

ANALYSIS OF MEASUREMENTS IN THE NULL REACTIVITY ZONE IN ZPR-9/25  
AND COMPARISONS WITH THE SCHERZO 556 MEDIUM

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I. INTRODUCTION

A series of uranium lattices with  $k_{\infty}$  close to unity have been studied in Europe and the results have been used to determine values of enrichment and reaction rate ratios for a homogeneous uranium medium of unit  $k_{\infty}$ ; called SCHERZO 556, which has been proposed as an international standard for intercomparison of experimental techniques and for data testing.<sup>1</sup> Previously (1969) a test zone of this type had been built on ZPR-9 (Assembly 25). Assembly 25 was not designed as part of the international comparison and, consequently, there were some difficulties encountered in making the comparisons for the homogeneous uranium medium. Nevertheless it is possible to derive from Assembly 25 enrichment and reaction rate ratios for the SCHERZO medium, and these values are compared with the published SCHERZO 556 results in this paper.

A description of the ZPR-9 measurements is given in Ref. 2. The reaction rate ratio measurements, are given in Ref. 3. The ZPR-9 measurements are different from those in Europe principally in three respects. Firstly, the experiments were aimed at determining the null composition as closely as possible by varying the ratio of depleted uranium to aluminum whereas the other measurements established a lattice with  $k_{\infty}$  within a few percent of unity. Secondly, ZPR-9 contained approximately twice as much structural steel, the ratio of steel to uranium mass being 0.062 (the aluminum to uranium mass ratio was less than one tenth of this). Thirdly, in Assembly 25 the  $^{235}\text{U}$  was included within 93% enriched uranium plates whereas the European assemblies used enrichments between 20 and 40%, resulting in greater heterogeneity in Assembly 25. Two uranium test zones were built in ZPR-9 giving a very useful test of heterogeneity calculations.

II. THE CALCULATION METHOD

The calculations used ENDF/B Version III data with the SDX code.<sup>4</sup> The basic calculation was made for an infinite array of cells with zero buckling to compare with the experimentally established null-zone. A base 156 group data library was used with SDX. The calculation proceeded in three main stages as follows.

1. A calculation of resonance shielded cross-sections for  $^{235}\text{U}$  and  $^{238}\text{U}$  for each plate in the cell using the equivalence theory algorithms of MCC2.
2. A calculation of the flux fine structure in the cell using the integral transport code CALHET and cell averaging of the data through the cell.
3. An infinite medium calculation with the SEF1D module of SDX, using the cell-averaged data from stage 2, in 156 groups to give  $k_{\infty}$ , spectrum and cell averaged reaction rates.

The cell model employed followed current ZPPR practice, in using midplate atom densities for uranium and actual plate thicknesses for stages 1 and 2, with steel from the matrix included in diluent regions. The actual homogeneous compositions were used in stage 3 for the final calculation. In addition, a comparison calculation was made in which the plate thicknesses were preserved but the materials were smeared over the mean lattice pitch, giving a lower estimate of heterogeneity.

### III. COMPARISON OF CALCULATION AND EXPERIMENT

The experimental and calculated values for  $k_{\infty}$  and reaction rate ratios are given in Table I. Calculations were made for SCHERZO 556 medium and for ZEBRA 8H<sup>5</sup> using the same codes and nuclear data, and in the case of ZEBRA 8H, the same cell-modeling prescription. The results for these are also included in Table I.

There is a significant difference in the calculated  $k_{\infty}$  for Assembly 25 and SCHERZO 556 of almost 1%, whereas the C/E for ZEBRA 8H is very close to that for SCHERZO. The C/E values for the reaction rate ratios agree well within the estimated errors, of 5 and 4% for the <sup>238</sup>U fission and capture ratios in the case of Assembly 25. The heterogeneity correction for assembly 25 is 0.46% whereas that for 8H is calculated as 0.16%. An identical value for ZEBRA was calculated with FGL5 data.<sup>5</sup>

### IV. TESTS OF HETEROGENEITY CALCULATIONS

In test zone 2 of ZPR-9/25, the heterogeneity of the cell was increased by bunching together the enriched uranium plates and the null composition reestablished. This provided a good test of the calculated heterogeneity corrections. As for test zone 1, heterogeneity calculations were made with 2 cell models, the first preserving mid-plate densities for uranium and the second smearing the plates to preserve the homogeneous atom densities. Calculations for the homogeneous compositions were also made for comparison. The results are given in Table II. The heterogeneity effects test zones 1 and 2 are calculated to be 0.46% and 0.94% for the cell model No. 1. The calculated  $k_{\infty}$  values are very consistent; for model No. 1, the difference is 0.04% and for model No. 2, both test zones are calculated identically. The calculations show that most of the heterogeneity correction results from the flux fine structure. For test zone No. 1, the resonance shielding contribution to the total  $\Delta k$  is only 0.05%. The reaction rate ratios are insensitive to the cell calculation model.

