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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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M.E. Sawan[1], C.S. Aplin[1], G. Sviatoslavsky[1], and A.R. Raffray[2]

[1] *Fusion Technology Institute, University of Wisconsin, Madison, WI, sawan@engr.wisc.edu*

[2] *University of California-San Diego, San Diego, CA, rraffray@ucsd.edu*

***Abstract*—A blanket concept made of SiC_f/SiC composite and utilizing Flibe as coolant and tritium breeder has been developed and integrated with the magnetic intervention system. To achieve tritium self-sufficiency, a 1 cm thick Be insert is utilized in the first wall coolant channel. All magnet, vacuum vessel, and personnel shielding requirements can be satisfied. The nuclear performance parameters of this blanket were compared to those of a lithium-lead blanket in two chamber core configurations. Because of the lighter blanket and shield weight that needs to be supported, the higher thermal power, and the lower electrical conductivity, the Flibe blanket option is particularly well suited for a laser fusion power plant with magnetic intervention.**

Keywords-neutronics; laser fusion; magnetic intervention; nuclear heating; shielding

I. Introduction

The option of using magnetic intervention to steer the ions emanating from directly driven targets away from the dry chamber wall can dramatically reduce the peak wall temperature and is being assessed by the High Average Power Laser (HAPL) program [1]. A cusp magnetic field is imposed on the chamber and the ions from the micro-explosion are trapped within the magnetic field and are directed to more readily accessible and replaceable dump plates at the equator and poles [2]. A large fraction of the magnetic energy can be dissipated in the chamber walls if an electrically resistive structural material is used. A conceptual study of the key components and systems forming the integrated magnetic intervention chamber core is underway [3].

A blanket concept made of the low electrical conductivity SiC_f/SiC composite (required for dissipating the magnetic energy resistively) and utilizing $Li_{17}Pb_{83}$ eutectic (LiPb) as coolant and tritium breeder was developed and integrated with the magnetic intervention system [4]. In this paper, we address the neutronics issues for a blanket that utilizes the molten salt Flibe (consisting of LiF and BeF_2, with a molar ratio of 2:1) in place of LiPb. Flibe has lower electrical conductivity that makes it an attractive breeder/coolant option in magnetic intervention systems. In addition, it has lighter weight to support, and good neutron attenuation properties. On the other hand, it has a relatively high melting point (459°C), lower thermal conductivity, lower tritium breeding potential, and requires careful chemistry control of the corrosive TF and F_2.

In order to compare the performance parameters, we carried out neutronics calculations for the Flibe blanket option using the same chamber configuration used previously with LiPb [4]. In this initial configuration, the chamber consists of an upright cone on top of an inverted cone, with the mid-plane space reserved for a toroidal ring cusp dump as shown in Fig. 1. The apex of each cone has a polar cusp armored dump, which is exposed to some of the diverted ions. The dump is shown schematically at the chamber first wall level but could be positioned away from the chamber to spread out the energy deposition over a larger area. A shield and a vacuum vessel (VV) are placed directly behind the blanket. The blanket consists of sub-modules that increase in depth from 70 cm at mid-plane to 106 cm at the ends. Each sub-module consists of two concentric conduits forming an annular channel and a large inner channel. Reference [4] gives a detailed description of the blanket design.

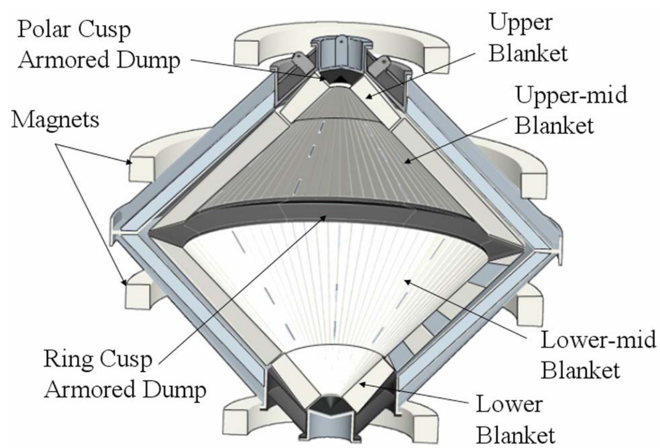

Fig. 1. Example chamber configuration with magnetic diversion.

