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ABSTRACT

A neutronics analysis for the MARS Li-Pb blanket and shield is presented. A thin blanket with a thick Fe-1422 reflector yields a tritium breeding ratio of 1.13 and an energy multiplication of 1.39. This blanket design has the attractive features of low cost, reduced activated waste, and ease of maintenance. A shield has been designed to provide adequate magnet protection.

INTRODUCTION

The Mirror Advanced Reactor Study¹ (MARS) is a conceptual design of a tandem mirror fusion power reactor. MARS utilizes a long cylindrical central cell (approximately 150 m long) consisting of 84 blanket modules where tritium breeding occurs and most of the energy is produced. Neutronics analysis has been performed for the Li-Pb blanket design of MARS. In this design, the liquid metal eutectic $\text{Li}_{17}\text{Pb}_{83}$ is used as the breeder and coolant. The ferritic steel alloy HT-9 is used for the structural material in the blanket. The blanket includes a front tube zone composed of several rows of close packed tubes 10.14 cm in diameter which provide for good heat removal and low stress where the energy deposition rates are highest. The back zone of the blanket consists of a single row of hollow rectangular beams which provides structural support for the blanket. The blanket is followed by a water cooled stainless steel reflector. The energy deposited in the blanket and reflector is recovered and represents the reactor's thermal power.

The primary goal of the neutronics analysis presented here is to determine the blanket design which yields the largest energy multiplication (M) with adequate tritium breeding ratio (T). This will have an impact on reducing the overall cost of produced electricity. A value of $T \approx 1.1$ is required in this work to account for any deficiencies and uncertainties in the calculational model and cross section data used. A set of neutronics calculations has been performed to determine the appropriate composition

and thickness for the different zones of the blanket and reflector.

Adequate shielding is required to protect the central cell superconducting solenoids from excessive radiation effects caused by neutrons and gamma photons which penetrate the blanket and reflector. The blanket is a poor neutron attenuator due to the large volume fraction of lead which is relatively transparent to neutrons. Hence, a separate effective shield is needed. Detailed shield analysis is presented here.

CHOICE OF CALCULATIONAL METHOD AND CROSS SECTION DATA

The discrete ordinates and Monte Carlo methods are the main calculational methods used in neutronics analyses. Different codes based on these methods are available. In order to compare the accuracy of these methods, a benchmark calculation of tritium breeding in a liquid lithium blanket with Nb structure was performed using 100-group cross section data based on ENDF/B-III.² Good agreement was obtained between the results of the different codes. Later results showed that good agreement can still be obtained for this benchmark problem with fewer energy groups. As a result, discrete ordinates codes, such as ANISN³ and ONEDANT,⁴ with 25-, 30-, and 46-group cross section libraries have been used for neutronics analysis of fusion reactor designs. However, the situation is quite different for a Li-Pb blanket, especially when natural Li is used. A benchmark problem was set for a Li-Pb blanket utilizing HT-9 as structure.⁵ Although the resulting T values from the different codes agree very well when the same multigroup cross section library is used, they differ considerably when different group structures or weighting spectra are adopted. The Li-Pb blanket has large amounts of Pb and Fe and hence a much softer neutron spectrum. The calculated neutronics behavior of a Li-Pb blanket is sensitive to the energy group structure. This effect is more pronounced for systems with low lithium enrichment. The discrete ordinates

codes yield values of T which are different from the results of the continuous energy MCNP⁶ Monte Carlo code even when 80 neutron groups are used.⁵ Therefore, in this work, MCNP is used to eliminate energy group structure effects. Since we are interested only in integral quantities such as T and M, low statistical uncertainties can be achieved with a reasonable number of histories. 4,000 histories were used in the calculations resulting in statistical uncertainties less than 1% for the quantities of interest.

Cross section data libraries based on the ENDF/B-IV and ENDF/B-V evaluations are available for use with MCNP. Our results show that using ENDF/B-IV data tends to overestimate T and underestimate M, when compared to ENDF/B-V data, for a Li-Pb system. Therefore, the cross section data library based on the most recent ENDF/B-V evaluation is used in this work.

