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Abstract

During the conceptual design phase of the International Thermonuclear Experimental Reactor (ITER), several tritium breeding blanket designs were proposed by the four international parties; the US, USSR, Japan (J) and European Community (EC). The US, J and EC designs utilize solid breeders with beryllium multiplier while the USSR proposes a LiPb blanket design. All blankets are water cooled and employ 316 SS as structural material. The shielding effectiveness of the different blanket designs was compared on the same bases and the radiation level at the superconducting toroidal field (TF) magnets was assessed. The analysis shows that the inboard (i/b) blanket, in particular, has significant impact on magnet damage and total heating. For the US design, all magnet radiation limits are met with the current 84 cm thick i/b region. For the other designs, the i/b blanket design should be modified to satisfy the magnet radiation limits, or 3-7 cm additional i/b shielding should be provided depending on the blanket type. The impact of the latest divertor design on the magnet damage was also analyzed and the combined effect of both blanket and divertor designs on the overall magnet heat load was assessed.

Introduction

The Conceptual Design Activity (CDA) of ITER [1] began in 1987 and ended in 1990, during which period each team of the four international parties has proposed a blanket design that fulfill as much as practicable the ITER requirements. No blanket has yet been selected as the reference design for ITER. However, the ceramic breeder blanket was chosen as the first option and the LiPb blanket as the back-up. There are still some critical issues associated with each blanket. Work is underway to improve the various designs and to solve the identified problems hopefully before the start of the Engineering Design Activity (EDA). Some design parameters for the proposed blankets are listed in Table 1 and the basic design features are described in detail in Reference 1. The US, J, and EC designs utilize solid breeders with Be multiplier while the USSR offers a LiPb blanket. All blankets are water cooled and employ 316 SS as a structural material. The blankets differ mainly in the mechanical configuration, forms of breeder and multiplier, and material density fraction.

The present study is undertaken to determine the shielding effectiveness of the various blanket designs and to estimate the amount of shielding required for each blanket to keep the radiation levels at the TF magnet within the guidelines. In order to evaluate the effect the blanket has on the total nuclear heating in the 16 TF magnets, it was necessary to update the nuclear analysis for the divertor region to be consistent with the reference divertor plate designs. The divertor results are briefly presented in one of the sections to follow and thereafter the total heat load to the magnet is estimated for the four blanket options.

Shielding Considerations

The ITER study considers two phases of operation, namely physics and technology. About 1 MW/m^2 neutron wall loading (Γ) is expected during the low fluence physics phase and a slightly lower Γ (0.7 MW/m^2) is anticipated during the extended technology phase. A fluence goal of 3 MW·y/m^2 was used for setting the ITER shielding requirements. A layout for the ITER device is shown in Fig. 1. The first wall, blanket, and shield are designed as an integrated module and are

Table 1. Pertinent Design Parameters for the Various Blanket Options.

Blanket Design	US	J	EC	USSR
i/b FW/Blanket Thickness (cm)	11.6	12	18.8	18
Breeder-Li Enrichment	Li_2O-95%	Li_2O-nat.	$LiAlO_2$-90%	LiPb-90%
Solid Breeder Form	Sintered Blocks	Sintered Pebbles	Sintered Cylindrical Pellets	
i/b Blanket Composition	10% Li_2O 80% Be 5% SS 5% H_2O	47% Li_2O 27% Be 9% H_2O 6% SS 11% void	9% $LiAlO_2$ 37% Be 16% H_2O 9% SS 6% He 23% void	43% LiPb 30% SS 10% H_2O 17% void

toroidally segmented. The first wall is protected by 2 cm thick graphite tiles in the physics phase and 0.05 cm W coating in the technology phase. Blankets are used on both inboard (i/b) and outboard (o/b) sides of the machine. The i/b side is constrained to 84 cm at the midplane and, consequently, the highest radiation damage occurs at the inner legs of the TF coils. On the other hand, there is ample space for shielding at the outboard side. The divertor region is a critical area from the shielding point of view as the tilted outer-end of the divertor limits the shielding space. Another critical area is identified right above/below the i/b blanket where the shield recesses to accommodate the inner-end of the divertor.

