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# Initial Nuclear Performance Evaluation of the FIRE Ignition Device

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**Abstract**-Nuclear parameters for the FIRE ignition device have been determined. These parameters included nuclear heating, radiation damage, and magnet insulator dose. Nuclear heating values as high as  $\sim 40 \text{ W/cm}^3$  are deposited in the in-vessel components. End-of-life damage is very low and will not limit the lifetime of the chamber components. The peak end-of-life insulator dose is  $1.5 \times 10^{10}$  Rads. The total nuclear heating in the 16 TF coils was estimated to be 27 MW.

## INTRODUCTION

The possibility of constructing a low cost (<\$1B) Fusion Ignition Research Experiment (FIRE) as Next Step Option (NSO) to address the burning plasma issues is being explored [1]. FIRE is a compact high field tokamak that utilizes cryogenically cooled copper coils. It has a major radius of 2 m, an aspect ratio of 3.8, and an average neutron wall loading of  $3 \text{ MW/m}^2$ . The device is expected to achieve a high fusion power gain,  $Q$ , of 10. A double walled vacuum vessel (VV) with integral shielding has been adopted. The VV thickness varies poloidally from 5 cm in the inboard (IB) region to 57 cm in the outboard (OB) region at midplane. The plasma facing components (PFC) inside the VV include a Be coated Cu first wall (FW) in the IB and OB regions and divertor plates made of tungsten rods mounted on water cooled Cu backing plates in the top and bottom regions. A cross sectional view of the FIRE tokamak is given in Fig. 1. Neutronics calculations have been performed at different poloidal locations to determine the nuclear performance parameters for the FIRE components. The results of the calculations are presented in this paper.

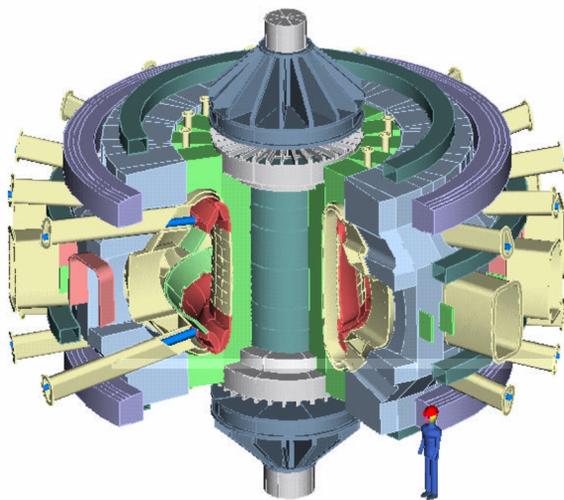


Fig. 1. Cross sectional view of the FIRE tokamak

## CALCULATION APPROACH

Neutronics and shielding analysis has been performed for the device configuration and radial build [1]. The average neutron wall loading is  $3 \text{ MW/m}^2$ . The poloidal distribution of neutron wall loading was scaled using the 3-D results for ITER [2]. Calculations were performed at the midplane for both the IB and OB regions. Calculations were also carried out at 60 cm above midplane in the IB region and at 90 cm above midplane in the OB region to give an indication of the

poloidal variation of the nuclear parameters. In addition, calculations were performed for the divertor region at the top and bottom of the machine. At each of these locations, the appropriate radial build was used along with the corresponding neutron wall loading. Table 1 lists the parameters used at these locations. The neutronics and shielding calculations were performed using the ONEDANT module of the DANTSYS 3.0 [3] discrete ordinates particle transport code system along with nuclear data based on the FENDL [4] evaluation.

316SS is used for the vacuum vessel (VV) structure. It is assumed that the space between the 1.5 cm thick front and rear VV facesheets (VV shield) includes 60% 304SS and 40% water except in the IB region where 10% 304SS and 90% water is used because of the small thickness (2 cm). The Cu TF coils are included in the model with Cu at 90% packing. A 316SS coil case is used in the OB region with 4 cm front thickness and 6 cm back thickness. The PFC/FW in the IB and OB regions is assumed to have a 0.5 cm Be layer followed by a 2 cm thick Cu layer with 5% void and 2.5 cm thick Cu layer with 40% void. The radial build for the divertor is assumed to be 0.5 cm W PFC, 2.5 cm heat sink (80% Cu, 20% water), and 17 cm structure (80% SS, 20% water). Figure 2 is a cross section showing the FIRE components.