Since the Monte Carlo method is not efficient in handling deep penetration problems and for accurately predicting local radiation effects, the one-dimensional discrete ordinates code ONEDANT was used in the shield neutronics analysis. A series of P₃S₈ calculations has been performed using a coupled 46 neutron-21 gamma group cross section library based on the VITAMIN-C data library⁷ and the MACKLIB-IV-82 response library.⁸

NEUTRON MULTIPLICATION IN Li-Pb BLANKET AND CHOICE OF BLANKET THICKNESS

Neutron multiplication via the Pb(n,2n) reaction results in attractive neutronics performance of Li-Pb blankets. A neutron multiplication (M_n) of up to 1.8 can be achieved in a Li₁₇Pb₈₃ blanket which has an impact on increasing both T and M. The neutron multiplication increases as the blanket thickness increases reaching a saturation level at a blanket thickness of approximately 30 cm as shown in Fig. 1. This implies that from the point of view of neutron multiplication, the lead in the back region of the blanket is ineffective. Hence, a thin blanket design was considered. To achieve adequate tritium breeding in such a design, lithium enrichment is essential. Neutronics calculations were performed for a thin blanket design in which the lithium is enriched to 90% ⁶Li and compared to a thick blanket design in which natural lithium is used. A saving of 49 cm (38.2 versus 87.2 cm) in blanket thickness was achieved for the same tritium breeding ratio (T = 1.1). This results in reducing the central cell cost because of the associated smaller magnet size. Furthermore, the blanket

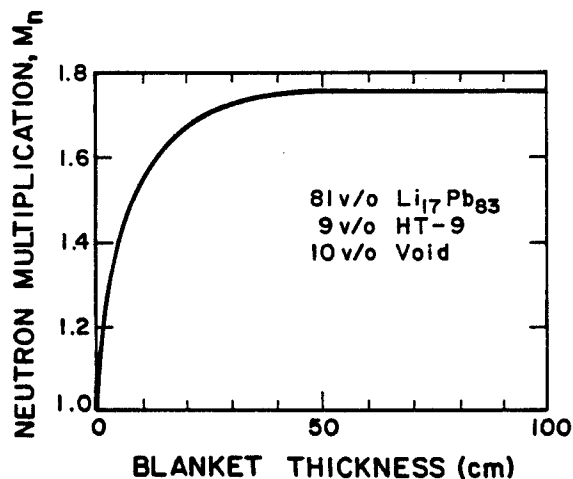


Fig. 1. Dependence of neutron multiplication on thickness of Li₁₇Pb₈₃ blanket.

has less weight and can be easily changed out with a reduced amount of activated waste. However, in comparison with the thick blanket a smaller M is obtained from the thin blanket when HT-9 is used as a reflector.

ENHANCEMENT OF M FOR THE THIN BLANKET

Analyzing the breakdown of the capital cost of a mirror reactor plant, it becomes clear that the cost of the central cell constitutes only a small fraction of the total cost. As a result, the significant saving in the central cell cost obtained by using a thin blanket design implies only a small saving in the total capital cost of the machine. On the other hand, the net electrical power of the system is almost directly proportional to M. Therefore, it is vital to maximize the energy multiplication of the blanket (M) in order to enhance the overall economic figure of merit.⁹ Several attempts have been made to enhance M while preserving the advantages associated with the thin blanket design. Two such ways were considered and are discussed below.

A. Decreasing Structural Material Content in Blanket

Decreasing the structure content in the beam zone of the blanket was found to increase M. Figure 2, which is reproduced from Ref. 10,

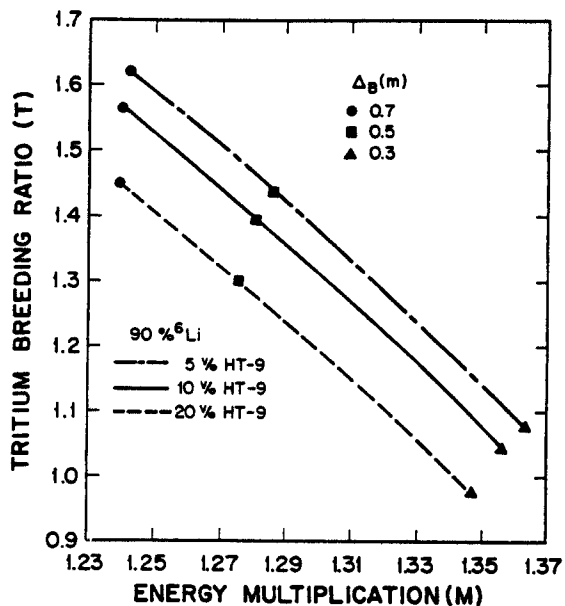


Fig. 2. The T-M plot showing effects of blanket thickness and structure content.

shows this trend for different Li-Pb blanket thicknesses. For a given blanket thickness, both T and M increase as the structure content decreases. For certain required values of T, larger M is obtained when a thinner blanket is used with a smaller structure content. The results in Fig. 2 were obtained using ONEDANT with the 46 neutron-21 gamma group cross section library. The results of MCNP with ENDF/B-V data display the same trend. A beam zone consisting of 85 vol% $\text{Li}_{17}\text{Pb}_{83}$ and 15 vol% HT-9 has been chosen to achieve high M while providing adequate support. From structural and thermal-hydraulics considerations, the volumetric fractions in the blanket tube zone have been chosen to be 73.7 vol% $\text{Li}_{17}\text{Pb}_{83}$, 7.1 vol% HT-9, and 19.2 vol% void. The tube and beam zones of the blanket have thicknesses of 19.2 and 19 cm, respectively.

