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A BURNABLE POISON PIN BENCHMARK STUDY IN DIMPLE

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ABSTRACT

Studies in the DIMPLE low power reactor are providing benchmark experimental data for the validation of the calculational methods employed in the design and operation of thermal power reactors. In the most recent phase of the programme, a series of burnable poison arrays were included in a cruciform lattice of 3% enriched uranium dioxide fuel pins. Extensive reaction-rate distribution measurements, coupled with diagnostic fine structure measurements through a fuel pin, poison pin and simulated empty guide thimble, have provided detailed data for the assessment of the accuracy of pin power predictions.

INTRODUCTION

A series of lattice studies in the DIMPLE low power reactor are providing benchmark experimental data for the validation of the calculational methods and data used in the design and operation of thermal power reactors. Studies in water reflected cylindrical systems have been extended to power reactor geometries by assembling a cruciform array of 3% enriched uranium dioxide fuel pins. This simulated the rectangular corner configuration of a PWR and effectively represented twelve fuel elements. Three major versions of the cruciform assembly have been constructed, the first (S06A) being water reflected as with the cylindrical systems. The cruciform assembly was then surrounded azimuthally by a 25mm thick stainless steel reflector to evaluate the impact of a typical PWR baffle region (S06B). The experiments concentrated on the measurement of pin powers at the complex radial core/reflector boundary, where it is important to quantify the accuracy of predictions for both fuel management operations and ex-core surveillance procedures.[1,2]

The most recent phase of the DIMPLE programme has investigated the impact of discrete burnable poison pins on reaction-rate distributions in the cruciform assembly (S06C). The burnable poison pins were of the type used in many current PWRs, comprising stainless steel clad annuli of borosilicate glass. Configurations ranged from a single isolated poison pin, through a central complex cluster which included simulated empty guide thimbles, to distributed poison arrays adjacent to the surrounding baffle. An asymmetric absorber loading was also designed to provide a 25% power tilt across the cruciform assembly. Axial and radial reaction-rate distributions were measured in key configurations, together with fine

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structure measurements through a fuel pin, burnable poison pin and a simulated empty guide thimble.

The DIMPLE S06 series of benchmarks has been calculated using the lattice code and options recommended for the Sizewell-B PWR. This paper provides a description of the burnable poison pin benchmark study and compares the experimental results with prediction.

THE MEASUREMENTS

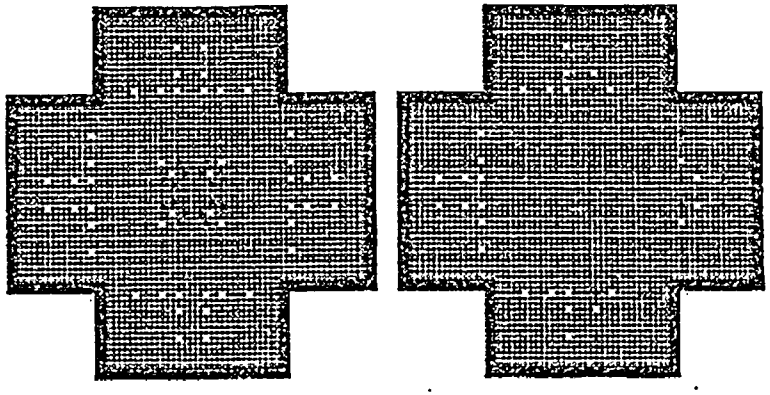
Brief Description of DIMPLE

DIMPLE is a versatile, low power, water moderated reactor used to investigate performance, safety and safeguards issues relevant to the entire nuclear fuel cycle. Thus, in addition to the lattice studies described in this paper, the current DIMPLE programme includes reactivity and neutron source measurements with samples of irradiated fuel discharged from power reactors,[3] criticality experiments relevant to fuel manufacturing, transport, storage and reprocessing issues,[4] and the development of sub-critical monitoring techniques.[5]

DIMPLE can accommodate a wide range of experimental configurations. Conventional assemblies consist of fuel pins supported, and precisely located, between upper and lower lattice plates inside a large aluminium tank (2.6m diameter and 4m high). Both simple geometry fuel pin benchmarks and more complex configurations, representative of operational or accident conditions, can be built. Flexibility is accomplished by varying the lattice plate design, fuel type and the inclusion of non-fuel components such as structural or absorber materials. Designs have been investigated for other fuel geometries (eg plate fuel and solutions) and systems with neutron spectra ranging from fast to well thermalised. The ability to control the reactor by means of moderator level alone, permits sub-critical and critical assemblies to be studied without the complicating perturbation of control rods.

