CORE/REFLECTOR BOUNDARY STUDIES IN DIMPLE

A. D. Knipe, B. L. H. Burbidge and B. M. Franklin

UK Atomic Energy Authority, AEE Winfrith,
Dorchester, Dorset, DT2 8DH, England

ABSTRACT

An experimental study of a cruciform core, simulating the rectangular corner configuration of a pressurized water reactor, has been conducted in the low power DIMPLE reactor. Extensive reaction-rate measurements were performed throughout the core, both with a radial fuel pin/water reflector boundary and with a stainless steel baffle region. The study, which concentrated on the complex radial boundary, has provided detailed data for the assessment of the accuracy of pin power predictions.

INTRODUCTION

The development and validation of the calculational methods and data used for thermal reactor design and analysis forms an important part of the reactor physics programme at Winfrith. The low power, water moderated, reactor DIMPLE plays a key role in this programme, providing benchmark experimental data for comparison with the recommended methods. The studies are of a generic nature and largely funded by an underlying research budget.

Measurements in water reflected cylindrical geometry assemblies in DIMPLE have shown that prediction consistently overestimates the pin power at the core/reflector boundary by about 10%. To extend these studies to power reactor geometries, a cruciform array of 3% enriched uranium dioxide fuel pins was assembled. This simulated the rectangular corner configuration of a Pressurized Water Reactor (PWR) and effectively represented twelve fuel elements, each comprising 16 x 16 pins. Two versions have been studied to-date, one with a fuel pin/water reflector boundary and one surrounded radially by a 25mm thick stainless steel reflector, to evaluate the impact of a typical PWR baffle region.

Measurements in the cruciform assemblies have provided detailed data for the assessment of pin power predictions, concentrating in particular at the complex radial core/reflector boundary where calculations are the most uncertain. In the PWR context, it is important to quantify the accuracy of these predictions for both fuel management operations and ex-core surveillance procedures. This paper describes the measurements relevant to the core/reflector boundary studies and compares the results with the predictions of LWRWIMS calculations performed using the latest data library.

THE MEASUREMENTS

Description of the Assemblies

Within DIMPLE, experimental assemblies of fuel pins are supported and precisely located between upper and lower lattice plates inside a large aluminium tank (2.6m diameter and 4m high). A wide range of assemblies can be built by varying the lattice plate design, the loading pattern, the fuel type and the inclusion of non-fuel components. The capability for reactor control by means of moderator level permits sub-critical and critical benchmark assemblies to be studied without the complicating perturbation of control rods. A more detailed description of the facility is provided in Reference 1.

The fuel pins used in these studies consisted of sintered 3% enriched uranium dioxide pellets, 10.13mm diameter, stacked within stainless steel cans, 10.94mm outer diameter, to a fuel height of 693mm. The cruciform array of 3072 fuel pins on a 12.51mm square pitch was common to both assemblies. Only the radial core boundary differed, with one configuration having a fuel pin/water reflector boundary (S06A) and the other having a 25mm thick baffle region between the core and water region (S06B). The inner baffle edge was located one-half pitch from the centre of the outermost pins.

Characterization of the Assemblies

The characterization of the two assemblies involved the measurement of a range of core physics parameters. Those relevant to the core/reflector boundary studies are described below.

The critical moderator height for each assembly was determined by the critical approach method. Inverse counts, from fission chambers in the radial reflector, were plotted against moderator height over a range of sub-critical values. The results for S06A and S06B, confirmed by water height reactivity coefficient measurements, were 476mm and 525mm respectively.

Comprehensive axial and radial reaction-rate distributions were measured in the two assemblies to provide detailed data for comparison with calculated values. Included were the three reactions of major significance to the overall neutron balance, namely fission in ^{235}U and ^{238}U and capture in ^{238}U.

Relative radial reaction-rate scans were performed with foils located at the plane of the peak axial flux in each core. Axial measurements were carried out with foils at a central core location and, more extensively, with a miniature fission chamber. The fission chamber, 6mm in outer diameter and with a 10mm sensitive length of 93% enriched ^{235}U, was employed at seven radial locations in S06A and twenty locations in S06B. At every radial location a computer controlled scanning system moved the chamber pre-determined steps within an empty fuel can, recording counts to an accuracy of better than ±0.3% at each axial position.

