Nuclear Heating and Damage Profiles in the ITER Divertor Cassette

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Abstract — Three-dimensional neutronics calculations have been performed to determine the detailed spatial distribution of the nuclear parameters in the divertor cassettes used in ITER. These parameters included power density, atomic displacement and helium production. The largest heating and damage occurs in the dome which has full view of the plasma. The power density in the tungsten plasma facing material at the dome is 16.4 W/cm^3. The total nuclear heating in the 60 divertor cassettes is 101.6 MW with the major contributors being the dome, vertical targets, and wings.

I. INTRODUCTION

The divertor cassette design of ITER went through several changes to improve its performance. The latest ITER design is the Detailed Design [1]. The design utilizes 60 divertor cassettes with vertical targets and a central dome. Knowledge of nuclear heating and radiation damage levels in the different components of the divertor cassette is essential for proper design analysis. Radiation damage to parts of the vacuum vessel (VV) in the divertor region need to be quantified to assess the feasibility of rewelding. Due to the geometrical complexity of the divertor region, three-dimensional (3-D) analyses are required. This design was preceded by the Interim Design of ITER [2]. Three-dimensional neutronics and shielding calculations were performed for the divertor region in the Interim Design to determine the nuclear parameters in the divertor cassette and surrounding vacuum vessel and TF coils [3]. Several changes in both geometrical configuration and material composition have been employed recently in the divertor cassette design. In addition, more detailed spatial distribution of nuclear parameters in the cassette was needed for precise mechanical and thermal-hydraulics design. A detailed 3-D model has been developed for the divertor cassette in the ITER Detailed Design to incorporate the design changes and determine more detailed nuclear parameters profiles.

II. THREE-DIMENSIONAL CALCULATIONAL MODEL

3-D neutron-gamma transport calculations have been performed for the divertor region using the continuous energy, coupled neutron-gamma-ray Monte Carlo code MCNP-4A [4] and the nuclear data based on the FENDL-1 evaluation [5]. The detailed geometrical configuration of the divertor cassette has been modeled for 3-D neutronics calculations. The model represents a nine degree toroidal sector of ITER. Hence, it includes one and a half cassettes with the associated nominal 1 cm gaps between adjacent cassettes. The model includes in detail the high heat flux plasma facing components (PFC), the vertical targets, the wings with associated plates, and the gas boxes, as well as the central dome and cassette bodies. The 37.5 cm wide and 17.5 cm thick divertor pumping duct at the bottom of each cassette is included in the model. The rails upon which the cassettes move toroidally during maintenance are also included. Each divertor cassette in the model was divided into 103 regions to provide detailed spatial distribution of nuclear heating and radiation damage. The layered configurations of the dome PFC and vertical targets were modeled accurately with the front tungsten layer modeled separately. Separate regions are included in the model to represent the mechanical attachments and coolant pipe connections for the dome, vertical targets, and wings. Fig. 1 shows a vertical cross section of the cassette model at a toroidal location at the center of the cassette through the pumping ducts.

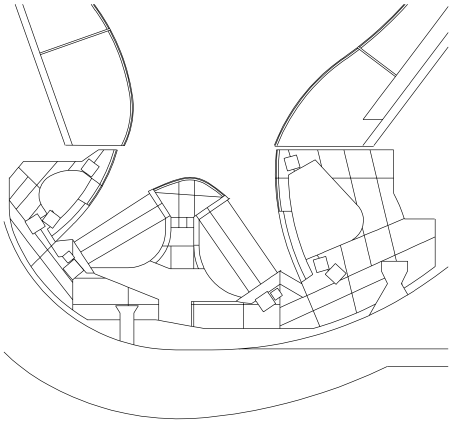

Fig. 1. Vertical cross section at the middle of the cassette model.

The divertor cassette model has been integrated with the general ITER model based on the Interim ITER Design. The integrated model includes detailed modeling of the first wall, blanket with associated coolant manifolds and back plates, VV, TF coils, central solenoid, and PF coils. While Be is used as the plasma facing material at the first walls of the blanket modules, tungsten is used for the inboard and outboard baffle modules above the divertor cassette. All toroidal and poloidal gaps between adjacent blanket modules are included. The major vacuum vessel penetrations are included in the model. This includes the divertor port at the bottom of the reactor. The blanket design in the ITER Interim Design was used since the blanket design was not fully developed in the Detailed Design. Since most of the design changes in the blanket are expected to be in the back plate, module attachment and manifolds, the impact will be mainly on shielding and streaming through the large ports and the impact on nuclear parameters in the divertor cassette will be minimal. The output of the MCNP geometry plotting routine given in Fig. 2 shows a vertical cross section through the middle of the vacuum vessel ports. Several splitting surfaces have been added in the divertor region to allow for utilizing the geometry splitting with Russian Roulette variance reduction techniques employed in MCNP which are needed to improve the accuracy of the calculated nuclear responses. A total of 543 surfaces and 593 cells have been used in the model.

