CONF-881252--1

A SURVEY OF CONTROL ROD MEASUREMENTS IN ZPPR AND THEIR ANALYSIS

P. J. Collins

Argonne National Laboratory
P. O. Box 2528
Idaho Falls, ID 83403-2528

CONF-881252--1

DE89 004199

Paper for:

IAEA Specialists' Meeting
Winfrith, UK
December 6-8, 1988

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

IAEA Specialists' Meeting on Methods for Reactor Physics Calculations for Control Rods in Fast Reactors

Summary Review

P. J. Collins
Argonne National Laboratory - West
Idaho Falls, ID USA

The accurate prediction of control rod worths has been of great concern in the United States. Optimum control configurations need to balance several often conflicting requirements of control through the operating cycle, while maintaining acceptable power shapes, safety considerations of overriding importance, together with seeking economy by minimizing the number of rods, reducing boron enrichment and lengthening replacement intervals. After control and shutdown requirements have been met, the most important safety concern is the transient overpower condition (TOP) which may be initiated by uncontrolled run-out of a primary rod. Stringent criteria for the primary and secondary systems may be that they are independently capable of shutting down the reactor even with one rod stuck. The TOP initiator may be greatly enhanced by control rod interaction effects. Control rod effects may have a strong impact on core design. For example, work on the integral fast reactor with metallic fuel at ANL has studied core designs which minimize the TOP reactivity by maintaining a minimum primary control bank insertion through tailoring the internal breeding gain.

The predicted control rod worths are very sensitive to the calculation methods used and to the accuracy of the basic nuclear data files. Required accuracies have been achieved only through the use of critical experiments on the ZPR and ZPPR facilities. Experiments on ZPR-3 and ZPR-9 produced satisfactory control predictions for the SEFOR, EBR-II and FFTF reactors.

The early years at ZPPR were devoted to experiments for the Clinch River Breeder Reactor (CRBR) and included many measurements of control rod worths and related effects. Through the use of detailed mockups of the CRBR designs and the use of analysis methods consistent with those for the project, the required accuracies were obtained by application of bias factors. Additional studies of control rod heterogeneity effects were necessary to make the extrapolation from the plate-type mockup rods used in ZPPR to the pin rods in the CRBR. Predictions of rod worths in the conventional designs were consistent at different positions in the core. With the change to a radially heterogeneous design, the discrepancies between calculation and experiment varied with radius (subassembly row) and with location relative to the internal blanket subassemblies. In this case, it was necessary to use separate bias factors for each control ring.

Following the CRBR work, measurements at ZPPR covered a variety of fast reactor cores which were of interest to the design community. Three major programs for cores of 700 MWe to 900 MWe size were conducted jointly with PNC of Japan. These were for two-enrichment zone conventional cores (JUPITER-I series), radially heterogeneous cores with a central blanket and two internal blanket rings (JUPITER-II) and axially heterogeneous cores

(JUPITER-III). The second part of the JUPITER-III program was a larger conventional core and was the only core which used any uranium fuel in its construction. Analysis for this latter core is presently is progress. Analysis of the other cores, with ENDF/B and JENDL data, showed a common characteristic of increasing discrepancies with the experimental control rod worths as a function of distance from the core center. These discrepancies were strongly correlated with mispredictions of fission distributions although the eigenvalues were consistent with analyses of smaller cores.

Benchmark studies were made in ZPPR-15 for metallic-fuelled cores as part of the ANL "integral fast reactor" program. Control rod worths were measured in a core with plutonium fuel loading and also in a core with 90% uranium and 10% plutonium fuel. Measurements of $^{10}B(n,He)$ reaction rates within the pins of a half-inserted control rod were made in this series.

Other measurements at ZPPR have been for a small, 10 MWe-size, power plant with a reflector control (ZPPR-14) and for space reactors typically 1 KWe size. The latter experiments for the SP-100 reactor involve control both by reflectors and by boron control rods and accurate analysis is a particular challenge.

Both experimental techniques and calculational tools have improved over the period of the ZPPR programs. Design methods have moved from two-dimensional diffusion calculations to routine use of economical nodal methods in three dimensions. The criticals analysis uses complex three-dimensional models treating detailed composition variations and refined calculations using three-dimensional transport codes ar now feasible.

The most recent work at ANL has been to include control rod worths, together with most other physics parameters measureable in critical experiments, in a sensitivity analysis with least-squares fitting by cross section adjustment. This system has major advantages over the bias factor approach in giving a stringent test of the consistency of the data base and providing well-founded predictions and uncertainty estimates for a target design. The results have been valuable in demonstrating the consistency of the spatial variations in control rod worth predictions with other parameters. It is apparent from these results that there is room for the improvements in critical experiment analysis to utilize fully the accuracy achievable in experiments.

A SURVEY OF CONTROL ROD MEASUREMENTS IN ZPPR AND THEIR ANALYSIS

P. J. Collins

Argonne National Laboratory
P. O. Box 2528
Idaho Falls, ID 83403-2528

Paper for:

IAEA Specialists' Meeting
Winfrith, UK
December 6-8, 1988

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

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

DO NOT MICROFILM
THIS PAGE

A SURVEY OF CONTROL ROD MEASUREMENTS IN ZPPR AND THEIR ANALYSIS

P. J. Collins

Argonne National Laboratory
P. O. Box 2528
Idaho Falls, ID 83403-2528

List of Figures

1. ZPPR Core Designs

2. Measured and Calculated Boron Capture Rate Profiles in a Control Rod

3. Cross-sectional Views of Rod Designs Used in ZPPR-10A to Study Geometry and Enrichment Effects

List of Tables

I. ZPPR Cores with Control Rod Measurements

II. Summary of Analysis with ENDF/B-IV Data

III. Comparison of Calculation and Experiment for Control Rod Banks in ZPPR-13

IV. Analysis of Control Rod Worths in ZPPR-15

V. Calculations of Control Rod Banks in ZPPR-17B by Different Methods

VI. Control Rod Worths in ZPPR-13C

VII. Results of Least-squares Adjustment to Control Rod Worths

VIII. Comparison of C/E Values for ^{235}U Fission Axial Distributions Near the Center of ZPPR-17A,17B and 17C

IX. Analysis of $^{10}B(n,He)$ and $^{235}U(n,f)$ Reaction Rates in a Control Rod

X. Results of ZPPR-10A Rod Geometry and Enrichment Studies

ABSTRACT

A large number of measurements of control rod worths have been made at ZPPR over the past 16 years, covering a wide range of fast reactor core designs. Both experimental techniques and analytical methods have improved over this period. The results of analysis using ENDF/B-IV and ENDF/B-V.2 nuclear data are reviewed and the calculation methods employed are described in some detail. Special experiments of control rod heterogeneity and boron enrichment effects have been made to aid extrapolation from critical experiments to power reactors. The analysis of parameters related to insertion of control rods into the core, such as fission rate distributions, is also summarized.

