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ITER Generic Diagnostic Upper Port Plug Nuclear Heating and Personnel Dose Rate Assesment Neutronics Analysis using the ATTILA Discrete Ordinates Code

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ITER Generic Diagnostic Upper Port Plug Nuclear Heating and Personnel Dose Rate Assesment

Neutronics Analysis using the ATTILA Discrete Ordinates Code

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Abstract—*Neutronics analysis to find nuclear heating rates and personnel dose rates were conducted in support of the integration of diagnostics in to the ITER Upper Port Plugs. Simplified shielding models of the Visible-Infrared diagnostic and of a large aperture diagnostic were incorporated in to the ITER global CAD model. Results for these systems are representative of typical designs with maximum shielding and a small aperture (Vis-IR) and minimal shielding with a large aperture. The neutronics discrete-ordinates code ATTILA® and SEVERIAN® (the ATTILA parallel processing version) was used. Material properties and the 500 MW D-T volume source were taken from the ITER "Brand Model" MCNP benchmark model. A biased quadrature set equivelant to Sn=32 and a scattering degree of Pn=3 were used along with a 46-neutron and 21-gamma FENDL energy sub-grouping. Total nuclear heating (neutron plug gamma heating) in the upper port plugs ranged between 380 and 350 kW for the Vis-IR and Large Aperture cases. The Large Aperture model exhibited lower total heating but much higher peak volumetric heating on the upper port plug structure. Personnel dose rates are calculated in a three step process involving a neutron-only transport calculation, the generation of activation volume sources at pre-defined time steps and finally gamma transport analyses are run for selected time steps. ANSI-ANS 6.1.1 1977 Flux-to-Dose conversion factors were used. Dose rates were evaluated for 1 full year of 500 MW D-T operation which is comprised of 3000 1800-second pulses. After one year the machine is shut down for maintenance and personnel are permitted to access the diagnostic interspace after 2-weeks if dose rates are below 100 µSv/hr. Dose rates in the Visible-IR diagnostic model after one day of shutdown were 130 µSv/hr but fell below the limit to 90 µSv/hr 2-weeks later. The Large Aperture style shielding model exhibited higher and more persistent dose rates. After 1-day the dose rate was 230 µSv/hr but was still at 120 µSv/hr 4-weeks later.*

I. INTRODUCTION

Most diagnostic systems on ITER are housed inside large equatorial and upper port plug structures. ITER port plugs perform many other important functions besides diagnostic support. The port plugs form the primary vacuum seal with the vessel extensions and the plugs function as important components of the vessel confinement and nuclear shielding. Performance specifications for the nuclear shielding function of the upper port plugs is given in Table 1.

TABLE I. UPPER PORT PLUG NEUTRONICS PARAMETERS

Nuclear Parameters	Requirements
ITER Neutronics Environment[a]	500 MW DT Operation 30,000 400-s pulses .3 MW-a/m2 Accumulated Fluence
Personnel Access to Interspace and Port Cell	Inside Cryostat: 100 µSv/hr ~12 days after shutdown Outside Bio-Shield: 10 µSv/hr ~24 hours after shutdown
TF and PF Coil Protection	Max Local Dose: 10 MGy Fast Neutron Flux: 5E21 n/m2 Total Heating to TF: 14 kW
Re-welding Steel Structures	Re-Welding of field joints and hydraulic piping – He Production Limit < 1 appm for thick plate welding -- He Production Limit<3 appm for thin plate and tube welding
Material Lifetime Nuclear Damage Limits	DPA Effects on 316LN-IG Ductility and other properties, See SDC-IC, Appendix A Peak DPA In First Wall Materials →5.3-1.6 DPA depending on material layer, Ref (1)

a. Ref (2)

A generic upper port plug structure will be used to house the various diagnostic applications. Each integrated port plug design will need a specific detailed neutronics assessment depending on how the generic structures and shielding plugs are modified. One common upper port diagnostic is the Visible-IR Diverter Camera installed in 6 places. The camera optics are housed in a long 360mm diameter tube that penetrates through the shielding plugs and views the diverter through a small aperture in the upper port blanket shield module (BSM). To allow for greater throughput or for large forward components there may also be diagnostics that require very large BSM apertures with minimal forward shielding. A Large Aperture diagnostic case loosely based on an ECH heating system bulk shielding model is used for this case. The Vis-Ir camera and the Large Aperture cases were used to bracket the neutronics; smallest aperture with the most forward shielding and a very large aperture with the least forward shielding. Figure 1 illustrates the two neutronics CAD models.

