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ADVANCED INBOARD SHIELDING DESIGN FOR TOKAMAK FUSION REACTORS

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ABSTRACT

The recent physics and technology advances in the field of high power density compact tokamak reactors have established the need for advanced inboard shielding design. This work presents the design of an optimal inboard shield and assesses the limits on the radiation effects in the magnets of a high wall loading (10 MW/m^2) tokamak design. A new material, boron hydride, was identified as a potential shielding material and more optimum combinations of TiH_2, B_4C, and W were identified as well.

INTRODUCTION

Recent studies have assessed the feasibility of shaping the plasma cross section into a "bean" shape to take advantage of the higher volume average beta (10-20%), higher power output, lower magnetic field, and reduced reactor size. This work is a part of a study[1] of a compact fusion power reactor operating in the second stability regime. A cross section showing the reactor is given in Fig. 1. A normal bean coil (to produce a starting bean-shaped plasma) encircles the inner legs of the TF S/C magnets which operate in a severe radiation environment and are designed for high performance (high magnetic field, high current density, etc.). The reactor is small in both physical size and output power (~ 1000 MW_{th}). Other features include the use of a He cooled static $Li_{17}Pb_{83}$ blanket and HT-9 structure with no inboard breeding. The cost of the tokamak reactor is extremely sensitive to the inboard shield thickness. Millions of dollars could be saved for every cm shaved off of the inboard shield thickness. On this basis, methods to improve the shielding capability of the inboard region are needed by innovative materials and/or geometric design modifications.

The optimum shield design depends on the allowable radiation damage limits for the S/C magnet. The radiation effects of concern in the S/C magnet are the nuclear heat load, the atomic displacement rate (dpa) in the stabilizer, the fast neutron fluence in the superconductor,

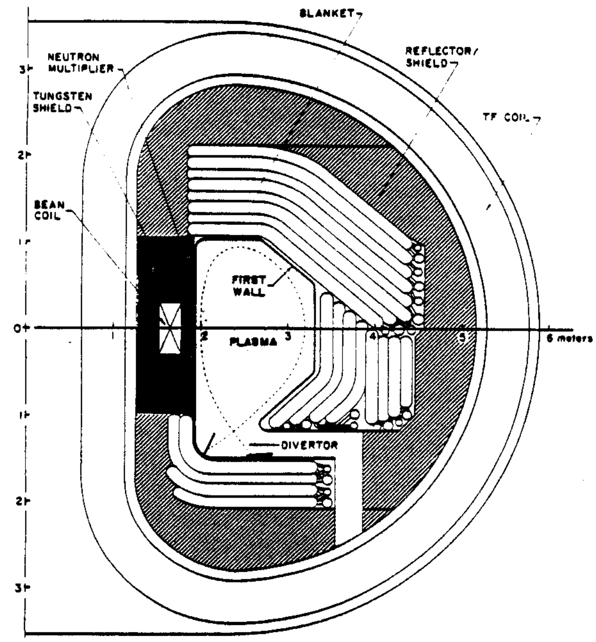


Fig. 1. Cross section of high wall loading compact tokamak reactor.

and the dose to the insulators. In the normal magnet the structural degradation of the insulator appears to be the lifetime limiting factor. The limited space available for the inboard shield to protect the S/C magnet from the intense neutron source strongly suggests the need for a shield optimization study to minimize the four most important responses mentioned above.

LIMITS ON RADIATION EFFECTS IN MAGNETS

A. Superconducting Magnet

The philosophy in this work is to use the latest information for radiation limits with possible extrapolation to future performance levels to achieve the thinnest inboard shield that protects the magnets from the severe neutron environment. The magnet components most sensitive to radiation are the superconductor, the stabilizer and the insulators. To obtain high magnetic fields, Nb_3Sn was chosen. Normal liquid helium (LHe-I) at 4.2 K is used as the coolant.

