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Titolo

Use of Monte Carlo to Evaluate Radiation Damage to Corium Detector in PWR Severe Accident Scenario

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Sommario

As in PAR reports of previous years, the activity of radiation transport by means of Monte Carlo modelling has proceeded along twin tracks: development and application. The development is directed at calculating local responses within eigenvalue calculations (as employed in reactor cores or storage arrays of fissile material). Currently considered application of presented method is that of the monitoring of the corium position in PWR severe accident scenarios. This is carried out in collaboration with IRSN (French Institute for Radiation Protection and Safety).

Note

This document has been prepared by the following main contributors:

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1. INTRODUCTION

As in PAR reports of previous years, the activity of radiation transport by means of Monte Carlo modelling has proceeded along twin tracks: development and application. The development is reported in the following §2 and the application in §3. The development is directed at calculating local responses within eigenvalue calculations (as employed in reactor cores or storage arrays of fissile material).

The methodology utilised takes advantage of a variance reduction (VR) technique within an eigenvalue source-iteration calculation. VR improvements and optimization have mainly been concerned with fixed source calculations where deep penetration problems frequently occur. By contrast, with the present method, a VR scheme within Monte Carlo eigenvalue source iteration calculations is considered.

The developed tool has been employed to evaluate ex-core as well as in-core responses within an eigenvalue calculation. Up till now, for ex-core problems it has been usual to split the procedure into 2 parts: first an eigenvalue problem in which the fission sites are binned and utilised as source terms in a second calculation in which the ex-core responses are obtained. Choosing the decoupling point as the fission sites, rather than, for example, the leakage current from the fissile region, reduces the stored data requirements since an analytic fission distribution is employed and therefore the neutron source energy and direction is not stored.

A currently considered application is that of the monitoring of the corium position in PWR severe accident scenarios. This is carried out in collaboration with IRSN (French Institute for Radiation Protection and Safety). Some innovative aspects of the EPR reactor design include several safety devices in order to deal with and contain severe accidents. Core meltdown is considered and the corium position is progressively detected by means of fibre optics cables within all containment layers downstream from the active part of the reactor core.

2. DEVELOPMENT OF MONTE CARLO ALGORITHMS EMPLOYED IN EIGENVALUE CALCULATIONS WITH THE SOURCE-ITERATION APPROACH

Following on from the development of Monte Carlo algorithms for fixed source radiation transport modelling (see for example /1/), the transfer of the algorithms to eigenvalue problems, as communicated in previous PAR reports (see for example /2/), has continued, culminating in /3/.

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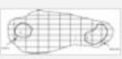

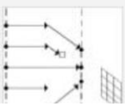

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Annals of Nuclear Energy

Volume 73, November 2014, Pages 218–240

Optimizing variance reduction in Monte Carlo eigenvalue calculations that employ the source iteration approach

This paper is dedicated to the memory of Lodovico Casalini (1955–2010) and of Carlo Artioli (1946–2014).

Kenneth W. Burn

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Highlights

- A variance reduction scheme within Monte Carlo eigenvalue calculations is proposed.
- It is based on the Direct Statistical Approach, already used in fixed source problems.
- Both in- and ex-core local responses are treated.
- Verifications are made that the fundamental mode is not distorted.
- One test problem showed a large advantage over the classical, adjoint-only approach.

Abstract

The question of variance reduction within the source-iteration scheme of a Monte Carlo eigenvalue calculation is tackled. The trade-off point between improving the statistics of a local response whilst simultaneously not damaging excessively the fundamental mode, the source for the calculation of the local response in the next fission cycle, is found. It is realized that applying less normalizations, i.e. employing superhistories, is advantageous. Realistic test problems, both fast and thermal fission, with in- and ex-core local responses, are treated. There is a good agreement between the predicted and actual gain in efficiency. A single comparison with the classic formalism, based purely on ϕ^*, shows large differences.

Keywords

Monte Carlo; Eigenvalue; Source-iteration method; Variance reduction; Direct statistical approach

Acknowledgments

The author would like to thank Reg Brissenden for introducing him to the world of Monte Carlo in the eigenvalue source iteration scheme (nearly 30 years ago). More recently Art Forster impressed on the author the fact that in realistic LWR calculations (and not only), it is necessary to run an appreciable number of fission cycles, however large the fission source can feasibly be made, so as to cover the fundamental mode.

