In the second stage of the study of SGHW reactor physics at AEE Winfrith, a number of multi-zone cores have been investigated in DIMPLE and JUNO to test the METHUSELAH-AIMAZ method of predicting power distributions and reactivities in SGHW design and performance calculations. The range of experiments includes cores with two radial zones, chess-board cores and three-batch roundelay cores. Channel perturbation effects and reflector effects have also been studied, and measurements with fuels containing up to 8 kg/Te of plutonium have been included to simulate the burn-up of feed enrichment SGHW fuel to a mean irradiation of 21 000 MWd/Te.

Further reactor physics studies for steam generating heavy water reactors

Part 2: Multi-zone cores for fuel management studies

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INTRODUCTION

The study of a wide range of uniform cluster Steam Generating Heavy Water lattices containing UO_2 or PuO_2/UO_2 fuel has been described in a companion paper in this journal.[1] This work forms part of a series of reactor physics investigations in support of the 100 MW(E) prototype SGHW reactor which was brought into operation at AEE Winfrith during 1967, and is described in detail elsewhere.[2,3]

2. Following the work with uniform cluster lattices, a wide range of multi-zone cores was studied in the zero energy reactors DIMPLE and JUNO at Winfrith to provide experimental confirmation of the methods of calculation to be adopted for optimization of the prototype fuel management scheme. The measurements made in a number of the more important cores are described in this Paper. The main features of the PATRIARCH design scheme of calculation are noted, and measured and predicted core reactivities and power distributions are compared in detail to provide a sound basis for assessing the confidence with which estimates of these parameters may be made for SGHW power reactors.

3. Burn-up of feed enrichment UO_2 fuel in an SGHWR to a mean irradiation level of 21 000 MWd/Te leads to the production of fuel containing about 7 kg/Te of plutonium. In planning the experimental programme, it was therefore important to provide adequate confirmation of the validity of the calculational methods for the case of adjacent channels containing fuels of widely differing isotopic content. Existing 3% enriched UO_2 and PuO_2/UO_2 containing 8 kg/Te of plutonium have been used in alternate channels of a chess-board array (Fig. 1) to provide a stringent test of the methods adopted for fuel management studies.

4. Like most other prototype reactors, the initial loading of the SGHWR contains a large proportion of non-standard fuel channels for testing vibro-compacted fuel, thinner cans, more highly rated fuel, larger diameter pins, etc., and many of these channels will have a perturbing effect on the power distribution in their vicinity. The results for perturbed cores are presented, and it is shown that the METHUSELAH-AIMAZ codes in the PATRIARCH scheme predict such effects with good accuracy in the central core region.

5. Although reflector effects on reactivity are seldom significant in large D_2O moderated reactors, their influence on the power distribution near the periphery of the core may well be important. This is especially so in cases such as the SGHWR prototype, where particularly non-standard channels are placed in edge positions, and check measurements of such effects in one of the experimental cores are compared with theory.

6. In a paper of this kind, it is not possible to include details of all the 40 or 50 multi-zone cores studied during this programme.

DESCRIPTION OF EXPERIMENTAL CORES AND MEASURING TECHNIQUES

Multi-zone lattices in DIMPLE and JUNO

The experimental study of multi-zone cores was divided into two parts. The first was concerned exclusively with uranium

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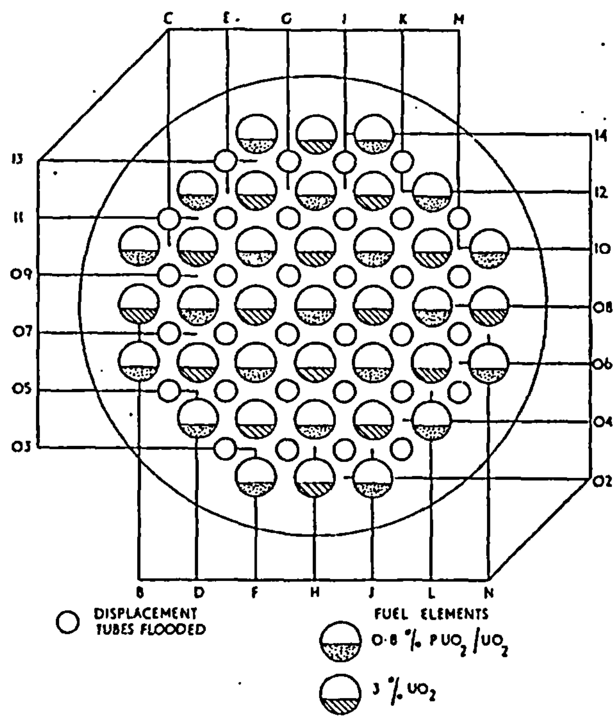

Fig 1 Plan of core SGP4/1 in JUNO

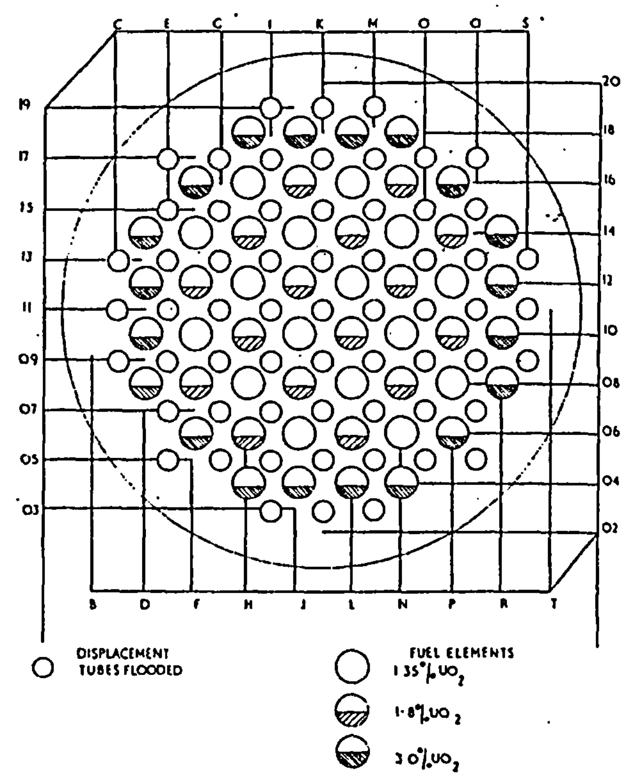

Fig 2 Plan of core SG18/E13 in DIMPLE

fuelled cores and was carried out in DIMPLE, while the second extended the study to include plutonium fuelled cores and was carried out in JUNO. Since the main design parameters of the SGHW prototype had been settled before this part of the programme started, it was possible to base these measurements on a core geometry similar in most important respects to the SGHWR prototype. The lattice pitch, coolant/fuel volume ratio and moderator/fuel volume ratio were all chosen on this basis, as shown by the core details which are listed in Tables 1 and 2. In general the cores were of four main types.

(i) *Two-zone cores with radial enrichment variation.* A uniform central zone is surrounded by an outer zone of different enrichment, e.g. SG17 and SGP2 (Figs 6 and 8).

(ii) *Chess-board cores.* The 'black' and 'white' channels have different enrichments and/or different types of fuel, e.g. SGP4 (Fig. 1).

(iii) *Three-batch roundelay cores.* A central chess-board region is surrounded by an outer annulus of channels at a higher mean enrichment, e.g. SG18 (Fig. 2). Fuel management studies using the METHUSELAH-AIMAZ calculational scheme led to the choice of a three-batch roundelay scheme for the operation of the prototype. In this scheme each batch of fresh fuel is initially loaded into the annular region round the core periphery and is then moved when partly irradiated into the 'black' or the 'white' central channels. Each channel is thus moved only once during its life in the core, and it has been shown that the power variations between adjoining channels can be kept to an acceptable level by this means. An enrichment scatter loading scheme can also lead to this type of core configuration. The experimental studies in this type of core are therefore particularly relevant to the operation of the prototype, while the earlier measurements in core types (i) and (ii) provide a direct check on individual points of core representation.

(iv) *Perturbed cores.* In these one or more fuel channels or other lattice components were non-standard. Measurements have been made both with a perturbed channel near the core centre, and in a position of high flux gradient near the edge of the core.

8. Facilities are available in the prototype for changing the void coefficient and radial power distributions during life by means of flooding or emptying an array of moderator displacement tubes (Fig. 2). Measurements have been made in a number of cores to check the calculation of the effect of altering the status of various patterns of moderator displacement tubes. One of the most severe tests of the theory was the case in which the displacement tubes in one half of a regular core (SG15/E3) were voided, leaving the tubes in the other half of the core flooded, hence producing a tilt of about 80% across the core. The experimental results from this core are compared with theoretical predictions in para. 53.

9. To provide a basis for comparison, the results of the

Table 1: *Composition of fuel elements studied in multi-zone SGHW cores*

Type of element	Material % by weight U-235	Pu-239	Pu-240	Pu-241	Geometry	$\frac{V_{coolant}}{V_{fuel}}$	$\frac{V_{moderator}}{V_{fuel}}$
Elements used in DIMPLE							
(a) 1·35% UO_2	1·35	—	—	—	74 × 0·4 in.	1·0	6·7
(b) 1·8% UO_2	1·80	—	—	—	126 × 0·3 in.	0·8	7·0
(c) 3% UO_2	3·01	—	—	—	74 × 0·4 in.	1·0	6·7
Elements used in JUNO							
(a) 1·35% UO_2	1·35				74 × 0·4 in.	0·9	6·7
(b) 3% UO_2	3·01				74 × 0·4 in.	0·9	6·7
(c) 0·25% PuO_2/UO_2	0·91	0·230	0·015	0·001	74 × 0·4 in.	0·9	6·7
(d) 0·8% PuO_2/UO_2	0·43	0·710	0·076	0·010	74 × 0·4 in.	0·9	6·7

Note: (a) The JUNO elements contained slightly less coolant because cans of increased diameter were necessary to accommodate encapsulated PuO_2/UO_2 fuel.
(b) Lattice pitch was 10·25 in. in all cores in both DIMPLE and JUNO.
(c) The coolants used were light water (Water) and mixtures of light and heavy water containing between 50 and 70% D_2O by weight (Mixture).

Table 2: *Details of multi-zone SGHW cores studied in DIMPLE and JUNO*

Core no.	Core type	Central zone: Type of element	No. of elements	Coolant composition % H_2O	Outer zone: Type of element	No. of elements	Coolant composition % H_2O	Moderator concentration of B_{10} p.p.m.	Notes
DIMPLE cores									
SG15/E3	Uniform	1·35% UO_2	68	31·5	N/A	N/A	N/A	0	Moderator displacement tubes flooded
SG15/E4	Uniform	1·35% UO_2	68	31·5	N/A	N/A	N/A	0	Moderator displacement tubes empty
SG17/E8	Two-zone	1·35% UO_2	44	32·0	1·8% UO_2	24	32·0	0	
SG16/E5	Chess-board	1·35% UO_2 3% UO_2	20 20	31·5	1·35% UO_2	28	31·5	5·2	Moderator displacement tubes empty in central zone
SG16/E7	Chess-board	1·35% UO_2 3% UO_2	20 20	100	1·35% UO_2	28	100	5·2	Moderator displacement tubes empty in central zone
SG18/E11	Three-batch roundelay	1·35% UO_2 3% UO_2	16 16	32·0	1·8% UO_2	20	32·0	4·0	Moderator displacement tubes empty
SG18/E13	Three-batch roundelay	1·35% UO_2 1·8% UO_2	16 16	32·0	3% UO_2	20	32·0	7·0	Average thickness of reflector 22·9 cm
JUNO cores									
SGP1/1	Uniform	0·25% PuO_2/UO_2	37	100	N/A	N/A	N/A	0	
SGP1/2	Uniform	0·25% PuO_2/UO_2	37	33·0	N/A	N/A	N/A	0	
SGP2/1	Two-zone	0·8% PuO_2/UO_2	21	48·8	1·35% UO_2	16	48·8	0	
SGP4/1	Chess-board	0·8% PuO_2/UO_2 3% UO_2	21 16	31·8	N/A	N/A	N/A	7·6	
SGP4/2	Chess-board	0·8% PuO_2/UO_2 3% UO_2	12 6	32·3	N/A	N/A	N/A	6·4	Average thickness of reflector 28·3 cm
SGP4/3	Chess-board	0·8% PuO_2/UO_2 3% UO_2	12 9	32·0	N/A	N/A	N/A	2·9	

reactivity and power distribution measurements in two uniform cluster lattices are included in this Paper, one fuelled with enriched UO_2 (SG15) and the other with PuO_2/UO_2 fuel (SGP1). Information on all the fuel and lattice components used in the multi-zone cores have already been given in reference 1, except for the 3% enriched UO_2. The latter is of the same nominal dimensions as the 1·35% enriched fuel (i.e. 0·4 in. dia.) but contains 3·01% U-235 by weight of total uranium.

