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SOURCE PROFILE ANALYSIS FOR THE ITER FIRST WALL/SHIELD MODULE 13

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Radiation shielding, thermal protection, and energy removal for ITER are provided by an array of first wall/shield modules (FWS). Nuclear analysis of the shield modules is important for understanding their performance and lifetime in the system. Using Direct Accelerated Geometry (DAG)-MCNPX, a coupling of traditional MCNPX with the Common Geometry Module (CGM) and the Mesh Oriented dAtaBase (MOAB) developed at UW, high-fidelity 3-D neutronics analysis is now possible. Particles are transported in the CAD geometry reducing analysis time, eliminating input error, and preserving geometric detail. The surface source read-write capability that exists in MCNPX has been used in DAG-MCNPX to combine realistic source conditions with an efficient analysis model. A surface source was written using a 3-D model of ITER with a detailed plasma source. The surface source was then used in a detailed 3-D CAD model of Module 13. 3-D high fidelity mesh tallies were used to calculate nuclear heating used in thermal-hydraulics analysis. Surface source results were compared against results using a hybrid 1-D/3-D approach in which a uniform neutron source is extended infinitely in the vertical direction. Results show that the hybrid source overestimated the total number and underestimated the average energy of particles incident on the FW. The hybrid approach was found to overestimate the nuclear heating at the front of the first wall by as much as 63%.

I. INTRODUCTION

The first wall/shield (FWS) components of ITER protect the vacuum vessel (VV) and magnets from the intense radiation of the fusion reaction.[1] The FWS is segmented into 18 rings of modules in the poloidal direction. Beginning on the bottom of the inboard side, modules are numbered from 1 to 18 progressing poloidally to the bottom of the outboard side. The US will design and construct modules 7, 12, and 13. Of interest in this paper, Module 13 is located above the mid-plane on the outboard side of the tokamak. Each ring of modules on the outboard side is further segmented into 36 similar modules. Rings on the inboard side are segmented into 18 similar modules.

The FWS consists of layers that provide a variety of functions, as shown in Fig. 1. The first wall (FW) is subject to both surface heating from the plasma and volumetric nuclear heating, while the shield is subject to only nuclear heating. The FW contains beryllium, CuCrZr, and steel layers. Beryllium tiles are used as a plasma facing component due to their high melting temperature, low Z, and lack of tritium retention. A CuCrZr alloy heat sink conducts energy to pressurized water cooling channels. Stainless steel provides structural support for the FW and forms coolant channels through the CuCrZr heat sink. The FW is cut into fingers to reduce eddy currents so that electromagnetic forces are manageable during a disruption. The shield block contains coolant manifolds across the front of the module. Behind the front manifold, coaxial coolant channels remove heat from the steel structure. They also provide the necessary water fraction for adequate shielding and to comply with the robotic maintenance weight requirement. Penetrations exist in the shield block for coolant connections and structural support for the FW. The back of the shield block is highly featured such that the coaxial connector, stub keys, and branch pipes can fit between the shield block and VV.

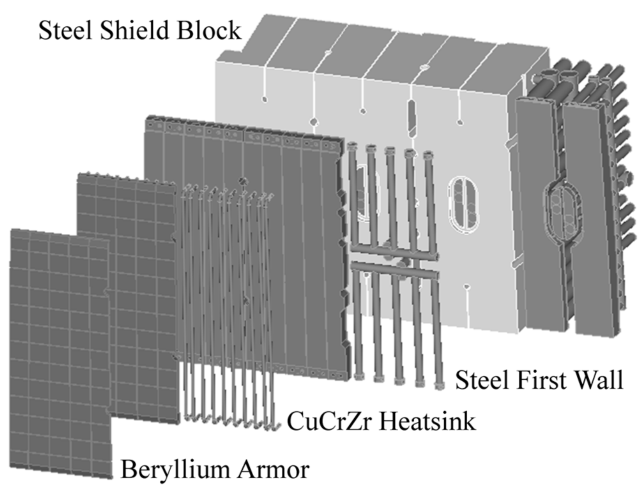

Fig 1. Detailed Module 13 CAD model created at Sandia National Laboratories.

