High Performance Inboard Shield Design for the Compact TIBER-II Test Reactor

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HIGH PERFORMANCE INBOARD SHIELD DESIGN FOR THE COMPACT TIBER-II TEST REACTOR

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Abstract

The compactness of the TIBER-II reactor has placed a premium on the design of a high performance inboard shield to protect the inner legs of the toroidal field (TF) coils. The available space for shield is constrained to 48 cm and the use of tungsten is mandatory to protect the magnet against the 1.53 MW/m^2 neutron wall loading. The primary requirement for the shield is to limit the fast neutron fluence to 10^{19} n/cm^2. In an optimization study, the performance of various candidate materials for protecting the magnet was examined. The optimum shield consists of a 40 cm thick W layer, followed by an 8 cm thick H_2O/ $LiNO_3$ layer. The mechanical design of the shield calls for tungsten blocks within SS stiffened panels. All the coolant channels are vertical with more of them in the front where there is a high heat load. The coolant pressure is 0.2 MPa and the maximum structural surface temperature is <95°C. The effects of the detailed mechanical design of the shield and the assembly gaps between the shield sectors on the damage in the magnet were analyzed and peaking factors of ~2 were found at the hot spots.

Introduction

TIBER-II [1] is pursued as the U.S. version of the International Thermonuclear Experimental Reactor (ITER). It is designed to test physics, engineering, and technology of fusion reactors. The test area amounts to ~20 m^2 and is located on the outboard (o/b) side. The rest of the space is filled with shield which has a primary objective of protecting the TF coils against radiation and a secondary objective of breeding as much tritium as possible. The baseline design calls for a compact device with a 3 m major radius and 0.83 m minor radius. Figure 1 shows a cross section view through the upper half of the TF coil. The machine operates steady state at a fusion power of 314 MW. During its planned 15 year life, 2.5 full power years (FPY) of operation are expected. Other features include the use of the primary candidate alloy (PCA) for structural material and the $H_2O/LiNO_3$ aqueous solution (16 g of $LiNO_3$/100 cm^3 of H_2O) as the shield coolant and tritium breeder.

The intent of this paper is to present a design of a high performance inboard (i/b) shield to protect the inner legs of the TF coils. The selection of the shield materials and configuration is driven by several factors including the space constraints and the radiation limitations imposed by the magnet designers. The i/b shield design was accomplished in three consequential stages. The first stage determined the shield materials and configuration based on the neutronics analysis and optimization study. The second stage included the mechanical design and arrangement of the shield layers so that the thermal hydraulic requirements are met. In the third stage, the effects of the detailed mechanical design and the assembly gaps between shield sectors were assessed.

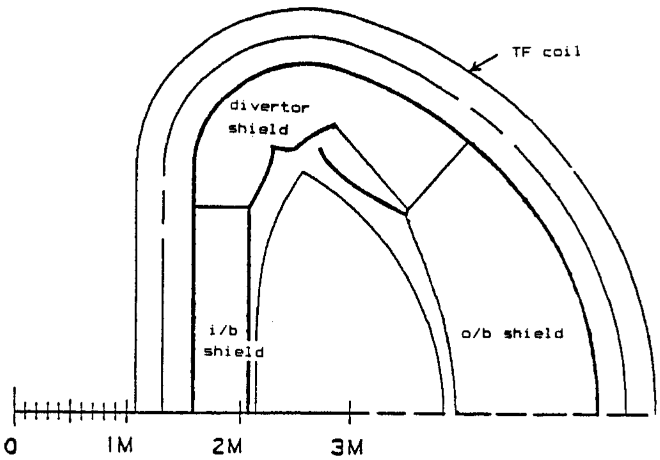

Fig. 1. A cross section through the TF coil of TIBER-II showing the different zones of the shield.

