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Novel hybrid Monte Carlo/deterministic technique for shutdown dose rate analyses of fusion energy systems

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HIGHLIGHTS

- Develop the novel Multi-Step CADIS (MS-CADIS) hybrid Monte Carlo/deterministic method for multi-step shielding analyses.
- Accurately calculate shutdown dose rates using full-scale Monte Carlo models of fusion energy systems.
- Demonstrate the dramatic efficiency improvement of the MS-CADIS method for the rigorous two step calculations of the shutdown dose rate in fusion reactors.

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ABSTRACT

The rigorous 2-step (R2S) computational system uses three-dimensional Monte Carlo transport simulations to calculate the shutdown dose rate (SDDR) in fusion reactors. Accurate full-scale R2S calculations are impractical in fusion reactors because they require calculating space- and energy-dependent neutron fluxes everywhere inside the reactor. The use of global Monte Carlo variance reduction techniques was suggested for accelerating the R2S neutron transport calculation. However, the prohibitive computational costs of these approaches, which increase with the problem size and amount of shielding materials, inhibit their ability to accurately predict the SDDR in fusion energy systems using full-scale modeling of an entire fusion plant. This paper describes a novel hybrid Monte Carlo/deterministic methodology that uses the Consistent Adjoint Driven Importance Sampling (CADIS) method but focuses on multi-step shielding calculations. The Multi-Step CADIS (MS-CADIS) methodology speeds up the R2S neutron Monte Carlo calculation using an importance function that represents the neutron importance to the final SDDR. Using a simplified example, preliminary results showed that the use of MS-CADIS enhanced the efficiency of the neutron Monte Carlo simulation of an SDDR calculation by a factor of 550 compared to standard global variance reduction techniques, and that the efficiency enhancement compared to analog Monte Carlo is higher than a factor of 10,000.

1. Introduction

Accurate predictions of dose rate estimates from activated structural materials during shutdown, referred to as 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. For example, accurate SDDR calculations are needed to find the balance between an adequate performance and the nuclear shielding necessary for the diagnostics, the electron cyclotron heating, the ion cyclotron heating, the neutral beam injection, the pellet injection, and the disruption mitigation systems in ITER. In the preliminary design phase of ITER, SDDR analyses must be accurately performed to ensure that these systems can still perform adequately even with the necessary amounts of shielding [1].

Because the SDDR is caused by decay photons emitted by radioisotopes generated during irradiation, an SDDR calculation involves three steps:

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

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The rigorous 2-step (R2S) computational system, developed for calculating SDDR in full 3-D geometries, entails Monte Carlo (MC) neutron and photon transport calculations coupled with a comprehensive activation step using a dedicated inventory code and library [2]. Accurate R2S estimation of the SDDR is impractical for large and geometrically complex problems because it requires calculating space- and energy-dependent neutron fluxes everywhere inside the structural materials. Biasing the neutron transport calculation using an importance function [3] is not straightforward because of the difficulty of explicitly expressing the response function of the neutron calculation, which depends on the next calculation steps.

The use of global MC variance reduction techniques [4–6] was suggested for accelerating the R2S neutron transport calculation [7]. These techniques, which attempt to calculate MC tallies with nearly uniform relative uncertainties in the low-flux space-energy regions as well as in 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 prohibitive computational costs of these approaches, which increase with the overall problem size and amount of shielding materials, inhibit their ability to accurately predict the SDDR in fusion energy systems using full-scale modeling of an entire fusion plant.

This paper describes a novel hybrid MC/deterministic technique that uses the Consistent Adjoint Driven Importance Sampling (CADIS) method, which has been successfully used for more than a decade in shielding calculations [8] but focuses on multi-step shielding calculations such as the R2S calculations of SDDR. This technique, referred to as Multi-Step CADIS (MS-CADIS), speeds up the R2S MC neutron transport calculations using an importance function that represents the importance of the neutrons to the final SDDR.

2. Theory and implementation

The importance sampling technique [3] uses an importance function—the expected score to a detector from a particle at some point in phase space—to modify the MC sampling process. In the CADIS method [8], this function is used in modifying both the sampling of particles emitted from the source and the sampling of particles being transported. If the exact importance function $I(\vec{r}, E)$ is known, the detector response R can be expressed as

$$R = \int_V \int_E I(\vec{r}, E) q(\vec{r}, E)\ dV\ dE, \tag{1}$$

where $q(\vec{r}, E)$ is the source distribution function.[1] Eq. (1) represents an integral equation describing a hypothetical, absolutely efficient MC process where the particles score the exactly correct expected value as soon as they get emitted from the source without going into any physical events. It is worth mentioning that if the importance function is exactly known, the MC calculation is not needed because the response can be calculated simply by integrating Eq. (1). However, throughout the last two decades, the hybrid MC/deterministic techniques have been very successful in dramatically increasing the efficiency of MC calculations using approximate importance functions. The use of these approximate importance functions in modifying the MC sampling process tends to speed up the MC calculation by decreasing the total number of events needed for scoring at the MC tally.

