The hybrid Monte Carlo (MC)/deterministic techniques - Consistent Adjoint Driven Importance Sampling (CADIS) and Forward Weighted CADIS (FW-CADIS) - enable the full 3-D modeling of very large and complicated geometries. The ability of performing global MC calculations for nuclear parameters throughout the entire ITER reactor was demonstrated. The 2 m biological shield (bioshield) reduces the total prompt operational dose by six orders of magnitude. The divertor cryo-pump port results in a peaking factor of 120 in the prompt operational dose rate behind the bioshield of ITER. The equatorial port, plugged by 2 m of shielding, increases the prompt dose rate behind the bioshield by a factor of 47. The peak values of the prompt dose rates at the back surface of the bioshield were 240 µSv/hr and 94 µSv/hr corresponding to the regions behind the divertor cryo-pump port and the equatorial port, respectively.

I. INTRODUCTION

Assessment of the dose rates throughout ITER is necessary to determine personnel accessibility, ensure occupational safety, and guide possible reactor building design changes. Due to the immense size and the complexity of the ITER structure, calculation of the radiation dose rates, especially outside the bioshield, has always depended on coupling the final 3-D analysis with 1- or 2-D analyses. These approaches ignore critical geometric details such as the large diagnostics ports. This paper shows how the use of the hybrid Monte Carlo (MC)/deterministic techniques - Consistent Adjoint Driven Importance Sampling (CADIS) and Forward Weighted CADIS (FW-CADIS) - can enable the full 3-D modeling of large and geometrically complex problems such as ITER. It also demonstrates the ability of performing global MC calculations for nuclear parameters throughout the entire ITER reactor.

The prompt dose rate at a single point outside the ITER’s bioshield was calculated using the CADIS method for speeding the MC simulation and without the use of the CADIS method. The calculation demonstrated the difficulty of calculating the dose rate outside the bioshield using conventional MC simulations and the necessity of the use of strong variance reduction techniques such as the CADIS hybrid method. To demonstrate the effect of the FW-CADIS method in simultaneously optimizing MC statistics of several tallies in one calculation, it was used to calculate the total prompt dose rate over a 5 million cell mesh tally covering the entire ITER geometry. The accuracy of this global MC calculation was verified by comparing the dose rates at four different points to those calculated from another MC simulation, for which the tallies optimized by the FW-CADIS method were localized at these four points only. The dose rates at the four points were also compared to those calculated from a very fine mesh deterministic calculation that was performed using the massively parallel deterministic code Denovo.

II. METHODOLOGY

The ITER 3-D model, Alite03, was used in the form of an MCNP5 input file representing a 40° sector of the ITER device. The fusion evaluated nuclear data library (FENDL-2.1) was used in this analysis. A multigroup 46-neutron/21-gamma FENDL-2.1 library was used for the deterministic calculations while continuous energy data was used in the MC calculations.

The CADIS method uses space and energy dependent fluxes from an adjoint deterministic calculation to calculate both the source biasing and weight window parameters for the MC calculation. It is designed to optimize the MC particle population throughout the geometry in order to improve the MC statistics of a single tally. An adjoint source with space and energy distributions similar to the tally to be optimized has to be specified for the adjoint deterministic calculation. If multiple adjoint sources corresponding to multiple tallies are specified, the tally closest to the physical source will converge faster than the other tallies and the running time will be solely dependent on the furthest tally from the physical source. FW-CADIS uses the inverse of the space-dependent responses calculated from a forward deterministic calculation to weight the adjoint sources’ strengths in the adjoint deterministic calculation. The
adjoint fluxes are then used to calculate the source biasing and weight-window parameters for the MC calculation.

The ADVANTG (AutomateD VAriaNce reducTion Generator) code\(^\text{6}\) was used to develop weight-window maps for subsequent MC simulations. For problems with complicated geometries such as ITER, the manual creation of an equivalent 3-D input file for the deterministic calculation is extremely difficult. One of the main advantages of ADVANTG is the automatic generation of the deterministic input file from the MC model. The ADVANTG package uses a modification of MCNP5-1.40 to map materials from the combinatorial geometry onto a user-defined orthogonal mesh. It drives the Denovo 3-D discrete ordinates (\(S_N\)) code to generate approximate forward and/or adjoint \(S_N\) solutions. Using the CADIS or FW-CADIS methods, ADVANTG then generates weight-window and source-biasing parameters in formats directly usable by MCNP5/X (i.e., as a WWINP file and SDEF cards, respectively).

