Shielding Effectiveness of Candidate Structural Materials and Liquid Metal Coolants for the ITER Blanket

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ABSTRACT

The shielding performance of candidate structural materials and liquid metal coolants has been assessed for ITER. The Cu structure yields the best shielding performance while the Ti structure results in the highest magnet damage. Liquid potassium coolant has the worst shielding performance among the liquid metals considered with Ga having the best shielding performance. Using an Inconel double wall vacuum vessel with liquid metal cooled double size tungsten carbide balls allows adequate magnet shielding with a self-cooled Li/V blanket.

I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) project has been moving steadily ahead since its inception in 1985. The first formal phase of the ITER project was the Conceptual Design Activity (CDA) which was conducted from May 1988 until December 1990.[1] The CDA blanket utilized Li_2O solid breeder, beryllium neutron multiplier, 316 SS structure and low temperature water coolant. The ITER project embarked on a new phase called the Engineering Design Activity (EDA) which is to be conducted from 1992 to 1997. One major requirement in the EDA design has been to allow for high temperature first wall (FW) bakeout. The FW is required to operate at relatively high temperature (300-400°C) with low coolant pressure. As a result using liquid metals as well as structural materials that can withstand the FW high temperatures and thermal stresses has been considered. As part of the U.S. ITER activity, the shielding effectiveness of the candidate blanket materials has been assessed. The effect of using different liquid metal coolants and structural materials in the first wall/blanket/shield (FW/B/S) on magnet radiation damage has been analyzed. The liquid metals considered are Na, NaK, K, Ga, Li, Pb, and $Li_{17}Pb_{83}$. The structural materials considered are austenitic steel 316 SS, ferritic steel HT-9, Ni alloy Inconel 600, Ni alloy Inconel 625, copper alloy C17510 (Cu-0.5Be-2Ni), vanadium alloy V5Cr5Ti and titanium alloy Ti6Al4V.

II. CALCULATIONAL MODEL

Neutronics calculations have been performed using the one meter minimum shielding space provided in the inboard region. A 65 cm thick first wall/blanket/shield (FW/B/S) is used followed by a 35 cm thick vacuum vessel (VV). The outboard region is 1.13 m thick with a 65 cm thick FW/B/S and 48 cm thick VV. A 5 mm thick FW is used in the analysis. A one-dimensional (1-D) toroidal cylindrical model with the inboard and outboard regions modeled simultaneously is used to account for the toroidal effects. The discrete ordinates particle transport code ONEDANT[2] is used with cross section data based on the ENDF/B-V evaluation.

The nominal ITER design has an average neutron wall loading of 1 MW/m^2 and a fluence of 1 MWa/m^2. However, the ITER EDA design guidelines indicate that it is desirable to operate at higher flux and fluence values with the permanent components handling a fluence level up to 3 MWa/m^2. The neutron wall loading varies poloidally with a peaking factor of 1.32 at the thinnest zone (1 m FW/B/S/VV) in the inboard region above the midplane. Based on this, the operating conditions used in the shielding analysis are a peak inboard neutron wall loading of 2.64 MW/m^2 and a peak fluence of 3.96 MWa/m^2. The peak magnet radiation effects will be determined by increasing the 1-D results by a factor of 3 to account for 2 cm wide assembly gaps between adjacent FW/B/S modules and uncertainties in nuclear data and modeling. The integrated magnet radiation effects are increased by a factor of 2. These correspond to the safety factors used during the CDA.

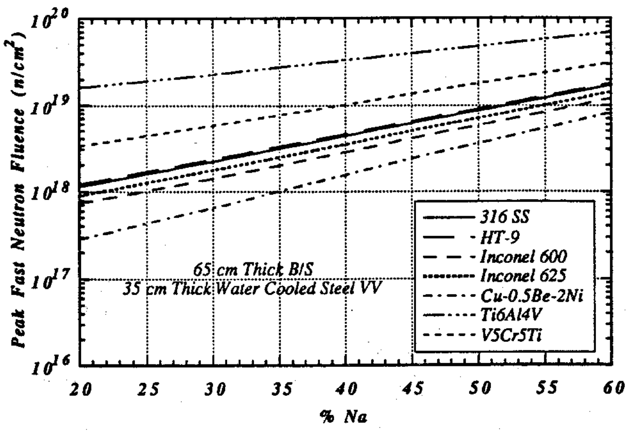

Fig. 1. Effect of liquid sodium content and structural material on the peak end-of-life fast neutron fluence.

