved in the plate shifting zone washed out the fluctuations.) The piecewise constant approximation is clearly a poor choice, giving worths that are about half as large as with the other methods.

TABLE II

Effect of Gradient Approximations for ZPPR-17A Experiments

Method	C/E	
	Plate Shift	Bowing Osc.
FCLI	0.971[a]	1.318
HCLI	0.995	1.273
HCLE	1.006	1.220
HCPC	0.561	0.660

[a]Constructed from flux solutions that had HC mesh.

Other Methods Improvements

Among the possible analysis improvements that have not been discussed is the use of transport theory to compute the reactor fluxes and transport perturbation theory to get motion worths. This global transport effect was calculated for the ZPPR-17A bowing oscillator experiment using a two-dimensional model. Using an S4 quadrature and fine mesh, the bowing worth was 3.2% larger than the worth from nodal diffusion theory. This is probably a representative result except near material interfaces, where a larger correction can be expected.

An attempt also was made to compute for this experiment, the effect of global flux redistribution, that is the FOP error, using the old design method (see PC approximation above). The bowing worth was 4.5% larger by exact perturbation theory than by FOP, but the percentage effect would be about half as large for the more accurate gradient

effect would be about half as large for the more accurate gradient approximation methods, since their FOP worths are about twice as large.

The effect of mesh spacing on the flux and adjoint solutions, as distinct from interpolation accuracy, can be significant. Reducing the spacing from FC to HC for the bowing oscillator calculation reduced the worth about 1%, using the FCLI gradient approximation in both cases. But this was with the nodal approximation and was not at the core edge; because it inherently has a larger spatial truncation error, few percent errors should be expected with the finite-difference approximation, and probably somewhat larger errors at the core edge cell.

An improvement that should be investigated is the use of bilinearly weighted cross sections. This cross section collapsing scheme is necessary to preserve worths rigorously. Wade and Bucher found in one assembly that the error from flux weighting cross sections in the energy collapse was less than 1% for fissile, fertile and absorber material worths, but 4% to 14% for scattering material worths.[9] This could lead to a significant error in expansion/bowing worth since, as we illustrate below, scattering materials make a large contribution.

A fixed-source perturbation approach was used to reanalyze the ZPPR-15A core edge fuel shifting experiment. This method accounts for mesh and transport effects in the vicinity of the experiment, allows for local flux changes, and avoids worth interpolation schemes. Basically the method described in the appendix of Ref. 10 was used, but it was necessary to use the directional adjoint from a nodal transport theory reactor calculation rather than from a cell calculation. A one-dimensional plate-by-plate model of the the shifting cell with a cell to each side was used with group-dependent bucklings and surface sources from the standard forward reactor flux calculation. This method yielded a C/E of 1.14, 8% higher than the standard C/E.

Axial Variation

In power reactor bowing the radial motion varies with axial elevation, but it is constant axially for the plate shifting and bowing oscillator. Therefore, in applying these C/Es to power reactors, information about accuracy as a function of axial position is also needed. Some information about this is available from experiments using the drawer oscillator in ZPPR-15. In the fuel and all-plate shifting experiments of ZPPR-15B and ZPPR-15D the radial shifting was done at two axial positions, whose axial center of mass differed by 11 cm. In all cases the C/Es from the two positions differ by less than 2%, indicating consistent accuracy with axial position. There also was a series of measurements in ZPPR-15B where a bundle of Pu-U oxide fuel pins was shifted and tilted in various ways. The axial center of mass of the bundle varied by 21 cm and the C/Es varied by as much as 10%. However, a smaller variation should be expected in a power reactor because the composition mismatch between the bundle and the surrounding core has been found to degrade computational accuracy considerably. Thus, axial variations in the radial displacement should not affect computational accuracy by more than a few percent.

Cell Material Contributions

Although fissile materials make the largest contribution to the expansion/bowing worth for an LMR core composition, diluent materials make major contributions. This makes predicting expansion/bowing worth much more difficult than predicting fissile worths.

The diluent worth gradients generally are opposite in sign to the fissile worth gradients, which leads to a relatively small and sensitive net motion worth. For example, the calculated contribution from the motion of the main cell section in the ZPPR-17A all-plate shifting experiment is less than half as large as it would be if only fissile material had moved.