Radiation Limits

The superconducting magnet components most sensitive to radiation damage are the superconductor filaments, stabilizer, and electrical insulators. In addition to its effect on winding temperatures, the nuclear heating affects the economic performance of the reactor through increased refrigeration cost. The philosophy of the TIBER-II design is to adopt aggressive radiation limits in order to design compact TF magnets. These limits are discussed thoroughly in the TIBER-II report [1]. The limit on the fast neutron fluence (E_n > 0.1 MeV) to the Nb_3Sn superconductor is taken as 10^{19} n/cm^2. The total nuclear heating in the winding packs of the 16 TF coils can be as high as 36 kW and this corresponds to ~10 mW/cm^3 peak nuclear heating in the inner legs of the coils. The end-of-life dose to the boron-free glass-fiber-filled (GFF) polyimide is taken as 1.3×10^{11} rads. The neutron-induced damage in the Cu stabilizer is limited to 6.2×10^{-3} dpa so that the total resistivity of Cu does not exceed 3 nΩm at any time during reactor operation. These limits include safety factors of 2-3 to account for both data and modeling uncertainties.

Nuclear Analysis

Preliminary neutronics calculations for the i/b shield indicated that satisfying the fast neutron fluence limit is the design driver for the i/b shield. Initial estimates of the fluence were determined for several preliminary configurations of the i/b shield to guide the design toward a final configuration. This led to the current TIBER-II configuration that allows for 48 cm tungsten based i/b shield plus a 2 cm first wall. An extensive shield optimization study was performed to minimize the fluence to the superconductor material. In the meantime, an effort was made to keep the nuclear heating in the magnet as low as possible to avoid a high cryogenic load and cost. Due to space constraints here, only the highlights of the optimization study will be mentioned and the details are considered in an associated paper [2].

The highest damage in the inner legs of the TF coils occurs at the midplane of the reactor where the wall loading peaks at a value of 1.53 MW/m^2. In addition to the 50 cm thick i/b shield and first wall, the space between the plasma edge and the winding pack consists of a 6 cm scrape-off zone, 2 cm gap behind the shield, 5.5 cm coil case, and 0.5 cm electric insulator. The coil case is cooled with 5 vol% liquid He and the winding pack is composed of 37 vol% 304 SS, 20.4 vol% Cu, 13.6 vol% Nb_3Sn, 6 vol% GFF polyimide, and 23 vol% liquid He. The problem was modeled for radiation analysis as an infinite toroidal cylinder and the calculations are performed using the one-dimensional (1-D) code ONEDANT with the MATXS5 data library based on ENDF/B-V in 30 neutron and 12 gamma groups, and the P_3-S_8 approximation.

The machinable tungsten alloy (97 wt% W, 2 wt% Ni, and 1 wt% Fe) is used as the main shielding material in the i/b shield. This alloy has good mechanical properties, good machinability, and it could be sintered to practically theoretical density. Several shielding materials were considered to back up the W-shield. These are TiH_2, B_4C and Pb. Water, borated water, and $H_2O/LiNO_3$ coolants were evaluated to assess their shielding capabilities. Throughout the i/b shield, 10 vol% PCA structure is used. Our preliminary calculations indicated that the W/TiH_2-shield is superior over the W/B_4C-shield in reducing the fluence. However, some safety concerns regarding the TiH_2 integrity in case of an accident have ruled out the use of TiH_2 in the i/b shield. When the W/B_4C-shield is backed by a Pb-shield the fluence increases which means that the Pb is not helping the fluence. These results pertain to the case of water coolant. When the water in the shield is replaced by borated water or $H_2O/LiNO_3$, the fluence dropped slightly (by ~20%) while the nuclear heating in the magnet decreased by a factor of ~2. This is due to the increased absorption of the low energy neutrons by boron and lithium in the coolant. Since the outboard shield utilizes the $H_2O/LiNO_3$ as a coolant, the decision was made to use the $H_2O/LiNO_3$ also to cool the i/b shield. This has the dual advantage of simplifying the cooling system of the reactor as a whole, and enhancing the tritium breeding capability of TIBER-II.

