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THE NUCLEAR DESIGN OF A VERY-LOW-ACTIVATION FUSION REACTOR

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ABSTRACT

An investigation was conducted to study the nuclear-design aspects of using very-low-activation materials, such as SiC, MgO, and aluminum for fusion-reactor first wall, blanket, and shield applications. In addition to the advantage of very-low radioactive inventory, it was found that the very-low-activation fusion reactor can also offer an adequate tritium-breeding ratio and substantial amount of blanket nuclear heating as a conventional-material-structured reactor does. The most-stringent design constraint found in a very-low-activation fusion reactor is the limited space available in the inboard region of a tokamak concept for shielding to protect the superconducting toroidal field coil. A reference design was developed which mitigates the constraint by adopting a removable tungsten shield design that retains the inboard dimensions and gives the same shield performance as the reference STARFIRE tokamak reactor design.

INTRODUCTION

Silicon carbide, MgO, graphite, and aluminum are very low activation materials because the radioactivity resulting from them in a fusion reactor environment is either extremely low at shutdown of the reactor (graphite and oxygen), or decays away by at least six orders of magnitude shortly after shutdown (about one day for Si and two weeks for Mg and Al).[1,2] The general feature of a fusion reactor fabricated using the very low activation materials is that the quantity of residual radioactivity to be disposed of and the corresponding radiation dose rate levels regarding maintenance exposure can be reduced by up to six orders of magnitude compared to a fusion reactor design such as the reference STARFIRE design[3] that employs conventional materials for the structure. Due to this low activation advantage, it is of interest to explore the nuclear characteristics of the low activation materials for the design of a very low activation fusion reactor.

An investigation to develop the conceptual design of a very low activation fusion reactor based upon the reference STARFIRE tokamak reactor was conducted recently under the support of the Department of Energy.[4,5] In general, the very low activation materials are capable of generating a large amount of nuclear heat and breeding adequate tritium in the blanket for commercial reactor purposes. However, because of the fact that they possess less neutron and gamma-ray attenuating capability than the conventional structural and shield materials such as stainless steel, lead, and tungsten, the very low activation design may need more space in the inboard region of a tokamak fusion reactor to protect the toroidal field superconducting (S/C) magnet from radiation damage.

In this paper we discuss the radiation shielding properties of the very low activation materials and present the nuclear design of a very low activation fusion reactor adapted to the design goals and geometrical constraints of the reference STARFIRE tokamak reactor.

METHODS OF STUDY

All neutronics calculations were performed using the one dimensional discrete ordinates transport code, ANISN,[6] with P_3S_8 approximation in cylindrical geometry. The transport cross-sections used were the 25 neutron and 21 gamma-ray group coupled cross-sections collapsed from the DLC41 library.[7] The reaction cross-sections, kerma factors, and atomic displacement cross-sections were obtained from the MACKLIB-IV library[8] and collapsed into the same group structure. The reactor model used for the one dimensional calculation is an infinite cylinder whose axis is the center line of the tokamak torus. The inner toroidal field coil, inboard shield and blanket, plasma, outboard shield and blanket, and the outer toroidal field coil are concentric cylindrical layers. For comparison purposes, this model appears adequate in addressing the overall quantities in tritium breeding and nuclear heating and the spatial parameters at midplane for a noncircular tokamak reactor.

INBOARD SHIELD DESIGN

The reference STARFIRE inboard shield composition, aiming at both optimizing the performance and minimizing the cost as described in Ref. 3, was achieved by incorporating a PCA structured blanket and a tungsten shield. The blanket consists of a 5 cm neutron multiplier (Zr_5Pb_3) region and a 28 cm $LiAlO_2$ tritium breeding zone. The shield consists of alternating layers of tungsten and boron carbide mixtures. The blanket and shield thicknesses are 0.37 and 0.6 m, respectively. It should be noted that the total available space between the inboard first wall and the coil case for the superconducting magnet is only 1.12 m. Within this, we need to install the inboard blanket for tritium production and nuclear energy recovery, the shield to protect the superconducting magnet from radiation damage, and thermal insulation to insulate the cryogenic superconducting magnet system from the shield system at slightly more than room-temperature.