1. INTRODUCTION

Many measurements of control rod worths and related effects have been made at ZPPR over the past 16 years. The first experiments followed the design evolution of the CRBR reactor through conventional and radial heterogeneous cores. Later experiments were made in the "mid-size" cores of conventional, radially heterogeneous and in axially heterogeneous designs. These experiments were a joint venture of USDOE and PNC of Japan. Benchmark experiments were also made for small metal-fueled cores with both plutonium and uranium fuel and recently on space-reactor cores for the SP-100 program. A brief description of the different assemblies is given in Table I and the core layouts are shown in Figure 1.

The early analyses were made with ENDF/B-III data but many cases were recalculated with ENDF/B-IV. An assessment of the control rod data up to 1982 has been given by McFarlane.[1] Calculations have been routinely made with revision 2 of ENDF/B-V since 1985. Both experimental techniques and analysis methods have improved over the period. Measurements of control rod worths can now be made, in most cases, with an accuracy of close to 1%, but relative uncertainties within a given core are usually only a few tenths of a percent. Calculations have improved from two-dimensional diffusion with few energy groups to three-dimensional transport with 20-30 groups. Most recent efforts have been in application of the control rod data together with other parameters in a sensitivity/least-squares analysis system.

This report gives a survey of the analytical results for control rod worths, control rod heterogeneity and enrichment effects, reaction rates in and around control rods and other related experiments.

2. EXPERIMENTAL METHODS

Measurements of subcritical reactivity are made at ZPPR by the modified source multiplication technique.[2] The reference core is slightly subcritical and its reactivity is established by inverse kinetic analysis of a rod drop. The only calculation input is the delayed neutron λ_i parameters and the measured reactivity is insensitive to these. The reference reactivity, in dollars, is obtained with an accuracy of better than 1%. Early measurements at ZPPR used only one or two detectors for the MSM method and the measured reactivity was dependent upon the accuracy of calculated detector efficiencies and effective source ratios. Significant improvements

in accuracy were obtained by introduction of first 16 in-core fission chambers (ZPPR-7) and then 64 fission chambers in ZPPR-9.

With the use of 64 fission chambers, the experimental reactivities (in dollars) are insensitive to the absolute accuracy of calculated efficiencies and source ratios so that a simple diffusion calculation representing the geometry of the rod pattern sufficies. A least squares fit of the worths from each detector versus the efficiency ratios is used to obtain the worth for an ideal detector with efficiency of unity. The source ratio is also corrected from this fit. Detector countrates are obtained to an accuracy of better than one percent and after the least squares fit the statistical uncertainty on the measured reactivity is a few tenths of a percent. Thus, relative reactivities within a given reference core can be made to high accuracy.

Up to ZPPR-7, the subcritical reference core was established to insertion of a single operating control rod. This was found to produce an appreciable perturbation of the core which was difficult to correct by calculation. Since that time, the reference has been established with all the operating control rods withdrawn and the reactivity lowered by reduction in the fuel enrichment, in selected drawers symmetrically disposed about the axes. All calculations of control rod worths are made with this fuel loading rather than the reference critical loading and advantage may be taken of the symmetry in the majority of cases.

Measurements for rod banks are made, by necessity, with mockup rods constructed out of natural boron carbide plates, either completely filling

ZPPR drawers or with half B_4C and half sodium plates. Studies of rod heterogeneity are made with natural and enriched B_4C rodlets for single rods at different locations.

3. CALCULATION METHODS

The calculation methods fall into two categories. Where a faithful mockup of a design exists, it is usual to analyze the experiments by the same methods used in design calculations leading to a direct application of bias factors for the control rods.[3] Because of the additional complexity of the experimental loading, a more detailed treatment of cell heterogeneity and streaming is necessary in processing the multigroup library. In order to understand the calculational discrepancies and guard against errors in bias factors due to differences between the mockup and the design, a number of measurements are calculated with the most refined methods practicable.

Developments in computer codes and increases in the efficiencies of computers over the past decade have lead to the increasing use of three-dimensional calculations; hexagonal-z for the design and xyz for the ZPPR experiments. However, budgetary constraints often require the use of few (6 to 9) energy groups.

The nodal diffusion method is more efficient than coarse-mesh finite difference diffusion and produces solutions with a very small truncation errors.[4] This method is now in routine use in the engineering physics division of ANL both for design calculations and criticals analyses.

A major advance in ZPPR analysis has been the introduction of the nodal transport method in xyz geometry.[4] This method, although approximate, provides the large part of the transport correction to diffusion calculations at a cost of only 50% more than nodal diffusion. Comparisons with TWODANT calculations in an xy model for a large heterogeneous core, ZPPR-13, showed that over 80% of the transport correction was obtained.[4] A further advantage is the ability to use anisotropic transport cross sections eliminating the need for streaming corrections after the calculation.

2.1 The Reference Calculation Method

Most of the calculations for ZPPR control rod worths have used the following method:

(i) diffusion theory

(ii) xy geometry

(iii) 8 or 9-group cross sections

(iv) group and region dependent absorption terms (bucklings) to treat axial leakage

(v) 1 or 4 mesh spaces per ZPPR matrix area (55 mm x 55 mm)

The worth (positive for convenience) is defined as

$$W(\$) = (k_1 - k_2)/(k_1 k_2 \beta)$$

with k_1 the k-effective calculated for the reference configuration, k_2 that

for the rodded configuration and β the β-effective calculated for the reference.

2.2 Multigroup Cross Sections

A multigroup library for all ZPPR calculations in a given core is prepared in the following manner:

(i) A 2082 group library for MC^2-II processed from ENDF/B files through the ETOE code. A fundamental mode spectrum calculation for the core composition (more recent calculations use, in addition, a spectrum calculation for the blanket with a core spectrum source input). Collapse to an intermediate library of 160 groups (ENDF/B-IV calculations) or 230 groups (ENDF/B-V.2 calculations). The 230 group library is tailored to treat the narrow resonances in diluent materials.

(ii) Processing of cell heterogeneities with the intermediate library and collapse to the working library in 28 groups or 21 groups.

Early calculations used asymptotic models with buckling search to unity for cell calculations and group collapse. More recent calculations used bucklings in the cell models recycled from a prior reactor calculation (or sometimes multi-drawer cell models) and regionwise group collapse using diffusion theory reactor models (one-dimensional).

(iii) Special cell calculations in 28 or 21 groups to generate anisotropic diffusion coefficients by the Benoist method

(iv) No special calculations are made for the experimental control rod cells or cells neighboring the rods. Boron cross sections are infinitely-dilute data collapsed in the core spectrum. Data for steel and sodium in the rods use homogenized cross sections.

2.3 Group Collapse

Collapse to the 8 or 9 groups for control rod calculations is made in reactor models:

(i) Cross sections for all regions are made with the reference model which usually has no control rods inserted. Older methods used an rz model while more recently xyz models are used.

(ii) If sodium/steel control positions (CRPs) are present in the reference, these data are obtained in step (i). If not, a further reactor calculation is made with the CRPs present. In rz models, the CRP is obtained from the central position.