The Experimental Assemblies

The S06C series of configurations was based on the S06B assembly described in Reference 1, which comprised a cruciform array of 3072 fuel pins on a 12.51mm square pitch. The assembly was surrounded by a 25mm thick stainless steel baffle, with the inner edge located one-half pitch from the centre of the outermost pins. The fuel pins consisted of sintered 3% enriched uranium dioxide pellets stacked within stainless steel cans. The design of the discrete burnable poison pin was based on the type proposed for Sizewell-B and comprised stainless steel clad annuli of borosilicate glass with a natural boron content of 4%. Moderator-filled vacant fuel pin locations were used to simulate empty guide thimbles and control overall reactivity. To accommodate a range of different poison pin arrays, the eight simulated outer elements in S06B were each modified to include five moderator locations. The resultant reactivity change from S06B to the poison pin reference assembly, S06C/0, was +0.0065Δ(-1/k).



S06C/8. S06C/11

Fig. 1. The S06C/8 and S06C/11 Assemblies

This paper concentrates on measurements made in the clean S06B assembly and the three key burnable poison configurations of a central array (S06C/8), a symmetric distributed array (S06C/10) and an asymmetric version (S06C/11). The central S06C/8 array is shown in Figure 1 and comprised sixteen poison pins and eight simulated empty guide thimbles. For the distributed arrays, burnable poison pins replaced three of the outer element moderator locations as shown for the asymmetric S06C/11 assembly in Figure 1.

Characterization of Assemblies

For each configuration, the critical moderator level and the water height reactivity coefficient were measured. The critical moderator height relative to the fuel base ranged from 525mm for S06B to 594mm for the central poison array (S06C/8). Axial and radial reaction-rate distributions were measured in the key configurations to provide detailed data for comparison with calculated values. Included were three reactions of major significance to the overall neutron balance in the fuel, namely fission in ^{235}U and ^{238}U and capture in ^{238}U, as well as fission in ^{239}Pu.

The comprehensive relative radial reaction-rate scans were performed with activation foils located at the plane of the peak axial flux. Axial measurements were carried out at a range of radial locations with foils and, more extensively, with a miniature fission chamber. 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.

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The foil techniques employed to measure the axial and radial reaction-rate distributions were based on established methods.[1] The foils, nickel coated U_3O_8 and Pu_2O_3 in a nickel cermet for ^{235}U fission and ^{239}Pu fission, respectively, and depleted uranium metal for ^{238}U fission and capture, were located between fuel pellets with high-quality end surfaces. The distributions measured for each reaction were related through central absolute reaction-rate ratio measurements performed using the techniques described in Reference 6.

An important addition to this phase of the experimental programme was the measurement of the ^{235}U fission-rate fine structure through a fuel pin, burnable poison pin and simulated empty guide thimble. The study was carried out at the centre of S06C/O using a demountable cluster arrangement with a well defined and reproducible geometry. The central position of the 3 x 3 cluster was occupied in turn by a fuel pin, a burnable poison pin and moderator. Measurements within adjacent fuel pins, and additional normalising locations well removed from the centre of the assembly, were simultaneously performed to allow a detailed intercomparison of results.

A demountable poison pin, comprising 10mm sections of borosilicate glass and associated inner can, allowed foils to be located in a similar manner to that employed for the fuel pins. Foils covering both the whole cross-sectional surface area and the central air region were inserted between the poison sections. Measurements were also made with rectangular foils attached to the inner and outer surfaces of both the fuel pin cladding and the poison pin cladding. For the empty guide thimble simulation, a foil with a diameter equivalent to a fuel pellet was irradiated in the moderator at the centre of the cluster. Cruciform geometry foils were employed in the moderator region between pins. The effect on the measured fission-rates due to the environment being perturbed by the presence of perspex holders in the demountable cluster, and the foils themselves, was determined experimentally and confirmed by calculation. The experimental corrections were derived by extrapolating measurements with stacks of foils and a range of perspex holders to zero thickness.