To simulate the toroidal configuration of a tokamak reactor and to study the total tritium production per D-T source neutron in such a geometry, it is necessary to include the outboard blanket and reflector in all calculations. According to the STARFIRE report,[3] the outboard blanket consists of a 1 cm PCA first wall, a 5 cm Zr_5Pb_3 neutron multiplier, another 1 cm PCA wall (second wall), and a 46 cm $LiAlO_2$ breeding zone. The reflector is 15 cm and is composed of 5% PCA, 5% H_2O, and 90% graphite, all by volume. A neutronics calculation was performed for the reference STARFIRE design using this model as a calibration and basis for comparison with the low activation substitutions. Note that there is no surprise in the minor differences in the results when compared to the STARFIRE report, since they were calculated primarily using quite different geometric models. Some differences may also arise due to the use of a lower theoretical density (0.90) for the tungsten in this work compared to a higher one (0.95) employed in the STARFIRE report.

In order to study the impact on the radiation damage parameters on the S/C magnet due to the use of low-activation materials in the inboard shield design, we directly substituted the low activation material mixtures for the tungsten mixture in the reference STARFIRE design. The tritium breeding zones of the inboard and outboard blankets were also replaced by the low-activation Li_2O breeding blanket. All the structural material in the present comparison study was SiC except the S/C magnet where low activation aluminum alloy was used as structure and pure aluminum as the stabilizing conductor. Two low-activation materials used to replace tungsten in the reference STARFIRE design were SiC and MgO. Magnesium-oxide was considered in this comparison study because it possesses better neutron attenuation properties than other low-activation materials and has been recently proposed for use as a shielding material for fast reactors.[9] Lead, which is a medium activation material, was also included in this study for comparison. Table 1 gives the material composition by volume for these mixtures. In the following we will refer to these three design substitutions as SiC + B_4C, MgO + B_4C, and Pb + B_4C designs.

TABLE 1
MATERIAL COMPOSITION BY VOLUME
FOR LOW-ACTIVATION MIXTURES

Mixture	Composition by Volume Percent
SiC	90% SiC + 10% H_2O
MgO	90% MgO + 10% H_2O
Pb	80% Pb + 10% Al + 10% H_2O
B_4C	90% B_4C + 10% H_2O
Tritium breeding	16% SiC + 64% Li_2O + 20% He[a]
S/C magnet	4% Nb_3Sn + 65% Al + 27% LHe + 6% insulator

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[a] Li_2O: 80% of the theoretical density and natural lithium in the compound.

Radiation Protection to Superconducting Magnet

The maximum radiation damage parameters on the S/C magnets for the low-activation substitution, as well as the Pb + B_4C designs, were calculated and compared to the reference STARFIRE design. It was found that the radiation dose to the insulator, atomic displacement in the stabilizer, neutron fluence, and local nuclear heating for the low-activation and Pb + B_4C designs, are about two orders of magnitude higher than the reference STARFIRE design. The MgO + B_4C design shows slightly better radiation protection to the S/C magnet compared to the SiC + B_4C design in terms of atomic displacement, insulator dose, neutron fluence, and nuclear heating. The gamma-ray fluences for the low-activation designs are almost three orders of magnitude higher than the reference STARFIRE design. The Pb + B_4C design shows lesser gamma-ray fluence and local nuclear heating rate at the S/C magnet compared to the SiC + B_4C and MgO + B_4C designs. However, they are still about two orders of magnitude higher than the reference STARFIRE design.

