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***Abstract*—Radiation shielding 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. While one-dimensional (1-D) analysis provides an adequate first approximation, three-dimensional (3-D) analysis is needed to validate the 1-D analysis and resolve fine geometric details that result from heterogeneities in the module. Using MCNPX-CGM, a coupling of traditional MCNPX with the Common Geometry Module (CGM), 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. A detailed 3-D CAD model of FWS Module 13 is inserted into a 1-D radial approximation including homogenized representations of the inboard FWS, plasma, and vacuum vessel (VV). A 14.1 MeV uniform source between the inboard and outboard sides is used to simulate the ITER plasma. Reflecting boundary conditions approximate the full extent of ITER in the poloidal and toroidal directions. Heating, radiation damage, and helium production profiles through Module 13 are determined using high-resolution mesh tallies. In the front manifold of the shield block, heating and helium production were found to be lower in steel than the homogenized 1-D model suggests. Peaking in nuclear heating and helium production in steel is observed at the interface with adjacent water zones.**

Keywords-ITER; shield modules; nuclear heating; helium production

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 to the top of the VV then down 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. Segmentation reduces the weight of individual modules which are limited to 4.5 tons each, for robotic maintenance.

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. 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 and provide the necessary water fraction 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.

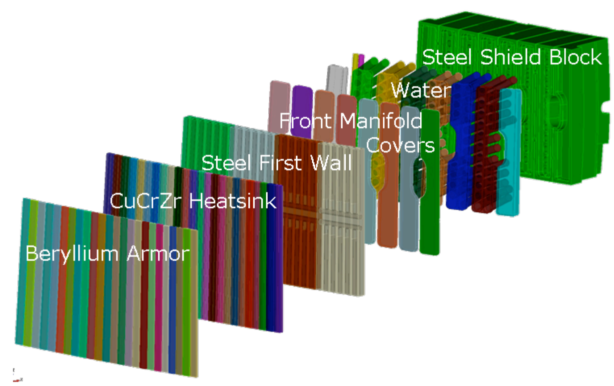

Fig. 1. The Module 13 CAD model contains intricate curved surfaces that would prove difficult to model with conventional MCNPX.

In prior work, a 40º segment of ITER was modeled with each FWS module containing homogenized materials, as displayed in Fig. 2 [2]. Neutron wall loading on each module was calculated using a neutron source distribution provided by the ITER International Organization (IO) [3]. Also in other work, one-dimensional (1-D) neutronics analyses were performed on ITER FWS modules 7, 12, and 13 [4]. Homogenized layers approximate different radial zones in each module. Computational fluid dynamics modeling requires knowledge of the nuclear heating profile in each module. Helium generation may inhibit welding during the replacement and maintenance of FWS modules. Radiation damage limits the lifetime of structural components inside the reactor. Although 1-D results provide an initial estimate of nuclear heating, helium production, and radiation damage, three-dimensional (3-D) analysis is needed to validate the 1-D analysis and resolve the fine geometric details that result from heterogeneities in the module.

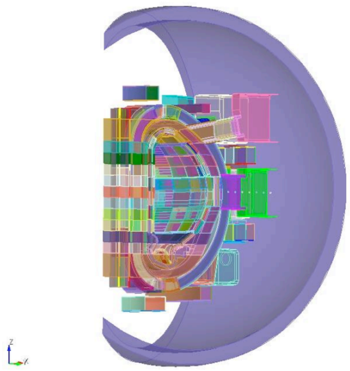

Fig. 2. 40º ITER model.

II. MCNPX-CGM SIMULATION

For this analysis, the MCNPX-CGM code was used [5,6]. Developed at the University of Wisconsin, MCNPX-CGM is a coupling of MCNPX to the Common Geometry Module (CGM). 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. MCNPX-CGM permits faster design iterations by reducing preparation time.

MCNPX requires all space to be defined, yet CAD models typically include only solid objects. The CAD model constructed at Sandia National Laboratories featured solid objects representing the FW and shield block of Module 13. The void surrounding the solid objects and the internal water volumes was created by subtracting solid objects from a large encompassing volume. Known as the *complement*, the void space surrounding Module 13 is the most complicated volume.

After the complement is created, neighboring surfaces must be paired, such that only one surface exists between two neighboring volumes. Error is introduced during CAD file format translations, often preventing coincident surfaces from being recognized. For this reason, creating the complement is a difficult and time-consuming process. Upon completion of this analysis a new version of MCNPX-CGM, called DAG-MCNPX (Direct Accelerated Geometry, MCNPX) was developed which implicitly creates the complement. Using relationships between surfaces and the volumes that they are associated with, DAG-MCNPX is able to recognize when a particle crosses into the complement without the complement existing as a solid object. DAG-MCNPX will be used in future analyses.