Denovo uses the Koch-Baker-Alcouffe (KBA) algorithm\(^\text{9}\) to parallelize transport sweeps on a 3-D structured grid and Krylov subspace methods to accelerate source convergence. It has demonstrated excellent scaling capabilities when running very large problems with very high resolution on hundreds of thousands of cores\(^\text{7}\). A very fine mesh standalone Denovo calculation was used to calculate the dose at four points to confirm the results of the global MC calculation. The spatial mesh of this \(S_N\) calculation contained 1.34 billion cells and the total number unknowns was 3.6 quadrillions. Such a high-performance-computing (HPC) calculation requires the simultaneous accessibility of thousands of processors. It was performed on the Oak Ridge National Laboratory (ORNL) supercomputer, Jaguar. An approximate source, peaked in the plasma zone, was used for all the Denovo calculations including the ones used for CADIS and FW-CADIS and the HPC calculation. The four points, at which the dose was calculated by the HPC Denovo calculation, all lie behind the cryostat. The massive amount of shielding between these points and the neutron source minimizes the effect of the spatial distribution of the neutron source inside the plasma. The 46-neutron/21-gamma FENDL2.1 library was used for all Denovo calculations. All the Denovo input files were created by ADVANTG from the Alite03 MCNP5 model.

In CADIS and FW-CADIS, the only objective of the deterministic calculations is to provide appropriate variance reduction parameters for the MC calculation and hence only approximate \(S_N\) solutions are needed. To accelerate the \(S_N\) calculations of the CADIS and the FW-CADIS calculations of the dose rate at one and four points, respectively, dimensions of the mesh elements for the forward and the adjoint calculations were nominally on the order of meters away from the points and were smaller (5-20 cm) near the points. For the FW-CADIS global dose calculation, the recently developed adjoint flux collapsing feature of ADVANTG was used to collapse the adjoint fluxes of an 8 million cell deterministic model that used a 46 neutron/21 gamma group structure to a 1 million cell model that used 17 neutron/5 gamma group structure for the weight-window map. This collapsing provided a factor of 24 reduction in the size of the MCNP weight-window file which was essential in running MCNP in parallel. Table I shows the number of cells, number of processors, and the running times for all the Denovo calculations including the CADIS, the FW-CADIS, and the HPC calculations.

<table>
<thead>
<tr>
<th>TABLE I. Denovo Running Parameters</th>
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<tr>
<td>Number of cells (millions)</td>
</tr>
<tr>
<td>Single point</td>
</tr>
<tr>
<td>Four points</td>
</tr>
<tr>
<td>Global</td>
</tr>
<tr>
<td>HPC</td>
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The first three calculations in Table I were used for CADIS and FW-CADIS. Of these, the first two calculations were performed on a single processor, while the global calculation was performed on multiple processors in parallel. The 5.9 processor-days total running time of the global FW-CADIS Denovo calculations is still very small compared to the running time required by a problem with this magnitude using either MC or fine resolution deterministic calculations. The total running time of the HPC Denovo calculation is 35 processors-years.

III. PROMPT DOSE RATE AT A SINGLE POINT

The prompt operational dose rate was calculated at the point illustrated in Figure 1. This calculation is a classic source-detector problem for which the CADIS method was designed. A point adjoint source was defined at the location of the dose rate tally. The group-wise energy spectrum of the adjoint source was defined as the flux-to-dose-rate conversion factors in an energy structure equivalent to that of the multi-group data library of the deterministic calculation. A point-detector tally was used for calculating the prompt operational dose rate outside the bioshield. Table II shows the dose rate and the MC figure of merit (FOM) of the point-detector tally with and without the use of CADIS.

<table>
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<tr>
<th>TABLE II. Dose Rate at a Single Point</th>
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<tr>
<td>Dose rate ((\mu\text{Sv/hr}))</td>
</tr>
<tr>
<td>MC (no CADIS)</td>
</tr>
<tr>
<td>MC (CADIS)</td>
</tr>
</tbody>
</table>
The point-detector MC calculation without CADIS showed the extreme difficulty in obtaining reliable MC results without additional types of variance reduction. Even after 610 processor-days of computational time, the statistical relative uncertainty (1σ) was 77%. The CADIS-based MC simulation achieved a statistical uncertainty of less than 5% and passed all of the MCNP statistical checks in less than 8 processor-days. Because of the high variance of the variance of the MC calculation without CADIS, it is difficult to calculate a reliable FOM for this case. However, the results suggest an improvement of ~21,000 due to the use of CADIS. In addition, we estimate that it will require about 400 processor-years to perform such a calculation in MCNP without the use of any variance reduction method other than the point-detector to achieve a statistical uncertainty comparable to that obtained with CADIS.

IV. GLOBAL PROMPT DOSE RATE

A 5 million cell Cartesian mesh tally covering the 40° sector of the Alite03 model was used to tally the total prompt operational dose rates throughout the entire ITER machine. The mesh tally has uniform cubical mesh elements that are 10 cm on a side. After a total MCNP run time of 120 processors-days, the use of the FW-CADIS method resulted in 87% of the voxels having relative uncertainties (RU) below 10% and 98.5% of the voxels having at least one MC score. Figure 2 shows the mesh tally results only at the voxels with relative statistical uncertainties less than 20%.

The dose rates at the bioshield were found to be strongly affected by the neutrons and photons streaming through the ITER machine. Figure 3 shows the dose rate map on the central plane of the model and on a plane rotated 20° from the central plane.

