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TUNGSTEN VERSUS STEEL IN INBOARD SHIELD OF ITER:
IMPACT ON MAGNET DAMAGE, REACTOR SIZE, AND COST

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ABSTRACT

The shield design of ITER is required to meet both magnet protection requirements and safety-related criteria. Although the W provides excellent magnet protection, its high specific decay heat caused some concern in case of an accident. A trade study was carried out in which W is replaced by steel in the high neutron flux zones of the inboard shield and the sensitivity of the machine size, cost, and magnet damage to such change was determined. Satisfying the 10^{19} n/cm^2 fast fluence limit for the magnet, the direct cost is essentially the same for the steel and W shields, although the steel shield is 0.1 m thicker. The 0.55 m thick inboard shield of ITER is configured in 3 main layers: a 0.05 m Be layer, followed by a 0.18 m steel layer, then a 0.18 m W layer. Five coolant channels, each 0.01 m wide, are properly distributed across the shield. About 0.1 m thick layer of aqueous Li salt solution at the back of the shield was found necessary to minimize the damage in the magnet. This design meets the neutronics, safety, and thermal hydraulics requirements and there appears to be no feasible problems associated with it.

INTRODUCTION

The inboard (i/b) shield is responsible for protecting the inner legs of the toroidal field (TF) magnets. The thickness of the shield is dependent on the radiation damage allowance for the magnet, the shielding materials used, and the level of neutron production in the reaction chamber. The philosophy of the shield design is to meet both the magnet protection requirements and the safety-related criteria. The latter has imposed some constraints on the material selection and location so that the reactor components will not be harmed by the shield decay heat during any abnormal operation.

The U.S. team has designed a compact version for the International Thermonuclear Experimental Reactor ITER. The design calls for a major radius of 4.04 m and provides a 0.55 m space for the i/b shield. The neutron wall loading peaks at the midplane at a value of 1.47 MW/m^2. The reactor operates at a fusion power of 631 MW. During its planned 15 year life, 2.9 full power years (FPY) of DT operation are expected. The configuration of the ITER i/b shield is based on an earlier work done on the compact TIBER-II reactor, in which an extensive optimization study was performed for a tungsten-based shield cooled with the aqueous Li salt solution.[1] The shield is envisaged to consist of W layers oriented circumferentially with vertical coolant channels and the layering of the W is progressively thicker. Although the W provides excellent magnet protection, its high specific decay heat, particularly in the front layers of the shield, caused some concern in case of LOCA/LOFA accidents, as indicated by the activation and safety analyses. This suggested the selection of different materials and/or the relocation of various components. On this basis, a trade study was carried out in which W is replaced with steel and the sensitivity of the machine size, cost, and magnet damage to such a change was determined.

MAGNET RADIATION LIMITS

The radiation limits for the TF magnets are of importance since they determine the required shield thickness that directly influences the cost of the reactor. The superconducting magnet components most sensitive to radiation damage are the superconductor filaments, stabilizer, and organic insulators. In addition to its effect on winding pack temperatures, nuclear heating affects the economic performance of the reactor through increased refrigeration costs. It is important to mention that all radiation effects are related as they are determined by the flux level at the magnet.

The effect of radiation on the critical properties of the superconductor material is related to the damage produced by fast neutrons through the production of defect cascades.[2] The amount of produced damage is usually measured in displacements per atom (dpa) or, more practically, damage energy available per atom in eV/atom. Due to the steep variation of the damage energy cross section with energy, the damage produced by the same neutron fluence in different facilities will be different depending on the neutron spectrum. The relative number of neutrons that produces equal damage in superconductors as that produced by one neutron in RTNS-II was calculated by Guinan et al.[2-4] to be 5.74, 7, 3.68 and 4.7 for HFBR, TFCX, STARFIRE and MARS, respectively. We calculated the corresponding numbers for MINIMARS and ITER to be 5.1 and 4.3, respectively.