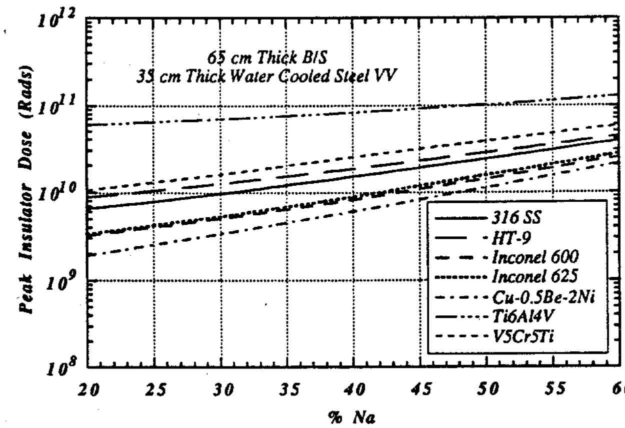

Fig. 2 Effect of liquid sodium content and structural material on the peak end-of-life magnet insulator dose.

The liquid metals considered in this analysis are Na, NaK, K, Ga, Li, Pb, and $Li_{17}Pb_{83}$. The structural materials considered are austenitic steel 316 SS, ferritic steel HT-9, Ni alloy Inconel 600, Ni alloy Inconel 625, copper alloy C17510 (Cu-0.5Be-2Ni), vanadium alloy V5Cr5Ti and titanium alloy Ti6Al4V. Water cooled double wall 316 SS vacuum vessel with steel balls has been considered in the EDA design. The effect of using the higher strength Inconel 625 structure in the VV is assessed. In addition, the shielding impact of replacing the steel balls in the VV by borated steel, boron carbide, or tungsten carbide balls has been analyzed and the option of replacing the water coolant in the VV by organic coolant or liquid metal has been considered.

The winding pack composition used in the calculations is 47% SS, 12% Cu, 10.5% non-Cu (3% Nb_3Sn, 7.5% Bronze), 17.2% liquid He, and 13.3% insulator (epoxy with 70% R-glass). The CDA magnet radiation limits have been used in the present analysis. These are a peak end-of-life fast neutron fluence of 10^{19} n/cm^2, a peak end-of-life dose to the organic insulator of 5×10^9 rads, a peak end-of-life copper stabilizer damage of 6×10^{-3} dpa, and a peak winding pack power density of 5 mW/cm^3.

III. IMPACT OF BLANKET STRUCTURAL MATERIAL ON MAGNET DAMAGE

Neutronics calculations have been performed using different structural materials in the blanket/shield (B/S). Figures 1 and 2 show the effect of the liquid sodium coolant content on the peak end-of-life fast neutron fluence and magnet insulator dose for different structural materials. For the same liquid metal content, the Cu structure yields the best shielding performance while the Ti structure results in the highest magnet damage. The Ni alloys Inconel 600 and Inconel 625 have a small difference in shielding effectiveness with Inconel 625 yielding slightly higher magnet damage. The austenitic steel 316 SS has slightly better shielding effectiveness than the ferritic steel HT-9. For 50% liquid Na, the relative magnet damage values are given in Table I. The structure effect is more pronounced for small liquid metal content. Increasing the liquid metal content in the FW/B/S results in higher magnet damage with the effect being more pronounced on neutron dominated radiation effects such as the fast neutron fluence and the Cu dpa. Increasing the liquid Na content by 10% with 316 SS results in increasing magnet heating and insulator dose by a factor of ~1.5 and increasing neutron fluence and Cu dpa by a factor of ~2. Similar effects are observed for the other liquid metals. Using beryllium in the front zone of the B/S results in lower magnet heating and insulator