The opposite motion of a small diluent segment in the all-plate shifting technique is an important component. That contribution is 28% in the ZPPR-17A experiment, 14% in the ZPPR-15B experiment and 40% for the full zone shifting in the ZPPR-13D experiment. Thus a mismatch between diluent motion in an experiment and the power reactor is a significant consideration.

Furthermore, the worth gradients of diluents and fissile material peak in different places, leading to diluent contributions that can vary greatly with core location. In the ZPPR-13D all-plate shifting experiment the shifting zone spanned the third fuel ring and involved 4 matrix columns of cells. The worth contribution of the opposing diluent section varied from 19%, in the outermost matrix column, to 91%, in the innermost column. Thus, in order to characterize the accuracy of expansion/bowing predictions well, it is necessary that experiments sample much of the core.

These notions can be applied to assess the importance of the missing sodium counter motion in the bowing oscillator experiment. Based on the worth of the clad sodium counter motion in the ZPPR-17A all-plate shifting, which covered a large portion of the outer core, one would expect that the missing sodium motion in the bowing oscillator is less than a 5% effect. However, it just happens that the bowing oscillator was located where the calculated sodium worth gradient peaks, so that, for this location, the missing sodium motion is calculated to be a 20% effect!

An experiment that, in principle, can measure worth gradients for the individual cell materials is the traditional radial-tube small-sample technique.[10] Typically a material sample spans a cell and its worth in each cell along a radius (worth traverse) is measured. From the many radial traverses over the years it appears that the worth profiles for fissile materials are reasonably well predicted, but the profiles for depleted uranium and scattering materials are more seriously mispredicted near the core edge and beyond. Worth gradients between adjacent cells were deduced from some recent traverses but, unfortunately, the experimental uncertainties are unacceptably large for most nonfissile cases. These fissile worth gradients are overpredicted in the outer cores of ZPPR-15 and ZPPR-17A by as much as 20%. There is some indication from experiments in ZPPR-15B that these gradients for depleted uranium and stainless steel are underpredicted in the outer core.

AXIAL EXPANSION

Axial Expansion Oscillator

Axial expansion was simulated using a new oscillator device that expands one drawer. A drawer corresponds to about 1/6 of the hexagonal area of a power reactor subassembly and 1/2 of its axial length. Uniform core density reduction corresponding to a length increase was simulated by creating 2 or 3 gaps, each typically 0.64 cm wide, spaced along the core portion of a special drawer. In this manner all the core cell constituents except the matrix tube expanded.

The results of 5 experiments using this technique are shown in Table III. All of these measurements were done with a DFC cell whose enrichment was in the 18% to 23% range. Each of the three ZPPR-17A measurements corresponds to a different radial position. From these it can be seen that the presence of the internal blanket in this axially heterogeneous core greatly reduces the axial expansion worth. In all cases the total experimental uncertainty is about 3%, which is dominated by an experimentally determined reproducibility component. Our standard FOP analysis was used, except that a higher order interpolation scheme was used to get worth gradients for the ZPPR-17A experiments, as explained below. Compared to the radial expansion/bowing results the axial expansion C/Es vary little, and they are reasonably close to unity.

TABLE III

Axial Expansion Oscillator Results

Assembly Location	ZPPR-15B Outer Core	ZPPR-15D Outer Core	ZPPR-17A Inner Core	ZPPR-17A Outer Core	ZPPR-17A Outer Core
E (¢)	-0.1907	-0.1062	-0.0498	-0.1044	-0.1106
C/E	1.16	1.09	1.03	1.06	1.03
Blanket Contribution	+7%	+14%	-21%	-1%	+2%

Validity of the Simulation

In the limit of a infinite number of uniformly spaced, infinitesimally small gaps, the gap-type perturbation approaches uniform expansion. The question is how similar are the two perturbations for the number and size of gaps used in the experiments.

To answer this question the worth of these kinds of gaps was computed two ways, by explicit k-difference and by FOP. First we demonstrated that uniform expansion of a few percent is essentially a first order perturbation. This was done by expanding by 2 cm the whole core of an RZ geometry model of ZPPR-15A. We refer to this below as the ZPPR-15A model problem. For this problem a fine mesh, S_{16}, k-difference solution and our standard FOP solution agreed to 1.2%. Next, 4 rings of gaps, each 4.6 cm wide in R and 0.5 cm thick in Z, were introduced in the outer core and the 91 cm core height increased correspondingly there. Solutions to this problem by the same two methods are discrepant by just 2.8%. Now, the FOP calculations for these two problems are basically the same; the first order worth of core material is computed. Thus, at least to the few percent level, the axial expansion oscillator experiment is a good simulation of uniform axial expansion.

