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INBOARD SHIELD OPTIMIZATION AND DIVERTOR SHIELD DESIGN FOR TIBER-II

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ABSTRACT

TIBER-II is the United States' contribution to the design of an international thermonuclear experimental reactor (ITER). The compactness of the reactor has placed a premium on the design of a high performance shield to protect the toroidal field (TF) magnets particularly in the inboard (i/b) side where the shielding space is constrained to 48 cm. The use of tungsten in the i/b shield is mandatory to protect the inner legs of the TF coils against the 1.5 MW/m^2 neutron wall loading impinging on the midplane of i/b side. A shield optimization study is performed to minimize the fast neutron fluence, which is the most crucial radiation effect in the magnet. In the optimization study, the performance of various candidate materials were examined. Beside W, the evaluated materials are TiH_2, B_4C, Pb, water, borated water, and $LiNO_3$ salt in water. The optimal shield is composed of two layers: a thick W layer followed by an 8 cm thick $H_2O/LiNO_3$ layer. The peak fast neutron fluence amounts to 7.7×10^{18} n/cm^2 and the radiation limits are all met with several magnet anneals needed during reactor life. The other critical area in the TIBER-II design occurs behind the divertor plates where the shield at some places is thinned to 48 cm. W in pebble form was proposed to shield the divertor zone and the less expensive PCA pebble bed is used in regions where the shielding space is less constrained. The proposed shield arrangement provides adequate protection for the TF coils and this is verified with a two-dimensional calculation where the poloidal variation of the radiation effects in the TF coils was generated.

1. INTRODUCTION

The TIBER-II design [1] 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 primary function of the i/b shield is to protect the inner legs of the TF coils against radiation. The magnet components most susceptible to radiation damage are the Nb_3Sn superconductor filaments, Cu stabilizer, and glass-fiber-filled (GFF) polyimide electrical insulator. In addition to the damage effects, the radiation deposits its energy in the magnet and raises the winding temperature, resulting in a high cryogenic load and cost.

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 a 48 cm tungsten based i/b shield plus a 2 cm first wall. 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 helium 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 helium.