1. Damage to the superconductor. The most important property for the superconductor is the critical current density (J_c). Unlike NbTi where a monotonic decrease in J_c is observed, an initial increase in J_c with neutron fluence for Nb_3Sn was observed.[2] Most available experimental data involve irradiating the samples at fission reactor ambient temperatures.[3] Experiments with cryogenic temperature irradiation showed that the initial J_c increase is larger by ~ 10% than that obtained with reactor ambient temperature irradiation. The relative increase in J_c is also larger for higher applied fields. An 80% increase in J_c with fluence was measured at a field of 10 T after irradiation to a fluence of 4×10^{18} n/cm^2 ($E_n > 0.1$ MeV) in the High Flux Beam Reactor (HFBR) at 400 K.[3] A larger increase in J_c is expected at the field of 12.3 T considered in this study.

Room temperature annealing of Nb_3Sn results in recovering the initial increase in J_c and should be avoided. Hence, the maximum allowable neutron fluence should not be reached until the end of life of the magnet. A lifetime fluence limit of 4×10^{18} n/cm^2 has been quoted by various researchers. However, the experimental results measured at 10 T after irradiation at 400 K show that J_c drops to its preirradiation value at a fluence of ~ 10^{19} n/cm^2.[3] This implies that higher fluences can be used without degrading J_c much below its original unirradiated value. In this work we use a fluence limit of 4×10^{19} n/cm^2 (E > 0.1 MeV). This is based on the prediction that the higher fields and lower temperatures used in this design will result in larger initial increases in J_c. Furthermore, the effect of heat treatment of the Nb_3Sn superconductor filaments has not been investigated. Extensive studies for NbTi have indicated that cold work enhances J_c.

2. Damage to the stabilizer. Most designs for fusion magnets have adopted the conservative principle of cryogenic stabilization. A low stabilizer resistivity is required. Neutron irradiation at cryogenic temperatures produces immobile point defects in the stabilizer resulting in a radiation induced resistivity $\Delta\rho_r$. This radiation induced resistivity must therefore be limited to a maximum value for the magnet to be cryostable. The upper limit on the total resistivity at field B is given by

$$\rho_{max}(B) = q''_{max} A_{st} P/I^2 \ , \qquad (1)$$

where A_{st} is the stabilizer cross section area, P is the wetted perimeter and I is the conductor current. q''_{max} is the maximum heat flux that can be removed by the coolant.

Determination of the dpa rate limit in Cu is complicated by the dependence of the resistivity at the operating field on the radiation induced resistivity and the purity of Cu. Furthermore, partial recovery (80-90%) of radiation induced defects can be achieved by room temperature annealing.[4] We have generated charts for determining the maximum allowable damage rate in copper stabilizer.[5] In this design we assume a maximum S/C current density of 8×10^4 A/cm^2. The Cu:S/C ratio is taken to be 16:1 and the conductor packing factor is assumed to be 85%, implying an average winding pack current density of 4000 A/cm^2. The conductor is assumed to have a square cross section with 50% of the conductor perimeter being wetted by the coolant.

LHe-I can handle a heat flux up to 0.3 W/cm^2. The coolant must remove the I^2R heat produced in abnormal conditions and the continuous nuclear heating in the magnet. In this study, we considered q_{max} to be 0.29 W/cm^2 leaving a 0.01 W/cm^2 margin to handle nuclear heating. Cu with a residual resistivity ratio RRR = 80 is considered here. The relation between $\Delta\rho_r$ and Cu dpa obtained by Guinan[6] is

$$\Delta\rho_r = 300[1 - e^{-240\ \mathrm{dpa}}]\ n\Omega\ \mathrm{cm}\ . \qquad (2)$$