Another configuration is currently being considered in which a larger VV encloses the blanket, shield, and magnets [3]. In this paper, we will provide a neutronics assessment of these configurations and compare the shielding requirements with the Flibe and LiPb blanket options.

II. Calculation Procedure

The ONEDANT module of the DANTSYS 3.0 discrete ordinates particle transport code system [5] was used to perform the neutronics calculations utilizing the FENDL-2.1 nuclear data library [6]. The chamber is modeled in spherical geometry with a point source at the center emitting neutrons with a softened energy spectrum resulting from interactions between fusion neutrons and the dense target materials. The reference HAPL target yield is 367.1 MJ. For a repetition rate of 5 Hz, this corresponds to a total fusion power of 1836 MW. The target emits 1.4×10^{20} neutrons per shot with an average energy of 12.3 MeV. In addition, 1.7×10^{16} gamma photons with an average energy of 6.1 MeV are emitted from the target. The neutron wall loading varies significantly along the first wall (FW) due to the large change in distance from the target and incidence angle of source neutrons. The neutron wall loading, calculated analytically, peaks at a polar angle of 45°. For a 6 m chamber radius at mid-plane, the peak neutron wall loading is 6 MW/m^2 and the average value is 4.3 MW/m^2. The neutron wall loading variation is accounted for in the neutronics results presented here.

III. Tritium Breeding

In order to ensure tritium self-sufficiency, the overall tritium breeding ratio (TBR) should exceed unity by an adequate margin to compensate for losses and radioactive decay of tritium, supply inventory for startup of other plants, provide reserve storage inventory, and account for uncertainties in nuclear data and modeling [7]. In this study, we require an overall TBR >1.1. The total breeding blanket coverage lost by the ring cusp, the two point cusps, and the 40 laser beam ports is 8.4% implying that the local TBR should be at least 1.2. A local TBR of 1.12 is obtained with a FW thickness of only 0.7 cm and 10% structure in the blanket. Increasing the blanket thickness has minimal effect on the TBR and enriching the Li in Flibe reduces the TBR. Adding a modest amount of beryllium in the FW coolant channel helps enhance the TBR as shown in Fig. 2. Tritium self-sufficiency can be achieved by attaching a 1 cm thick Be insert to the back wall of the FW coolant channel. The Be insert in contact with the Flibe helps with the chemistry control process [8].

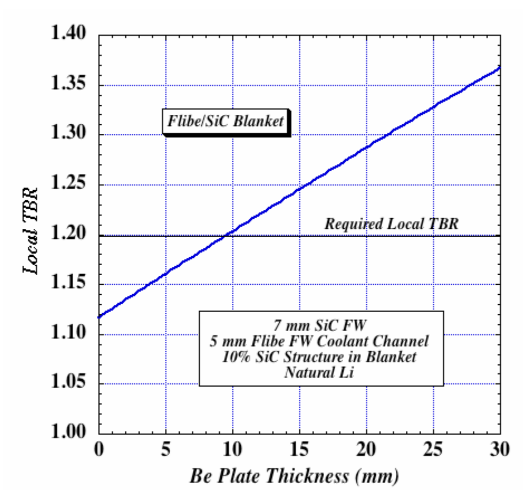

Fig. 2. Impact of Be insert thickness on TBR.

IV. Nuclear Heating

Nuclear heating profiles in the blanket components were determined and used in the thermal hydraulics analysis. Fig. 3 shows the distribution as a function of depth in the blanket at the polar location with highest neutron wall loading. The peak power densities in Be, Flibe, and SiC are 37, 46, and 31 W/cm^3, respectively. The blanket nuclear energy multiplication is 1.232. The power density in SiC FW is similar to that with LiPb while the peak heating in Flibe is half that in LiPb. On the other hand, the energy multiplication is ~4% higher than with LiPb. The energy partitioning of the target as well as the blanket coverage fraction was accounted for to yield a total blanket thermal power of 1878 MW. This consists of 1548 MW volumetric nuclear heating, 307 MW volumetric ion energy dissipation, and 23 MW x-ray surface heating. The thermal power in the 50 cm thick water-cooled shield is only 3 MW. With 7.7% coverage, the total cusp dump thermal power is estimated to be 240 MW including 106 MW volumetric nuclear heating, 132 MW ion surface heating, and 2 MW x-ray surface heating. If the energy deposited in the cusp dumps and shield is included in the power cycle, the total plant thermal power will be 2121 MW which is ~2.5% higher than that with a LiPb blanket [4].