The PWR-2D problem formed part of a wider collaboration with Giovanni Bruna and Antonio Sargeni of IRSN concerning the problem of flux tilt.

The author would like to take this opportunity to thank Salvatore Podda and Pietro D'Angelo of the Informatics Dept., ENEA Frascati for support in the implementation and running of MCNP on the sp5 (AIX) machines at ENEA, Frascati.

The author also wishes to express his appreciation of the efforts of the referees whose various suggestions improved the manuscript. In particular the effort to demonstrate when the fundamental mode is, and is not, maintained (Fig. 16, Fig. 17, Fig. 18 and Fig. 26) and the generation of less noisy results for problem 6.4 (Table 15) is due to one of the referees.

This work has been funded under the program agreement: Italian Ministry of Economic Development – ENEA, "Annual Plan 2012, Project B.3.1: Development of Expertise in Nuclear Safety".

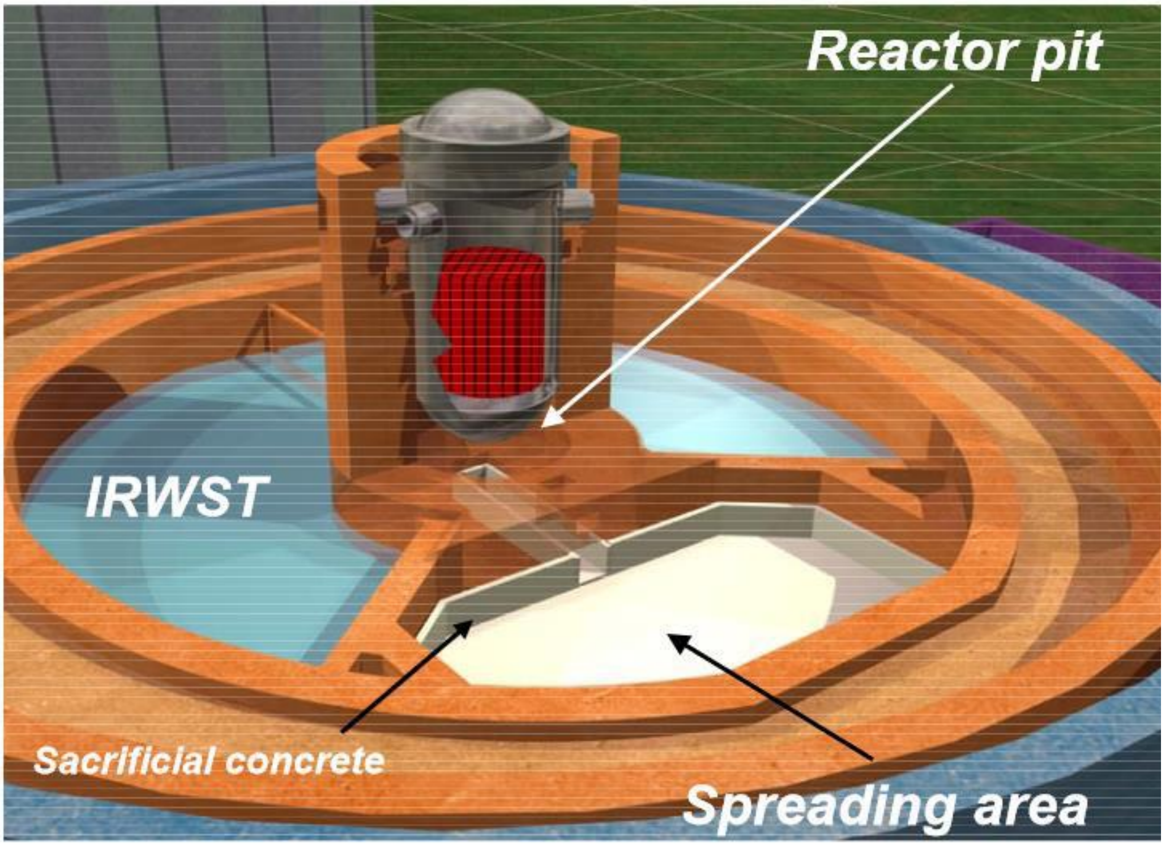
We attach in the Appendix a summary, in presentation form, of this work.