Experimental techniques

The measurements made in these cores were of three types:

(i) radial power distribution across the core

(ii) power sharing between adjacent channels in chess-board cores

(iii) buckling measurements to check the overall prediction of reactivity.

Axial buckling measurements were made in all cores, and in some cases it was also possible to infer radial bucklings from the power distribution measurements.

11. The radial distribution measurements were all made with detectors which measured the U-235 fission rate. In each core, measurements were made of the relative U-235 fission rates in the centres of representative fuel clusters using small fission chambers positioned in the centre tube of the cluster, which is normally empty. A cross section of a typical cluster

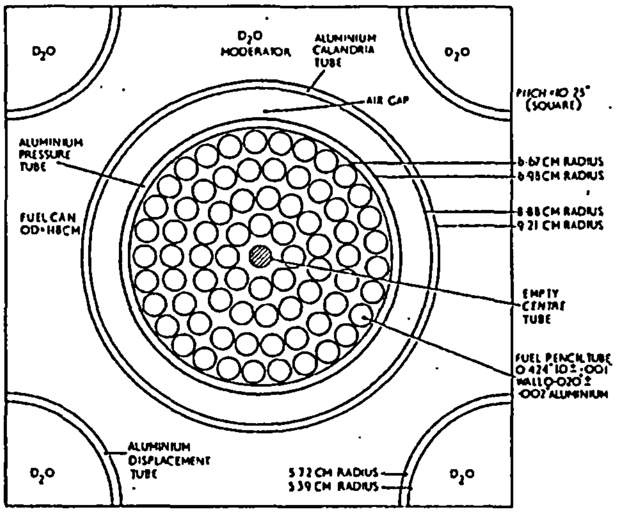

Fig 3 Lattice cell for a 74-rod cluster in JUNO

is shown in Fig. 3. In typical channels of each enrichment measurements were made of the radial distribution of U-235 fission rate across the cluster, using standard foil irradiation techniques.[2] These foil measurements were used to define a 'dip factor' for each type of element as follows:

$$\text{dip factor} = \frac{\text{mean U-235 fission rate in fuel cluster}}{\text{U-235 fission rate in centre of fuel cluster}}$$

This definition is convenient in present circumstances since similar dip factors are required during the operation of the prototype at power to transform the activities of copper flux measuring wires into the equivalent channel powers. On the assumption that the dip factor does not vary with position across the core the mean U-235 fission rate, for a channel of type X, is then given by:

$$(\text{mean U-235 fission rate})_X = (\text{U-235 fission rate in cluster centre})_X\ (\text{dip factor})_X$$

12. Use of this procedure allowed measurements to be made in a much larger number of fuel channels in each core than would have been possible if only direct measurements of mean U-235 fission rate had been made by foil techniques. However the price to be paid for this advantage was that the variation of dip factors with core position introduced a small additional uncertainty into the analysis of the measurements. The validity of the assumption of constant dip factors was tested experimentally and the results are discussed in para. 47. With the exception of the outermost ring of fuel elements in reflected cores the variation of dip factor leads to an uncertainty of less than $\pm 1\%$. Other typical contributions to the random error are

(i) measurement of U-235 dip factors: $\pm 1\frac{1}{2}\%$

(ii) measurement of central U-235 fission rates: $\pm 1\%$.

Combining these uncertainties leads to a total uncertainty of about $\pm 2\%$ (1σ). In the reflected cores irregularities in the outermost zone led to a greater variation of dip factor of up to $\pm 3\%$. In core SG18/E13 this variation was measured, so no additional random errors affect the outer channels. The other two reflected cores SGP4/2 and SGP4/3 (Fig. 9) were studied in JUNO; no measurements of the variation of dip factor were made, so the total uncertainty on the relative powers from the outer channels in these cores is about $\pm 4\%$ (1σ). These uncertainties are considered acceptable against a general requirement to predict relative channel powers in the prototype SGHWR to an accuracy of $\pm 5\%$.

13. The measurements of power sharing between the black and white channels of the chess-board cores were made by conventional foil irradiation techniques, to an accuracy of $\pm 1\%$ using U-235/Ni foils. In fact these measurements formed part of the determination of dip factors discussed in para. 12.

14. Measurements of buckling were all made by measuring flux distribution with U-235 fission chambers traversed through the cores. Axial bucklings were determined in this way for each core, corrections being made for the effect of the moving fission chamber on the measured flux distributions.[5] Radial bucklings were inferred for the central zone of each of the unperturbed cores. Simple analysis sufficed for the cores with uniform central zones, but the chess-board cores presented some problems, partly owing to the variations between adjacent channels, and more seriously owing to the azimuthal variation of the flux caused by the loading of a chess-board pattern into a moderator centred lattice. This work is fully described in reference 6, in which it is shown that radial buckling with an uncertainty of about $\pm 0{\cdot}05\,\text{m}^{-2}$ can be inferred from measurements in quite small chess-board cores provided that the necessary corrections for the azimuthal flux variations are properly applied.

THEORETICAL TECHNIQUES

Introduction

The design method of computation for enriched SGHW reactors is based on the PATRIARCH system of computer programmes[7] which is designed to cover all aspects of nuclear-thermal-hydraulic reactor performance. In the previous paper[1] on experiments with uniform arrays, the only part of the PATRIARCH scheme which was tested was the METHUSELAH programme[8] which computes the fine structure and reaction rates in an array of similar cells using a five-group model. For comparison, some more elaborate multi-group transport theory calculations were carried out using the WIMS programme.[9]

16. In the present Paper, results are presented for non-uniform arrays in which the fuel composition varies from channel to channel, and reflector and perturbation effects are also involved. These experiments have been devised to test further aspects of the PATRIARCH scheme, and the METHUSELAH-AIMAZ, JANUS 2, JANUS 5 and QUAVER codes are involved at various stages of the comparisons with experiment. The main characteristics of these programmes are described below.

Programmes used for comparison with experiments

METHUSELAH[8]

This is a five-group diffusion theory programme with two overlapping thermal groups for computing fine structure, reactivity and reaction rates in a cell in an infinite array of similar cells. It can also perform reactivity calculations for uniform cores with a fundamental mode buckling. The version of the programme used in this Paper is METHUSELAH II[10] which is an improved version of the original programme as described in reference 1. An output option in METHUSELAH provides punched input data cards for the various programmes of the PATRIARCH schemes.

JANUS 2[11]

This is a two-group diffusion theory programme which does fine structure and reaction rate calculations for a pair of cells of an infinite chess-board array of such cells. The upper limit of the thermal group is at 0·625 eV as in METHUSELAH. The cylindrical cell approximation is made for each of the two cells. The fluxes at the boundaries of each cell are equal; also the net current out of one cell is equal to the net current into the other for both energy groups. This gives the same boundary conditions for mean fluxes and currents as occur in a physical cell array. There is also an option whereby an inner region can be excluded from one or both cells, the boundary conditions for these inner regions being specified by extrapolation length matrices. METHUSELAH will punch input data cards for this programme or for JANUS 5.

JANUS 5[11]

This programme is similar to JANUS 2 except that it uses five groups, and also it does not have the option for excluding inner regions. It uses exactly the same group structure as METHUSELAH with three fast and two overlapping thermal groups. Hence, if the two cells are identical JANUS 5 will merely reproduce the METHUSELAH results.

AIMAZ[12]

This is a two-group, two-dimensional, homogeneous diffusion code for reactor performance assessment. It deals with a whole core having a multiplicity of various fuel channels, and is able to follow the changes due to burn-up over a succession of time steps. AIMAZ has been used to predict the power output per channel, flux shapes and reactivities for comparison with the measurements in these multi-zone cores. METHUSELAH will punch input data cards for the various channel types for AIMAZ.

QUAVER[14]

This is a programme designed to produce data for use with the Feinberg–Galanin[14] source-sink method of treating heterogeneous cores which is incorporated in PRESTO. Its original purpose is to derive monopole and dipole boundary conditions for cylindricalized SGHW-type cells. In the process it computes multi-group diffusion theory fine structure with set neutron currents into or out of the cell which are different for different energy groups. This routine can be used to refine the cell-smearing technique used in this Paper.

Discussion of theoretical methods

A number of options are available in AIMAZ as discussed in reference 7. In testing AIMAZ against zero energy measurements, it is clearly desirable to use it in the same way that it has been used in the calculations for the SGHWR prototype, and every effort has been made to achieve this objective. The important options are discussed below.

Choice of cell averaged or boundary flux normalization

Cell smeared cross sections are required as input for each mesh region of an AIMAZ calculation. There is ambiguity, however, in the method of obtaining these cross sections from a programme such as METHUSELAH. First, the cross sections for each region of the lattice cell are flux and volume weighted and summed to give total group reaction rates for the cell. These reaction rates must then be divided by appropriate fluxes to provide the required cell smeared cross sections. The method originally adopted in SGHWR design calculations was to use the mean cell fluxes for this purpose. The resultant cross sections are then used in AIMAZ calculations and continuous flux distributions from cell to cell are produced. To be consistent, these AIMAZ fluxes must now be identified with the mean cell fluxes. Physically, however, the mean fluxes in adjacent cells are discontinuous, and this is especially marked in many of the present cases where adjoining cells contain fuel at different enrichments.

24. An alternative technique which overcomes this inconsistency involves the use of cell boundary fluxes instead of the mean cell fluxes for obtaining group average cross sections from the METHUSELAH reaction rates. The smoothly varying fluxes computed by AIMAZ can now be identified with the cell boundary fluxes which are clearly continuous. Although this boundary flux normalization technique is based on a reasonable conjecture, the justification for its use is somewhat empirical. In the course of the experimental programme described in this Paper, it has been found that significant improvements in the comparison between the theoretical and experimental power maps have resulted from the use of this technique, particularly in the outer regions of reflected cores. Comparisons of the results obtained from cell average and boundary normalization are given for three typical cores in this Paper. All other cores use boundary flux normalization which was adopted as the standard technique for SGHWR design calculations.

Mesh spacing

In the design calculations, two mesh spaces per cell side are used, thus dividing the cell into four quadrants. It has been argued that the cell has already been smeared in the calculations, and hence the use of a finer mesh would be pointless. Four quadrants per cell is the minimum which can deal with the displacement tubes at the cell corners, as shown in Fig. 4. In the situation where the contents of the displacement tubes vary around the corners of a lattice cell, four separate METHUSELAH calculations are required. In each of these calculations it is assumed that there is an infinite array of identical cells, the contents of the displacement tubes being constant throughout. The smeared cross sections from these METHUSELAH calculations are then used in the appropriate cell quadrants. In making the cylindrical cell approximation, the displacement tube is put around the outside of the moderator, while the tube contents form the outermost region of the cylindrical cell; all volumes are conserved in this process.

