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Analysis of Shutdown Dose Rate in Fusion Energy Systems Using Hybrid Monte Carlo/Deterministic Techniques

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INTRODUCTION

Accurate assessments of shutdown dose rate (SDDR) are critical to support operation, maintenance, and waste disposal planning and to guide possible design changes of critical components in fusion energy systems. An SDDR calculation involves three steps:

1. a neutron transport calculation to determine the space and energy neutron flux distributions,
2. an activation calculation for computing the photon source distribution, and
3. a photon transport calculation for the estimation of the final SDDR.

A companion paper [1] describes the challenges of SDDR computations in fusion energy systems and the status of the techniques that are currently being used in SDDR analysis. Of these techniques, the rigorous 2-step (R2S) computational system entails Monte Carlo (MC) neutron and photon transport calculations coupled with a comprehensive activation step using a dedicated inventory code and library [2].

The use of global MC variance reduction techniques was suggested for accelerating the SDDR MC neutron transport calculation [3]. These techniques, which attempt to calculate MC tallies with nearly uniform relative uncertainties in both the low-flux space-energy regions and the high-flux space-energy regions, do not preferentially focus the MC computational efforts toward space-energy regions of high importance to the final decay dose. The ability of these approaches to accurately predict SDDR is inhibited by their prohibitive computational costs, which will be on the order of thousands of processor-years for full-scale modeling of an entire fusion plant [4].

The companion paper [1] describes the theoretical background of the Multi-Step Consistent Adjoint Driven Importance Sampling (MS-CADIS) method, which has been proposed to speed up SDDR MC neutron calculations. The MS-CADIS method uses the CADIS method [5], which has been successfully used for more than a decade in shielding calculations, but focuses on multistep shielding calculations such as SDDR analyses. The companion paper also describes a new method for calculating the uncertainties in SDDR due to uncertainties in the MC neutron calculation. This new method of uncertainty propagation uses the MS-CADIS neutron adjoint source to propagate the uncertainties in the neutron fluxes to the SDDR.

This paper describes the application of the MS-CADIS method for speeding up the SDDR MC calculations and for calculating the SDDR uncertainty due to the neutron flux uncertainties. A new metric for assessing the reliability of SDDR calculations was also suggested and used in this analysis. The ITER benchmark problem was used in this analysis [6]. The problem resembles the configuration and geometrical arrangement of an upper port plug in ITER. The analysis compared the efficiency of the MS-CADIS method to the traditional approach of using global MC variance reduction techniques for speeding up SDDR MC neutron calculation.

PROBLEM DESCRIPTION

The model used in this analysis consists of a 7 m long cylinder with a 1 m radius. It has a central straight-streaming path with a radius of 0.075 m. A 0.48 m radius stainless steel/water (80%–20%) shielding zone, which surrounds the central streaming path and has a length of 2.1 m, is included. The outer shielding zone is made of 100% stainless steel with an outer radius of 1 m. It has a rear stainless steel plate 0.15 m thick. A 0.02 m straight gap between the outer and inner shielding zones extends all the way through the model. A large, 3.25 m long cavity runs between the back of the stainless steel/water shield and the rear plate. A 14.1 MeV isotropic neutron source with a thickness of 0.01 m is represented by a disk region placed at a distance of 0.1 m from the front edge. SDDR was calculated using four tallies representing four circular discs, each 0.1 m thick. All the discs are placed in air at a distance of 0.3 m from the rear plate. The inner-outer radii of the discs are 0.0 m–0.15 m, 0.15 m–0.3 m, 0.3m–0.45 m, and 0.45 m–0.6 m. Figure 1 shows the problem geometry and the SDDR tallies.

