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L.A. El-Guebaly

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Laila A. El-Guebaly
Fusion Technology Institute
University of Wisconsin
1500 Johnson Drive, Madison, WI 53706-1687

Abstract

Optimization studies were performed to design an efficient shield to protect the toroidal field (TF) magnets of the International Thermonuclear Experimental Reactor (ITER). Several options for the shield design were examined and many shielding materials have been evaluated. The pure SS/H_2O shield does not satisfy the magnet radiation limits. When boron carbide, lead, or boron steel is incorporated in the shield, all design limits are met. The highest damage occurs at the midplane of the inner legs and at the top/bottom parts of the magnets due to the limited space for the shield. The safety factors associated with the different magnet responses were quantified. These factors account for the increase in damage due to the presence of the assembly gaps between the shield modules and the uncertainties in data, codes, and modeling.

Introduction

We present here design options for the shield taken from work performed at the University of Wisconsin in support of the U.S. effort for the nuclear-related work for the ITER study. ITER [1] is an experimental tokamak reactor designed to accommodate two phases of operation. During the 15 year life of the machine, ~3 full power years (FPY) of operation are expected: 0.05 FPY in the physics phase and 3 FPY in the technology phase. The overall dimensions of the magnets are fixed and the two phases differ mainly in the size of the plasma and shield. The main function of the shield is to protect the toroidal field (TF) magnets. The highest radiation damage in the magnets occurs at the inboard midplane where the space available for the first wall/blanket/shield/vacuum vessel is constrained to 75 and 85 cm in the physics and technology phases, respectively. Other high damage regions exist at the top/bottom parts of the TF magnets due to the limited shielding space behind the outer end of the divertor plates. A vertical cut showing the different components of the reactor is given in Fig. 1.

Several options for the shield were examined. They were designed under a common set of design guidelines. For instance, the peak neutron wall loadings on the inboard and outboard sides are 1.04 and 1.43 MW/m^2 in the physics phase and 1.13 and 1.59 MW/m^2 in the technology phase, respectively. The first wall is an integral part of the shield and is composed of 2 cm C tiles followed by 1.6 cm water cooled SS layers. The U.S. design of the vacuum vessel (V.V.) is 10 cm thick and consists of 1 cm SS outer plates connected by thin SS ribs. The winding pack contains 38 v/o SS, 20 v/o Cu, 3 v/o Nb_3Sn, 5 v/o bronze, 1 v/o V, 20 v/o He, and 13 v/o boron-free glass-fiber-filled epoxy. The magnet radiation tolerance in both physics and technology phases is summarized in Table 1.

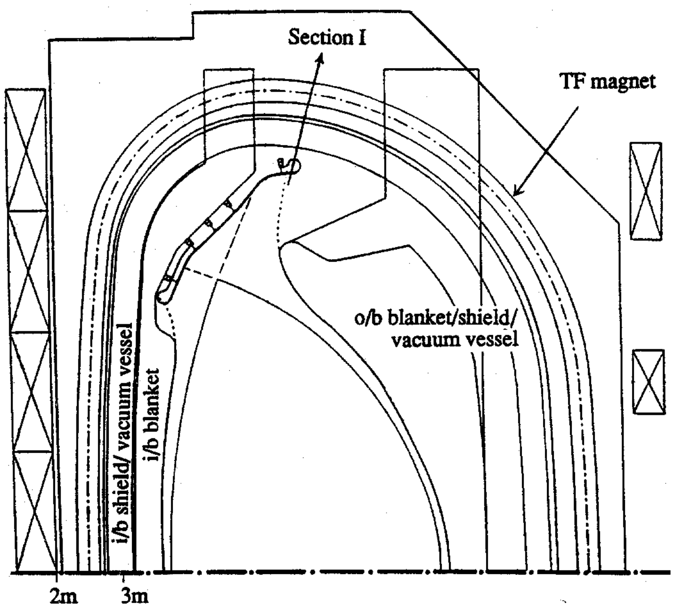

Fig. 1. Cross section through ITER.