(iii) For the control rod cross sections, a reactor calculation is made with rods fully inserted. For rz models this again is in the central position.

2.4 Buckling Generation

Buckling generation follows a similar procedure to that used for group collapse except that reactor calculations are made in 8 or 9 groups. Group-dependent DB^2 terms are calculated to preserve the axial leakage from each radial zone, control rod and CRP, from the appropriate models. The bucklings are normally generated at the core/axial blanket interface.

2.5 Past and Present Applications

The reference calculation method has been used for all ZPPR control rod analyses except for the axially heterogeneous core ZPPR-17 and space reactor benchmarks ZPPR-16 and ZPPR-20. For the CRBR mockup cores (ZPPR-3, 4, 5, 6, 7, 8, 11), the method paralleled that of the project. For the conventional cores (ZPPR-3, 4, 5, 6), a mesh spacing of 55 mm was used. For control rod worths, this coarse mesh results in a strong cancellation of positive diffusion-mesh and negative transport corrections. For the 350 MWe-size heterogeneous core, the mesh size was halved in some calculations because of the rather thin, 110 mm, spacing between fuel and blanket rings.

These methods were carried over for the 700-900 MWe-size conventional cores (ZPPR-9, 10) and radially-heterogeneous cores (ZPPR-13).

With the introduction of ENDF/B-V.2 data, a joint analysis method was adopted by the ANL core design group and the ZPPR analysis group. Reference calculations were made with 21 group cross sections and three dimensional nodal diffusion theory. Control rod calculations were made with an 8 group

condensation of the 21 group set so that the rods could be economically represented in burnup calculations for the design. Changes in group structures have a relatively small impact on comparisons with previous data but the nodal method compares more closely with the finer mesh finite difference results. Calculations with Version V.2 data at ZPPR started with ZPPR-14 (reflector control) and for control rods with the metal fuel benchmarks in ZPPR-15.[5] The same methods as used for ZPPR-15 were also applied to analysis of the axially heterogeneous cores (ZPPR-17) and the large conventional cores (ZPPR-18).

Calculations are also required to obtain the highest accuracy from the experiments. A ZPPR control rod campaign frequently measures a large number of control patterns and special experiments. For experimental data processing, both adjoint fluxes and source-driven fluxes are calculated in each subcritical configuration to obtain detector efficiencies and source ratios. For economy these are usually calculated using two-dimensional models akin to the reference method of 2.1. The adjoint k-effective values provide initial results for the reactivities. Depending on these results in comparison with experiment, three-dimensional calculations are made for a number of selected cases (usually symmetric rod patterns).

An exception to this approach was ZPPR-17. Early test calculations for the axially heterogeneous core showed a strong sensitivity to the variation in axial buckling as a function of radius which was complicated to model. All calculations for ZPPR-17 used xyz models but most cases used a further reduction to 6 group data.

2.6 Refined Calculations

A recent project at ANL has been construction of a database to provide the most effective predictions and uncertainties for power reactor performance parameters.[6] Control rod worths are important quantities in this effort. For effective use in the least squares fitting process, the uncertainties in calculated worths must be minimized by using the best calculations available. Some results from this study are given in Section 3.4.

As is well known, several variations in calculation methods produce changes in rod worths of a few percent. To give an accuracy of 1% for a rod worth $1, the difference in two k-effectives must be accurate to about 3×10^{-5}.

Many examples of corrections to two-dimensional diffusion calculations are available in the literature, see for example reference.[1] Corrections are often made by rz and xy transport theory. They may be complex, varying between different core types and also with position in a given core. The separability of the corrections may be in question.

Recent calculations for ZPPR have used the xyz nodal transport code which is very convenient. However, more extensive validation is required. A major advance this year has been the use of the TRITAC S_N code in xyz geometry from Osaka University.[7] A comparison with TWODANT rz S_4 calculation for ZPPR-17A, which had good cylindrical symmetry, gave excellent agreement. A six group calculation for ZPPR-17 with 55 mm meshes

required 40 minutes CPU on the CRAY XMP14 machine, but the code has been implemented in free time on the ZPPR computer used for data collection. Calculations of rod worths for ZPPR-17 showed significant improvements over the nodal transport results.[8]

A further advance in ZPPR calculation has been the use of very detailed xyz calculation models. With the more sensitive large heterogeneous cores it became clear that local variations in composition had signficant effects on reactor-wide properties. In one case, the relative predictions for two control rods were affected by 4%. Variations about the nominal composition for a given drawer type may be of the order of 1% in heavy metal content due to different piece lengths that are necessarily used. Compositions are now modeled on a drawer-to-drawer basis. Since the models became very complex, these are constructed automatically from the experimental database. This modeling has been used for all cores since ZPPR-13. Some inconsistencies seen in analysis of previous cores may also be affected.

3. COMPARISONS BETWEEN CALCULATED AND MEASURED CONTROL ROD WORTHS

Literally hundreds of control rod measurements have been made at ZPPR. Results from the earlier cores were analyzed with ENDF/B-IV data and a detailed assessment is given by McFarlane.[1] Analysis with ENDF/B-V.2 data gives significantly different results. At this stage, only ZPPR-13C has been consistently calculated with both versions of ENDF/B, although this is one of the more interesting cases in the sense of the discrepancies with experiment.

In this section, the comparisons with experiment are summarized for the two sets of analysis. References to detailed results are provided for the analysis with ENDF/B-V.2.

3.1 Analyses with ENDF/B-IV Data

A summary of the C/E results using the reference diffusion calculations in xy geometry and 55 mm mesh is given in Table II.[1] Average C/E results are compared for rods in similar locations from the center to the outer banks. Results for all rods in a given position -- single rods, partial banks and full banks are included. Many other results for bank combinations have not been included. These generally have C/E values between those for the individual banks. The large heterogeneous cores (ZPPR-13B) had five banks, positioned in fuel zones and in or near gaps in the two internal blanket rings. These are labeled Ring 1 to Ring 5. In all cases, except the small conventional cores, the analysis shows an increasing C/E with radius of 5% to 7%. Similar C/E values are seen for rods in the outer core between 1.04 and 1.07 except for the 350 MWe heterogeneous cores and ZPPR-13C. These latter cases also showed azimuthal biases in predictions.

Corrections to the reference calculations for mesh-size, transport, bucklings, streaming in CRPs and group condensation have been made in a number of cases, see for example reference [1]. The net corrections range from 1% to 5% and are somewhat uncertain. Effects in the heterogeneous cores with rods near to blanket rings are complex and vary with radial position. Table III compares C/E results for rod banks in ZPPR-13 for the reference and corrected methods.[9]

The corrected calculations do not improve the radial dependence in predictions and in most cases it is enhanced. In general, the corrections give improved consistency between results for different core types.

3.2 Analyses with ENDF/B-V.2 Data

ENDF/V.2 has been used in all calculations for the metal-fueled benchmarks (ZPPR-15), the axially heterogeneous cores (ZPPR-17)[8] and the large conventional cores (ZPPR-18). Analysis of ZPPR-18 is in progress.