Thorough optimization analyses have been carried out by all 4 parties to improve the performance of the ITER shield. These analyses are beyond the scope of this paper and the reader is directed to References 1-6 for further information. Nevertheless, the shield has some important

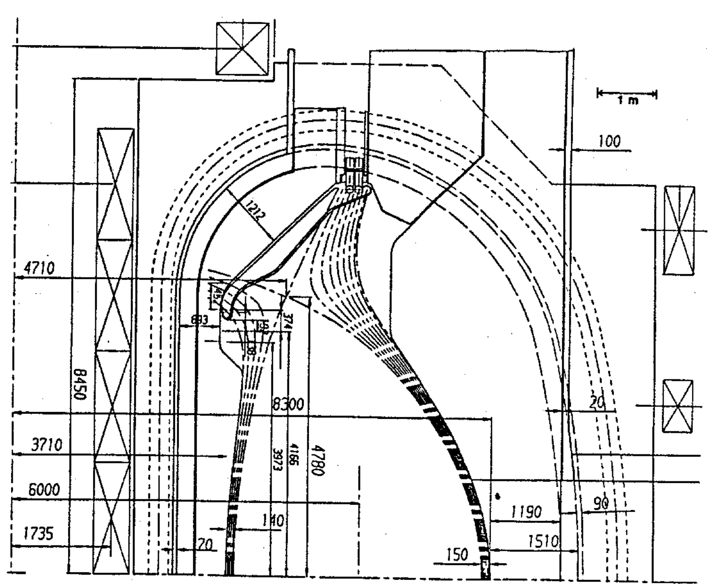

Fig. 1. Vertical cross section of the upper half of ITER.

Table 2. Radiation Effects in Inner Legs of TF Magnets for the US Solid Breeder Blanket

Physics Phase	
Tile Thickness (cm) - material	2-C
Peak Nuclear Heating (mW/cm^3):	
Winding Pack	1.77
Coil Case	3.29
Heating per Unit Length (kW/m):	
Winding Pack	2.47
Coil Case	2.12
Total	4.59
Total Heating in Inner Legs‡ (kW)	11.12
Technology Phase	
Tile Thickness (cm) - material	0.05-W
# of FPY's	3.8
Peak Dose to Insulator (10^9 rads)	5.79
Peak Fast n Fluence to Nb_3Sn (10^{18} n/cm^2)	6.61
Peak dpa in Cu Stabilizer (10^{-3} dpa)	3.38
Peak Nuclear Heating (mW/cm^3):	
Winding Pack	1.59
Coil Case	2.96
Heating per Unit Length (kW/m):	
Winding Pack	2.22
Coil Case	1.98
Total	4.20
Total Heating in Inner Legs‡ (kW)	10.19

‡z = ±6.8 m

Table 3. Radiation Effects in Inner Legs of TF Magnets for the J Solid Breeder Blanket (Mixed Pebble Bed)

Physics Phase			
Tile Thickness (cm) - material	2-C	2-C	2-C
Peak Nuclear Heating (mW/cm^3):			
Winding Pack	1.60	2.43	2.43
Coil Case	–	3.57	3.59
Heating per Unit Length (kW/m):			
Winding Pack	–	3.54	3.55
Coil Case	–	2.67	2.68
Total	–	6.21	6.23
Total Heating in Inner Legs‡ (kW)	14.6	14.0	14.0
Technology Phase			
Tile Thickness (cm) - material	2-C	2-C	0.05-W
# of FPY's	3.0	3.0	3.8
Peak Dose to Insulator (10^9 rads)	7.41	5.93	8.56
Peak Fast n Fluence to Nb_3Sn (10^{18} n/cm^2)	19.86	6.90	9.96
Peak dpa in Cu Stabilizer (10^{-3} dpa)	5.04	3.68	5.33
Peak Nuclear Heating (mW/cm^3):			
Winding Pack	1.16	1.90	2.18
Coil Case	–	2.79	3.22
Heating per Unit Length (kW/m):			
Winding Pack	–	2.77	3.19
Coil Case	–	2.09	2.41
Total	–	4.86	5.60
Total Heating in Inner Legs‡ (kW)	10.68	10.95	12.63