Figure 1 shows the experimental data for the effect of irradiation on the critical current density (J_c) compared on a damage energy basis. An initial rise in J_c was observed with a subsequent drop at high fluences. Comparing the results of higher temperature HFBR irradiation[4] with the 4 K irradiation of the nearly identical monofilament sample[3] indicates that high temperature irradiation yields larger J_c degradation. This is due to defect mobility and subsequent cascade collapse during the high temperature irradiation resulting in a lower flux pinning. Hence, using the high temperature irradiation data yields conservatively low fluence limits. Recently, two commercial Nb_3Sn wires supplied by two manufacturing companies have been irradiated at 4.2 K in RTNS-II to a 14 MeV fluence of 1.3×10^{18} n/cm^2 (~ 6×10^{18} n/cm^2 in ITER).[5] At this fluence, the two wires have J_c values that are above their preirradiation values by factors of 1.8 and 1.5. Based on these data, a fast neutron fluence limit of 10^{19} n/cm^2 is used in ITER.

Experimental data for fiber-reinforced organic insulators indicate that the mechanical properties degrade at a lower dose than do the electrical ones. Polyimides are 5 to 10 times more radiation resistant than epoxies. Reviewing the available 5 K irradiation experimental data, it was found that the best glass-fiber-filled (GFF) epoxy retained 75% of the mechanical strength for doses up to 10^9 rads. The corresponding dose for the best GFF polyimide is 10^{10} rads.[6] Recently, 0.5 mm-thick disks of GFF organic insulators were irradiated at 325 K to a mixed gamma and neutron dose of $\simeq 4 \times 10^{11}$ rad and tested in compressive fatigue.[7] No failures were observed for the insulators containing S-glass when cycled to a 345 MPa stress for over 1.5×10^5 cycles. No failures were observed in static compression tests with 2750 MPa stress.[7] In these experiments, no interlaminar shear occurs and the results are applicable to designs with compressive strains only. The dose limit recommended for ITER is 10^{10} rads for GFF polyimides with the possibility of raising the limit to ~ 4×10^{11} rads if the magnet is designed with the insulator loaded in compression only. Notice that in this case the insulator dose will not be a design driver since this dose corresponds to an excessive fast neutron fluence of ~ 4×10^{20} n/cm^2.

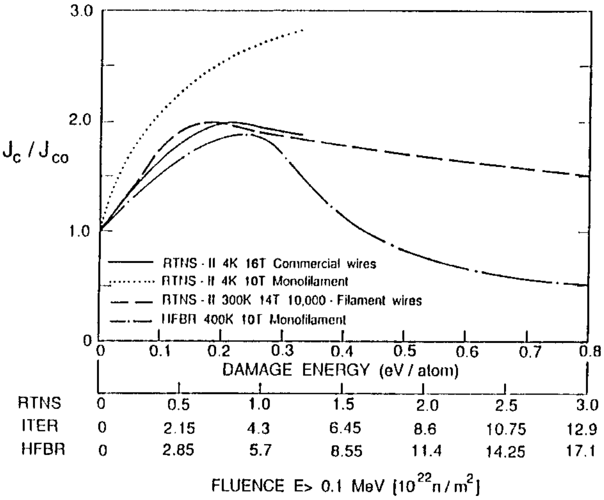

Fig. 1. Experimental data for the effect of irradiation on J_c compared on a damage energy basis.

Neutron irradiation at cryogenic temperature produces immobile point defects in the stabilizer resulting in a zero-field radiation induced resistivity $\Delta\rho_r$ which impacts the total resistivity at field. Based on Kohler's plot for Cu, we generated a chart relating $\Delta\rho_r$ to the total resistivity at field given the field B and the residual resistivity ratio RRR of Cu.[8] The effect of stabilizer resistivity increase on both magnet stability and protection is design dependent. The forced-flow cable-in-conduit conductors (CICC) used in ITER are less sensitive to the Cu resistivity increase. Stability against disturbances is more dependent on the heat capacity of helium and less limited by heat transfer and Cu conductivity as with typical cryostable conductor designs. The total Cu resistivity in ITER is limited to 3 nΩm by stability and protection considerations. For a field of 12 T and Cu RRR value of 100, the charts of Ref. 8 imply a limit on radiation induced resistivity of 2.33 nΩm. This corresponds to a dpa limit of 6.3×10^{-3} dpa. Using this limit and the calculated peak dpa rate in the stabilizer one can determine the number of anneals required for the total resistivity not to exceed 3 nΩm taking into account the 80-90% recovery of defects with annealing.[8]

The main effect of nuclear heating in a force-cooled CICC design is the coolant and conductor temperature rise from inlet to outlet. This can be reduced by shortening the flow path and/or increasing the mass flow per path. The total nuclear heating limit required to maintain adequate temperature and stability margins needs to be provided by the magnet designers. A total heating limit of 72 kW for TIBER-II resulted in a temperature margin of > 1 K and a stability margin of > 300 mJ/cm^3.[9] This limit is used as a guide in the ITER shield design.