ZPPR-15 had both uranium and plutonium fueled phases.[5] Control rods at the center and the six outer bank were designated primary operating rods and a middle bank of six rods were designated secondary rods. Table IV shows analysis of rods in 15B (all ^{239}Pu fuel) and 15D (90% ^{235}U fuel/10% ^{239}Pu fuel). Calculations have been made by nodal diffusion and nodal transport in xyz geometry.

The central and primary rods have a lower C/E in 15D than in 15B. The results are less consistent than would be expected for small conventional cores. This is attributed to inaccuracies in treating heterogeneities in the cells which were more complex in ZPPR-15.

Table IV also shows predictions of CRP worths relative to fuel. Diffusion calculations always overpredict these worths by 10% to 20% due principally to overestimations of leakage in dilute regions.[1] However, S_N methods produce improvements of about 10% and C/Es of about 1.05, similar to

those found for fuel worths with ENDF/B data. It is apparent that the nodal transport method is only partially effective in this case.

Results for the axially heterogeneous core, ZPPR-17, are given in Table V.[8] Calculations for the rod banks were made by finite-difference diffusion, nodal diffusion, nodal transport and by the TRITAC code in S_4 with xyz models. Modeling effects were found to be much larger in this core due to a part of the rods passing through the internal blanket. The diffusion mesh error was 10% (compare finite difference with nodal). The group correction varied with radius by up to 5%. Nodal transport and S_N calculations agree well for the outer rod bank which was in the fuel region but have a progressive bias going towards the core center. The TRITAC results, conceptually the best available, show decreasing bias in C/E towards the center of 10%.

3.3 Comparison of ENDF/B-IV and ENDF/B-V.2 for ZPPR-13C

Consistent calculations for control rods in ZPPR-13C have been made with both versions of ENDF/B using nodal transport calculations in xyz geometry.[10] The C/E results are compared in Table VI. With Version IV data, discrepancies with experiment vary by up to 12% both radially and axially. The discrepancies are about halved with Version 5.2 data. These results are correlated with errors in predicted fission distributions.

3.4 Sensitivity Analysis

Control rod worths have been included in a major program of sensitivity analysis and least squares fitting of critical experimental parameters.[6] At present control rod data from ZPPR-13C, ZPPR-15 and ZPPR-17 only are available with ENDF/B-V.2 analysis. Table VII shows the results of fitting these data together with over 200 other parameters (the results in reference 6 for ZPPR-15 have been revised with the nodal transport values from section 3.2). The fitted results are consistent within the combined calculation and measurement uncertainties of 3%. It is important to note that very similar predictions for the rod worths are obtained if the rod worths themselves are omitted from the fitting.

The marked spatial variations in rod worth predictions in ZPPR-13C are eliminated after fitting the data which shows that these effects are consistent with nuclear data uncertainties and with predictions of other parameters. Preliminary studies in other cases have indicated that spatial variations should also be consistent but these need to be recalculated with ENDF/B-V.2 data and added to the sensitivity database. An important use of the sensitivity methodology is that it will given a strong indication of discrepant data provided that a wide enough database exists.

3.5 Space Reactor Cores

Benchmark cores for the SP-100 space reactor [11] have been studied in a short program in ZPPR-16 and in more detail in ZPPR-20. Control worths both by beryllium reflectors and by inserted boron rods, have been

measured. The cores are small and highly enriched with high leakage fractions and are not amenable to calculations by diffusion theory. Some configurations can be reasonably modeled by two dimensional S_n codes but the MCNP Monte Carlo code has been used to treat the full complexity. Calculated worths with statistical uncertainties of 1% to 2% for control worths of 20$ can be obtained by runs of a few hundred thousand histories.

Some results for ZPPR-16 are given by Sapir.[12] The C/E results are relatively low, in the range 0.85 to 0.90 but effects are complex, involving movement of beryllium as well as boron.

4. CORES WITH INSERTED CONTROL RODS

4.1 Criticality

A number of ZPPR cores have been made critical with control rods withdrawn and partially or fully inserted. Predictions of the eigenvalues are generally consistent to within 0.1% by transport calculations and slightly less consistent by diffusion calculations. [13] Comparisons with the predictions of control rod worths at this level are dependent on the accuracy of the modeling corrections. Any uncertainty in β-effective is also significant in converting from dollars to Δk units. For example, the k-effective for ZPPR-17C, which had 13 control rods half inserted, is 0.1% higher than for 17B with no rods.[8] This is inconsistent with the control rod C/E results but an increase in β-effective of 3-4% would produce agreement.

4.2 Reaction Rates

Reaction rates in cores with control rods inserted are calculated with similar accuracy to those in cores without rods. Exceptions arise for the more decoupled cores of ZPPR-13 for asymmetric rod patterns. A number of measurements have been made adjacent to inserted control rods. Table VIII shows recent results near the center of ZPPR-17 for ^{235}U fission rates in fuel (17A), adjacent to a CRP (17B), and adjacent to a half-inserted control rod (17C). The calculations are normalized to an average C/E of unity for foil measurements covering the whole core. (The low C/E results near the center are due to the bias in calculation with radius.) With nodal transport calculations, the results agree within 1-2%. As expected, diffusion calculations are less consistent and vary by 5% or more in the immediate vicinity of the control rod.

4.3 Reaction Rates within Control Rods

Measurements of ^{10}B helium production rates have been made in several cores by helium accumulation fluence monitors (HAFMs).[14] The HAFMs are mounted in small holes drilled in boron rodlets in pin-rod control mockups. ^{235}U foils are also inserted between rodlets in the same irradiation and a number of foils are also irradiated through the core for normalization.

Comparisons of calculation and measurement within a half-inserted enriched-boron rod in ZPPR-15 are shown in Figure 2. The mean C/Es for 23 measurements throughout the rod and for ^{235}U fission are given in

Table IX. Also included in the table are earlier measurements in ZPPR-12 and in the core region of ZPPR-13.

Analysis with both ENDF/B-IV and ENDF/B-V.2 shows underestimation of $^{10}B(n,He)$ and overestimation of ^{235}U fission within the control rod when normalized to ^{235}U fission in the core. The C/E results are much closer to unity if the boron (n,α) cross sections are increased by a nominal 10% but the detailed sensitivity analysis does not support so large a change.[6]

5. STUDIES OF GEOMETRY AND ENRICHMENT EFFECTS

The rod bank measurements are made using plate-loaded mockup rods of 4, 6 or 9 drawers in extent. A number of studies throughout the series of cores has been made with more representative mockup rods constructed of boron and steel rodlets inside sodium-filled calandria. Both natural and 92%-enriched boron rods have been measured. The inventory limits the studies to a single rod but comparisons with plate-type rods have been made for off-center as well as center positions.