‡z = ±7.7 m

features that are of general interest. The main structural and shielding material is 316 SS. Water is employed for cooling and shielding purposes. The outermost part of the shield is occupied by the 25 cm thick vacuum vessel (V.V.) which is made of 316 SS with water coolant channels. Attached to the V.V. (at the magnet side) is a 5 cm thick layer of B_4C and Pb to further improve the efficiency of the shield. The main function of the shield is to protect the TF magnets against radiation and the shield design is governed by the magnet radiation limits. These limits were set by the magnet designers to be 5×10^9 rads, 55 kW, 5 mW/cm^3, 10^{19} n/cm^2, and 6×10^{-3} dpa for the end-of-life dose to the epoxy insulator, total nuclear heating in the 16 TF coils, end-of-life fast neutron fluence ($E_n > 0.1$ MeV) to the Nb_3Sn superconductor, and displacement damage to the copper stabilizer, respectively. The predominant radiation limits are the total nuclear heating and the dose to the insulator. The heating limit is more important to be met in the physics phase due to the higher level of fusion power while the dose limit needs to be satisfied at the end of the 3.8 full power years (FPY) operation time of the technology phase.

Analysis Procedure

To the extent that the i/b and o/b blanket/shield components can be approximated as toroidal cylinders around the machine axis with source neutrons produced from the middle plasma region, the calculations can be performed using the one-dimensional (1-D) discrete ordinates method. The accuracy of the 1-D method was tested by comparing the 1-D and 3-D Monte Carlo results. They have been found in good agreement when the appropriate safety factors are included [2,3]. The safety factors are design dependent and are used to correct the results obtained from the analyses. They essentially depend on the materials used, assembly gaps, and uncertainty in cross section data. The recommended safety factors for the 1-D analysis of the ITER shield design are 2 for integral quantities (e.g. total magnet heating) and 3 for local values (such as dose, fluence, and dpa). All results cited here include the established safety factors. The radiation transport calculations have been performed using the ONEDANT code [7], the 46 neutron and 21 gamma cross section library based on ENDF/B-V data, and the P_3 – S_8 approximations.

Blanket Comparison

During the CDA phase, the 4 parties have analyzed their blanket/shield designs with respect to the effect on magnet radiation damage. There are some differences between the various analyses regarding the codes and cross section data, V.V. configuration, magnet composition, FW tile/coating thickness, and machine operating time. Although close contact was maintained with the designers of the various reactor components, certain assumptions had to be made by each team to finalize the shielding calculations. These assumptions are not completely consistent with the final design parameters and their effect on the magnet damage along with that of the blanket design are investigated in this paper.

The reference design calls for a radial i/b thickness of 84 cm at the midplane gradually increasing along the poloidal direction, 1100 MW of fusion power and 2 cm thick FW C tiles in the physics phase, 860 MW of fusion power and 0.05 cm thick W coating in the technology phase, 6.8 m high inboard blanket, and 3.8 FPY machine lifetime. Table 2 details the magnet radiation effects for the US blanket/shield design and the reference parameters are used in the calculations. The inner leg heating is integrated over a length of 6.8 m, the height of the i/b blanket. The poloidally increased i/b shield has reduced the heating by a factor of ~ 2 compared to a uniformly thick i/b shield. All magnet radiation limits are met except for the dose at the midplane. Aside from thickening the i/b shield, this problem is alleviated by employing W in the back layer instead of Pb/B_4C over the 1 m high critical zone around the midplane. The analyses for the J, EC, and USSR blankets are reported in Tables 3, 4, and 5, respectively. The first column lists the results reported by the other parties for the proposed blanket/shield designs as of the summer of 1990. The second column provides the US analysis for the different designs using the same parameters and

Table 4. Radiation Effects in Inner Legs of TF Magnets
EC Solid Breeder Blanket

Physics Phase

Tile Thickness (cm) - material	2-C	2-C	2-C
Peak Nuclear Heating (mW/cm^3):			
Winding Pack	3.36	4.14	4.07
Coil Case	5.94	6.49	6.47
Heating per Unit Length (kW/m):			
Winding Pack	4.65	5.59	5.61
Coil Case	4.22	4.56	4.55
Total	8.87	10.15	10.16
Total Heating in Inner Legs‡ (kW)	18.6	21.16	21.18