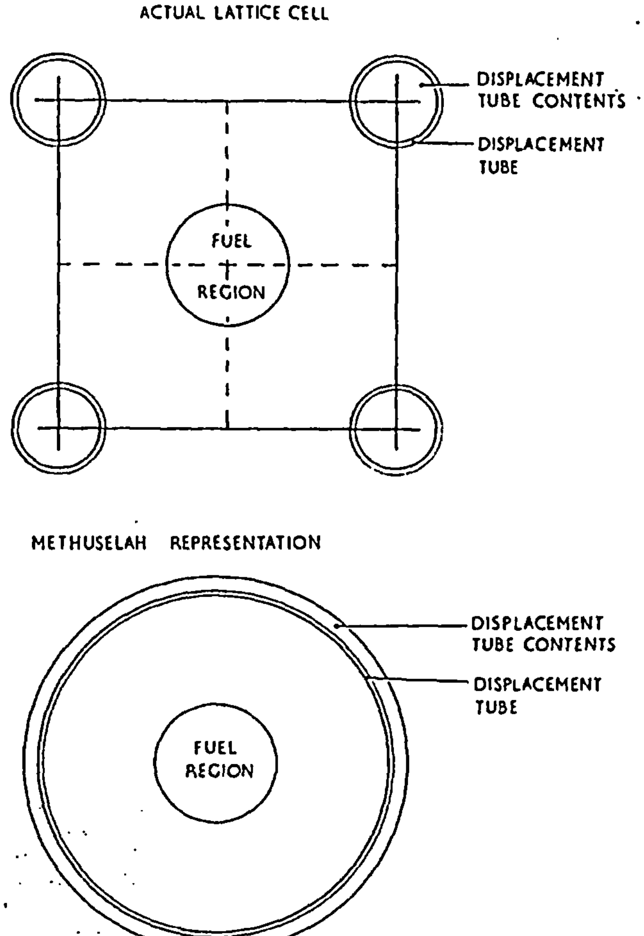

Fig 4 **Use of METHUSELAH to obtain cross sections for each quadrant of a lattice cell for data input to AIMAZ**

26. The experimental cores were restricted by the dimensions of the DIMPLE and JUNO tanks, 8 ft 6 in. and 6 ft 3 in. respectively in diameter. To make the most efficient use of the available tank areas, most of the cores were built without significant D_2O reflectors and thus had high flux gradients in the peripheral channels. In addition, fitting channels on a square lattice pitch into a cylindrical tank inevitably leaves small irregular D_2O areas near the core periphery (Fig. 5). The representation of the curved boundaries of these areas in the AIMAZ calculations is difficult with a coarse square mesh and a much more satisfactory representation can clearly be obtained by increasing the number of mesh spaces per cell. Because of these conflicting demands, both two-mesh and four-mesh calculations have been carried out. The mesh representations of the outer core boundaries are shown in Fig. 5. The aim has been to represent the correct volume of extraneous heavy water, but it is impossible to fulfil this requirement exactly with a finite mesh spacing. The actual volumes of heavy water external to the cells and the volumes given by the mesh spacing are quoted on the relevant figures. In order to economize on space the more realistic four-mesh calculations have been used as the main basis for the comparisons with experiment in this Paper, but in three representative cases both two-mesh and four-mesh calculations are presented to show the effect of mesh spacing on the SGHWR design calculations. The comparison discussed in para. 44 has shown that when a radial D_2O reflector of average thickness 9 in. is present, the prediction of relative powers in peripheral channels is not substantially altered by a change from four to two mesh points per cell. The SGHWR prototype has an effective radial reflector thickness of 10 in. and it is therefore reasonable to assume that similar conclusions would apply.

Computation of U-235 fission dip factors with buckling recycle

The U-235 dip factor, defined as the fuel mean to centre fission rate ratio in a channel, is calculated by METHUSELAH on the assumption that the cell is surrounded by an infinite array of identical cells. The calculation is therefore incapable of predicting the variation of dip factor with environment, although measurements made during this programme have shown that variations of up to 5% occur in peripheral channels. An alternative method of calculation is therefore required, both for the interpretation of copper flux wire measurements in the prototype and for obtaining additional information from some of the experimental cores in JUNO and DIMPLE, where core power distribution measurements were made with fission chambers in the centres of the clusters only.

28. The buckling recycle technique provides a method of computing the dip factor variation. This technique, in a somewhat more elaborate form than is used here, has been employed successfully to improve the predictions of relative channel powers in AGR lattices.[16] For SGHW lattices, use has been made of the QUAVER code,[13] which will perform a fine structure calculation with set leakage into or out of the cell. The first step in the computation is to perform the usual METHUSELAH calculations for the various types of cell in order to obtain mean cell cross sections using the boundary flux normalization method, and then to use these cross sections in an AIMAZ calculation in the normal way. For each channel of the core the calculation gives, *inter alia*, the ratio of fast to thermal fluxes. This ratio generally differs from the original ratio given by METHUSELAH. Using the original absorption, removal and fission cross sections, a pair of leakage terms can be inserted into the two group equations for any region to give this new value of flux ratio. If C denotes the ratio of fast to thermal fluxes, then using customary nomenclature, the relevant pair of equations is

$$[(DB^2)_f + \Sigma_{af} + \Sigma_{rf}]\, C = \frac{1}{k_{-eff}}\, [(\nu\Sigma_f)_f C + (\nu\Sigma_f)_t]$$

$$\{(DB^2)_t + \Sigma_{at}\} = \Sigma_{rf} C$$

These two equations determine the fast and thermal leakage parameters $(DB^2)_f$ and $(DB^2)_t$. These two leakage terms are then used with the METHUSELAH cross sections to provide data for the QUAVER computation of fine structure and cross sections. The fine structure results weighted by the appropriate cross sections then give the dip factors as required for interpreting experimental measurements made at cluster centre positions. The validity of calculating the effect of channel environment on dip factor by the QUAVER

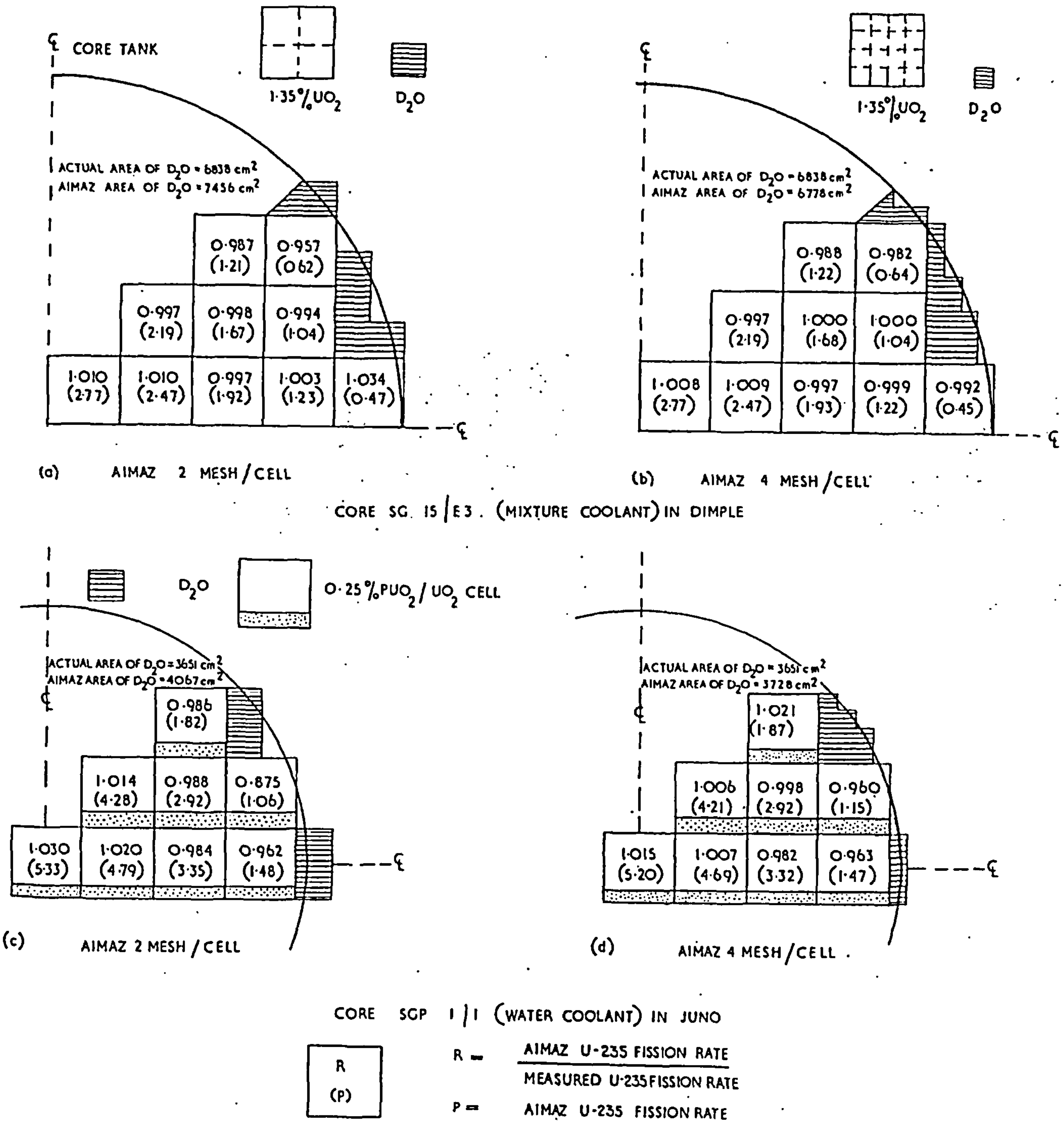

Fig 5 Effect of mesh spacing on U-235 fission power maps in uniform cores

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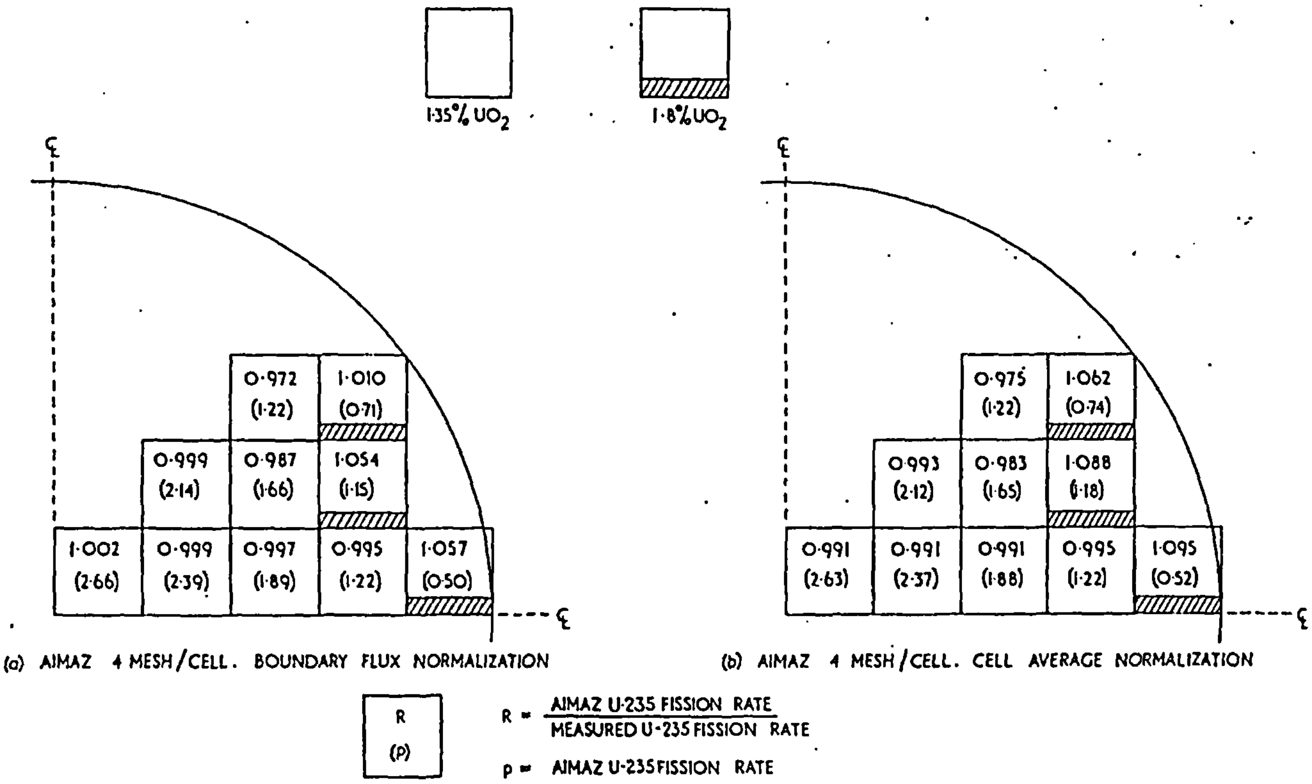


Fig 6 **Effect of boundary flux normalization on the U-235 fission power map in a two-zone core SG17/18 (mixture coolant)**

method has been investigated experimentally during this programme with encouraging results, as discussed in para. 48.

29. A limited form of buckling recycle has also been investigated by re-running the AIMAZ core calculations using average two-group cell cross sections obtained from the QUAVER calculation. The effect on the predicted power map is shown in Figs 11 and 12 and discussed in para. 49.