3. Support to IRSN (Fr) on the DISCOMS Project (Monitoring the Position of the Corium following Perforation of the Pressure Vessel): Calculation of Neutron and Gamma Spectra at Various Positions of the Collectrons outside the Pressure Vessel and Estimation of Radiation Damage to the Fibre Optics Cables.

The detection system consists of fibre optics cables and collectrons, monitoring the neutron and gamma fluxes. Both collectrons and fibre optics cables will be placed at a variety of positions outside the pressure vessel and in the lower part of the pressure vessel well, the reactor pit, melt discharge channel and spreading area (lined with sacrificial material). The neutron and photon spectra are required at each proposed collectron position for design purposes (type of collectron to be employed, shape of expected signal). The neutron flux and gamma dose are required for radiation damage estimates to the fibre optics cables at a limited number of positions.

This work is ongoing. As a first step, the “classic” approach of decoupling the in-core eigenvalue calculation from the ex-core fixed source calculation is currently underway, with the point of decoupling being the fission sites, as described in §1. As a second step, the algorithm described in §2 will be employed. For reasons of confidentiality, very little reporting of this activity can be made at the moment.

Corium spreading test at the French CEA VULCANO facility (UO_2 with some ZrO_2) (http://www.iaea.org/NuclearPower/Downloads/INPRO/Files/2010-Feb-DF-WS/15-Teller.pdf)



Core melt retention system

(http://www.iaea.org/NuclearPower/Downloads/INPRO/Files/2010-Feb-DF-WS/15 Teller.pdf)

4. References

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- Burn, K.W., 2013. Use of Monte Carlo in state-of-the-art PWR design: study of tilt in the NEA UAM PWR benchmark and development and testing of new algorithms within Monte Carlo eigenvalue calculations employing the source iteration method. ENEA-ADPFISS-LP1-015
- Burn, K.W., 2014. Optimizing Variance Reduction in Monte Carlo Eigenvalue Calculations that Employ the Source Iteration Approach. *Ann. Nucl. Energy* 73, 218-240.

Appendix

ESTIMATING LOCAL IN- AND EX-CORE RESPONSES WITHIN MONTE CARLO SOURCE ITERATION EIGENVALUE CALCULATIONS

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• We wished to transfer the techniques developed in Monte Carlo fixed source, deep penetration calculations to eigenvalue calculations (with the source iteration technique).

• To make the source iteration algorithm more similar to the fixed source one, we started off by introducing superhistories, typically with a length of 10 fission generations (Brissenden & Garlick, 1986). In this way the neutron histories are reasonably uncorrelated.

Brissenden, R.J., Garlick, A.R., "Biases in the Estimation of K_{eff} and Its Error by Monte Carlo Methods", *Ann. Nucl. Energy* **13(2)**, 63-83 (1986)

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• With the source iteration algorithm, the estimate of the fundamental mode of the distribution of spatial fission points is constantly re-calculated, so as to cover the real fundamental mode. This is crucial in weakly connected problems (large thermal cores; criticality safety; ....).

• Therefore we must always calculate properly the distribution of fission sites for each subsequent fission generation.

• We must also simultaneously calculate the local response (or responses) that we are interested in.

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• Calculating properly the distribution of fission sites for each subsequent fission generation is straightforward – as the neutron distribution returns naturally to the fundamental mode after each fission generation, we run analogue Monte Carlo.

• Instead the choice of our local detector(s) is governed by external factors and many positions, in- and ex-core as well as many response functions (with energy) will not be a “natural” destination of the fission neutrons.

• Thus for the local detectors, we must employ variance reduction (VR) to achieve reasonable quality results. VR has been extensively developed for fixed source, deep penetration, problems.

• However, employing VR for a particular response can seriously damage the statistical quality of other responses – e.g. the components of the fundamental mode spatial fission distribution and through this, the local response at future fission generations:

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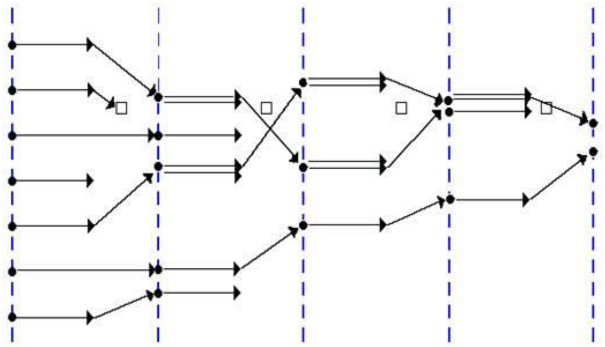