The conclusions of the preliminary study are used to define the starting point for the i/b shield optimization study. The major emphasis is now placed on the use of W, B_4C, and $H_2O/LiNO_3$ materials with the appropriate distribution in the i/b shield to minimize the fluence at the magnet. The starting configuration for the optimization study consists of two layers of shield: a 44.4 cm thick W-shield (75 vol% W alloy at 98% density factor [d.f.], 10 vol% PCA and 15 vol% $H_2O/LiNO_3$) followed by a 3.6 cm thick B_4C-shield (85 vol% B_4C at 90% d.f. and 90% ^{10}B in B, 10 vol% PCA and 5 vol% $H_2O/LiNO_3$). The optimization study was performed in several steps as indicated below:

1) Varying the volume content of the W and coolant in the W-shield.

2) Varying the volume content of the B_4C and coolant in the B_4C-shield.

3) Varying the thickness of the W-shield and B_4C-shield under the constraint that the total shield thickness remains fixed at 48 cm.

4) Repeating the above steps as necessary till no significant change in the fluence takes place.

In the first step, the coolant content in the W-shield was varied from 5 vol% to 25 vol%, trading W for coolant, and the fluence minimized at 13 vol% $H_2O/LiNO_3$. In the second step, the coolant content in the B_4C-shield was varied from 5 vol% to 90 vol%, trading B_4C for coolant. Figure 2 shows that the presence of B_4C at the back of the W-shield does not help the fluence. This is due to the fact that the hydrogen in the $H_2O/LiNO_3$ coolant is more effective in moderating the high energy neutrons than B_4C. On the other hand, B_4C is superior in reducing the nuclear heating because ^{10}B has a much higher absorption cross section than Li for the low energy neutrons. However, the increase in the heating due to the use of pure $H_2O/LiNO_3$ in the back layer is not excessive and the peak nuclear heating is still much below the design limit. In the third step, the thickness of the $H_2O/LiNO_3$-shield was varied under the constraint that the total shield thickness remains 48 cm. The fluence is minimized at 9.4 x 10^{18} n/cm^2 @ 2.5 FPY for 6 cm thick $H_2O/LiNO_3$-shield. Upon changing the coolant content in the W-shield, the fluence was found to decrease with the coolant content, as illustrated in Fig. 3. The minimum amount of coolant needed for the i/b shield is 7 vol%. Accordingly, the optimal homogeneous composition of the W-shield is taken as 83 vol% W alloy, 10 vol% PCA and 7 vol% $H_2O/LiNO_3$ and this leads to a fluence of 7.4 x 10^{18} n/cm^2 @ 2.5 FPY. It should be mentioned that further changes in the shield composition and thickness did not result in a significant reduction in the fluence.

The W-shield is treated so far for nuclear analysis as a homogeneous mixture of coolant, structure and shielding materials. In practice, a homogeneous W-shield is difficult to construct and a more realistic design calls for layers of W plates with several coolant channels between them. A detailed breakdown of the nuclear heating in the shield, as shown in Fig. 4, was calculated as input to the

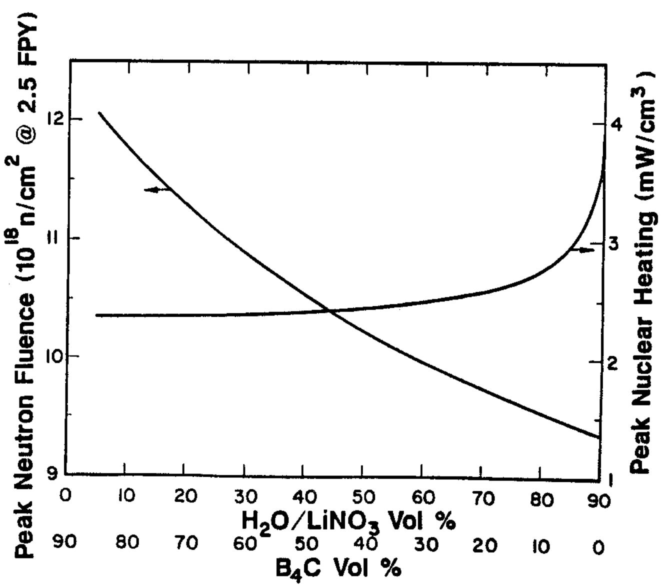

Fig. 2. Effect of trading B_4C for $H_2O/LiNO_3$ in 3.6 cm thick back layer of B_4C-shield.

