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ABSTRACT

The need for a thin blanket design in fusion reactors provides a driving force to improve the performance of a LiPb-type blanket through adding a moderator to the breeder to soften the neutron spectrum and, thus, enhance the tritium breeding. As a result, the LiPb blanket performed much better with a beryllium moderator and the design of a 0.17 m thick blanket has become feasible.

INTRODUCTION

The main function of the blanket in a D-T fusion reactor is to breed tritium and recover and multiply the neutron energy. In addition, it cooperates with the reflector and shield in providing adequate radiation protection for the superconducting (S/C) magnet. However, the blanket has less shielding performance and keeping its thickness to a minimum reduces the sizes of the reflector, shield, and magnet, and, thus, decreases the overall reactor cost. Other advantages for thin blankets include reduced tritium and Li inventories, light weight modules which greatly ease the replacement and maintenance process of the blanket. This work presents an attempt to design a thin blanket for MINIMARS[1] that satisfies all requirements of neutronics, safety, thermal-hydraulics, and mechanical design. It should be mentioned that realistic blanket designs reported in the literature[2] have thicknesses of at least 0.24 m. Recent studies for minimizing blanket thickness used idealized blankets with semi-continuously varying composition and no allowance for cooling.[3,4]

The MINIMARS study offered a significant improvement in mirror reactor attractiveness by exploiting innovative concepts and the potential of fusion for inherently safe operation. It is a one and a half year study of a compact tandem mirror power reactor to produce 600 MW of net electric power with a competitive cost of electricity (less than 50 mills/kW·h) and a mass utilization factor higher than 100 kWe/tonne. A tritium breeding ratio (TBR) of 1.05 is a design goal for the MINIMARS blanket and as large energy multiplication as possible is highly desirable to improve the reactor economics. A significant effort was put into the blanket design as it strongly affects the design of other components and is critical in achieving both the cost of electricity and safety goals of MINIMARS. The first year's work included the evaluation of several blanket concepts and the production of a set of baseline parameters for which the point design was completed in the second year.

BLANKET MATERIAL SELECTION

The MINIMARS study group selected the LiPb/Be/He/HT-9 blanket among four competing blanket designs utilizing Li/Be/He/V, FLiBe/Be/He/V and FLiBe/V materials. The $Li_{17}Pb_{83}$ breeder has some salient features regarding reactor safety, tritium breeding, tritium extraction, and energy multiplication (M). The low activation modified HT-9 ferritic steel, reported in the BCSS study,[5] is the structural material in the blanket and reflector. The principal advantage of this material, relative to long term disposal, is the reduction in the molybdenum content. The helium has some unique advantages over other coolants, such as its chemical inertness which makes it compatible with many materials. It also has the potential for operation at very high temperature to achieve a high thermal efficiency.

As will be shown later, the use of beryllium is essential in designing a thin LiPb blanket. The Be has three major drawbacks that are causing some concern within the fusion community. These are the resource limitation of Be, its chemical toxicity, and the neutron-induced swelling in Be. Fortunately, some of these are not as severe as thought before. Recent studies[6,7] of the national and worldwide Be resources concluded that a substantial fusion economy can be supported by projected resources under the condition that an efficient (low loss) recycling process for Be can be developed. Kulcinski[6] estimated that the U.S. reserves of Be can support 455 MINIMARS-type reactors operated simultaneously in the year 2000 and a factor of 3 higher number can be supplied by U.S. resources. Preuss[8] has recently reported that solid Be does not present any health risks unless finely divided into dust or fumes. The use of effective environmental controls on the work site leads to the production and fabrication of Be without undue risk to employees or the general public. The last concern is the neutron-induced swelling in Be which is mainly caused by He production immediately following the (n,2n) reaction of Be with the high energy neutrons ($E_n > 1.7$ MeV). The relative change in Be volume irradiated at intermediate temperatures (400-600°C) and fluences is given by the relation[9]

$$\frac{\Delta V}{V} = 0.00549\ \phi^{1.035} + 7.8 \times 10^{-4}\ (2.5)^{\chi}$$

where ϕ is the neutron fluence in 10^{26} n/m^2 ($E_n > 1$ MeV) and $\chi = T(°C)/100$. The average fluence in the MINIMARS blanket amounts to 4.5 x 10^{26} n/m^2 at the end of 5 full power years (FPY), the design lifetime of the blanket. This corresponds to 10 vol% swelling in Be at 500°C. On this basis, a lower density beryllium (at 90% theoretical density) will be used in the blanket to allow for swelling.

