2.0 THERMAL REACTORS

CALCULATIONS OF POWER DISTRIBUTIONS AND REACTIVITIES

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Introduction

A detailed analysis is in progress of the critical experiments conducted in the PRCF under a cooperative program[1] between the USAEC and the Italian CNEN. The purpose of this analysis is to evaluate calculational methods and models by comparing calculated power distributions and reactivities with those measured in the USAEC-CNEN program. The experimental program comprised a large number of lattice configurations using 2.35 wt% enriched UO_2 rods and PuO_2-UO_2 rods of several enrichments. The configurations ranged from simple uniform lattice arrays to arrays which simulated boiling water reactor fuel bundles with rods of lower enrichments on the edges and corners to reduce power peaking.

The analysis thus far has been applied to arrays in which a single type of fuel rod was used. This study comprises a total of 12 loadings, six configurations for each of two fuel types, 2.35 wt% enriched UO_2 and 2 wt% PuO_2-UO_2 (8% ^{240}Pu) rods. The six configurations were (1) a regular uniform loading of rods; (2) the same loading but with a water hole in the center (i.e., the central fuel rod was removed); (3) water slab (a row of fuel rods removed); (4) water cross; (5) a 7 × 7 rod array surrounded by water slots; (6) a similar 9 × 9 rod array.

In these twelve experiments, spatial power distributions were measured by gamma-scanning selected fuel rods. The k_{eff} for an infinitely-reflected array was also determined for each case. The main interest in the power distribution measurements was in the rod-to-rod distribution, expecially the effects of water slots on the power peaking.

The series of experiments, ranging from the simplest (regular) array to one simulating a 7 × 7 or 9 × 9 bundle, provides a systematic test for the evaluation of calculational methods.

Calculations

In the analysis of H_2O-moderated and reflected experiments (especially clean critical experiments) one generally assumes the reactor is composed of two regions: core and reflector. Few-group cross sections are calculated, assuming that an infinite medium spectrum applies in each region. The few-group cross sections are then used in a diffusion theory calculation of k_{eff}.

In an earlier study[2] it was pointed out that such a two-region, infinite medium model generally does not predict the power distribution well, although it may yield a satisfactory value for k_{eff}. In general, this method shows a pronounced trend, such that if the power distribution is normalized at the center of the core, the power near the core-reflector interface is consistently under-estimated. A simple modification, which resulted in considerably improved correlations, was reported in Reference 2. This simple modification consisted in introducing an extra reflector region (one lattice unit thick, adjacent to the core) which is represented by cross sections averaged over a spectrum characteristic of the core.

The multigroup transport theory codes HRG and Battelle-Revised - THERMOS were used to generate four-group cross sections for core and reflector regions. These cross sections were used in the two-dimensional diffusion theory code 2DB in an x-y calculation of power distributions and k_{eff}.

Four mesh points per cell were used in the 2DB calculations. This mesh description was carried out two lattice units

into the reflector; then the mesh points were more widely spaced. An axial buckling of 8.9 m^{-2} was used consistently.

In our current analysis we have compared three variations of our calculational model:

Model 1. The usual two-region, infinite-medium model (described in previous section);

Model 2. A simple modification consisting of an additional reflector region whose cross sections are obtained from cell calculations performed for the core (described in the previous section). In this model all water gaps also contained these modified reflector cross sections.

Model 3. A more detailed representation of the differences in spectrum in successive rows of fuel and water. This was accomplished with THERMOS calculations in slab geometry, with appropriate homogenized regions of core, reflector and gaps; editing was done over the proper spatial points to obtain average cross sections for each "row" of fuel and water. For analysis of the UO_2 loadings, five sets of core cross sections were used to represent fuel rods in various locations, and four sets of cross sections were used to represent water. For analysis of the UO_2-PuO_2 loadings, three sets of core cross sections and three sets of water cross sections were used.

Results

Power Distributions

Power distributions calculated using the three models described above were compared with measured distributions.

The trend that is so evident in the regular lattices when using Model 1 (i.e., calculated power consistently underestimated near core-reflector boundary) was significantly reduced when the modified models were used. The simple

modification used in Model 2 gives a better correlation than the more refined modification used in Model 3. This is evident especially in the case of the mixed oxide loading.

The lattice position that one chooses for a normalization point is rather arbitrary, yet this choice can affect the trends that one sees as well as the overall goodness or badness of the correlation. The center of the core is one likely normalization point. However, if this point is chosen, then one is basing his whole correlation on the accuracy of that one measurement (since there is only one rod in the center). A better choice might be a location away from the center and also away from water boundaries, a location which would permit four or eight symmetrical rods to be measured, the average of these measurements then providing a more reliable normalization point. However, multiple symmetrical rods were not measured in every case. Furthermore, no matter what point one chooses, there are always nonuniformities in the fuel rods, in the lattice plates, and bowing of fuel rods, etc., which introduce unknown errors into the normalization.