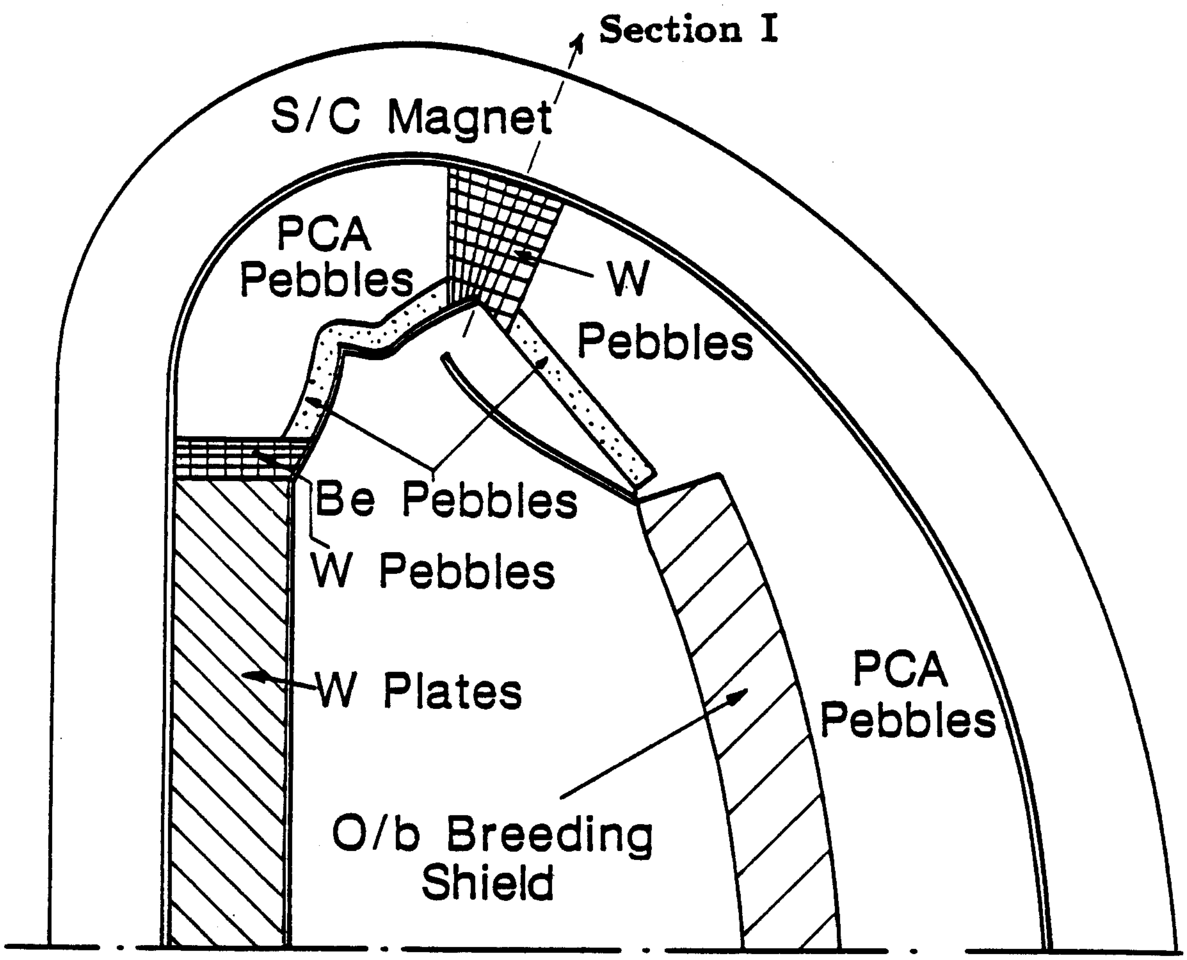

Fig. 1. A cross section through the TF coil of TIBER-II showing the different zones of the shield.

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. The limit on the fast neutron fluence (E > 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 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.

2. INBOARD SHIELD OPTIMIZATION

The highest radiation damage in the inner legs of the TF coils occurs at the midplane of the reactor where the neutron wall loading peaks at a value of 1.53 MW/m^2. The problem was modeled for radiation analysis as an infinite toroidal cylinder and the calculations were performed using the one-dimensional code ONEDANT [2] with the MATXS5 data library based on ENDF/B-V in 30 neutron and 12 gamma groups, and the P_3-S_8 approximation.

2.1 Preliminary Calculations

The use of tungsten as the main i/b shielding material is mandatory to provide adequate protection for the inner legs of the magnets. Several coolants were evaluated to assess their shielding capabilities. These coolants are water, borated water (30 g boric acid/100 cm^3 of H_2O), and water with $LiNO_3$ salt (16 g of $LiNO_3$/100 cm^3 of H_2O). PCA is used as the structural material in TIBER-II and 10 vol% of it is used in the i/b shield. Several shielding materials were considered to back the W-shield. These are B_4C (at

90% density factor [d.f.] and 90% ^{10}B in B), TiH_2 (at 90% d.f.), and Pb. Our calculations showed that replacing the last 3.6 cm of the W-shield by B_4C-shield reduces the fluence by a factor of 1.5. The corresponding value for an 8 cm thick TiH_2-shield is 2.5. When the W/B_4C-shield or the W/TiH_2-shield is backed by a layer of Pb-shield (keeping the total i/b shield thickness fixed), the fluence increases. This means that the Pb is not helping and a W/B_4C-shield or W/TiH_2-shield is more effective in reducing the fluence. These results pertain to the case of water coolant at a volume content of 15 vol% and 5 vol% in the W-shield and back layers, respectively. When the water in the shield is replaced by borated water (B-H_2O) or water with $LiNO_3$ salt ($H_2O/LiNO_3$), 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.

This preliminary study showed that the W/TiH_2-shield is preferable as it results in the least value for the fast neutron fluence. However, some safety concerns regarding the integrity of TiH_2 in case of an accident have ruled out the use of TiH_2 in the i/b shield of TIBER-II. The study also showed that B-H_2O and $H_2O/LiNO_3$ have the advantage of reducing both the fluence and the heating in the magnet. Since the outboard (o/b) 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.

2.2 Optimization Study

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 tungsten considered in the preliminary study was in powder form. Since the W powder is difficult to sinter to 100% of theoretical density and the sintered product is difficult to machine because of its brittle character, machinable tungsten alloys [3] are of interest because of the good mechanical properties, good machinability, and its ability to be sintered to practically theoretical density. The commercially available W alloys typically contain 90-97 wt% W and 3-10 wt% Ni-Fe-Cu. The high density W alloy (97 wt% W, 2 wt% Ni, and 1 wt% Fe) was selected for the i/b shield for TIBER-II as it has a high W content which results in better radiation attenuation.