TUNGSTEN VERSUS STEEL TRADE STUDY

The neutronics analysis of the i/b shield has indicated that satisfying the fast neutron fluence limit for the TF magnets is the design driver for the i/b shield. On this basis, an optimization study was performed and the i/b shield that minimizes the fluence was found to consist of a thick W shield followed by an 0.08 m thick aqueous Li salt (LiNO$_3$ or LiOH) layer.[1] In order to meet the thermal hydraulics requirements, the W shield was configured into alternating W layers and coolant channels. The layering of the W shield is progressively thicker. Thickness constraints of 0.01 and 0.07 m are imposed on the first and second layers of the W shield, respectively. The next W layers could be as thick as 0.15 m. The W shield and aqueous Li salt coolant channels contain 15 vol% and 4 vol% structure, respectively. The primary candidate alloy (PCA) is used as a representative of the structural material of the shield. In addition to the 0.57 m thick i/b shield and first wall, the rest of the space between the plasma edge and the winding pack consists of a 0.1 m scrape-off zone, a 0.06 m gap behind the shield, a 0.05 m coil case and a 0.005 m electric insulator. The coil case is cooled with 5 vol% liquid helium and the winding pack is composed of 38 vol% 304 SS, 28 vol% Cu, 7 vol% Nb$_3$Sn, 7 vol% GFF polyimide, and 20 vol% liquid helium.

Although the W provides an excellent protection for the TF magnets, the activation and the safety analyses[10] of the i/b shield have identified several drawbacks to using W. The W has higher specific decay heat than steel and that makes the i/b shield vulnerable to significant damage and public safety risks under LOCA/LOFA accident conditions. In order to design an inherently safe i/b shield, the decision was made to replace the W by steel, particularly in the plasma-facing components of the shield where the neutron flux is high and the decay heat problem is most severe.

Three iron-based materials are considered for the i/b shield. These are PCA, boron steel (B-SS), and iron boride (FeB). The problem was modeled for radiation analysis as infinite toroidal cylinders around the machine axis and the calculations performed using the one-dimensional (1-D) code ONEDANT[11] 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 radiation effects at the TF magnets are reported in Table 1 for the different shielding materials. Our estimates show that the nuclear heating in the straight legs of the TF coils amounts to ~ 70% of the total heating in the 16 TF magnets. The W shield yields the lowest radiation effects at the magnets, followed by the FeB shield, then the B-SS shield and the PCA shield. As indicated by the fluence, the W actually overshields the magnets while the PCA and B-SS do not provide the necessary shielding.

The effects of the i/b shielding material and thickness on the plasma parameters, overall size and cost of ITER were assessed using the TETRA systems code with the assumptions and constraints used to generate the ITER design base case. The i/b shield thickness was varied over the range 0.5-0.75 m. The results show that the fusion power, reactor size, and thus cost increase with the i/b shield thickness. For each centimeter increment in the i/b shield the major radius changes by ~ 0.015 m. Figure 2 shows the variation of the direct cost with the i/b shield thickness for both W and Fe based shields, assuming the same unit cost for PCA,

Table 1. Radiation Effects in Inner Legs of the TF Magnets
for the Nominal ITER Baseline Design

Shield Type	W	PCA	B-SS	FeB
Peak Fast n Fluence (10^{19} n/cm^2 @ 2.9 FPY)	0.31	1.59	1.24	0.82
Peak Nuclear Heating in Winding Packs (mW/cm^3)	1.81	10.49	4.69	2.45
Peak dpa rate in Cu (10^{-3} dpa/FPY	0.97	5.03	3.88	2.41
# of Anneals Required for Cu resistivity < 3 nΩm	1	∞	10	4
Peak Dose to GFF Polyimide (rads @ 2.9 FPY)	4.26×10^9	2.33×10^{10}	1.34×10^{10}	7.69×10^9
Nuclear Heating in Straight Legs (kW):				
Winding Packs	5.33	29.06	16.6	9.63
Coil Cases	9.13	54.01	20.49	9.70