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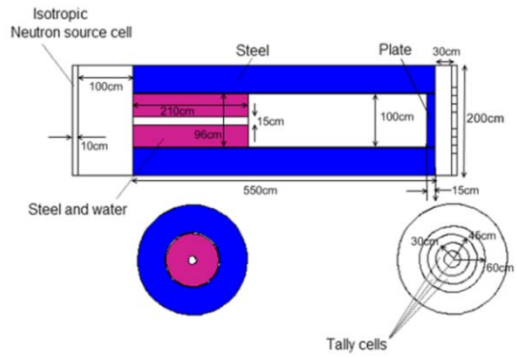

Fig. 1. Problem geometry [6].

The source strength and irradiation history used in this analysis are shown in Table I [7]. SDDR was calculated at the four tallies after 10^6 s from the last step in the irradiation scenario.

Table I. Neutron Production Scenario [7]

Source Strength	Duration	Number of times
1.0714×10^{17}	2 years	1
8.25×10^{17}	10 years	1
0	0.667 years	1
1.6607×10^{18}	1.33 years	1
0	3,920 sec	17
2.0×10^{19}	400 sec	
0	3,920 sec	4
2.8×10^{19}	400 sec	

METHOD

The Standardized Computer Analyses for Licensing Evaluation, version 6.1 (SCALE6.1), shielding analysis sequence, MAVRIC was used for the neutron and photon transport calculations, and the ORIGEN code system was used for the activation and decay calculations in this analysis. MAVRIC uses the discrete-ordinates, structured mesh code Denovo for the deterministic calculations and the multi-group MC code Monaco for the MC calculations [8]. A 200-neutron group ENDF-VII data library was used for the neutron Monaco calculations, a 27-neutron group ENDF-VII data library was used for the Denovo neutron calculations, and a 19-photon group ENDF-VII library was used for both the Monaco and the Denovo photon transport calculations. All the ORIGEN calculations used the ENDF-VII activation library.

The semiautomatic coupling between Monaco and Denovo on one side and ORIGEN on the other side was implemented using Python scripts. With a total of about 250,000 mesh elements, the element sizes varied between 1.5 and 5 cm in the horizontal (X and Y) directions and between 5 and 10 cm in the axial (Z) direction. In each mesh element, the material used for the Denovo and the ORIGEN calculations was set to be the material present at the center of the element in the Monaco model.

The SDDR calculations were performed using three approaches. The first approach used analog Monaco neutron calculations, the second used the standard forward-weighted CADIS (FW-CADIS) method for speeding up the Monaco neutron calculations, and the third used the MS-CADIS method. All the calculations used the same running time (1 h) for the Monaco photon calculations and used the same photon importance map (weight windows) based on the CADIS method. The CADIS adjoint photon source was defined as a rectangular parallelepiped surrounding the four tallies. The side length of the CADIS adjoint photon source was 1.2 m and the height was 0.1 m. The only difference between the three approaches was the method used to speed up the Monaco neutron calculation. The use of FW-CADIS as a reference in this analysis provides a reasonable efficiency comparison with respect to other global MC methods because it has been demonstrated that methods such as FW-CADIS that use both forward and adjoint estimates are more efficient in calculating more uniform relative uncertainties across a global mesh tally than other global MC methods that use only forward estimates [9].

For all the cases for which the uncertainties in SDDR with the different approaches were compared, the relative uncertainties in the photon Monaco calculations did not exceed 1%. These uncertainties were not included in the total SDDR uncertainties because the latter were dominated by the uncertainties in the neutron Monaco calculations. The uncertainties of the neutron Monaco calculations were propagated using an extension of the method described in [10]. This extension, which is described in the companion paper [1], uses the MS-CADIS adjoint neutron source to propagate the uncertainties in the neutron fluxes to the uncertainties in SDDR. Because this method ignores the correlation terms in the uncertainty propagation formula, the uncertainties calculated in this analysis represent only a lower bound of the true uncertainties in SDDR. Only one uncertainty estimate will be reported for the four SDDR tallies in each calculation. This uncertainty estimate represents the SDDR uncertainty at a detector enclosing all of the tally regions (the CADIS adjoint photon source) due to the uncertainties in the neutron Monaco calculations.