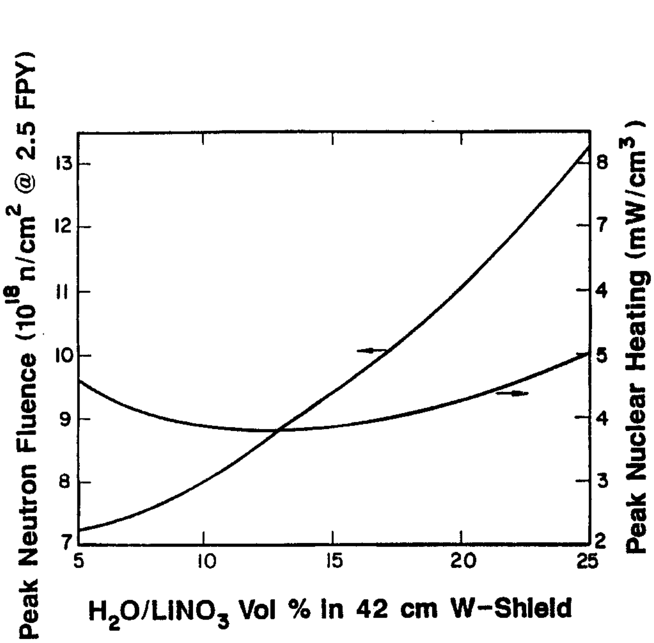

Fig. 3. Effect of trading $H_2O/LiNO_3$ for W.

shield thermal hydraulics calculations in order to determine the thicknesses of the various layers of the W-shield. As shown later, the layered shield design that satisfies the thermal hydraulics requirements consists of a 1 cm thick W layer (90 vol% W alloy and 10 vol% PCA) followed by a 1 cm thick coolant channel (90 vol% $H_2O/LiNO_3$ and 10 vol% PCA), then a 7 cm W layer followed by a 1 cm coolant channel. The next W layer could be as thick as 15 cm. Figure 5 illustrates the optimal arrangement of the various layers of the 48 cm thick i/b shield. It should be mentioned that this layered shield design preserves the same material volume content as that of the homogeneous shield. Moreover, the end-of-life fast neutron fluence for the layered shield is minimized at 7.7×10^{18} n/cm^2 for an 8 cm thick back layer of the $H_2O/LiNO_3$ shield.

The radiation effects in the inner legs of the TF coils are reported in Table 1. Our estimates indicate that the nuclear heating in the straight inner legs amounts to >50% of the total nuclear heating in the TF coils. As noticed, the optimal shield provides more shielding than the design goals

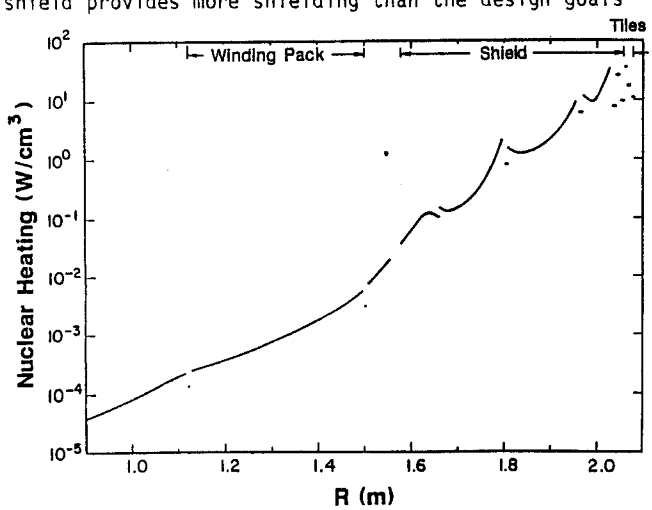

Fig. 4. Nuclear heating distribution at the midplane of the i/b shield and magnet.