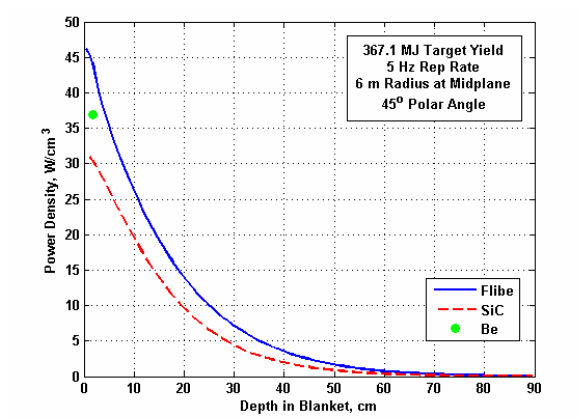

Fig. 3. Nuclear heating at 45° polar angle.

V. Radiation Damage in SiC Structure

The lifetime of the SiC_f/SiC composite material in the fusion radiation environment has been a major critical issue. The radiation effects in the fiber, matrix, and interface components of the composite material represent an important input for lifetime assessment. Neutronics calculations were performed to determine the radiation damage parameters for the SiC fiber/matrix and the candidate interface materials. The leading interface material candidates are graphite for near-term applications, and multilayer or porous SiC for longer-range applications. The radiation damage parameters were calculated for both the carbon and silicon sublattices. The SiC_f/SiC damage parameters were determined at the FW and as a function of depth in the blanket. Table I gives the peak radiation damage parameters at a polar angle of 45°. The results indicate that the dpa rate in the C sublattice is larger than in the Si sublattice of the SiC fiber/matrix. The dpa values are about half those obtained with LiPb while the gas production and burnup rates are ~10% higher than with LiPb [4]. This reflects the fact that Flibe is more effective attenuating intermediate and low energy neutrons while LiPb is more effective attenuating high-energy neutrons. The damage parameters drop as one moves deeper in the blanket as illustrated in Fig. 4 for burnup rates. dpa values have steeper radial drop compared to that in the LiPb blanket while gas production and burnup rates have less steep radial drop.

Lifetime considerations of SiC_f/SiC structure in fusion reactors have been addressed in a recent paper [9]. The useful lifetime of SiC_f/SiC composites in a fusion neutron environment can now only be speculated. It depends primarily on effects of He and metallic transmutants. If we consider an optimistic 3% burnup limit (corresponding to 135 dpa, 15500 He appm, and 6320 H appm), the blanket lifetime is 2.94 FPY which is slightly shorter (by ~10%) than for LiPb blanket [4]. A determination of the effect of fusion-neutron transmutations on the thermomechanical properties of SiC will be required for better assessment of SiC_f/SiC lifetime in the HAPL chamber.

TABLE I. PEAK DAMAGE PARAMETERS IN SiC_F/SiC

	C Sublattice	Si Sublattice	SiC	Graphite Interface
dpa/FPY	45	47	46	30
He appm/FPY	8127	2413	5270	8127
H appm/FPY	5	4291	2148	5
% Burnup/FPY	0.35	0.67	1.02	0.35

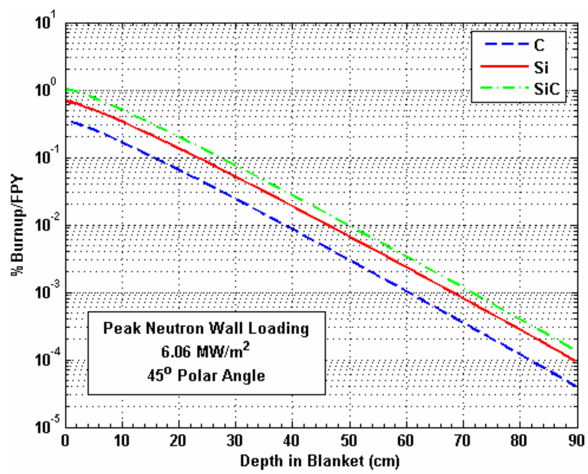

Fig. 4. Radial variation of burnup rate in the SiC.

