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LESSONS LEARNED FROM APPLYING VIM TO FAST REACTOR CRITICAL EXPERIMENTS*

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Introduction

VIM is a continuous energy Monte Carlo code first developed around 1970 for the analysis of plate-type, fast-neutron, zero-power critical assemblies.[1] In most respects, VIM is functionally equivalent to the MCNP code[2] but it has two features that make uniquely suited to the analysis of fast reactor critical experiments: 1) the plate lattice geometry option, which allows efficient description of and neutron tracking in the assembly geometry, and 2) a statistical treatment of neutron cross section data in the unresolved resonance range. Since its inception, VIM's capabilities have expanded to include numerous features[3], such as thermal neutron cross sections, photon cross sections, and combinatorial and other geometry options, that have allowed its use in a wide range of neutral-particle transport problems.

The earliest validation work at Argonne National Laboratory (ANL) focused on the validation of VIM itself.[4,5] This work showed that, in order for VIM to be a "rigorous" tool, extreme detail in the pointwise Monte Carlo libraries was needed, and the required detail was added. The emphasis soon shifted to validating models, methods, data and codes against VIM. Most of this work was done in the context of analyzing critical experiments in zero power reactor (ZPR) assemblies.

The purpose of this paper is to present some of the lessons learned from using VIM in ZPR analysis work. This involves such areas as uncovering problems in deterministic methods and models, pitfalls in using Monte Carlo codes, and improving predictions. The numerical illustrations included here were taken from the extensive documentation cited as references.

Infinite Lattice Calculations

A systematic study was executed to validate the cross section processing scheme used in ZPR analysis at Argonne National Laboratory,[6,7] with emphasis on unit cell homogenization. VIM and deterministic solutions were compared for a series of model problems, ranging from infinite homogeneous media to infinite lattices of three-dimensional plate and pin unit cells with an imposed buckling. Based on these comparisons, one-dimensional modeling approximations and methods approximations were established that accurately predict cell average fluxes, reaction rates and leakage for core unit cells of typical

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liquid-metal fast reactor (LMR) mockups.

Even before that study was completed, difficulties were encountered in the analysis of a mockup of a different reactor concept, the gas-cooled fast reactor (GCFR). Using VIM solutions to infinite lattice problems as a reference, the standard deterministic method for treating neutron streaming in coolant channels were found to be inadequate when the channels were essentially voids, as in the GCFR. An alternative diffusion coefficient was developed to treat this situation.[8] Other problems occurred in the analysis of the steam-filled GCFR mockup, representing the postulated steam ingress accident.[9] It was found, through comparisons with VIM cell calculations, that errors caused by the narrow resonance approximation (NRA), which for the LMR and normal GCFR cells were unimportant, were large when steam was introduced. The data in Table I, taken from this evaluation of the NRA, illustrate the detailed level at which comparisons were made to diagnose problems in the calculations. Neglect of energy loss in anisotropic scattering, the "inconsistent P_1" approximation, also was found to cause an significant error in deterministic calculations of steam ingress reactivity.

Assembly Eigenvalue Calculations

A practical barrier to making criticality predictions with VIM for ZPR experiments was the difficulty of producing a detailed, three-dimensional whole core model. A high fidelity model requires many thousands of lines of input, even in plate lattice geometry, the hand production of which is tedious, time consuming and prone to error. Despite this, a number of ZPR assemblies were modeled successfully by hand. Reasonable compromises were made in which only representative unit cells were modeled but these were quite detailed. The task was partially automated at the ZPR 6 and 9 facilities. Ultimately, an automatic VIM input generation system, BLDVIM, was created at the ZPPR facility, which accessed the full assembly description on the ZPPR computer database. Fig. 1, which is a two-dimensional slice through one cell modeled using BLDVIM, gives an indication of the detail included in the model. This automation was important for three reasons: it made practical the modeling of assemblies in full detail, it greatly reduced the amount of labor required to produce a model and, most importantly, it offered a high degree of quality assurance, i.e., the probability of input errors was reduced markedly.

Probably the first benefit derived from whole core ZPR calculations with VIM was the discovery of a bug in VIM. Two sets of VIM calculations of Reactor Safety Research assemblies, produced independently by different analysts, had eigenvalue solutions that were close but uniformly discrepant beyond one standard deviation. Recognition that the results taken as a whole were statistically inconsistent precipitated an investigation that uncovered the code bug.