Technology Phase

Tile Thickness (cm) - material	2-C	2-C	0.05-W
# of FPY's	3.0	3.0	3.8
Peak Dose to Insulator (10^9 rads)	6.84	8.72	12.42
Peak Fast n Fluence to Nb_3Sn (10^{18} n/cm^2)	8.19	10.12	14.30
Peak dpa in Cu Stabilizer (10^{-3} dpa)	5.10	4.84	6.86
Peak Nuclear Heating (mW/cm^3):			
Winding Pack	2.58	3.24	3.64
Coil Case	4.59	5.07	5.79
Heating per Unit Length (kW/m):			
Winding Pack	3.58	4.37	5.01
Coil Case	3.26	3.56	4.06
Total	6.84	7.93	9.07
Total Heating in Inner Legs‡ (kW)	14.2	16.54	18.92

‡z = 8 m

Table 5. Radiation Effects in Inner Legs of TF Magnets

Physics Phase

Tile Thickness (cm) - material	2-C	2-C	2-C
Peak Nuclear Heating (mW/cm^3):			
Winding Pack	1.30	2.31	2.27
Coil Case	2.41	3.75	3.70
Heating per Unit Length (kW/m):			
Winding Pack	1.76	3.12	3.10
Coil Case	1.55	2.58	2.57
Total	3.31	5.70	5.67
Total Heating in Inner Legs‡ (kW)	(9.15)†	15.76	15.67

Technology Phase

Tile Thickness (cm) - material	2-C	2-C	0.05-W
# of FPY's	3.0	3.0	3.8
Peak Dose to Insulator (10^9 rads)	2.48	4.80	6.82
Peak Fast n Fluence to Nb_3Sn (10^{18} n/cm^2)	3.13	5.49	7.83
Peak dpa in Cu Stabilizer (10^{-3} dpa)	2.06	2.61	3.72
Peak Nuclear Heating (mW/cm^3):			
Winding Pack	1.01	1.81	2.06
Coil Case	1.89	2.93	3.34
Heating per Unit Length (kW/m):			
Winding Pack	1.38	2.44	2.75
Coil Case	1.21	2.02	2.30
Total	2.59	4.46	5.05
Total Heating in Inner Legs‡ (kW)	(7.15)†	12.32	13.96

†US estimate
‡z = 8.22 m

configurations utilized by the different parties. The discrepancies between the first and second columns are primarily due to the differences in the calculational tools and data base. While the US employs the ONEDANT code and ENDF/B-V data, the J, EC, and USSR use the ANISN code and ENDF/B-IV data (except for J where the JENDL-3 library is used). The last column lists the US calculations for the proposed blanket and shield configurations using the reference parameters in terms of operation time, tile/coating and magnet dimension/composition. Comparing the first and third columns, it is apparent that the J, EC, and USSR underestimate the heating by factors of 1.2, 1.3, and 2, and the end-of-life dose by factors of 1.2, 1.8, and 2.8, respectively.

Table 6 compares the third column results of all blanket/shield designs. Calculations for the latest layered solid breeder Japanese design are also reported. Here, the comparison is done on the same bases and the difference in results is essentially due to the different blanket/shield concepts. From the shielding viewpoint, the US blanket/shield design has the highest performance. The J, EC, and USSR designs result in 1.3-1.6, 2, and 1.2 higher magnet damage, respectively, compared to US. The insulator dose exceeds the limit in all cases. As mentioned before, a W back layer reduces the dose below the limit for the US design. For the other designs, the W will not help. To meet the dose limit, the blanket designs need to be modified or, alternatively, extra shields should be added to the current 84 cm thick i/b region. Approximately 5, 7, and 3 cm of extra shields are required for the J, EC, and USSR designs, respectively.

Divertor Region

Special emphasis was devoted to the divertor region where the shield is thinned as a result of the inclined divertor plates. The minimum shield thickness in this region is 48 cm. Additional shielding is provided by the divertor plates (DP) and their support structure. The reference divertor design calls for a 5.5 cm thick DP in the physics phase and a relatively thicker DP (9.5 cm) for the technology phase. The electric insulator surrounding the winding pack is further protected by the fairly thick coil case ($\sim$ 30 cm). Our results show that all magnet radiation limits will be satisfied if the upper end of the o/b blanket is extended inward up to the plasma boundary to provide extra protection for the top divertor region. This modification seems feasible from the engineering standpoint and has the advantage of reducing the magnet heating by $\sim$ 5 kW. On this basis, the heating in the divertor region amounts to 26 and 15 kW in the physics and technology phases, respectively.

