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APPLICATIONS OF THE MODIFIED SOURCE-MULTIPLICATION TECHNIQUE IN SUB-CRITICAL ASSEMBLIES

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ABSTRACT

The Modified Source Multiplication technique has recently been used in the Dimple zero-power reactor to establish the k-values of sub-critical arrays of 3% enriched uranium oxide pins in a boron-steel walled CAGR fuel transport skip.

With a neutron source installed in the assemblies, count-rates from neutron detectors were measured relative to those in a reference assembly, where a known negative reactivity had been imposed. Source-mode and eigen-value calculations were then used to establish the relationship between count-rate ratio and reactivity ratio.

Typical uncertainties are ±7% of the amount the assembly is sub-critical for k-values in the range 0.92 down to 0.77.

1 INTRODUCTION

Sub-critical monitoring plays an important role in the experimental programme in zero-power reactors at AEE Winfrith. One of the methods used, the Modified Source Multiplication technique (MSM), was developed to measure shut-down margins, as part of a series of core performance studies in the zero-power fast reactor Zebra. This technique has been used recently in a series of sub-critical fuel transport flask arrays in the water-moderated zero-power reactor Dimple, as part of a programme to validate the methods and data used to assess criticality hazards in the UK.

The technique as applied in Dimple is described below, and is illustrated by two examples from the fuel transport flask programme.

2 MSM TECHNIQUE

In the MSM technique neutron sources are placed within a sub-critical assembly and the corresponding power level is monitored with neutron detectors. In its simplest form, the relationship between the power-level P, the total neutron source strength, S, and the amount an assembly is sub-critical, ρ can be expressed as:

$$\rho = \frac{1}{k} - 1 = \frac{S}{P\,\nu}$$

where k is the k-value of the system, P is measured in fissions/sec, and ν is the mean number of neutrons per fission. It is inherently assumed in this expression that the source neutrons have the same worths as fission neutrons, ie the same energy distribution and the same spatial distribution. This inverse proportionality between reactivity and power level holds in systems which are close to critical. However, as the amount the system is sub-critical is increased, the power deviates from the eigen-mode distribution and it becomes necessary to consider a more general expression for ρ, ie:

$$\frac{\iint S(V)\chi(E)\phi^*(V,E)dEdV}{\iint\left[\int \nu\Sigma_f(V,E)\phi(V,E)dE\right]\chi(E)\phi^*(V,E)dEdV}$$

where the numerator now incorporates the importance weighting of the source strength per unit volume, which, for simplicity, is still assumed to have a fission neutron spectrum; the denominator has a similar weighting of the neutron production from fission.

In principle it would be possible, but time-consuming, to relate the effective source and fission neutron production terms experimentally. At the other extreme, with a known neutron source strength and a precise calculation, the amount an assembly is sub-critical could be obtained simply by measuring the count-rate in the assembly with an absolutely calibrated detector. In practice, although there have been considerable improvements in calculation methods, it is unlikely that this degree of precision is currently attainable. The approach adopted here is to use calculation to predict detector count-rates as a function of reactivity, but to lessen the sensitivity to systematic errors in the calculations, the count-rates and reactivities are expressed relative to a reference state with a known imposed negative reactivity. Thus the measured amount a system is sub-critical, $\rho_2(E)$, relative to $\rho_1(E)$, the measured amount the reference assembly is sub-critical, is given by:

$$\frac{\rho_2(E)}{\rho_1(E)} = F \times \frac{E_1}{E_2}$$

E_1 and E_2 are detector count-rates measured in the two assemblies and F is a calculated correction factor given by:

$$F = \frac{\rho_2(C) \times C_2}{\rho_1(C) \times C_1}$$

where the detector count-rates C_1 and C_2 are from source-mode calculations and the reactivities, $\rho_1(C)$ and $\rho_2(C)$, are from eigen-value calculations.