To provide axial bucklings, necessary for the 2D calculations described in the next section, a cosine function was fitted to each of the measured axial reaction-rate scans. The amplitude, width and centre position were varied to achieve a best-fit over a number of specified heights.

To relate the distributions measured for each reaction, experiments were performed at a central core location to determine the ^{238}U to ^{235}U fission ratio and the Relative Conversion Ratio (RCR). In the context of this work the RCR is defined as the ratio of the capture-rate per atom of ^{238}U to the fission-rate per atom of ^{235}U in the DIMPLE core, relative to the corresponding ratio measured in the well-defined thermal column spectrum of the Winfrith source reactor NESTOR.

In addition to the pin power study, absolute $^{32}S(n,p)^{32}P$ and $^{103}Rh(n,n')^{103m}Rh$ threshold reactions were measured at various ex-core locations in S06B. Here the aim was to assess the uncertainties in the predicted radial fast neutron fluxes at shielding locations spanning the equivalent PWR barrel position. The absolute fission-rate in the core was measured at a central core location using the $U(n,f)^{140}Ba \rightarrow ^{140}La$ reaction in samples of 3% uranium dioxide fuel. The experimental procedures were the same as those employed in the NESTOR Shielding and Dosimetry Improvement Programme (NESDIP)[2] at Winfrith, where a well characterized fission plate source was used to study neutron penetration through typical PWR shields. The DIMPLE shielding study, which extended the experimental data-base by including the complex source geometry of the reactor core, is outside the scope of this paper but has been reported elsewhere.[3]

Reaction-Rate Measurements

The foil techniques employed to measure axial and radial reaction-rate distributions were based on established methods.[4,5] The foils, nickel coated U_3O_8 in a nickel cermet for ^{235}U fission and depleted uranium metal for ^{238}U fission and capture, were located between fuel pellets with high-quality end surfaces. Protection from fission product contamination was provided by 0.025mm thick aluminium guard foils. The foil irradiations were performed at a peak reactor power equivalent to about 10^8 fissions/s/g of ^{235}U. The duration of the ^{235}U and ^{238}U irradiations were 30 minutes and 120 minutes respectively, with scans being repeated to reduce the random uncertainties. Following irradiation, the foils were counted at the Winfrith Counting Laboratory using automatically operated foil comparators.

The ^{235}U foils were counted for fission product beta activity using single 1mm thick x 45mm diameter plastic scintillators. The fission products contributing to the beta activity are those of high (4-6%) yield and with half-lives in the region of 1 to 10 hours, eg ^{97}Zr, ^{132}Te and ^{143}Ce. Each count was corrected for counter dead-time, background activity, predetermined natural and residual activity (where all of these corrections were less than 0.5%), radioactive decay and, by intercalibration, the effective mass of each foil. The decay correction was obtained from a monitor foil of identical composition to the scan foils and subjected to the same irradiation conditions as those at the central measurement locations. The uncertainties in the results were predominantly due to the counting statistics (±0.3%) and foil mass calibration (±0.3%).

For the fission-rate measurements in the ^{238}U foils, as capture events contribute significantly to the beta activity, the fission product gamma activity above 1.28MeV was detected using pairs of 50mm thick x 50mm diameter sodium iodide (thallium activated) detectors. The 1.28MeV threshold was chosen to eliminate gamma activity from ^{238}U capture events. The principal fission products contributing to the observed activity above this threshold energy are ^{92}Sr, ^{135}I and ^{88}Kr. The data were analyzed in a similar manner to that from the ^{235}U foils, with an additional small correction for gamma-ray attenuation within the foil. Counting statistics (±0.6%) and the foil mass calibration (±0.3%) were the main uncertainties for these results.

After a period of at least twenty-four hours, when the fission activity became acceptably small, the ^{238}U foils were counted for activity resulting from capture events. The ^{239}Np decay activity, which is preferred to ^{239}U detection mainly because of the greater time allowed for counting, was used to characterize the ^{238}U capture. One of the decay routes for ^{239}Np leads to the emission of a 106keV gamma-ray followed by higher energy gamma-rays in cascade. These higher energy gamma-rays are partially internally converted, giving rise to plutonium x-rays at 99keV, 104keV and 117keV in coincidence with the 106keV gamma-ray. Gamma-ray and x-ray activities were detected with the foils positioned between two NaI(Tl) detectors, 50mm thick x 112mm diameter. After amplification, the pulses corresponding to the 85keV to 125keV energy band were selected and the signals from each detector applied to a coincidence unit. Each coincidence count was corrected for counter dead-time, background activity (0.1-1%), natural activity (up to 1%), residual activity (negligible), gamma-ray and x-ray self-absorption in the foil (the relative effect reduced to about 1% by using foils of matched size and weight), chance coincidence events (about 0.2%), and was decay corrected back to the end of the irradiation using the ^{239}Np half-life (2.35 days).