BLANKET NEUTRONICS ANALYSIS

In a LiPb blanket, the tritium breeding results from neutron multiplication in the lead followed by a slow neutron capture in the ^{6}Li. Therefore, it is beneficial to enrich the Li in ^{6}Li to enhance the breeding. Further enhancement can be achieved if more neutron energy spectrum softening is possible. Our investigations show that this is feasible upon adding neutron moderator materials to the LiPb blanket. Although the study was carried out for the LiPb system, we feel that the trends observed here hold true for other breeding materials such as Li and Li_2O. Here we describe how the choice of a neutron moderator affects the TBR, M, and the blanket thickness, and hence the overall size of the central cell. Candidate moderators are hydrogen compounds, graphite, and beryllium. Hydrides are good neutron moderators. However, beryllium has the dual advantage of acting as moderator and multiplier.

Two generic configurations were examined; the moderator in the first is TiH_2, while in the second is Be. The results of the two cases were then compared to the case of a pure LiPb blanket, which represents a MARS-type design. All the calculations were carried out in one dimensional (1-D) cylindrical geometry using the discrete ordinates transport code ONEDANT[10] with the LANL nuclear data library (30 neutron and 12 gamma groups) which is based on the ENDF/B-V evaluation. In the analysis, we considered 10 vol% He coolant and 10 vol% HT-9 structure in all blankets. A meter thick He cooled HT-9 reflector was placed behind the blanket to reflect some of the leaked neutrons and intercept most of their energy. The first wall was located at a radius of 0.5 m and the 14.1 MeV neutron source was uniformly distributed throughout the 0.7 m diameter plasma region.

The results of the analysis show that a 0.275 m thick LiPb blanket yields a TBR of 1.05 and M of 1.32. The energy in the blanket amounts to 67.4% of the total and the gamma heating contributes 42% of the blanket energy, whereas in the reflector the energy is mostly produced by gamma rays. The TiH_2 (at 80% theoretical density) was gradually added to the LiPb blanket (trading LiPb for TiH_2) and Fig. 1 illustrates the effect on the TBR and M. The optimum mixture that maximizes the TBR consists of 10 vol% TiH_2 and 70 vol% LiPb yielding TBR and M of 1.37 and 1.23, respectively. The enhancement in the TBR is expected since the hydrogen slows down the neutrons through elastic scattering collisions, which causes more neutrons to be available for tritium production by ^{6}Li. As noticed, the 0.275 m thick LiPb/TiH_2 blanket provides more tritium breeding than is needed and in order to get a TBR of 1.05 the blanket thickness was reduced to 0.145 m. This corresponds to almost half of the LiPb blanket thickness and results in an M of 1.28. Comparing blankets of the same TBR, the addition of TiH_2 causes M to slightly drop by 3%, reduces the fraction of energy deposited in the blanket to 65%, and lowers the gamma heating contribution in the blanket to 34%.

Although the performance of the TiH_2 is acceptable from the neutronics standpoint, the decomposition of the TiH_2 at elevated temper-

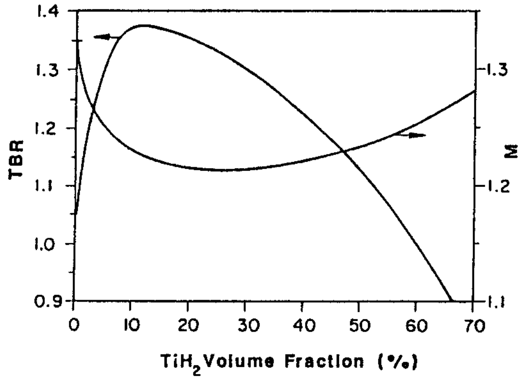

Fig. 1. Effect of adding TiH_2 to the LiPb blanket.