Originally, we assumed an operating conductor current of 500 A yielding a conductor size of 0.354 cm. Equation (1) yields $\rho_{max}(B)$ = 96.62 nΩ cm. The charts of Ref. 5 imply that $\Delta\rho_r$ should not exceed 17.4 nΩ cm which gives a dpa limit of 2.5×10^{-4}. The reactor life was assumed to be 24 FPY and the minimum time between magnet anneals was set to 1 FPY. Assuming a recovery fraction of 0.85, the charts of Ref. 5 indicate that the time before the first magnet anneal should be at least 4.45 FPY and the dpa rate should not exceed 5.6×10^{-5} dpa/FPY. The 66 cm thick optimized shield that gives a fast neutron fluence at the S/C of 4×10^{19} n/cm^2 was found to yield a dpa rate of ~ 1.5×10^{-3} dpa/FPY in the stabilizer. This implies that the magnet will not be unconditionally cryostable if a conductor current of 500 A is used. For unconditional cryostability without increasing the shield thickness, one must reduce the conductor current and size with the total coil cross sectional area remaining the same. The maximum conductor current that can be used for the magnet to be cryostable with a peak dpa rate of 1.5×10^{-3} dpa/FPY is 52 A. This corresponds to a conductor size of 0.114 cm.

It is interesting to note that Eq. (2) implies a saturation value of 300 nΩ cm for $\Delta\rho_r$. Hence, if the magnet is designed such that the coolant can remove the I^2R heat corresponding to the saturation radiation induced resistivity, it will be unconditionally cryostable regardless of the damage produced. In such a design, no limit needs to be specified for the dpa rate and no magnet annealing will be necessary. To achieve this, the conductor current should not exceed 35 A and the conductor size should be 0.093 cm at most. This can be achieved by designing a braided conductor placed in a steel jacket. This is possible based on experience with the Westinghouse Nb_3Sn LCP forced flow conductor. The largest damage occurs only in the innermost layers of the coil and larger conductor sizes and currents can be used in the outer layers.

3. Nuclear heating limit. The heat flux margin that can be used by nuclear heating is 0.01 W/cm^2. For the chosen conductor parameters, this corresponds to a power density of ~ 182 mW/cm^3 which does not impact the shield design. However, much lower power densities are required to avoid excessively high cryogenic refrigeration and plant costs. The 66 cm thick optimized shield used in this study yields a peak power density of ~ 1.3 mW/cm^3. Since this high power density occurs only on the inboard section of the coil where limited shielding space is available, it does not result in excessive cryogenic heat loads. The total power generated in the inboard sections of the twelve coils is ~ 3 kW.

4. Dose limit to the insulators. Mechanical strength tests have shown that polyimides are 5 to 10 times more radiation resistant than epoxies.[7] More than 65% of the compression strength of glass filled fiber (gff) polyimide is retained up to a dose of ~ 10^{10} rad. The samples are representative of relatively thick sheets of insulators placed between conductors. Both compression and interlaminar shear are important in this mode of application of the insulator materials. Recently, thin disks of gff epoxies and polyimides were irradiated at 325 K and tested at room temperature.[8] These are representative of thin sheets of insulators sandwiched between large conductor plates and held in compressive load only. The samples were irradiated to doses of ~ 4 x 10^{11} rads and static compression tests to a stress level of 2750 MPa produced no failures. This indicates that dose limits of ~ 4 x 10^{11} rads can be used for the polyimide insulator provided it is used as thin disks loaded in compression only.

The superinsulator is located in front of the magnet case and is exposed to doses higher than those in the electrical insulators. Aluminized mylar was used in previous designs as superinsulator. Recent experiments showed a large drop in its strength after irradiation to 6 x 10^8 rads while no failure was observed in aluminized Kapton up to a dose of 10^{10} rads.[9] Aluminum sheets supported with glass paper are even more radiation resistant and are used for superinsulation in this design.