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% 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, 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. The results are plotted in Fig. 2 and indicate that the fluence is 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 3 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

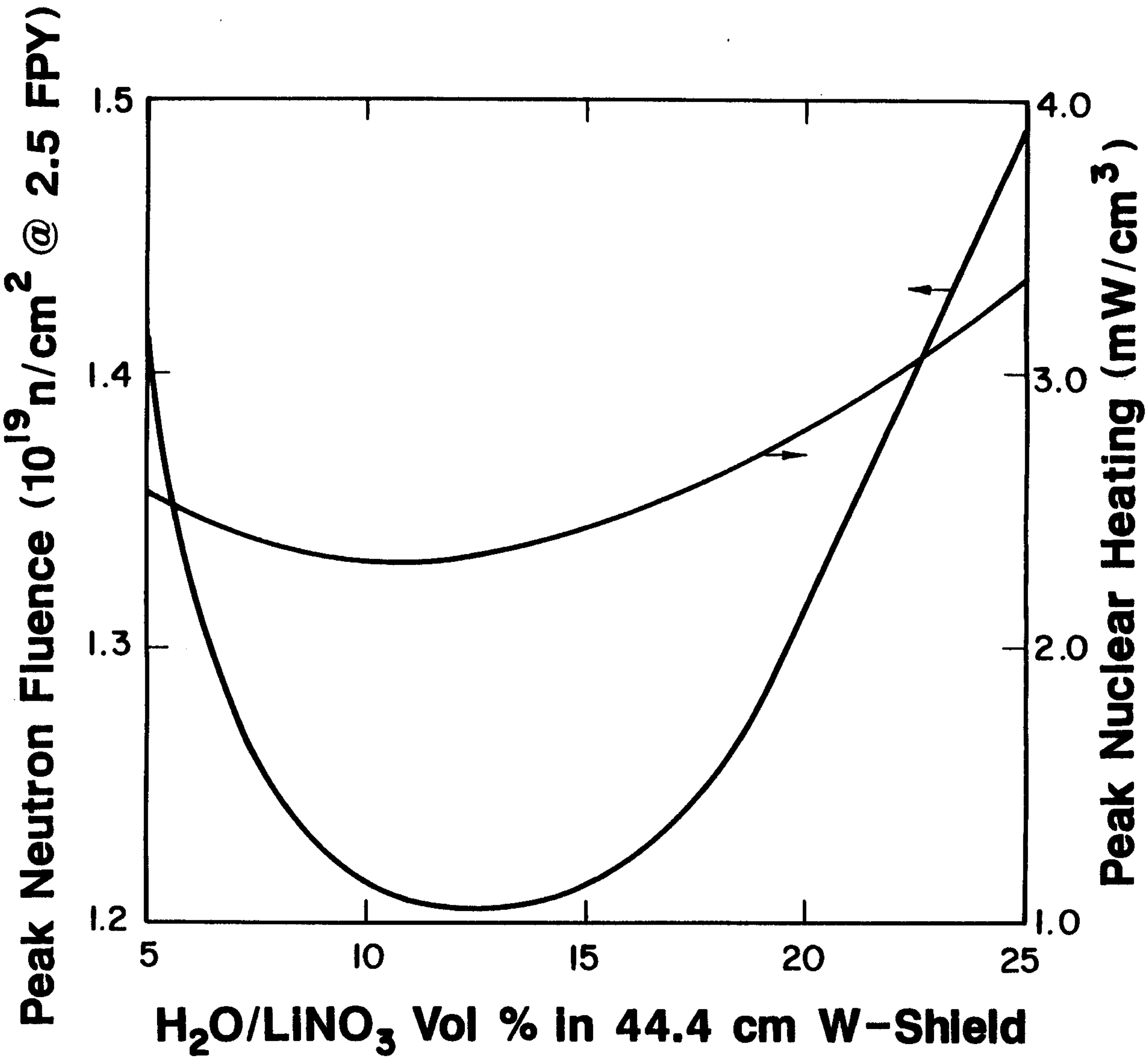

Fig. 2. Effect of trading $H_2O/LiNO_3$ for W on damage in magnet.