COMPARISON OF PREDICTED AND MEASURED POWER MAPS

The measured U-235 fission power maps in the cores chosen for presentation in this Paper are compared with the corresponding theoretical predictions in Figs 5–15. In the multi-zone cores, except where otherwise stated, U-235 fission dip factors have been measured in one representative channel of each enrichment, and then used to interpret the fission chamber measurements made in the centres of all similar channels.

31. In each core, measurements have been made in all channels in a symmetry unit so that average core values of the U-235 fission rate/atom can be obtained. The values from each measuring position are normalized to give the same channel average value as the AIMAZ prediction for the same channels.

32. For each measured channel, the ratio R of the predicted to measured average channel U-235 fission rate/atom is tabulated. All the AIMAZ calculations have used four mesh points per cell and boundary flux normalization unless otherwise stated. Since the importance of any discrepancy between theory and experiment varies as the power output from the channel, AIMAZ estimates of the total U-235 fission rate, P, from each channel, normalized to 100 for the whole core, are printed in parentheses below the R values.

One-zone uniform cores

The results from two uniform cluster lattices are shown in Fig. 5 for comparison with the subsequent multi-zone core results, viz. the SG15/E3 core with 1·35% enriched UO_2 in DIMPLE and the SGP1/1 core with 0·25% PuO_2/UO_2 in JUNO. In each case the calculations have been done both with two mesh points and with four mesh points per cell, and the effect of this change in mesh spacing on the representation of the cylindrical tank boundary is also shown in Fig. 5. With two mesh points per cell the representation of the DIMPLE tank in Fig. 5(a) is necessarily somewhat crude, and the amount of additional D_2O outside the array of cells is too large by 9%. The relative power from one of the peripheral channels is underestimated by about 4%. Doubling the number of mesh points per cell significantly improves the representation of the core boundary and the maximum discrepancy in channel power is reduced to 2%.

34. In the smaller JUNO tank the use of two mesh points per cell is a more severe restriction and the power from one

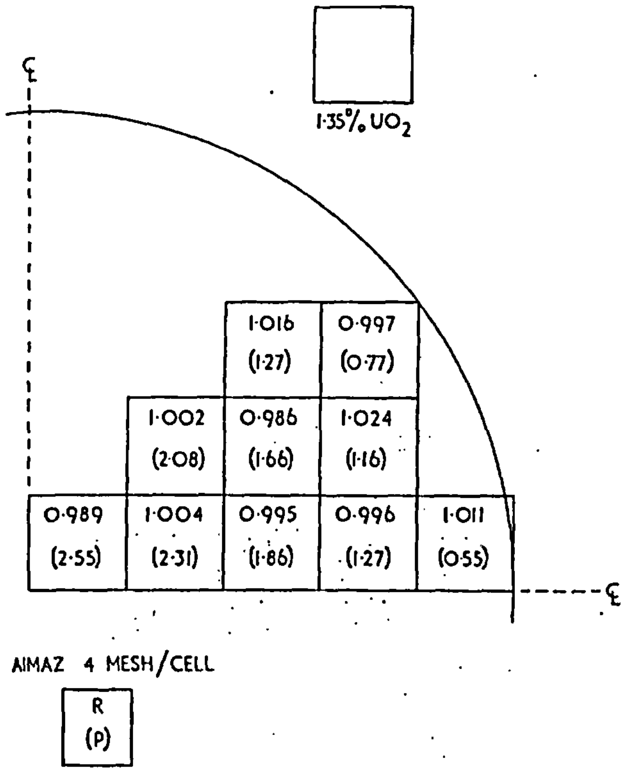


Fig 7 **U-235 fission power map in a uniform core with all displacement tubes empty. SG15/E4 (mixture coolant)**

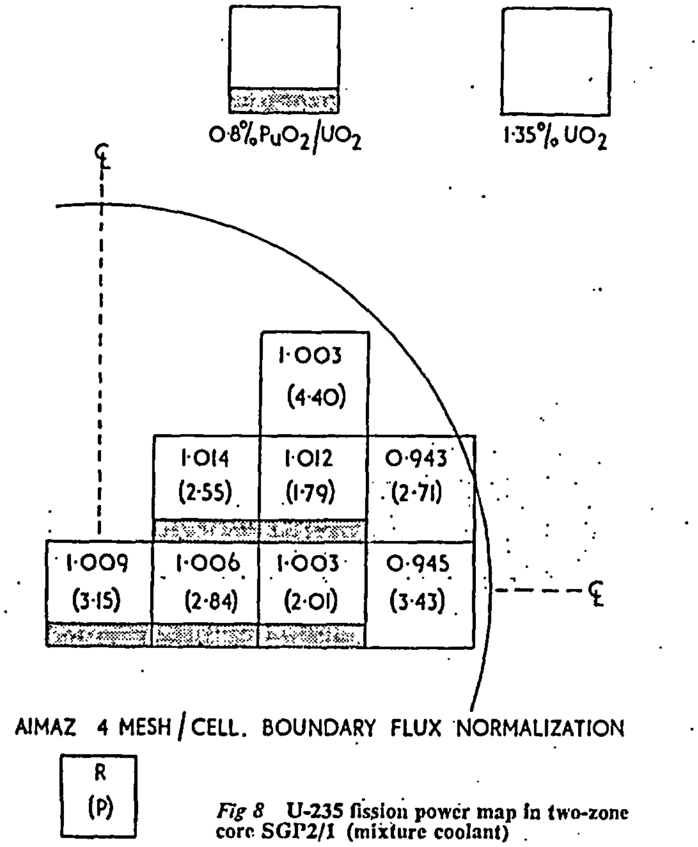


Fig 8 **U-235 fission power map in two-zone core SGP2/1 (mixture coolant)**

peripheral channel is underestimated by 13%. Doubling the number of mesh points reduces this discrepancy to 4%. It is therefore concluded that the use of two mesh points per cell is inadequate to describe the DIMPLE and JUNO tank boundaries, but that four mesh points per cell is enough. This difference will be much less important in the larger power reactor cores and later measurements in a reflected core in DIMPLE (Fig. 10) have shown that the difference is small if a D_2O reflector is present. The use of two mesh points per cell is therefore justified for SGHWR design calculations, but four mesh points per cell have been used for the analysis of the measurements in all subsequent experimental cores.

35. The results from one further uniform core SG15/E4 are shown in Fig. 7. This core is identical to the E3 core except that the displacement tubes at the interstitial positions are emptied. It will be seen that the agreement between theory and experiment using four mesh points per cell is again very good, the maximum discrepancy being about 2½%. The object of this experiment was to provide a datum for experiments on cores with some, but not all, of the displacement tubes voided (Fig. 15).

Two-zone cores

The use of cell average or cell edge flux normalization (see para. 23) in converting METHUSELAH reaction rates to input cross sections for the AIMAZ core calculations has no effect on calculations for uniform cores consisting of arrays of identical channels. For two-zone cores however, the flux fine structures are not the same in the channels of different enrichment and the choice of flux normalization therefore affects the agreement between measured and predicted power distributions. This point is illustrated in Fig. 6, where the results for the two-zone core SG17/E8 with an outer boundary of more highly enriched UO_2 are shown both with cell average and with cell edge flux normalization. The latter choice gives a clear improvement, the average discrepancy in the outer channels being 4%, compared with 8% using cell average normalization.

37. Results for a second two-zone core (SGP2/1) with a PuO_2/UO_2 zone surrounded by a ring of UO_2 channels are presented in Fig. 8. Using boundary flux normalization, the average discrepancy in the outer channels is about 3%, and these results thus present a very similar picture to those from the two-zone SG17/E8 core containing UO_2 fuel only.

Chess-board cores

Results for chess-board cores with alternate channels of different types are presented in Fig. 9 and some additional measurements are included in Table 3. The first core SG16/E5 contained UO_2 fuel channels at 1·35% and 3·00% enrichment. The agreement between the AIMAZ calculation

Table 3: *Ratios of average U-235 fissions per atom in adjoining channels of chess-board cores*

Core	Coolant (% H_2O by wt.)	D.T.(a) (State)	B_{10} in D_2O (ppm)	Fuel	Experiment: Foils(b)	Experiment: Fission chambers(c)	JANUS 5: Hetero-geneous	JANUS 2: Hetero-geneous	JANUS 2: Homo-geneous (Cell averaged)	JANUS 2: Homo-geneous (Boundary flux normalized)	AIMAZ
SG16/E5	31·5	Empty	5·2	1·35% UO_2/3·06% UO_2	1·486 ± 0·009	1·473 ± 0·017	1·543	1·486	1·446	1·503	1·488
SG16/E7	10·0	Empty	5·2	1·35% UO_2/3·06% UO_2	1·477 ± 0·009	1·479 ± 0·018	1·538	1·458	1·427	1·477	1·458
SG18/E11	32·2	Empty	4·0	1·35% UO_2/3·06% UO_2	—	1·479 ± 0·017	1·543	1·488	1·437	1·494	—
SG18/E13	32·0	Full	7·0	1·35% UO_2/1·80% UO_2	—	1·186 ± 0·023	1·190	1·176	1·164	1·183	1·178
SGP4/1	31·7	Full	7·6	0·8% PuO_2/UO_2/3·00% UO_2	—	1·314 ± 0·024	1·259	1·212	1·244	1·267	1·262
SGP4/2	32·3	Full	6·4	0·8% PuO_2/UO_2/3·00% UO_2	1·304 ± 0·007	1·325 ± 0·025	1·263	1·212	1·245	1·265	1·261
SGP4/3	32·0	Full	2·94	0·8% PuO_2/UO_2/3·00% UO_2	—	1·335 ± 0·022	1·266	1·218	1·248	1·270	1·266

Note: (a) Moderator displacement tubes—either all empty or all full.
(b) Measured with U-235/Ni foils.
(c) Derived from fission chamber measurements in cluster centres using dip factors derived from foil measurements.

and the measured U-235 fission rates is very good, the relative power from the two channels being predicted to within about 2%.

39. When mixed plutonium/uranium oxides are used to fuel one of the sets of channels, the agreement is not quite so good. For the central core region, AIMAZ overestimates the relative power in the more highly rated UO_2 fuelled channels by about 5% on average. Two of the comparisons with mixed oxide fuel loadings [Figs 9(c) and 9(d)] involve cores which are identical except for the different concentrations of boron dissolved in the D_2O bulk moderator. The very similar results obtained in the two cases show that the METHUSELAH–AIMAZ calculation is adequately representing the effect of boron poisoning on the power sharing between the two different types of cell. However, the relative powers in adjacent cells which are given in parentheses on the figures show that the effect of boron on chess-board power sharing is very small.

40. A further theoretical investigation of various aspects of the design method of predicting chess-board core parameters was carried out with the JANUS codes.[11] The following comparisons have been made.

(i) *Number of groups.* JANUS 2 and JANUS 5 calculations using heterogeneous ring smeared cell geometries show the effect of reducing from five to two neutron energy groups.

(ii) *Cell smearing.* Heterogeneous ring smeared and homogeneous cell smeared JANUS 2 calculations show the effect of adequate cell geometry representation. Results for the homogeneous case are presented for both cell average and boundary flux normalization.

(iii) *Cell cylindricalization.* This effect is studied by comparing the AIMAZ prediction with the results of the JANUS 2 calculation using boundary flux normalization in both cases.

41. The results are given in Table 3. A comparison of JANUS 2 and JANUS 5 calculations, both with detailed cell representation, shows that using two groups instead of five decreases the power sharing ratio by about 4% in every case except core SG18/E13, where the difference is reduced to 1%. This change is almost certainly explained by the much smaller difference in enrichment between the two types of cell in this particular core.

42. A comparison of the JANUS 2 results with discrete representation of the cells with the results using cell-averaged cross sections shows that changes of the order of 3% occur when the cell-smearing process is adopted, but these are in opposite directions for UO_2 and mixed UO_2/PuO_2UO_2 chess-boards. When cell average is replaced by boundary flux normalization, the predicted power sharing ratio is increased by up to 4%. It will also be seen that the JANUS 2 smeared cell results using boundary normalized fluxes show good agreement with the AIMAZ values, a result to be expected provided that the use of a cylindrical cell in JANUS does not introduce additional errors.