An extensive series of measurements for control rods occupying 9 matrix positions (275 cm^2 area) was made at the center of ZPPR-10A.[1] The rod designs are shown in Figure 3. Analysis was made by rz diffusion theory with a two-region model, an inner region containing boron/sodium/steel and an outer region of sodium/steel preserving the areas. The calculations show good consistency (Table X) in the range 1.043 to 1.066. No significant variation is seen for natural and enriched rods (note that the relative experimental uncertainties are only a few tenths of a percent).

Off-center pin rods were measured for the CRBR project [3] in ZPPR-11. Heterogeneity factors of 0.91 were calculated for the two-region rod models at the center of one-dimensional transport models and applied to off-center locations. Results for the same pin rod were consistent to within ± 1.5% but differences of 1 to 5% existed between pin and plate rods in the same locations. These differences were improved by use of xy diffusion calculations with a fine mesh which modeled the details of the pin rods and the local environments. [1] Further improvements might be expected from xy transport calculations.

Measurements of pin rods of 122 cm^2 and 183 cm^2 area were made in the larger radially heterogeneous core, ZPPR-13B/4, at five radial positions.[9] Heterogeneity factors were calculated by diffusion theory in xy geometry. The predictions for enriched pin rods showed a 7% variation with radial position consistent with that for the rod banks. Biases of 0 - 3%, in comparison with the reference plate rods at the same locations were obtained.

6. SUMMARY

Modern experiments at ZPPR by the modified subcritical multiplication technique with 64 in-core detectors are very accurate with total uncertainties on control rod worths close to one percent and relative accuracies for measurements in the same core of a few tenths of a percent. The experimental values are insensitive to the absolute values of calculated efficiency ratios and effective source ratios used in the data processing. More recent calculation methods, using three-dimensional diffusion and

transport codes and detailed reactor models show improvements in consistency compared with earlier calculations, which require a number of corrections to be applied. A selection of older measurements should be reanalyzed with these methods and ENDF/B-V.2 data.

Present accuracies achievable in the calculation of rod worths (excluding nuclear data uncertainties) are estimated to be about 2%. These fall short of the experimental accuracies, especially for relative measurements in a given core. The general comparisons of the data suggest that improvements in the treatment of plate-cell heterogeneities in the neighborhood of control rods should be investigated.

The general features of the ZPPR analysis are as follows:

(i) Relative control rod worths are consistently predicted in small homogeneous cores but systematic variations as a function of distance from the core center are present in heterogeneous cores and large conventional cores. These are reduced with ENDF/B-V.2 data compared with ENDF/B-IV but significant discrepancies remain. Spatial variations in control worth predictions are correlated with those for fission distributions.

(ii) Control rod interactions are well calculated for rods in a given bank, even by simple diffusion methods, but predictions of interactions between banks are biased because of the spatial variations.

(iii) Rod heterogeneities and boron enrichment effects have been studied in pin geometry. Variations in worth are well predicted for central rods. Rod geometry effects for off-center rods in flux gradients and adjacent to internal blankets are calculated with fine-mesh diffusion in xy geometry to within 2-3%. It is expected that further improvements would be effected by transport calculations.

(iv) The reactivities of sodium followers (CRPs), relative to fuel, are overestimated by 10-20% with diffusion theory. These overestimations affect calculated control rod worths and eigenvalue predictions. Calculations with transport and S_4 quadrature give good agreement with fuel worth predictions; which have C/E values of about 1.04 in plutonium-fueled cores with ENDF/B data.[15] The CRP leakage effects are less accurately predicted with the nodal transport method.

(v) Calculated control rod worths, using transport methods, are in good agreement with small-sample boron perturbation worths.[15] Boron worths are systematically lower than fuel worths with ENDF/B data. Calculated $^{10}B(n,\alpha)$ reaction rates relative to ^{235}U fission rates are low by about 10%.

(vi) Fission rate distributions in cores with inserted control rods are generally well calculated (that is with similar spatial biases to those in the reference cores). However, marked errors are found in more sensitive cores with asymmetric rod patterns. Reaction

rates adjacent to inserted control rods are predicted within 1-2% by transport codes.

Finally, sensitivity analysis and least squares fitting shows that the differences between calculated and experimental control rod worths are consistent with the discrepancies for other parameters.

REFERENCES

[1] McFARLANE, H.F., COLLINS, P.J., Control Rods in LMFBRs: A Physics Assessment, Rep. ANL-82-13, Argonne Natl Lab., IL (1982).

[2] CARPENTER, S.G., Measurements of Control Rod Worths using ZPPR, (Proc. Specialists' Mtg. Control Rod Measurement Techniques: Reactivity Worth and Power Distributions, Cadarache, France, CEA 1976), NEACRP-U-75 (1976) Session III.

[3] LAKE, J.A., DONCALS, R.A., "The use of critical experiments data in developing LMFBR control rod worth baises and uncertainties," (Proc. Topical Meeting on Reactor Physics and Shielding Chicago, IL 1974) Am. Nucl. Soc. Vol II 635-646.

[4] LAWRENCE, R.D., "Three-dimensional nodal diffusion and transport methods for the analysis of fast-reactor critical experiments," op cit [3] Vol II 814-828.

[5] McFARLANE, H.F., et al., "Benchmark physics tests in the metallic-fuelled assembly ZPPR-15, (Proc. International Conf. on Advanced in Reactor Physics, Mathematics and Computation, Paris, France, 1987) Vol 1 139-158.

[6] POENITZ, W.P., COLLINS, P.J., Utilization of Experimental Integral Data for the Adjustment and Uncertainty Evaluation of Reactor Design Quantities (Proc. Specialists' Meeting on Applications of Critical Experiments and Operating Data to Core Design via Formal Methods of Cross Section Data Adjustment, Jackson WY, 1988), NEACRP-L-307.

[7] BANDO, M., et al., Three-dimensional transport calculation method for eigenvalue problems using diffusion synthetic acceleration, J. Nucl. Sci. Tech. 22 10 (1985) 814-850.

[8] COLLINS, P.J., BRUMBACH, S.B., "Experiments and analysis for an axially heterogeneous LMR assembly at ZPPR" (Proc. Int. Reactor Physics Conference, Jackson WY 1988) Am. Nucl. Soc., Vol. II 309-320.

[9] COLLINS, P.J., et al., "Measurements and Analyses of Control Rod Worths in Large Heterogeneous LMFBR Cores" op cit [3] 647-658.

[10] ATKINSON, C.A., COLLINS, P.J., "The Performance of ENDF/B-V.2 Data for Fast Reactor Calculations," op cit [5] Vol 2 963-974.

[11] COWAN, C., et al., "SP-100 nuclear reactor design" op cit [8] Vol IV 315-326.