The predominant uncertainties associated with the ^{238}U capture measurements were again the counting statistics (±0.3%) and foil mass calibration (±0.3%). However, the foil activities contained contributions from fission products, ranging from about 0.4% at the core centre to about 0.7% at the core edge. As the differential effect was small no corrections were applied, the uncertainties at the edge of the core being increased by up to ±0.3% to cover this omission.

The depleted metal foils used for the ^{238}U fission and capture measurements contained about 0.04 w/o ^{235}U. The ^{238}U to ^{235}U fission gamma activity ratio was about 0.0024 at the core centre and decreased towards the core edge. A significant fraction of the detected activity therefore originated from fission in the ^{235}U, necessitating corrections ranging from 17% at the core centre to 58% in the outermost pins in S06A and 17% to 22% in S06B. The corresponding uncertainties ranged from ±0.2% to ±1.4% in S06A and from ±0.2% to ±0.8% in S06B. The enriched uranium foils contained their principal isotope at a sufficiently high purity to render secondary fission corrections unnecessary.

All foil diameters accurately matched those of the adjacent pellets and therefore radial positional effects within the fuel can were insignificant compared to other measurement uncertainties. Based on the dimensional uncertainties of the reactor components, each foil was located within the assembly to an accuracy of about ±0.3mm. This was converted into uncertainties on the reaction-rates using the measured distributions and, depending on location and isotope, varied from about ±0.2% to ±2% in S06A and ±0.2% to ±0.7% in S06B.

The uncertainties in the measured ^{235}U fission-rates at the core boundary were dominated by the positional uncertainties because of the steep flux gradients, while at the core centre counting and mass uncertainties were largest. For ^{238}U fission both foil counting and secondary isotope uncertainties were significant, whereas for capture the counting uncertainty generally dominated. Typically, for all reactions the overall experimental uncertainty amounted to better than ±0.4% for the central measurements, increasing to between approximately ±1% and ±2% at the core edge.

The techniques used for the central reaction-rate ratio measurements were similar to those described above, with fission product gamma counting for the fission-rate measurements and coincidence counting for ^{238}U capture. The main difference was the use of fuel pellet material for the ^{235}U fission and ^{238}U capture measurements to minimize the perturbation introduced by the measurement technique. The uncertainties were typically ±3% for ^{238}U fission relative to ^{235}U fission, where the predominant uncertainty was in the calibration factor relating gamma activity to fission-rate in the two isotopes, and about ±0.5% for ^{238}U capture relative to ^{235}U fission where the predominant uncertainty was the counting statistics. A full description of the technique and the associated corrections is given in Reference 5.

CALCULATIONS

Calculations were performed with the general 2D discrete ordinates code TWOTRAN within the LWRWIMS framework.[6] A series of sensitivity calculations were carried out to investigate the influence of a range of input variables on the predicted k-eff values and reaction-rates. These included the choice of core zoning and edge mesh treatment, the calculational group structure and order of quadrature. Based on this investigation, a quarter plan model was established, the S06B version being shown in Figure 1. The model was constructed on a 39 x 39 mesh grid, with meshes 1 to 35 being one pin pitch in width and 36 to 39 in the radial reflector being two pin pitches. The outer two fuel pin meshes were sub-divided into four. The axial leakage was represented by applying a buckling term derived from the axial fission-rate measurements. Core averaged values of $24.7m^{-2}$ and $21.3m^{-2}$ were used for S06A and S06B, respectively. An LWRWIMS multi-cell collision probability calculation was used to condense the 1986 69-group WIMS data library,[7] with transport corrected total scatter and self-scatter cross-sections, to 16-group sets for the model regions in each assembly. The TWOTRAN calculations were performed in S4 quadrature to a convergence equivalent to $0.0001\Delta(-1/k)$.