43. Since the JANUS 5 calculation involves fewer approximations than any of the other methods with which it is compared in Table 3, it should give the best agreement with the measured values, but this is not always found to be the case. For chess-board cores containing UO_2 at two different enrichments and with empty moderator displacement tubes, the JANUS 5 predictions are consistently 4% too high, whereas the AIMAZ estimates agree well with experiment. For mixed PuO_2/UO_2 fuelled cores with full moderator displacement tubes, JANUS 5 and AIMAZ give very similar predictions and hence overestimate the power in the more highly enriched channels by about 5%, as has been previously observed. Thus it is clear that in some cases the errors resulting from the METHUSELAH model are being compensated by the further errors inherent in condensing to two groups and smearing the contents of the cells.

Three-batch roundelay cores

Core SG18/E13 is illustrated in Fig. 2. This core was designed to simulate the core arrangement proposed for the SGHWR prototype as closely as was possible in DIMPLE with the aluminium clad UO_2 fuel available at that time. It consisted of a central chess-board of 1·35% and 1·80% enriched UO_2 channels with an outer annulus of 3·00% enriched UO_2, and a radial reflector of D_2O 9·0 in. thick on average. In view of the importance of this core for providing an early test of the power map predictions for the prototype, previous tests of mesh point spacing and flux normalization were repeated for this core arrangement with the results shown in Fig. 10. These show that with a reflected core of this kind, the results from two mesh and four mesh point per cell calculations are

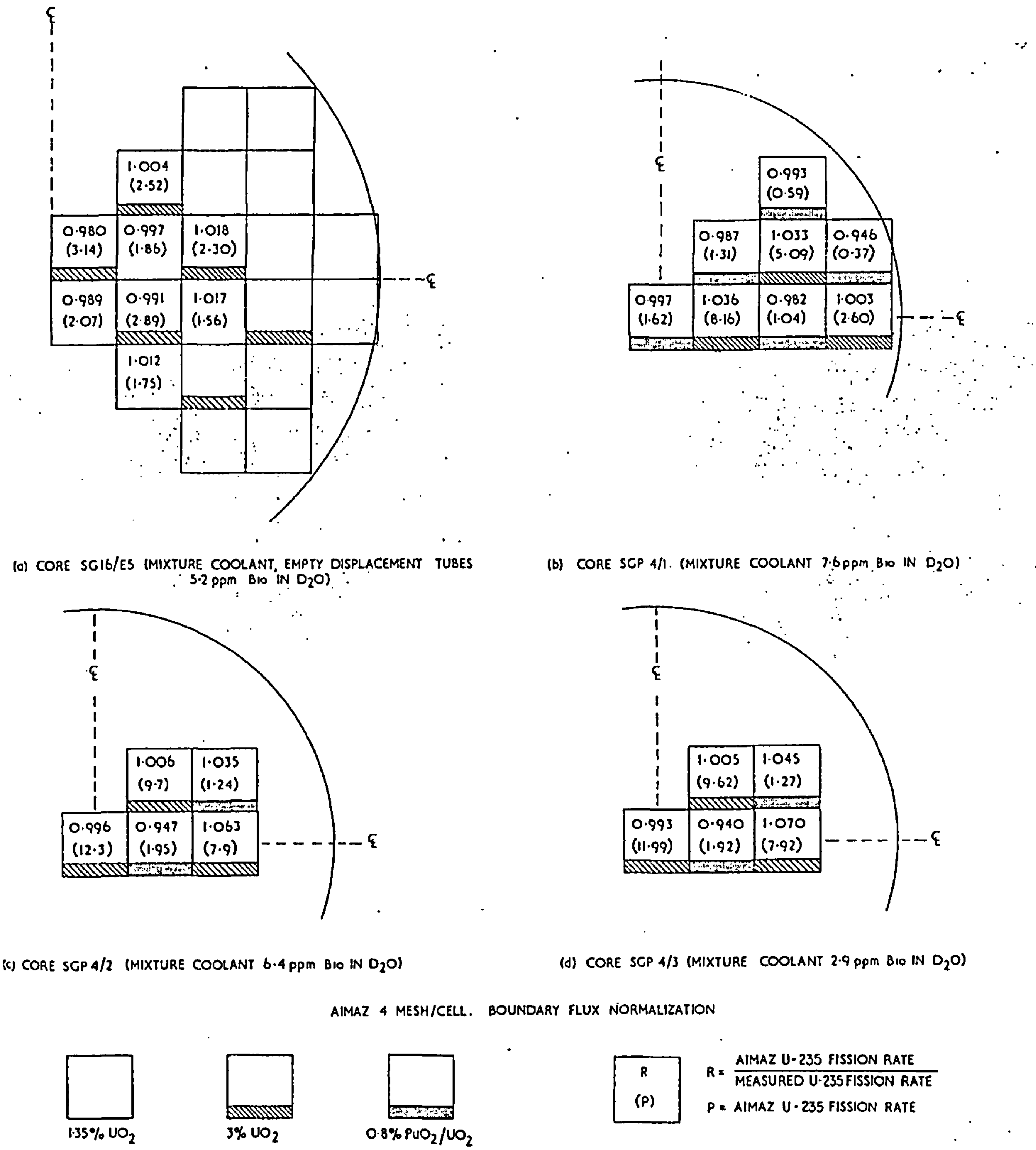


Fig 9 **U-235 fission power maps in chess-board cores**

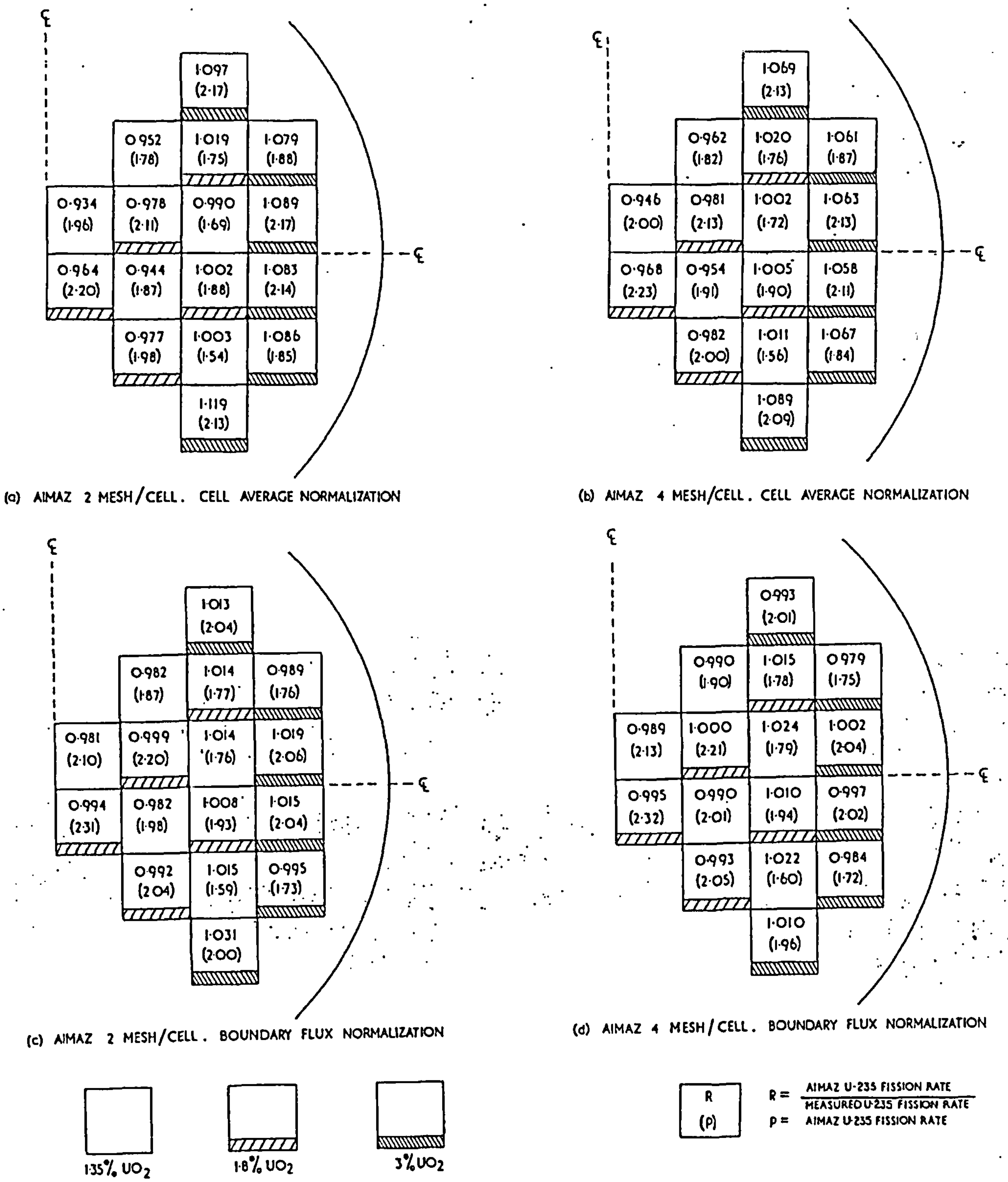


Fig 10 **Effect of mesh spacing and flux normalization on the U-235 fission power map in a three-batch roundelay core SG18/E13 (mixture coolant)**

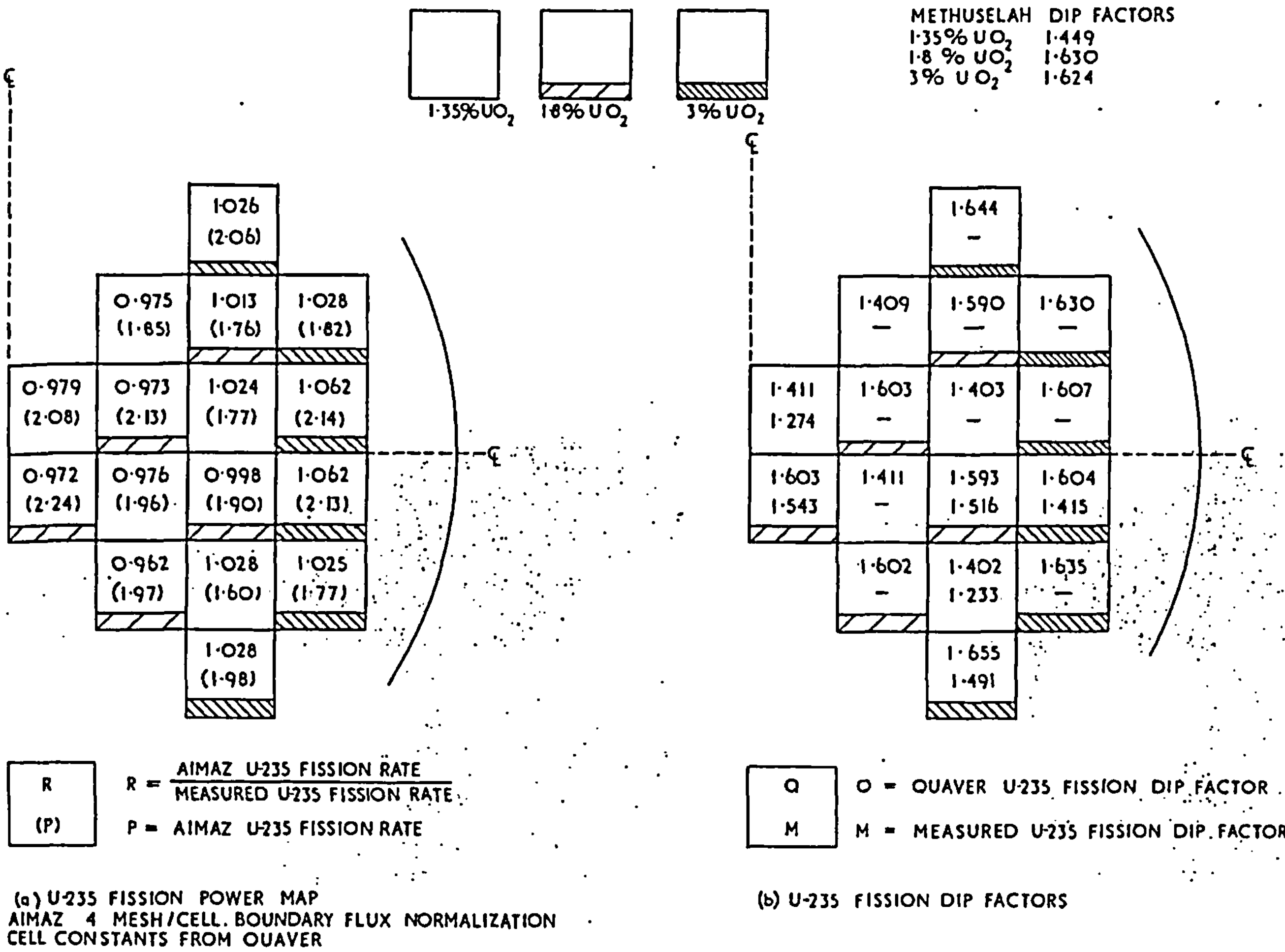


Fig 11 **Effect of buckling recycle on a three-batch roundelay core SG18/E13 (mixture coolant)**

very similar, since the peripheral channels are effectively insulated from an inadequate representation of the core boundary by the presence of the reflector.