Module 13 and its complement were inserted into a previous 1-D cylindrical model, creating a 1-D/3-D cylindrical hybrid model as shown in Fig. 3. In this model the inboard and outboard FWS were represented as homogenized layers of Be, CuCrZr, and steel with varying percentages of water coolant. While the inboard FWS was unchanged, the outboard layers were replaced with the CAD model. Some components surrounding the shield block were not included, such as first wall legs, water manifolds, stub keys, branch pipes, and the coaxial connector. Because the complement occupied space that would otherwise hold these components, homogenized steel and water was assigned as the material of the complement. In this manner, the reflection from missing components was simulated. Material composition was specified by the ITER IO [7], and cross sections from the FENDL-2.1 nuclear data library were used [8].

The 14.1 MeV neutron source was approximated as being evenly distributed in the plasma zone between the inboard and outboard first walls. The neutron source was normalized to neutron wall loading of 0.693 MW/m^2 previously calculated using the 40º ITER model. The poloidal and toroidal extent of ITER was approximated by using reflective boundary conditions on the right, left, top, and bottom sides of the model. A high resolution mesh tally was superimposed over the CAD geometry, resolving heating (Fig. 5), radiation damage, and helium production in 0.5 cm x 0.5 cm x 1.0 cm voxels. Due to the use of mesh tally multipliers, helium production and radiation damage were calculated as if steel was subjected to the neutron flux at each location. This result is not physically accurate, but gives insight to nuclear responses of steel in regions of large water content. This occurs in the steel T-drivers of the front water manifold. To accelerate convergence, mesh-based, energy-dependent radial weight windows were targeted on a tally of the vacuum vessel. 17 million source particles were simulated in 15.8 computer-weeks on 17 parallel 1.4/1.7 GHz Athlon processors.

Fig. 3. To create the 1-D/3-D hybrid model, a 3-D CAD model of FWS Module 13 was inserted into a 1-D cylindrical build of homogenized layers.

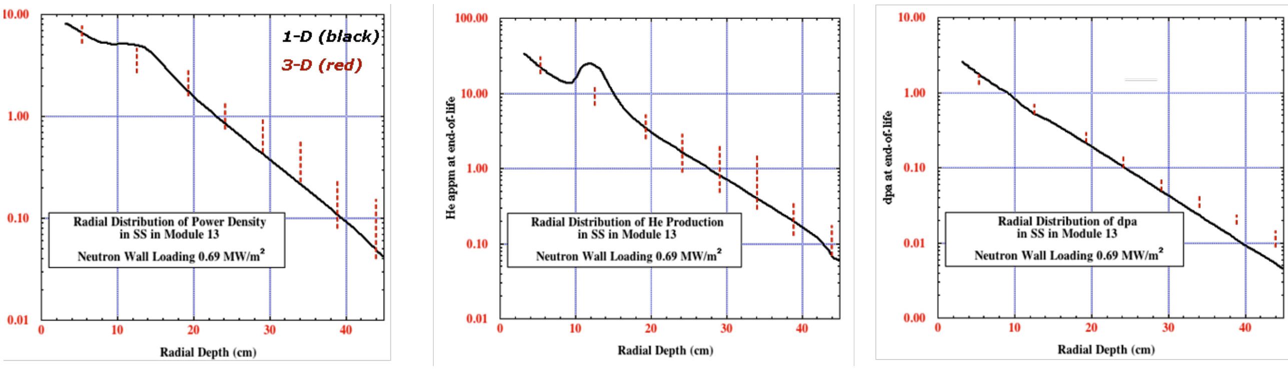

Fig. 4. Significant variation between 1-D and 3-D results exist in nuclear heating and helium production, while less variation is found in radiation damage.

III. High-Fidelity 3-D Results

3-D results were compared with previous 1-D data in Fig. 4. Existing as a range of values at each radial location, 3-D results show significant variations in heating and helium production because of heterogeneity. Much less variation is seen in radiation damage. This is because of the larger impact of neutron slowing down and gamma generation in water on nuclear heating and helium production in steel.

One important effect observed from these high-fidelity 3-D results was increased heating at the steel-water interface of the front manifold, as shown in Fig. 6. At this location steel nearest the water is exposed to the highest nuclear heating. Using 1-D slab models it was determined that this is due to gamma generation in the water. In addition, neutrons softened in the water produce more gamma particles in the steel.