CALCULATIONS

Whole Assembly

The DIMPLE S06 benchmarks have been calculated using the LWRWIMS lattice code and options recommended for the Sizewell-B PWR. Reference 7 provides an overview of the main capabilities of LWRWIMS, where for power reactor calculations the package is used to generate data for the 3D steady state, transient and fuel management code PANTHER.[8]

A quarter plan model of the basic cruciform assembly 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 about two pin pitches. Each mesh was occupied by a cell type representing fuel pin, poison pin, moderator or baffle region. The geometry and materials of the pin-cell types were specified as annular regions, being sub-divided further where the change in spectrum or reaction-rate was significant. As an example, the model for the central burnable poison configuration is shown in Figure 2.

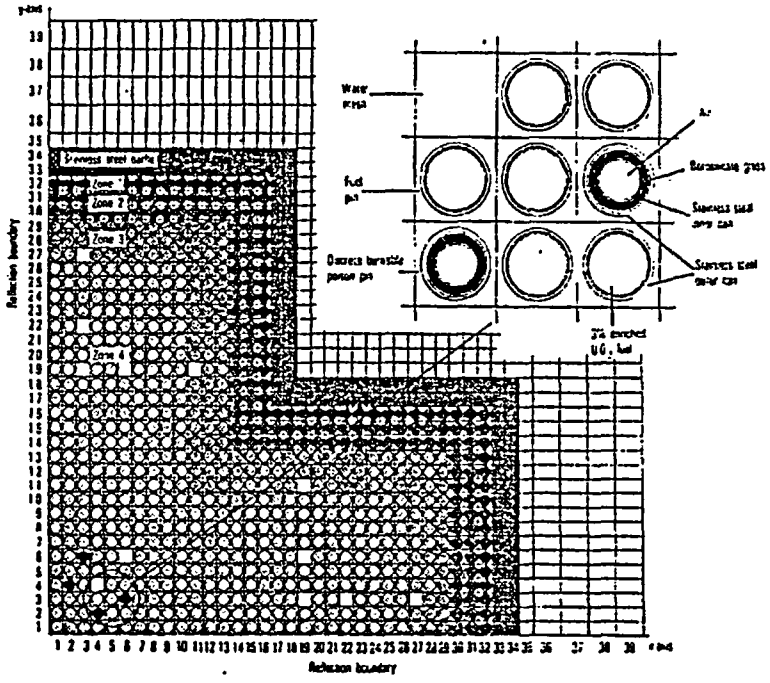

Fig. 2. The Calculational Model for Assembly S06C/8

Within the LWRWIMS framework, macroscopic cross-sections were calculated using the 1986 WIMS data library.[9] In the code package, collision probabilities are calculated for each cell type, with individual cell probabilities coupled using a multicell method which ensures a consistent interaction treatment. Following the recommended route, the cross-section data were generated in a 6-group smeared pin form for a GOG diffusion calculation with modified diffusion coefficients derived using the CACTUS DMOD option.[7] CACTUS employs a characteristics solution of the differential transport equation in the unsmeared pin-cell geometry. This provides a method for deriving effective diffusion coefficients for lattice heterogeneities that makes allowance for transport to diffusion differences, pin-cell smearing and finite difference effects.

The axial leakage in the whole assembly calculations was represented by applying a buckling term derived from the axial fission-rate measurements. A core averaged value of $21.3m^{-2}$ was used for S06B, $18.4m^{-2}$ for S06C/8, $19.2m^{-2}$ for S06C/10 and $21.3m^{-2}$ for S06C/11. The DMOD-GOG calculations were performed to a convergence equivalent to $0.0001\Delta(-1/k)$.

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As reported in Reference 1, the S06A and S06B cruciform assemblies have also been calculated using the general 2D discrete ordinates code TWOTRAN. The basic model and data preparation were as described above, except that the outer two fuel pin meshes were sub-divided into four and the calculation was performed in 16 groups. However, even with a fine mesh treatment, the LWRWIMS-TWOTRAN route proved unsuitable for predicting pin powers in the heterogeneous S06C assemblies.

Fine Structure

A 5 x 5 pin model with reflective boundary conditions was established to calculate the fine structure measurements. Three separate calculations were performed, where the central mesh location was occupied by a fuel pin, poison pin or moderator. Each cell type was represented in more detail than the equivalent whole assembly version. For example, a total of twelve annular regions were used for the poison pin. Initial data preparation followed the same route as the whole assembly calculations described above. However, final reaction-rates were calculated using the CACTUS option in LWRWIMS, with the 6-group cross-section data maintained for each region in each cell type. To assess the influence of model size, and the resultant poison pin or water mesh repetition, additional GOG calculations were performed using the same model and with the single poison pin or water mesh in their correct environment.