Detailed nuclear analysis was performed previously for an earlier design configuration of the FWS Module 13 (Ref. 2). High-resolution nuclear heating results were created for use in computational fluid dynamics simulations. In the analysis a hybrid 1-D/3-D model was used. This approach is described in Section II. The source in the hybrid 1-D/3-D approach does not accurately represent the angular and energy distribution of neutrons incident on the front surface of Module 13, and could lead to erroneous results. In this paper we perform calculations for a recent FWS configuration (Fig. 1) utilizing the surface source. Results are compared to calculations performed with the hybrid source approach for the same FWS configuration.

II. 1-D/3-D CYLINDRICAL HYBRID MODEL

In this approach, the detailed CAD model of Module 13 was inserted into a 1-D cylindrical model, creating a 1-D/3-D cylindrical hybrid model as shown in Fig. 2 (Ref. 2). In this model the inboard FWS was represented as homogenized layers of Be, CuCrZr, and steel with varying percentages of water coolant. The outboard side consisted of the CAD model. Some components surrounding the shield block were not included, such as water manifolds and stub keys. Material composition was specified by the ITER IO,[3] and cross sections from the FENDL-2.1 nuclear data library were used.[4]

The isotropic 14.1 MeV neutron source was approximated as being uniformly distributed in the plasma zone between the inboard and outboard first walls. In prior work, a 40º segment of ITER was modeled with each FWS module containing homogenized materials, as displayed in Fig. 3 (Ref. 5). Neutron wall loading on each module was calculated using a neutron source distribution provided by the ITER International Organization (IO).[6] These values were used to normalize the results of the 1-D/3-D hybrid model to the neutron wall loading of 0.693 MW/m^2 at Module 13.

In the cylindrical hybrid model, reflecting boundary conditions approximated the full extent of ITER in the poloidal and toroidal directions. In this approximation, the neutron source was assumed to be infinitely extended in the vertical direction. This resulted in a more tangential angular distribution of the source neutrons incident on the first wall compared to the case with the actual distributed finite source of ITER.

A high resolution mesh tally was superimposed over the CAD geometry, resolving nuclear heating in 3 mm x 3 mm x 3 mm voxels. The accuracy of the nuclear calculation, including nuclear heating, is determined by how accurate in location, angle, and energy the neutron source at the module surface is represented. This motivated the development of an improved neutron source treatment.

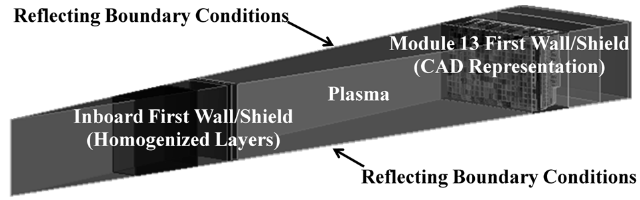

Fig 2. 1-D/3-D cylindrical hybrid model.

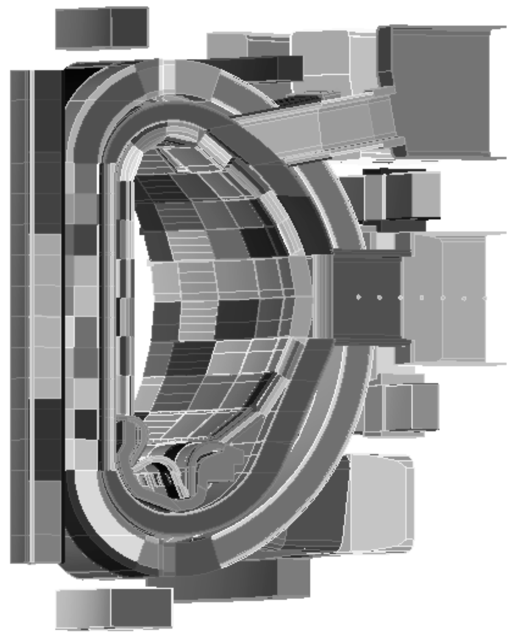

Fig. 3. 3-D model of the 40º sector of ITER.

III. SURFACE SOURCE SIMULATION

For this analysis, the DAG (Direct Accelerated Geometry)-MCNPX code was used.[7,8] Developed at the University of Wisconsin, DAG-MCNPX is a coupling of MCNPX to the Common Geometry Module (CGM) and Mesh Oriented DatABase (MOAB). This arrangement allows CAD models to be analyzed without using the standard approach of surface equations and Boolean operations of MCNPX. Such automation eliminates human error in preparing MCNPX geometry input. Since particles are transported directly in the CAD geometry, exact geometric details are preserved. DAG-MCNPX permits faster design iterations by reducing preparation time.

