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

L.A. El-Guebaly, I.N. Sviatoslavsky

October 1987

UWFDM-736

Presented at the 12th Symposium on Fusion Engineering, 12-16 October 1987, Monterey CA; published in Proc. IEEE.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
High Performance Inboard Shield Design for the Compact TIBER-II Test Reactor

L.A. El-Guebaly, I.N. Sviatoslavsky

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

http://fti.neep.wisc.edu

October 1987

Presented at the 12th Symposium on Fusion Engineering, 12-16 October 1987, Monterey CA; published in Proc. IEEE.
HIGH PERFORMANCE INBOARD SHIELD DESIGN FOR THE COMPACT TIBER-II TEST REACTOR

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

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/m² neutron wall loading. The primary requirement for the shield is to limit the fast neutron fluence to $10^{19}$ n/cm². 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$_2$O/ 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 m² 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$_2$O/LiNO$_3$ aqueous solution (16 g of LiNO$_3$/100 cm³ of H$_2$O) 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.

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$_3$Sn superconductor is taken as $10^{19}$ n/cm². 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/cm³ 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 $1.3 	imes 10^{-1}$ rads. The neutron-induced damage in the Cu stabilizer is limited to $6.2 	imes 10^{-3}$ dpa so that the total resistivity of Cu does not exceed 3 ncm 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/m². 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% Nb3Sn, 6 vol% G10 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 OMEGA with the MATXS data library based on ENDF/B-V in 30 neutron and 12 gamma groups, and the P₃-S₅ 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 TiH₂, B₄C, and Pb. Water, borated water, and H₂O/LIN03 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/TiH₂-shield is superior over the W/B₄C-shield in reducing the fluence. However, some safety concerns regarding the TiH₂ integrity in case of an accident have ruled out the use of TiH₂ in the I/B shield. When the W/B₄C-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 H₂O/LIN03, 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 H₂O/LIN03 as a coolant, the decision was made to use the H₂O/LIN03 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, B₄C, and H₂O/LIN03 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% H₂O/LIN03) followed by a 3.6 cm thick B₄C-shield (85 vol% B₄C at 90% d.f. and 90% ¹⁰B in B, 10 vol% PCA and 5 vol% H₂O/LIN03). 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 B₄C and coolant in the B₄C-shield.
3) Varying the thickness of the W-shield and B₄C-shield under the constraint that the total shield thickness remains fixed at 48 cm.

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% H₂O/LIN03. In the second step, the coolant content in the B₄C-shield was varied from 5 vol% to 90 vol%, trading B₄C for coolant. Figure 2 shows that the presence of B₄C at the back of the W-shield does not help the fluence. This is due to the fact that the hydrogen in the H₂O/LIN03 coolant is more effective in moderating the high energy neutrons than B₄C. On the other hand, B₄C is superior in reducing the nuclear heating because ¹⁰B 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 H₂O/LIN03 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 H₂O/LIN03-shield was varied under the constraint that the total shield thickness remains 48 cm. The fluence is minimized at 9.4 x 10¹⁸ n/cm² @ 2.5 FPY for 6 cm thick H₂O/LIN03-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% H₂O/LIN03 and this leads to a fluence of 7.4 x 10¹⁸ n/cm² @ 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 B₄C for H₂O/LIN03 in 3.6 cm thick back layer of B₄C-shield.](image-url)
H$_2$O/LiNO$_3$ Vol % in 42 cm W-Shield

Fig. 3. Effect of trading H$_2$O/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$_2$O/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 $7.7 \times 10^{18}$ n/cm$^2$ for an 8 cm thick back layer of the H$_2$O/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.

Table 1. Radiation Effects in TF Coils

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak fluence to Nb$_3$Sn (n/cm$^2$ @ 2.5 FPY)</td>
<td>$7.72 \times 10^{18}$</td>
<td>$9.3 \times 10^{18}$</td>
</tr>
<tr>
<td>Peak nuclear heating in winding pack (mW/cm$^3$)</td>
<td>4.65</td>
<td>5.55</td>
</tr>
<tr>
<td>Peak dose in GFF polyimide (rad @ 2.5 FPY)</td>
<td>$1.04 \times 10^{10}$</td>
<td>$1.25 \times 10^{10}$</td>
</tr>
<tr>
<td>Peak dpa rate in Cu stabilizer (dpa/FPY)</td>
<td>$2.8 \times 10^{-3}$</td>
<td>$3.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Nuclear heating in straight inner legs of:

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding packs (kW)</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Coil cases (kW)</td>
<td>15</td>
<td>17</td>
</tr>
</tbody>
</table>

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 assembly.

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$_2$O/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/cm². Mass flow rates in each cooling passage are adjusted to ensure 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 42°C is equal to 93°C. The maximum coolant velocity is 3 m/s and the maximum pressure drop is <0.1 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 <0.1 MPa. Table 2 gives the thermal hydraulic parameters of the i/b shield.

Table 2. Thermal Hydraulic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power (MW)</td>
<td>74</td>
</tr>
<tr>
<td>Mass flow rate (kg/s)</td>
<td>1231</td>
</tr>
<tr>
<td>Inlet coolant temp. (°C)</td>
<td>40</td>
</tr>
<tr>
<td>Avg. coolant outlet temp. (°C)</td>
<td>55.8</td>
</tr>
<tr>
<td>Hot spot temp. (°C)</td>
<td>79.4</td>
</tr>
<tr>
<td>Design pressure (MPa)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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 TOWART 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 shielded materials amount to ±35%. With a peaking factor of 1.8 due to the detailed mechanical design of the i/b 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 10¹⁹ n/cm² @ 2.5 FPY, 13.3 mW/cm², 3 x 10¹⁰ 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 H₂O/LiNO₃ 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

This work was performed under the auspices of the U.S. Department of Energy.

References