B. Normal Magnet

In this magnet, there is concern with both electrical and mechanical degradation of the ceramic insulation and the electrical resistivity of the copper conductor due to neutron-induced transmutations. In addition irradiation radiolytic decomposition of water leads to corrosion/erosion product formation. Among these mechanisms, the neutron-induced swelling in the ceramic insulator was found as lifetime limiting for the normal coil.[10] The neutron fluence limits for the use of the solid polycrystalline spinel and compacted powder magnesia in normal magnets are 4 x 10^{22} and 2.35 x 10^{23} n/cm^2 (E_n > 0.1 MeV), respectively, in the temperature range 100-300°C. These are based on 3 vol % swelling in spinel and 60% filling factor for the powdered MgO (67% swelling).

NORMAL MAGNET SHIELDING

In view of the fact that the peak neutron wall loading at the inboard shield is ~ 10 MW/m^2, the normal magnet is highly irradiated. It is designed to operate for 24 full power years (FPY); the designed lifetime of the reactor. The one-dimensional calculations result in an end of life peak neutron fluence (E_n > 0.1 MeV) of ~ 4 x 10^{24} n/cm^2 for the case where the normal coil is positioned with no intervening shield between its coil case (0.02 m thick) and the first wall. This indicates that some shielding needs to be introduced in front of the normal magnet in order to satisfy the design limits for the insulators. Our results show that 16 cm of W-shield [80 v/o W (95% d.f.), 10 v/o Fe 1422, and 10 v/o H_2O] adequately protect the normal magnet. Moreover, the MgO powder insulator can be used in the front 14 cm thick layers of the magnet and the spinel in the back layers where stresses are severe. In the calculations the 0.2 m thick normal magnet composition was taken as 64 v/o Cu, 24 v/o insulator, and 12 v/o H_2O.

INBOARD SHIELD OPTIMIZATION

The primary motive for the optimization study is to find an optimal combination of the shielding materials that minimizes the fast neutron fluence in the S/C magnet which was found to be the design driver for the shield. However, it is beneficial from the cost standpoint to reduce the nuclear heating as much as possible. The space for the normal magnet and the shield is constrained to 0.66 m in addition to the 0.11 m thick cryostat (.08 m effective steel). In this regard the use of tungsten in the shield is essential to provide adequate protection for the S/C magnet. A series of one-dimensional (1-D) calculations was performed to determine the optimal shield configuration using the discrete ordinates code ONEDANT,[11] the cross section library XSLIB (30 neutron and 12 gamma energy groups) based on the ENDF/B-V evaluation, and the P_3-S_8 approximation, in toroidal