Problems with deterministic cross section processing codes were uncovered as a result of VIM calculations for ZPR mockups whose core compositions were dominated by iron and ^{235}U. When standard deterministic eigenvalue predictions for a critical configuration were found to be more than 3% below unity, a whole core VIM calculation was run. The VIM

prediction agreed much better with experiment. This motivated comparisons between VIM and deterministic solutions in a series of related model problems. The main error was found to be neglect of resonance behavior in the ENDF/B high energy "smooth" elastic scattering cross sections of structural materials such as iron.[10] Algorithms to treat this phenomenon were implemented in the deterministic codes.[11]

How results from plate critical experiments should be applied in power reactor design depends on how well calculations account for the heterogeneity difference between the plate cells of critical assemblies and the pin cells of power reactors. Pin and plate versions of nearly the same core design were built, first in the UK[12] and later at ZPPR. VIM was used to calculate eigenvalues for these assemblies, helping to separate discrepancies into data, methods and experimental components.

In time, VIM eigenvalue calculations were made for enough ZPR assemblies that trends and biases could be observed.[13] Table II is an example from Ref. 13. Eigenvalues for mixed-oxide-fueled LMR mockups are larger by about 0.2% when computed by the standard deterministic approach compared to those from VIM. For a wider range of fast reactor compositions the discrepancy is as large as 0.5%. These errors are mostly associated with misprediction of leakage.[10] There is a 3% spread among eigenvalues computed for critical ZPR assemblies with VIM and ENDF/B Version 4 nuclear data, implying the existence of significant deficiencies in the basic ENDF/B data.

Having VIM predictions of integral parameters (primarily eigenvalues) for a wide range of fast critical assemblies makes it possible to reduce markedly the impact of deficiencies in cross section data.[14,15] Using ENDF/B Version 5 data, VIM calculations have been done for dozens of assemblies, including ones built at Los Alamos, at ZEBRA in the UK and at the ZPRs at ANL. A generalized least squares procedure has been used to adjust multigroup cross section sets within their uncertainties such that the integral parameters as a whole are predicted more accurately. As one example of the insight gained, errors in Version 5 high energy boron absorption cross sections were identified through a difference in the error in control rod worths from a hard spectrum space reactor mockup compared to those from LMR mockups.

Calculating Other Assembly Parameters

As computing power increased, it became practical to compute, with adequate statistical precision, experimental quantities besides eigenvalue using VIM. VIM was used to investigate mispredictions of reaction rate distributions in a ZPR mockup of the radially heterogeneous Clinch River Breeder Reactor. Comparisons of radial reaction rate distributions from experiments, deterministic calculations and VIM calculations revealed that the discrepancies with experiment were a combination of deficiencies in the ENDF/B Version 4 nuclear data and inaccuracies in the deterministic cross section processing methods used for the mix of core and blanket plate cells in this reactor design.[16] Table III is an example from Ref. 16 showing the increasing error in nonthreshold reaction rates as radius increases that is attributable to deficiencies in the ENDF/B-IV data.

Another investigation of errors in radial reaction rate distributions lead to the discovery that the uncertainty estimates from VIM could be misleading. For radial reaction rates in the very large, radially heterogeneous assembly, ZPPR-13A, the variance was observed not to have the expected linearly inverse relationship with fission rate. This was traced to serial correlations among successive batches, caused by the use of the fission source distribution computed in the previous batch, and made important by the unusually small eigenvalue separation between the fundamental mode and the first harmonic.[17]

VIM has also been used to test the accuracy of a correction factor needed in the reduction of experimental subcritical multiplication data. Ordinarily, source importance ratios[18] can be computed accurately by standard deterministic methods but, in the case of reflector worth in the SP-100 space reactor mockup, those methods were of questionable validity. The VIM calculations confirmed the suspicion that the conventionally-computed factors were less accurate than usual and allowed appropriate uncertainty estimates to be assigned to the experimental worths.

Conclusion

The VIM code was used for many years in conjunction with fast reactor critical experiments, yielding a wealth of information. Long ago the frequency and severity of deficiencies uncovered in VIM decreased to the point where it was considered to be a mature, reliable tool whose accuracy is limited only by statistical precision and the accuracy of basic cross section data. This not withstanding, it is incumbent on users always to be critical evaluators searching for evidence of code deficiencies, input errors, etc. VIM has been used to improve standard modeling and to identify errors in deterministic calculations. It has even been helpful in the discovery of errors in cross section data.