The application of this technique in the zero-power fast reactor Zebra has already been described elsewhere (1). Briefly, the aim of this work was to study the influence of various control-rod patterns on shut-down reactivities. The neutron source used was that due to spontaneous fission and (α,n) reactions in the fuel. A Cf252 source was used to assess the influence of an irregular source distribution. The main conclusions from these studies, which covered k-values down to 0.90, were:

(a) consistent estimates of sub-criticality were obtained from neutron detectors in a range of locations in the core and reflector regions;

(b) because of the cancellation of systematic errors in the calculated reactivities and count rates, the correction factors, F, were relatively insensitive to the nuclear data used;

(c) the MSM results agreed satisfactorily with those obtained using a pulsed-source technique, the differences in reactivity being about 5%, which was comparable to the overall accuracy of each of the methods.

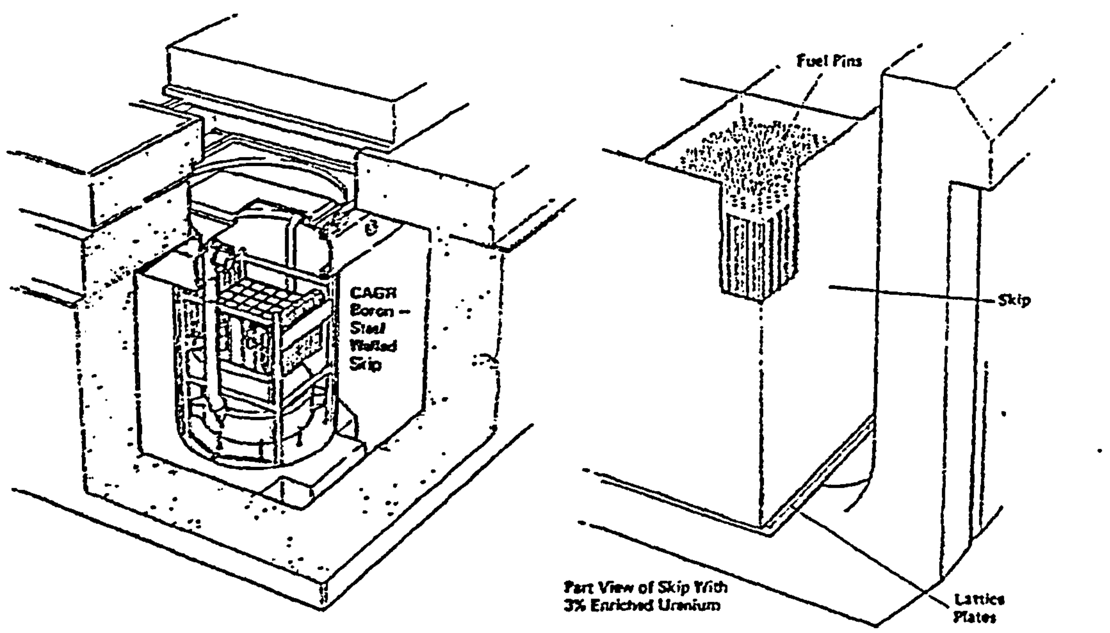

FIG 1 LAYOUT OF CAGR SKIP IN DIMPLE

3 DIMPLE MEASUREMENTS

3.1 Assembly Layout

Dimple is a versatile, zero-powered, water-moderated reactor. A full description of the plant and its current, criticality-related, programme is given in Reference 2.

The MSM measurements were made in a series of light-water moderated arrays of steel-clad uranium oxide pins in a skip used for the transport of fuel for the CAGR reactors. The fuel is enriched to 3.0% and is 10.1mm in diameter and 693mm high. Figure 1 shows the reactor with the 20 compartment skip installed. The skip has steel walls 5mm thick, containing 1.1w/o of boron, and is 1.3mx1.1mx0.7m high. To vary the configurations studied, aluminium lattice plates, with a total of 365 possible fuel pin locations were provided in each compartment.