A new metric was used to assess the reliability of the different SDDR calculations in this analysis. To calculate the energy-dependent neutron fluxes throughout the problem geometry, the Monaco neutron calculation used a mesh tally with 4.844×10^7 space-energy elements. For all of the Monaco neutron calculations, nonzero MC scoring, which indicates calculating a MC tally result, did not occur in all the space-energy elements. In fact, the maximum fraction of non-zero-scoring elements was only

50.5% in any of the Monaco neutron calculations. However, not all the zero-scoring elements are important to the SDDR. Elements with energies at which the cross sections of the radioisotopes-producing neutron transmutation reactions are very low and elements that are very far from the SDDR detectors do not have a high contribution to SDDR at the detectors. A deterministic approximation for the contribution of each space-energy element to SDDR at the detectors can be estimated by multiplying the MS-CADIS adjoint source strength at this element by the deterministic neutron (forward) flux estimate at this element. The fraction of non-zero-scoring elements important to detector SDDR can be determined by adding the SDDR contribution of all non-zero-scoring elements and dividing this sum by total SDDR. This deterministic estimate of the fraction of the SDDR response that exists in non-zero-scoring space-energy elements was used as the reliability metric to determine the degree of undersampling in SDDR calculations.

RESULTS

To assess the ability of each approach to reliably calculate SDDR, the time of the Monaco neutron calculations was varied and SDDR was computed at the four tallies using each approach. The activation and the photon transport calculations did not change in this analysis. Figure 2 shows the SDDR values at the four tallies as a function of the running time of the Monaco neutron calculation.

For each approach individually, the differences between the maximum and the minimum SDDR did not exceed 12% after 2 days of running time for the neutron Monaco calculations. However, SDDRs of the analog cases were clearly undersampled even after 32 days of running time for the neutron Monaco calculation.

For the Monaco neutron calculations with running times greater than 4 days, the fractions of space-energy elements at which the Monaco neutron calculations were able to calculate a flux value are shown in Fig. 3. The SDDR response fractions that exist in non-zero-scoring elements are also shown in Fig 3. The latter fractions were calculated by multiplying the MS-CADIS adjoint neutron source strength at each space-energy element that had MC scoring by the forward flux value at the element.

The fraction of non-zero-scoring elements was about 15%–20% less with the MS-CADIS approach than with the standard FW-CADIS approach. However, the response fraction in the non-zero-scoring elements was greater by a factor of between 0.3% and 0.9% with the MS-CADIS approach. For all the analog cases with different running times, the fractions of non-zero-scoring elements were less than 35% and the fractions of the responses in non-zero-scoring elements were less than 60%.

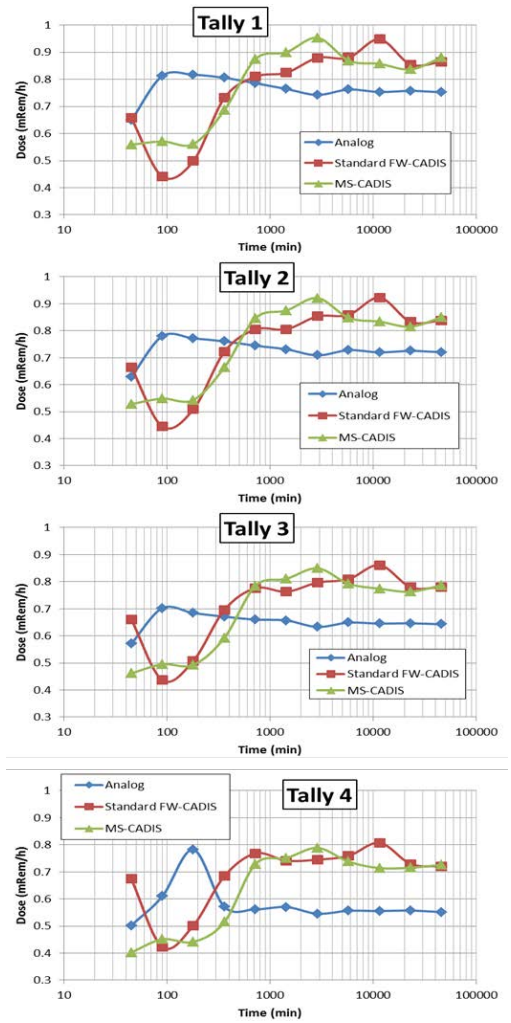

Fig. 2. SDDR estimates at the four tallies as a function of time of Monaco neutron calculations.