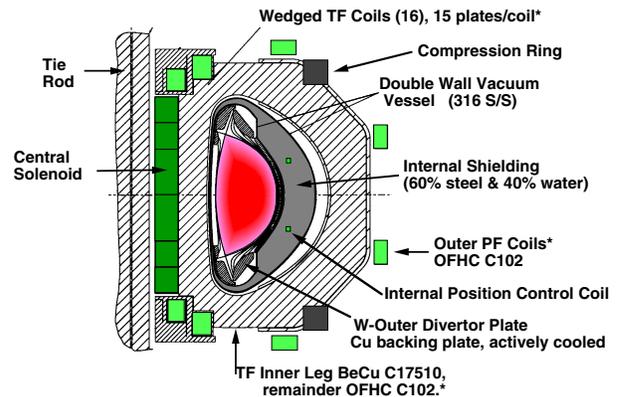


Fig. 2. FIRE components

Table 1. Neutron wall loading and VV thickness used at different poloidal locations

	Total VV thickness (cm)	Neutron wall loading ( $\text{MW/m}^2$ )
IB midplane	5	2.7
IB Z= 60 cm	5	2.4
OB midplane	57	3.6
OB Z= 90 cm	45	2.7
Divertor	12	1.8

## NUCLEAR HEATING

Nuclear heating deposited in the different components during the DT pulses was determined and used in the thermal analysis. Table 2 gives the nuclear heating values in the FW and VV. The largest power density values in the PFC/FW occur in the OB region at midplane due to the largest wall loading. The power density in the rear VV sheet peaks in the

IB region at midplane with the minimum being in the OB region at midplane due to the increased VV shield thickness. Figure 3 shows the radial variation of nuclear heating in the OB VV at midplane. Nuclear heating drops by an order of magnitude in ~18 cm of VV.

Table 3 gives the magnet nuclear heating. The largest magnet power density occurs in the IB region at midplane with the minimum being in the OB region at midplane due to the 52 cm thicker VV. Magnet nuclear heating in the OB region at 90 cm above midplane is about a factor of 3 higher than that at midplane because of the combined effect of the 12 cm thinner VV and the 25% lower wall loading. Figure 4 shows the radial variation of nuclear heating in the OB

magnet. It drops by an order of magnitude in ~20 cm. Nuclear heating in the IB magnet drops by an order of magnitude in ~22 cm. The smaller radial attenuation in the IB magnet is due to the toroidal geometrical effects.

Table 4 lists the nuclear heating values in the different components at the top and bottom of the machine. Relatively high nuclear heating is deposited in the W PFC. The total nuclear heating in the 16 TF coils was estimated, based on the results of the 1-D calculations, to be 26.86 MW. The variation of neutron wall loading and shielding thickness was taken into account. The lightly shielded IB legs' contribution is 26 MW while the divertor and OB regions contribute only 0.8 and 0.06 MW, respectively.

Table 2. Nuclear heating ( $W/cm^3$ ) in the FW and VV at different poloidal locations

	Be PFC	Cu FW	Plasma-side VV facesheet	Average in VV shield	Coil-side VV facesheet
IB midplane	32.2	37.7	33.5	16.8	28.7
IB Z= 60 cm	28.6	33.5	29.8	14.9	25.5
OB midplane	37.4	43.3	32.4	5.1	0.046
OB Z= 90 cm	28.1	32.5	24.3	4.5	0.151