VI. SHIELD RADIATION DAMAGE

A 50 cm thick shield that doubles as VV is used behind the blanket in this example configuration. The shield is made of steel and is cooled by 25% water. Two types of steel were considered; the austenitic steel 316SS and the low activation ferritic steel F82H [10]. The shield radiation damage parameters are highest at 85° polar angle. Figs. 5 and 6 give the radial variation of end-of-life (after 40 FPY operation) dpa and He production in the 316SS and ferritic steel shields, respectively. The dpa values are lower than with the LiPb blanket but the He production rates are higher. The peak end-of-life radiation damage in the shield is only ~1 dpa implying that it will be a lifetime component. Helium production in the 316SS shield is about an order of magnitude higher than in the ferritic steel. For the shield/VV to be reweldable, the helium production should not exceed 1 appm. The back of the shield/VV is reweldable with either 316SS or F82H. If ferritic steel is used, rewelding is possible at locations at least 10 cm deep in the shield. On the other hand, if 316SS is used, rewelding will be possible only at locations at least 20 cm deep in shield.

VII. DAMAGE PARAMETERS IN CUSP COILS

The largest magnet damage occurs at 85° polar angle with ferritic steel shield/VV. The peak end-of-life values for fast neutron (E>0.1 MeV) fluence and insulator dose are 7.93×10^{21} n/m^2 and 1.14×10^7 Gy, respectively, in the superconducting cusp coils. These are below the limits of 10^{23} n/m^2 and 10^8 Gy [11]. The insulator dose is a factor of ~2 lower than with the LiPb blanket. Using 316SS provides slightly better magnet shielding. The results indicate that the cusp coils are well protected with the 50 cm shield/VV and no restrictions should be imposed on the location of the coils from the shielding point of view.

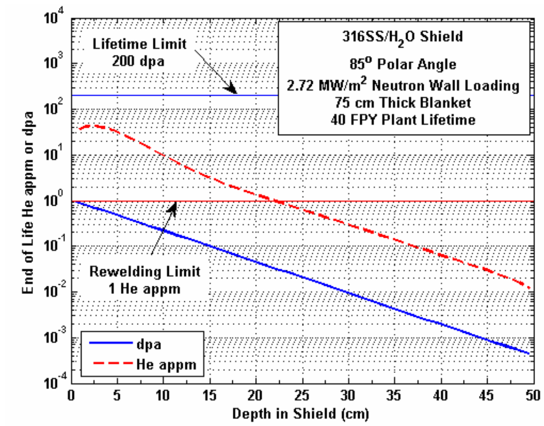

Fig. 5. Radial variation of dpa and He in 316SS shield.

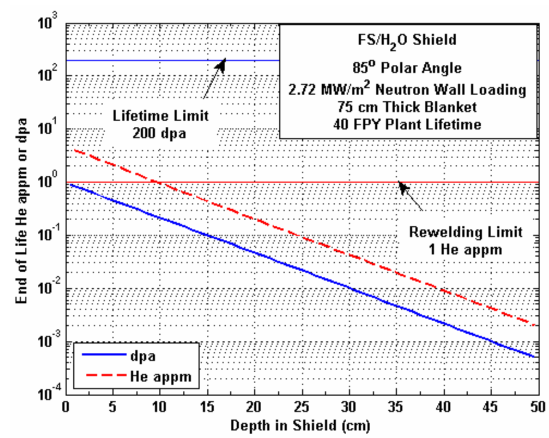

Fig. 6. Radial variation of dpa and He in F82H shield.

VIII. REQUIRED BIOLOGICAL SHIELDING

The biological dose rate behind the shield/VV during operation is 1.5×10^7 mrem/h. Hence, a biological shield is required to allow operational personnel access. A biological shield (containment building) made of 70% concrete, 20% carbon steel C1020, 10% water is used with inner surface at 20 m from the target. Fig. 7 shows the effect of biological shield thickness on the operational biological dose rate outside the containment building. The results indicate that a ~1.5 m thick biological shield is required. The thickness should be at least ~2.5 m behind the beam ports to shield personnel from streaming neutrons.