Measurements were done in ZPPR-15D to confirm this experimentally. An expansion of 1.91 cm was created two ways, using two equal gaps and using 8 equal, uniformly distributed gaps. The experimental worths from these two case agree to within the 3% measurement uncertainty. Similarly the C/Es for these two cases agree to this level.

Analysis methods

Design calculations with the SASSYS code use the PC approximation to get the worth of axial expansion.[12] For the ZPPR-15B and ZPPR-15D experiments we tried this approximation as well as the LI approximation. Using a 5 cm axial mesh, the worths with the PC approximation were 4.5% higher for ZPPR-15B and 1.2% higher for ZPPR-15D.

The calculations for ZPPR-17A were done with nodal diffusion theory, which has a smaller spatial truncation error than finite difference. Accordingly we used an axial node spacing as large as 15 cm. With such a large mesh the PC approximation is totally inadequate (errors of 25% to 98% for the experiments) and even the LI approximation is not good. The ZPPR-17A results in Table III are based on a spline interpolation, where the integral of worth over mesh intervals along the direction of motion was fit to a cubic spline and then the spline was evaluated to get the worth of moving materials. The LI approximation gave C/Es that are lower than the ones in the table by 8% to 16%. This does not reflect on current design calculations, since they use the finite-difference approximation.

Another approximation made in using the SASSYS code is to ignore the reactivity effect of displacing the material above the core when the core expands. From calculations of the experiments it has been observed that displacement of the axial reflector was less than a 0.3% effect, but the blanket displacement was not always negligible. That blanket motion contribution is shown in the last row of Table III. The axial blanket contribution is most important when the core enrichment is low, and above the internal blanket in axially heterogeneous designs. Almost all of the blanket contribution comes from removing blanket near the core/blanket interface and very little from adding it near the blanket/reflector interface. Accordingly, a simple but accurate design method improvement would be to generate a core reactivity table that, in the original blanket region, has the worth of core replacing blanket rather than core added to blanket.

Other approximations were tested with the ZPPR-15A model problem. Linearizing the diffusion theory leakage term in FOP calculations had less than a 2% effect. Diffusion theory and S_4 transport theory results agreed to within 1%. Expanding the mesh within the core in a coarse mesh diffusion calculation gave a worth within 1% of the fixed, fine mesh diffusion theory solution; such a mesh expansion procedure has been proposed as a design method by Khalil.[13]

Motion of Core Cell Components

A limitation of the axial expansion oscillator is that fuel, structure and coolant all expand simultaneously. This would only happen in very slow transients in a power reactor. In some transients of interest only the fuel moves, and in others only the fuel and its cladding move. Attempts to separate the cell components using small-sample tube-type measurement were frustrated by precision limitations, as noted for radial expansion. It should be possible in the future to isolate at least the fuel component by expanding individual columns using the plate column oscillator.

An important observation we have made regarding cell components is that the calculations become very tenuous as the core enrichment is lowered. The first experiment with the axial expansion oscillator, which was in ZPPR-15A, was not reported

because the C/E is absurdly sensitive to many of the standard approximations. (E.g., 82% difference from PC vs. LI approximation, factor of 2 from leakage linearization and 52% from omitting blanket contribution.) This sensitivity was traced primarily to the low cell enrichment, 10.8%, which leads to a very small expansion worth that is a delicate balance of competing effects.

CONCLUSIONS

The C/Es from the expansion/bowing experiments are summarized in Table IV. In cases where more than one calculated result is available for an experiment, the C/Es that best represent the accuracy of design calculations are shown. (Core axial expansion is an exception, as discussed below.) This usually is the most rigorous calculation, since calculational improvements usually were sought in order to account for difficulties that are peculiar to the experiments.