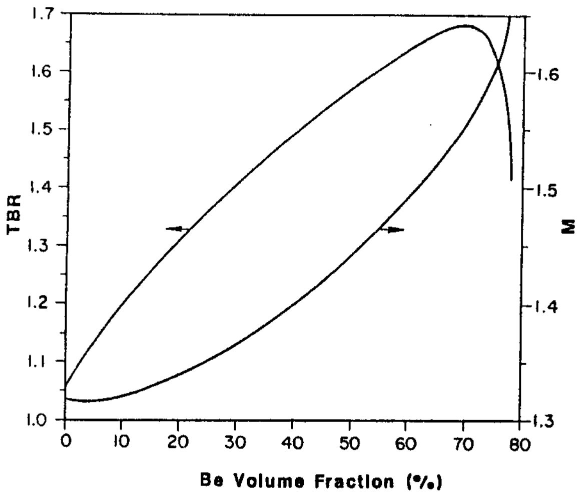

Fig. 2. Effect of adding Be to the LiPb blanket.

atures limits its use in the blanket. For a He cooled LiPb blanket, with HT-9 structure, the operating temperature ranges between 400 and 500°C and is limited by the mechanical properties of the HT-9 structure. Within this temperature range, the TiH_2 slowly decomposes with the release of hydrogen. This major problem has ruled out the option of using TiH_2 as a moderator, in the MINIMARS blanket.

The alternative option is to use beryllium as a moderator. Beryllium is not only an excellent moderator, but it is also an effective neutron multiplier. It increases the total number of neutrons through a high (n,2n) reaction cross section with relatively low threshold energy at 1.7 MeV (compared to 6.7 MeV for Pb). The effect of Be is demonstrated in Fig. 2 upon adding the Be (at 90% theoretical density) to the 0.275 m thick LiPb blanket (trading LiPb for Be). As shown, the TBR peaks at 70 vol% Be and 10 vol% LiPb at a value of 1.68 and the corresponding value of M is 1.56. One reason for the remarkable increase in M is that the fraction of energy lost in the (n,2n) endothermic reaction is less compared to that in Pb, causing more neutron energy to be available for heating. The 0.275 m thick LiPb/Be blanket gives excessive breeding and in order to meet the design goal for the TBR, the blanket thickness was decreased and a 0.137 m thick LiPb/Be blanket was found to give a TBR of 1.05 and M of 1.57. The fraction of energy in the blanket is 57.6% and 81% of it is neutron heating.

Clearly, the LiPb/Be concept yields the thinnest breeding blanket with the largest energy multiplication. Several runs of the Tandem Mirror System Code (TMSC)[1] have shown that the LiPb/Be blanket yields the lowest cost of electricity compared to the LiPb and LiPb/TiH_2 as well as the other blanket concepts considered for MINIMARS. This was the main reason for selecting the LiPb/Be as the MINIMARS baseline blanket design. Two important factors must be considered in the design of a LiPb/Be blanket, however. Firstly, due to the small volume content of the LiPb in the thin LiPb/Be blanket, the Li will be depleted rapidly and the TBR will decrease during reactor operation. Therefore, during the process of slowly circulating the LiPb for tritium removal, a Li replenishment must be done continuously in order to maintain a constant ^6Li concentration in the breeder. Secondly, at the MINIMARS flux level, the Be swells by 10 vol% at the end of the 5 FPY design lifetime of the blanket. At that time the blanket will be changed and the Be must be reprocessed.