The skip was first loaded to critical to provide a reference for the MSM measurements. The compartment loading, 196 pins on a 17.9mm pitch, which is shown in Figure 2a, was critical with a flooded fuel height of 50cm. This was subsequently reduced to provide a sub-critical reference configuration, with a k-value of 0.993, the water level reactivity coefficient being calibrated by period measurements.

Two examples of the sub-critical compartment loadings studied are shown in Figures 2b and 2c. The first of these has 137 pins arranged to form a cluster 229mm in diameter. The second has 152 pins in a 215mm diameter cluster, with a high fuel density at the edge, to increase interaction between the compartments. In these sub-critical cases the skip was fully flooded, the water level extending 7.5cm

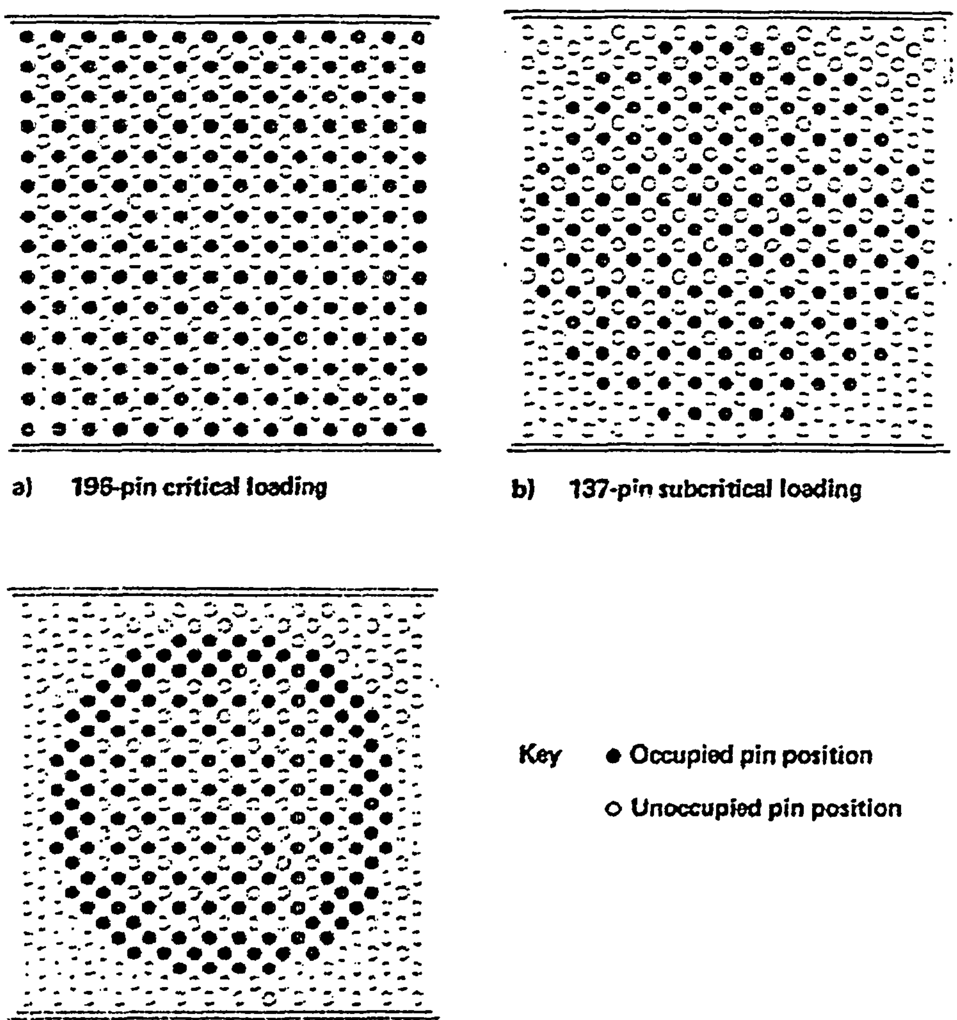

FIG 2. CRITICAL AND SUBCRITICAL COMPARTMENT LOADINGS

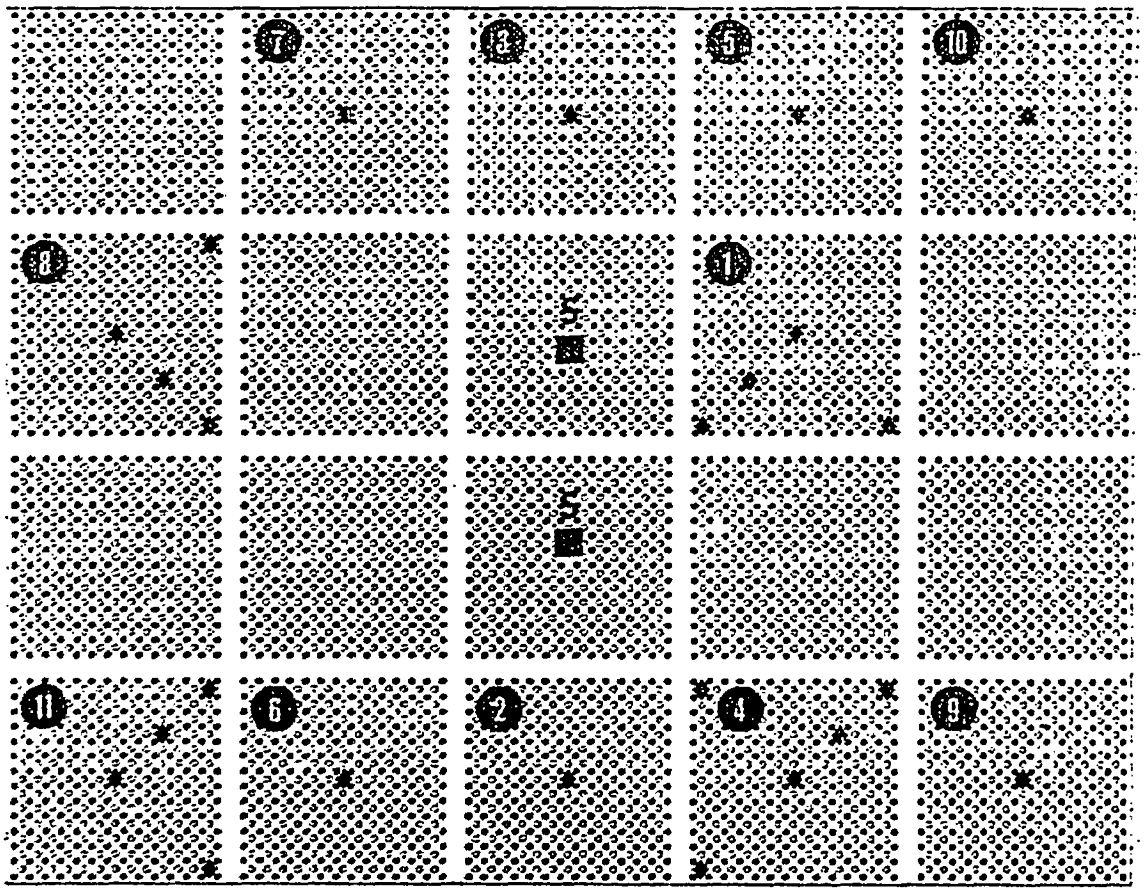

FIG 3 RADIAL LOCATION OF DETECTORS AND SOURCES(S)

above the top of the fuel. Other sub-critical loadings, relating to the proposed use of the skips by BNFL for the storage of dismantled CAGR fuel, are discussed in Reference 3.

3.2 Experimental Equipment

Six Cf 252 sources, each emitting ~$8x10^6$n/sec, were used in the sub-critical assemblies. These were arranged in groups of three in 23mm diameter steel tubes located near the centres of the two central compartments, see Figure 3. Cylindrical steel spacers separated the sources in each tube, to approximate to a source spread axially along the submerged fuel height.

