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APPLICATION OF NOVEL GLOBAL VARIANCE REDUCTION METHODS TO FUSION RADIATION TRANSPORT PROBLEMS

Andrew Davis and Andrew Turner
EURATOM/CCFE Fusion Association
Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK
andrew.davis@ccfe.ac.uk; andrew.turner@ccfe.ac.uk

ABSTRACT

It is known that *a priori* information on the distribution of neutron fluxes over neutron transport models can improve the computational efficiency of Monte Carlo transport calculations via the use of variance reduction techniques. The uncertainty lies in finding a method which obtains this information as fast and effortlessly as possible. A number of global variance reduction techniques were tested on the ITER reference neutronics model for their applicability for performing large three-dimensional transport simulations for ITER. Among these, we propose a new method which is computationally fast and efficient in determining the *a priori* flux information. The new method, known as MAGIC (Method of Automatic Generation of Importances by Calculation), was found to perform well. The MAGIC method uses an initial analogue run to determine an approximate distribution of particle flux across as much of the problem as possible. The output of this run is then used to produce an MCNP weight window file and used as the input for a subsequent calculation. This iterative stage proceeds until the entire mesh is populated. The MAGIC method was applied to the ITER Tritium Breeding System (TBS) model, which has an extent of over 20 metres, and used to produce a mesh weight window file for MCNP. The weight window was capable of providing high resolution neutron spectra over the entire model domain.

Key Words: Monte Carlo, Variance Reduction, Weight Windows

1. INTRODUCTION

There is now an increasing need to perform computationally intensive, high resolution transport and shutdown dose analyses for ITER [1], involving large and complex geometries. Variance reduction (VR) methods are used within Monte Carlo (MC) transport codes to improve the computational efficiency of a given simulation by increasing the number of successful particle contributions to a given tally, thus reducing the variance of the tally. Methods termed “global” variance reduction (GVR) attempt to transport particles everywhere in a model, thereby reducing the variance of some hypothetical global particle tally.

The most successful method of generating a GVR map is when some *a priori* knowledge of the particle flux has previously been generated. To date, this global particle flux has traditionally been obtained using a discrete ordinates technique, such as in [2] where the Forward Weighted Consistent Adjoint Driven Importance Sampling (FW-CADIS) [3] method is used. There are also “rules of thumb” such as those of [4], or simply using analyst judgement to estimate cell weights or importances based on experience. Each method has benefits and drawbacks;

for example when using a discrete ordinates code to generate a GVR map, it is necessary to replicate to some extent the MC model in another format for a different transport code than the one being used for the actual calculation.

2. The MAGIC method

The GVR method known as MAGIC: Method of Automatic Generation of Importances by Calculation [5], is described. The authors focus on the implementations with MCNP [6] in mind, but the methods could be applied to other Monte Carlo transport codes. The method uses an initial analogue run to determine an approximate distribution of particle flux across as much of the problem as possible. The output of this run is then processed into MCNP weight window format and used as the input for a subsequent calculation. This iterative stage proceeds until the entire mesh is populated.

The particle distribution information can be obtained in the form of fluxes, populations or weights, and can be used to generate either cell- or mesh-based weight windows, or a cell-based importance map. Comparisons were performed [5] using a standard ITER reference model [7], with a total flux mesh tally covering the entire geometry. An average Figure of Merit (FOM) metric was devised for the global mesh tally, in order to make a quantitative comparison of the methods. The FOM accounts for the statistical error of the tally and the amount of computational time used in that particular calculation. The computational time used in the FOM was that from the final MCNP calculation, and did not include the time spent generating and iterating the weight windows (on the basis that these steps need only be performed once, whilst the resulting GVR map can be re-used in different runs using the same model). A higher FOM indicates a more effective GVR method. Global average FOM results were compared for analogue (AN), MAGIC weight window in cell (MWIC) and MAGIC Weight Window in mesh (MWIM), as well as an FW-CADIS weight window mesh kindly provided by the University of Wisconsin.

Table I: Summary of results from the comparison

Parameter	AN	FW-CADIS	MWIC	MWIM
CPU Time (mins)	13468	12511	10672	12522
Av. error	92.52%	13.80%	20.50%	11.16%
%age not scoring	86.90%	0.86%	10.90%	0.03%
Av. FOM	8.67×10^{-5}	4.20×10^{-3}	2.28×10^{-3}	6.41×10^{-3}

The initial guess of particle flux, experience has shown, is likely to be poor, but serves as the foundation of further iterations. Each iteration increases the depth to which particles in the problem penetrate, where ultimately particles contribute to tallies all across the problem geometry.