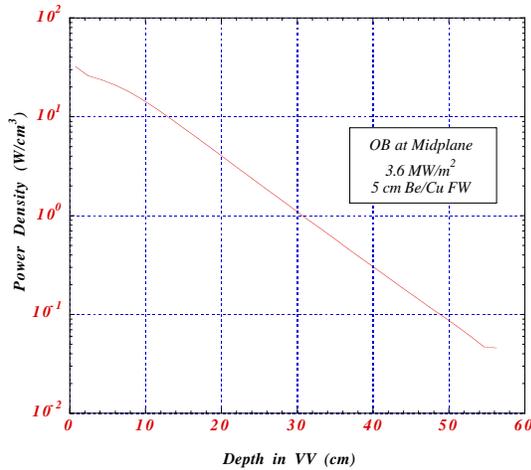


Fig. 3. Radial variation of VV nuclear heating

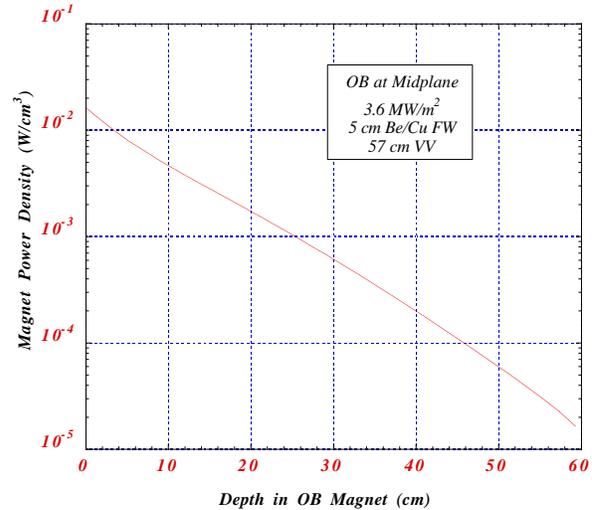


Fig. 4. Radial variation of magnet nuclear heating

Table 3. Magnet nuclear heating ( $W/cm^3$ )

	Peak in coil case	Peak in magnet	Average in magnet
IB midplane	NA	20.3	4.22
IB Z= 60 cm	NA	18.0	3.75
OB midplane	0.012	0.014	0.002
OB Z= 90 cm	0.105	0.044	0.005

Table 4. Nuclear heating at top and bottom of machine

	Nuclear heating ( $W/cm^3$ )
W divertor PFC	45.6
Cu divertor heat sink	17.9
SS divertor structure	14.1
SS VV front sheet	2.8
SS VV back sheet	0.9
Magnet	0.6

## RADIATION DAMAGE

The peak radiation damage rates were calculated for the FW, VV, divertor, and magnet. Atomic displacement (dpa) and He production rates were determined. As for nuclear heating, the largest damage values in the FW and VV front sheet occur in the OB region at midplane with the lowest values being at the top and bottom. The damage in the magnet peaks in the IB region at midplane with the minimum being in the OB region at midplane due to the increased VV shield thickness. For the operation scenario of 3000 DT pulses with 10 s width, the peak cumulative end-of-life dpa and helium production values in the different components were determined. The results are given in Table 5. These values are low and will not limit the lifetime of these components. The peak end-of-life helium production in the VV is lower than the 1 appm limit for rewelding, implying that reweldability of the VV should not be a concern.

Another issue of concern is the amount of tritium production in the Be PFC. The poloidal variation of tritium production in the Be PFC was determined and the total end-of-life tritium production was estimated to be ~ 0.022 g (220

Ci). This is a very small amount and does not pose any safety problem.