Further neutronic calculations were performed for the above designs varying the shield thickness and the results were provided to establish the radiation attenuation coefficients for those shielding material mixtures of interest. Table 2 summarizes the additional thicknesses of these shielding material mixtures needed to achieve the reference STARFIRE performance in various radiation damage parameters. It is seen from Table 2, if SiC + B_4C, MgO + B_4C, and Pb + B_4C were employed as the shielding material mixtures, the modified STARFIRE design inboard shield thickness should increase by about 1.0, 0.64, and 0.55 meters, respectively, in order to protect the S/C magnet to the same level as the reference STARFIRE design. Note that the dominant damage parameter for all systems is the radiation dose to the G-10CR insulating material employed in the reference STARFIRE design. Inorganic insulating materials may be able to tolerate a radiation dose more than three orders of magnitude higher than organic materials so that one of the other parameters would then be limiting if they are used in the modified design.

TABLE 2
ADDITIONAL THICKNESSES OF SEVERAL SHIELDING MATERIAL MIXTURES OF INTEREST NEEDED TO ACHIEVE THE REFERENCE STARFIRE PERFORMANCE IN PROTECTING THE SUPERCONDUCTING MAGNET

	SiC + B_4C	MgO + B_4C	Pb + B_4C
Atomic displacement	0.56 m	0.36 m	0.46 m
Insulator dose	0.99 m	0.64 m	0.55 m
Neutron fluence	0.25 m	0.18 m	0.24 m
Gamma-ray fluence	0.60 m	0.47 m	0.34 m

Alternate Materials Evaluation

Alternate materials arrangements were investigated in the inboard region, attempting to reduce the ultimate radiation damage parameters on the S/C magnet while minimizing the additional material thickness required to protect the S/C magnet. The areas considered include (1) the use of gamma-ray shielding material; (2) eliminating the inboard breeding zone; and (3) the use of a more effective radiation attenuation material such as W + B_4C mixture.

The results previously discussed revealed that the high insulator dose associated with the low-activation designs is partly due to the gamma-ray heating. It would therefore be prudent if a layer of efficient gamma-ray shielding material such as lead be placed between the shield and S/C magnet to reduce the gamma-ray heating. We found that at the back of the shield a 0.1 m Pb is about a factor of three more capable of reducing the dose rate on the insulators than is the SiC + B_4C mixture of the same thickness.

Substituting the Li_2O breeding material for SiC or MgO in the low-activation inboard design was found to reduce the insulator dose rate by about a factor of three. However, elimination of inboard tritium breeding would require the incorporation of a large quantity of beryllium in the outboard region in order to obtain adequate tritium breeding.

In view of the limited space in the inboard region available for satisfying the important requirements of a tokamak fusion reactor, namely to breed adequate tritium and to guarantee operation of the S/C magnets for the entire plant lifetime, it seems necessary to consider the use of other, more effective shielding materials, despite possible introduction of higher levels of radioactivity and accompanying high decay dose rates and radiological hazards. However, there are ways to mitigate the post-shutdown radioactivities in the inboard compartment during maintenance and disposal. One of them is the development of a removable and storable shield component concept. During normal reactor operation, the higher activation shield components are inserted in the positions to function effectively as highly efficient neutron and gamma-ray attenuators. When the reactor shuts down for routine maintenance or component disposal, the higher activation shield can be removed from the inboard shield compartment and stored in a shielded area for resue.[5]

TRITIUM BREEDING

One of the most important functions of the fusion blanket is to breed adequate tritium for fueling the D-T plasma. The reference STARFIRE design employs a solid breeder $LiAlO_2$ with the assistance of a neutron multiplier, Zr_5Pb_3. The tritium breeding ratio obtained for such a design is about 1.19 tritons per D-T neutron with a one-dimensional idealized model calculation without considering any loss due to the surface coverage from the pumping ports and other penetrations. A three-dimensional calculation was performed for the reference STARFIRE design to investigate the effect of the surface coverage.[3] It was found that the net tritium breeding ratio is 1.04 tritons per D-T neutron which is about 15% lower than the one-dimensional idealized model calculation.

