ANL/RA/CP--85791

Paper for Invited Presentation

Conf-9505195--7

**Embedded Topical Meeting on
Misapplications and Limitations of Monte Carlo Methods
Directed Toward Criticality Safety Applications**

**Nuclear Criticality Technology and Safety Project Annual Meeting
San Diego, CA
May 17, 1995**

**Monte Carlo Neutronic Analysis
of A Loosely Coupled Reactor***

Roger N. Blomquist

Argonne National Laboratory
Reactor Analysis Division
9700 S. Cass Ave. — RA/208
Argonne IL 60439-4842

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

* Work supported by the U. S. Department of Energy, Nuclear Energy Programs, under Contract W-31-109-ENG-38.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Monte Carlo Analysis of A Loosely Coupled Reactor*

Roger N. Blomquist (ANL)

In this paper, we discuss the difficulties encountered in Monte Carlo analysis (using VIM¹) of the Zero Power Physics Reactor Assembly 13A, a neutronically loosely-coupled radial heterogeneous fast reactor. In particular, the fission rate statistical errors in large reactor core zones were badly underestimated, although the statistics were apparently quite good. The principal eigenvalue was not affected, however.

The reactor consists of a square array of steel lattice sites into which are slid rectangular, open-top "drawers" containing plates of fuel, structure, coolant, control, and other materials. The drawers are arranged in a radially heterogeneous pattern, so from the center outward, there are the inner blanket, the inner core, a middle blanket, the middle core, a second middle blanket, the outer core, the radial blanket, and a reflector. Each blanket consists of relatively densely packed blanket pins which are rather strongly absorbing; hence the radial decoupling among the three radial core zones.

In "well-behaved" Monte Carlo reactor calculations, i.e., in which the generations are essentially independent after convergence to the fundamental mode, the estimated variance σ^2 is proportional to $1/N$, where N is the number of scores and the proportionality is a function of the dispersion of the scores. For a reactor in which the phase space is well-sampled and in which essentially no variance reduction methods are applied to the random walks, we should observe relatively lower relative variances in regions with higher fission rates. Nevertheless, in one ZPPR-13A calculation, the track-length fission rate estimates were $0.148 \pm 1.63\%$, $0.330 \pm 0.93\%$, and $0.523 \pm 1.22\%$, for the inner, middle, and outer radial cores, respectively. If, based on the number of scores, we extrapolate the one-sigma error estimate from the middle core to the outer core, we would expect an error of only 0.74%; but the observed error estimate was high by a factor of over 1.6.

An independent calculation with 240 generations of 1000 histories per generation was performed to provide data for further statistical analysis. To consider the effects of serial correlation among generations, the average estimates of the outer core fission rate over sets of 20 consecutive generations were computed, and are shown in Table 1. Between sets of generations, the fission rate undergoes remarkable shifts which are far outside of statistics (e.g., 6σ at generation 60).

To better understand these anomalies, we chose to investigate the dramatic rise in the fission rate near generation 60. Examining the fission rate for each generation showed that the overall change in the fission rate occurred because of a 10% increase between the ends of generations 63 and 64 to a level which then persisted for 17 generations. We restarted the Monte Carlo calculation from the fission sites produced during generation 62, repeating generations 63 and 64 ten times, each time with a new random number sequence. Because the only information passed between generations is the continuation of the random number series and the fission site distribution, we could determine whether the increase in fission rate was preordained by the spatial distribution of starting particles, or whether it arose during the course of generation 63 or during generation 64. Over the ten independent repeats, the generation 63 and 64 fission rates were only 0.1372 ± 0.0023 (with a maximum of 0.148) and 0.1392 ± 0.0024 (with a maximum of 0.151), respectively. This indicated that the generation 62 fission site distribution was consistent with the previous generations, and contained no shift which could have caused the higher outer core fission rate after

generation 63.

Taking the set of fission sites produced by the original generation 63, we then repeated (independently) generation 64 six times. The average fission rate estimate was $0.1508 \pm 0.004\%$ (with a minimum of 0.137), nearly 3σ above the preceding generation. This indicated that the shift in the fission rate was indeed caused by a shift in the fission site distribution during generation 63. A comparison of the radial fission site distributions for the two generations did show a clear spatial shift; the sites produced in generation 63 were spatially much more similar to those produced in generation 64 than to those produced in the independent repeats of generation 63. The fission sites were inspected to verify that no particular sites were chosen many times, an occurrence which would have indicated a code bug or other non-physical and non-statistical problem.