Shield Optimization

An extensive optimization study was carried out for both physics and technology phases. The shield is designed to minimize the most crucial radiation effects in the magnet which are the total nuclear heating and the end-of-life dose to the insulator in the physics and technology phases, respectively.

The neutronics analysis was performed using the one-dimensional code ONEDANT [2] and the cross section library is based on the ENDF/B-V evaluation. The 46 neutron and 21 gamma energy group structure and the P_3-S_8 approximation were used. The different reactor components were modeled as infinite cylinders around the machine axis, permitting the representation of both inboard (i/b) and outboard (o/b) sides. The neutron source was taken to be uniform over half of the plasma width.

Table 1. Radiation Limits for TF Magnets and Vacuum Vessel

PHASE	PHYSICS	TECHNOLOGY
Flux Dependent Criteria		
Total nuclear heating (kW)	50	20
Peak nuclear heating in winding pack (mW/cm^3)	5	2
Fluence Dependent Criteria		
Peak dose to insulator (rads)		5x 10^9
Peak fast neutron fluence to Nb_3Sn (n/cm^2)		10^{19}
Peak dpa in Cu stabilizer (dpa)		6 x 10^{-3}
He production in V.V. (appm)		1

Inboard Shield

The shielding capability of several materials was assessed. Besides 316 SS and H_2O, these materials include B_4C, Pb, boron steel (B-SS), and borated water (B-H_2O). The boron in all boron compounds is enriched to 90% ^{10}B and the boron content in the B-SS is taken as 3 w/o. An optimum coolant content, B_4C/Pb layer thickness, and coolant channel arrangement were obtained. In addition, we analyzed in detail two options for locating the B_4C/Pb layer with respect to the V.V. In the first option, all shielding materials are placed within the shield box inside the V.V. (at the plasma side). In the second option, the B_4C/Pb layer is placed outside the V.V. (at the magnet side).

In the physics phase, the front 12 cm of the shield was configured in five alternating layers of SS and H_2O to warrant a proper cooling of this high heat load zone. In the technology phase, there is ~22 cm thick aqueous salt blanket [3] in front of the shield. Therefore, ~50 cm thick region is left to be optimized with respect to material composition and coolant content. Several options for the shield were examined. They are presented in Tables 2 and 3. As shown later, the integrated quantities (such as total nuclear heating) and the local values (e.g. dose, fluence, dpa) should be multiplied by safety factors of 2 and 3, respectively, before comparison to the design limits. The low level of He production in the steel indicates that the V.V. is well protected. The first two options are for pure SS/H_2O shield with gas or water-filled V.V. The gas-filled V.V. results in an excessive dose to the insulator and heat load to the magnet. Even when B_4C, Pb or B-SS was included in the shield the damage level at the magnet was unacceptable. When the V.V. is filled with water (option 2), the dose to the insulator is still higher than the limit. Therefore, other materials should be incorporated in the shield. It was found that a B_4C layer backed by a Pb layer is more effective in reducing the damage than using either one separately. In option 3, the B_4C/Pb layer is placed inside the V.V. This option has the advantage of simplifying the mechanical design of the V.V. by mounting the shielding materials on one side only of the V.V. A lower damage is obtained when the B_4C/Pb layer is placed outside the V.V. (option 4). No significant reduction in the damage is obtained when the borated water is used in the SS/B_4C/Pb shield (option 5). The borated water is more effective when used to fill the V.V. However, this raised some concerns because the use of borated water increases the possibility of "stress-corrosion-cracking" of the V.V. Option 7 shows a significant reduction in damage when B-SS is introduced in the shield. The additional reduction in damage obtained through the use of B_4C/Pb or B-H_2O with B-SS is marginal as shown in the last two cases.