Figure 3 also shows, in plan view, the locations of the neutron detectors. Four BF_3 counters were installed in steel tubes inside the skip, with their effective centres aligned axially with the centre of the submerged fuel region. These detectors, which were intercalibrated to better than ±1%, were moved radially to investigate variations in the flux distribution within compartments and from compartment to compartment. Additional measurements checked the sensitivity of the results to radial deflections and showed a maximum variation of ±1% per mm for detectors within a cluster and ±2% per mm for detectors in the skip corners. In practice, radial location was generally better than ±1mm.

Two large BF_3 counters were located in tubes attached to the outside of the skip. These were also adjusted axially to align with the centre of the submerged fuel.

Finally, two fission counters and a BF_3 counter were installed in submersible pods in the water reflector, 50mm to 100mm from the skip wall. The axial locations in this case were not changed, but remained level with the lower part of the fuel throughout.

3.3 Calculated Corrections

Diffusion theory, using the SNAP code, (4), was used to provide the correction factors for the measurements. This facilitated 3D modelling and was used in conjunct-

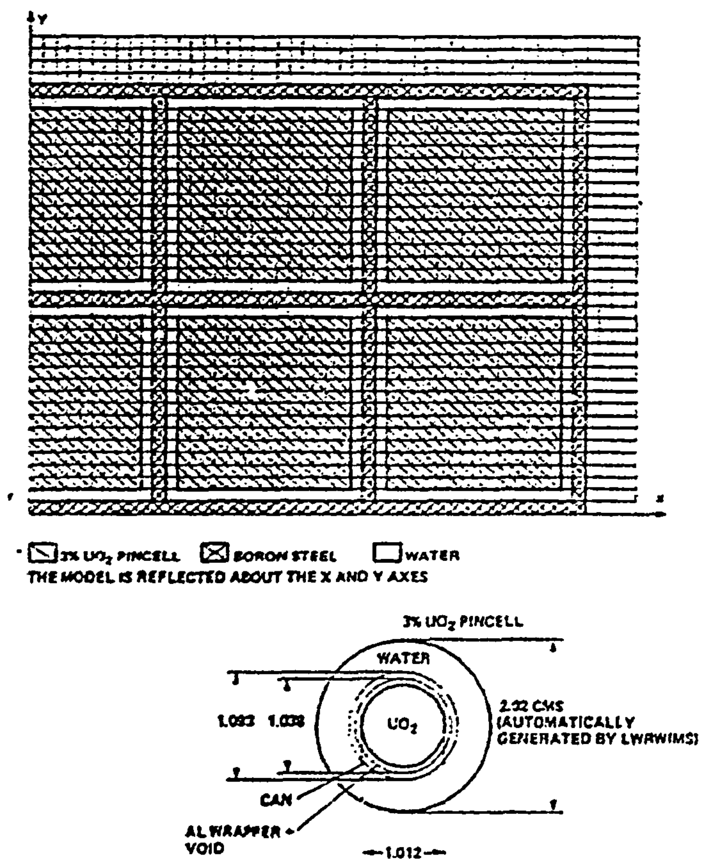

FIG 4 ¼ PLAN X-Y MODEL USED FOR LWRWIMS CALCULATIONS FOR REFERENCE ASSEMBLY

ion with 8 group cross-sections derived from LWR-WIMS data (5).

In practice most of the analysis used XY geometry models; a typical example, that for the reference loading, is shown in Figure 4. To represent axial leakage an experimentally derived axial buckling was applied to the models, that for the reference loading being adjusted by the equivalent of -0.013dk, to match the experimental k-value.

For the XY source-mode calculations the source strength was equated to experiment assuming a cosine variation in the magnitude and worth of source neutrons, as defined by the axial buckling. The validity of this assumption was confirmed by comparing an XY model and the centre plane of the corresponding XYZ model, where the axial distribution of the sources was modelled exactly. The differences in the detector reaction rates were small, ie about 1%. Similar comparisons showed that, for those detectors which were not aligned with the horizontal centre-plane of the core, axial corrections based on a cosine variation introduced errors of less than 1%.

