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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/m²) tokamak design. A new material, boron hydride, was identified as a potential shielding material and more optimum combinations of TiN₂, B₄C, 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 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 MWth). Other features include the use of a He cooled static LiInPb₃ 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, 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, Nb₃Sn 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 \( J_c \) at a field of 10 Tesla. Unlike NbTi, where a monotonic decrease in \( J_c \) is observed, an initial increase in \( J_c \) with neutron fluence for Nb₃Sn was observed. Most available experimental data involve irradiating the samples at fission reactor ambient temperatures. Experiments with cryogenic temperature irradiation showed that the initial \( J_c \) increase is larger by \( \sim 10\% \) 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 Tesla after irradiation to a fluence of \( 4 \times 10^{18} \text{n/cm}^2 \) (\( E \geq 0.1 \text{ MeV} \)) in the High Flux Beam Reactor (HFBR) at 400 K. A larger increase in \( J_c \) is expected at the field of 12 T considered in this study.

Room temperature annealing of Nb₃Sn 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 \( 4 \times 10^{18} \text{n/cm}^2 \) has been quoted by various researchers. However, the experimental results measured at 10 Tesla after irradiation at 400 K show that \( J_c \) drops to its pre-irradiation value at a fluence of \( \sim 10^{19} \text{n/cm}^2 \). This implies that higher fluences can be used without degrading \( J_c \) much, provided the original unirradiated value. In this work we use a fluence limit of \( 4 \times 10^{19} \text{n/cm}^2 \) (\( E \geq 0.1 \text{ MeV} \)). This is based on the prediction that the higher fluences and lower temperatures used in this design will result in larger initial increases in \( J_c \). Furthermore, the effect of heat treatment of the Nb₃Sn 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 mobile 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 8 is given by

\[
\rho_{\text{max}}(B) = \rho_{\text{max}} \frac{A_{\text{st}}}{P} \frac{1}{12}, \tag{1}
\]

where \( A_{\text{st}} \) is the stabilizer cross section area, \( P \) is the wetted perimeter and \( I \) is the conductor current. \( q_{\text{max}} \) 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. We have generated charts for determining the maximum allowable damage rate in copper stabilizer. In this design we assume a maximum S/C current density of \( 8 \times 10^4 \text{ A/cm}^2 \). 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/cm². The conductor is assumed to have a square cross section with 50\% of the conductor perimeter being wetted by the coolant.

\[
\Delta \rho_r = 300[1 - e^{-240 \text{ dpa}}] \text{nA cm}. \tag{2}
\]

Originally, we assumed an operating conductor current of 500 A yielding a conductor size of 0.35 cm. Equation (1) yields \( \rho_{\text{max}} \) = 96.82 nA cm. The charts of Ref. 5 imply that \( \Delta \rho_r \) should not exceed 17.4 nA cm which gives a dpa limit of 2.5 \times 10^4. The reactor life was assumed to be 24 FFPY and the minimum time between magnet anneals was set to 1 FFPY. 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 FFPY and the dpa rate should not exceed 5.6 \times 10^3 dpa/FPY. The 66 cm thick optimized shield that gives a fast neutron fluence at the S/C of \( 4 \times 10^{21} \text{n/cm}^2 \) was found to yield a dpa rate of \( \sim 1.5 \times 10^3 \) 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 \( 1.5 \times 10^3 \) 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 nA cm for \( \Delta \rho_r \). Hence, if the magnet is designed such that the coolant can remove the I²R heat corresponding
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 Nb₃Sn 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/cm². For the chosen conductor parameters, this corresponds to a power density of ~ 182 mm²/cm² 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 mm²/cm². 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. More than 65% of the compression strength of glass filled fiber (gff) polyimide is retained up to a dose of ~ 10¹² rad. The samples are representative of 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. 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 10¹¹ rads and static compression tests to a stress level of 2750 MPa produced no failures. This indicates that dose limits of ~ 4 x 10¹¹ 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. Alumini-}

mized mylar was used in previous designs as superinsulator. Recent experiments showed a large drop in its strength after irradiation to 6 x 10¹¹ rads while no failure was observed in alumina and graphite up to a dose of 10¹⁴ rads. Aluminum sheets supplied 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 radolytic 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. The neutron fluence limits for the use of the solid polycrystalline spinel and compacted powder magnesium in normal magnets are 4 x 10²⁵ and 2.35 x 10²⁵ n/cm² (Eₙ > 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 powderized MgO (67% swelling).