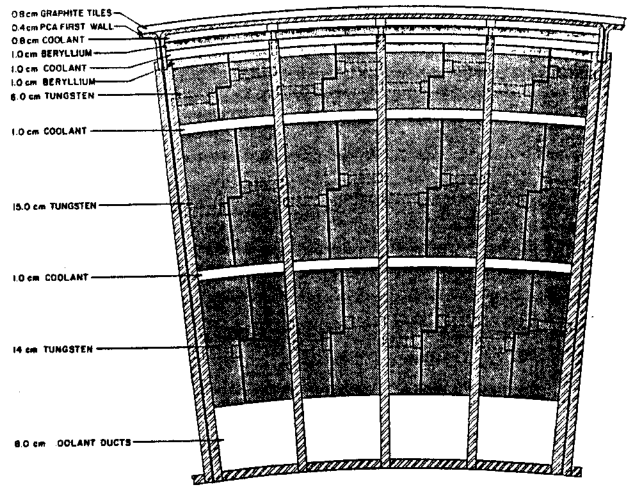

Fig. 5. Schematic of the inboard shield.

and in order to increase the tritium breeding capability of both the i/b and o/b shields, the front 2 cm of the W-shield was replaced by beryllium. This change results in a slight increase in the neutron fluence, as indicated in Table 1, and a 10% increase in the overall tritium breeding ratio of TIBER-II.

Table 1. Radiation Effects in TF Coils

Front two cm in W-Shield	W	Be
Peak fluence to Nb_3Sn (n/cm^2 @ 2.5 FPY)	7.72×10^{18}	9.3×10^{18}
Peak nuclear heating in winding pack (mW/cm^3)	4.65	5.55
Peak dose in GFF polyimide (rad @ 2.5 FPY)	1.04×10^{10}	1.25×10^{10}
Peak dpa rate in Cu stabilizer (dpa/FPY)	2.8×10^{-3}	3.4×10^{-3}
Nuclear heating in straight inner legs of:		
winding packs (kW)	10	12
coil cases (kW)	15	17

Mechanical Design and Thermal Hydraulic Analysis

The i/b shield is envisaged to consist of W alloy plates oriented circumferentially with vertical coolant channels located strategically throughout as shown in Fig. 5. The first wall is made of 0.8 cm thick protective graphite tiles attached to a 0.4 cm thick PCA plate which is followed by a cooling channel. The layering of the shielding material is progressively thicker. The W plates are encapsulated in PCA structure and then impregnated with lead. During normal operation the lead is solid and provides good thermal contact between the plates and the cladding material, and also provides rigidity to the assemblage.

The thermal hydraulics of the i/b shield is straightforward. Heat transfer coefficients as functions of velocity are obtained from forced convection correlations for turbulent flow in vertical passages between parallel plates, using the properties of $H_2O/LiNO_3$ aqueous solution. Similarly, pressure drop calculations are made which show that even for velocities of 4 m/s the pressure drops are trivial.

Figure 4 shows the nuclear heating as a function of radius. The average surface heat is taken as 25 W/cm^2. Mass flow rates in each cooling passage are adjusted to insure that the hot spot is consistent with the coolant conditions used for the o/b shield. The hot spot in the i/b shield occurs on the rear surface of the second cooling passage and for an inlet temperature of 40°C is equal to 93°C. The maximum coolant velocity is 3 m/s and the maximum pressure drop is <.01 MPa. The temperature peaks at the centerlines of the W zones. The maximum temperature is 198°C and the melting temperature of lead is 327°C. The design pressure is the same as for the o/b shield, 0.2 MPa, although the pressure drop in all channels is <.01 MPa. Table 2 gives the thermal hydraulic parameters of the i/b shield.

Table 2. Thermal Hydraulic Parameters

Thermal power (MW)	74
Mass flow rate (kg/s)	1231
Inlet coolant temp. (°C)	40
Avg. coolant outlet temp. (°C)	55.8
Hot spot temp. (°C)	79.4
Design pressure (MPa)	0.2

Hot Spots at TF Magnets

The radiation effects at the magnet reported so far were determined using a 1-D code where the PCA structure was treated as uniformly distributed throughout the shield. Any change in the shield arrangement could result in higher radiation effects at the magnets than the nominal values reported therein. For instance, the detailed mechanical design of the i/b shield and the presence of the assembly gaps between the shield sectors can lead to local hot spots in the inner legs of the TF coils. These hot spots can best be quantified using a two-dimensional (2-D) code as discussed below.