BLANKET DESIGN

In the above scoping analysis, we have considered 10 vol% coolant and 10 vol% structure that were invariant with the blanket thickness (Δ_B). In the actual design, these quantities vary according to the blanket thickness in order to meet the mechanical and thermal hydraulic requirements. The final central cell design of MINIMARS calls for a first wall radius of 0.542 m and a neutron wall loading of 3.3 MW/m^2. There are 24 blanket modules in the 88 m long central cell. Each module is 3.6 m long and contains 18 cells. Figure 3 shows an axial cross section through adjacent blanket cells. The He gas runs in small tubes immersed in a

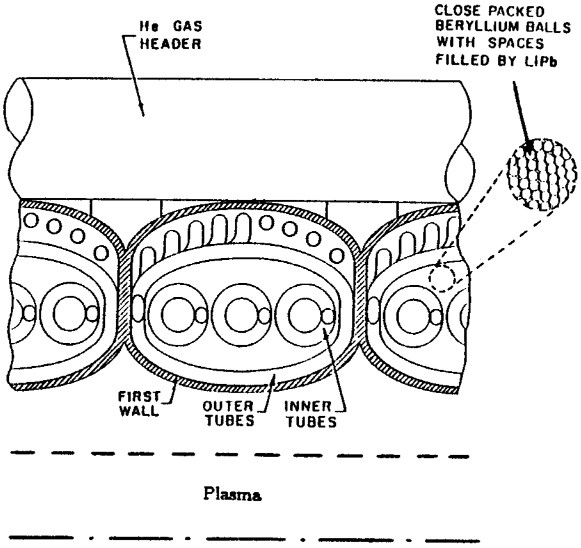

Fig. 3. Axial cross section through several blanket cells.

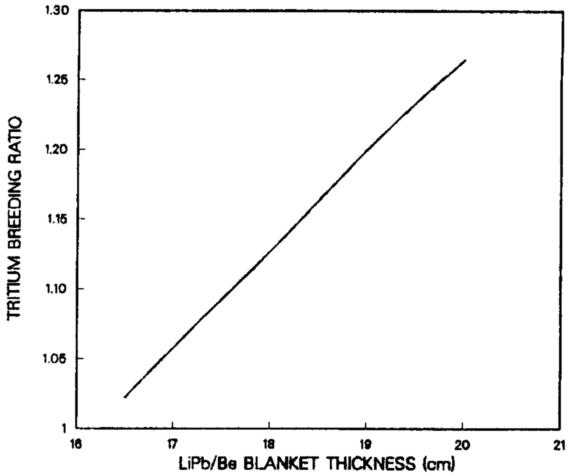

Fig. 4. Variation of TBR versus LiPb/Be blanket thickness.

close-packed matrix of Be balls. The space between the Be balls is filled with the LiPb. The outer tubes cool the front and back zones and the inner tubes cool the center of the blanket.[11] Each blanket module has 8 helium manifolds attached to the outer perimeter. They cover 33% of the area at the back of the blanket and each is 0.12 m thick.

With the constraint of 1.05 TBR, many iterations were performed to determine the blanket thickness and content that satisfy all requirements for neutronics, thermal hydraulics, and mechanical design. The blanket was modeled for the 1-D code as 5.2 mm thick front and back HT-9 walls sandwiching a breeding zone consisting of a homogeneous mixture of LiPb, HT-9, and the He/void. The LiPb to Be ratio was reoptimized for the thin blanket with the TBR being maximized. The variation of the TBR with the total blanket thickness is given in Fig. 4. It is worth mentioning that a few centimeters increase in the blanket thickness yields considerably higher TBR, an indication of a high performance breeding blanket. The results show that the required blanket thickness is 0.17 m and the breeding zone between the front and back walls consists of 12.73 vol% LiPb, 58.76 vol% Be, 5.41 vol% HT-9 with the balance being void and He coolant.