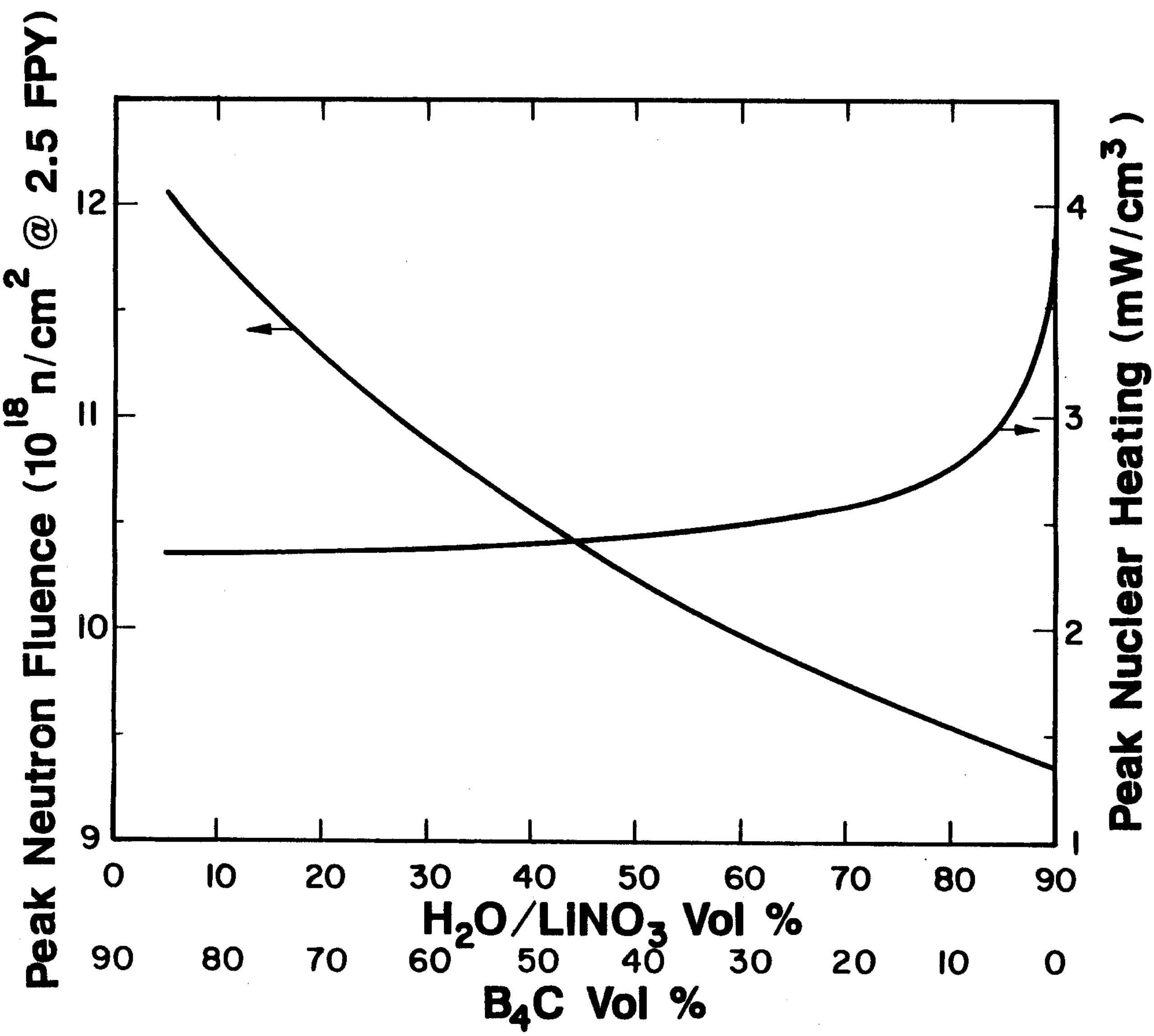

Fig. 3. Effect of trading B_4C for $H_2O/LiNO_3$ in 3.6 cm thick back layer of B_4C-shield.

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. As shown in Fig. 4, 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. 5. The minimum amount of coolant needed to cool the i/b shield is 7 vol% [4]. 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 build 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 was calculated as input to the shield thermal hydraulics calculations in order to determine the thicknesses of the various layers of the W-shield. The layered shield design that satisfies the thermal hydraulics requirements consists of a [4] 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 6