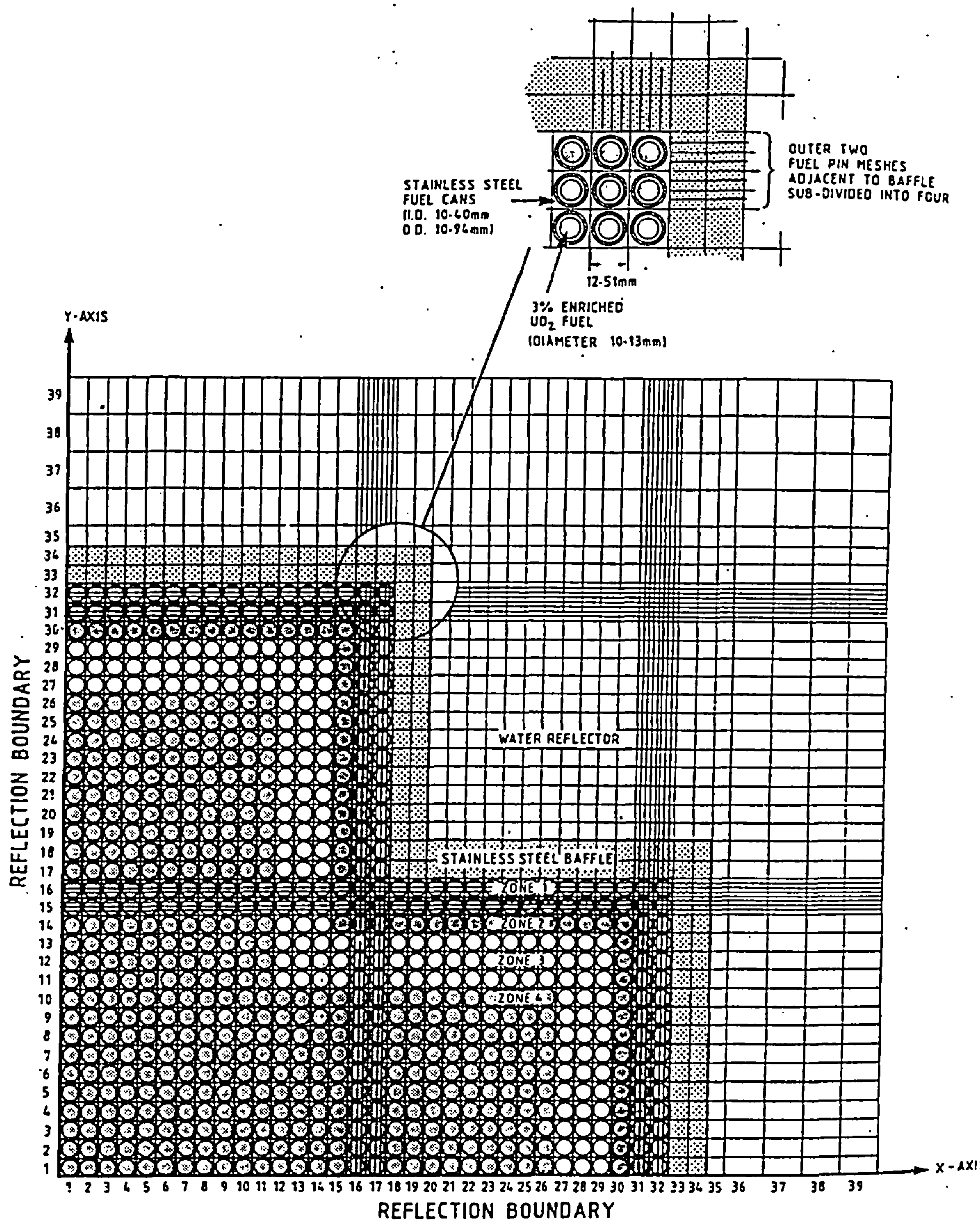

Figure 1. The Calculational Model for DIMPLE Assembly S06B

COMPARISON OF THE MEASUREMENTS AND CALCULATIONS

The calculated k-values for S06A and S06B are 0.9913 and 0.9897 respectively. The differences from unity are significantly greater than the experimental uncertainties of $\pm 0.0012 \Delta(-1/k)$, where those associated with the definition of assembly geometry, material composition and measured axial buckling predominate.