As shown in Table I, utilising flux data in the form of a mesh was found to be the most effective method. It was also determined that the generation of weight windows in two energy groups optimised this calculation for fusion problems due to the unique shape of the neutron spectrum in fusion devices. The speed of iterations (prior to the final one) can be substantially increased by using multi-group data and energy truncation methods.

In summary, the MAGIC method is composed of these steps;

1. Run MCNP in analogue mode, with multigroup option (MGOPT) on and a high energy cutoff (ECUT $< 10^{-3}$ MeV is recommended)
2. Use results (flux, population density, weight in cells, etc) from this run to determine a weight window map / importance map for a subsequent run
3. Iterate as necessary
4. The final iteration of the map, and subsequent production runs, should use the appropriate cross-sections and physics options

The advantages of MAGIC over other methods are: no user judgement nor secondary model and code are required, and the determination of the *a priori* flux information is fast due to the use of the CUT and MGOPT cards which run $\sim$ ten times faster than a conventional analogue run. The benefit of this method over intrinsic MCNP methods, such as the built-in weight window generator (WWG) is that particles can contribute over the entire model, rather than to a specific tally region. The method has been found to be effective for deep penetration problems, but also in cases where streaming contributions are important. This is particularly applicable to large fusion devices like ITER where both phenomena occur to various extents.

3. Examples of use of the MAGIC method

The MAGIC method was applied to a number of shielding problems that would have been previously unsolvable, or would have been practically unsolvable within the task time frame using conventional means.

A consummate example is that of the analysis of the ITER European Union (EU) Test Blanket System (TBS) [8]. The TBS aims to test the tritium breeding capabilities of two different concepts namely the Helium Cooled Lithium Lead (HCLL) and the Helium Cooling Pebble Bed (HCPB). The system is composed of breeding modules at the front of the system, a complex series of coolant and breeder pipes that penetrate shielding, which eventually lead to the ITER concrete bioshield. Beyond the bioshield lies the port cell, where the vital pumping and coolant feeds lead from and to the outside world.

3.1 Neutronic Analysis of the ITER TBS

Neutronic analysis of the ITER TBS was required in order to verify the neutron activation of major in-vessel and ex-vessel components, which in turn was used to determine the dose rate after shutdown. This shutdown dose rate should be low enough to allow manned access to various areas around the device. The CAD model was provided by Fusion For Energy (F4E) and was converted using the CAD to MCNP translator MCAM [9] from the FDS Team at ASIPP in China. The CAD model was converted and simplified in order to insert the model into the official MCNP model of ITER - Alite [7]. When converted and simplified the total number of cells was 8062 and the total number of surfaces was 7788. The converted and simplified model is shown in Figure 1. The horizontal extent of the model is some 26 metres in depth, 25 metres in height and 16 metres in width. The Alite fusion neutron source consists of a toroidally symmetric, isotropic neutron source within the vacuum vessel, with a peak energy of 14.1 MeV. The source strength is centrally peaked, with an elliptical-triangular profile following the magnetic contours, as shown in Figure 1.