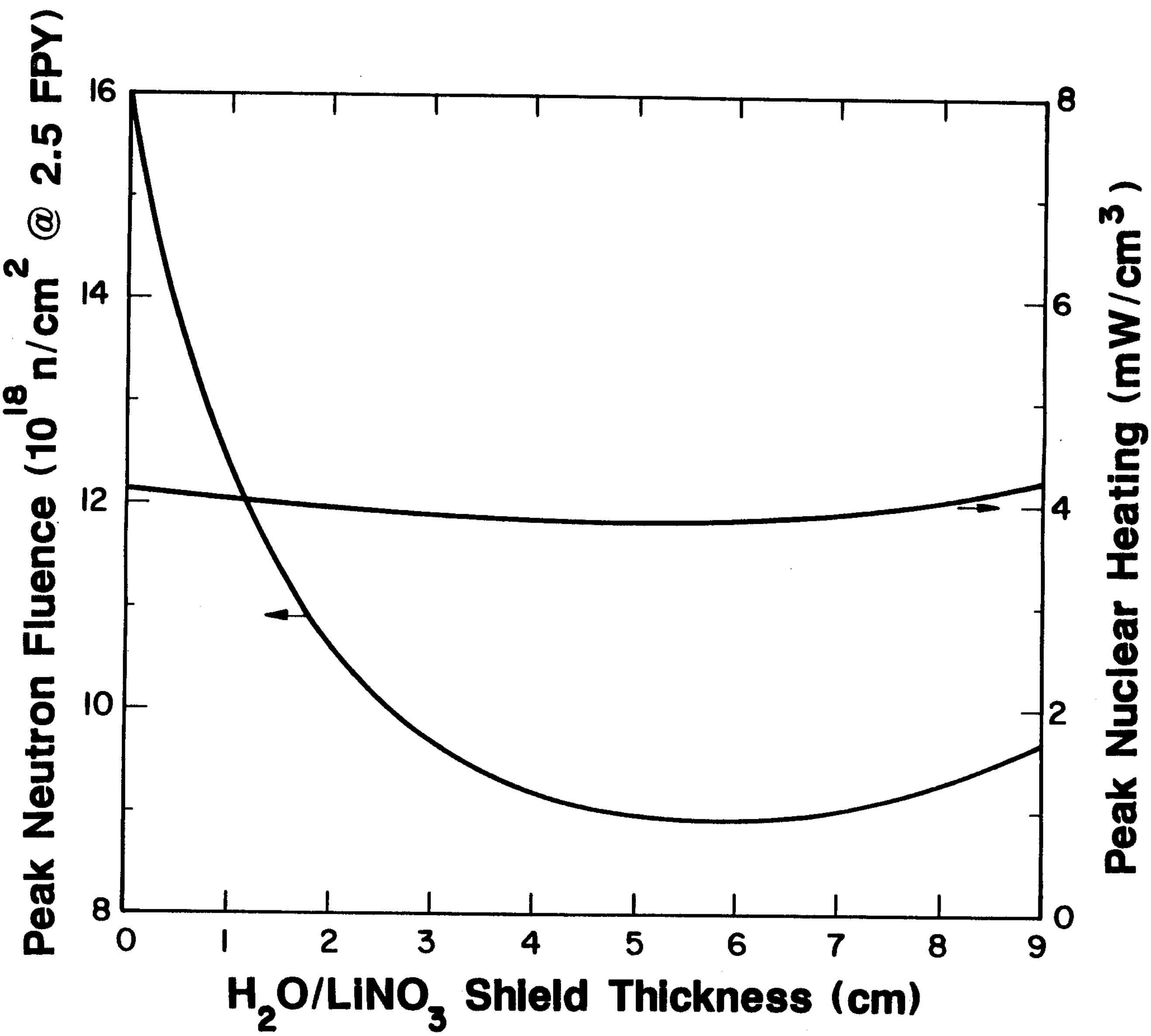

Fig. 4. Variation of the radiation effect in the coil with the $H_2O/LiNO_3$-shield thickness.