COMPARISON OF THE MEASUREMENTS AND CALCULATIONS

Whole Assembly

The DMOD-GOG calculated k-value for S06B is 0.9904. Similar under-predictions exist for the three S06C poison pin configurations, where the k-values are 0.9895, 0.9900 and 0.9893 for S06C/8, S06C/10 and S06C/11, respectively. Such differences from unity are significantly greater than the experimental uncertainties of typically ±0.0012Δ(-1/k), where those associated with the definition of assembly geometry, material composition and measured axial buckling predominate.

The impact of differences between measured and predicted reaction-rates on calculated neutron balances was examined in Reference 1. Correcting the neutron balances with spatially averaged C/E reaction-rate values did not account for the overall underpredictions in the k-values. Although part of the discrepancy may be associated with factors such as unassessed absorption contributions, it appears the core leakage component is overpredicted.

The C/E values for ^{238}U fission, ^{239}Pu fission and ^{238}U capture relative to ^{235}U fission at the S06B core centre are 0.988±0.035, 1.008±0.010 and 0.996±0.006, respectively. In each case 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.

Over one thousand radial fuel pin foil measurements were performed in the S06B and S06C assemblies and, to assist assimilation of comparisons with the predicted reaction-rates, mean C/E values have been derived for representative regions. Table I provides the mean C/E values and associated standard errors for the four zones defined in the calculational model shown in Figure 2. The S06C/8 reaction-rate measurements were concentrated in the region around the central burnable poison array and thus values for Zone 4 only are provided. The uncertainties in the measured ^{235}U and ^{239}Pu fission-rates were dominated by positional uncertainties in regions of steep flux gradient, with counting and mass uncertainties being the most important elsewhere. 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%(1σ), increasing to between approximately ±1% and ±2% in regions of steep flux gradient.

Table I demonstrates good overall agreement between the measured reaction-rates and those calculated using the LWRWIMS code package throughout the bulk of each assembly. However, it is evident from the mean C/E fission values for Zone 1 that measurement and prediction deviate in the outer row of fuel pins adjacent to the baffle. It was shown in Reference 1 that the presence of the baffle, which prevents the majority of the neutrons thermalised in the water reflector from re-entering the core and enhancing the edge pin power, reduces the discrepancy in the outermost pins by over a factor of three. However, the overprediction in the ^{235}U fission-rate of 2-3% and underprediction of the ^{238}U fission-rate of about 4% indicates the spectrum is being incorrectly calculated for this boundary region.

TABLE I

Mean Assembly C/E Values

Reaction	S06B				S06C/10				S06C/8
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 1	Zone 2	Zone 3	Zone 4	Zone 4
^{235}U fission	1.026 ±0.005	0.995 ±0.002	0.995 ±0.005	0.997 ±0.002	1.019 ±0.005	0.994 ±0.005	0.997 ±0.006	1.009 ±0.003	1.005 ±0.002
^{238}U fission	0.957 ±0.007	0.980 ±0.010	0.984 ±0.006	1.001 ±0.002	0.962 ±0.008	0.986 ±0.007	1.002 ±0.004	1.000 ±0.002	0.996 ±0.002
^{238}U capture	1.002 ±0.005	0.990 ±0.006	0.989 ±0.006	1.005 ±0.003	1.009 ±0.003	0.995 ±0.002	1.000 ±0.005	1.004 ±0.002	1.007 ±0.003
^{239}Pu fission	1.012 ±0.005	0.991 ±0.003	0.990 ±0.003	0.997 ±0.002	1.015 ±0.004	1.000 ±0.003	0.996 ±0.004	1.005 ±0.002	1.002 ±0.001

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Results from the S06C configurations show the same high level of agreement for fuel pin positions adjacent to a poison pin or water mesh and more distant locations. Figure 3 provides a comparison of the measured and calculated ^{235}U fission-rate distribution along the diagonal axis of the S06C/8 assembly. The scan includes two simulated empty guide thimbles and demonstrates the typical good agreement of measurement and prediction in adjacent fuel pins.