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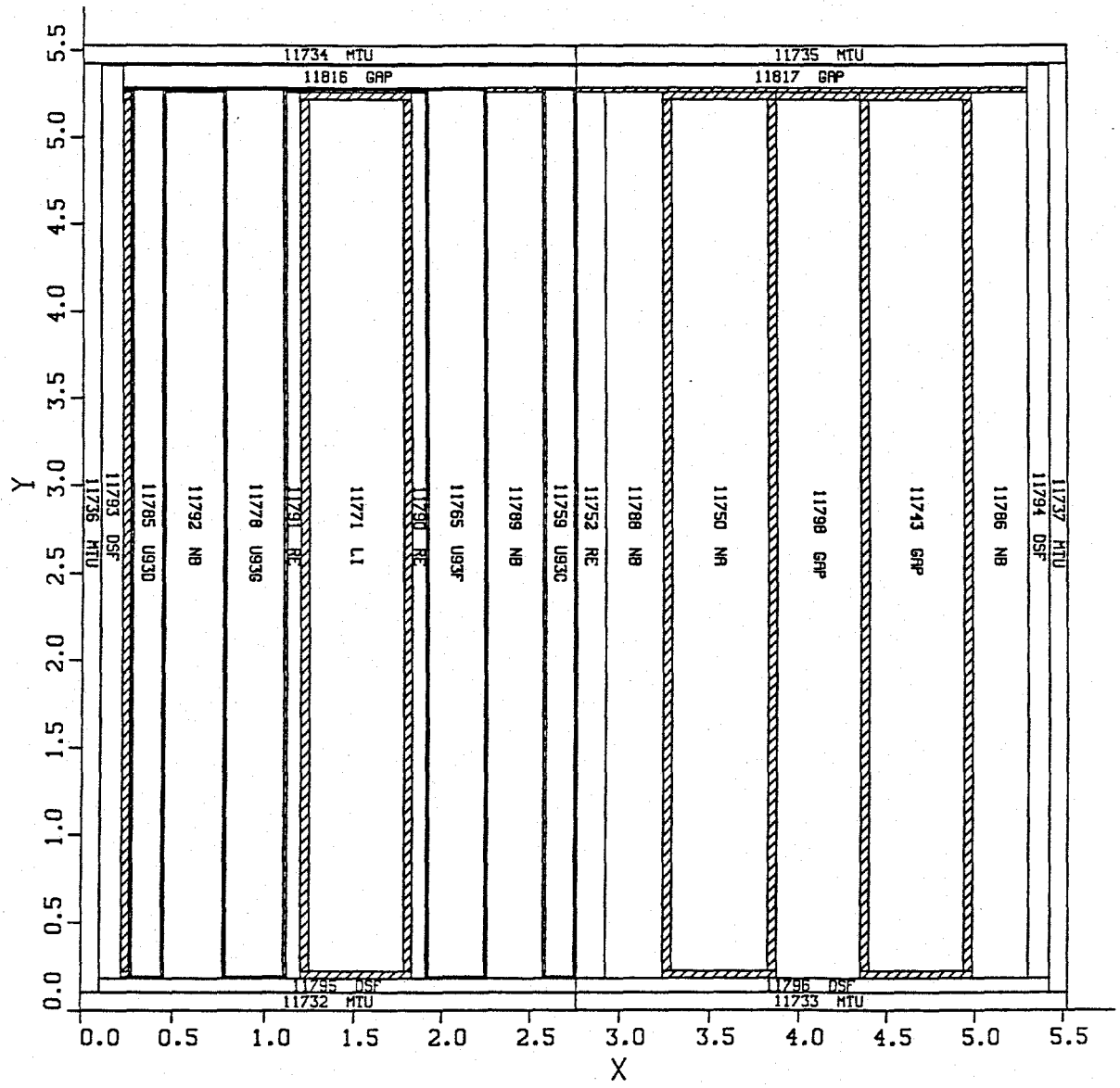

Fig. 1. XY Plane Through Model of Drawer Master 20-2-206 at Z=13.0 cm.

Table I. Errors in Deterministic (MC^2 Code) Calculations of ^{239}Pu Absorption Rate In a Normal (Dry) and Steam-Filled (Wet) GCFR Mockup