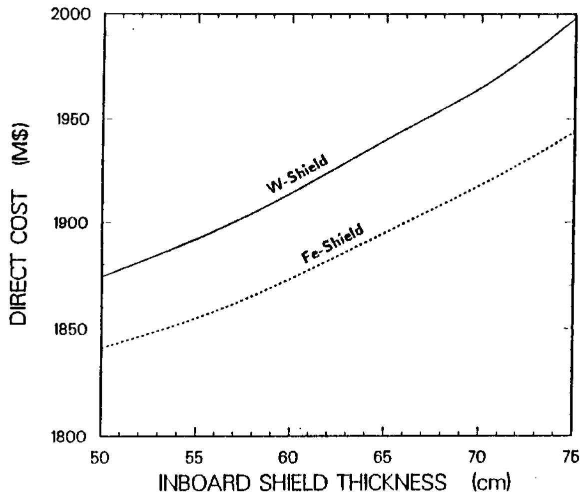

Fig. 2. Effect of the i/b shield thickness on the direct cost of ITER.

B-SS, and FeB shields. The direct cost increase is ~ \$5 M and \$4 M per centimeter increase in the W and steel shields, respectively. Neutronics calculations were then performed for each i/b shield thickness using the different shielding materials to determine the peak radiation effects in the TF coils. This led to the attenuation curves shown in Fig. 3. These curves indicate that the required shield thicknesses to meet the 10^{19} n/cm^2 fluence limit are 0.475, 0.58, 0.56 and 0.53 m for the W, PCA, B-SS, and FeB shields, respectively.

It is interesting to combine Fig. 2 and 3 to generate the variation of the direct cost with the fluence at the magnets. This variation is given in Fig. 4 and there are several features that should be noted. Satisfying the 10^{19} n/cm^2 fast fluence limit for the magnet, the direct cost is essentially the same for the PCA and W shields, although the inboard shield is 0.1 m thicker for the PCA shield. At this fluence, the higher cost of the W shield is offset by the lower cost of the smaller size TF magnets. Importantly, the PCA shield improves the reactor safety at no additional cost. The use of steel shield is cost effective only for higher radiation limits than those adopted for the ITER study. For lower fluence limits, the use of W instead of steel is beneficial in terms of smaller TF magnets and, thus, considerably lower direct cost. For ITER-type devices, the penalty for employing an order of magnitude lower fluence limit is about \$65 M increase in the direct cost and ~ 0.25 m increase in the major radius. Because of the limited data-base for the B-SS and FeB materials, they will not be considered further in the present analysis.

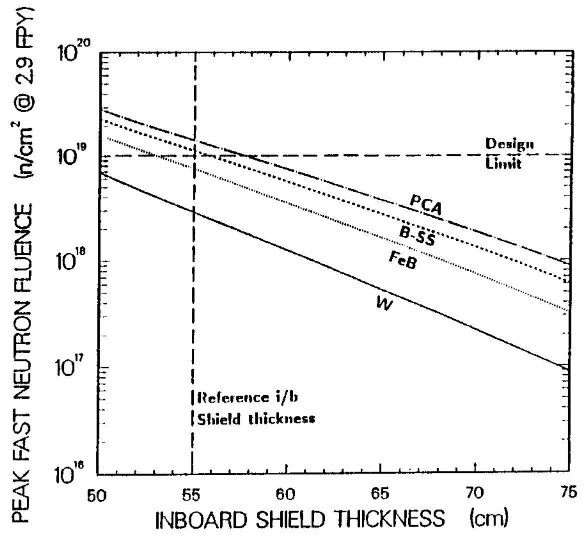

Fig. 3. Variation of the fluence at the TF magnets with the i/b shield thickness.

REFERENCE DESIGN

In the current design of ITER, where the i/b shield is 0.55 m thick, the all PCA shield resulted in radiation effects that exceed the design limits for the TF coils. In order to meet the limits without increasing the size of the machine, it was decided to combine both PCA and W in the i/b shield so that the PCA be placed in the front layers of the shield where the neutron flux is high. This offers the advantage of lessening the severity of the decay heat problem without altering the dimensions of