**NORMA L MAGNET SHEILDING**

In view of the fact that the peak neutron wall loading at the inboard shield is ~ 10 MW/m², 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 (Eₙ > 0.1 MeV) of ~ 4 x 10²⁵ n/cm² for the case. The normal coil is positioned with no intervening shield between its coil case (0.02 m thick) and the 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 [50 v/o W (95% d.f.)], 10 v/o Fe 1422, and 10 v/o H₂O 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 H₂O.

**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 (0.08 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, which can be used to calculate shielding performance for energy groups based on the ENDF/B-V evaluation, and the P₃=8 approximation, in toroidal

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3
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 (B₄C), titanium hydride (TiH₂), lead (Pb), and boron hydride (B₁₀H₁₄) - 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/cm³ at room temperature and a melting point of 100°C. It should be emphasized that the B₁₀H₁₄ 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 B₁₀H₁₄ in this position needs to be carefully examined. There is some concern for using B₁₀H₁₄ 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 B₁₀H₁₄.

TiH₂ (95% d.f.), B₄C (87% d.f.), and B₁₀H₁₄ 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 H₂O, and 90% ¹⁹B in B were
Table I. Peak Radiation Effects in S/C Magnet (10 MW/m²)

<table>
<thead>
<tr>
<th>Optimum Shield Composition</th>
<th>Fast Neutron Fluence (10¹⁸ n/cm²)</th>
<th>Nuclear Heating (mW/cm²)</th>
<th>dpa in Cu Stabilizer (10⁻³ dpa/FPY)</th>
<th>Dose in GFF Polyimide (10¹⁰ rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe⁴⁺</td>
<td>26.25</td>
<td>11.28</td>
<td>8.39</td>
<td>44.07</td>
</tr>
<tr>
<td>W⁶⁺</td>
<td>7.37</td>
<td>2.65</td>
<td>1.56</td>
<td>12.26</td>
</tr>
<tr>
<td>W/B₄C⁵⁺</td>
<td>5.57</td>
<td>1.73</td>
<td>1.82</td>
<td>7.10</td>
</tr>
<tr>
<td>W/TiH₂⁴⁺</td>
<td>3.31</td>
<td>2.13</td>
<td>1.29</td>
<td>6.28</td>
</tr>
<tr>
<td>W/B₁₀H₁₄⁵⁺</td>
<td>3.34</td>
<td>1.31</td>
<td>1.48</td>
<td>5.59</td>
</tr>
<tr>
<td>Design Limits</td>
<td>~1</td>
<td>~</td>
<td>~</td>
<td>40</td>
</tr>
</tbody>
</table>

a³⁰ v/o borated water
b¹⁸ v/o H₂O, 10 v/o Fe 1422 structure
c¹⁰ v/o H₂O, 10 v/o structure
d¹⁰ 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 %. Our results show that the borated water was only effective in the case of the W/TiH₂ shield where the power density was reduced by ~30%. However, a lower nuclear heating was achieved with the optimum combination of water cooled W/B₁₀H₁₄ 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/TiH₂ and W/B₁₀H₁₄ 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 optimum water contents are 30 and 18 vol %, respectively.

The optimum thicknesses of the B₄C, TiH₂, and B₁₀H₁₄ shields that minimize the fast neutron fluence are 0.07, 0.08, and 0.06 m, respectively (Fig. 2). Table 1 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/B₁₀H₁₄ shield is the best for meeting the combined criteria of reducing both responses and, hence, provides the thinnest possible inboard shield.

Fig. 3. Comparison of the effectiveness of the optimal shields.
This conclusion is in agreement with previous studies\(^1\) in which the shielding effectiveness of the Pb was examined. The analysis was carried out for the W\(_{80}\)H\(_4\) shield and is expected to hold true for the other shields.

**CONCLUSION**

The advanced shielding designs for the in-board 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 TFTR and INTOR.

**ACKNOWLEDGEMENT**

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**REFERENCES**


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| & 1 & 2 & 3 & 4 | Flux (Torr cm\(^2\)) | Peak Nuclear Heating (W/cm\(^2\)) | Total Nuclear Heating (W/cm\(^2\)) |
|---|---|---|---|---|---|---|
| 1 & 2 & 3 & 4 & 5 | 0.34 | 1.21 | 1.127 |
| 1 & 2 & 3 & 4 & 5 | 0.44 | 1.24 | 0.97 |
| 1 & 2 & 3 & 4 & 5 | 0.78 | 0.06 | 0.61 |
| 1 & 2 & 3 & 4 & 5 | 0.74 | 0.07 | 0.71 |

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