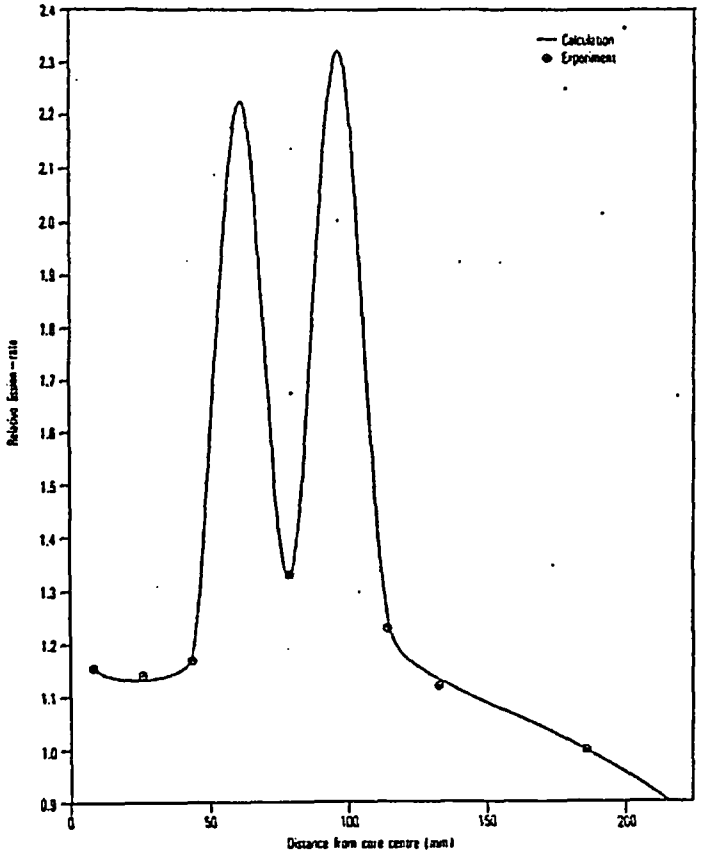

Fig. 3. The ^{235}U Fission-Rate Distribution Through Empty Guide Thimbles in S06C/8

A similar comparison involving a burnable poison pin is given in Figure 4, where the scan is parallel to the x-axis in the third row of pins from the centre. In addition to the fuel pin measurements in S06C/8, foils were included within the poison pins. These foils covered the whole cross-sectional area of the absorber and central air region. The approximate 2% overprediction of the poison pin foil measurement in Figure 4 is typical of other locations and is discussed further in relation to the fine structure investigation.

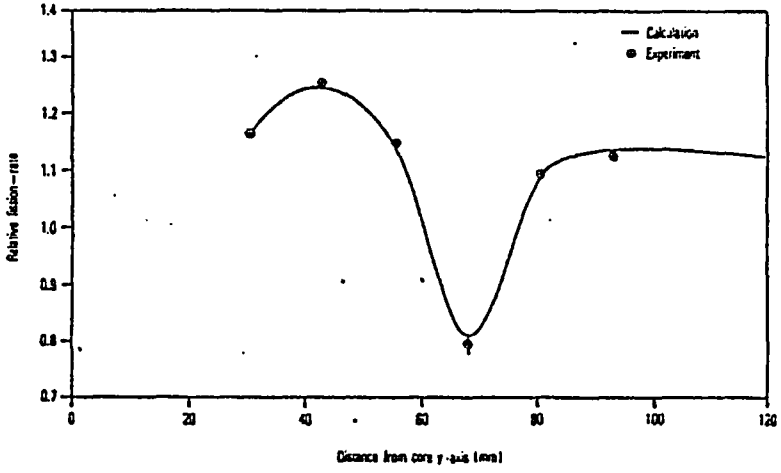

Fig. 4. The ^{235}U Fission-Rate Distribution Through a Burnable Poison Pin in S06C/8

The ^{235}U fission-rate measurements performed along the major axis of the asymmetric burnable poison configuration, S06C/11, are compared with prediction in Figure 5. Agreement can be seen to be excellent, with a mean C/E value and associated standard error of 1.002±0.002.

Fine Structure

The calculated ^{235}U fission-rate fine structure results are based on the CACTUS model described in the previous section, with small corrections from DMOD-GOG predictions to account for the limited model size and the gradient between the core centre and the measurement position. The uncertainties associated with the fine structure investigation arise largely from counting and mass uncertainties and the perturbation effects discussed previously.