Illustration of a superhistory containing 4 fission generations with a local response (and with VR parameters directed towards the local response)

→ There exists a multi-response variance reduction capability, developed for fixed source Monte Carlo, that is applicable to such problems: it optimizes VR parameters to a number of responses simultaneously:

Burn, K.W., Nava, E., "Optimization of Variance Reduction Parameters in Monte Carlo Radiation Transport Calculations to a Number of Responses of Interest", In: Proc. Int. Conf. Nuclear Data for Science and Technology, Trieste, Italy, 260-264 (Italian Physical Society), 1997

Burn, K.W., Gualdrini, G., Nava, E., "Variance Reduction with Multiple Responses", In: Proc. MC 2000, Lisbon, 687-695 (Springer), 2000

Burn, K.W., "Optimizing Monte Carlo to Multiple Responses: the Direct Statistical Approach, 10 Years On", *Nucl. Technol.* **175**, 138-145 (2011)

• In our case we have one or more local responses and the spatial fission distribution, mocked-up by a spatial binning of the fission distribution. (Experience has shown that such binning can actually be relatively gross.)

• We categorize this multi-response capability as aiming to equalize (and minimize) the statistical error of <u>a limited number of responses</u> (that can however number up to several hundred). It is based on the Direct Statistical Approach (DSA) – see references above.

You may be interested to note that there exists another school of multi-response VR in fixed source Monte Carlo that aims to equalize (and minimize) the statistical error everywhere (essentially an unlimited number of responses). This is often referred to as "global VR".

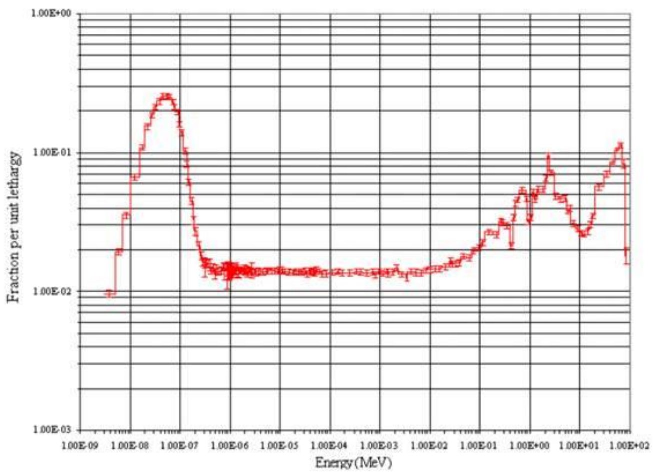
Becker, T.L., Wollaber, A.B., Larsen, E.W., "A Hybrid Monte Carlo – Deterministic Method for Global Particle Transport Calculations", *Nucl. Sci. Eng.* **155,** 155-167 (2007)

Wagner, J.C., Blakeman, E.D., Peplow, D.E., "Forward-Weighted CADIS Method for Global Variance Reduction", Trans. Am. Nucl. Soc. 97 630-633 (2007)

Solomon, C.J., Sood, A., Booth, T.E.,"A Weighted Adjoint Source for Weight-Window Generation by Means of a Linear Tally Combination", In: Proc. Int. Conf. Advances in Mathematics, Computational Methods, and Reactor Physics. Saratoga Springs, NY 3-7 May, 2009

Van Wijk, A.J., Van den Eynde, G., Hoogenboom, J.E., "An Easy to Implement Global Variance Reduction Procedure for MCNP", *Ann. Nucl. Energy* **38**, 2496-2503 (2011)

Returning to the multi-response VR capability that is based on the DSA (and that is employed in this work), it has been employed for many years in fixed source problems and has proved to be an extremely useful tool in a wide range of Monte Carlo applications:



Neutron spectrum in the earth below the 8 m thick concrete foundations of a 30 mA 100 MeV proton accelerator calculated with Monte Carlo with the DSA multi-response capability

Thus the game is to employ the DSA multi-response capability to include both the local response(s) and a sufficient number of spatial components of the fundamental mode in the variance reduction and optimize the VR parameters [splitting or Russian roulette parameters or weight lines (collapsed weight windows)] to all these responses simultaneously.