A method was needed to obtain an accurate neutron source distribution in location, angle and energy. Placing the entire FWS Module 13 CAD geometry in the 3-D 40˚

ITER model would significantly extend the simulation time required to yield low statistical error for high-fidelity mesh tallies. Instead, using the recently implemented surface source feature, Module 13 can be analyzed in a radial approximation using the detailed source of the 3D ITER model.

A surface source was written using the 3-D 40˚ ITER model shown in Fig. 3 that has a detailed neutron source distribution provided by the ITER IO. A surface was placed directly in front of the Module 13 FW. The location, angle, and energy of all particles crossing the surface were recorded to a file.

A Module 13 surface source model was created in which the CAD geometry was surrounded by reflecting boundary conditions in the poloidal and toroidal directions. The reflecting surfaces simulate the effect of neighboring FWS modules. A homogenized vacuum vessel was added behind Module 13. A surface was added directly in front of the FW, as shown in Fig. 4 that corresponds to the surface from the 3-D 40˚ ITER model on which the surface source was recorded. Source particles were then "born" on this surface. Each recorded particle crossing from the 40˚ ITER model was read as a source particle in the Module 13 surface source model. Both the plasma volume and inboard FWS are absent from the Module 13 surface source model. Instead, all secondary contribution from the inboard and outboard FWS is accounted for in the surface source.

IV. SURFACE SOURCE RESULTS

IV.A Source Profile at the First Wall

The neutron and photon angular distributions at the FW using the surface source model were compared to those of the cylindrical hybrid model in Fig. 5. The results are normalized to one neutron or photon incident on Module 13. As expected, the cylindrical hybrid model exaggerates the component of neutrons tangential to the FW. This is because reflecting boundaries simulate an infinite neutron source in the z-direction as shown in Fig. 2. Differences in the photon angular distribution are more subtle than in the neutron angular distribution because all photons are secondary particles that originate from other FWS modules.

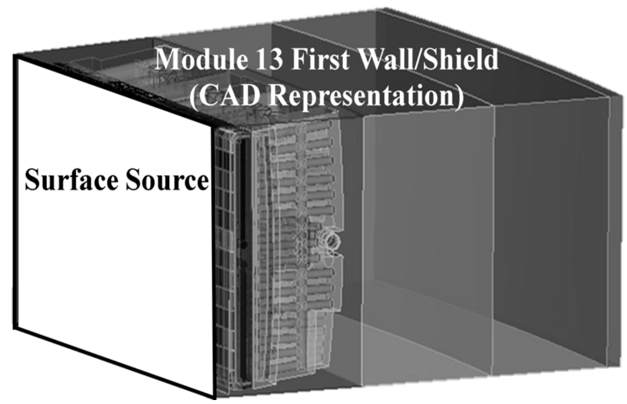

Fig. 4. Surface source model.

The normalized neutron and photon energy distributions at the FW are compared in Fig. 6. The high-energy peak is due to uncollided 14.1 MeV deuterium-tritium fusion source neutrons. The hybrid source overestimates both the number of neutrons and gamma photons incident on the FW of Module 13, as shown in Table I. This is because the geometry of the hybrid model creates tangential source particles which result in additional reflection into the chamber. The average energy of particles in the hybrid distribution is lower, suggesting a softer neutron and gamma photon spectra.