The C/E values for ^{238}U fission and ^{238}U capture relative to ^{235}U fission at the core centre are 0.988±0.035 and 0.996±0.006, respectively. In both cases experiment and prediction agree within the experimental errors, which are admittedly relatively large in the case of ^{238}U fission. This measure of agreement is typical of that obtained in other DIMPLE assemblies with the 1986 WIMS data.

For both S06A and S06B the radial reaction-rate measurements, performed at 66 different core locations, have been compared with the TWOTRAN predictions. Examples of such comparisons are provided in Figures 2 and 3 for S06A and S06B respectively, where the measured and calculated ^{235}U fission-rates along the central radial axes and core boundaries are shown. The marked difference in overall fission-rate distribution between the two assemblies is evident from the figures, where in S06B the radial baffle prevented neutrons thermalized in the water reflector re-entering the core and enhancing the fission-rate in the outermost pins as was the case in S06A.

Figures 2 and 3 indicate that the measured and calculated fission-rates along the central axes are in good agreement away from the outermost pins. However, in both assemblies the ^{235}U fission-rates in the edge pins are significantly overpredicted, the discrepancy varying azimuthally and giving maximum C/E values in S06A and S06B of 1.13 and 1.05 respectively.

To assist assimilation of the comparisons between measurement and prediction, the data are summarized in Table I in the form of mean C/E values and associated standard errors for each of the four zones defined in the calculational model (Figure 1).

Throughout the bulk of both assemblies, represented here by Zone 4, there is good overall agreement between the measured reaction-rates and those calculated by TWOTRAN. However, it is evident from the mean C/E values in Table I that prediction and measurement deviate in the proximity of the core boundary. In S06A, the average discrepancies are consistent with those found previously in the cylindrical assemblies. However, significant C/E variations from pin-to-pin in the outer zones indicate that inadequacies in the calculational treatment of the boundary geometry is an additional complication. In S06B, as a result of the stainless steel region between the core boundary and water reflector, the discrepancies are notably smaller.

As previously stated, the measurements covered three reactions of major significance to the neutron balance, with fission in ^{235}U and ^{238}U and capture in ^{238}U respectively accounting for approximately 45%, 5% and 22% of the absorption component. The impact of the differences between these measured reaction-rates and predicted values on the calculated