3.4 Experimental Results

Tables 1 and 2 show the results from detectors at the centres of the skip compartments for the 137 and 152 pin clusters respectively. In both cases the results are arranged in terms of increasing detector distance from the skip centre, see Figure 3. The measured count-rates are shown in the second column of the tables and have been normalised on the basis of the inter-calibration of the four detectors used and corrected for the decay of the Cf252 sources relative to the reference configuration. The validity of this correction, which is based on a half-life of 2.65 years, was confirmed by repeat measurements in the reference configuration separated by nearly 150 days, corresponding to a 10% decrease in source strength. The calculated count-rates are in the third column of the tables. The apparently good agreement between these and the measured values in Table 1 is largely fortuitous, as the calculated results are based on nominal chamber sensitivities only.

It can be seen from the tables that, when the results are expressed relative to the reference configuration, there are marked variations in count-rate ratios with position. With the 137 pin clusters, where the calculated amount the assembly is sub-critical has been increased by a factor of 16, the calculated count-rates reduce by a factor of about 20 near the skip centre to about 70 at the skip edge. The variations are even larger with the 152 pin clusters, where a factor of 27 increase in sub-criticality produces reductions in count-rates from about 40 to over 200, imposing a severe test on the MSM technique.

The uncertainty in the count-rate ratios in Tables 1 and 2 due to counting statistics is generally less than ±1%, (1 standard deviation). A further ±1% arises from counter reproducibility and the influence of asymmetries within the skip, which is apparent from the tables, contributes ±3%. Combining these uncertainties with a further ±1%, due to the use of XY rather than XYZ models in the calculations, leads to an overall random uncertainty of just over ±3% in the count-rate ratios and consequently in the estimated reactivities at each location. In practice the variations in reactivities in Tables 1 and 2 are ±4% and ±8% respectively, primarily due to calculation tending to under-estimate the count-rates in the outer regions of the skip, as the

TABLE 1, Experimental Results for 137 Pin Clusters (using compartment-centre detectors)

Detector Location	Count-Rate (cps)		Count-Rate Ratio		ρ	keff
	Experiment (E2)	Calculation (C2)	Experiment $\frac{E1}{E2}$	Calculation $\frac{C1}{C2}$		
1	296.4	301.4	20.64	20.84	0.116	0.896
2	224.9	223.6	18.38	18.36	0.117	0.895
3	212.4	223.6	18.47	18.36	0.118	0.894
4	100.9	98.52	34.52	34.56	0.117	0.895
5	100.2	98.52	31.94	34.56	0.108	0.902
6	108.0	98.52	31.78	34.56	0.108	0.903
7	101.3	98.52	32.08	34.56	0.109	0.902
8	59.51	56.04	49.56	54.20	0.107	0.903
9	26.15	24.00	65.60	69.11	0.111	0.900
10	25.97	24.00	62.36	69.11	0.106	0.904
11	28.31	24.00	62.13	69.11	0.105	0.905

Mean 0.900±0.004

Note:

ρ, the amount the assembly is sub-critical is given by:-

$$\rho = \frac{\rho_2(C)}{\rho_1(C)} \times \frac{C_2}{C_1} \times \frac{E_1}{E_2} \times \rho_1(E)$$

where $\rho_2(C)$ = 0.1183 from the SNAP eigen-mode calculation

$\rho_1(C)$ = 0.00719 from the SNAP eigen-mode calculation in the reference assembly

$\rho_1(E)$ = 0.00713 from experiment in the reference assembly

TABLE 2 Experimental Results for 152 pin Clusters (using compartment-centre detectors)