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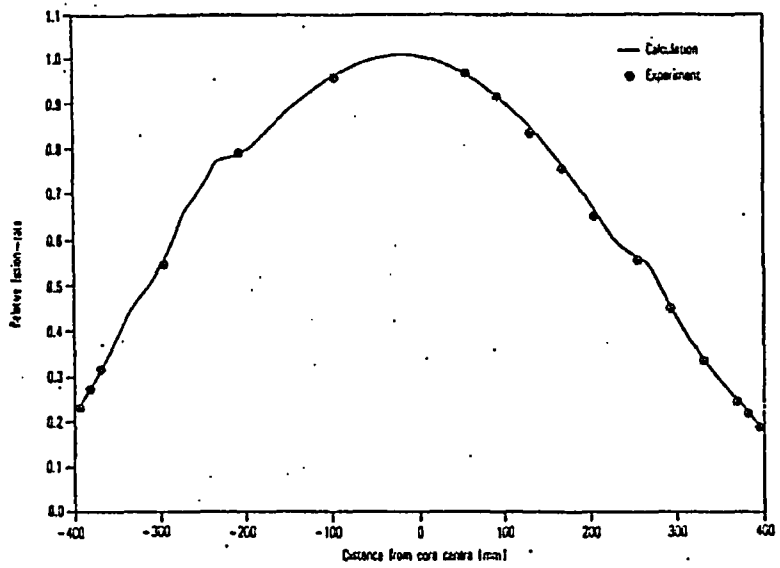

Fig. 5. The ^{235}U Fission-Rate Distribution Across S06C/11

As expected, the fuel pin fine structure measurements performed in the absence of any singularities compare well with prediction. There is also agreement within the experimental uncertainties for both the empty guide thimble simulation and burnable poison pin situation, with the exception of the central air region in the latter. The results of the poison pin investigation are summarised in Table II, where it can be seen the measurement in the annular poison region is well predicted. The significant overprediction for the central air region accounts for the apparent 2% discrepancy observed in the S06C/8 global measurements.

TABLE II

Summary of Burnable Poison Pin Fine Structure Investigation

Measurement Location	Calculation	Experiment	C/E
Adjacent Fuel Pin	1.000	1.000	1.000±0.007
Interstitial Moderator	1.139	1.131	1.007±0.009
Poison Pin Can	0.926	0.924	1.002±0.012
Annular Poison	0.734	0.739	0.993±0.006
Central Air	0.768	0.736	1.043±0.006

CONCLUSIONS

The most recent phase of the DIMPLE reactor physics programme has investigated a series of benchmark lattice configurations containing discrete burnable poison pins. The study is a continuation of a diagnostic, step-by-step assessment of pin power predictions.

Calculations have been performed with the LWRWIMS lattice code and options recommended for the Sizewell-B PWR. The k-values for the various versions of the cruciform core are underpredicted by about 1%, significantly greater than the experimental uncertainties. Comparisons of the measured reaction-rates with predictions show good overall agreement and any differences have a small effect on the calculated neutron balance. Although part of the discrepancy could be associated with factors such as unassessed absorption contributions, there is evidence the core leakage component may be overpredicted. The measured and calculated fission-rates deviate in the outer row of pins of both the S06B and S06C assemblies, with ^{235}U being overpredicted by 2-3% and ^{238}U underpredicted by about 4%. Whilst these comparisons indicate inadequacies in the LWRWIMS DMOD-GOG treatment of the core/reflector boundary, the discrepancies are not significant in terms of power reactor calculations. The recommended LWRWIMS-PANTHER route provides a more accurate estimate of core leakage using explicit reflector data derived from TWOTRAN calculations.

The overall results from the S06C configurations demonstrate LWRWIMS ability to predict pin powers adjacent to poison and water mesh locations with equal precision to clean lattice geometries and within the target accuracies for Sizewell-B. Measurements of the average ^{235}U fission-rate across the burnable poison pins themselves are overpredicted by about 2%. However, an experimental investigation of the reaction-rate fine structure has revealed the absorber region itself is well predicted and the apparent discrepancy is attributable to a 4% overprediction in the central air region.

Lattice studies in DIMPLE are providing valuable benchmarks for the validation of the calculational methods and data employed in the design and operation of thermal power reactors. The proposed future programme for DIMPLE is aimed at providing experimental data relevant to advanced reactor designs.

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REFERENCES

1 A. D. KNIPE, B. L. H. BURBIDGE AND B. M. FRANKLIN, "Core/Reflector Boundary Studies in DIMPLE," *Proc. Int. Reactor Physics Conf.*, Jackson Hole, Wyoming, September 18-22, 1988, Vol. III, p465 (1988).