A modified version of the "Brand" ITER global neutronics CAD model was used for the generic upper port plug analysis. The latest "A-lite" global model was not available at the time this analysis was started. Computational resource limits required the use of an abbreviated 20-degree sector global model rather than the full 40-degree convention. Symmetry was used to reduce the model to a 20-degree sector with a reflecting boundary condition on the central cut-plane. Further modifications include the omission of most OH and PF coils, most of the bio-shield and the equatorial and lower vessel ports. The global model used for the Vis/IR and Large Aperture analysis is also shown in Figure 1. Solidworks CAD software was used for all modeling and the models are exported to ATTILA in Parasolid (.x_t) format. A uniform 20-mm installation gap between the vacuum vessel extension and the port plug was used to capture streaming effects on the interspace dose rate.

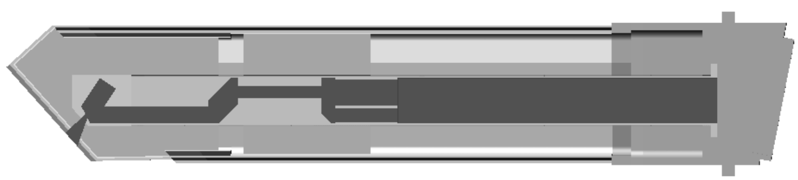
Material models and the plasma volume source model were taken from the “Brand” model definitions. See Ref (4) and Ref (5). Additional 80%-20% and 90%-10% Steel-Water mixtures were added for parametric shielding studies. The FENDL-2.1 fusion data library was used and further condensed into 46 neutron and 21 gamma energy groups. Generation of activation sources for personnel dose rate calculations in ATTILA require the use of special “un-grouped” neutron only libraries. Transpire generated 29 and 46 group neutron only FENDL sub-libraries for this purpose.

New to the upper port neutronics analysis is the use a biased quadrature set that favors the global x-axis and a mesh rotation that aligns the upper port plug with the x-axis. The biased quadrature set is equivalent to Sn=32 and helped with the resolution of streaming neutrons along the upper port installation gaps and piping. A scattering order of Pn=3 was used for all calculations.

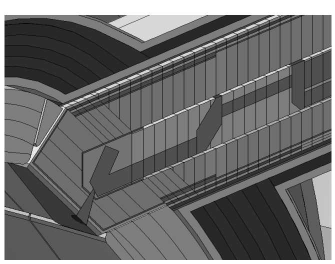
The implementation of ATTILA for finding the structural nuclear heating rates and for finding the dose to personnel is somewhat different. Nuclear heating from neutrons and prompt gammas involves one combined ATTILA transport calculation and then a secondary post-processing step. Dose rate calculations are a multi step process. First a neutron only transport calculation is conducted. A time stepping scenario is then implemented for a second ATTILA run where activation sources are generated at user specified intervals. Each activation volume source is then used to run gamma-only transport calculations. Finally flux-dose conversion factors are applied in post-processing runs to find the personnel doses. ANSI/ANS-6.1.1-1977 factors were used.

ATTILA is a static code but a time stepping scenario is needed for the generation of activation sources. The dose rate analysis is quasi-static in that ATTILA assumes the neutron flux at any given time step is constant. Diagnostic upper port plug dose rates were determined for 1-year of 500 MW D-T operation. There are 3000 pulses per year and each pulse is “on” for 400 seconds and “off” for 1800 seconds. For computational efficiency and to capture effects of short lived isotopes the “dose rate analysis year” was further divided in to two parts. There is an initial single long pulse equivalent to the 2,842 pulses that occur in the first 49 weeks of the year. During this first segment the pulse is on for 13.16 days (2,842 pulses *400 seconds) and off for 8.46 weeks when the pulse are lumped together. Discrete pulses are used for the remaining 3 weeks of the analysis year. Since there are 58 pulses per week there are 174 discrete analysis pulses which translates in to 348 ATTILA time steps (1 step for the “on” portion and one step for the “off” portion). The On-Off periods have also been reversed to be more conservative.