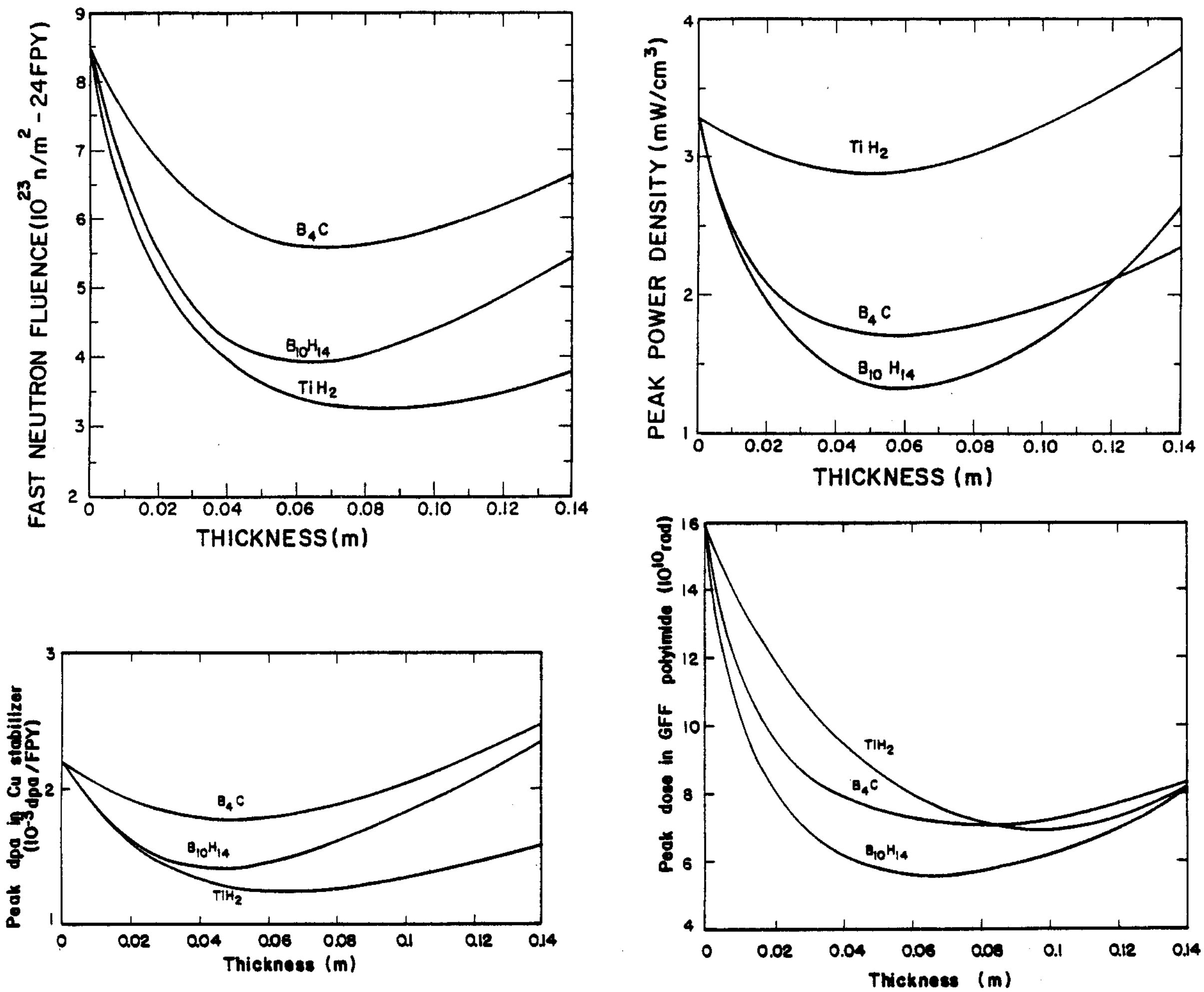


Fig. 2. Peak radiation effects in the S/C magnet versus backup layer thickness.

cylindrical geometry.

Several materials have been considered for the shield to reduce the fast fluence and the nuclear heating in the S/C magnet. These materials are tungsten (W), stainless steel (Fe 1422), boron carbide (B_4C), titanium hydride (TiH_2), lead (Pb), and boron hydride[1] ($B_{10}H_{14}$) - a new material for shielding applications. Boron hydride is a well-developed material. It has been produced commercially on a large scale although it is presently expensive for small quantities (~ $450/kg). It is quite reactive, kinetically stable up to 150°C, and decomposes at higher temperatures. Thus, to avoid the reaction of the products with air it must be kept in an inert atmosphere; it slowly hydrolyzes in water. It has a density of 0.94 g/cm^3 at room temperature and a melting point of 100°C. It should be emphasized that the $B_{10}H_{14}$ will only be placed at the back of the shield where the temperature is surely below its melting point. Also, the extent of radiation damage of $B_{10}H_{14}$ in this position needs to be carefully examined. There is some concern for using $B_{10}H_{14}$ in the shield from a safety standpoint. However, it is a useful candidate and its applicability for fusion reactor shielding deserves further consideration. Many more stable products are known and a very large number of polymers have been produced. All of these have enhanced thermal stabilities up to ~ 300°C. However, none of them provides neutronically the required properties as compared to the parent $B_{10}H_{14}$.