In the low-activation design approach, the tritium breeding design should also follow the low-activation principle. Liquid lithium and Li_2O are possible tritium breeding materials which may not need a neutron multiplier. Beryllium and lead can be used as neutron multipliers; however, lead must be in a form that can be drained after shutdown of the reactor for blanket maintenance and other purposes to reduce the radiation level so that the features of a low activation fusion reactor can be maintained. In this study we chose Li_2O solid breeder as our target breeder, since it is of less safety concern compared to the other candidate, liquid lithium. $Li_{17}Pb_{83}$ was considered to be an alternate breeding material because of its superior tritium breeding capability, safety features, and ease of draining.

Tritium breeding ratios and total nuclear heating rates for the low-activation substitution designs and the reference STARFIRE design were obtained from the neutronic calculations. The low-activation designs employing either SiC or MgO shield materials give a one-dimensional tritium breeding ratio of about 1.02 tritons per D-T neutron. Of that, about 32% is contributed by the $^7Li(n,n'\alpha)$ reaction. If the 10% cross-section reduction in $^7Li(n,n'\alpha)$ reaction is taken into account,[10] the tritium breeding ratio will be 0.99 tritons per D-T neutron. This is clearly inadequate compared to the reference STARFIRE design that shows a tritium breeding ratio of about 1.19 due to the employment of an external neutron multiplier, Zr_5Pb_3. The Pb + B_4C design gives a tritium breeding ratio between the reference STARFIRE design and the low-activation designs. After reduction of the $^7Li(n,n'\alpha)$ reaction cross-section, it is about 1.07 tritons per D-T neutron.

The total nuclear heating rates for the reference STARFIRE, SiC + B_4C, MgO + B_4C, and Pb + B_4C designs are 17.60, 16.26, 16.25, and 17.07 MeV per D-T neutron, respectively. It is of interest to observe that metallic alloy structured blankets with higher tritium breeding ratios also give higher total nuclear heating rates.

In the previous simple substitution designs, Li_2O was found to produce a tritium breeding ratio of about 0.99 tritons per D-T neutron with inboard breeding. Because the $^7Li(n,n'\alpha)$ reaction rate in the inboard region is smaller than that in the outboard region due to the thinner inboard breeding zone, the Be(n,2n) reaction in the inboard region can contribute more to the tritium breeding than the $^7Li(n,n'\alpha)$ reaction lost in the substitution of Li_2O with beryllium. A reduction of required beryllium inventory may also be achieved by incorporating the beryllium-based neutron multiplier only in the inboard region. Thus, we investigated the addition of 10 to 50 mm of BeO, Be, and Pb neutron multipliers in the inboard region of the simple Li_2O system to increase the breeding ratio. Table 3 shows the tritium breeding ratios for these design modifications. Note that all these cases with neutron multipliers show a breeding ratio greater than one.

REFERENCE LOW-ACTIVATION DESIGN

For the low activation fusion reactor design, due to the known lesser attenuation properties of the lower atomic number low-activation materials such as SiC and B_4C, it is required that a thicker shield be installed in the inboard region if it is to meet the same attenuation requirement to protect the S/C magnet when compared to the case where conventional shield materials such as stainless steel or tungsten are to be used. The increased shield thickness may be accommodated by combinations of increasing the plasma major radius, reducing the magnet region and/or breeding zone thicknesses, or radiation hardening the S/C magnet so a less effective and thinner shield is tolerable. However, the overall economic impact of these changes on the low-activation design cannot be

TABLE 3
TRITIUM BREEDING RATIOS FOR SEVERAL Li_2O BLANKET DESIGNS WITH NEUTRON MULTIPLIER IN THE INBOARD REGION ONLY

Neutron Multiplier(a)	BeO(b)	Beryllium		Lead
Thickness (cm)	5	1	5	5
^{6}Li(n,α)	0.762	0.728	0.847	0.832
^{7}Li(n,n$'\alpha$)(c)	0.299	0.325	0.301	0.285
Total tritium breeding ratio	1.061	1.053	1.148	1.117