The central plane passes through the center of an upper diagnostics port and the center of an equatorial port. The rotated plane passes through the centers of an upper port, an equatorial port, and a divertor port. The effect of the upper port on increasing the dose rate at the bioshield is not apparent because it is fully plugged by 5 m of shielding in the Alite model. The equatorial port, which is only plugged by 2 m of shielding, has some effect on the dose at the bioshield especially at the 2 cm gap between the port wall and the shielding plug. Two types of divertor ports exist in the 40° sector Alite model. Both of the divertor ports do not have shielding plugs and both affect the prompt dose rate at the bioshield. The first divertor port is a cryo-pump port and the second is a remote handling port. Figure 4 shows the dose rates at the back surface of the bioshield.
Figure 4. Prompt dose rates at back surface of bioshield.

The hot spots in Figure 4 correspond to regions behind the equatorial ports and the divertor ports. Figure 5 shows the prompt dose rates along three lines on the back surface of the bioshield. The first line is an axial line passing through the center of the back surface of the bioshield, the second is an axial line representing the left edge of the 40° sector of the back surface of the bioshield in Figure 4, and the third is an axial line representing the right edge of Figure 4.

Figure 5. Dose along three lines behind bioshield.

The maximum prompt dose rate on the center line is 94 μSv/hr. This occurs 100 cm above the center of the equatorial port opening corresponding to the 2 cm gap between the port plug and the upper wall of the port. At the same azimuthal and axial position, the dose rate in front of the bioshield is 204 Sv/hr. The effect of the bioshield in decreasing the prompt dose rate is a factor of $2 \times 10^6$ at this position. Similar degrees of attenuations due to the bioshield were found at other positions. For the divertor ports, the left edge passes through the center of a cryo-pump port, while the right edge passes through a remote handling port. The maximum dose rate on the left edge is 240 μSv/hr which is a factor of 2.7 higher than the maximum dose rate on the right edge. This is because the cryo-pump port has circular opening, with a 135 cm diameter, at its end while the remote handling port is closed. Figure 6 shows the difference between the two divertor ports in the Alite model.

Figure 6. Divertor ports in the Alite model.

V. ACCURACY OF GLOBAL PROMPT DOSE RATE CALCULATION

Even with the enhanced efficiencies provided by variance reduction techniques, MC simulations of all phase-space regions in the entire ITER machine require large amount of time and computing resources. Different levels of accuracies in global MC simulations of problems with the magnitude of ITER are expected. To develop confidence in the accuracy of our FW-CADIS calculation, the global MC results at four points were compared to the results of two other complementary approaches. The four points represent interesting positions inside and outside the bioshield at mid-plane and bottom of the tokomak. The positions of the four points used in the validation of the global MC calculation are shown in Figure 7.

Figure 7. Four points used for verification.
The results of the global MC calculation at these four points were compared to results from a MC calculation using four point-detectors at the four positions. The use of the FW-CADIS method was necessary for this calculation since the computer time required for doing such a calculation using conventional MC simulations is too large. Compared to global problems, the MC convergence is much faster when the FW-CADIS method is optimizing localized tallies. Four point adjoint sources were specified for this calculation, with an energy spectrum equal to the flux-to-dose-rate conversion factors in the 46 neutron/21 gamma energy group structure used in the deterministic calculation. The use of the next event estimator of the flux-to-dose-rate conversion factors in the 46 neutron/21 gamma energy group structure used in the deterministic calculation.

TABLE III. Prompt Dose Rates (μSv/hr) at Four Points

<table>
<thead>
<tr>
<th>Points</th>
<th>Mesh tally</th>
<th>Point-detector</th>
<th>Denovo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9×10^7 ± 4.7%</td>
<td>2.8×10^7 ± 5.5%</td>
<td>2.2×10^7</td>
</tr>
<tr>
<td>2</td>
<td>15 ± 5.5%</td>
<td>15 ± 4.4%</td>
<td>14.2</td>
</tr>
<tr>
<td>3</td>
<td>4.2×10^6 ± 1.2%</td>
<td>5.3×10^6 ± 2.1%</td>
<td>4×10^6</td>
</tr>
<tr>
<td>4</td>
<td>2.3 ± 15.7%</td>
<td>2.3 ± 2.8%</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Considering the 13 to 14 orders of magnitude attenuation between the source region and points 2 and 4 and the 7 to 8 orders of magnitude attenuation between the source and points 1 and 3, the global MC results had very good agreement with both the point-detector and the HPC Denovo results. The maximum relative difference between the global MC results and the point-detector results is 30% while the maximum relative difference between the global MC results and the Denovo results is 19%. These differences are also physically expected since the global MC results are averaged across cubical mesh cells 10 cm on a side, the Denovo results are averaged across cubical mesh cells 2 cm on a side, and the point detector results are not averaged.

VI. CONCLUSION

The ability of performing full 3-D MC analysis for problems with the overall size and complexity of ITER using the hybrid MC/deterministic techniques has been demonstrated. The maximum prompt dose rate behind the bioshield was found to be 240 μSv/hr corresponding to the region behind the pump opening of the cryo-pump divertor port. The global MC results from a FW-CADIS calculation matched with a localized FW-CADIS calculation of the dose rates at four points and with the dose rates calculated deterministically.

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