TiH_2 (95% d.f.), B_4C (87% d.f.), and $B_{10}H_{14}$ shield layers were used separately to back up the W-shield between the normal and superconductor magnets. In all shields, 10 v/o Fe 1422 structure, 10 v/o H_2O, and 90% ^{10}B in B were

Table I. Peak Radiation Effects in S/C Magnet (10 MW/m^2)

Optimum Shield Composition	Fast Neutron Fluence (10^{19} n/cm^2)	Nuclear Heating (mW/cm^3)	dpa in Cu Stabilizer (10^{-3} dpa/FPY)	Dose in GFF Polyimide (10^{10} rad)
Fe[a]	26.25	11.28	8.39	44.07
W[b]	7.37	2.65	2.16	12.25
W/B_4C[c]	5.57	1.73	1.82	7.10
W/TiH_2[d]	3.31	2.13	1.29	6.28
$W/B_{10}H_{14}$[c]	3.94	1.31	1.48	5.59
Design Limits	4	~ 1	-	40

[a]30 v/o borated water
[b]18 v/o H_2O, 10 v/o Fe 1422 structure
[c]10 v/o H_2O, 10 v/o structure
[d]10 v/o borated water, 10 v/o structure

used. The thicknesses of these layers were varied between zero (an all W-shield) and 0.14 m and the total shield thickness was kept fixed. A comparison between the effectiveness of these shielding materials in reducing the radiation effects in the S/C magnet is outlined in Fig. 2. Obviously, hydrides are effective in minimizing the fast neutron fluences by moderating the neutrons via elastic scattering interactions with hydrogen. On the other hand, borides are superior in reducing the nuclear heating due to the remarkably high absorption cross sections of boron for intermediate and low energy neutrons. Furthermore, boron hydride has proven to be competitive with the other conventional shielding materials and has the beneficial effect of minimizing both responses simultaneously.

An attempt was made to reduce the nuclear heating without substantially affecting the fluence by using borated water to cool the shield. The solubility of boric acid in water has a strong temperature dependence. For an inlet coolant temperature of ~ 100°C in the inboard shield, the maximum allowable concentration of boric acid in water is ~ 11 vol %.[1] Our results show that the borated water was only effective in the case of the W/TiH_2 shield where the power density was reduced by ~ 30%. However, a lower nuclear heating was achieved with the optimum combination of water cooled $W/B_{10}H_{14}$ shield.

The effect of the water content in the inboard shield was examined. To minimize the fast neutron fluence, as little water as possible is required for the cases of W/TiH_2 and $W/B_{10}H_{14}$ shields. Thus, the water content in the shield should be dictated by cooling requirements, rather than neutronics performance. In order to meet the cooling demand for this high wall loading reactor, a 10 vol % water content was considered in the shield. If all steel or tungsten shields are used the optimal water contents are 30 and 18 vol %, respectively.

The optimum thicknesses of the B_4C, TiH_2, and $B_{10}H_{14}$ shields that minimize the fast

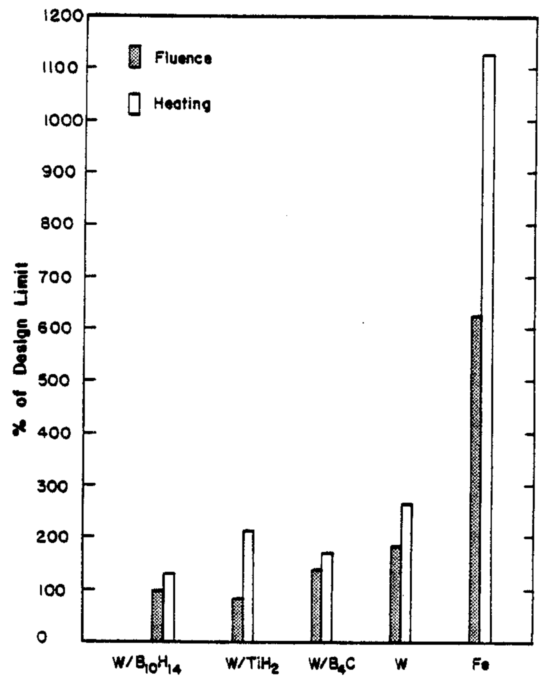
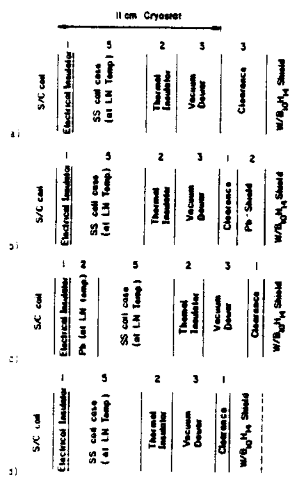