Table 5. Peak cumulative dpa and helium production in the different components

	dpa	He appm
Be PFC	0.017	1.35
Cu FW	0.034	0.32
W Divertor PFC	0.005	0.003
Divertor Heat Sink	0.014	0.137
Divertor Structure	0.009	0.102
SS VV	0.017	0.17
SS Coil Case	0.00003	0.00022
Cu Magnet	0.0076	0.041

### INSULATOR DOSE

The dose rate to the insulator in the TF magnet was calculated at different poloidal locations. The dose rate was determined at the front layer of the magnet winding pack. Because of the minimal shielding provided by the thin VV in the IB region, the peak value occurs in the IB side at midplane. The dose rate decreases as one moves poloidally from the IB midplane to the OB midplane. The neutron contribution to the insulator dose varies between 50% at the front of the winding pack to 30% at the back. For 3000 DT pulses with 10 s width the peak end-of-life insulator dose is  $1.44 \times 10^{10}$  Rads in the IB region at midplane. This value drops to  $3.9 \times 10^8$  Rads in the divertor region and  $1.03 \times 10^7$  Rads in the OB region at midplane. The impact of VV thickness on the peak magnet nuclear heating and insulator dose is illustrated in Fig. 5. 18 cm of VV thickness provides an order of magnitude reduction in magnet radiation effects.

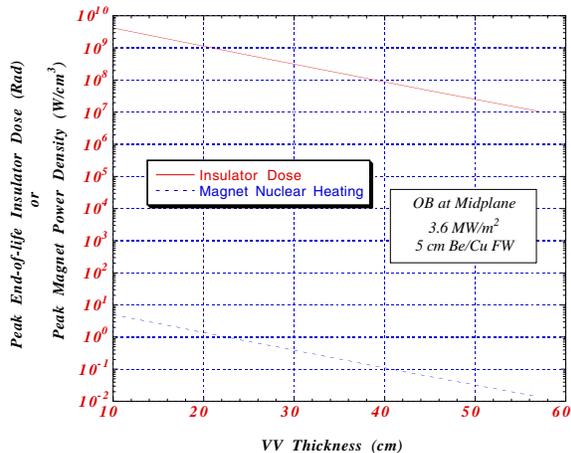


Fig. 5. Impact of VV thickness on magnet heating and insulator dose

The mechanical strength, dielectric strength, and electric resistivity are the important properties that could be affected by irradiation. Experimental results indicate that the electrical properties are not degraded as much as the mechanical properties. The shear strength is the property most sensitive to irradiation. The commonly accepted dose limit for epoxies is  $10^9$  Rads. This is the limit used in ITER [2]. Polyimides and bismaleimides are more radiation resistant with experimental data showing only a small degradation in shear strength at dose levels in excess of  $10^{10}$  Rads. However, they are difficult to process due to their high viscosity and require high temperatures to fully cure. Hybrids of polyimides or bismaleimides and epoxies could provide radiation resistant insulators with more friendly processing requirements [5].

One should keep in mind that the results presented here were obtained by performing 1-D calculations. Based on previous studies, accurate modeling of the chamber geometry and source profile in a 3-D calculation results in about 20% lower peak IB results [6]. In addition, in the FIRE design, the peak shear stresses occur at the top and bottom of the IB leg behind the divertor [1]. The end-of-life dose to the insulator at this location is reduced to  $\sim 4 \times 10^8$  Rads due to the additional shielding provided by the divertor. The insulator dose decreases as one moves radially from the front to the back of the winding pack, as shown in Fig. 6. The dose decreases by an order of magnitude in  $\sim 22$  cm of the IB magnet. Based on the analysis performed so far, it is expected that the magnet insulator will last for the whole device lifetime.