Total Heat Load to TF Magnets

The nuclear heating deposited in the various parts of the TF coils is summarized in Table 7. The streaming radiation into the divertor pumping ducts contributes 3-4 kW of heating. As is apparent from the table the total heat load to the TF magnets ranges between 31 and 57 kW. The higher number slightly exceeds the heating limit. This will not affect the reliability of the magnet but rather will have some impact on the economics of the cryogenic system. As noticed, the US design gives the lowest heat load while the other designs result in 2-12 kW more heating. In general, most of the heat is deposited in the divertor region and the level of contribution from the inboard depends on the blanket/shield design concept.

Conclusions

Based on the results of the shielding analyses conducted during the conceptual design phase for ITER, it is concluded that the current inboard configuration is suitable for the US blanket and shield design. For the other concepts, it is mandatory to modify the J, EC, and USSR blanket designs or, alternatively, increase the inboard shield by 3-7 cm in order to satisfy the insulator dose limit. The latter option will surely require a revision

Table 6. Radiation Effects in Inner Legs of TF Magnets

Blanket/Shield Design	US	J-M**	J-L‡	EC	USSR
Physics Phase (2 cm C tiles)					
Peak Nuclear Heating (mW/cm^3):					
Winding Pack	1.8	2.4	2.9	4.1	2.3
Coil Case	3.3	3.6	4.3	6.5	3.7
Heating per Unit Length (kW/m):					
Winding Pack	2.5	3.6	4.3	5.6	3.1
Coil Case	2.1	2.7	3.2	4.6	2.6
Total	4.6	6.2	7.5	10.2	5.7
Total Heating in Inner Legs (kW)	11.1	14.0 (13.9)*	18.2 (18.2)	21.2 (22.9)	15.7 (12.7)
Technology Phase (0.05 cm W coating)					
Peak Dose to Insulator (10^9 rads)	5.8	8.6	10.3	12.4	6.8
Peak Fast n Fluence to Nb_3Sn (10^{18} n/cm^2)	6.6	10.0	12.0	14.3	7.8
Peak dpa in Cu Stabilizer (10^{-3} dpa)	3.4	5.3	6.4	6.9	3.7
Peak Nuclear Heating (mW/cm^3):					
Winding Pack	1.6	2.2	2.6	3.6	2.1
Coil Case	3.0	3.2	3.9	5.8	3.3
Heating per Unit Length (kW/m):					
Winding Pack	2.2	3.2	3.8	5.0	2.8
Coil Case	2.0	2.4	2.9	4.1	2.3
Total	4.2	5.6	6.7	9.1	5.1
Total Heating in Inner Legs (kW)	10.2	12.6 (12.6)	16.3 (16.2)	18.9 (20.4)	14.0 (11.5)
Extra Shield Required to Meet Dose Limit (cm)	1†	4	5	7	3

*Based on US methodology for total heating calculations (z = 6.8 m)
†or W back layer over 1 m height with no need for extra shield
**mixed pebble bed
‡layered pebble bed

of the overall ITER dimensions. The present divertor shield adequately protects the magnet providing that the upper ends of the outboard blanket side modules located underneath magnets are extended inward up to the plasma boundary. Calculations of the resulting nuclear heating show that the total heat load to the TF magnets is acceptable and most of the heat is dissipated in the divertor and inboard regions. It is highly recommended to consider the above changes in the blanket/shield design before starting the Engineering Design Phase of ITER.

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Table 7. Total Nuclear Heating (kW) in TF Magnets

Blanket/Shield Design	US/J/EC/USSR
Physics Phase	
Inboard	11/18/23/13
Recess	4
Divertor	26
Penetrations	4
Total	45/52/57/47
Technology Phase	
Inboard	10/16/20/12
Recess	3
Divertor	15
Penetrations	3
Total	31/37/41/33