[1] For simplicity, all the distributions were assumed to be isotropic, but the derivation can be generalized to include the angular variation in a straightforward way.

Because the transport equation is a linear integro-differential equation, a related adjoint equation can be formulated using the identity

$$\langle \phi(\vec{r}, E), H^+\phi^+(\vec{r}, E)\rangle = \langle \phi^+(\vec{r}, E), H\phi(\vec{r}, E)\rangle, \tag{2}$$

where $\phi(\vec{r}, E)$ is the space- and energy-dependent particle flux, $\phi^+(\vec{r}, E)$ is the space- and energy-dependent adjoint flux, H is the transport operator, H^+ is the adjoint transport operator, and the angle brackets $\langle\ \rangle$ signify integration over all energy and space. Substituting the forward and adjoint transport equations into Eq. (2) leads to another form of the adjoint identity,

$$\langle \phi(\vec{r}, E), q^+(\vec{r}, E)\rangle = \langle \phi^+(\vec{r}, E), q(\vec{r}, E)\rangle, \tag{3}$$

where $q^+(\vec{r}, E)$ is the adjoint source space and energy distribution function. This adjoint identity is valid for any adjoint source function [9]. However, the adjoint flux can represent the importance function defined in Eq. (1) if the adjoint source function is carefully chosen so that the left-hand side of Eq. (3) represents the response that must be calculated.

The SDDR caused by the decay photons is defined as

$$SDDR = \langle \sigma_d(\vec{r}, E_p), \phi_p(\vec{r}, E_p)\rangle, \tag{4}$$

where σ_d is the flux-to-dose-rate conversion factors at the position of the detector and ϕ_p is the photon flux. Using Eqs. (3) and (4) and setting the photon adjoint source equal to σ_d lead to the following relationship for the photon transport problem:

$$SDDR = \langle q_p^+(\vec{r}, E_p), \phi_p(\vec{r}, E_p)\rangle = \langle q_p(\vec{r}, E_p), \phi_p^+(\vec{r}, E_p)\rangle. \tag{5}$$

In Eq. (5), the adjoint photon flux $\phi_p^+(\vec{r}, E_p)$, expressing the final SDDR caused by a unit photon source at position $\vec{r}$ and with energy E_p, represents the importance function defined in Eq. (1). An approximate deterministic estimate of the photon adjoint flux can be used in speeding up the MC photon transport calculation of an SDDR problem.

In SDDR analyses, the neutron and photon calculations are separated by an activation calculation. Finding the adjoint source of the SDDR neutron calculation is not as simple as the photon calculation because the SDDR is not directly caused by the neutrons but rather is caused by the decay photons of the neutron-activated structural materials. In the Multi-Step CADIS (MS-CADIS) method, we seek an adjoint neutron source whose inner product satisfies the following relationship for the neutron transport problem:

$$SDDR = \langle q_n^+(\vec{r}, E_n), \phi_n(\vec{r}, E_n)\rangle = \langle q_n(\vec{r}, E_n), \phi_n^+(\vec{r}, E_n)\rangle, \tag{6}$$

where q_n is the neutron source, ϕ_n is the neutron flux, q_n^+ is the neutron adjoint source, and ϕ_n^+ is the neutron adjoint flux. Even though it may seem counterintuitive to set the *neutron* adjoint identity to be equal to a *photon* response, this can lead to the development of an importance function that represents the importance of the neutrons to the final SDDR. From Eqs. (6) and (5), it is clear that the MS-CADIS adjoint neutron source will satisfy the integral equation

$$\langle q_n^+(\vec{r}, E_n), \phi_n(\vec{r}, E_n)\rangle = \langle q_p(\vec{r}, E_p), \phi_p^+(\vec{r}, E_p)\rangle. \tag{7}$$

If a relationship between the photon source and the neutron flux can be determined, then an adjoint neutron source whose inner product satisfies Eq. (7) can be found.

The photon source can be calculated using a deterministic neutron transport calculation followed by an activation calculation, but finding the relationship between them requires considering all the neutrons transmutation interactions that affect the radioisotope inventory either by creation or depletion. The exact equation describing the radioisotope inventory as a function of the neutron flux is rather complicated [10]. However, a simple relationship between the photon source and the neutron flux can be derived using quantities calculated by a deterministic neutron transport calculation followed by an activation calculation.