B. Choice of Reflector Material and Thickness

Further enhancement of M can be achieved by appropriate choice of reflector material and thickness. For a thin blanket, a relatively large fraction of energy is deposited in the reflector and the overall energy multiplication

is sensitive to the reflector design. Materials considered in this analysis include HT-9, 316-SS, graphite, Ta, and Fe-1422. The low activation steel Fe-1422 was found to yield the largest M, primarily due to the large neutron absorption in manganese (14 wt%).

Increasing the reflector thickness was found to increase M further reaching a saturation value after a thickness of approximately 43 cm. Figure 3 shows the effect of reflector thickness and material on energy multiplication for a thin blanket utilizing 90% enriched lithium and a thick blanket with natural lithium. Both blanket designs give similar values of T. Increasing the reflector thickness from 28 cm to 43 cm for the thin blanket was found to increase M from 1.35 to 1.39. The fraction of energy deposited in the reflector increased from 24.5% to 27.6% while the fraction of energy deposited as low grade heat in the shield decreased from 3.85% to 0.76%. It is clear from the results of Fig. 3 that the improvement in M is more pronounced for the thin blanket design. According

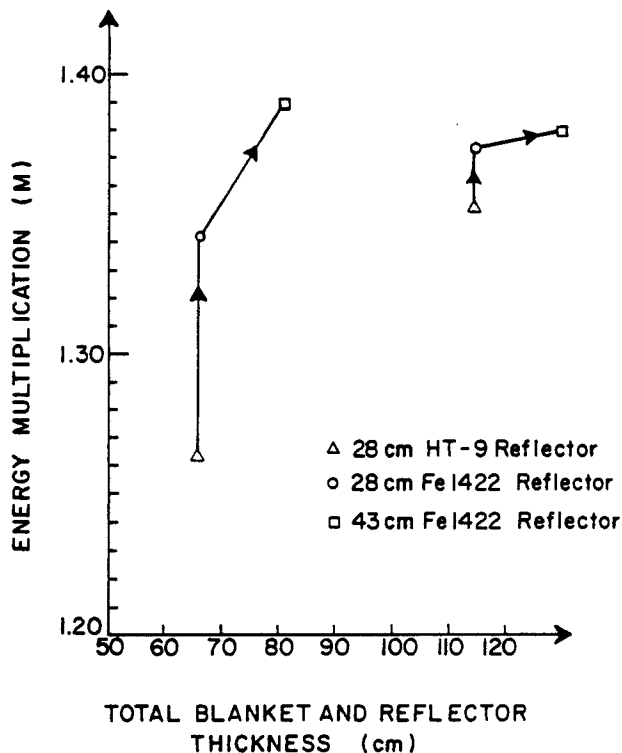


Fig. 3. Energy multiplication for different reflectors of the Li-Pb blanket.

to this analysis, a 43 cm thick Fe-1422 reflector was chosen to be used with the thin blanket design. The main disadvantage of the thin blanket design is the large fraction of heat deposited in the water cooled reflector. This results in a reduced overall thermal efficiency. This was taken into account in a detailed cost analysis which revealed that the thin blanket design had a better overall economic figure of merit than the thick blanket design.

NEUTRONICS PERFORMANCE OF MARS Li-Pb BLANKET

A schematic of the MARS Li-Pb blanket, reflector, shield, and magnet is given in Fig. 4. A summary of the tritium production results for the MARS blanket is given in Table I. The overall tritium breeding ratio is 1.13. Almost all tritium is produced in the ${}^6\text{Li}(n,\alpha)\text{t}$ reaction. The nuclear heating results are summarized in Table II. The total recoverable energy is 19.6 MeV/fusion which corresponds to an overall energy multiplication of 1.39. About 60% of the total heating comes from gamma heating. This is a direct result of using a metallic reflector. Based on a neutron wall loading of 5 MW/m^2 , the