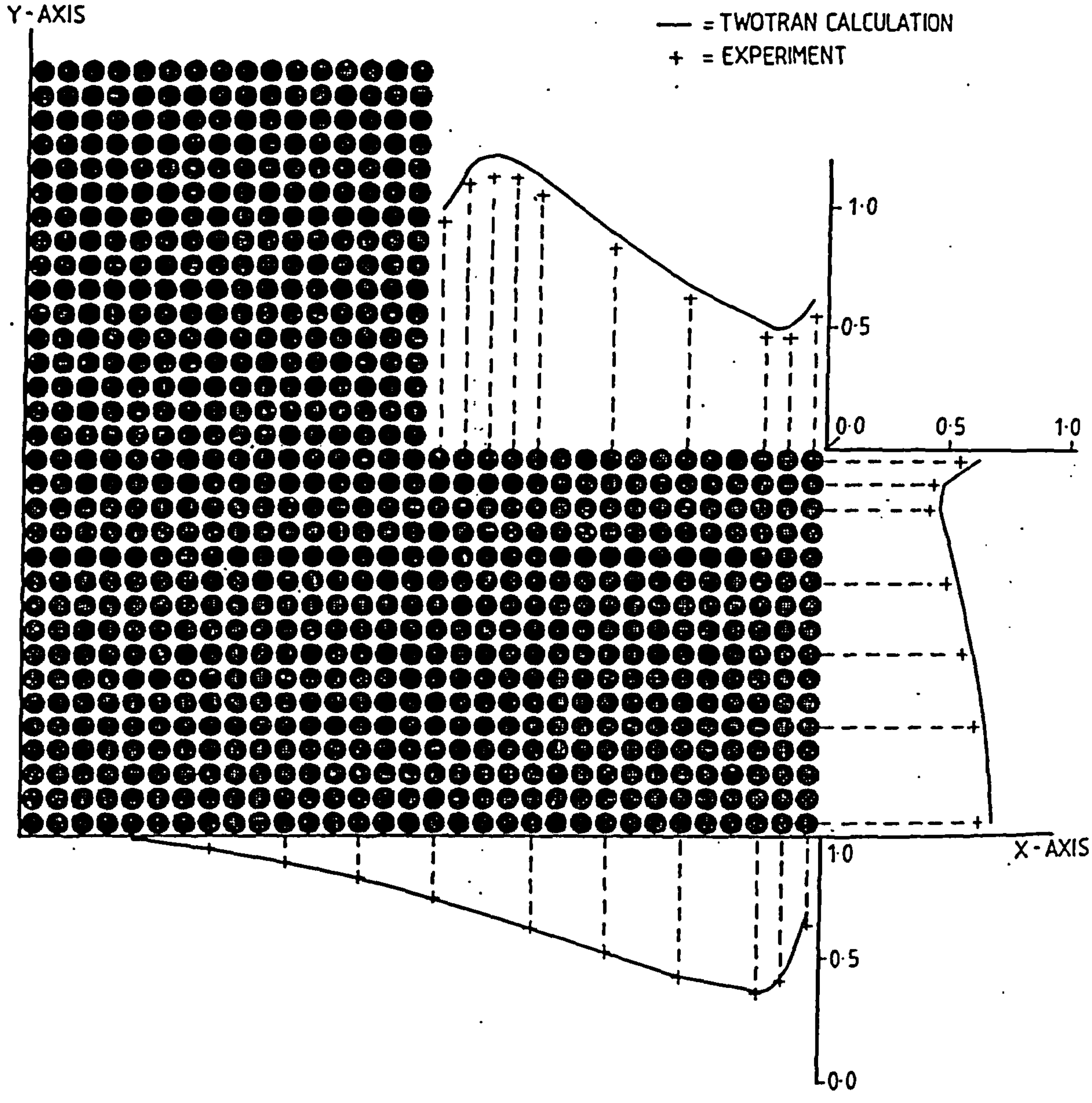

Figure 2. The ^{235}U Fission-Rate Distribution in Assembly S06A

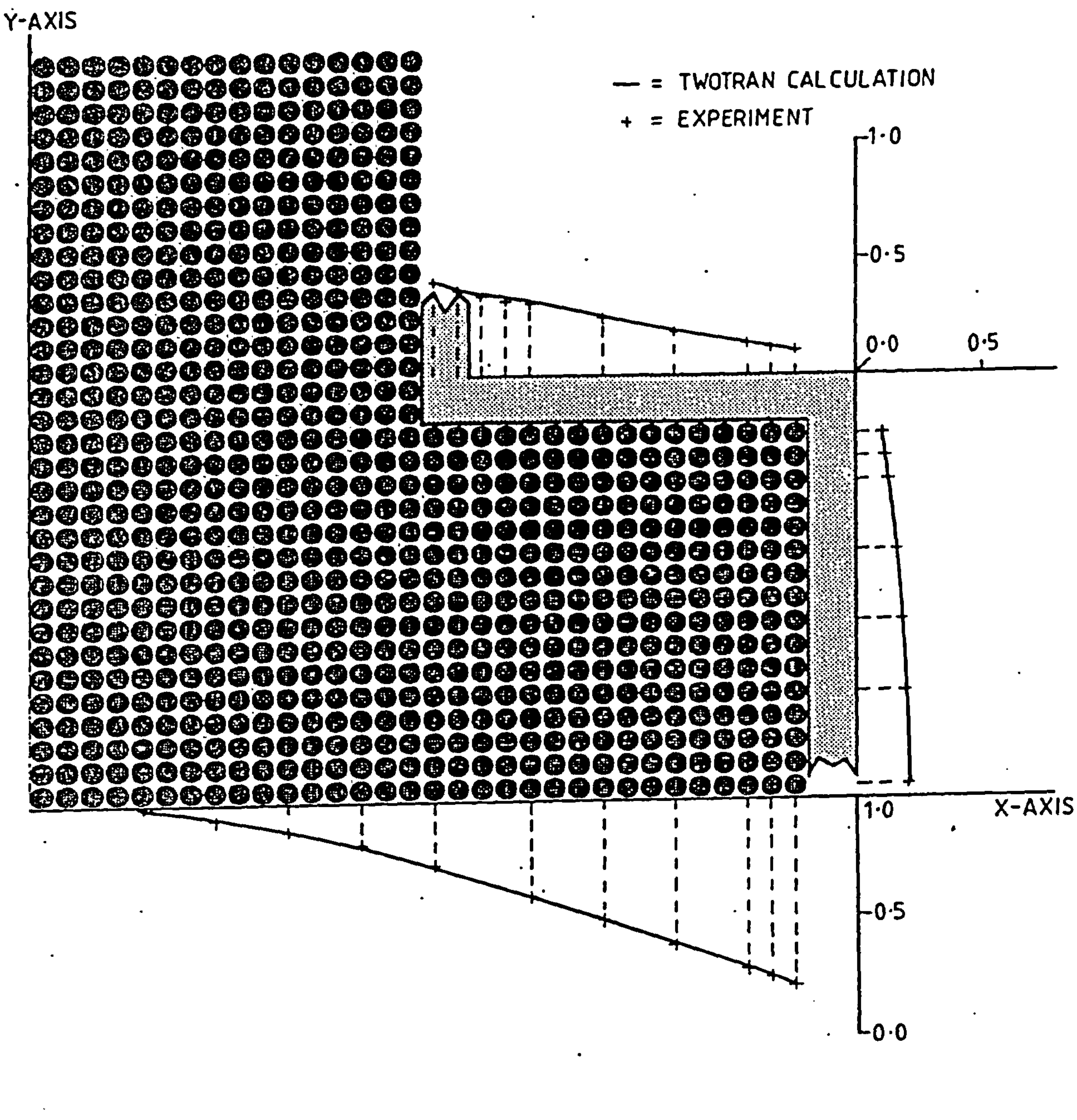

Figure 3. The ^{235}U Fission-Rate Distribution in Assembly S06B

TABLE I

Mean C/E Values for S06A and S06B

Reaction	Assembly S06A				Assembly S06B			
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 1	Zone 2	Zone 3	Zone 4
^{235}U fission	1.085 ±.006	1.040 ±.006	1.014 ±.002	1.001 ±.002	1.025 ±.004	1.003 ±.002	1.001 ±.003	0.999 ±.001
^{238}U fission	0.979 ±.006	1.028 ±.008	1.009 ±.003	0.998 ±.004	0.971 ±.006	0.997 ±.005	0.989 ±.002	0.999 ±.003
^{238}U capture	1.074 ±.005	1.029 ±.006	1.022 ±.002	0.995 ±.003	0.997 ±.006	0.984 ±.006	0.989 ±.003	0.997 ±.004

neutron balance for each assembly has therefore been examined. This entailed interpolation between measurements to produce spatially averaged corrections to the predicted neutron balance for each of the four zones. In the case of Zones 1 and 4, the derived values and uncertainties are broadly similar to those in Table I. For Zones 2 and 3 the significant pin-to-pin variations, and a limited number of measurment locations, result in the spatially averaged corrections differing by up to 3% from those in the table, with the associated uncertainties ranging from ±1% to ±1.5%. Because of the relatively good agreement between prediction and experiment for the central reaction-rate ratios, the inclusion of these data is of negligible consequence.

Correcting the neutron balances with the spatially averaged C/E values has a small but significant effect. In S06A, the decrease in ^{235}U fission produces a 0.9% decrease in the k-value, where the outermost row of pins alone contributes 0.4%. This change is partly offset by the decrease in ^{238}U capture, which increases the k-value by about 0.2%. As previously noted, there is much closer agreement between measurement and prediction in S06B, with the resultant changes in k-value being an order of magnitude smaller than S06A.

The uncertainties associated with the spatially averaged C/E values are equivalent to an uncertainty in the k-values of about ±0.3%. Correcting the k-values for the differences between the predicted and measured reaction-rate distributions gives 0.984±0.003 for S06A and 0.989±0.003 for S06B, where the deviations from unity are still significant. The discrepancies are also significant compared with the estimated uncertainties in the unassessed absorption contributions to the neutron balance, ie absorption in ^{235}U, the moderator, the cans and the baffle. On the basis of this analysis, the overprediction of the leakage component could be up to approximately 6% in both assemblies. This interpretation also tends to be supported by the overprediction of the ^{235}U fission-rates in the outermost fuel pins.