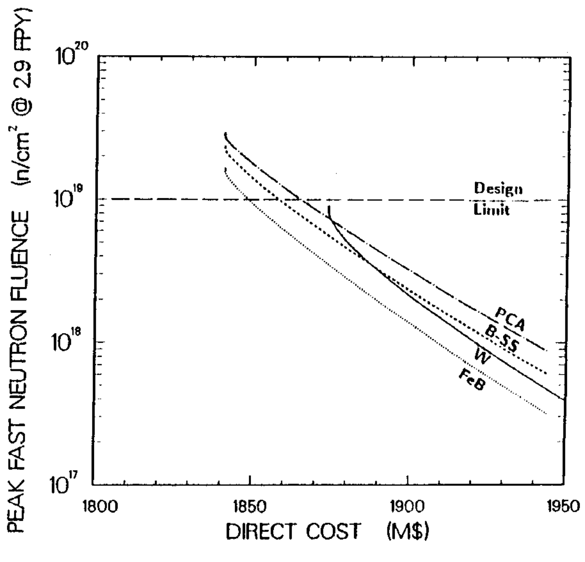

Fig. 4. Fluence at the TF magnets versus cost.

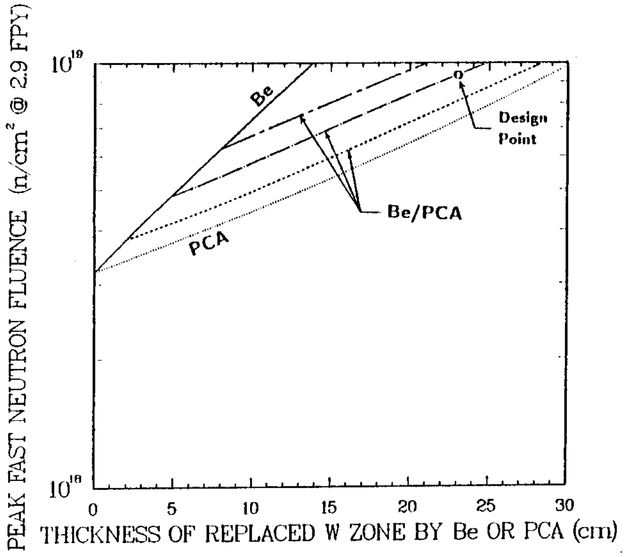

Fig. 5. Effect of replacing the front W layers of the i/b shield by Be or PCA on the fluence at the TF magnets.

the device. It was also found that several centimeters of Be behind the first wall of the i/b shield will enhance the tritium breeding capability of the reactor. Therefore, the i/b shield is configured in 3 main layers: Be layer, followed by a PCA layer, then a W layer. The thicknesses of the 3 layers were determined based on the effect the different materials have on both the damage in the magnets and the tritium breeding ratio (TBR).

The effects of replacing the front layers of W by Be or PCA on the fluence and TBR are demonstrated in Figs. 5 and 6. The TBR includes both the i/b and o/b breeding as calculated in the toroidal 1-D model. The origin of the abscissa represents the all W shield case. Of the 0.55 m thick i/b shield, 0.417 m is occupied by the W shield. As shown in the figures, replacing the W by Be or PCA increases the damage in the magnets, with a more pronounced effect for Be. The TBR varies appreciably when Be is used but does not vary strongly when PCA is used. This is because of the remarkably enhanced neutron multiplication in Be.

As illustrated by Fig. 5, there are many options for replacing the front layers of the W by Be, PCA or a combination of Be and PCA. About 0.14 m of Be or 0.3 m of PCA can replace the W without exceeding the 10^{19} n/cm^2 fluence limit for the magnets. Many combinations of Be and PCA with a variety of thicknesses are also possible. For example, Be/PCA thicknesses of 0.02/0.26, 0.05/0.2, and 0.08/0.13 m are acceptable. Hence, the choice between the different options should be based on the effect on the

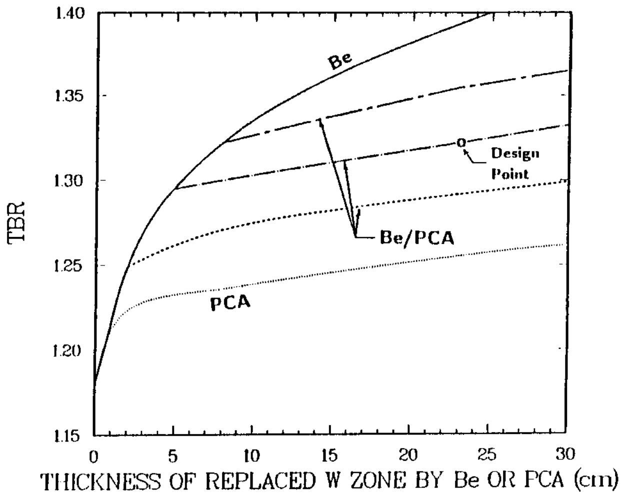

Fig. 6. Effect of replacing the front W layers of the i/b shield by Be or PCA on the tritium breeding ratio.