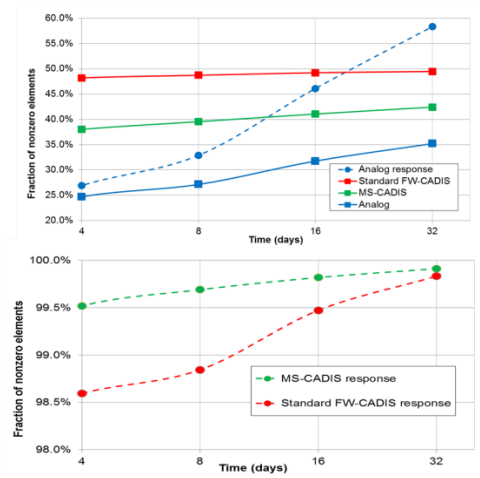

Fig. 3. Fractions of non-zero-scoring space-energy elements and fractions of SDDR responses in non-zero-scoring space-energy elements in the Monaco neutron calculations.

Figure 4 shows the uncertainties in the SDDR calculations for both the standard FW-CADIS and the MS-CADIS approaches. Because the calculated uncertainties of undersampled MC simulations are meaningless, the relative uncertainties were neither calculated for the analog cases nor for the standard FW-CADIS and MS-CADIS cases before 2 days of Monaco neutron calculations.

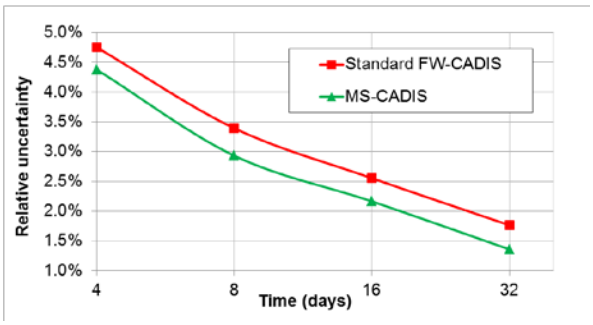

Fig. 4. Relative uncertainties in SDDR calculations.

The relative uncertainties with the MS-CADIS approach were less than the relative uncertainties with the standard FW-CADIS approach by factors of between 8% and 21%. These correspond to increases in the MC figure of merit of between 18% and 69% if the times of the activation calculations and the photon transport calculations were disregarded. The MS-CADIS approach was previously shown to enhance the efficiency of SDDR calculation by a factor of 500 compared to the standard FW-CADIS approach [11]. However, the standard FW-CADIS approach, which tends to spend more computational efforts in simulating particles in the low flux regions, is specifically well-suited for this problem because the tallies are located at the regions of the lowest flux values. Additionally, the cross sections of the transmutation reactions with the highest contribution to SDDR, namely ^{59}Co (n,γ) ^{60}Co, ^{181}Ta (n,γ) ^{182}Ta, and ^{58}Fe (n,γ) ^{59}Fe, are highest at low energies, where the neutron flux values are the lowest.

CONCLUSION

The application of the MS-CADIS method to SDDR calculations in fusion energy systems was tested using the ITER benchmark problem. Compared to the standard FW-CADIS method, the increase in the efficiency of the SDDR neutron MC calculation due to the use of the MS-CADIS method was between 18% and 69%. The MS-CADIS method also increases the fraction of non-zero-scoring mesh tally elements in the space-energy regions of high importance to the final SDDR.

Implementation of the MS-CADIS method in the SCALE and the ADVANTG [12] code systems is currently under way.

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