An ideal combination from the neutronics viewpoint would be to use B-SS, B_4C and Pb in the shield and B-H_2O in the V.V. However, this proposal would complicate the shield design due to the requirement for two cooling circuits and the need for mounting the B_4C/Pb layer on the outside of the V.V. A recommended design which offers a good compromise between the design simplicity and the shielding requirements is that of option 7.

An attempt was made to match the neutronics and engineering requirements for the shield. The B-SS/H_2O shield was modeled so far in the calculations as a homogeneous mixture of B-SS and H_2O with a 316 SS support structure of 10% by volume. It is preferable from the mechanical point of view to layer the shield into separate coolant channels and B-SS zones. The location and width of the channels are based on the nuclear heat deposition within the shield, the optimum content of the coolant, and the thermal stress limitations imposed on the size of the steel layers. The optimum configuration from the neutronics point of view that complies with the thermal hydraulic requirements was found to consist of 5 coolant channels [4]. The

Table 2. Radiation Effects at Inner Legs of TF Magnets in Physics Phase

Option	1	2	3	4	5	6	7	8	9
Shield Type	SS/H_2O	SS/H_2O	SS/B_4C/Pb/H_2O	SS/B_4C/Pb/H_2O	SS/B_4C/Pb/B-H_2O	SS/B_4C/Pb/B-H_2O	B-SS/H_2O	B-SS/B_4C/Pb/H_2O	B-SS/H_2O
V.V. filling material	--	H_2O	H_2O	H_2O	H_2O	B-H_2O	H_2O	H_2O	B-H_2O
B_4C/Pb outside V.V.	--	--	--	4 cm Pb 2 cm B_4C	3.5 cm Pb 1 cm B_4C	3.5 cm Pb 1 cm B_4C	--	1 cm Pb 1 cm B_4C	--
B_4C/Pb inside V.V.	--	--	2 cm Pb 1 cm B_4C	--	--	--	--	--	--
Optimum H_2O in SS shield (v/o)	25	20	17	15	15	10	13	10	13
Peak nuclear heating (mW/cm^3):									
Winding Pack	2.28	1.14	0.87	0.55	0.54	0.47	0.38	0.26	0.26
Coil Case	5.80	5.34	3.69	1.09	1.07	0.81	1.63	0.77	0.69
Nuclear Heating(kW/m):									
Winding Pack	4.05	1.48	1.25	1.15	1.10	0.99	0.57	0.47	0.32
Coil Case	3.31	2.41	1.72	0.71	0.70	0.57	0.74	0.42	0.38
TOTAL	7.36	3.88	2.97	1.86	1.80	1.56	1.31	0.89	0.70
Total Heating (kW):									
Winding Pack	10.34	3.77	3.20	2.92	2.80	2.53	1.44	1.21	0.81
Coil Case	8.44	6.13	4.38	1.83	1.79	1.45	1.90	1.06	0.98
TOTAL	18.78	9.90	7.58	4.75	4.59	3.98	3.34	2.27	1.79