### V. EXTRAPOLATION OF THE RESULTS TO PURE URANIUM BY THE 'C/E METHOD'

This method assumes that uncertainties in the calculated effects of heterogeneity and of impurities are sufficiently small so that calculation for the infinite <sup>235</sup>U/<sup>238</sup>U medium can be used to find the enrichment giving  $k_{\infty} = 0.9852$  as obtained for Assembly 25.

As shown in Table I, the  $k_{\infty}$  obtained for SCHERZO 556 was 0.9760. A further calculation was made for uranium enrichment of 6% which gave a  $k_{\infty}$  of 1.0125, and a value:

$$\frac{\Delta k}{\Delta E(\%)} = 0.0830$$

A similar value is given by the FGL5 calculation, Fig. 7 of Ref. 5; which also shows the variation to be closely linear over this range.

Similarly, the two calculations gave the variation of reaction rate ratios with percentage enrichment as:

$$\Delta(F_8/F_5)/\Delta E(\%) = +0.0012$$

$$\Delta(C_8/F_5)/\Delta E(\%) = -0.0011$$

Thus the critical uranium enrichment, for  $k = 0.9852$  was obtained as 5.67%.

To obtain the experimental reaction rates, the calculated values for an enrichment 5.67% were corrected by the C/E values in Table I.

The results for the SCHERZO medium are given in Table III. A discussion of the errors is given in the next section.

## VI. UNCERTAINTIES IN THE URANIUM ENRICHMENT

1. Due to the null balance and uranium weights: these uncertainties are combined in Ref. 1 as an effective error on the Depleted to Enriched uranium weight ratio. This results in an enrichment uncertainty of 0.25% or  $\pm 0.014\% \Delta E$  for the enrichment 5.67%.

2. Neglect of  $^{236}\text{U}$ : data for  $^{236}\text{U}$  was not available for the calculations and the isotope was omitted from the cell. It is assumed that the  $^{236}\text{U}$  worth is similar to that for  $^{238}\text{U}$ . The neutron balance then predicts a negligible correction of  $-0.010\% \Delta k$  or  $-0.001\% \Delta E$ .

3. Calculated heterogeneity: good agreement was obtained between the  $k_{\infty}$  values for test zones 1 and 2 within 0.04% in  $k$ . However, to guard against possible systematic errors in the calculation it would be prudent to assume an uncertainty of twice this amount giving an uncertainty in enrichment of 0.01%.

4. Calculated steel worth: a homogeneous calculation for ZPR-9/25 with no steel gave a  $k_{\infty}$  of 1.017 for zone No. 1 and thus predicts that the effect of the steel is to lower the  $k_{\infty}$  by 3.01%. However, the ENDF/B III calculations for steel

worth relative to fuel are commonly in error by as much as 15%. Since no direct calculations have been made yet for assembly 25 steel worth for comparison with experiment, it is necessary to take at present an uncertainty of 0.5% in k or 0.06% in enrichment.

5. Errors due to  $^{234}\text{U}$  and aluminum are negligible.

6. No direct estimate of the 'zero error' due to flux transients or flux gradients at the null zone have been obtained. However radial worth measurements with scattering samples showed good spectral convergence at the null zone.<sup>1</sup> We will assume a zero-error similar to that for ZEBRA 8H of  $\pm 0.11\%$  in  $k_{\infty}$  or  $\pm 0.013\%$  in enrichment.

7. The errors on the reaction rates due to the projection to the pure uranium medium are small compared with the basic uncertainty in the measurements.