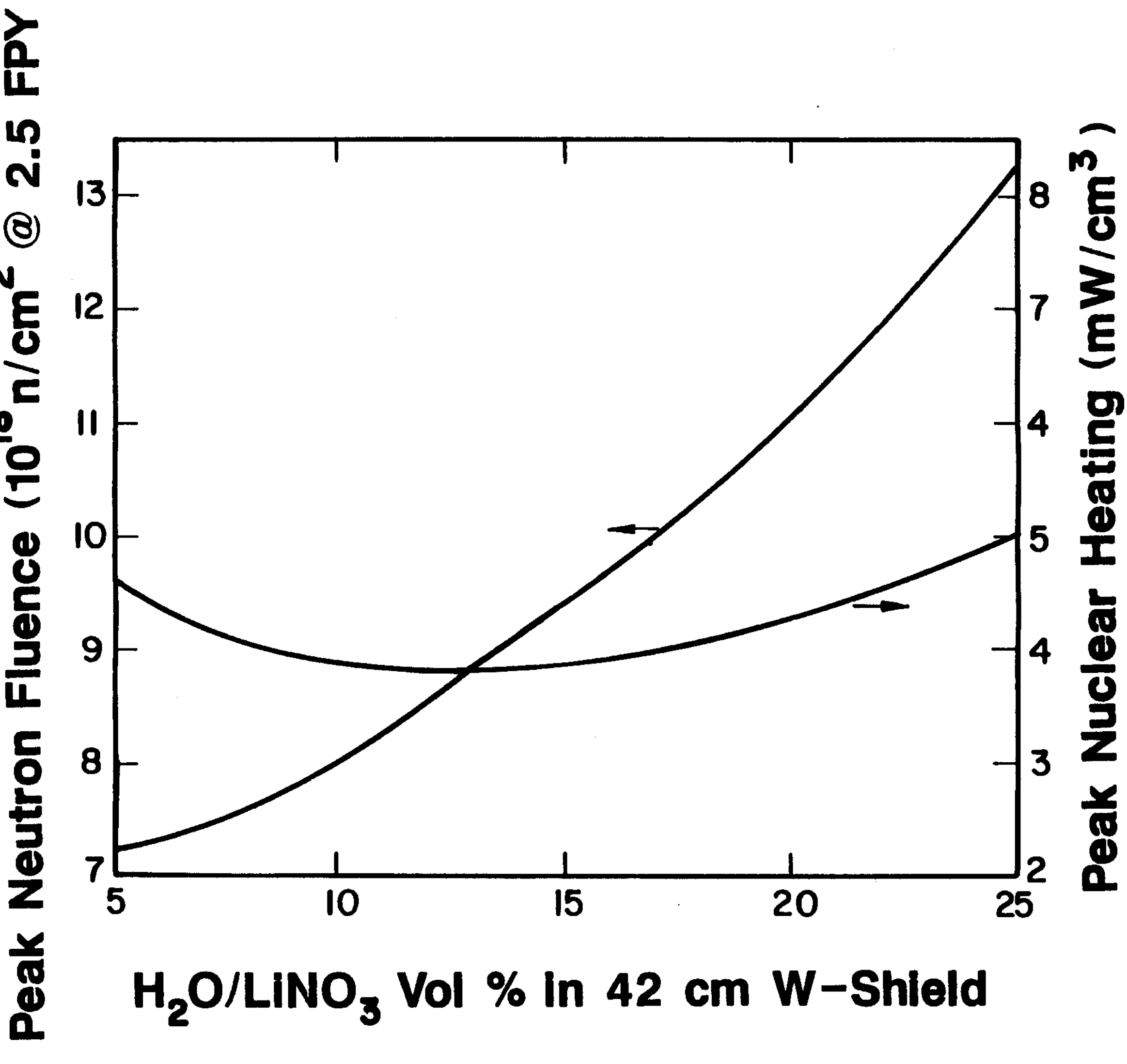

Fig. 5. Effect of trading $H_2O/LiNO_3$ for W on damage in magnet.

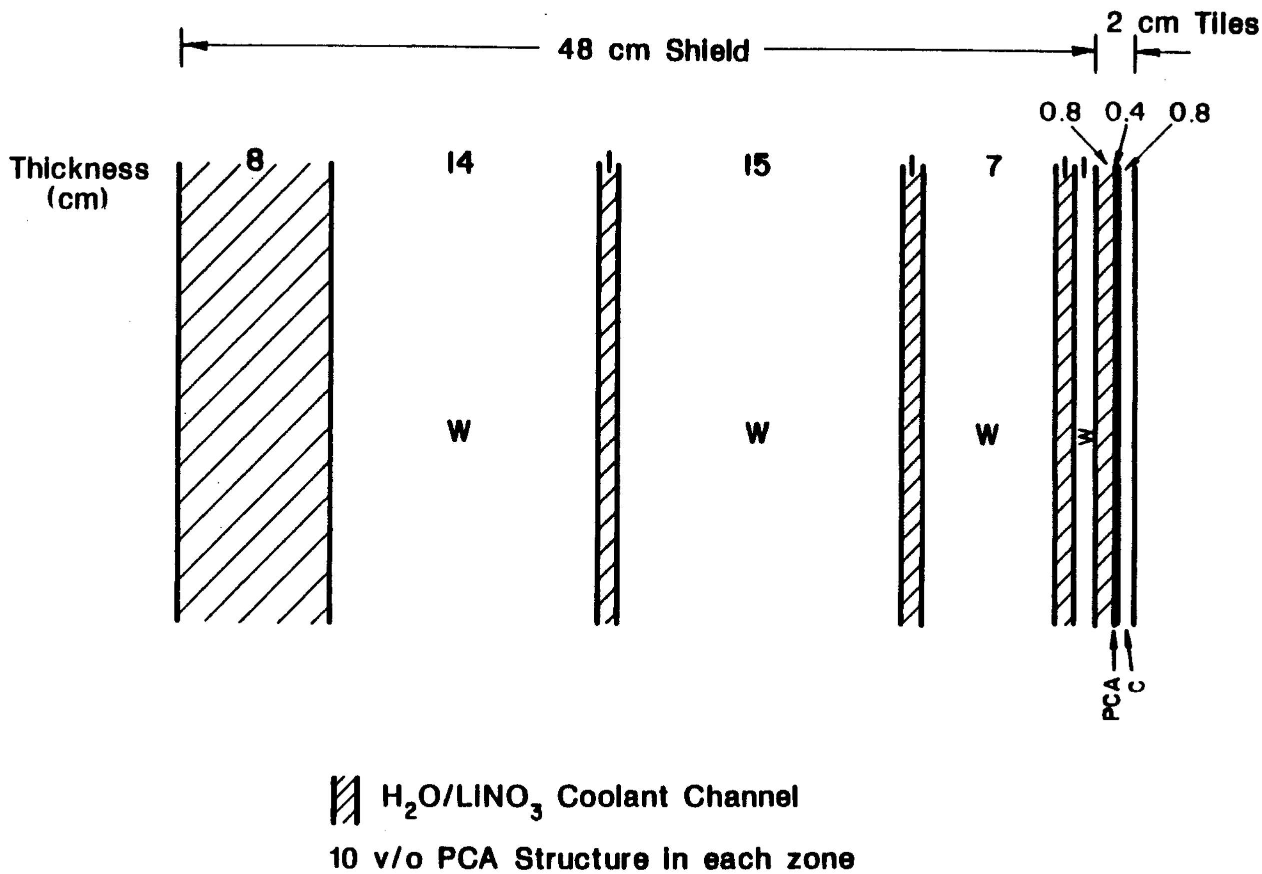

Fig. 6. Layered i/b shield configuration.