Two statistical techniques were applied to fission rate tallies from two independent Monte Carlo calculations to correct for the effects of correlation: (1) generation grouping, and (2) MacMillan's method. In grouping, we lumped the tallies into groups of N generations (for N=1, 2, 4, 8, and 16), and recomputed the error estimates for the grouped data in each simulation. The effect of grouping the generations is to reduce the effects of serial correlation, since the histories in the i-th group are N generations removed from those in the i-1-th group. Table 2, which includes results from the above-mentioned calculation and a separate independent replica, shows this quite clearly; the correlation coefficients tend to zero and the error estimates increase as the group size is increased. In fact, the fluctuations noted in Table 1 are consistent with the larger error estimates resulting from grouping generations.

For non-independent samples, the variance of the mean is

$$\sigma^2 = E \left[\frac{(\sum \xi_i)^2}{N} \right],$$

where ξ_i is the deviation of the i^{th} sample from the mean. The usual calculation of the error estimate relies on the fact that the cross terms in the square of the summation cancel, which they do not when they are correlated. By making an assumption about the distribution of the higher mode eigenvalues, MacMillan² derived an estimate of a multiplicative factor to correct for the correlation among generations. The sums of the cross terms were shown to be the lag-n autocorrelation coefficients, so the correction factor can be given by

$$C = \sqrt{1 + \frac{1 + 2r_1}{1 - r_2/r_1}},$$

where r_1 and r_2 are the lag-1 and lag-2 correlation coefficients, respectively, and their ratio is the eigenvalue dominance ratio. Table 2 also shows the MacMillan factors computed for the fission rate, for each group size. The erratic correlation coefficients for N=16 are probably indicative of inadequate statistics for generating the correction factors – they appear to be too unreliable to use in MacMillan's scheme.

The ZPPR-13A calculations point out a recurring feature of Monte Carlo calculations of loosely coupled systems. It is crucial to understand the effects of the higher eigenmodes on the fission source iteration process, not just because of the well-known contamination of final tallies by the fission source guess, but also because the stochastic simulation process itself can excite higher modes and produce misleading error estimates.

References

- [1] R. N. Blomquist, "VIM", proc. ANS topical meeting on *Advances in Mathematics, Computations, and Reactor Physics*, April 28 - May 2, 1991, Pittsburgh, PA.
- [2] D. B. MacMillan, "Monte Carlo Confidence Limits for Iterated-Source Calculations," *Nucl. Sci. Eng.*, **50**, 73-87

(1973).

Table 1: Outer Core Fission Rate Trends

Generations	Fission Rate
1-20	$0.138 \pm 1.1\%$
21-40	$0.139 \pm 1.6\%$
41-60	$0.134 \pm 1.3\%$
61-80	$0.153 \pm 1.6\%$
81-100	$0.147 \pm 1.7\%$
101-120	$0.147 \pm 2.0\%$
121-140	$0.139 \pm 1.7\%$
141-160	$0.142 \pm 2.6\%$
161-180	$0.152 \pm 1.3\%$
181-200	$0.145 \pm 1.8\%$
201-220	$0.150 \pm 1.3\%$
221-240	$0.150 \pm 1.4\%$

Table 2: Outer Core Fission Rate Statistics (Grouped Generations)

Run	Gens/ Batch	VIM σ	r_1	r_2	r_2/r_1	C
1	1	0.00066	0.642	0.540	0.84	3.01
1	2	0.00084	0.682	0.531	0.78	2.68
1	4	0.00111	0.632	0.340	0.54	1.93
1	8	0.00146	0.433	-0.027	-	~1
1	16	0.00190	-0.019	0.011	-	~1
2	1	0.00066	0.692	0.614	0.89	3.63
2	2	0.00086	0.731	0.503	0.69	2.39
2	4	0.00113	0.608	0.372	0.61	2.03
2	8	0.00148	0.560	0.243	0.43	1.72
2	16	0.00184	0.512	0.462	0.90	3.35