Table 3. Radiation Effects at Inner Legs of TF Magnets in Technology Phase

Option	1	2	3	4	5	6	7	8	9
Shield Type	SS/H_2O	SS/H_2O	SS/B_4C/Pb/H_2O	SS/B_4C/Pb/H_2O	SS/B_4C/Pb/B-H_2O	SS/B_4C/Pb/B-H_2O	B-SS/H_2O	B-SS/B_4C/Pb/H_2O	B-SS/H_2O
V.V. filling material	---	H_2O	H_2O	H_2O	H_2O	B-H_2O	H_2O	H_2O	B-H_2O
B_4C/Pb outside V.V.	---	--	--	2.5 cm Pb 1 cm B_4C	2 cm Pb 1 cm B_4C	2 cm Pb 1 cm B_4C	--	1 cm Pb 1 cm B_4C	--
B_4C/Pb inside V.V.	---	--	2 cm Pb 1 cm B_4C	--	--	--	--	--	--
Optimum H_2O in SS shield (v/o)	25	20	15	15	18	18	10	10	10
Peak dose to insulator (10^9 rads)	4.4	1.77	1.47	1.29	1.28	1.18	0.71	0.61	0.55
Peak nuclear heating (mW/cm^3):									
Winding Pack	1.70	0.84	0.65	0.46	0.44	0.37	0.32	0.21	0.20
Coil Case	4.34	4.00	2.89	1.27	1.14	0.75	1.44	0.63	1.55
Nuclear Heating (kW/m):									
Winding Pack	3.00	1.08	0.92	0.82	0.80	0.74	0.44	0.38	0.35
Coil Case	2.47	1.79	1.32	0.72	0.66	0.49	0.64	0.34	0.30
TOTAL	5.47	2.87	2.24	1.54	1.46	1.23	1.08	0.72	0.65
Total Heating (kW):									
Winding Pack	8.50	3.06	2.61	2.32	2.27	2.10	1.25	1.07	1.00
Coil Case	7.00	5.07	3.74	2.04	1.87	1.38	1.82	0.96	0.85
TOTAL	15.50	8.13	6.35	4.36	4.14	3.48	3.07	2.03	1.85
Peak fast n fluence (10^{18} n/cm^2)	4.1	0.93	0.91	1.11	1.13	1.13	0.46	0.52	0.46
Peak dpa in Cu stabilizer (10^{-3} dpa)	2.27	0.67	0.63	0.71	0.75	0.75	0.32	0.35	0.32
He production in V.V. (appm)	0.032	0.026	0.024	0.036	0.037	0.037	0.012	0.016	0.012

first two channels are 0.7 cm wide followed by 0.8, 0.8, and 2 cm channels. The first B-SS layer is 2 cm thick and is followed by 6, 8, 11, 10, and 8 cm thick layers. Several neutronics calculations were then performed to investigate the effect of the shield heterogeneity on the damage at the magnet. Our results showed that the increase in damage due to the heterogeneity is only marginal (<2%). Of interest from these calculations is the amount of tritium generated in the various layers of the shield. At the end of the physics and technology phases, nearly 3 and 35 g of T are produced in the borated steel, respectively. This amount is small compared to the 1.5 kg of T generated in the blanket by Be and it should not pose any safety problems.

Divertor Shield

The thinnest shield in the divertor zone is 60 cm thick at Section I behind the outer end of the divertor plates. The neutron wall loading therein is ~0.4 MW/m^2. Additional space is available for shield when proceeding towards the i/b and o/b sides. A poloidal extent of ~1 m at each of the top and bottom parts of the magnets is subject to a high damage. The toroidal coverage of the magnet in this region amounts to ~50%. The coil cases are fairly thick (30 cm) and provide additional shielding for the winding packs. The radiation effect of most concern is the nuclear heating which is mainly generated in the coil cases. The divertor plates contain a total of 4 cm of materials (C, Cu, H_2O, SS). A 20 cm space behind the plates is reserved for the cooling tubes and mechanical support. An idea of partially filling this space with either water or shielding materials was abandoned because of the added complexity to the system due to the need for cooling, supporting, and electrically insulating the added shield.

The radiation effects at the top and bottom portions of the TF coils were calculated using the ONEDANT code in poloidal cylindrical geometry around the plasma axis. The pure SS/H_2O results in nuclear heating and dose to the insulator of 10 kW and 3.5 x 10^8 rads, respectively. Although the dose level is acceptable, the heating load is quite high. When B-SS is introduced in the shield, the heating and dose dropped to 5.7 kW and 2 x 10^8 rads. Safety factors of 1.5 and 2 for the heating and dose, respectively, are used in the divertor region providing that the assembly gaps of the divertor shield are located away from the high damage region. This implies that a total nuclear heating of ~9 kW is expected in the divertor zone.