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 more than 50% of the total nuclear heating in the TF coil. The Cu damage implies that few magnet anneals are needed during reactor life. It is noticed that the optimal shield actually provides more shielding than the design goals and in order to increase the tritium breeding capability of both the inboard and outboard 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.

3. DIVERTOR SHIELD DESIGN

The divertor zone is bounded by the i/b and o/b shields, as shown in Fig. 1. The thinnest shield in the divertor zone is 48 cm thick at Section I. The wall loading in this zone is relatively low and varies from 0.6 MW/m^2 at the left boundary to 1.1 MW/m^2 at the right boundary with a value of 0.7 MW/m^2 at Section I. The most suitable form of the shield for the divertor zone is the pebble bed as it is inexpensive and simple in design. The use of W pebbles at Section I is essential to adequately protect the top and bottom parts of the TF coils. About 5 vol% PCA structure is needed in the divertor zone and the maximum volume content of the single-size W pebbles that can be

Table 1

Radiation Effects in the Inner Legs of the TF Coils for 48 cm Thick Layered Shield

Front two cm in W-Shield	W	Be
Peak fast neutron 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 pack (kW)	10	12
coil case (kW)	15	17

used is 59.4%. The rest of the space amounts to 35.5 vol% and is filled with $H_2O/LiNO_3$ coolant.

One-dimensional calculations were performed to assess the radiation effects in the portions of the TF coils behind the divertor shield using the ONEDANT code [2] and its data library, and the P_3-S_8 approximation in poloidal cylindrical geometry. At Section I, the peak fast neutron fluence, which is the most crucial radiation effect in the magnet, amounts to 7.8×10^{18} n/cm^2 @ 2.5 FPY. Other data of interest are the peak nuclear heating, the peak dpa rate in the Cu stabilizer, and the peak dose in the GFF polyimide. These are 2.2 mW/cm^3, 2.6×10^{-3} dpa/FPY, and 7×10^9 rads @ 2.5 FPY, respectively. These values pertain to the case of the all W pebbles shield. According to the inboard shield optimization study, a thin layer of $H_2O/LiNO_3$-shield (90 vol% $H_2O/LiNO_3$ and 10 vol% PCA) at the back of the W-shield helps reduce the fluence. Upon replacing the back zone of the W-shield by $H_2O/LiNO_3$-shield, the fluence is minimized at 6.9×10^{18} n/cm^2 @ 2.5 FPY for 3 cm thick $H_2O/LiNO_3$-shield. However, the inboard shield utilizes an 8 cm thick $H_2O/LiNO_3$-shield and the cooling system of the inboard and divertor shields is simplified if the 8 cm thick back layer can be extended to the divertor zone. This will result in ~ 20% increase in the radiation effects in the magnet, but the design limits can still be met.

The shield thickness in the divertor zone varies from 48 cm to 85 cm. In order to make the shield somewhat less expensive, the W pebbles can be replaced by PCA pebbles for shield thicknesses > 55 cm without resulting in excessive radiation effects at the magnet. Moreover, the front 10 cm of the PCA pebbles could be replaced by Be pebbles to enhance the tritium breeding capability of the reactor. This could be done in regions where the shield is thicker than 58 cm, as illustrated in Fig. 1. It should be mentioned that the proposed shield design of the divertor zone is strictly from a neutronics point of view and the mechanical design of the divertor zone may call for some changes in the proposed arrangement of the shield.

4. DAMAGE PROFILE IN TF COILS

The divertor shield design caused some concern. The presence of a less dense shield zone (the PCA pebbles zone) adjacent to a dense shield zone (the W pebbles zone) could result in a higher magnet damage than expected at the back of the dense shield. This coherent effect of the adjacent shield zones with widely different compositions can best be determined by a 2-D code. Therefore, the shield arrangement of Fig. 1 was modeled for the TWODANT code [5] for the case of Be in the front 2 cm of the i/b W-shield and an 8 cm thick layer of $H_2O/LiNO_3$-shield at the back of both the i/b and divertor shields. The calculations were performed in a r-z geometry and an effort was made to minimize the geometrical approximations of the shield. The actual plasma D-shape was modeled for the code. The poloidal variation of the peak fast neutron fluence in the TF coil is shown in Fig. 7. The results are normalized to the fluence value at the midplane of the i/b shield. The vertex of the poloidal angle is taken at the 3 m plasma major radius.