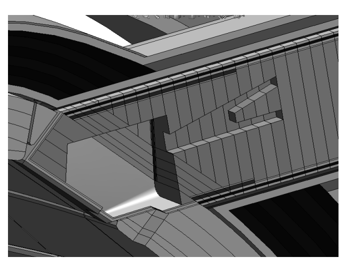
“Severian” is the distributed memory parallel implementation of ATTILA. All neutron and gamma transport problems were run using Severian which greatly reduces run time over the serial memory version of ATTILA. Analysis that ran for 10 days using ATTILA SMP ran for only ~1.5 days on ATTILA Severian. Severian was run on the KITE cluster at Princeton Plasma Physics. The kite cluster is a parallel computing cluster comprised of 48 AMD Opteron processors (2.4Ghz). There is a total of 144GB of memory, and 1.9TB of



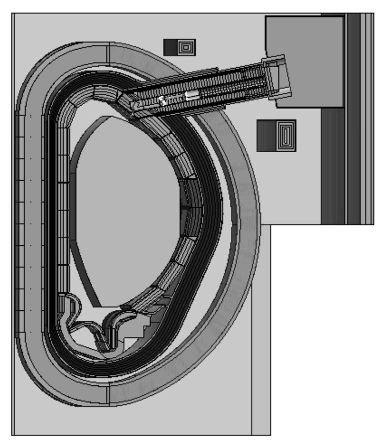
Vis/IR Camera Upper Port Plug CAD Model



Vis/IR Aperture and Forward Shielding



Large Aperture and Forward Shielding



Modified ITER Global Model

***Figure 1:** A 20-degree truncated global ITER CAD model (based on the ITER “Brand” benchmark model) was used in the Upper Port Plug neutronics analysis. Two variations in internal plug shielding were used to find best and worst case heating and dose rate levels. The Visible-IR camera design has the most front end shielding and smallest aperture while the Large Aperture Diagnostic style shielding has a very large aperture and much less forward shielding.*

disk space. Each system is connected to a gigabit Ethernet switch for file system access. Each system also has a 10Gb Infiniband connection used by parallel codes to communicate data via the MPI calling interface.

II. Nuclear Heating Results

One of the main goals of this study was to evaluate nuclear heating in the generic components of the diagnostic upper port plug structure. Two examples of integrated systems were used to model the internal shielding components of the port plug. The Visible/IR diagnostic has the smallest aperture and the most forward shielding mass. The Large Aperture system has the largest aperture and the least amount of forward shielding mass. A third configuration studied is the Vis/IR system with the plug blanket shield removed. Adjacent machine mounted BSM are extended over forming a 10 cm gap. Heating results for the Vis/IR Camera and Large Aperture system were evaluated using 70-30 and 80-20 steel-water ratio mixes in the shielding plugs. Table 2 summarizes heating results for the major model components.

Case A exhibits the highest total nuclear heating of 382 kW because it contains the largest volume of heated mass near the plasma. Case B or the case where the BSM is removed exhibits the lowest total heating because the plasma facing layers and the first 100 mm of the forward shielding plug are removed. The Large Aperture mock-up model has high local heating on the inner walls of the BSM shell and flange and front of the port plug structure. For the 70-30 versus 80-20 cases the larger water content softens the neutron energy leading to higher (n,gamma) absorption reactions in steel and subsequently higher heating rates.