Table I

The Relative Magnet Damage Levels With Different Structural Materials

Structure	Magnet Heating	Insulator Dose	Neutron Fluence	Cu dpa
Cu-0.5Be-2Ni	1	1	1	1
Inconel 600	1.19	1.25	1.65	1.62
Inconel 625	1.26	1.38	2.02	2.01
316 SS	2.08	2.13	2.47	2.45
HT-9	2.49	2.50	2.61	2.58
V5Cr5Ti	3.08	3.42	5.14	5.30
Ti6Al4V	8.31	9.19	13.74	14.29

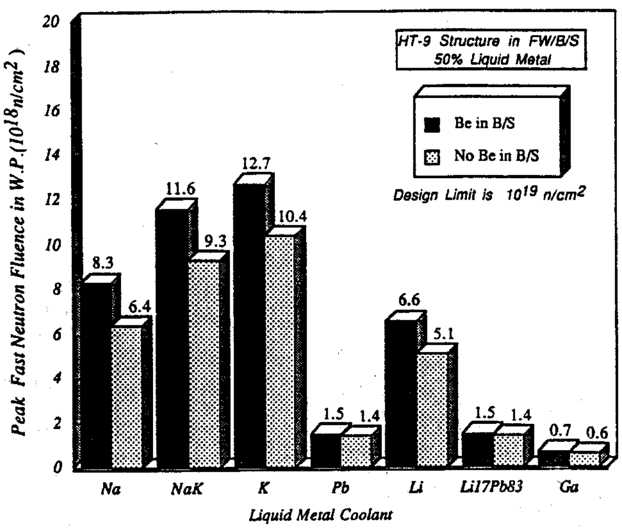

Fig. 3. Effect of liquid metal coolant on peak end-of-life fast neutron fluence.

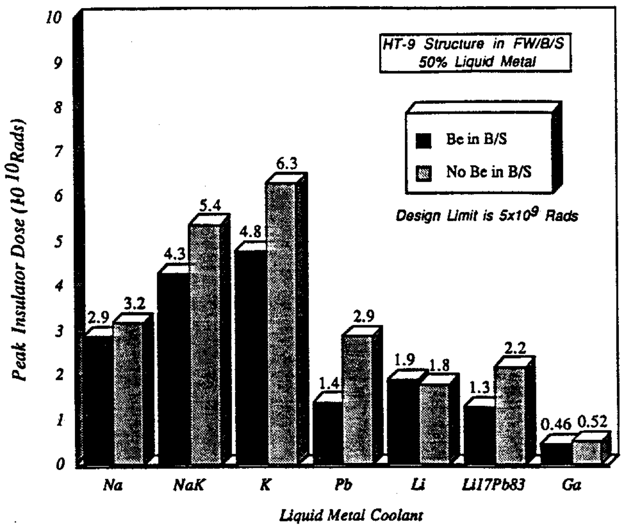

Fig. 4. Effect of liquid metal coolant on peak end-of-life insulator dose.

dose, which are the main shield design drivers, with a shallow minimum in the range 10-25% Be. Hence, using Be in the front zone of the B/S to enhance tritium breeding will improve the shielding performance.

IV. EFFECT OF LIQUID METAL COOLANT ON MAGNET DAMAGE

Figures 3 and 4 show the effect of using different liquid metal coolants on the peak end-of-life fast neutron fluence and insulator dose. The coolant volumetric content is assumed to be 50%. HT-9 structure is used in the B/S. The results are given for two cases with and without 20% Be in the front 25 cm zone of the B/S. A water cooled double wall VV with steel balls is used and no special shielding material is utilized at the back of the VV.

Liquid potassium coolant has the worst shielding performance among the liquid metals considered followed by NaK. The lowest neutron dominated magnet radiation effects, such as peak fast neutron fluence and Cu stabilizer damage as well as peak helium production in the VV, are obtained with Ga followed by Pb and $Li_{17}Pb_{83}$. For gamma dominated magnet radiation effects, such as peak nuclear heating and insulator dose, Ga has the best shielding performance followed by natural liquid Li. The peak magnet nuclear heating and insulator dose, which are the main shield design drivers, are excessive with 50% liquid metal. Hence, the smallest feasible liquid metal content should be used. Special shielding materials should be used in and/or behind the VV.