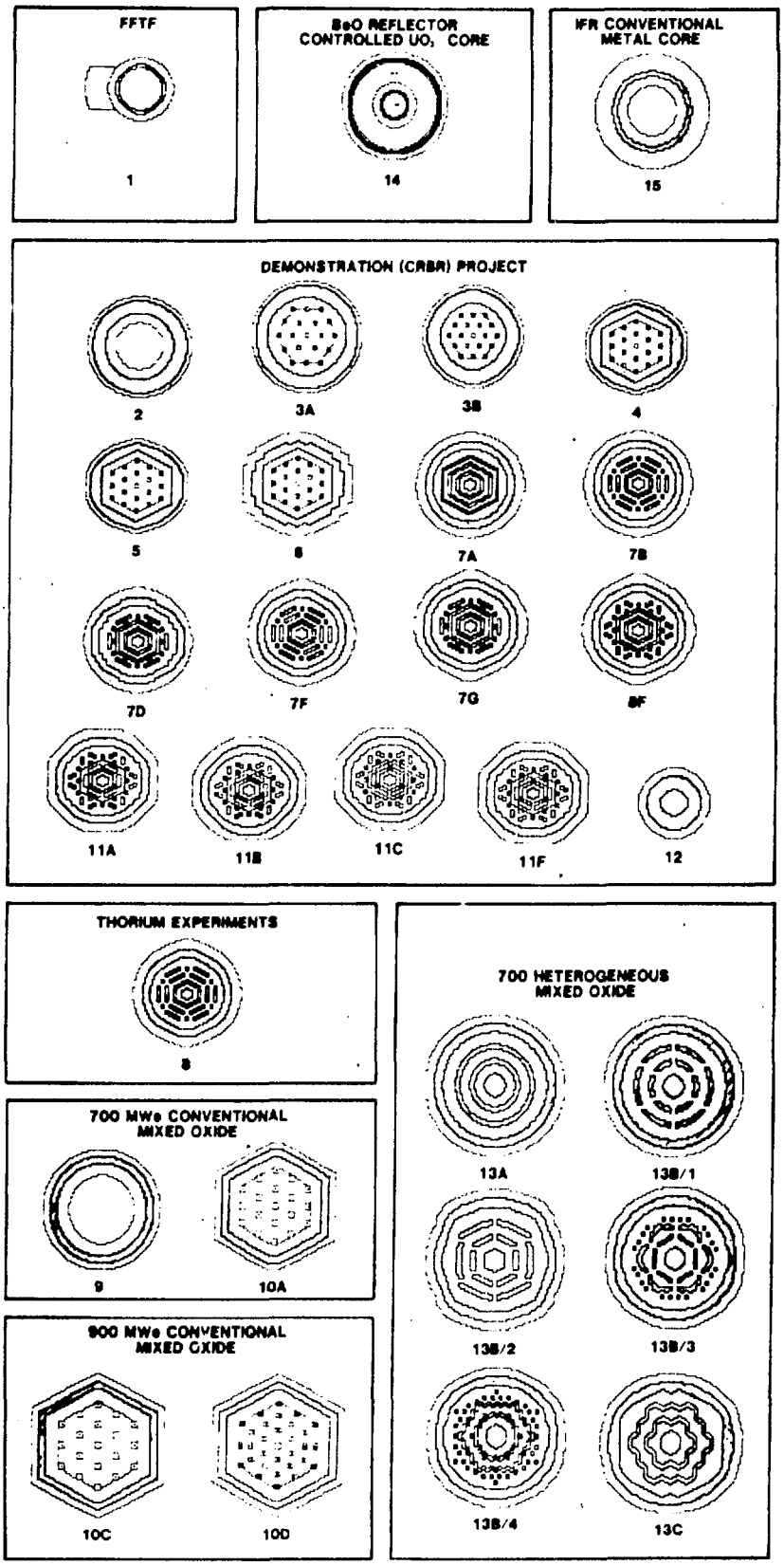
[12] SAPIR, J., et al., "Analysis of SP-100 critical experiments" op cit [8] Vol IV 327-340.

[13] McKNIGHT, R.D., COLLINS, P.J., OLSEN, D.N., "The critical eigenvalue in LMFBRs: a physics assessment" op cit [3] Vol II 750-762.

[14] BRUMBACH, S.B., et al., "Measurements and Calculations of $^{10}B(n,He)$ and $^{235}U(n,f)$ Reaction Rates in a Control Rod Mockup in ZPPR," (Proc. Topical Meeting on Reactor Physics and Safety, Saratoga Springs NY, 1986) Am. Nucl. Soc. Vol II 1145-1156.

[15] COLLINS, P.J., POENITZ, W.P., McFARLANE, H.F., "Integral Data for Fast Reactors" (Proc. Int. Conf. Nuclear Data for Science and Technology, Mito Japan, 1988).