This should ensure a good statistical quality of both the local response(s) and the fission distribution (and, through the fission distribution, the local response(s) in the next fission generation and the fission distribution at the end of the next fission generation, and so on).

And this does indeed obtain and it works very nicely!

Some associated details:

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• All the work employs patches to MCNP - currently MCNP ver. 5 (1.40). This means that conversion to any other MC code is foreseen.

• An interface code does the mathematical optimization and employs an IMSL routine – *DUMING*. This could be substituted by open software.

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• The difference between the DSA multi-response algorithm and the previously-mentioned global multi-response algorithm is that the former employs the second moment whilst the latter employs the first moment. (For this reason the latter can deal with an unlimited number of responses.) We refer to the latter approach as the "classical" approach.

• For fixed sources, comparisons have been made between the DSA and the classical approach for a single response. Also possible weaknesses in the classical approach have been further analyzed:

Booth, T.E., Burn, K.W., "Some Sample Problem Comparisons between the DSA Cell Model and the Quasi-Deterministic Method", *Ann. Nucl. Energy* **20(11)**, 733-765 (1993)

Booth, T.E., "Common misconceptions in Monte Carlo particle transport", *Appl. Radiat. Isot.* **70**, 1042-1051 (2012)

• **In one of the test eigenvalue problems, more than an order of magnitude difference was found between the DSA and the classical approach (with the classical approach performing worse).** This difference remains to be explained.

The paper presented to the congress is based on the following full journal article:

K.W. Burn: "Optimizing Variance Reduction in Monte Carlo Eigenvalue Calculations that Employ the Source Iteration Approach", *Ann. Nucl. Energy* **73** 218-240 (2014)

The method is completely general and has been employed in thermal and fast cores for in- and ex-core responses.

The in-core and the ex-core problems are fundamentally different:

• The in-core problem involves calculating quantities that, if currently estimated, are done within an analogue calculation. Alternatively they may not be currently calculated at all. Examples could be neutron detectors, local pin powers, local perturbations (to populate properly the zone around the perturbation). Here we propose that we can calculate much more precisely what we calculated previously and furthermore that we can calculate responses that previously were simply not estimated.

• The ex-core problem involves calculating quantities that, if currently estimated, are done by decoupling the calculation, and thereby introducing an approximation. (The point of decoupling is usually chosen as the fission sites, as the energy and direction of the fission sites are analytic.) As well as being approximate, this procedure is long and cumbersome. (The only doubt with the new algorithm was how far we could go out from the fissile zone. Tests indicate that we can go far – for example much farther out than the PV well of a PWR.)

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• Critical safety problems with arrays of fissile material and responses both within and outside the arrays look to involve a mixture of in- and ex-core issues.

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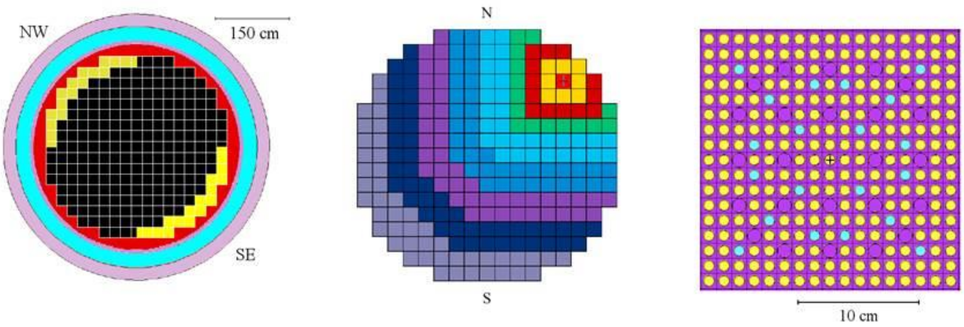
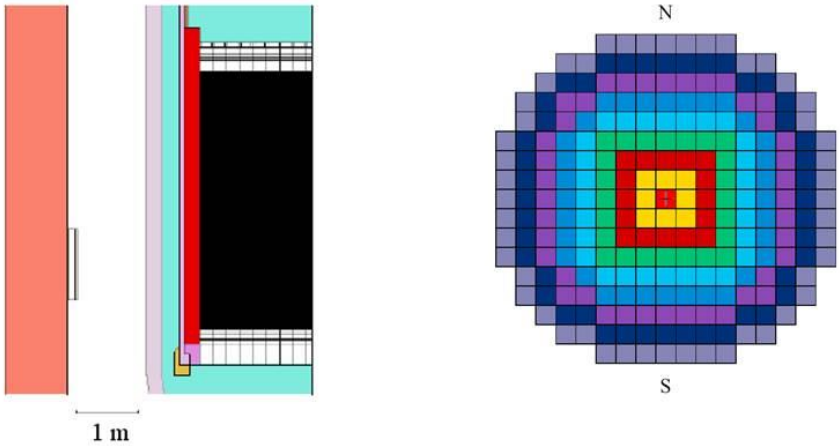
• In the full journal article, 4 realistic test problems are examined:

1) 2-D model of large PWR with a steel reflector and ±1.5% water density variations in the outer assemblies in two core quarters



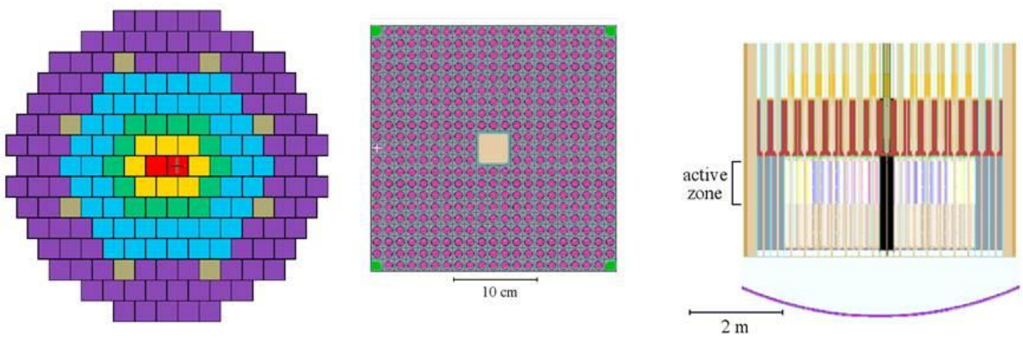
Response: fission rate in one pin of one assembly (see above)

2) 3-D model of large PWR with a steel reflector



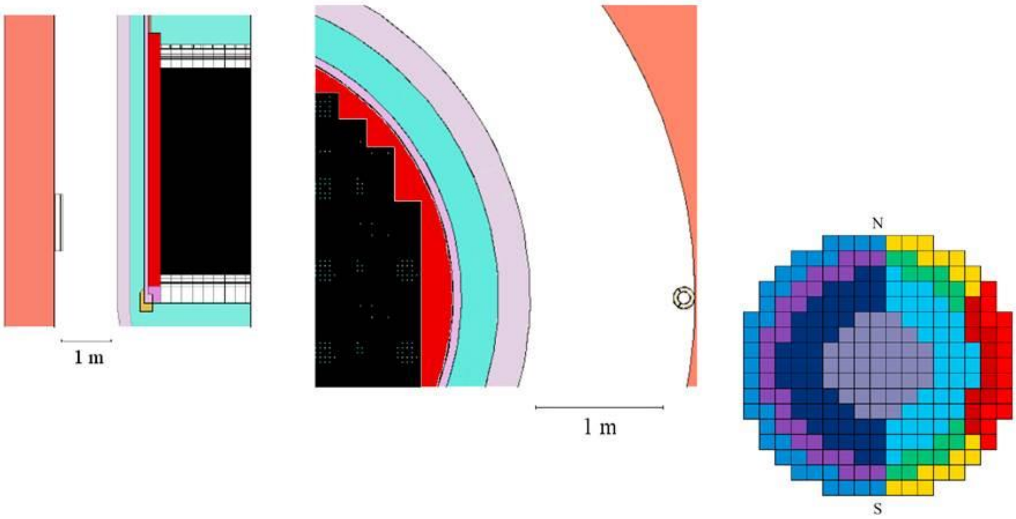
Response: fission rate in one pin of one assembly (see above) over an axial length of 8 cm around the core mid-plane. (Height of fissile region ~ 4 m.)

3) Liquid lead-cooled FR



Response: fission rate in one pin of one assembly (see above) over an axial length of ±1.5 cm around the core mid-plane.