Detector Location	Count-Rate (cps) Experiment (E2)	Count-Rate (cps) Calculation (C2)	Count-Rate Ratio Experiment $\frac{E_1}{E_2}$	Count-Rate Ratio Calculation $\frac{C_1}{C_2}$	ρ	keff
1	178.0	153.8	34.36	40.84	0.164	0.859
2	129.1	114.3	32.03	35.93	0.174	0.852
3	124.4	114.3	31.53	35.93	0.172	0.854
4	49.24	41.00	70.75	83.04	0.167	0.857
5	49.12	41.00	65.17	83.04	0.153	0.867
6	52.43	41.00	65.49	83.04	0.154	0.866
7	50.48	41.00	64.38	83.04	0.152	0.868
8	24.84	18.99	118.7	159.9	0.145	0.873
9	10.24	7.51	167.4	220.9	0.148	0.871
10	10.08	7.51	160.7	220.9	0.142	0.875
11	11.19	7.51	157.2	220.9	0.139	0.878

Mean = 0.865±0.009

Note:

ρ the amount the system is sub-critical is given by:-

$$\rho = \frac{\rho_2(C)}{\rho_1(C)} \times \frac{C_2}{C_1} \times \frac{E_1}{E_2} \times \rho_1(E)$$

where $\rho_2(C)$ = 0.1972 from the SNAP eigen-mode calculation

$\rho_1(C)$ = 0.00719 from the SNAP eigen-mode calcuation in the reference assembly

$\rho_1(E)$ = 0.00713 from experiment in the reference assembly

assembly becomes more sub-critical. It is nonetheless encouraging that this level of consistency is achieved, particularly in the 152 pin cluster case, where the calculated reactivity differs markedly from the experimental value.

The trend for the experimental reactivities to vary with position is even more apparent when the results from other detector locations are considered. This is illustrated in Table 3, which shows that the k-values from detectors located in the skip corners tend to be low, while those in the water reflector around the skip tend to be high. The mean, fortuitously, is in good agreement with the value from the cluster centres.

A transport theory analysis for selected assemblies in this series showed that these spatial variations in k-value estimates were due to deficiencies in the diffusion theory predictions of fine structure within the compartments and of the macroscopic changes from compartment to compartment (3). This analysis also confirmed that, with diffusion theory, the most reliable results were obtained from detectors located in the fuel, ie those in Tables 1 and 2, the approximations in this approach introducing an additional systematic uncertainty of ±4%.

TABLE 3 Comparison of Experimental k-values from Different Detector Locations

Assembly	Detector Locations			
	Compartment Centre	Compartment Corner	Outside Skip	All
137-pin clusters	0.900 ±0.004	0.882 ±0.007	0.907 ±0.005	0.895 ±0.012
152 pin clusters	0.865 ±0.009	0.849 ±0.012	0.883 ±0.012	0.863 ±0.016

Note:

The errors are standard deviations about the mean for each group of detectors.

Table 4 Comparison of Measured and Calculated k-values

Assembly	Measurement	Calculation	
		Diffusion Theory	Transport Theory
137-pin clusters	0.900±0.007	0.894	0.916
152-pin clusters	0.865±0.009	0.835	0.875

Table 4 shows the recommended k-values for the 137 pin and 152 pin clusters and compares the results with transport theory and diffusion theory predictions obtained with LWR-WIMS data. The experimental errors quoted now include a ±5% systematic contribution arising from the measurement of the amount the reference assembly was sub-critical, which was due mainly to uncertainties in the delayed neutron data used in the analysis of the period measurements. The total uncertainty corresponds to about ±7% of the amount the system is sub-critical, which is typical of the results obtained from the other assemblies in this series of measurements. Table 4 shows that the transport theory predictions provide consistently good agreement with experiment, a trend that was also evident from the other arrays studied in the skip, where the k-values ranged from 0.92 down to 0.77. (3).

4 Conclusions

Modified source multiplication measurements are proving a valuable and relatively simple means of measuring the k-value of sub-critical assemblies. Typical uncertainties are about ±7% of the amount the system is sub-critical in the present Dimple work.

The technique has been cross-checked against pulsed-source measurements in the Zebra reactor and some preliminary comparisons have been made with auto-correlation and cross-correlation noise techniques in the skip assemblies in Dimple. Further work is planned to continue these comparisons and to extend the range of the MSM studies down to lower k-values.

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