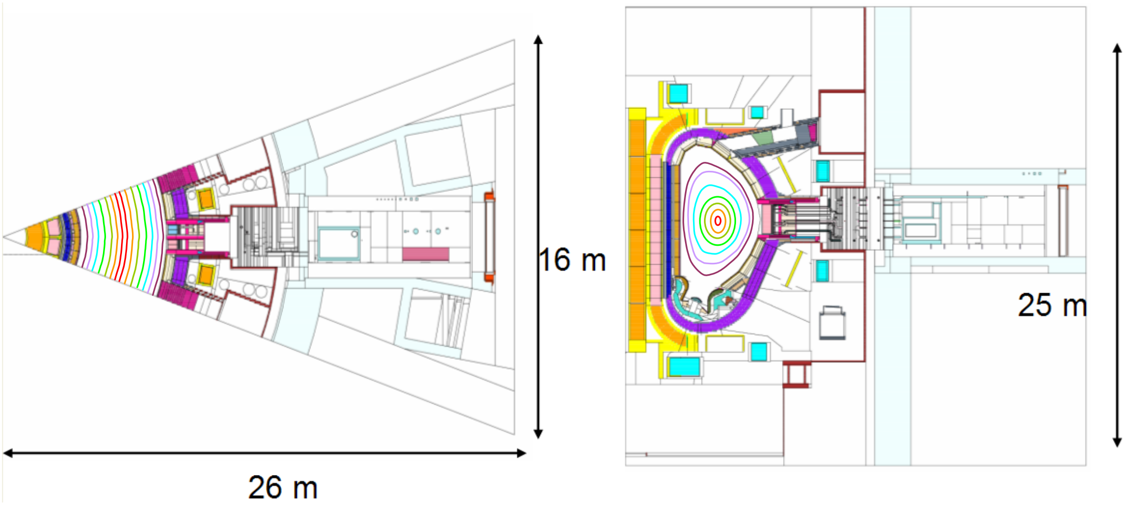

Figure 1: MCNP model of the ITER TBS System, left - X-Y view of ITER and the TBS system, right - X-Z view of ITER and the TBS system.

The objective of the analysis was to determine the activation of the entire system due to prolonged irradiation by 14 MeV neutrons. For such analysis there is a requirement that the neutron flux distribution is determined with high spatial and energy resolution. To obtain a low uncertainty in the flux over all mesh voxels, the use of an effective GVR method is essential. The MAGIC method was applied to the TBS model, using a weight window mesh (WWM).

A summary of options used for the runs are shown in Table II. The results of the initial run with MGOPT on, are shown in the upper left portion of Figure 2 after 200 CPU minutes. Particles typically did not penetrate further than 30 cm into the ITER first wall and TBS. A small number of high weight particles have streamed into the rear portions of the model, but the global flux is not particularly well distributed. Using the WWM generated by this run enabled the 2nd run, taking 240 CPU minutes, shown in the upper right portion of Figure 2, particles

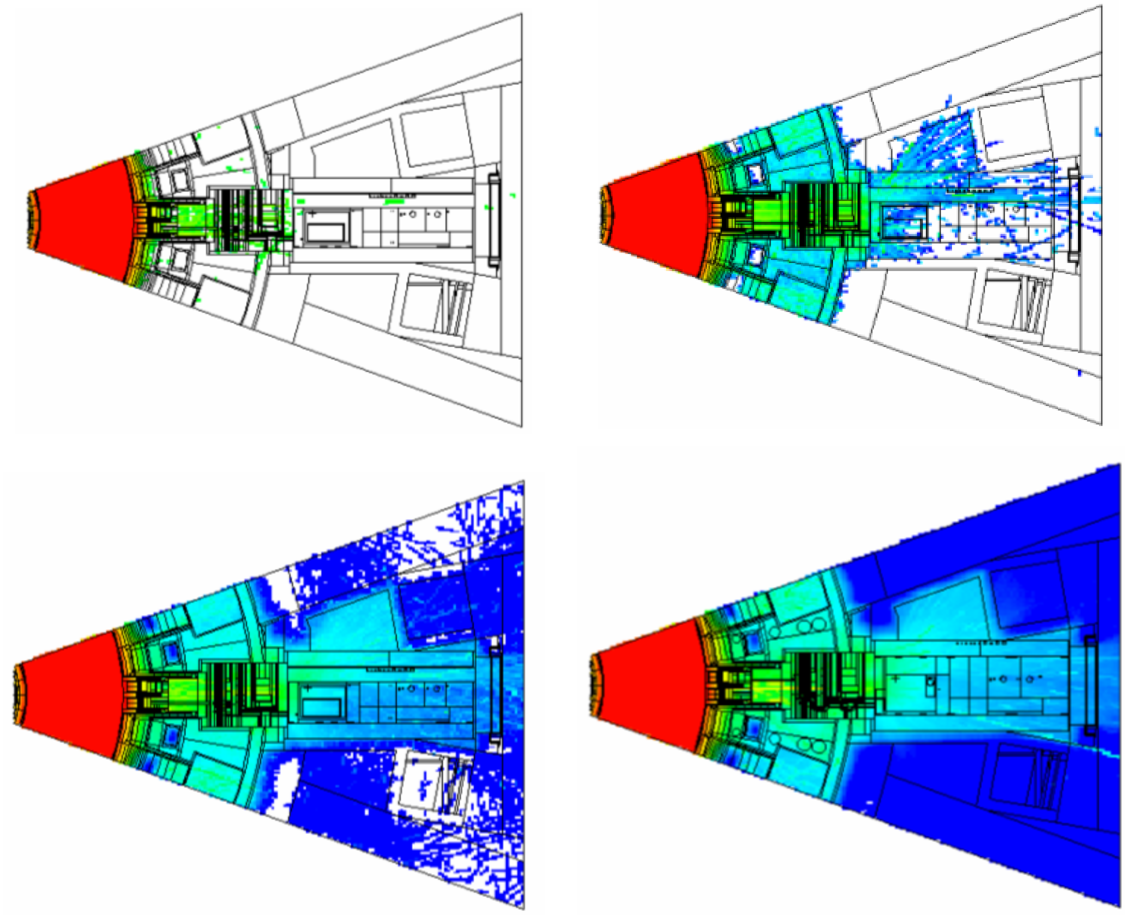

Figure 2: Iterations of the WWM, upper left - 1st iteration, upper right - 2nd iteration, lower left 3rd iteration and lower right 4th iteration.