CONCLUSIONS

A major reactor physics study has been completed in DIMPLE as part of a diagnostic, step-by-step, approach to the assessment of pin power predictions. Studies in water reflected cylindrical pin arrays have been repeated in a cruciform array simulating the rectangular corner configuration of a PWR, and then extended further by including a typical radial stainless steel baffle region. Measurements in the cruciform assemblies, concentrating in particular at the complex core/reflector boundary, provided a range of detailed reaction-rate data.

Calculations have been performed with the general 2D discrete ordinates code package LWRWIMS-TWOTRAN using the 1986 WIMS nuclear data library. The k-values for the two versions of the cruciform core are underpredicted by about 1%, significantly greater than the experimental uncertanties. Comparison of the measured reaction-rates and those calculated by TWOTRAN show good overall agreement throughout the bulk of the core. However, in both assemblies prediction and measurement deviate in the proximity of the core boundary, with the average discrepancies in the fuel pin/water reflector configuration being consistent with the previous studies in cylindrical assemblies. Significant C/E variations from pin-to-pin in the outer zones of the cruciform core indicate that inadequacies in the calculational treatment of the boundary geometry is an additional complication.

Comparison of the results from the two assemblies show a general reduction in the discrepancies where the radial stainless steel baffle prevents neutrons thermalized in the water reflector from re-entering the core and enhancing the fission-rate in the outermost pins. In the configuration without the baffle region the edge ^{235}U fission-rates are on average overpredicted by 8.5%, with a maximum of about 13%. These values reduce by over a factor of two for the assembly surrounded by the radial baffle, with the mean and maximum discrepancies being 2.5% and 5% respectively.

The impact of the differences between the measured and predicted reaction-rates on the calculated neutron balances has been examined. Correcting the neutron balances with spatially averaged C/E values does not account for the overall underpredictions in the k-values for both assemblies. Although part of the discrepancy may be associated with factors such as the unassessed absorption contributions, the overprediction of the ^{235}U fission-rates in the outermost pins tentatively supports the conclusion that the core leakage component is being overpredicted. In line with the step-by-step approach, the next phase of the cruciform core programme will investigate the impact of burnable poisons on reaction-rate distributions and these studies may provide further evidence of the source of the discrepancy.

The DIMPLE cruciform cores are regarded as valuable benchmarks for the validation of calculational methods and data. The experimental data will be used to assess current power reactor design and analysis routes. The inclusion of burnable poisons will further extend the experimental data base, as will proposed future studies aimed at providing data relevant to advanced reactor designs.

ACKNOWLEDGEMENTS

The authors are appreciative of all those involved in the experimental programme and in particular acknowledge the work of Mr M F Murphy and Mr M R March of the Winfrith Counting Laboratory. In addition, the authors are indebted to Mr G Ingram for valuable discussions during this study.

REFERENCES

1. G. INGRAM, "DIMPLE and its Current Experimental Programme", Proceedings of the International Seminar on Criticality Studies, Programs and Needs, Dijon, 19-22 September 1983, 455-468.

2. M. D. CARTER, I. J. CURL, P. C. MILLER and A. PACKWOOD, "The LWR Radial Shield Benchmark Studies of the NESTOR Shielding and Dosimetry Improvement Programme NESDIP", Proceedings of the 6th ASTM-EURATOM Symposium on Reactor Dosimetry, Jackson Hole, Wyoming, 31 May - 5 June 1987.

3. A. D. KNIPE, P. C. MILLER, K. G. GREENHOUSE and M. F. MURPHY, "The Use of a DIMPLE Mock-up Experiment to Assess the Uncertainties in the Radial Shield Fluxes of a PWR", Proceedings of the 7th International Conference on Radiation Shielding, Bournemouth, 12-16 September 1988.

4. W. A. V. BROWN, et al, "Measurements of Material Buckling and Detailed Reaction Rates in a Series of Low Enrichment UO_2 Fuelled Cores Moderated by Light Water", AEEW-R 502 (September 1967).

5. M. F. MURPHY, "Fast Fission Ratio and Relative Conversion Ratio Measurements in Gadolinium Poisoned Water Moderated UO_2 Lattices", AEEW-R 1714 (January 1984).

6. LWRWIMS User Guide, ANSWERS Service, Winfrith.

7. M. J. HALSALL and C. J. TAUBMAN, "The '1986' WIMS Nuclear Data Library", AEEW-R 2133 (September 1986).