TABLE IV

Summary of C/Es for Expansion/Bowing Experiments

Experiment	C/E	Experiment	C/E
Control Driveline Expansion		Coolant Expansion in ZPPR-17A	1.10
ZPPR-13D, 0.00 to 2.54 cm	1.07		
ZPPR-13D, 2.54 to 7.62 cm	0.80	Core Radial Expansion/Bowing	
ZPPR-13D, 7.62 to 10.16 cm	1.01		
		ZPPR-13D Uniform Expansion	1.05
		ZPPR-15A Fuel Shift	1.14
Core Axial Expansion		ZPPR-15B Fuel Shift	1.33
		ZPPR-15D Fuel Shift	1.42
ZPPR-15B	1.16	ZPPR-13D All-Plate Shift, center	1.17
ZPPR-15D	1.09	ZPPR-13D All-Plate Shift, edge	1.33
ZPPR-17A, Inner Core	1.03	ZPPR-15B All-Plate Shift	1.16
ZPPR-17A, Outer Core	1.06	ZPPR-17A All-Plate Shift	1.01
ZPPR-17A, Outer Core	1.03	ZPPR-17A Bowing Oscillator	1.25

The variation in control expansion worth C/Es is probably related to the inaccuracy of diffusion theory near the core/blanket interface. An analytical study and more data would help clarify this. Control driveline expansion is one of the less important feedbacks in designs that never have rods parked deep in the core. Consequently the accuracy indicated here may be adequate, despite its variability. For deeply inserted control rods, the feedback coefficient is nearly a constant, and its C/E should closely resemble the C/E for full rod insertion worth. The latter quantity has been measured numerous times, and the C/Es for these experiments are generally within 10% of unity.[14]

The accuracy of coolant expansion reactivity calculations has not yet been well characterized. The C/E for this feedback coefficient can be expected to vary substantially with position in the core as well as with reactor type, but we have only one result. Furthermore, analysis of the one experiment required large corrections in order to account for differences between the simulation and true coolant expansion. Still, the C/E shown in Table IV is encouraging. More

measurements of this type would help clarify the situation, even if an improved experimental simulation is not devised. The large database of bulk sodium voiding C/Es provides some indication that coolant expansion coefficients should be accurate to at least the 30% level; its applicability is limited, however, by the fact that bulk voiding produces a major flux change while expansion does not.

The core axial expansion C/Es are all reasonably consistent and fairly close to unity. It was found, however, that this becomes an extremely delicate parameter to calculate when the core enrichment is low (around 11%). Fortunately, designs with a zone of such low enrichment normally have a higher enrichment zone, and the latter would dominate the core expansion feedback. The inner core of an axially heterogeneous design has somewhat heightened sensitivity to methods approximations, but it is a manageable situation.

The analysis method used for the axial expansion experiments includes two simple improvements over the design method. One is that the reactivity from moving the axial blanket upwards is accounted for. The effect of this on the expansion worth C/Es varies between 1% and 21%. The other improvement was to allow for worth variations within a mesh interval. With a 5 cm mesh, assuming linear variation between mesh centers changed the C/Es up to 5%.

These axial expansion experiments simulated equal expansion of all the core constituents - fuel, coolant and structure. Some more effort in the future should be made to do experiments that expand the constituents individually, since their relative motion in a power reactor varies with the type of transient.

The calculation methods reflected in the radial expansion/bowing C/Es are similar to the latest design methods. The first value is based on the procedure for computing a uniform expansion coefficient. The others use a method that is very similar to the CTHS of Finck.

There is a large spread in the C/E values from the radial expansion/bowing experiments. It appears that a substantial part of the variability is due to difficulties posed by the experiments that are less important in the power reactor phenomena. We have attempted to account for these features in selected cases, in order to quantify their importance, but they have not been treated systematically. Thus it is likely that the accuracy of power reactor expansion/bowing reactivity calculations is better than some of the C/Es in Table IV would suggest.

One of these difficulties is the cell heterogeneity change that accompanies some of the simulations. Cell heterogeneity is stronger in a ZPPR plate cell than in a power reactor unit cell, and furthermore the disruption of the cell is greater in the simulations, particularly the plate shifting techniques. The effect is illustrated by the 17% drop in the ZPPR-17A all-plate shifting C/E when the heterogeneity change was accounted for.

A complexity unique to the experiments is the worth gradient variations induced by the mix of ZPPR core cell types. These variations are on the order of 10% for fissile materials but a factor of 2 for some diluents. Deficiencies in calculating this effect probably account for a significant portion of the differences among a number of the C/Es.

There is a disproportionate emphasis in Table IV on core material motion within a few centimeters of the radial blanket. All of the ZPPR-15 measurements and one of the ZPPR-13D measurements were made in this location. The worth gradients change more rapidly there than elsewhere in the core. Coarse-mesh finite-difference diffusion theory, which was used in most of the calculations, probably is adequate overall, but its accuracy degrades near region boundaries.