By inspection of Fig. 7, several observations can be made: 1. The divertor shield design does not affect the damage at the midplane of the inner legs of the TF coils; 2. The highest radiation effects in the divertor zone occur at the boundary between the W and PCA pebble zones on the outboard side; 3. The peak radiation effects in the divertor zone are still below the design limits; 4. The ripples in the curve are due to the change in the composition, thickness, and neutron wall loading at the different zones of the shield;

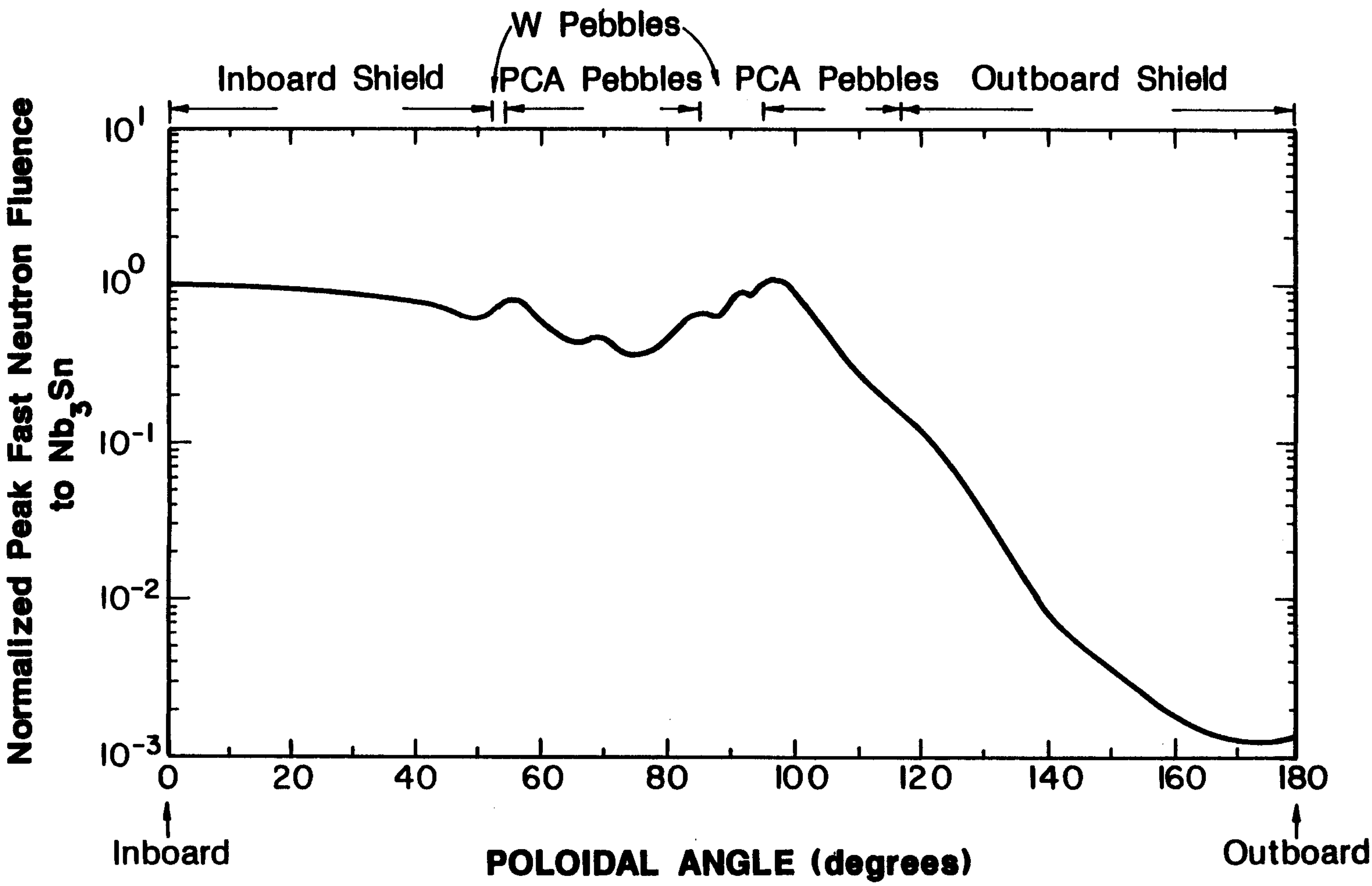

Fig. 7. Poloidal variation of the fluence in the TF coils.

5. The damage in the outer legs at the reactor midplane is three orders of magnitude lower than that at the inner legs of the TF coils.

CONCLUSIONS

The optimization study has led to a high performance inboard shield design that satisfies all radiation limits at the TF coils. Some arrangement of the shielding materials in the divertor zone was proposed based on the neutronics viewpoint. The poloidal variation of the damage in the TF coil was generated and it validated the proposed arrangement of the shield.

ACKNOWLEDGMENT

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