Fig. 3. Comparison of the effectiveness of the optimal shields.

neutron fluence are 0.07, 0.08, and 0.06 m, respectively (Fig. 2). Table I summarizes the radiation effects in the S/C magnet for the different optimal shields. The results are also presented by bar charts in Fig. 3. It is worth mentioning that extra ~ 0.04 m of shield is required to reduce the radiation effects by a factor of 2, if necessary. Evidently, the $W/B_{10}H_{14}$ shield is the best for meeting the combined criteria of reducing both responses and, hence, provides the thinnest possible inboard shield.



	Fluence (10^{19} n/cm^2)	Peak Nuclear Heating (mW/cm^3)	Total Nuclear Heating (W/m)
a)	3.94	1.31	1127
b)	3.64	1.24	967
c)	3.73	0.99	981
d)	2.74	1.07	791

Fig. 4. Modified cryostat to reduce the nuclear heating in the S/C magnet.

The option of using lead in the shield was also investigated. The motivation for considering Pb for the shield is that ~ 80% of the nuclear heating in the S/C magnet is gamma heating and Pb is a good gamma absorber. A 2 cm thick layer of Pb-shield was added behind the $W/B_{10}H_{14}$ shield and the clearance zone thickness between the shield and the S/C magnet was reduced to 1 cm. The effect on the two most important responses is reported in Fig. 4b along with the integrated total nuclear heating in the S/C coil per unit length. It is worth mentioning that the gamma heating in the S/C coil results from gamma rays:

- transported from the shield,
- generated in the coil case and vacuum dewar,
- generated in the S/C coil itself.

Baking the $W/B_{10}H_{14}$ shield with Pb-shield helps attenuate the first source of gamma rays and in order to attenuate the other two sources a 2 cm thick Pb-shield was added inside the cryostat as shown in Fig. 4c. In this case, the Pb-shield is cooled at LN temperature and should be strong enough to pass the magnetic forces to the coil case. It is clear, from the comparison of Fig. 4c with the other cases, that the Pb in this position is very effective in reducing the nuclear heating. A final option was considered where the $W/B_{10}H_{14}$ shield thickness was increased by 2 cm (keeping the W to $B_{10}H_{14}$ ratio the same). Figure 4d reveals that a remarkable decrease in the fast neutron fluence and the total nuclear heating is achieved in this case. Therefore, the nuclear heating in the S/C magnet can be reduced by increasing the thickness of the optimal $W/B_{10}H_{14}$ shield which is more effective than using $W/B_{10}H_{14}$ and Pb shields. This conclusion is in agreement with previous studies[10] in which the shielding effectiveness of the Pb was examined. The analysis was carried out for the $W/B_{10}H_{14}$ shield and is expected to hold true for the other shields.

CONCLUSION

The advanced shielding designs for the inboard region of this system represent a significant step forward. The conventional limits on the radiation effects in the S/C magnet were pushed to allow for progress in the next 5-10 years. The use of boron hydride or titanium hydride significantly reduces the thickness of the inboard shield required to protect the magnet. The design and philosophy in this study should also have applicability in near term facilities such as TFCX and INTOR.

ACKNOWLEDGEMENT

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