V. SHIELDING IMPACT OF VACUUM VESSEL MATERIALS

Shielding calculations have been performed to assess the impact of using different structural materials, filling materials, and coolants in the VV. The effect of replacing the 316 SS VV structure by the higher strength Inconel 625 structure is demonstrated in Table II. The VV contains single size 316 SS balls cooled with water. The results are for a B/S utilizing HT-9 structure with 50% Li. Using Inconel structure in the VV reduces magnet damage by ~20%. He production in the VV increases by a factor of ~2. The shielding impact of replacing the steel balls in the VV by borated steel, boron carbide, or tungsten carbide balls has been analyzed. Using boron carbide balls in the VV results in higher magnet damage compared to the design with 316 SS balls. Using borated steel balls in VV instead of 316 SS balls reduces magnet heating and insulator dose by a factor of 2-3 and neutron fluence and Cu damage by ~15%. The largest shielding improvement results from using tungsten carbide balls in the VV. Magnet heating and insulator dose are reduced by a factor of 3-5 and neutron fluence and Cu stabilizer damage are reduced by ~30% compared to the design with 316 SS balls.

The effect of using a Pb/B_4C layer at the back of the VV on magnet damage has been assessed. Table III shows the effect for the case of a B/S utilizing HT-9 structure with 50% Li and a water cooled double wall Inconel VV with single size WC balls. Replacing the 5 cm back layer of the shield by a Pb/ B_4C layer at the

Table II

Effect of Replacing the 316 SS VV Structure by Inconel 625

VV Structure	316 SS	Inconel 625
Peak nuclear heating in magnet (mW/cm^3)	20.4	15.2
Peak fast neutron fluence in magnet (n/cm^2)	5.1×10^{18}	4.6×10^{18}
Peak organic insulator dose (Rads)	1.8×10^{10}	1.4×10^{10}
Peak Cu dpa in magnet (dpa)	3.4×10^{-3}	3.1×10^{-3}
Peak He production in VV (appm)	2.3	4.5
Total magnet nuclear heating (kW)	170	131

Table III

Effect of Using a Pb/B_4C Layer at the Back of the VV

Back Layer Composition	None	1 cm 316 SS 3 cm Pb 1 cm B_4C
Peak nuclear heating in magnet (mW/cm^3)	3.1	1.0
Peak fast neutron fluence in magnet (n/cm^2)	3.2×10^{18}	2.2×10^{18}
Peak organic insulator dose (Rads)	4.6×10^9	2.1×10^9
Peak Cu dpa in magnet (dpa)	2.4×10^{-3}	1.5×10^{-3}
Peak He production in VV (appm)	4.5	7.1
Total magnet nuclear heating (kW)	45	23

back of the VV reduces magnet heating and insulator dose, which are the primary design drivers, by factors of 2-3. Neutron fluence and Cu damage decrease by a factor of ~1.5. Helium production in the VV increases by a factor of ~1.6. The combined effect of using tungsten carbide balls in the VV and Pb/B_4C back layer is to reduce heating and insulator dose by a factor of 7-15 and neutron fluence and Cu damage by a factor of ~2.

Due to safety concerns related to using water in the VV with alkaline liquid metals in the blanket, the options of cooling the VV with organic coolant or liquid metal have been assessed. Table IV shows the effect of replacing the VV water coolant by Li or organic coolant. A double wall Inconel VV with single size WC balls is used with a 5 cm back layer of Pb/B_4C shield. The B/S is composed of 50% HT-9 and 50% Li. Replacing water in the VV by Li results in increasing magnet radiation damage by factors of 5-10 due to the elimination of hydrogen. Replacing the water coolant in the VV by organic coolant results in increasing magnet radiation effects by 60-80% due to the lower hydrogen content in the organic coolant compared to water. Although the organic coolant has a shielding advantage over the liquid metal coolant, the decomposition rate of the organic coolant in the VV is calculated to be ~150 kg per hour of irradiation. This resulted in discarding the organic coolant option.