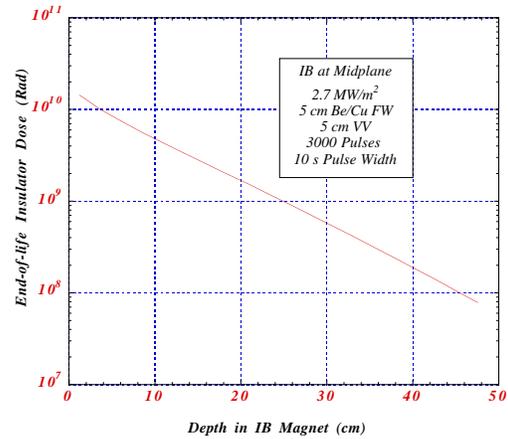


Fig. 6. Radial variation of insulator dose in the IB magnet

### NEUTRONICS FOR THE DD PULSES

30000 DD shots are expected in the initial phase of the machine operation. Assuming that the density and temperature will be the same as in the DT pulses, the fusion power during these DD shots is 1 MW compared to 200 MW for the DT pulses. The tritium produced in the DD reactions is assumed to be removed from the plasma. Hence, no 14 MeV neutrons are produced in the DD shots. The neutron production rate (2.45 MeV neutrons) during the DD pulses is a factor of 0.012 of that for the DT pulses (14.1 MeV neutrons). The neutron wall loading during the DD pulses is a factor of 0.0021 of that for the DT pulses. The pulse length is assumed to be 10 s in both cases.

Nuclear heating during the DD shots is more than an order of magnitude lower than for the DT pulses. The 30000 DD shots contribute 4-10% of the peak end-of-life cumulative dpa. The dpa values are still very small and will not limit the lifetime of the components. The contribution from DD shots to the end-of-life helium production is negligible because of the high threshold energy for the helium production reactions. No tritium is produced in the Be PFC during the DD shots since DD neutrons are below the 11.8 MeV threshold energy for tritium production.

Table 6 gives the peak end-of-life dose to the TF magnet insulator in the IB, divertor and OB regions including the contribution from the DD shots. The relative contribution from the DD shots to the insulator dose at the front of the winding pack decreases as one moves poloidally from the IB midplane to the OB midplane due to the increased attenuation of the DD neutrons compared to the attenuation of the high energy DT neutrons. The DD shots contribute 6% to the total end-of-life peak insulator dose in the IB region. The

contribution reduces to 3% and 0.7% in the divertor and OB regions, respectively. The peak end-of-life insulator dose in the TF coils increases from  $1.44 \times 10^{10}$  Rads to  $1.53 \times 10^{10}$  Rads when the contribution from the DD shots is added. This small increase does not change the conclusion that it is expected that the magnet insulator will last for the whole device lifetime.

### SUMMARY

Nuclear heating and damage profiles were determined in the different components of FIRE. The largest nuclear parameters in the PFC and VV occur in the OB region at midplane due to the largest wall loading. Nuclear heating values as high as  $\sim 40 \text{ W/cm}^3$  are deposited in the in-vessel components. End-of-life damage (based on 30000 DD and 3000 DT pulses each with 10 s width) is very low and will not limit the lifetime of the chamber components. The peak end-of-life helium production in the VV is 0.17 appm implying that reweldability of the VV should not be a concern. About 220 Ci of tritium is produced in the Be PFC on the FW over the machine life. The total nuclear heating in the 16 TF coils

during a DT pulse was estimated to be 27 MW. Nuclear heating and damage rate values during the DD shots are less than  $\sim 1\%$  of those during the DT pulses. On the other hand, the DD shots contribute  $\sim 6\%$  of the end-of-life cumulative damage. Magnet heating and damage peak in the IB region at midplane and decrease as one moves poloidally to the OB midplane due to increased shielding by the VV. The impact of VV thickness on magnet heating and insulator dose was assessed. 18 cm of VV thickness provides an order of magnitude reduction in magnet radiation effects. The magnet insulator dose at the front surface of the magnet peaks in the IB side. The peak end-of-life insulator dose is  $\sim 1.5 \times 10^{10}$  Rads with about 50% contributed by neutrons and 50% contributed by gamma rays. With the present machine configuration, insulators that have radiation tolerance up to that dose level should be used.

### ACKNOWLEDGMENT

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Table 6. Total peak end-of-life insulator dose

	Peak End-of-life Insulator Dose (Rads)			
	DT	DD	Total	% from DD Shots
IB Midplane	$1.44 \times 10^{10}$	$9.17 \times 10^8$	$1.53 \times 10^{10}$	6.0%
Divertor	$3.90 \times 10^8$	$1.22 \times 10^7$	$4.02 \times 10^8$	3.0%
OB Midplane	$1.03 \times 10^7$	$7.17 \times 10^4$	$1.04 \times 10^7$	0.7%

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