IX. ASSESSMENT OF CONFIGURATION WITH OUTER VV

We assessed an alternate configuration in which a larger VV encloses the blanket and magnets [3]. In this case, each magnet is encased in a dedicated shield. A biological shield (containment building) encloses the VV. We performed several neutronics calculations for that configuration to determine the thicknesses required to ensure that the shield, magnets, and VV are lifetime components, the VV is reweldable, tritium self-sufficiency can be achieved, and personnel access during operation is possible outside the biological shield. Several iterations were carried out with conditions at polar angle of 85° to determine the dimensions that simultaneously satisfy all the design requirements. For the Flibe blanket option, the blanket thickness should vary from 100 cm at mid-plane to 150 cm at the top/bottom of the chamber. The SS/water magnet shield should be 25 cm thick. With 10 cm thick VV, the required biological shield thickness is 1.9 m.

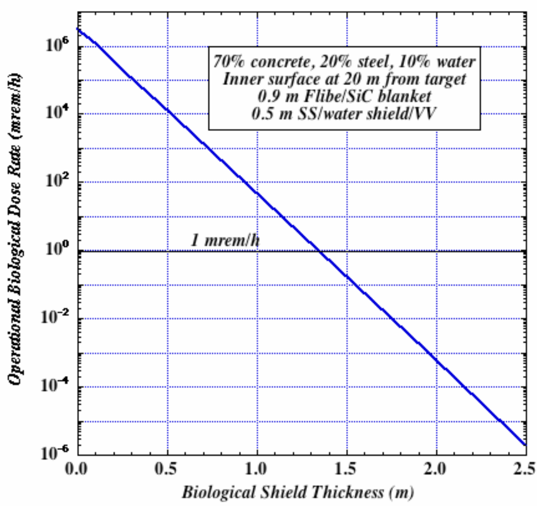

Fig. 7. Biological shield requirement.

Using the same dimensions with LiPb does not allow for simultaneously satisfying all design requirements. The higher tritium breeding capability of LiPb results in excessive TBR (~1.5) and the less effective shielding capability of LiPb leads to unsatisfactory magnet and personnel shielding. The solution is to reduce the blanket thickness, reduce Li enrichment to ~10% ^{6}Li, and increase magnet shield thickness. The blanket thickness varies from 80 cm at mid-plane to 120 cm at the top/bottom of the chamber. The magnet shield thickness has to be at least 45 cm and the biological shield should be 2.2 m thick. Although the LiPb blanket is thinner than the Flibe blanket, the weight is still larger. In addition, the magnet shield is a factor of ~2 heavier resulting in more support requirements. Furthermore, ~0.3 m thicker biological shield is needed. We find the Flibe blanket to be well suited for this configuration based on the above findings and because of its lower electrical conductivity.

X. SUMMARY AND CONCLUSIONS

A blanket concept made of the low electrical conductivity SiC_f/SiC composite and utilizing Flibe as coolant and tritium breeder has been developed and integrated with the magnetic intervention system. Neutronics issues related to tritium breeding adequacy particularly with the area lost to the dump plates at the ring and point cusps were addressed. To achieve tritium self-sufficiency, a 1 cm thick Be insert is utilized in the FW coolant channel. The Be insert in contact with the Flibe helps with the chemistry control process. At the 6 MW/m^2 peak neutron wall loading, the peak power density values in Be, Flibe, and SiC are 37, 46, and 31 W/cm^3, respectively. The total plant thermal power is 2121 MW which is ~2.5% higher than with a LiPb blanket. For a 3% SiC burnup limit, the blanket lifetime is 2.92 FPY which is ~10% shorter than for a LiPb blanket. However, a determination of the effect of fusion-neutron transmutations on the thermomechanical properties of SiC will be required for better assessment of the SiC lifetime in the HAPL chamber. The peak end-of-life radiation damage in the shield/VV is only ~1 dpa implying that it will be lifetime component. Although the back of the 0.5 m thick shield/VV is reweldable, it is recommended to use ferritic steel to allow rewelding near the front of the shield/VV. The superconducting cusp coils are well protected. A ~1.5 m thick concrete biological shield is required for operational personnel access.

We assessed an alternate chamber core configuration in which a larger VV encloses the blanket and magnets. Each magnet is encased in a separate magnet shield. Thicknesses of blanket, shield, VV, and biological shield were determined to ensure that all design requirements are simultaneously satisfied. The magnet shield with the LiPb blanket is a factor of ~2 heavier than with the Flibe blanket resulting in more support requirements. In addition ~0.3 m thicker biological shield is needed. We find the Flibe blanket to be well suited for this configuration based on the above findings and because of its lower electrical conductivity.

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