Outboard Shield

There is an ample space available for the o/b shield. There is no need for materials other than SS and H_2O to shield the outer legs of the TF magnets. When the 155 and 225 cm outboard spaces in the physics and technology phases, respectively, are filled with blanket/shield/V.V., the damage level in the outer legs was found to be 6-8 orders of magnitude lower than the design limit. Since the winding packs are well protected by the 40 cm thick coil cases the only concern is the heating in the outer legs. Our calculations show that for the heating in the outer legs to be ~2 orders of magnitude lower than the heating in the inner legs, only 120 and 135 cm of blanket/shield/V.V. are required in the physics and technology phases, respectively.

Safety Factors

The safety factors are used to correct the one-dimensional (1-D) results for the actual effects of radiation in the TF magnets. These factors are design dependent. They depend strongly on the presence and characteristics of the assembly gaps between blanket/shield modules. Also, they include the uncertainties associated with the nuclear data, transport codes and modeling.

The i/b blanket/shield/V.V. was modeled for the two dimensional (2-D) code TWODANT [5] to assess the effect of the streaming through the assembly gaps on the damage at the magnet. The radial depth of the gap is ~70 cm. The results are summarized in Table 4 for both 1 and 2 cm wide straight gaps. The peaking factor is defined as the ratio of the 2-D to the 1-D values for the damage at the magnet. As noticed, the peaking factors increase with the gap width and are slightly different for the various response functions. The enhancement factor for the total nuclear heating in the magnet is 1.25.

Previous studies [6] have indicated that the uncertainties in the nuclear data of a steel-based shield amount to ±20%. The uncertainties associated with transport codes and modeling are estimated to be ~10%. With peaking factors of 1.25 for integral and 1.7 for local quantities, it is reasonable to consider safety factors of 2 for integral and 3 for local values for the 1 cm wide straight gaps. For wider gaps, the option of bending the gap should be considered to reduce the streaming effects. It should be noted that the safety factors are space dependent. The factors of 2-3 calculated above are restricted to the damage at the inner legs of the magnets. For other parts of the magnet (e.g. top/bottom or outer legs), lower safety factors can be used because of the flexibility in locating the assembly gaps off the high damage regions.

Heat Load to TF Magnets

The heat load to the TF magnets was estimated by integrating the nuclear heat in the different parts of the magnet over both toroidal and poloidal directions. The inboard side was segmented poloidally to calculate the heating in the inner legs taking into account the vertical increase in the shield thickness and the average wall loading over each segment. As the first wall follows the plasma contour, the i/b shield thickness increases gradually and reaches a maximum of 105 cm at the top and bottom ends. The total height of the inner legs is ~9 m. Based on the results of Tables 1 and 2 and using a safety factor of 2, the heating in the inner legs amounts to 6-7 kW for the B-SS/H_2O shield. As mentioned before, a total heating of 9 kW is generated at the top/bottom parts of the magnets. Neglecting the amount of heat deposited in the outer legs, the heat load to the magnet totals ~16 kW. It should be mentioned that neutrons streaming through large penetrations (such as neutral beam ports, divertor cooling tubes, and pumping ducts) will result in an additional heat deposition in the magnets. With careful penetration shield design, this heat can be as low as 3 kW.

Table 4. Peaking factors for 1 and 2 cm wide straight assembly gaps

Gap width	1 cm	2 cm
Peak dose to insulator	1.61	2.7
Peak nuclear heating in winding pack	1.69	2.64
Peak fast neutron fluence	1.62	2.52
Peak dpa in Cu stabilizer	1.68	2.75

Conclusions

An extensive optimization study has been performed for the inboard shield of ITER. Iterations between neutronics and thermal hydraulics calculations have been done to comply with cooling requirements. The inclusion of boron steel in the bulk shield led to appreciably lower radiation damage at the magnet. For a water-cooled boron steel shield, the end-of-life dose to the insulator and heat load to the magnet amounts to 2 x 10^9 rads and 19 kW, respectively. These values include safety factors of 3 for the dose and 2 for the heating and they are below the design limits. Therefore, it can be concluded that the proposed shield provides adequate protection for the TF magnets of ITER.

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