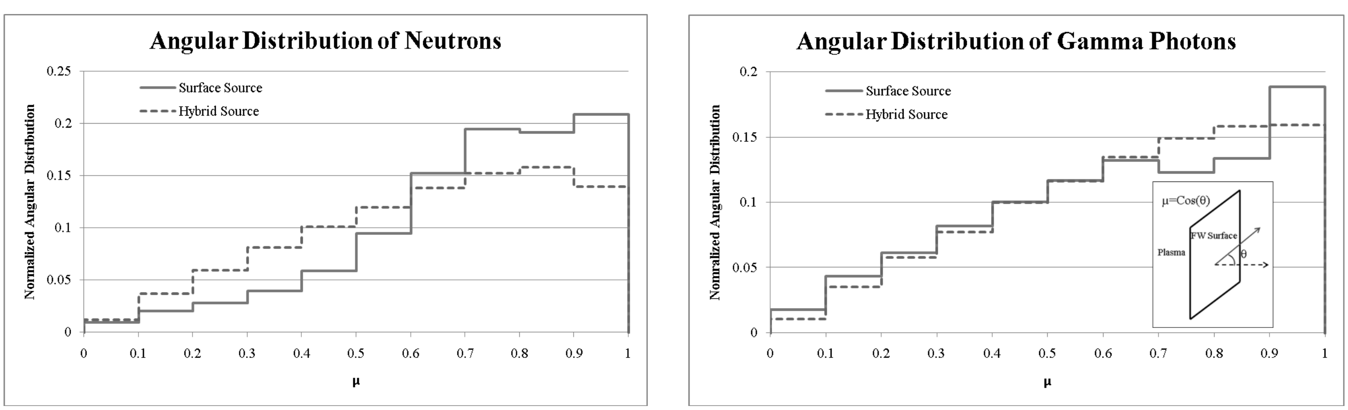

Fig. 5. Normalized neutron and gamma photon angular distributions incident on Module 13.

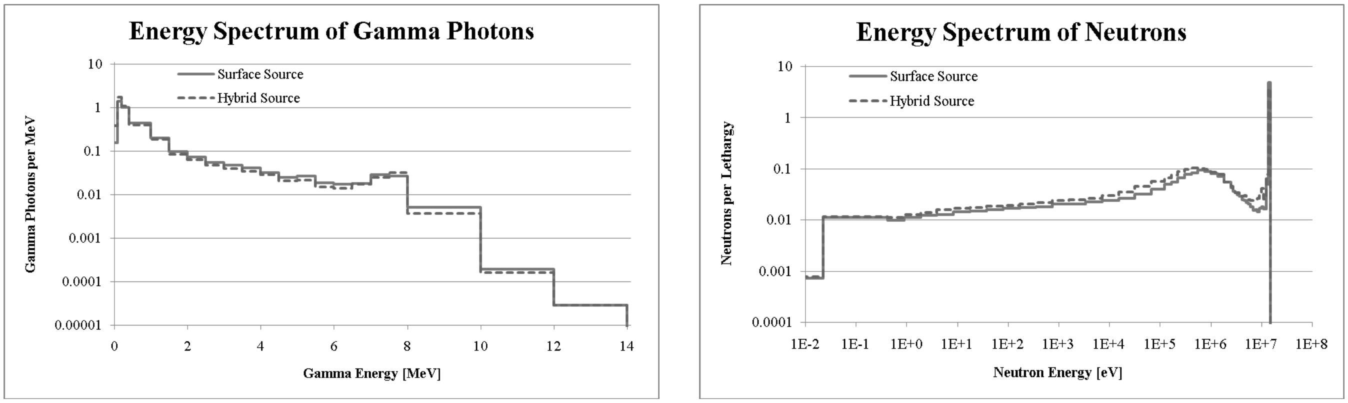

Fig. 6. Normalized neutron and gamma photon energy distribution incident on Module 13.

TABLE I. Summary of Particles Incident on First Wall

	Surface Source	Hybrid Source
Total Neutrons [neutrons/s]	6.64×10^{17}	8.77×10^{17}
Average Energy of Neutrons [MeV]	7.37	5.87
Total Gamma Photons [photons/s]	2.61×10^{17}	3.32×10^{17}
Average Energy of Gamma Photons [MeV]	1.48	1.33

IV.B Nuclear Heating in the First Wall

High-resolution structured mesh tallies were produced for each of the four materials of the FWS (Be, CuCrZr, Steel, H_2O). Nuclear heating was calculated in the first wall using 3 mm x 3 mm x 3 mm voxels. From the 250 million histories simulated in the 40˚ ITER model 14.5 million particles crossed the surface source and were recorded to the surface source file. The entire calculation required 22.8 computer-weeks on 2.66/3.20 GHz Intel processors. The structured mesh tallies were then interpolated onto a conformal tetrahedral mesh used for computation fluid dynamics simulations. In Fig. 7 nuclear heating results are shown for the **c**ylindrical **h**ybrid and **s**urface **s**ource models. Table II compares the mean values of nuclear heating for the surface source and hybrid models by material. The overestimation due to the hybrid source is greatest at the front of the first wall. 1-D investigation of the mesh data has revealed the overestimate in nuclear heating at the front of the FW to be as much as 63%. The greatest statistical standard error was 11%, found in the CuCrZr.