ZPPR ASSEMBLIES



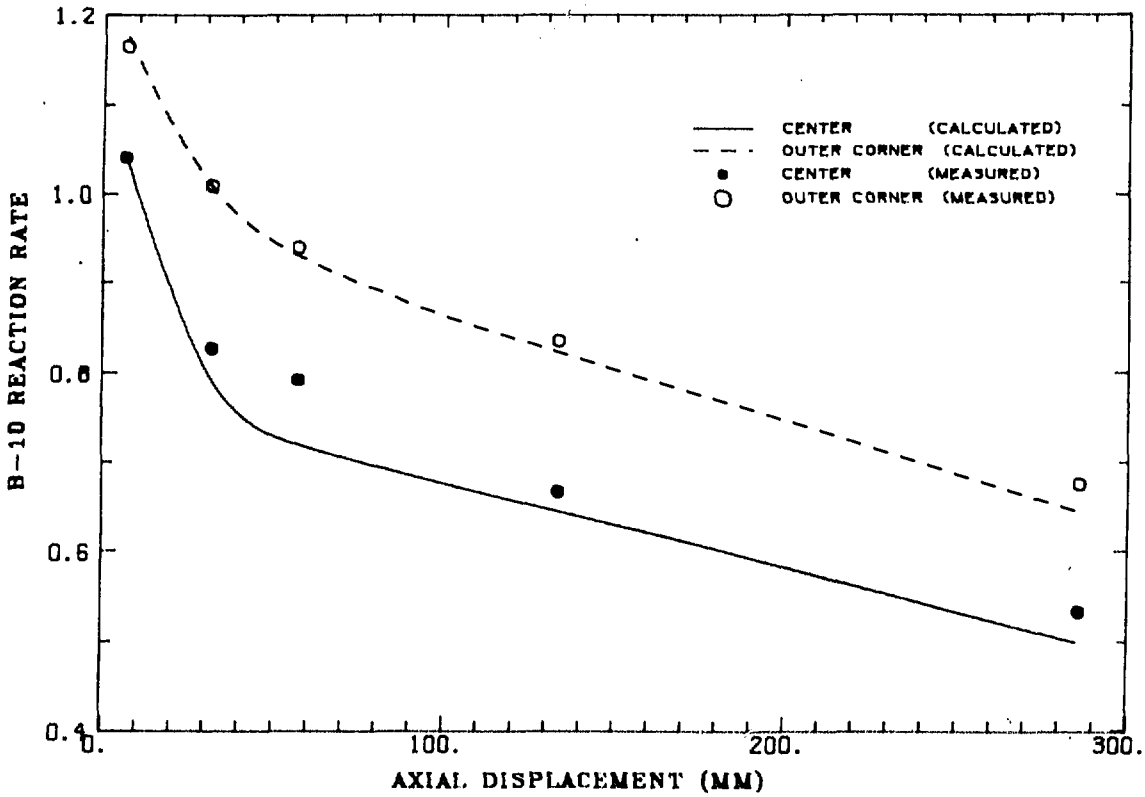


Fig. 2 Measured and Calculated Boron Capture Rate Profiles in a Control Rod

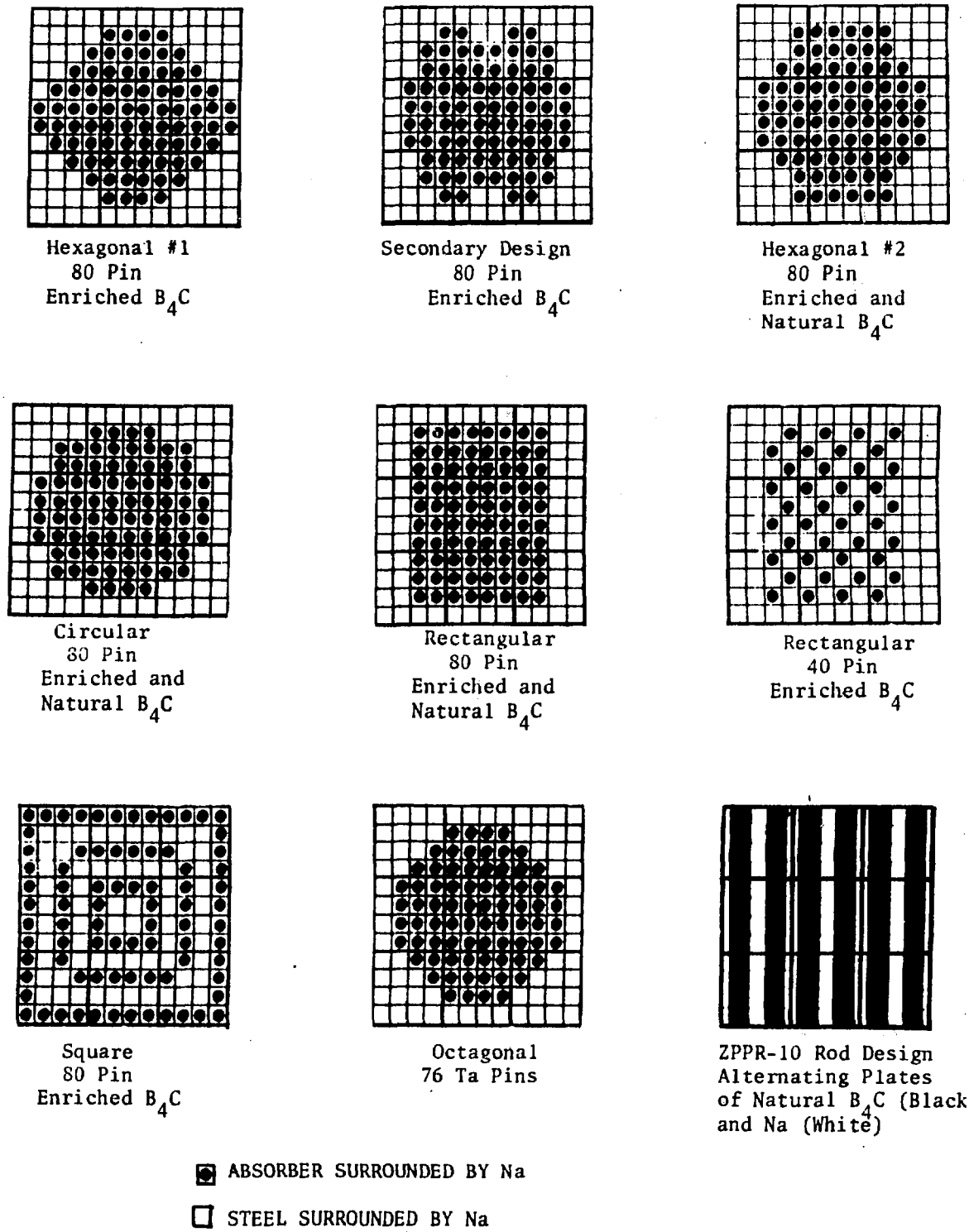


Fig. 3 Cross-sectional Views of Rod Designs Used in ZPPR-10A to Study Geometry and Enrichment Effects

Table I. ZPPR Cores with Control Rod Measurements

ZPPR Assembly	Core size, type	Analysis
3,4,6	350 MWe conventional	ENDF/B-IV
7,8,11	350 MWe radial heterogenous	ENDF/B-IV
9,10A,10B	700 MWe conventional	ENDF/B-IV
10C,10D	900 MWe conventional	ENDF/B-IV
13	700 MWe radial heterogeneous	ENDF/B-IV
15	330 MWe conventional, metal fuel	ENDF/B-V.2
17	650 MWe axial heterogeneous	ENDF/B-V.2
18	1000 MWe conventional	ENDF/B-V.2
16,20	100 KWe space reactors	ENDF/B-V.2

Table II. Summary of Analysis with ENDF/B-IV Data

Core Type	Size, MWe	No. of Data	Rod Location	Mean C/E[a]	RMS Deviation
Conventional	350	7	Central	1.054	0.014
		11	Inner	1.049	0.030
		10	Outer	1.060	0.019
Radial Heterogeneous	350	11	Inner	0.921	0.021
		40	Outer	0.984	0.012
Conventional	700-900	4	Central	1.023	0.009
		9	Inner	1.032	0.020
		19	Outer	1.069	0.018
Radial Heterogeneous No blanket gaps (ZPPR-13A)	700	2	Inner	0.987	---
		16	Middle	1.013	0.009
		18	Outer	1.043	0.016
Radial Heterogeneous with blanket gaps (ZPPR-13B)	700	7	Ring 1	0.982	0.014
		9	Ring 2	0.989	0.013
		10	Ring 3	1.005	0.015
		9	Ring 4	1.020	0.007
		15	Ring 5	1.044	0.015
Radial Heterogeneous "snow flake" (ZPPR-13C)	700	3	Inner	0.947	0.004
		13	Middle	0.973	0.015
		13	Outer	1.019	0.018

[a]Calculations finite-difference diffusion, 55 mm mesh, 8 or 9 groups.

Table III. Comparison of Calculation and Experiment for Control Rod Banks in ZPPR-13

Core	Calculation	Ring 1 Inner Fuel Zone	Ring 2	Ring 3 Middle Fuel Zone	Ring 4	Ring 5 Outer Fuel Zone
13A	Ref. DT[a]	0.987	---	1.010	---	1.044
	Corrected	0.980	---	1.011	---	1.059
13B/1	Ref. DT	0.992	1.001	1.019	1.032	1.059
	Corrected	1.004	1.006	1.033	1.045	1.068
13B/4	Ref. DT	0.968	0.972	0.977	1.014	1.027
	Corrected	0.986	0.996	1.007	1.042	1.063
13C	Ref. DT	0.951	---	0.986	---	1.042
	Corrected	0.949	---	0.990	---	1.054

[a]Reference diffusion theory, 8 groups, xy geometry 55 mm mesh.