(a)80% neutron multiplier + 20% helium.
(b)80% dense.
(c)After 10% reduction in the reaction rate is made.

estimated without conducting a full-scale reactor design and subsequent system analysis. Such a task involves a much more complete analysis beyond the scope of the present work. Thus the reference STARFIRE design thickness requirements will be maintained in our low-activation inboard design. This results in the requirement for selection of the most efficient shielding material, tungsten.

Based upon the above investigations, a reference low-activation tokamak fusion reactor design was completed. It consists of the following features:

1. A helium-cooled blanket is employed that incorporates Li_2O breeder and SiC structure, with beryllium included in the inboard region as a neutron multiplier.
2. It has five layers of removable tungsten plates, each 6 cm thick, inserted in aluminum tanks and cooled by water. These must be removed as a whole block, including the three intervening B_4C layers, to shielded storage before maintenance in the inboard region can be attempted.[5]
3. All structural materials in the shield are replaced with low-activation aluminum alloy.
4. The total inboard blanket and shield thickness is the same as that of the reference STARFIRE design.
5. The S/C magnet system employs epoxy-reinforced graphite fiber as the coil case and is designed based upon the minimum thickness, low-activation, S/C magnet design concept as described in Ref. 11.

As given in Table 3, the one-dimensional tritium breeding ratio for the reference low-activation design can be 1.15 tritons per D-T neutron or more. The total nuclear heating in the system is about 16.93 MeV per D-T neutron. Of that, about 11.81 MeV per D-T neutron is deposited in the outboard region. Most of the inboard nuclear heating, about 5.12 MeV per D-T neutron is deposited in the inboard neutron multiplier and breeding zones. About 2.6% of the total nuclear heating is deposited in the inboard shield region where it is removed by water at low temperature.

Neutronic calculations also show that this design is able to achieve the nuclear design requirements demanded by the reference STARFIRE design while still having a very low radioactivity inventory in the reactor structures. Table 4 shows the maximum radiation damage parameters on the S/C magnet for the reference low-activation and STARFIRE designs. As seen in this table, the radiation dose to the S/C magnet insulators after 30 full-power years reaches about 5.5×10^{7} Gy which is about a factor of three higher than that in the reference STARFIRE design. This is primarily due to the use of different structural materials in both designs. However, this can be mitigated by employing a more radiation-resistant organic insulation material, such as polyimide.[12]

CONCLUSION

In conclusion, a low-activation tokamak fusion reactor design can be achieved that realizes the basic advantages of low-residual radioactivity and satisfies the fundamental nuclear design requirements of adequate tritium production and acceptable shielding of the superconducting magnets. Radwaste disposal problems and limitations on personnel access for plant maintenance should be much improved.

TABLE 4
MAXIMUM RADIATION DAMAGE PARAMETERS
ON THE S/C MAGNET FOR THE
REFERENCE LOW ACTIVATION AND STARFIRE DESIGNS

	Reference Low-Activation Design	Reference STARFIRE Design
Atomic displacement (dpa/7.5 FPY)(a)	7.5×10^{-4}	2.1×10^{-4}
Insulator dose (Gy/30 FPY)	5.5×10^{7} (81% neutron)	1.8×10^{7} (85% neutron)
Neutron fluence (n/m^2/30 FPY)	5.3×10^{22}	9.7×10^{21}
Gamma-ray fluence (γ/m^2/30 FPY)	2.6×10^{22}	5.3×10^{21}
Conductor nuclear heating (W/cc)	3.3×10^{-5} (35% neutron)	2.3×10^{-5} (19% neutron)

(a) FPY = full power years.

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