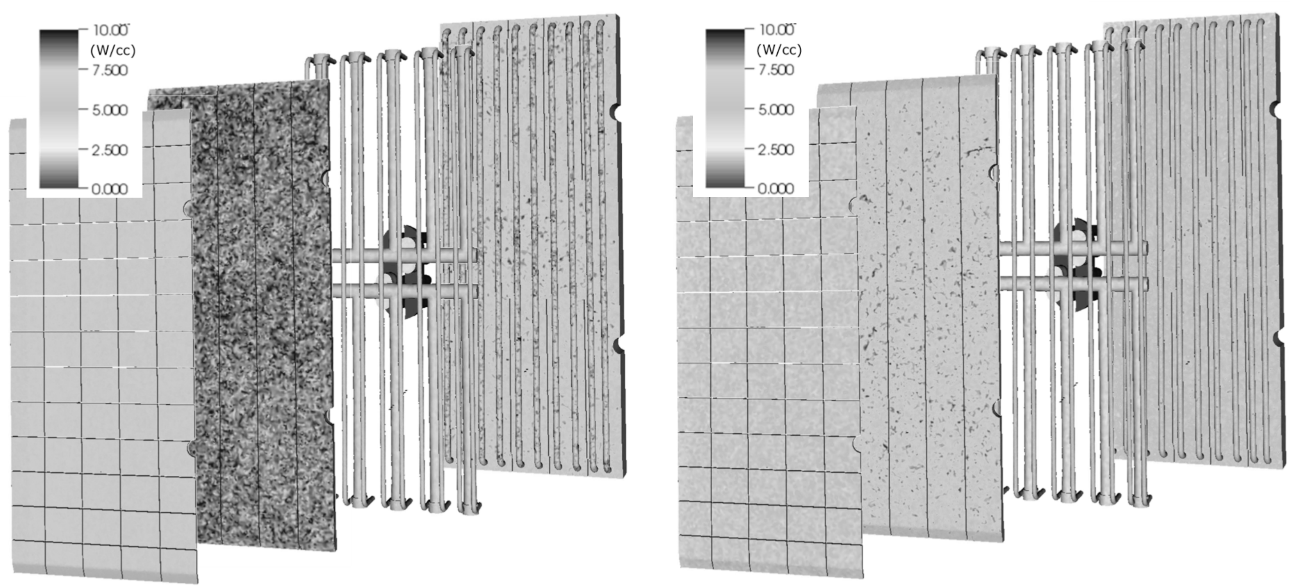

Fig. 7. Module 13 FW heating in the cylindrical hybrid model (left) and surface source model (right).

TABLE II. Mean values of nuclear heating in the FW

	Surface Source [W/cc]	Hybrid Source [W/cc]
Beryllium	4.35	6.26
CuCrZr	6.47	8.26
Water	4.07	5.17
Steel	5.39	6.77

V. SUMMARY

Computational fluid dynamics modeling requires knowledge of the nuclear heating profile in each module. The accuracy of nuclear heating results depends upon the accuracy of the neutron source distribution. Previous simulations used a neutron source distribution that extended infinitely in the poloidal direction due to reflecting boundaries. This resulted in a more tangential angular distribution of the source neutrons incident on the first wall compared to the case with the actual distributed finite source of ITER. As a result, using the uniform source in the simplified 1-D radial configuration leads to overestimating the calculated nuclear parameters at the front of the FWS model.

Using DAG-MCNPX's surface source feature, an improved neutron source was used that increased simulation accuracy. The improved neutron source was created by recording particle crossings in the 40º ITER model, then reading the same particle crossings as source particles in the Module 13 surface source model. Using mesh tallies nuclear heating was found to be overestimated by as much as 63% at the front of the FW. The hybrid source both overestimated the total number and underestimated the average energy of particles incident on the FW. When compared with placing the Module 13 CAD geometry inside the full 40º ITER CAD model, surface source modeling reduces the time required to achieve desired statistical accuracy for the high-fidelity mesh tallies.

ACKNOWLEDGMENT

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