TABLE II. UPPER PORT PLUG NUCLEAR HEATING

`	**Vis-IR 70-30**	**Vis-IR 80-20**	**Vis-IR No BSM**	**L.A. 70-30**	**L.A. 80-20**
Total (kW)	382	373	176	354	337
BSM Face and Shell					
Total (kW)	152	150	N/A	142	141
Max n (W/cm^3)	1.4	1.4		1.4	1.4
Max g (W/cm^3)	3.5	3.5		3.2	3.2
BSM Flange Layers					
Total (kW)	**1.8**	1.8	3.4	**27**	25
Max n (W/cm^3)	.01	.01	.02	.15	.16
Max g (W/cm^3)	.07	.07	.16	.81	.76
Forward Shielding Module					
Total (kW)	211	205	145	166	154
Max n (W/cm^3)	.61	.52	.38	.53	.542
Max g (W/cm^3)	2.34	2.4	1.6	2.2	1.94
Main Body Structure					
Total (kW)	.62	.59	.89	19	18
Max n (W/cm^3)	.001	.0004	.002	.1	.11
Max g (W/cm^3)	.009	.008	.02	.6	.54
Vis/IR Tube and Shielding					
Total (kW)	16.3	15.9	27.7	N/A	N/A
Max n (W/cm^3)	.05	.05	.1		
Max g (W/cm^3)	.3	.3	.54		

III. Interspace Personnel Dose Rates

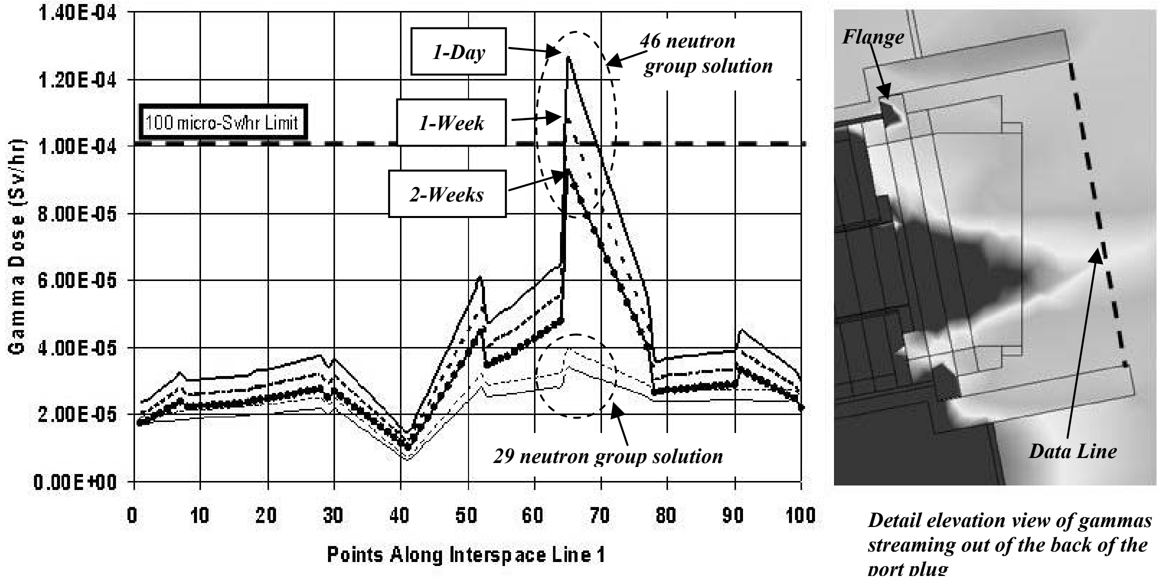
ATTILA handles the calculation of dose rates in a three part process. There is a neutron transport step, the generation of an activation gamma source and then a gamma transport calculation. The neutron transport calculations were performed with a very coarse 29-neutron group library and separately with a 46-neutron group library. All of the gamma transport analysis were run with the full 46 FENDL gamma group library.

Personnel dose rates for the Visible-Infrared Upper Port Plug are shown in Figure 2. Dose rates are calculated at points along a line running down the back of the port plug where a maintenance person would stand. ANSI-ANS-6.1.1 1977 flux to dose conversion factors are used. Personnel are allowed access to this location if dose rates fall below 100 micro-Sieverts per hour 2 weeks after machine shutdown. In the case of the Visible-Infrared camera dose rate levels peak near 140 micro-Sieverts per hour but fall below the ITER allowable after 2 weeks. Figure 2 also shows a contour plot of the gamma flux out the back of the upper port plug. There is a distinct plume correspondent with the output of the camera optics shielding labyrinth.