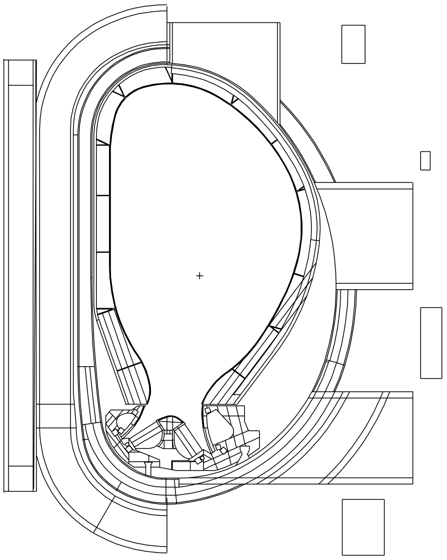

Fig. 2. Vertical cross section through the VV ports of the ITER 3-D model for MCNP calculations.

A source subroutine has been written to modify MCNP to sample source neutrons from the source distribution in the ITER plasma provided numerically at 1600 mesh points. Cell flux and energy deposition tallies are used to determine the volume averaged parameters and total nuclear heating in the components of the divertor. The appropriate material compositions are used for the different cells of the model. The material composition used for the divertor cassette is given in Table I. The calculation has been performed using 50,000 source particles yielding statistical uncertainties less than 5% in the calculated nuclear responses at the locations of interest. The results are normalized to the nominal fusion power of 1500 MW. The end of life fluence related radiation effects have been determined for 1 full power year (FPY) of operation corresponding to a fluence of 1 MW·a/m^2.

III. NUCLEAR PARAMETERS IN THE DIVERTOR CASSETTE

The neutronics parameters have been calculated in the different components of the divertor cassette. These parameters included nuclear heating, atomic displacement and helium production. The radiation damage was calculated for the structural material used in each region. The volume averaged parameters were determined for 103 segments of the cassette using cell flux and energy deposition tallies. The peak heating and damage values are given in Table II for each of the cassette zones. The largest heating and damage occurs in the dome PFC which has a full view of the plasma and has the largest neutron wall loading. The power density in the W PFC at the dome is 16.4 W/cm^3. The PFC at the top of the vertical targets experiences relatively high levels of heating and damage. The rest of the vertical targets and wings experience moderate levels of heating and damage with values dropping rapidly as one moves deeper in the cassette body. In general, the nuclear parameters in the inboard side of the cassette are lower than in the outboard side that has a larger view of the plasma. Atomic displacements in Cu are slightly higher than in SS (by ~10% at the front and ~30% at the back) while helium production is much lower (about two-thirds at the front and an order of magnitude lower at the back) because of the higher threshold energy of nuclear reactions producing helium. The nuclear heating map in the cassette is given in Fig. 3 based on the 3-D results. Table III gives the total amount of nuclear heating for each of the zones used in the MCNP calculation. The total nuclear heating has been calculated for the 60 divertor cassettes to be 101.6 MW. The major contributors are the dome, vertical targets, and wings.

Table I
Material composition

Dome PFC	1 cm W
	2 cm 75% Cu, 25% water
	Cu dome body 85% Cu, 15% water
	SS dome body 75% SS, 25% water
Wings	16% W, 79% Cu, 5% water
	packing fraction: 21% outer, 26% inner
Gas Box Liners and Wing Plates	8% W, 74% Cu, 18% water
Vertical Targets	top section:
	1 cm W
	2.5 cm 82% Cu, 18% water
	back region 97% SS, 3% water
	lower section:
	5.5 cm 89% C, 4% Cu, 7% water
	back region 97% SS, 3% water
Cassette Body	80% SS, 20% water
Mechanical Attachments	100% SS
Coolant Pipe Connections	70% SS, 30% water
Rails	100% SS

IV. NUCLEAR PARAMETERS IN VACUUM VESSEL

Streaming through the pumping ducts in the bottom of the cassette can result in damage hot spots in the VV behind it. In the design considered here, the pumping ducts are inclined towards the outer and inner divertor legs such that the VV behind them does not see any direct neutrons from the plasma. This helps cut down the He production which is critical for rewelding. Only low energy secondary neutrons stream through the pumping ducts. The VV results were determined both for toroidal locations away from the ducts and behind the ducts by segmenting the front surface of the VV below the cassette. The results are given in Table IV. A peaking factor of about 2 results from streaming through the ducts. The peak helium production value of about 0.2 He appm/FPY indicates that rewelding of parts of the VV behind the pumping ducts might be feasible. Since these areas of relatively high helium production are very small, the design of the VV can locate the welds away from streaming path if these values are of concern for rewelding.