Table II: Summary of run times

Run number	Energy Cut-off (MeV)	Run Time (CPU-mins)
1	$1{\times}10^{-3}$	200
2	$1{\times}10^{-5}$	240
3	$1{\times}10^{-7}$	5000
4	$1{\times}10^{-11}$	5000

have now penetrated significantly further into the geometry with particles interacting in the near side of the ITER bioshield. There are still large parts of the model where particles have not yet interacted, mostly beyond the bioshield, but even the middle of the equatorial port and the toroidal field coils. Particles that do make it beyond the port cell door stream along the port cells, since this region is filled with air. The 3rd run, shown in the lower left portion of Figure 2, having taken 5000 CPU minutes, particles are now contributing across the majority of the model except in the true depths of the bioshield, the flux is also variable around the port cell. In the 4th run, shown in the lower right part of Figure 2, results are presented after 5000 CPU minutes, particles are contributing across the entire model even through the thick ITER bioshield.

3.2 Long Histories

When the final WWM was used in the production run of the analysis, the runtime was of the order of 10 days on 96 3.0 GHz processors. A lot of this physical time is wasted due to one or two processors being locked in tracking the high splitting of very few particles. These long histories are hypothesised [4] to be due to high weight source particles streaming along various gaps in the model, then interacting in a part of the model that has significantly lower weight bounds. The authors have devised a method to prevent this problem when using weight windows, extensive and exhaustive testing of this approach is currently being undertaken.

4. CONCLUSIONS

The use of the MAGIC method variance reduction implementation was discussed. It was shown that for a large model (26 m horizontal) thickness, an MCNP weight window can be generated in less than 15,000 CPU minutes. This WWM was then used in subsequent calculation in order to generate high spatial fidelity neutron spectra. This method allowed computation of the required variance reduction in minimal time. The required strength of variance reduction meant that long histories were encountered, which dominate the required simulation time for the production run. A solution for the long history problem has been devised and is currently being tested.

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REFERENCES

1. A Davis and R Pampin. Benchmarking the MCR2S system for high-resolution activation dose analysis in ITER. *Fusion Engineering and Design*, 85(1):87 – 92, 2010.
2. A M Ibrahim, S W Mosher, T M Evan et al. ITER Neutronics Using Hybrid Monte Carlo/S_n and CAD-based Monte Carlo Methods. *Fusion Science and Technology*, 2010.
3. E D Blakeman et al. PWR Facility Dose Modeling Using MCNP5 and the CADIS/ADVANTG Variance-Reduction Methodology. Technical Report ORNL/TM-2007/133, Oak Ridge National Laboratory, 2007.
4. F Wasastjerna. *Using MCNP for fusion neutronics.* PhD thesis, Helsinki University of Technology, 2008.
5. A. Davis and A. Turner. Comparison of Global Variance Reduction methods for Monte Carlo Radiation Transport Simulations of ITER. In *Proceedings of the 26th Symposium on Fusion Technology - SOFT-26*, 2010.
6. Judith F Briesmeiser. MCNP$^{\text{TM}}$ a General Monte Carlo N-Particle Transport Code. Technical Report LA-13709-M, Los Alamos National Laboratory, March 2000. MCNP 4C3.
7. M J Loughlin, P Batistoni, C Konno et al. ITER Nuclear Analysis Strategy and Requirements. *Fusion Science and Technology*, 56:566 – 572, 2009.
8. O Bede, T Baross, J-P Martins. Preliminary layout of TBS sub-systems in PC and preliminary integration information. Technical Report 05.6_TBMCA.2009.D4SI.0001_f1.1, F4E, 2009.
9. Y Li, L Lu, A Ding, H Hu, Q Zeng, S Zheng and Y Wu. Benchmarking of MCAM 4.0 with the ITER 3D model. *Fusion Engineering and Design*, 82(15-24):2861 – 2866, 2007. Proceedings of the 24th Symposium on Fusion Technology - SOFT-24.