Figure 3 illustrates the personnel dose rates in the interspace for the Large Aperture mock-up case. The Large Aperture case dose levels peak near 250 micro-Sieverts per hour but do not drop below the 100 micro-Sievert per hour limit even after 4 weeks of cool down time. It is important to note that his result could be easily lowered by adding more layers of shielding material in the secondary shielding plug. The authors did not have the opportunity to reconstruct and re-mesh the CAD model in this way. There could also be optical or waveguide components in the Large Aperture design that would also enhance shielding to the diagnostic interspace.

There was a major improvement in the dose rate results for the Visible-IR model when 46 neutron groups were used rather than 29 groups. Greater refinement in the neutron energy groups lead to a more accurate neutron transport solution. Subsequently this lead to greater fidelity in the activation gamma volume sources. In Figure 2 you can see this improvement. Dose rates were greatly under-predicted for the 29 neutron group calculations. The deployment of ATTILA Severian on the PPPL KITE cluster allowed for the use of more neutron groups. Future studies will include the assessment of the solution if all 175 FENDL neutron groups are used.

ATTILA allows for the selection of regions to be included in the activation source generation. A study was conducted in which only the components of the upper port plug were "burned". Dose rate results showed that almost 90% of the gamma flux comes from the highly activated in-vessel components like the surrounding blanket shields and the diverter. The components of the upper port plug do become activated but it is important to include all the structures that the port-based diagnostic views to get an accurate activation gamma ray flux.



Detail elevation view of gammas streaming out of the back of the port plug

Figure 2: Personnel dose rates for the Visible-IR camera model from gamma rays are shown plotted along a vertical line at the back end of the port plug. The contour plot on the right shows activation gamma rays streaming out the back of the Visible-IR camera flange. Dose rate levels are below the acceptable level 2 weeks after shutdown. 29 neutron group calculations were inaccurate due to problems with the neutron trasnport portion of the calculation.

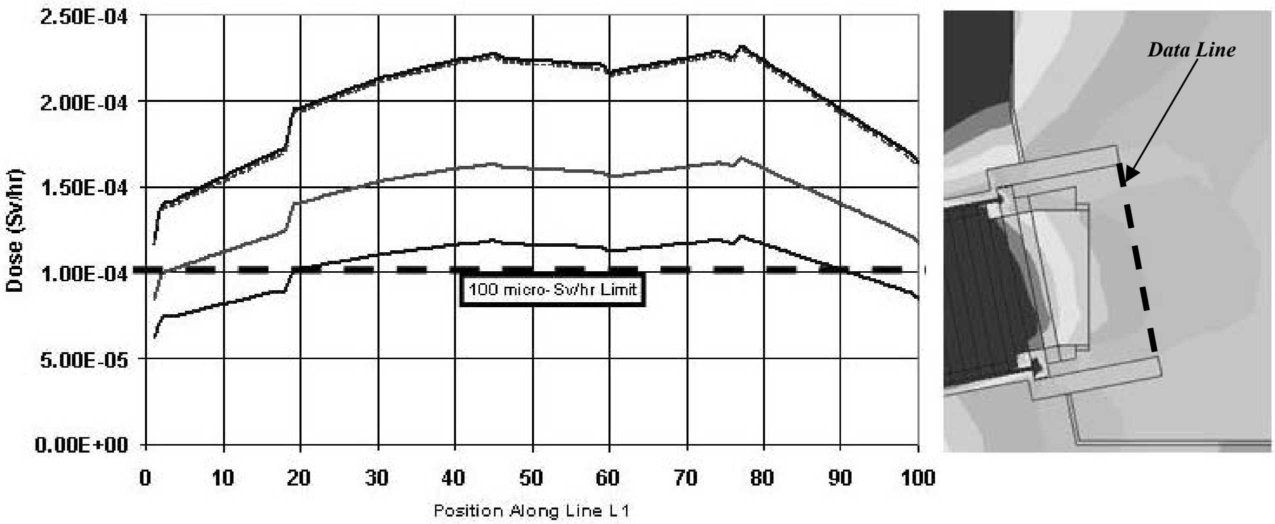


Figure 3: Personnel dose rates for the Large Aperture style shielding model from gamma rays are shown plotted along a vertical line at the back end of the port plug. The contour plot on the right shows activation gamma rays streaming out the back of the port plug. Dose rate levels for this shielding model were above the allowable limits even 4-weeks after shutdown but there are simple ways to improve this result.

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