Table V. Calculations of Control Rod Banks in ZPPR-17B by Different Methods

Rods	F.D. Diffusion C/E[a]	Nodal Diffusion C/E	Nodal Transport C/E	TRITAC S_4 C/E
Central Rod	0.885	0.968	0.966	0.920
6 Inner Ring	0.925	1.007	0.995	0.965
6 Middle Ring	0.931	1.031	1.005	0.981
12 Outer Ring	0.953	1.064	1.015	1.009

[a]Finite difference, 55 mm mesh size.

Table IV. Analysis of Control Rod Worths in ZPPR-15

	Control	Measured Worth, $	Nodal Diffusion C/E	Nodal Transport C/E
ZPPR-15B (^{239}Pu fuel)	Central CRP	0.503	1.17	1.11
	Central CR	2.83	1.018	0.988
	7 Primary CRs	19.3	0.980	0.952
	All 13 CRs	37.6	0.953	0.925
ZPPR-15D (^{235}U fuel)	Central CRP	0.158	1.18	1.12
	Central CR	1.39	0.960	0.932
	7 Primary CRs	9.58	0.952	0.939
	All 13 CRs	19.14	0.950	0.962

Table VI. Control Rod Worths in ZPPR-13C

Control Rod Bank	Measured Worth ($)	ENDF/B-IV C/E[a]	ENDF/B-V.2 C/E[a]
6 Inner Ring	4.65	0.947	0.955
12 Middle Ring	16.48	0.987	0.988
12 Outer Ring	16.69	1.054	1.016
4 near X-axis	6.94	1.083	1.046
4 near Y-axis	1.18	0.967	0.964
Radial Variation		11%	6%
Azimuthal Variation		12%	8%

[a]Calculations using consistent nodal transport models.

Table VII. Results of Least-squares Adjustment to Control Rod Worths

Core	Control Rods	C/E-1	A/E-1[a]	P/E-1[b]
ZPPR-13C	Ring 1	-5.4	0.2	0.2
	Ring 2	-2.1	1.6	1.4
	Ring 3	+0.7	-2.0	-2.1
	4 CRs at x	+3.7	0.6	0.4
	4 CRs at y	-4.4	0.0	-0.1
ZPPR-15B	Center CR	-1.2	+2.4	+2.1
ZPPR-15D	Center CR	-6.8	-0.5	-1.0
	7 Primary	-6.1	-1.8	-2.4
	All 13 CRs	-3.8	+0.3	-0.9
ZPPR-17A	Center CR	-7.8	-2.2	-2.1

[a]Adjusted calculations with control rods included in the least squares fit.

[b]Predicted control rod worths without control rods in the fit.

TABLE VIII Comparison of C/E Values for ^{235}U Fission Axial Distributions Near the Center of ZPPR-17A,17B and 17C

		ZPPR-17A	ZPPR-17B	ZPPR-17C	
Zone[a]	Axial Height (cm)	Fuel	Adjacent to CRP	Adjacent to CR	Adjacent to CRP
IB	2.6	1.004	0.973	0.949	0.963
IB	5.0	0.999	0.973	0.958	0.955
IB	7.7	0.991	0.974	0.971	0.949
IB	10.0	0.992	0.992	0.961	0.950
IB	12.8	0.994	0.969	0.960	0.955
		---	---	---	---
Zone Average C/E		0.986	0.976	0.960	0.955
Standard Deviation		0.005	0.010	0.009	0.006
IC	17.9	0.978	0.944	0.961	0.930
IC	22.9	0.972	--	0.969	0.959
IC	28.0	0.972	0.956	0.961	0.960
IC	33.1	0.977	0.969	0.983	0.959
IC	38.1	0.974	--	0.977	0.956
IC	43.3	0.979	0.952	0.958	0.968
IC	48.3	0.968	0.944	0.957	0.963
		---	---	---	---
Zone Average C/E		0.974	0.953	0.965	0.957
Standard Deviation		0.004	0.010	0.012	0.013
AB	53.4	0.968	0.957	0.966	0.979
AB	58.5	0.976	0.950	0.982	0.991
AB	63.6	0.963	0.957	0.983	0.961
AB	68.7	0.970	0.955	1.013	0.992
AB	73.7	0.995	0.956	1.054	1.072
		---	---	---	---
Zone Average C/E		0.974	0.955	1.000	1.000
Standard Deviation		0.012	0.003	0.037	0.045

[a]IB is internal blanket, IC is inner core, and AB is axial blanket. Results normalized to ^{235}U fission for the same distributions in the three cores. Axial distances measured from the midplane.

TABLE IX Analysis of ^{10}(n,He) and ^{235}U(n,f) Reaction Rates in a Control Rod

Reaction	Environment	ENDF/B-IV C/E[a]	ENDF/B-V C/E[a]	ENDF/B-V Increased 10% C/E[a]
^{235}U(n,f)	ZPPR-15A Control Rod	1.071	1.094	1.049
^{10}B(n,He)	ZPPR-15A Control Rod	0.983	0.961	0.998
^{235}U(n,f)	ZPPR-12MB Control Rod	1.025	1.035	1.010
^{10}B(n,He)	ZPPR-12MB Control Rod	0.945	0.928	0.983
^{10}B(n,He)	ZPPR-13 Core	0.921	0.913	1.006[b]

[a]All results are normalized to a C/E value of unity for ^{235}U(n,f) in the core regions.

[b]Based on calculations made for ZPPR-15A.

Table X. Results of ZPPR-10A Rod Geometry and Enrichment Studies

Cross-Sectional Geometry[a]	Material	Enrichment	^{10}B Mass, kg	Measured Worth,[a] $	C/E[b]
Circular	B_4C	Natural	1.58	-1.659	1.060
Hex #2	B_4C	Natural	1.58	-1.654	1.063
Rectangular	B_4C	Natural	1.58	-1.670	1.053
Rectangular	B_4C	92%	7.82	-2.712	1.043
Hex #1	B_4C	92%	7.82	-2.692	1.051
Hex #2	B_4C	92%	7.82	-2.689	1.052
Circular	B_4C	92%	7.82	-2.680	1.055
Secondary	B_4C	92%	7.82	-2.705	1.045
Square	B_4C	92%	7.82	-3.086	1.048
Rectangular	B_4C	92%	3.91	-2.139	1.066
Plates	B_4C	Natural	3.64	-2.608	1.069

[a]The total uncertainty in a measured value is 1%, but for purposes of comparing measurement, the uncorrelated part of the uncertainty is only about 0.1%.

[b]Exact geometries were not considered in the calculations so that the same calculation was used for the first three rods, a second calculation for the next five rods, and separate calculations for each of the last three rods. The calculations were done with diffusion theory in rz geometry with 28 energy groups. The control rod was modeled in two regions.