Table II
Peak nuclear responses in the divertor cassette zones

Zone	Power Density (W/cm^3)	dpa in Structure (dpa/FPY)	He Production in Structure (appm/FPY)
Dome PFC	1.64512E+01	3.50658E+00 Cu	3.14168E+01 Cu
Dome Body	3.96214E+00	2.15013E+00 Cu	1.68394E+01 Cu
Central Body	3.63142E-01	9.74313E-02 SS	2.53758E+00 SS
Outer Wings	3.07969E+00	1.74438E+00 Cu	1.42428E+01 Cu
Inner Wings	2.98566E+00	1.62231E+00 Cu	1.38155E+01 Cu
Outer Leg	5.07270E-01	1.12983E-01 SS	3.66545E+00 SS
Inner Leg	2.75638E-01	4.35025E-02 SS	1.99259E+00 SS
Outer Vertical Target	1.18348E+01	1.93672E+00 Cu	1.32544E+01 Cu
Inner Vertical Target	8.41348E+00	7.79391E-01 Cu	1.88168E+00 Cu
Gas Box Liners	7.78658E-01	2.99092E-01 Cu	1.60511E+00 Cu
Rails	6.71779E-03	2.14094E-03 SS	2.60569E-02 SS

Table III
Total nuclear heating in the 60 divertor cassettes

Zone	Total nuclear heating (MW)
Dome PFC	11.2072
Dome Body	20.1350
Central Body	5.1229
Wings	16.5391
Wing Plates	12.7733
Outer Leg	5.7487
Inner Leg	1.2922
Outer Vertical Target	16.3581
Inner Vertical Target	6.5259
Gas Box Liner	3.8153
Attachments and Coolant Pipe Connections	2.0736
Total	101.5913

Table IV
Peak nuclear responses in the VV behind the divertor cassette

	Power Density (W/cm^3)	dpa (dpa/FPY)	He Production (appm/FPY)
Behind pumping duct	0.027	0.008	0.183
Behind cassette body	0.018	0.003	0.100

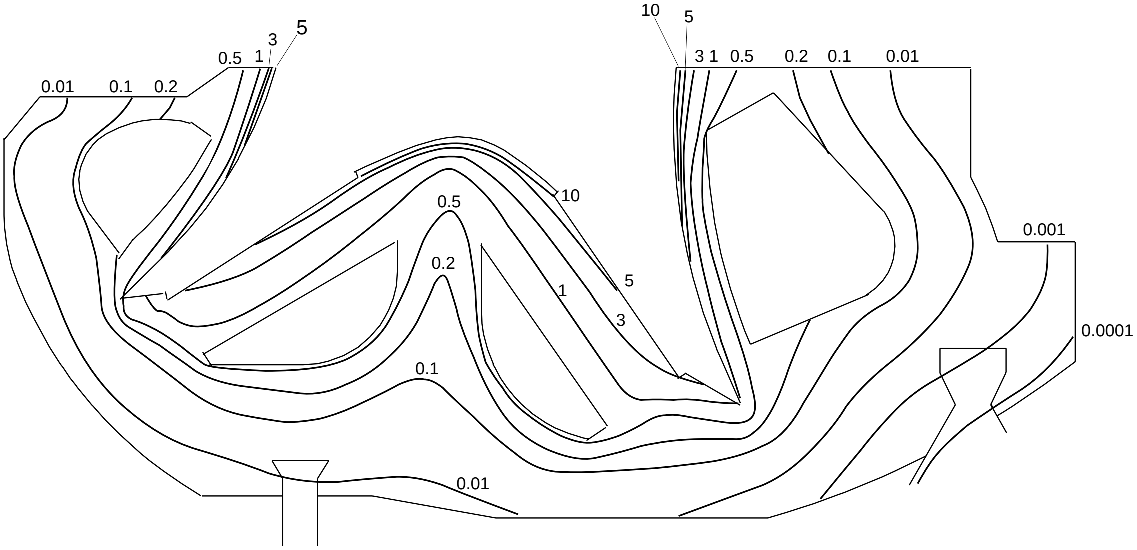

Fig. 3. Nuclear heating (W/cm^3) map in the divertor cassette

V. SUMMARY AND CONCLUSIONS

3-D neutronics and shielding analyses have been performed for the divertor region. A detailed 3-D model has been developed for the divertor region of the ITER Detailed Design. Each divertor cassette was divided into 103 regions to provide detailed spatial distribution of nuclear heating and radiation damage. The layered configurations of the dome PFC and vertical targets were modeled accurately with the front tungsten layer modeled separately. Separate regions are included in the model to represent the mechanical attachments and coolant pipe connections for the dome, vertical targets, and wings. The divertor cassette model was integrated with the general ITER model. Since the blanket design was not fully developed, additional changes in the general model will be included in the future. Since most of the design changes in the blanket are expected to be in the back plate, module attachment and manifolds, the impact will be mainly on shielding and streaming through the large ports and the impact on nuclear parameters in the divertor cassette will be minimal.

The nuclear parameters were provided at the 103 cassette regions used in the model. These parameters included power density, atomic displacement and helium production. The largest heating and damage occurs in the dome PFC which has full view of the plasma. The power density in the W PFC at the dome is 16.4 W/cm^3. The total nuclear heating in the 60 divertor cassettes is 101.6 MW with the major contributors being the dome, vertical targets, and wings. The peak helium production in the VV behind the pumping ducts is 0.2 He appm/FPY implying that rewelding might be feasible.

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