	Dry				Wet			
	VIM		MC^2 - NRA	MC^2/RABANL	VIM		MC^2 - NRA	MC^2/RABANL
Group	$\Sigma_a\phi$[a]	% Uncertainty[b]	% Error	% Error	$\Sigma_a\phi$[a]	% Uncertainty[b]	% Error	% Error
1	1.104E-3	4.85	+0.77		1.164E-3	5.78	-1.80	
2	3.887E-3	1.60	+1.44		3.871E-3	2.04	-2.82	
3	1.128E-2	1.15	+0.98		1.043E-2	1.27	+0.86	
4	1.736E-2	0.82	-1.56		1.509E-2	1.10	+2.52*	
5	2.229E-2	0.87	-0.36		1.903E-2	0.96	-0.16	
6	4.623E-2	0.56	+0.48		3.364E-2	0.71	-0.83	
7	3.727E-2	0.45	+0.16		2.471E-2	0.57	+0.93	
8	4.673E-2	0.36	-0.49		2.704E-2	0.73	+0.07	
9	5.015E-2	0.39	-0.08		2.492E-2	0.55	+0.40	
10	4.684E-2	0.35	-1.11*		2.136E-2	0.95	-0.47	
11	4.411E-2	0.30	-0.18		1.872E-2	0.57	+2.08*	
12	3.194E-2	0.35	-0.41		1.509E-2	0.86	+0.99	
13	3.961E-2	0.31	-0.58		1.787E-2	0.75	+0.39	
14	3.154E-2	0.46	-0.13		1.737E-2	1.12	+0.23	
15	1.985E-2	0.39	+0.10		1.569E-2	0.82	-0.64	
16	2.302E-2	0.51	-1.56*	-0.56	2.141E-2	1.13	-0.79	+0.23
17	2.138E-2	0.47	-2.01*	-0.61	2.471E-2	0.94	-2.91*	-0.63
18	1.769E-2	0.67	-0.68	-0.28	2.689E-2	0.96	-3.68*	-0.70
19	1.222E-2	0.85	+0.33	-1.88*	2.836E-2	1.25	5.68*	-2.49
20	8.106E-3	1.00	+4.54*	-1.28	3.267E-2	1.00	3.58*	-1.67
21	3.265E-3	1.44	+8.82*	-2.66	2.628E-2	1.51	-0.68	-1.68
22	2.929E-3	2.00	+10.86*	+0.20	5.683E-2	1.44	+0.53	+2.54
23	2.018E-3	11.2	+55.30*	+7.48	4.071E-2	2.30	+23.29*	+3.35
24	1.569E-6	53.9	+3.12	+5.35	1.548E-2	3.42	+38.37*	+2.34

[a]Track Length Estimators.

[b]One Standard Deviation.

*More than 2 standard deviations.

Table II. K_{eff} Predictions for Six Assemblies Using Deterministic and Monte Carlo Methods

Assembly	VIM Histories	$k_{eff} \pm 1\sigma$ (VIM)[a]	k_{eff}(MC^2-2/SDX)[b]	k_{eff}(MC^2-2/SDX) - k_{eff}(VIM)[a]
ZPR-6/7	300,000	0.9781 ± 0.0011	0.9809	+0.0028 ± 0.0011
ZPR-9/32	200,000	0.9952 ± 0.0016	1.0005	+0.0055 ± 0.0016
ZPR-9/34	100,000	0.9817 ± 0.0026	0.9865	+0.0047 ± 0.0026
ZPR-9/36	100,000	1.0070 ± 0.0022	1.0101	+0.0030 ± 0.0022
ZPPR-11B	500,000	0.9858 ± 0.0009	0.9909	+0.0051 ± 0.0009
ZPPR-12	250,000	0.9983 ± 0.0013	0.9994 0.9983[c]	+0.0011 ± 0.0013 +0.0000 ± 0.0013

[a] Uncertainty is 1σ estimate from the VIM Monte Carlo calculation only.

[b] These MC^2-2/SDX eigenvalues are reference multigroup diffusion theory calculations corrected for higher order effects (e.g., transport, streaming, mesh, etc.) of known significance.

[c] This value is calculated with three-dimensional nodal transport methods [9].

Table III. Comparison of Reaction Rates by Radial Zone From VIM and Experiment

	VIM Calculation/Experiment			
Zone[a]	$^{239}Pu(n,f)$	$^{235}U(n,f)$	$^{238}U(n,\gamma)$	$^{238}U(n,f)$
CB	-	1.006	1.045	0.958
F1	0.986	1.006	1.029	0.966
B1	-	1.011	1.042	0.961
F2	0.987	1.036	1.050	0.954
B2	-	1.014	1.051	0.983
F3	0.999	1.039	1.050	0.935
B3	-	1.059	1.063	0.977
F4,5	1.018	1.059	1.075	0.968
RB	-	0.995	1.042	0.935

[a] Radial zones from center, outward (CB=central blanket; F1=fuel ring 1, etc.; B1=internal blanket ring 1, etc.; RB=radial blanket). For the three nonthreshold reactions, VIM 1σ uncertainties vary from 1.5% in CB to 0.5% in RB, and for ^{238}U fission the range in 2.5% to 1%.