#### VII. SCHERZO ENRICHMENT BY THE $\rho_8/\rho_5$ METHOD

Following Ref. 1 it is assumed that the ratio of  $^{238}\text{U}$  to  $^{235}\text{U}$  reactivity worths per gram is insensitive to small changes in enrichment, steel content and spectrum mismatch. The critical enrichment for the homogeneous uranium with  $k = 1$ , is then given by:

$$1 + \frac{1-E}{E} \frac{A_8 \rho_8}{A_5 \rho_5} = 0$$

where  $A_8$ ,  $\rho_8$  and  $A_5$ ,  $\rho_5$  are the atomic weights and reactivity worths per gram of  $^{238}\text{U}$  and  $^{235}\text{U}$  respectively. The material worths within the ZPR-9/25 test region are given in Ref. 2, Table II-19-VI. Assuming a statistical uncertainty on the reactivity measurements of 1%, the following values of critical enrichment are obtained for the two test zones:

Test zone 1  $E = 5.58 \pm 0.08$

Test zone 2  $E = 5.52 \pm 0.08$

#### VIII. CONCLUSION

The C/E value for k-infinity for the as-built Assembly 25 null composition is about one percent greater than C/E values for SCHERZO 556 and ZEBRA 8H. Calculations were used to derive an enrichment value for the SCHERZO medium from the measured Assembly 25 null composition. A value of  $(5.67 \pm 0.06)$  a/o was obtained by the C/E method. This compares with an enrichment  $(5.56 \pm 0.02)$  a/o obtained by combining the European results. The significantly larger error on the ZPR measurement results almost entirely from uncertainties in the effects of the steel structural materials. Use of the measured steel worth data from Assembly 25 may result in a

slightly altered derived value for the SCHERZO medium with a somewhat reduced error. This work has not yet been completed. The differences in the C/E values for the as-built compositions will remain, however.

Values of 5.58 a/o and 5.52 a/o are obtained from the reactivity ratio method in good agreement with the SCHERZO value although the estimated errors of 0.08% are rather large.

The reaction rate ratio values are in agreement with those derived for SCHERZO but have appreciably greater error estimates.

The calculations accurately predict the heterogeneity change between test zones 1 and 2 in Assembly 25. This is a good test of the ability of the analytical techniques to predict heterogeneity effects where most of the heterogeneity is due to flux fine structure and little due to resonance shielding.

REFERENCES

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TABLE I. Calculations with ENDF/B VIII Data for ZPR-9/25, SCHERZO 556 and ZEBRA 8H

Test Zone	Uranium <sup>a</sup> Enrichment	Diluents	Parameter	Experiment	Calculation	C/E
ZPR-9/25	6.050	Steel aluminum (U234 + U-236)	k-infinity	1.000	0.9854	0.985
			$F_8/F_5$	0.0225 ± 0.0012	0.02082	0.925 ± 0.049
			$C_8/F_5$	0.116 ± 0.004	0.1200	1.034 ± 0.036
			$\Delta k$ (het) <sup>b</sup>	--	0.46%	--
ZEBRA 8H	6.082	Steel	k-infinity	1.030 ± 0.003	1.0038	0.975 ± 0.003
			$F_8/F_5$	0.02278 ± 0.0048	0.02153	0.945 ± 0.020
			$C_8/F_5$	0.1136 ± 0.0017	0.1188	1.046 ± 0.016
			$\Delta k$ (het) <sup>b</sup>	--	--	--
SCHERZO 556	5.56 ± 0.02	NONE	k-infinity	1.000	0.9760	0.976
			$F_8/F_5$	0.0227 ± 0.0002	0.02159	0.951 ± 0.008
			$C_8/F_5$	0.1154 ± 0.0017	0.1183	1.025 ± 0.015
			$\Delta k$ (het) <sup>b</sup>	--	0	--

<sup>a</sup>Enrichment in Atoms/o U-235/(U-235 + U-238)

<sup>b</sup> $\Delta k$ (het) = k(heterogeneous lattice) - k(homogeneous composition) by calculation

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TABLE II. Calculations for ZPR-9/25

		Test Zone 1	Test Zone 2
$k_{\infty}$	cell model #1	0.9852	0.9856
	cell model #2	0.9850	0.9850
	homogeneous	0.9806	0.9762
$\Delta k(\text{het})$	model #1	+0.46%	+0.94%
	model #2	+0.44%	+0.88%
$F_8/F_5$	model #1	0.02083	0.02029
	model #2	0.02083	0.02035
	homogeneous	0.02107	0.02101
$C_8/F_5$	model #1	0.1200	0.1188
	model #2	0.1201	0.1189
	homogeneous	0.1211	0.1209

Note: Model #1 preserves uranium densities for heterogeneity calculation; Model #2 uses plates smeared over the lattice pitch and preserves cell average densities, see Section 2.

TABLE III. Parameters for the SCHERZO Medium Derived from ZPR-9 Assembly 25

$k_{\infty}$	1.000
Enrichment (a/o)	5.67 ± 0.06
$F_8/F_5$	0.0234 ± 0.0012
$C_8/F_5$	0.1143 ± 0.0040