REFLECTOR AND SHIELD DESIGN

The energy multiplication depends on the thickness of the reflector as the energy is recovered from both blanket and reflector. In MINIMARS, the reflector acts as the first layer of the magnet shield and its thickness depends on the kind of shield, the allowable radiation limits at the magnet, and the neutron wall loading. An extensive study has been performed to optimize the shield and determine the thickness that adequately protects the magnet. The HT-9 reflector is followed by a layer of B_4C-shield and then a layer of Pb-shield. In all layers 10 vol% structure and 10 vol% He were considered. The three layers were varied in thickness and the optimum composition and thickness of the shield are determined such that the nominal peak S/C winding pack nuclear heating is minimized at 0.1 mW/cm^3 (based on economic considerations). The optimal shield was found to consist of 54.3% reflector, 34.5% B_4C-shield, and 11.2% Pb-shield. The values indicate percentage of the total reflector and shield thickness which is 0.91 m. The reflector is 0.494 m thick and the corresponding value for the energy multiplication is 1.42. Appropriate reflector cutouts are used to accommodate the He manifolds implying that the reflector thickness is reduced by 0.12 m at the azimuthal locations where the manifolds are located. Allowing enough space for the magnet cryostat and some clearances, the magnet inner bore radius was set at 0.173 m. Some additional information related to the nominal radiation effects at the inner bore of the S/C magnet are the dose to the electric insulator, dpa in the Cu stabilizer, and fast neutron fluence to the NbTi superconductor. These are 3.6×10^9 rad at 30 FPY, 1.1×10^{-4} dpa/FPY, and 4.5×10^{22} n/m^2 at 30 FPY, respectively. Although the He manifolds may result in a factor of ~ 5 higher values at some magnet locations, the radiation effects are still below the adopted design limits for MINIMARS.

SAVINGS IN CENTRAL CELL SIZE

It is interesting to quantify the savings in the central cell size and the COE for the thin LiPb/Be blanket. Satisfying the same magnet criteria, the LiPb blanket would require a magnet inner bore radius of 1.78 m. This corresponds to a reflector thickness (Δ_R) of 0.406 m and energy multiplication of 1.18. Table 1 compares the parameters of the central cell components for the LiPb and LiPb/Be blankets for the same TBR, peak nuclear heating at the magnet, and net electric power. Less than one tenth of the amount of LiPb in the LiPb blanket is required to breed tritium in the LiPb/Be blanket. This translates to lower Li and T inventories in the LiPb/Be blanket. Also, the volume of the LiPb/Be blanket amounts to half of that of the LiPb blanket. This means lighter blanket modules, easier to replace and maintain, and, more importantly, less material to be disposed of at the end of the 5 FPY blanket lifetime. Moreover, the LiPb/Be blanket results in a remarkably higher energy multiplication. A run of the TMSC code shows that the 17% reduction in the central cell size combined with the 20% increase in the energy multiplication results in up to 6% decrease in the cost of electricity, which is significant. It should be pointed out that the savings in the magnet

Table 1. Comparison Between the Size of the Central Cell (CC) Components for the LiPb and LiPb/Be Blankets

Blanket	LiPb*	LiPb/Be+
Δ_B (m)	0.29	0.17
V_B (m^3)	125.2	59
V_{LiPb} (m^3)	99.3	7
$ID_{S/C}$ (m)	3.56	3.46
$\Delta_{R,S}$ (m)	0.84	0.91
Δ_R (m)	0.406	0.494
M	1.18	1.42
L_c (m)	~ 100	88
V_{CC} (m^3)	1018	845

* 79.3 vol% LiPb, 8.5 vol% HT-9, 12.2 vol% He/void.

\+ 12 vol% LiPb, 55.1 Vol% Be, 11.2 vol% HT-9, 21.7 vol% He/void

size and COE are more pronounced for reactor designs that call for a higher TBR as a design goal. For example, a TBR of 1.2 would require 0.19 and 0.36 m thick LiPb/Be and LiPb blankets, respectively, and the difference in the inner bore diameters of the S/C magnets is up to 0.2 m.

CONCLUSIONS

The design of a viable thin helium cooled blanket has been made possible through an optimization study which combines the Be moderator and the LiPb breeder and results in a novel blanket of excellent neutronic performance. Through the design of the LiPb/Be blanket, the MINIMARS goals of adequate tritium breeding, high energy multiplication, low cost of electricity, high mass utilization factor, and Class-C blanket waste disposal - are all met.

ACKNOWLEDGEMENT

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