45. The use of cell edge instead of cell average flux normalization (para. 23) leads to a significant improvement in the AIMAZ power predictions. With four mesh points per cell, the average power from the peripheral annulus of more highly enriched channels is overestimated by 6·6% with cell average normalization, whereas the discrepancy is reduced to −0·7% using cell edge normalization. It was mainly the evidence from this detailed study of core SG18/E13 which led to the general adoption of cell edge normalization in AIMAZ for all SGHWR design calculations. Measurements in cores with perturbed channels confirm that cell edge normalization improves the agreement with experiment, as discussed in paras 51 and 52.

46. The measurement of U-235 fission dip factors in representative channels in each core has been discussed in para. 11. Fig. 2 shows that the outer channels adjoining the reflector in core SG18/E13 vary considerably in the amount of excess D_2O which should be associated with each channel. This has the effect of varying the macroscopic flux gradient across the channel and hence the mean to centre flux ratio or dip factor. Measurements have therefore been made in a number of representative positions in this outer annulus, and these have shown that the dip factor varies between channels by a total of 5·4%, as shown in Fig. 11.

47. The QUAVER code provides a means of carrying out a cell calculation with different input bucklings in the fast and thermal groups, as discussed in para. 27. Two group flux ratios from a straightforward AIMAZ calculation have been used to provide input bucklings for QUAVER calculations for each representative cell in the outer annulus. Dip factors obtained from these calculations are compared with the measured values in Fig. 11, and it is clear that the variations of dip factor round the annulus are being reasonably predicted, the calculated spread being 3·2% compared with the experimental value of 5·4±1·6%.

48. The variation of dip factor over the central region of the core is estimated by QUAVER to be less than 1%.

whereas the measured values indicate a change of about 2%, thus showing the same tendency to underestimate the variation as in the outer zone. Fig. 11 also shows the METHUSELAH calculation of dip factors for each type of cell. For each enrichment the QUAVER value is lower than the METHUSELAH value, which shows that net leakage out of the cell is significantly affecting the fine structure in the core centre, as well as near the reflector. A comparison with the absolute experimental dip factors shown in Fig. 11 shows that both METHUSELAH and QUAVER overestimate the dip factors. The discrepancies are in the range 12±2% for the 1·35% and 3% channels, both of which are 74-rod clusters, but are rather smaller for the 1·8% channels which have different internal geometry. This behaviour has been confirmed by later measurements in other cores and is associated with the inability of diffusion theory to describe the detailed geometry effects in the vicinity of the central empty tube. It does not significantly affect the prediction of the maximum/average fission rate across the cluster, which has been shown[1] to be well predicted by METHUSELAH.

49. Modified two-group cross sections from the QUAVER programme have then been used to repeat the AIMAZ power map calculation for core SG18/E13, with the results shown in Fig. 11. Comparison with Fig. 10(d) shows that in this case, where good agreement was formerly obtained, this limited form of buckling recycle significantly flattens the calculated thermal flux distribution, and so increases the discrepancies near the edge of the core. In a second test, where the introduction of a perturbed channel led to significant discrepancies with theory, the use of this form of buckling recycle again failed to give a worthwhile improvement (para. 52).

Perturbed cores

Single channel perturbations

A number of U-235 fission power distribution measurements have been made in an enrichment flattened, two radial zone core (SG17/E8) in which a single channel perturbation has been made. The results of the measurements are compared with AIMAZ predictions in Figs 13 and 14. In the first two cases, a 1·35% enriched UO_2 channel from the central region of the core was removed to leave a D_2O/H_2O coolant mixture and was replaced by a 3·01% enriched channel. Measurements of U-235 fission rate were then made with fission chambers in the vicinity of the perturbed channel and along a core diameter. In the second two cases, similar perturbations were made in an edge channel position.

51. The results of AIMAZ calculations, using both cell average and boundary flux normalization, are presented for the central region perturbation in Fig. 13. For the channel containing coolant only, cell constants were obtained by using the JANUS 5 code[11] to calculate the fine structure in a cylindrical coolant cell surrounded by adjacent cells containing the appropriate fuel. The results in Fig. 13 show that both calculations underestimate the reduction in power in channels adjacent to the pressure tube from which the fuel was removed. Boundary flux normalization reduces the maximum discrepancy from 12% to 7%. The effect of loading a single 3·01% enriched element into the core centre is to increase the power in adjacent channels. Both methods of calculation give a good account of this effect, the discrepancies being in the range ±1%.

52. The corresponding comparisons for the perturbations at the edge of the core are shown in Fig. 14. With coolant only in the perturbed channel, the use of boundary flux normalization decreases the discrepancy with theory from about 21% to 13%. However, such a discrepancy is still significant, and the AIMAZ calculation has therefore been repeated using the QUAVER code to incorporate the effects of buckling recycle as discussed in para. 28. The results shown in Fig. 12 are disappointing, indicating that no further improvement is obtained by this means. The comparisons for the fuel enrichment perturbation in a core edge channel are also shown in Fig. 14, the maximum discrepancies being 9% and 5% for the two calculations. For each type of perturbation the discrepancy is larger for a perturbation near the edge of the core than for a similar one near the core centre.

Moderator displacement tube perturbations

In the uniform core SG15/E3 fuelled throughout with 1·35% enriched UO_2 a severe flux tilt was induced along a core diameter by voiding all of the 26 moderator displacement tubes at one side of the core, leaving the remaining 35 tubes full of D_2O. Each tube is 4·5 in. in diameter and its contents constitute 23% of the total D_2O bulk moderator volume in the cell. In the early AIMAZ calculations, no corrections were made for streaming effects on leakage, i.e. $D_r = D_z$ for both fast and thermal groups. The results for such a calculation are compared with the measured U-235 fission power map in Fig. 15(a) and are seen to give fair agreement, a flux tilt of about 70% (i.e. ±35% relative to the central flux) being overestimated by 12%.

54. Reactivity measurements in uniform cores with and without voided displacement tubes[1] have shown the importance of streaming effects. Benoist[16] leakage corrections for the gas annulus and further simple displacement tube streaming corrections based on a method proposed by Leslie[17] are applied to the METHUSELAH results before these are used in the PATRIARCH scheme. These effects are large, giving an increase in leakage of 58% in the thermal region and 31% in the fast region. A comparison with the results of a more recent METHUSELAH-AIMAZ calculation is shown in Fig. 15(b) and it is clear that the discrepancy with experiment has been significantly increased by 40%.

55. The root of the difficulty is that the theory of streaming is incompatible with the assumptions made in the derivation of the diffusion equation. Attempts to incorporate the effects of channels really involve the use of diffusion theory in non-diffusing regions. This is done by trying to make a single correction to a diffusion parameter to allow for more than one change of reactor characteristic. In this case we really need one set of diffusion parameters to get the power distribution correct, and another set to get the total core leakage correct. In some respects this is analogous to a similar difficulty to that encountered in the first stage of the SGHW physics programme, when single-zone cores were being studied. Diffusion coefficients were assigned to the non-diffusing voided annuli which led to the prediction of the correct fine structure. The use of these diffusion coefficients to find the mean diffusion coefficients for the cell gave values which predicted absurd leakages. In METHUSELAH therefore, the diffusion coefficients for leakage were derived in a different way, using the method of Benoist, with very satisfactory results, as shown in reference 1. Alternative methods

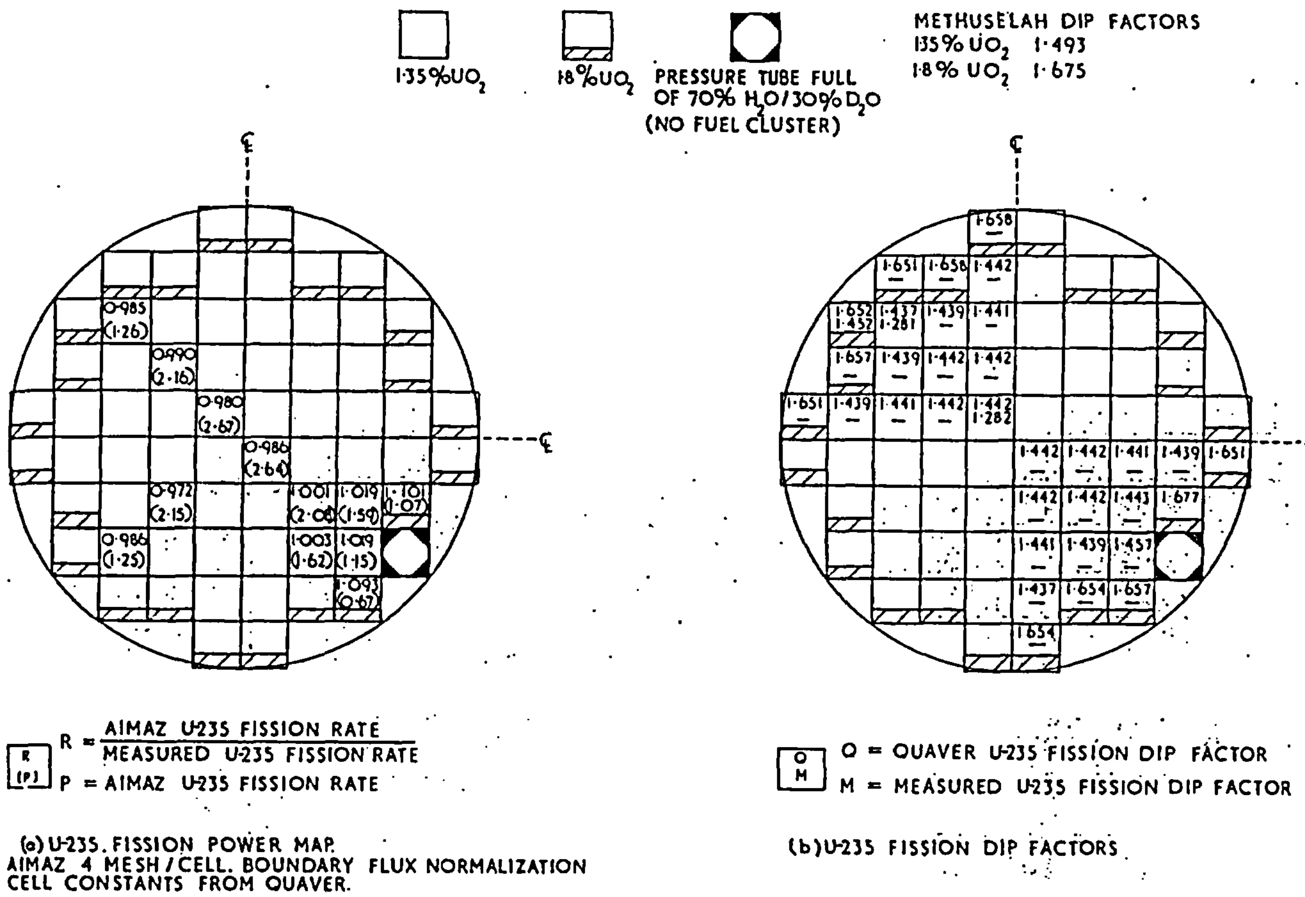


Fig 12 **Effect of buckling recycle on core SG17 with a single channel perturbation near the core edge**

of improving the METHUSELAH–AIMAZ predictions of gross macroscopic flux tilts are being investigated.