Another important effect observed from the 3-D results was increased helium production at the steel-water interface of the front manifold, as seen in Fig. 7. Neutrons slow down in the bulk water of the manifold then are absorbed by boron in the steel. ^{10}B has a large (n,α) cross section at low energy and is present as an impurity in the steel. In addition, the softer spectrum increases helium production due to ^{58}Ni being transformed into ^{59}Ni and then undergoing the ^{59}Ni(n,α) reaction at low energy [9]. 316LN-IG steel used in the FWS modules has 10 wppm boron and 12.25 wt% nickel [7].

IV. Summary and Continuing Work

Using MCNPX-CGM the ITER FWS Module 13 was inserted into a 1-D cylindrical model of ITER. Direct Monte Carlo transport in the CAD model of the ITER FWS yields high-fidelity, high-resolution nuclear responses that greatly help in the design process. It was determined that heating and helium production vary significantly from 1-D results using homogenized layers. Both nuclear heating and helium generation in steel are increased at the steel/water interfaces due to the effect of enhanced neutron slowing down and gamma generation in the adjacent water zone. Results of the calculation that preserve all exact details of the module reveal important heterogeneity effects on nuclear parameters that should be accounted for in the design.

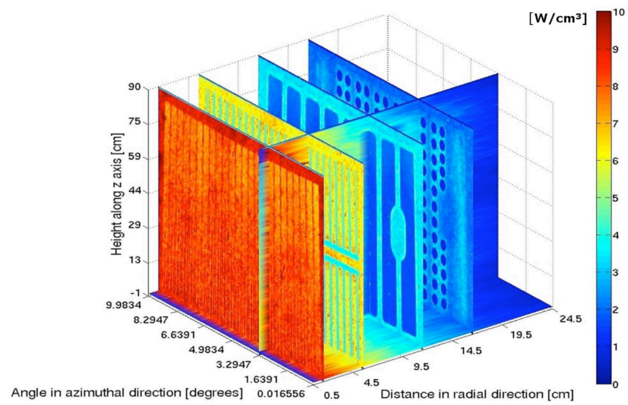

Fig. 5. Heating in Module 13 is displayed using visualization tools developed for 3-D neutronics analysis.

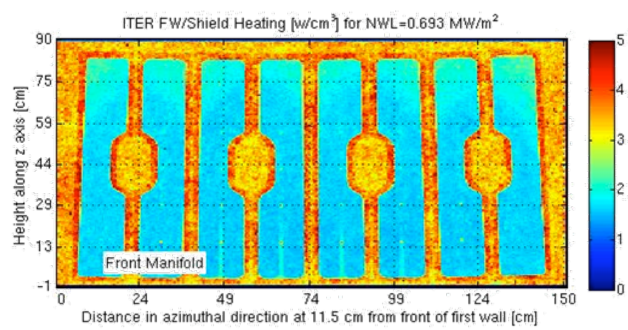

Fig. 6. Increased nuclear heating is seen at the steel/water interface of the front manifold.

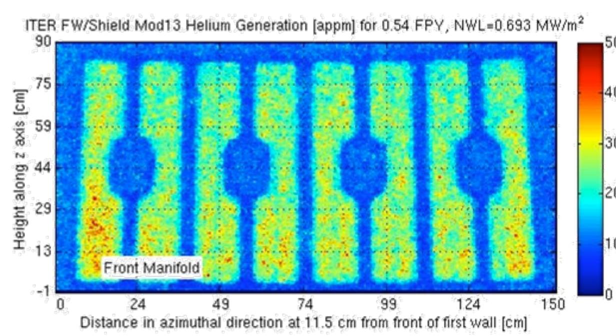

Fig. 7. Increased helium generation is seen at the steel/water interface of the front manifold.

A new Module 13 model is being developed that includes first wall legs, water manifolds, stub keys, branch pipes, and the coaxial connector. The improved Module 13 model will be placed inside the 40º ITER model. This simulation will better represent the actual ITER conditions because the 40º ITER model uses the neutron source distribution provided by the ITER international organization. Other FWS modules are located in their actual positions providing more accurate reflection than in the 1-D/3-D hybrid cylindrical model. Detailed nuclear heating data will be generated on 3 mm edge-length voxels for use as a source in computational fluid dynamics calculations. Streaming through shield block penetrations will be calculated by using an implicit complement void.

ACKNOWLEDGMENT

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