To eliminate this arbitrariness, and to provide a meaningful and consistent criterion for comparison of methods, we chose to represent the goodness of each correlation by a standard deviation, σ, defined by[1]

$$\sigma = \sqrt{\sum_{i}^{N} (\bar{\delta} - \delta_i)^2/(N - 1)}$$

where N is the number of rods measured,

$$\delta_i = \frac{P_{calc} - P_{meas}}{P_{meas}} \text{ for the } i^{th} \text{ rod,}$$

and $$\bar{\delta} = \sum_{i}^{N} \delta_i/N.$$

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The definition of σ implies an "effective" normalization such that the average fractional deviation, δ, is zero. This definition thus makes σ independent of the particular choice of normalization, and provides us a meaningful, consistent measure for purposes of comparing methods.

The σ's for the various cases are given in Table 2.1. We can make the following general observations:

- In every case σ was significantly reduced when modifications were made to the simple two-region, infinite medium model (Model 1).
- In most cases, Model 2 gives the best correlation.

The significant improvement, and the goodness of the correlations obtained with the simple modification (Model 2), as well as its simplicity, make this model attractive for calculating power distributions in H_2O cores.

Calculation of k_{eff}

The modifications that were introduced to the two-region, infinite-medium model to improve power distribution correlations resulted in increases in calculated values of k_{eff}. This is consistent with comparisons between transport and diffusion theory results[3] which indicate that transport theory gives higher values of k_{eff}. That is, when one represents the core-reflector boundary with a better model (be it transport theory or a modification to diffusion theory) this results in higher values of k_{eff}. The calculated values of k_{eff} are listed in Table 2.2.

For the UO_2 loadings, the k_{eff} calculated using Model 1 were consistently low, with discrepancies ranging from 0.24 to 1.7%. Best agreement between measured and calculated k_{eff} values was obtained using Model 2, with discrepancies ranging from +0.34% to -0.17%. Model 3 gave consistently high values of k_{eff} (by 1.0% to 1.7%).

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TABLE 2.1. Standard Deviation (%) in Power Distributions

	UO_2			PuO_2-UO_2		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Regular	2.09	1.18	1.05	3.37	1.86	2.17
H_2O-hole	1.48	0.98	1.14	2.48	1.78	-
H_2O Slab	1.95	1.48	1.56	1.60	1.38	1.13
H_2O Cross	1.57	1.37	1.21	2.13	1.40	-
7 x 7	1.96	1.72	2.16	2.26	1.69	1.78
9 x 9	2.91	2.67	3.12	2.29	1.90	-

TABLE 2.2. Values of k_{eff}

	UO_2				PuO_2-UO_2			
	Exp.	Model 1	Model 2	Model 3	Exp.	Model 1	Model 2	Model 3
Regular	1.0032	1.0008	1.0051	1.0164	1.0006	0.9960	1.0080	1.0009
H_2O Hole	1.0025	1.0000	1.0046	1.0161	1.0020	0.9973	1.0096	-
H_2O Slab	1.0018	0.9957	1.0044	1.0162	1.0068	0.9982	1.0182	1.0063
H_2O Cross	1.0010	0.9924	1.0039	1.0161	1.0054	0.9956	1.0231	-
7 x 7	1.0010	0.9888	1.0044	1.0175	1.0038	0.9867	1.0220	1.0007
9 x 9	1.0027	0.9858	1.0010	1.0133	1.0078	0.9928	1.0245	-

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For the PuO_2-UO_2 loadings, the k_{eff} calculated using Model 1 were consistently low, with the discrepancies ranging from 0.5 to 1.7%. The k_{eff} calculated using Model 2 were consistently high, with discrepancies ranging from 0.7 to 1.8%; Model 3 gave the closest agreement with measured k_{eff} values.

Conclusions

The simple modification incorporated in Model 2 of our analysis significantly improved power distribution correlations for the twelve configurations that were analyzed.

This improvement, together with the simplicity of this method, makes this method attractive for calculating power distributions in H_2O cores. The simplicity of the model comes about because cross sections for the modified water regions (water gaps and the reflector adjacent to the core) are obtained directly from cell calculations for the core. No additional calculations are necessary.

The method will next be used to calculate power distributions in more complex loadings which contain fuel rods of several enrichments.

References

1. P. Loizzo, et al. *Experimental and Calculated Results for UO_2 and UO_2-PuO_2 Fueled H_2O-Moderated Loadings*, To be published, Battelle-Northwest.

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3. S. R. Dwivedi. "Multiplication Dependence on Energy and Angular Detail in Transport Theory Calculations," *Plutonium Utilization Program Technical Activities Quarterly Report, June, July, August 1969*, BNWL-1224, Battelle-Northwest October 1969.

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