REACTIVITY PREDICTIONS FOR MULTI-ZONE SGHW CORES

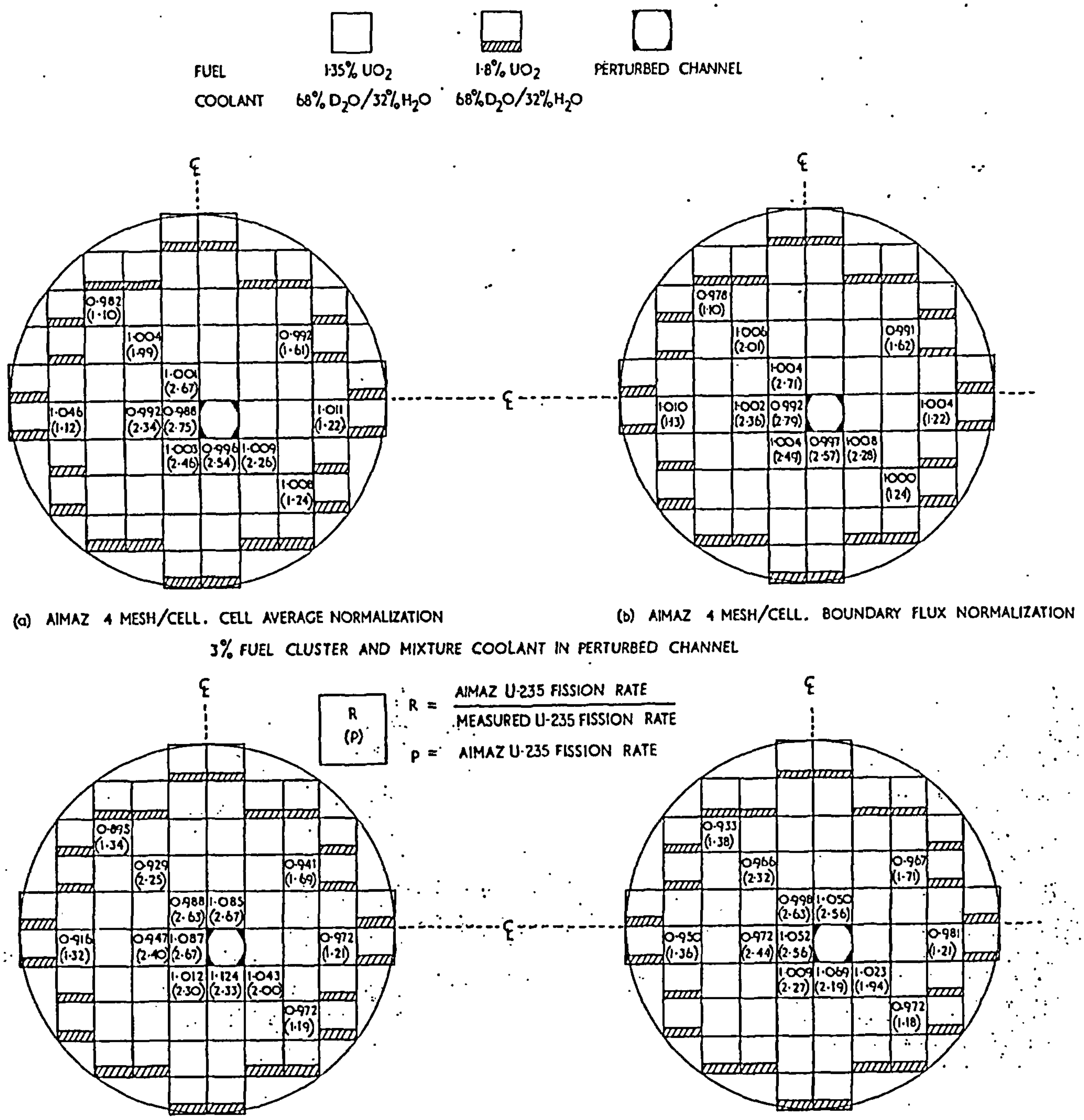
The consistency of METHUSELAH predictions of the material bucklings of uniform cores were demonstrated in Part 1 of this Paper.[1] This work provides a framework in which to assess the performance of AIMAZ in the prediction of the reactivity of the multi-zone SGHW cores studied in DIMPLE and JUNO. The results of AIMAZ calculations for the cores reported in this Paper are summarized in Table 4 and discussed below. In general, the conclusions drawn from these results apply to the many similar cores which have been studied, but are excluded from this Paper on grounds of space.

One-zone uniform cores

In some of the cores, buckling measurements were made in the central zone, and in these cores METHUSELAH reactivities based on the measured axial and radial bucklings, are also listed. The differences between the METHUSELAH single mode calculations and the AIMAZ reactivities for these cores represent the effect of the difference between the measured radial distribution and the radial power distribution calculated by AIMAZ; there may also be a contribution from the condensation from five to two groups for the AIMAZ calculation, but this is known to be small. The uniform cores SG15 and SGP1 thus provide a test of the AIMAZ representation of the core tanks of DIMPLE and JUNO respectively. It has already been shown in paras 33 and 34 that the calculated radial power distributions are in good agreement with the measurements, and this is confirmed by the reactivities. For both DIMPLE and JUNO it appears that for uniform cores the errors in reactivity caused by defects in core and tank representation in AIMAZ are worth not more than 0·2%.

Two-zone cores

A similar comparison between AIMAZ and METHUSELAH is possible for the two-zone cores SG17 and SGP2. For the all uranium core SG17 the AIMAZ reactivity is in good agreement with the reactivity bias of METHUSELAH for uranium fuelled cells, although this is not a stringent test



(a) AIMAZ 4 MESH/CELL. CELL AVERAGE NORMALIZATION

(b) AIMAZ 4 MESH/CELL. BOUNDARY FLUX NORMALIZATION

3% FUEL CLUSTER AND MIXTURE COOLANT IN PERTURBED CHANNEL

(c) AIMAZ 4 MESH/CELL. CELL AVERAGE NORMALIZATION

(d) AIMAZ 4 MESH/CELL. BOUNDARY FLUX NORMALIZATION

NO FUEL CLUSTER, BUT MIXTURE COOLANT CONTAINING 70% H_2O/30% D_2O IN PERTURBED CHANNEL

Fig 13 **Effect of boundary flux normalization on the U-235 fission power map in core SG17 with single channel perturbations near the core centre**

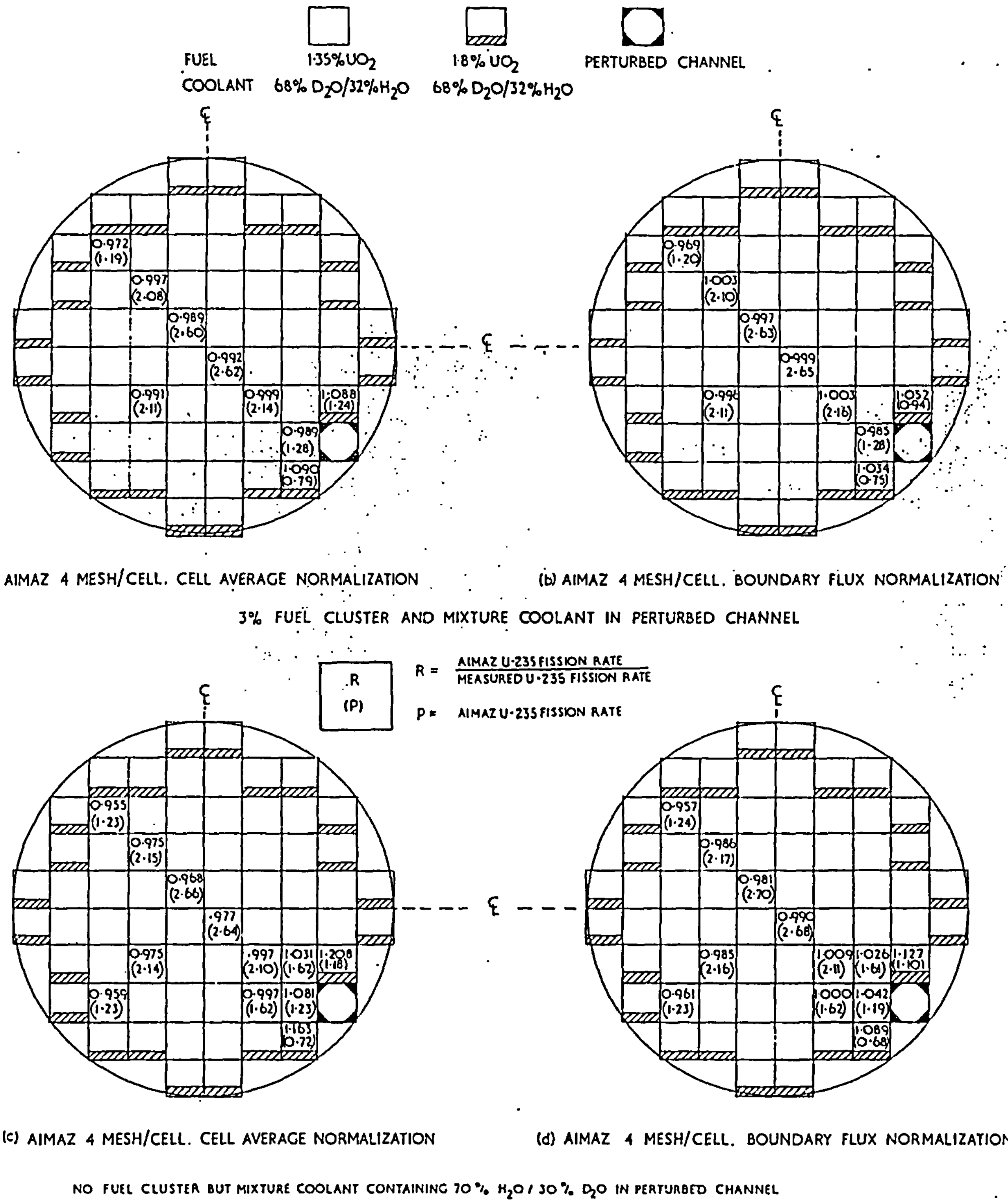


Fig 14 **Effect of boundary flux normalization on the U-235 fission power map in core SG17 with single channel perturbations near the core edge**

Table 4: *Calculated reactivities for critical cores*

Core No.	Core type	Measured B_z^2 m^{-2}	AIMAZ Reactivity 4 mesh/cell Boundary flux normalization	Central zone	Measured B_r^2 m^{-2}	METHUSELAH* Reactivity
DIMPLE						
SG15/E3	Uniform	3·56±0·07	1·0042	1·35% UO_2	3·16±0·03	1·0055
SG15/E4	Uniform	1·28±0·07	0·9956	1·35% UO_2	2·91±0·03	0·9934
SG17/E8	Two-zone	3·73±0·03	1·0043	1·35% UO_2	2·97±0·02	1·0053
SG16/E5	Chess-board	3·32±0·23	0·9850	1·35% UO_2/3% UO_2	2·95±0·03	—
SG18/E13	Three-batch roundelay	3·21±0·10	1·0087	1·35% UO_2/1·8% UO_2	1·69±0·06	—
JUNO						
SGP1/1	Uniform	0·52±0·02	0·9990	0·25% PuO_2	5·66±0·06	1·0015
SGP1/2	Uniform	1·28±0·04	0·9997	0·25% PuO_2	5·69±0·07	1·0012
SGP2/1	Two-zone	2·22±0·02	0·9956	0·8% PuO_2	5·96±0·13	0·9949
SGP4/1	Chess-board	3·27±0·02	0·9928	3% UO_2/0·8% PuO_2	5·71±0·08	—
SGP4/2	Reflected chess-board	2·78±0·01	1·0020	3% UO_2/0·8% PuO_2	6·75±0·22	—
SGP4/3	Reflected chess-board	4·07±0·02	1·0039	3% UO_2/0·8% PuO_2	6·49±0·18	—

* Trends in the METHUSELAH reactivity predictions for uranium and plutonium fuelled cells are discussed in detail in Reference 1.

of AIMAZ because the difference in enrichment between the central and outer zones is not great (1·35% compared with 1·8%). Core SGP2 presents a different result, because the METHUSELAH eigenvalues are different for the plutonium fuelled central zone (0·994) and the uranium fuelled outer zone (1·006). If the radial distribution across this core were correctly calculated, the AIMAZ reactivity would be expected to be an appropriately weighted average of the two values, and the AIMAZ reactivity of 0·996 is indeed consistent with the simple flux weighted average.