An issue that adds to the radial expansion/bowing C/E variation, but that also is significant in the power reactor phenomena, is the contribution of diluent motion to the total reactivity. Diluent worths are well known to be more difficult to predict than fissile worths. Unfortunately, diluent motion makes a large and highly variable contribution to expansion/bowing reactivity. This difficulty is aggravated in our results by the fact that the diluent motion was different in almost every experiment. In any case, this complexity dictates that many core locations be sampled when trying to determine the accuracy of radial expansion/ bowing for a particular reactor design.

This is the first assessment of expansion and bowing feedback reactivity calculations based on critical experiments. The accuracy range found here should bracket the accuracy of power reactor feedback reactivity calculations. Thus it can be concluded that generally the design calculations overpredict the feedback reactivity and the magnitude of the error is less than 30%. Considering that the magnitude of the material displacements is often quite uncertain, this accuracy may be considered acceptable. Accumulation of more data, and refinements of the experiments and calculations should help identify the accuracy of design calculations more precisely in the future.

ACKNOWLEDGEMENTS

Much of the design work for the new oscillators was done by P. L. Schaffer. S. B. Brumbach, R. W. Goin and D. N. Olsen were the reactor supervisors for most of the experiments. G. L. Grasseschi generated the standard cross section sets and produced most of the XYZ forward and adjoint fluxes. Discussions with the ANL reactor design and safety groups were helpful in meshing this study with design interests. This work was supported by the U.S. Department of Energy, Nuclear Energy Programs, under contract No. W-31-109-Eng-38.

REFERENCES

1. D. C. WADE and Y. I. CHANG, "The Integral Fast Reactor (IFR) Concept: Physics of Operation and Safety," Proc. Inter. Topical Meeting on Advances in Reactor Physics, Mathematics and Computation, Paris, France, April 27-30, 1987.

2. P. J. COLLINS et al., "Measurements and Analysis of Control Rod Worths in Large Heterogeneous LMFBR Cores," Proc. Topical Meeting on Reactor Physics and Shielding, Chicago, IL, September 17-19, 1984.

3. H. F. MCFARLANE et al., "Benchmark Physics Test in the Metallic-Fuelled Assembly ZPPR-15," Proc. Inter. Topical Meeting on Advances in Reactor Physics, Mathematics and Computation, Paris, France, April 27-30, 1987.

4. P. J. COLLINS and S. B. BRUMBACH, "Experiments and Analysis for an Axially Heterogeneous LMR Assembly at ZPPR," these proceedings.

5. S. G. CARPENTER et al., "Conclusions Drawn From Subcritical Multiplication Results in ZPPR," Proc. Topical Meeting on Advances in Reactor Physics, Gatlinburg, TN, April 10-12, 1978.

6. R. W. GOIN et al., "Inverse Kinetics Techniques Applied to ZPPR Fast Critical Assemblies," ANL-7910, p. 208, Argonne National Laboratory (1971).

7. D. C. WADE, "Monte Carlo-based Validation of the ENDF/MC^2-II/SDX Cell Homogenization Path," ANL-79-5, Argonne National Laboratory (1979).

8. K. S. SMITH, "The Effects of Intracell Adjoint Flux Heterogeneity on First-Order Perturbation Reactivity Calculations," Nucl. Sci. Eng., 81, p. 451 (1982).

9. D. C. WADE and R. G. BUCHER, "Conservation of the Adjoint Neutron Spectrum by Use of Bilinear-Weighted Cross Sections and Its Effect on Fast Reactor Calculations," Nucl. Sci. Eng., 64, p. 517 (1977).

10. K. S. SMITH and R. W. SCHAEFER, "Recent Developments in the Small-Sample Reactivity Discrepancy," Nucl. Sci. Eng., 87, p. 314 (1984).

11. P. J. FINCK, "A Technique for Computing Bowing Reactivity Feedback in LMFBRs," Trans. Am. Nucl. Soc., 55, p.581 (1987).

12. F. E. DUNN et al., "The SASSYS-1 LMFBR Systems Analysis Code," Proc. Int. Mtg. Fast Reactor Safety, p. 999, Knoxville, TN, April 1985.

13. H. KHALIL, "Techniques for Computing Reactivity Changes Caused by Fuel Axial Expansion in LMR's," these proceedings.

14. H. F. MCFARLANE and P. J. COLLINS, "Control Rods in LMFBRS: a Physics Assessment," ANL-82-13, Argonne National Laboratory (1982).