In order to improve the shielding performance of liquid metal cooled VV, using double size WC balls with a packing fraction of 80% is considered. Using double size instead of single size WC balls in the Li cooled VV reduces the magnet radiation effects by a factor of ~2. In addition, replacing the 5 cm back layer of the shield by a 1 cm Pb/3 cm B_4C layer at the back of the VV reduces magnet radiation effects by factors of 1.5-3.5. The effects of VV wall thickness and liquid metal coolant with double size WC balls are given in Table V. Using 3 cm Inconel VV walls instead of 5 cm thick walls reduces magnet damage by ~20%. Replacing Li in the VV by NaK increases magnet damage by ~20%. For the 1 m total FW/B/S/VV thickness, magnet radiation effects are satisfied for a Li cooled HT-9 FW/B/S with a VV cooled by either Li or NaK.

VI. SHIELDING PERFORMANCE OF A CANDIDATE BLANKET DESIGN

The shielding performance of a candidate ITER EDA blanket design proposed by the U.S. home team has been assessed. It utilizes poloidally flowing liquid lithium in V5Cr5Ti structure. The design includes a 7 cm thick beryllium layer to enhance tritium breeding. Fig. 5 shows the radial build for the inboard region. It is clear from the results in Table VI that all magnet design limits are satisfied for this design even if liquid metal cooling is used in the VV. The effect of replacing some Li in the blanket by Be has been assessed. This results in reducing all magnet radiation effects. However, the cost penalty is significant and tritium breeding enhancement is negligible, for a fixed blanket thickness, as illustrated in

Table IV

Effect of VV Coolant on Shielding Performance

VV Coolant	Water	Lithium	Organic Coolant
Peak nuclear heating in magnet (mW/cm^3)	1.0	11	1.8
Peak fast neutron fluence in magnet (n/cm^2)	2.2×10^{18}	1.0×10^{19}	3.5×10^{18}
Peak organic insulator dose (Rads)	2.1×10^{9}	1.2×10^{10}	3.3×10^{9}
Peak Cu dpa in magnet (dpa)	1.5×10^{-3}	5.4×10^{-3}	2.1×10^{-3}
Total magnet nuclear heating (kW)	23	184	38

Table V

Effect of VV Wall Thickness and Liquid Metal Coolant With Double Size WC Balls

VV Wall Thickness (cm) VV Coolant	5 Li	3 Li	3 NaK
Peak nuclear heating in magnet (mW/cm^3)	3.8	3.1	3.8
Peak fast neutron fluence in magnet (n/cm^2)	3.3×10^{18}	2.6×10^{18}	3.2×10^{18}
Peak organic insulator dose (Rads)	4.5×10^{9}	3.7×10^{9}	4.5×10^{9}
Peak Cu dpa in magnet (dpa)	1.9×10^{-3}	1.6×10^{-3}	1.9×10^{-3}
Total magnet nuclear heating (kW)	55	46	56

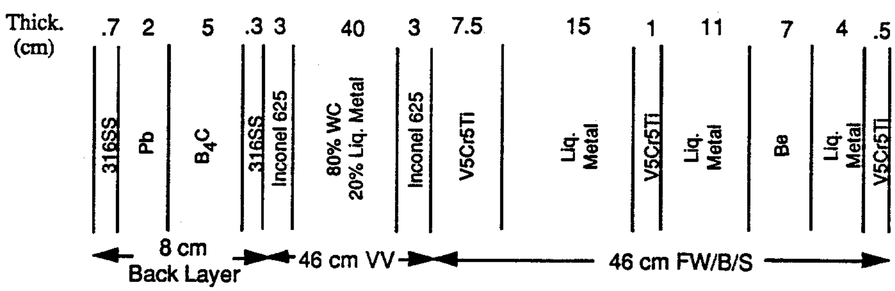

Fig. 5. Radial build for the inboard region.