Chess-board cores

The reactivity of the uranium fuelled chess-board core SG16/E5 is about 1% lower than the METHUSELAH eigenvalues for uniform cores with empty displacement tubes (reference 1). There are two effects to consider. Firstly, the relative fission rates in the two types of cells appear to be calculated to within 2% by AIMAZ, so errors in the calculation of the fine structure in the flux produced by the chess-board pattern do not appear to be responsible. Secondly, the measured power distribution across the central region of the core implies that AIMAZ is significantly underestimating the radial buckling of the chess-board region [Fig. 9(a) and reference 6]. Thus the error in radial buckling is of the wrong sign to explain the discrepancy in reactivity. One feature which may be partly responsible is the treatment of streaming along voided displacement tubes. In the uniform core SG15, voiding the displacement tube resulted in a reduction of 1·2% in eigenvalue. This effect might be greater in the more reactive chess-board cores, because of the increased bucklings.

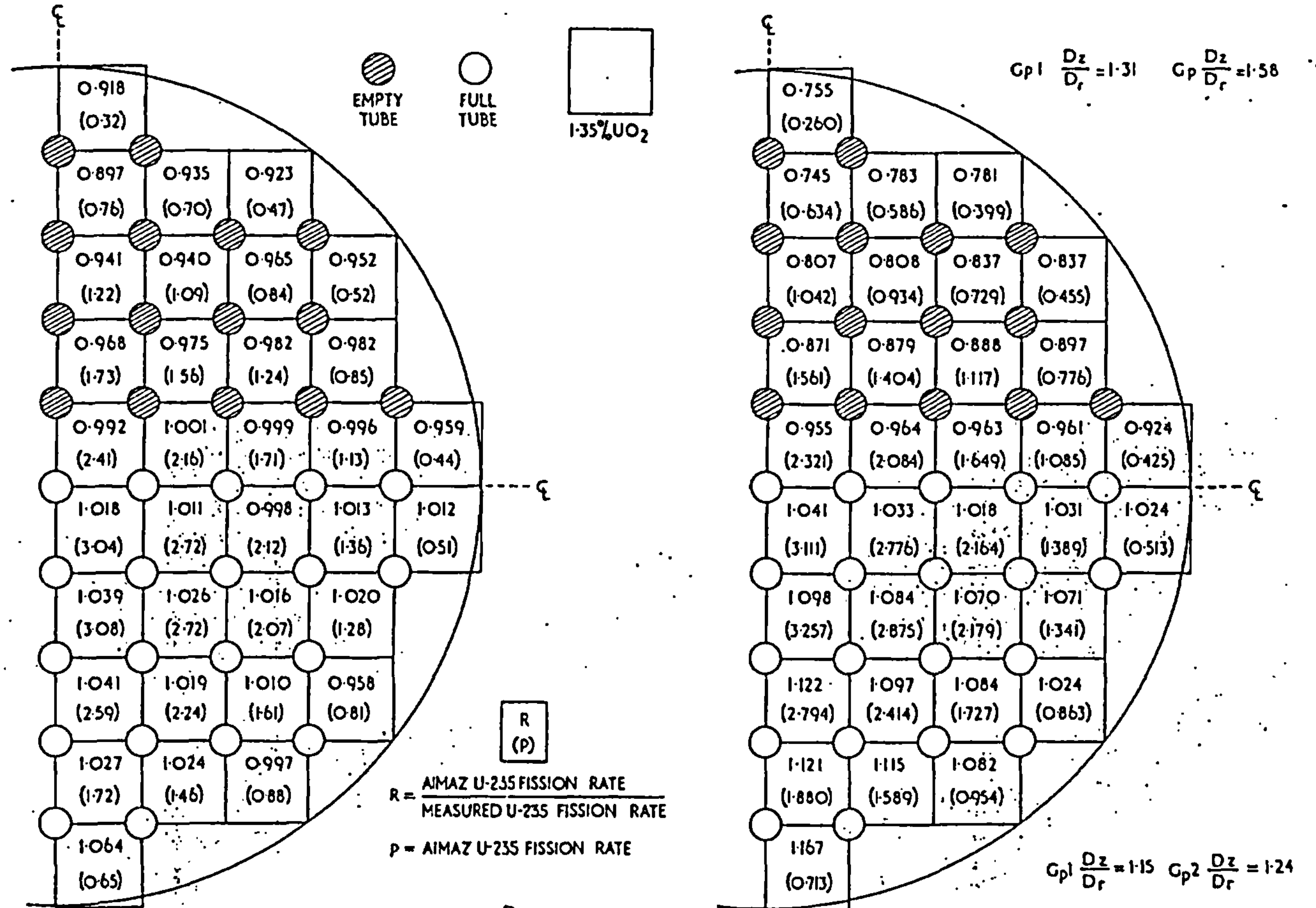
60. The mixed PuO_2/UO_2 chess-board core SGP4/1 did not have voided displacement tubes, but its reactivity is again slightly lower than might be expected from its components of 16 uranium fuelled and 21 plutonium fuelled elements. The discrepancy is not so great in this case, but it would appear that there is some evidence for a general trend for AIMAZ to underestimate the reactivity of a chess-board core relative to that of uniform cores of comparable fuel elements.

61. The two reflected chess-board cores in JUNO SGP4/2 and SGP4/3 have eigenvalues about 1% higher than for the unreflected cores. This is a general effect and is consistent with the observed overestimate of the fission rate in the outer channels of about 5% observed in the power maps of Fig. 9.

Three-batch roundelay core

The AIMAZ prediction of reactivity for the three-batch roundelay core SG18/E13 is 1·009, which is about 0·005 greater than for other unreflected cores fuelled with UO_2. Later results have suggested that this difference is probably due to the presence of a reflector, rather than to the difference in the arrangement of fuel enrichments. It was shown in para. 45 that the use of cell average flux normalization leads to some errors in the predicted radial power distribution and hence to a further increase of 0·4% in eigenvalue.

63. The general conclusion to emerge from this study is that AIMAZ can predict the reactivity of multi-zone cores to within ±1% over a range of enrichment and geometrical arrangements of the fuel, some being reflected and some being bare. The one core which lies outside this range is a chess-board core with empty displacement tubes. This is a high leakage core, and it is possible that errors in the calculations of streaming corrections may be responsible. Within the range of ±1% a number of trends may be observed, measurements in uranium fuelled cores of similar geometry giving the same reactivity to within ±0·2%. The same is true for plutonium fuelled cores, except for the trend of predicted reactivity with plutonium content which was observed in the uniform cores in Part 1 of this Paper.[1] New features observed in the present study of multi-zone cores are the tendencies for the reactivity of reflected cores to be higher than that for bare cores by ½–1%, and the tendency for chess-board cores to have lower eigenvalues than equivalent uniform cores. The reflector effect appears to be caused by small errors in the AIMAZ radial power distribution. The effect of the choice of normalization for the cross sections input to AIMAZ has been shown to produce changes of 0·4% in reactivity in a three-batch roundelay core; more consistent



(a) AIMAZ 4 MESH/CELL. NO STREAMING CORRECTIONS. $\frac{D_z}{D_r} = 1{\cdot}0$

(b) AIMAZ 4 MESH/CELL. STREAMING CORRECTIONS CALCULATED FOR GAS GAPS AND VOIDED DISPLACEMENT TUBES

Fig 15 **Effect of corrections for neutron streaming on the calculated U-235 fission power map in a uniform core with all the moderator displacement tubes in one half of the core voided. E3/26E (mixture coolant)**

eigenvalues closer to unity are obtained using boundary flux normalization rather than cell average normalization.

CONCLUSIONS

U-235 fission power maps in one zone and multi-zone SGHW cores have been made in the DIMPLE and JUNO reactors with tank diameters of 8 ft 6 in. and 6 ft 3 in. respectively. It has been shown that two mesh points per cell are inadequate to describe the tank boundaries in two-dimensional AIMAZ diffusion theory calculations of the power distributions, but four mesh points per cell are sufficient. In the larger power reactor cores, two mesh points per cell may well be sufficient, and if a radial D_2O reflector is present (as in the SGHWR prototype), there is no significant difference in the power distributions calculated with two and four mesh points per cell.

65. In cores containing channels of different types or irradiation histories, fine structure varies between channels, and core power map calculations are therefore influenced by the fluxes used to convert cell averaged reaction rates into smeared cross sections. It has been shown that boundary flux normalization gives consistently better map predictions than cell average normalization for multi-zone cores; on this basis boundary flux normalization was adopted in AIMAZ in all SGHWR design calculations.

66. AIMAZ calculates the relative powers from adjoining channels of significantly different enrichment in a UO_2 fuelled chess-board to within about 2%. When mixed PuO_2/UO_2 fuel is present in alternate channels, AIMAZ overestimates the power in the more highly rated channels by about 5%.

67. The codes JANUS 2 and JANUS 5 have been used to investigate particular aspects of the AIMAZ calculations for chess-board cores, e.g. number of groups, smearing model, cylindrical cell approximation. It is concluded that some of the assumptions made in calculating chess-board power distributions with METHUSELAH-AIMAZ

introduce errors which are not negligible, but the relatively good agreement obtained with experiment shows that such errors are being compensated to a large extent by other defects in the model.

68. A three-batch roundelay core has been built in DIMPLE to simulate important features of the SGHWR core arrangement. The DIMPLE core consisted of a peripheral annulus of 3·01% enriched UO_2 channels, reflected radially by D_2O, and surrounding a central chess-board of 1·35% and 1·80% enriched UO_2 channels. Using boundary flux normalization, the AIMAZ calculation predicts the relative power from every channel in the core to within a standard deviation of ±2%.

69. The use of the 100 MW(E) SGHWR prototype to investigate a wide variety of non-standard fuel channels will lead to significant perturbations of the multi-zone flux profiles studied in DIMPLE and JUNO. This problem will be less severe in a commercial SGHWR, but there, too, fuel management schemes, burn-up effects, etc. will lead to some flux perturbations and a number of single and multi-channel effects have therefore been studied to provide a further test of the AIMAZ predictions of power distribution. For example, a single channel containing coolant only in a peripheral position was found to lead to an AIMAZ overestimate of the power in the adjoining channel by 13%, and an attempt to improve this prediction by taking cell leakage into account by using a limited form of buckling recycle was unsuccessful. A gross core flux tilt of 70% induced by voiding all of the moderator displacement tubes in one half of the core is overestimated by about 40% by an AIMAZ calculation. It is suggested that the latter effect is associated with the incorporation of streaming effects in diffusion theory, so that two different sets of diffusion parameters are really required to predict the power distribution and total core leakage correctly. The possibility of improving the AIMAZ predictions of gross flux tilts by some such technique is being considered, but on a longer time scale the possible use of heterogeneous source-sink methods is also being investigated.

70. The power map measurements in this three-batch roundelay core SG18/E13 included U-235 fission fine structure determinations in representative channels at each enrichment to interpret fission chamber measurements made at the centre of each channel. It was found that in the outer annulus of channels, the irregularity of the core boundary due to the use of a square pitch (Fig. 2) led to a variation of 5·4% in the mean to centre fission rate ratio, whereas this effect is not represented in METHUSELAH. The QUAVER code provides a means of calculating cell parameters with different bucklings in the fast and thermal groups, and this was used with input bucklings from AIMAZ to recalculate the fine structure in the outer channels. The QUAVER prediction of the variation in fine structure flux ratio between outer channels was 3·2%, in reasonable agreement with the measured value of 5·4±1·6%.

71. Measurements of axial buckling were made in each of the multi-zone cores, and these have been used to test the accuracy of AIMAZ predictions of reactivity. Since cross sections for use in AIMAZ are calculated by METHUSELAH, some correlation between AIMAZ and METHUSELAH eigenvalues is to be expected. For the uniform cores the eigenvalues of the two calculations are very similar, implying that the AIMAZ calculations of the radial buckling are in good agreement with experiment. AIMAZ calculations confirm the trends identified in METHUSELAH eigenvalues for uniform cores in Part 1,[1] namely that the eigenvalue is higher for uranium fuelled cores than for cores containing plutonium [if η_0(Pu-239)=2·114], and that the leakage is overestimated in cores with voided moderator displacement tubes. The effects on reactivity of going from a uniform core to a multi-zone core seem to be well predicted by AIMAZ, although two further trends have been identified. Firstly, there is a general tendency for the calculated reactivity of reflected cores to be about 0·5 to 1·0% higher than that for an equivalent bare core. Secondly, there is some evidence that the reactivity of chess-board cores has some tendency to be lower than for equivalent uniform cores. Without making any allowance for these trends AIMAZ has proved itself able to predict the reactivity of a range of experimental cores to within ±1%. If allowance is made for the trends which have been identified, predictions to within ±0·2% in reactivity can be made.

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