4) 3-D model of large PWR with a steel reflector.



Response: ^{10}B(n,α) rate in ex-core neutron detector placed in PV well

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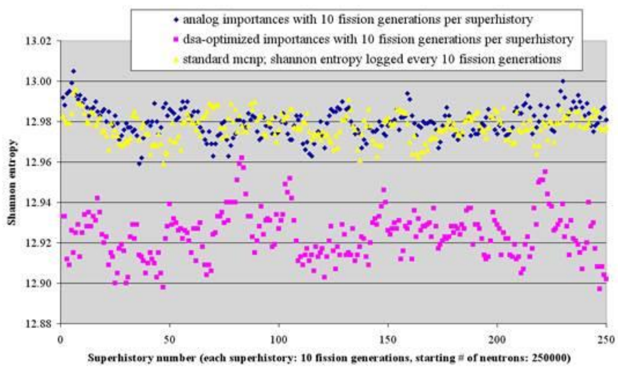
A key aspect of the method is that the fundamental mode should not be altered by the variance reduction, necessary to obtain the response(s) of the local detector(s). (Of course it may become noisier.)

The PWR 3-D in-core problem was employed to verify possible distortions in the fundamental mode in various circumstances: with the optimal VR parameters; with VR parameters that exert strong Russian roulette; with a deliberately imposed distortion (an artificial absorption).



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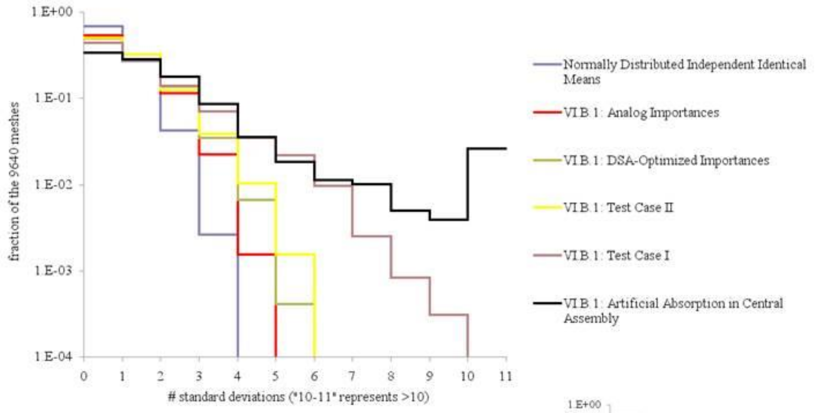

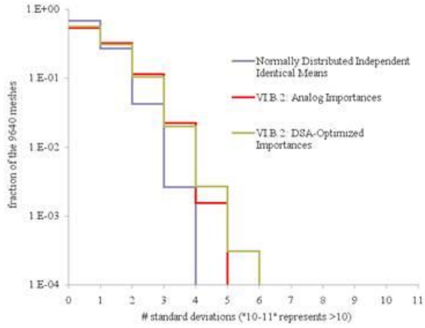

Measure of the maintenance of the fundamental mode for two solutions of the PWR 3-D in-core problem.

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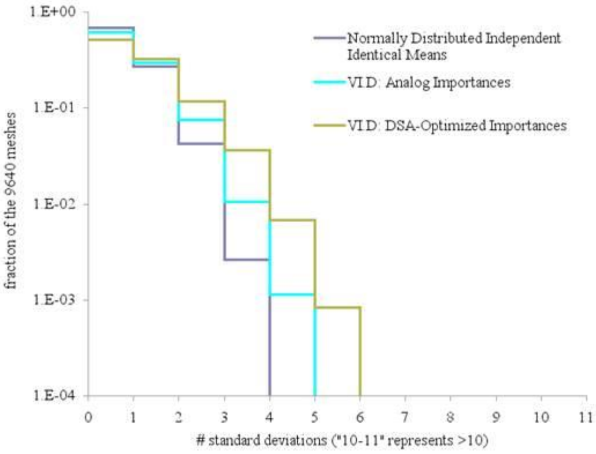

Measure of the maintenance of the fundamental mode for the PWR 3-D ex-core problem.

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For full details, please see:

K.W. Burn: "Optimizing Variance Reduction in Monte Carlo Eigenvalue Calculations that Employ the Source Iteration Approach", *Ann. Nucl. Energy* **73** 218-240 (2014)