TABLE I
Tritium Production in MARS Li-Pb Blanket

	${}^6\text{Li}(n,\alpha)\text{t}$	${}^7\text{Li}(n,n'\alpha)\text{t}$	Total
Tube zone	0.565	0.0020	0.567
Beam zone	0.567	0.0004	0.567
Total blanket	1.132	0.0024	1.134

TABLE II

Nuclear Heating (MeV/Fusion)
in MARS Li-Pb Blanket

	Neutron	Gamma	Total
Blanket tube zone	4.488	4.657	9.145
Blanket beam zone	3.296	1.720	5.016
Reflector	0.339	5.103	5.442
Shield	0.016	0.135	0.151
Total	8.139	11.615	19.754

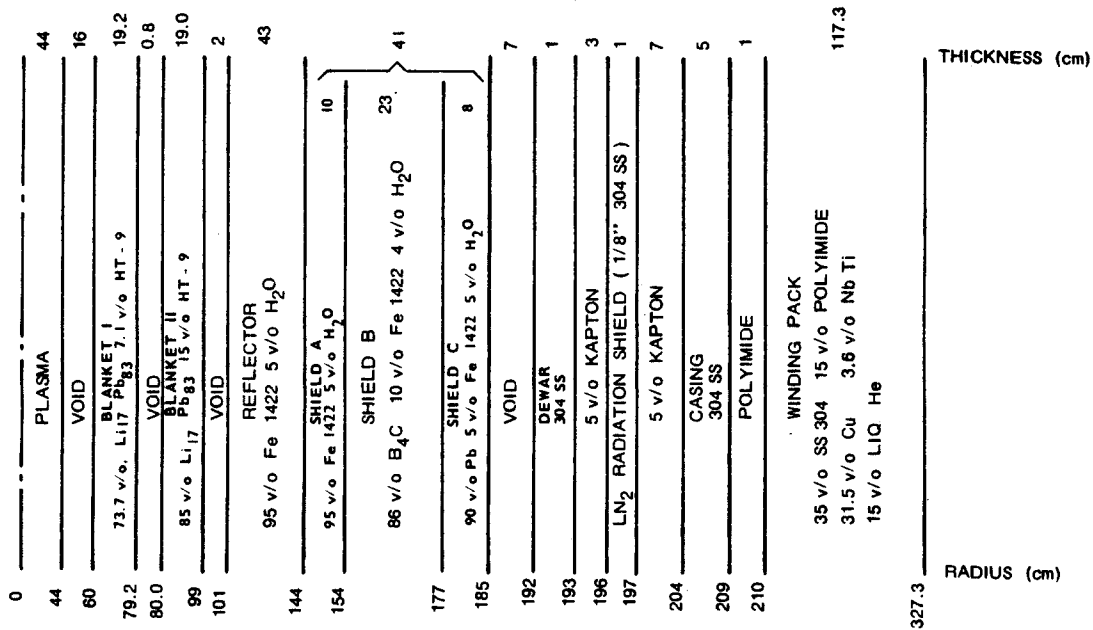


Fig. 4. Schematic of blanket, reflector, shield and magnet.

peak power densities in the blanket, reflector, and shield are 36.0, 3.6, and 0.089 W/cm³, respectively.

SHIELD DESIGN

The shielding requirements for the superconducting central cell magnets are determined by a number of radiation limits. The displacements per atom (dpa) in the copper stabilizer of these 8 tesla coils should not exceed 1.1×10^{-4} dpa before the first magnet anneal. This corresponds to a 20% increase in resistivity. Annealing at room temperature results in only 80-85% recovery of the radiation induced defects. Based on reactor availability requirements, a minimum period of one full power year (FPY) should be maintained between magnet anneals. For an estimated reactor life of 24 FPYs, this implies that the first magnet anneal should occur after at least 5 FPYs. Therefore the dpa rate in Cu should not exceed 2.2×10^{-5} dpa/FPY.

Polyimide is used for electrical insulation in the MARS coils. Aluminized Kapton, which is about 100 times more radiation resistant than aluminized Mylar, is used for thermal insulation. Radiation effects on organic insulators are not reversible and it is essential that they last for the whole reactor life. The limits on the dose for the electrical and thermal insulators were considered to be 5×10^9 and 10^{10} rads, respectively. The limit on the peak heat load in the magnet winding pack was taken to be 0.06 mW/cm³. This requirement was established to ensure that the nuclear heat load on the magnet does not cause excessively high cryogenic plant cost and power.

