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The Critical Eigenvalue in LMFBRs: A Physics Assessment

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This paper summarizes recent work to put the analysis of past critical eigenvalue measurements from the U.S. critical experiments program on a consistent basis. Such an assessment is a necessary prelude to full utilization of the critical experiment data in LMFBR design and safety evaluations. The experimental data base for this assessment includes over 70 reference configurations constructed in fast critical facilities by Argonne National Laboratory from 1969 to 1984. The integral data base includes 53 configurations built in 11 ZPPR assemblies which simulate mixed oxide LMFBRs. Both conventional and heterogeneous designs representing 350, 700, and 900 MWe sizes and with and without simulated control rods and/or control rod positions have been studied. The review of the integral data base includes quantitative assessment of experimental uncertainties in the measured excess reactivity. Analyses have been done with design level and higher-order methods using ENDF/B-IV data. Comparisons of these analyses with the experiments are used to generate recommended bias factors for criticality predictions. Recommended methods for analysis of LMFBR fast critical assemblies and LMFBR design calculations are presented. Unresolved issues and areas which require additional experimental or analytical study are identified.

This study identifies the uncertainties and adjustments made to the measurement of the critical eigenvalue in the ANL fast critical facilities. In general, these include: uncertainties in the measurement of the excess reactivity; adjustments for temperature, parked safety rods, and midplane gap; and uncertainties in effective delayed neutron fraction, closure reproducibility, material location, material mass, isotopic composition, and decay of ^{241}Pu. The statistical sum of all these uncertainties is less than 0.1% δk, which is shown to be much smaller than the uncertainty in the calculated eigenvalue.

Eigenvalue calculations for the ZPR critical assemblies are performed with a variety of analytical methods and models. In complex assemblies, three-dimensional diffusion calculations (which account for plate heterogeneity and streaming) are done, with transport effects provided by S_n calculations in one or two dimensions. One point is fundamental -- the analytical methods must adequately treat the plate structure of the ZPR assemblies. This study describes the analytical methods, and identifies corrections and uncertainties associated with the eigenvalue calculation. The reference calculational method for the present study is: ENDF/B-IV data in 28-groups; XYZ diffusion model; mesh spacing close to 55 mm; and streaming effects in the plate cells treated by anisotropic diffusion coefficients generated by the Benoist method.

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Eigenvalue C/E results obtained with the reference (diffusion theory) methods are summarized in Table I. The results are grouped according to the different core characteristics. The standard deviation and range of variation

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TABLE I. Summary of Eigenvalue C/E Results with Diffusion Theory

		Number	Mean	σ	Range of Variation
All ZPPR Cores		32	0.9784	0.0026	0.0100
Conventional Cores					
All		12	0.9805	0.0017	0.0051
Small		5	0.9800	0.0018	0.0047
Large		7	0.9809	0.0016	0.0044
Heterogeneous Cores					
All		20	0.9772	0.0022	0.0072
ZPPR-7/8		7	0.9754	0.0023	0.0054
ZPPR-11		7	0.9789	0.0013	0.0036
ZPPR-13		6	0.9772	0.0014	0.0036
Clean Cores					
All		8	0.9805	0.0038	0.0067
Conventional		2	0.9828	0.0001	0.0001
Heterogeneous		6	0.9786	0.0028	0.0036
Cores with CRPs					
All		17	0.9774	0.0024	0.0069
Conventional	Small	3	0.9789	0.0007	0.0012
	Large	3	0.9794	0.0007	0.0013
Heterogeneous	BOC	7	0.9752	0.0021	0.0056
	EOC	4	0.9787	0.0008	0.0019
Cores with CRs					
All		7	0.9807	0.0014	0.0048
Conventional		4	0.9814	0.0012	0.0027
Heterogeneous		3	0.9797	0.0011	0.0020

are quoted as a measure of the spread in the results. The following conclusions are drawn from these results:

- Different bias factors could be applied to conventional and heterogeneous cores. Since enrichments are determined for the cores with CRPs, these biases are determined from the following k_{eff} C/E results:

Conventional cores	0.9792
Heterogeneous cores	0.9765

- There is a bias in the C/E results for the heterogeneous cores between beginning- and end-of-cycle. The results for the EOC heterogeneous cores are in close agreement with the results for the conventional cores.

Heterogeneous cores	0.9752 at BOC
	0.9787 at EOC

- The ranges of variation of the results, when grouped into two basic core types, are consistent with the estimated uncertainties in the calculations (0.25%). On the basis of the spread in the results we recommend:

  > The (1σ) uncertainty in the biased value resulting from the critical assembly analysis alone should be taken to be 0.25%.

- Transport-corrected results have been obtained for 18 of the ZPPR critical configurations in the data base. The transport calculations show a significant improvement in consistency. The overall standard deviation and range of variation are reduced by a factor of two (relative to the reference diffusion theory results).

Results have also been obtained using Monte Carlo methods. Six full assembly calculations were modelled in explicit three-dimensional, platewise detail with the VIM Monte Carlo code and compared with "fully-corrected" deterministic methods. That is, the VIM results were compared with results of reference multigroup diffusion theory calculations corrected for higher order effects of known significance, such as transport, streaming, mesh, etc. These detailed three-dimensional Monte Carlo calculations (with 1σ of ~0.1-0.2% on k_{eff}) indicated a potential bias of ~0.4% relative to the standard deterministic methods.

Considerable improvement in the prediction of critical eigenvalue for fast reactors has been achieved over the past decade. Despite the significant progress, this assessment indicates that three fundamental problems remain. Most apparent is the systematic ~2% underprediction of k_{eff} for critical configurations of standard LMFBR composition, when the calculations are based on the ENDF/B-IV library. The second problem, also applicable to normal LMFBR designs, is the ~0.4% discrepancy between the standard methods and the more-exact Monte Carlo results. Third, when the range of critical configurations is opened to include other (than LMFBR) compositions and smaller sizes, the range of k_{eff} values increases by an order of magnitude, from a few tenths of a percent to about three percent. Furthermore, there are serious omissions or deficiences in the integral data base given the current emphasis on innovative designs. The present data base cannot provide sufficient support for designs that incorporate any major deviations from conventional assumptions about size and composition.

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