Fig. 6. Another penalty of using much Be in the blanket is the need to remove more thermal power due to the enhanced energy multiplication. The option of using helium coolant in the blanket has been considered due to concerns about MHD pressure drop in flowing liquid metals. Replacing Li by He in the blanket results in increasing all magnet radiation effects. Hence, an effort should be made to reduce the He coolant content in the blanket. It is concluded that adequate magnet shielding can be achieved with a blanket design that provides adequate tritium breeding and satisfies the thermal hydraulics and safety requirements for ITER.

VII. SUMMARY

The shielding performance of candidate structural materials and liquid metal coolants has been assessed for ITER. The Cu structure yields the best shielding performance while the Ti structure results in the highest magnet damage. Liquid potassium coolant has the worst shielding performance among the liquid metals considered followed by NaK. Ga has the best shielding performance followed by Li (nat.) and $Li_{17}Pb_{83}$. For 50% liquid metal content, the peak magnet nuclear heating and end-of-life insulator dose which are the main shield design

Table VI

Magnet Radiation Effects in the Candidate Liquid Metal Self-Cooled Blanket

Liquid Metal Coolant	Li (nat.)
Peak nuclear heating in magnet	2.6 mW/cm^3
Peak end of life fast neutron fluence in magnet	3.9×10^{18} n/cm^2
Peak end of life organic insulator dose	4.1×10^9 Rads
Peak end of life Cu dpa in magnet	2.4×10^{-3} dpa
Total nuclear heating in 24 TF coils	51 kW

drivers exceed the CDA design limits of 5 mW/cm^3 and 5×10^9 Rads. Hence, the smallest feasible liquid metal content should be used and special shielding materials should be used in and/or behind the VV.

The effect of using the higher strength Inconel 625 structure in the VV was found to reduce magnet damage by ~20% compared to the 316 SS case. The shielding impact of replacing the steel balls in the VV by borated steel, boron carbide, or tungsten carbide balls has been analyzed. The largest shielding improvement results from using tungsten carbide balls in the VV. The combined effect of using tungsten carbide balls in the VV and Pb/B_4C back layer is to reduce heating and insulator dose by a factor of 7-15 and neutron fluence and Cu damage by a factor of ~2. Due to safety concerns related to using water in the VV with alkaline liquid metals in the blanket, the option of cooling the VV with liquid metal has been assessed.

The shielding performance of a candidate ITER EDA blanket design proposed by the U.S. home team has been assessed. It utilizes poloidally flowing liquid lithium in V5Cr5Ti structure. The design includes a 7 cm thick beryllium layer to enhance tritium breeding. All magnet design limits are satisfied for this design even if liquid metal cooling is used in the VV. It is concluded that adequate magnet shielding can be achieved with a self-cooled Li/V blanket design that provides adequate tritium breeding and satisfies the thermal hydraulics and safety requirements for ITER.

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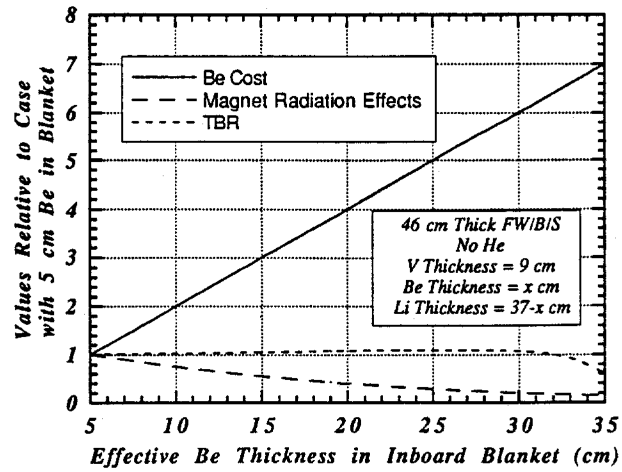

Fig. 6. Impact of Be content in the inboard self-cooled Li/V/Be blanket on Be cost, magnet shielding and tritium breeding.

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