A water cooled shield consisting of layers of Fe-1422, B₄C, and Pb was considered. The shield consists of three zones as shown in Fig. 4. The design for the central cell magnets allows for a 41 cm shielding space. Shield optimization has been performed to determine the optimum shield configuration that results in the best utilization of this available space. Preliminary results showed that the limit on the peak power density in the magnet is the most severe requirement which drives the shield design. The optimum dimensions of the different shield layers are, therefore, those which minimize the peak magnet heat load. The results presented here are normalized to a neutron wall loading of 5 MW/m².

Figure 5 shows the result of changing the thickness of the B₄C shield at the expense of the Fe-1422 shield with the Pb shield thickness kept constant. The results show that the lowest

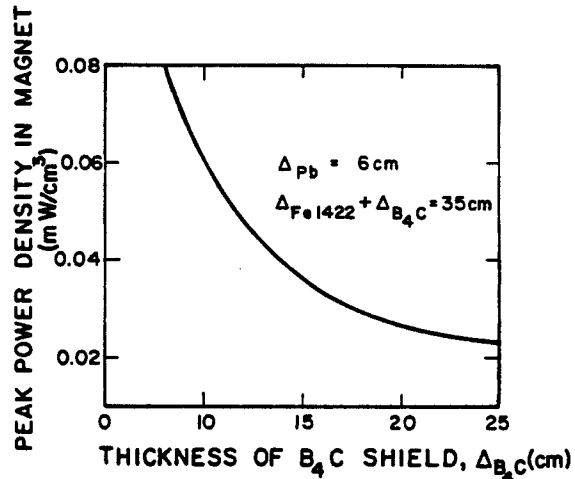


Fig. 5. Effect of B₄C shield thickness on peak magnet heat load.

magnet heat load can be obtained when the smallest thickness of shield A is used. The reason is that the 43 cm thick reflector will act as a Fe-1422 shield. A shield A thickness of 10 cm was chosen for the overall energy multiplication not to be affected by the strong neutron absorption in B₄C. Fixing the thickness of shield A, the thickness of the Pb shield was varied at the expense of the B₄C shield. The results of Fig. 6 show that the optimum shield design should have thicknesses of 23 and 8 cm for the B₄C and Pb shields, respectively. Most of the heat deposited in the magnet comes from gamma absorption. Since neutrons absorbed in the 5 cm thick steel casing will produce secondary gamma photons, a relatively large B₄C shield is needed for neutron attenuation.

For the optimum shield configuration shown in Fig. 4, a peak dpa rate of 4.5×10^{-6} dpa/FPY was obtained in the copper stabilizer implying that no magnet annealing is needed during the whole reactor life. The peak radiation doses in the electrical and thermal insulators after 24 FPYs are 4.63×10^8 and 9.55×10^8 rads, respectively, which are well below the design limits. The peak heat load in the magnet is 0.021 mW/cm³. Our results show that all design

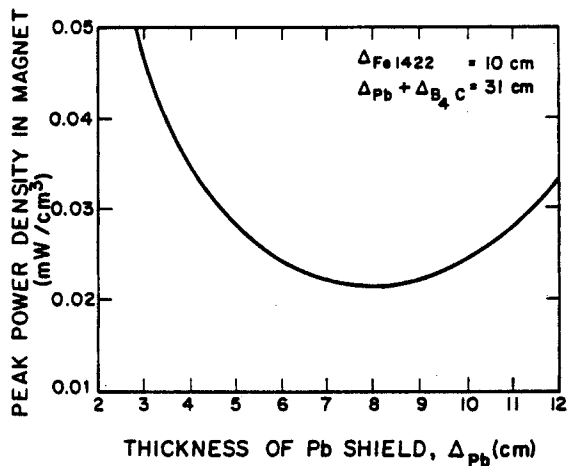


Fig. 6. Effect of Pb shield thickness on peak magnet heat load.

criteria can still be met if the shield thickness is reduced by ~ 6 cm. However, for cost considerations and to allow for possible data uncertainties and calculational deficiencies, the larger shield thickness is used in MARS.

SUMMARY

Neutronics analysis has been performed to determine the blanket design which yields the largest energy multiplication with adequate tritium breeding ratio. The choice of reflector material and thickness has an impact on the overall energy multiplication. A thin Li-Pb blanket with a thick Fe-1422 reflector was found to yield larger energy multiplication, smaller magnet size, and better overall figure of merit as compared to the thick blanket design. Other attractive features of this design are the reduced activated waste and the ease of maintenance. This blanket design results in a tritium breeding ratio of 1.13 and an overall energy multiplication of 1.39. Magnet shield optimization was performed to design a shield which provides adequate magnet protection with a comfortable margin which allows for possible data uncertainties and calculational deficiencies.

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