There are 16 identical i/b shield sectors to protect the inner legs of the 16 TF coils. The radial ribs and assembly gaps provide a relatively clear path for the neutrons to stream through and produce local hot spots in the magnets. Although there are no windings behind the assembly gaps, these gaps cause damage peaking at the corners of the windings that are close to the gaps. The problem was modeled for the 2-D code TWODANT in x-y geometry as shown in Fig. 6. The peaking factors, defined as the value at the hot spot divided by the nominal value obtained from the 1-D calculations for uniformly distributed PCA structure, are determined behind the steel ribs and at the corner of the coil. These locations are indicated in Fig. 6 by I, II, and III at the coil. The results show that the peaking factors for the fast neutron fluence are 1.25, 1.43, and 1.78, respectively, and the corresponding values for the nuclear heating are 0.96, 1.08, and 1.15. As noticed, the highest radiation effects occur at the corner of the coil. This is due to the combined effects of the assembly gaps and radial ribs. Moreover, the peaking factors are less pronounced for the nuclear heating than for the fluence. The reason is that while the lead is not effective in reducing the neutron fluence, it helps absorb the neutron-induced gamma rays which cause most of the heating in the magnet.

It is important to mention that the nuclear data sensitivity analysis performed for the TIBER-II study [1] indicated that the uncertainties in the calculated magnet radiation effects due to the uncertainties in the nuclear data of the i/b shielding materials amount to ± 35%. With a peaking factor of 1.8 due to the detailed mechanical design of the i/b

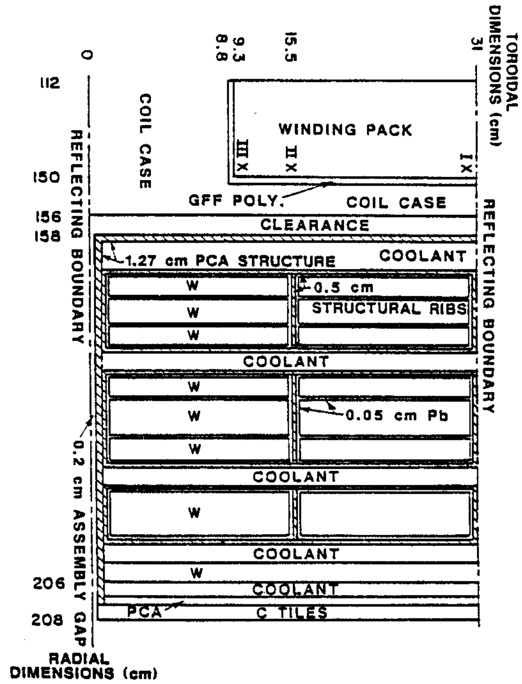

Fig. 6. Schematic of the inboard shield sector modeled for the 2-D calculations.

shield, values up to a factor of 2.4 of the calculated magnet radiation effects could be obtained at the hot spots. Nevertheless, this is lower than the safety factor of 3 considered in the study. Therefore, the maximum local hot spot values expected in the TF coils are 2.2 x 10^{19} n/cm^2 @ 2.5 FPY, 13.3 mW/cm^3, 3 x 10^{10} rads @ 2.5 FPY, and 8.2 X 10^{-3} dpa/FPY for the fast neutron fluence, nuclear heating, dose in the GFF polyimide, and dpa in the Cu stabilizer, respectively. The radiation effects at the hot spots are below the design limits and the Cu damage implies that 4 magnet anneals are needed during reactor life.

Conclusions

The optimization study of the i/b shield has led to a simple design composed of W alloy and $H_2O/LiNO_3$ aqueous solution. The shield is designed in alternate layers of W plates and coolant channels so that the neutronics, thermal hydraulics, and structural requirements are all satisfied. In the TF coils, several hot spots were identified as a result of the detailed mechanical design of the shield and even at these hot spots the magnet radiation limits are all met.

Acknowledgment

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