2 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," *Proc. 7th Int. Conf. Radiation Shielding*, Bournemouth, September 12-16, 1988, Vol. I, p231 (1988).

3 J. MARSHALL, G. INGRAM, N. T. GULLIFORD AND M. DARKE, "Irradiated Fuel Measurements in DIMPLE," *Proc. Int. Conf. Physics of Reactors: Operation, Design and Computation*, Marseille, April 23-27, 1990.

4 J. M. STEVENSON, B. M. FRANKLIN, B. L. H. BURBIDGE, A. PRESCOTT AND G. POULLOT, "Benchmark Experiments to Simulate a Nuclear Transport Flask Loading Accident with Fuel Elements of Unequal Reactivity," EUR-12048-EN, Commission of the European Communities (1989).

5 G. INGRAM, A. D. KNIPE AND B. M. FRANKLIN, "Development of Subcritical Monitoring Techniques Using the DIMPLE Reactor," *Proc. Int. Topl. Mtg. Safety Margins in Criticality Safety*, San Francisco, California, November 26-30, 1989, p104 (1989).

6 M. F. MURPHY, "Fast Fission Ratio and Relative Conversion Ratio Measurements in Gadolinium Poisoned Water Moderated UO_2 Lattices," AEEW-R 1714, United Kingdom Atomic Energy Authority (1984).

7 M. J. HALSALL, D. POWNEY AND M. R. MOXOM, "LWRWIMS, The WIMS Code for Light Water Reactors," *Proc. Int. Conf. Physics of Reactors: Operation, Design and Computation*, Marseille, April 23-27, 1990.

8 J. C. A. EMMETT and P. K. HUTT, "PANTHER and the UK Code Package for Fuel Management Calculations," *IAEA Technical Committee on Improvements of In-Core Fuel Management Codes*, Madrid, July 12-15, 1988.

9 M. J. HALSALL AND C. J. TAUBMAN, "The '1986' WIMS Nuclear Data Library," AEEW-R2133, United Kingdom Atomic Energy Authority (1986).

CRITICAL EXPERIMENTS AT VERY HIGH TEMPERATURE REACTOR CRITICAL ASSEMBLY(VHTRC)

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ABSTRACT

In order to verify the calculation accuracy related to the neutronic design of HTTR(High Temperature Engineering Test Reactor), critical experiments have been conducted using the critical assembly VHTRC(Very High Temperature Reactor Critical Assembly), which has pin-in-block fuel. The VHTRC-1 core was made by loading rods which contained fuel compacts of the coated particles of the 4% enriched uranium.

The following measurements were carried out on the VHTRC-1 core: 1)critical mass, 2)reactivity worths of HTTR mockup control rod and burnable poison rod, 3)neutron flux distribution, 4)temperature coefficient of reactivity and 5)kinetic parameter β_{eff}/Λ.

Calculations were performed with the SRAC code system using the nuclear data based on the ENDF/B-IV. The agreements between calculations and experiments were fairly good for most experimental items except the value of kinetic parameter. The results obtained satisfy the accuracy requirments for fundamental nuclear design of HTTR.

INTRODUCTION

Since 1969, research and development for a High Temperature Gas Cooled Reactor(HTGR) have been continued at the JAERI. An HTTR[1] is under the licensing to start the construction in 1990. The core of HTTR comprises the prismatic pin-in-block type fuel blocks using the uranium of 6% enrichment on the average. Such a core structure is different from both of the pebble-bed type reactors, the Arbeitsgemeinschaft Versuchsreaktor(AVR) and the thorium high temperature reactor(THTR) in the Federal Republic of Germany(FRG) and the multihole-type reactor, the Fort St.Vrain(FSV) reactor in the United States. A critical assembly VHTRC[2] was constructed by modifying the SHE(Semi-Homogeneous Experiment) assembly[3] in order to verify the nuclear design accuracy of HTTR.

This paper describes the outline of experimental results on the initial loading core,VHTRC-1,which is loaded with the coated particles of 4% enriched uranium. The experimental items are the critical mass, the reactivity worths of HTTR mockup control rods and burnable poison rods, the neutron flux distribution, the temperature coefficient of reactivity and the kinetic parameter. The analyses were performed with the SRAC code system using the nuclear data based on the ENDF/B-IV data file.

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