TBR. Figure 6 shows that significant enhancement in the TBR is achieved with a 0.05 m thick Be layer and thicker Be layers do not benefit the breeding much. Therefore, we selected the option of a 0.05 m front Be layer, followed by a 0.18 m PCA layer, then a 0.187 m W layer to be the reference design for the 0.55 m thick i/b shield of ITER.

The arrangement of the various shield layers and coolant channels is shown in Fig. 7. The thick layer of aqueous solution at the back of the shield is necessary to minimize the damage in the magnet. The neutronics results are summarized in Table 2 and show that the radiation effects slightly increase when the

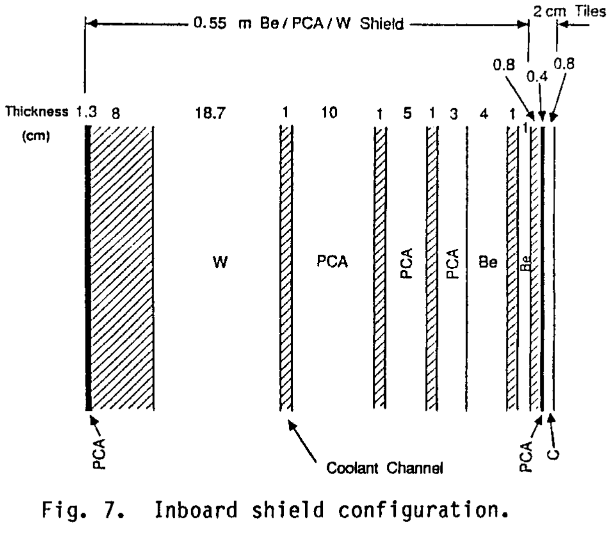

Fig. 7. Inboard shield configuration.

Table 2. Radiation Effects in TF Magnets for the 0.55 m thick Be/PCA/W Shield

Coolant	H_2O/ $LiNO_3$	H_2O/ LiOH	H_2O
Peak Fast n Fluence (10^{19} n/cm^2 @ 2.9 FPY)	0.93	0.97	1.0
Peak Dose to GFF Polyimide (10^{10} rads @ 2.9 FPY)	0.96	1.0	2.16
Peak dpa Rate in Cu Stabilizer (10^{-3} dpa/FPY)	2.8	2.9	3.1
Min. # of Anneals Needed for $\rho < 3$ nΩm	1	1	1
Peak Nuclear Heating in Winding Packs (mW/cm^3)	5.1	5.4	16.1
Nuclear Heating in Straight Legs (kW):			
Winding Packs	16	16.5	34.3
Coil Cases	25.6	26.8	109.5
Total Nuclear Heating in 16 TF Magnets (kW):			
Winding Packs	23	23.7	49
Coil Cases	36.6	38.3	156

LiOH replaces the $LiNO_3$ salt in the aqueous coolant and the design limits are still satisfied. It should be mentioned that in the non-breeding physics phase of ITER, either pure water or borated water might be employed to cool the shield. Compared to the pure water case, the borated water will result in lower radiation effects at the magnets. If pure water is used in the physics phase (0.4 FPY) and the aqueous solution is used in the breeding technology phase, the end-of-life fluence and insulator dose as well as the nuclear heating in the magnet are still acceptable.

CONCLUSIONS

The impact of the i/b shielding materials is analyzed with respect to magnet protection, reactor size, and cost. The use of a steel shield is cost effective only for higher radiation limits than those adopted for the ITER study. An arrangement of the Be, PCA, and W materials within the i/b shield of the base case of ITER was proposed. The neutronics, safety, and thermal hydraulics requirements are all met and there appear to be no feasible problems in the Be/PCA/W i/b shield design. It is hoped that this work will be valuable to the international design of ITER and serve as a basis for future analysis.

ACKNOWLEDGMENT

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