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A MINIMUM-THICKNESS BLANKET/SHIELD WITH OPTIMUM TRITIUM BREEDING AND SHIELDING EFFECTIVENESS*

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A blanket/shield assembly for a fusion reactor has been designed through extensive optimization studies. The design was optimized under the following constraints: (a) minimum overall thickness, (b) tritium breeding ratio of 1.10, (c) thermal energy recovery of 90%, (d) acceptably flat temperature distribution, and (e) excluding all "exotic" or problematic materials. The optimized blanket/shield has an overall thickness of 36 cm and conforms with all the above requirements. All tritium breeding is accomplished in a 24-cm-thick breeding zone using stagnant enriched lithium-6, and lead as a neutron multiplier. The energy recovery in this breeding zone is 71% which, together with an additional energy extraction of 19% in a 12-cm-thick laminated stainless steel/boron carbide shield zone, results in the desired overall thermal efficiency of 0.90 which is considered adequate if normal-conducting magnets are used for plasma confinement.

INTRODUCTION

For most fusion reactor designs, no matter if a magnetic or inertial confinement concept is used, it is most desirable that the blanket/shield system requires a minimum of space. Here we define as blanket that portion of the design which is needed to breed tritium and which is usually located inboard of the toroidal field coil in a Tokamak design. Since every blanket also acts as a radiation shield, it is necessary to consider the combination of a tritium breeding blanket with any additional primary shielding as a blanket/shield system. Specific shielding requirements, in contrast to tritium breeding requirements, differ however widely depending on the particular reactor design. In the following we consider a magnetic confinement concept (Tokamak, z-pinch, or mirror) which operates with normal conducting magnets and has its blanket/shield assembly located inboard of the main field coils, i.e., between the plasma and the magnet coils. For such reactor concepts relatively general and simple requirements for the blanket/shield assembly can be specified:

(1) minimum overall thickness,
(2) tritium breeding ratio of 1.10,
(3) overall shielding effectiveness resulting in a 90% energy recovery, within the blanket/shield assembly,
(4) reasonably flat temperature distribution resulting in acceptable thermal stress characteristics, and
(5) exclude all "exotic" materials which are difficult to handle and/or may constitute a resource problem (e.g., Be), and materials which may cause undue engineering problems due to unfavorable mechanical or thermal properties (e.g., graphite or water).

Requirement (3) for a thermal efficiency of 90% for the desired blanket/shield system is somewhat

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arbitrary but seems to assure sufficient radiation shielding for normal conducting magnets. It should be noted, however, that this requirement is much less demanding than the usual specification of a shielding effectiveness of greater than 99% for fusion reactors operating with super-conducting magnets. Any specification for a minimum shielding effectiveness of the blanket/shield assembly will also assure an upper limit for other radiation induced systems effects on coils and other components outboard of the coils, such as radiation damage, induced activity, biological dose rates, and others.

A complete blanket/shield optimization under all conceivable constraints is a formidable task because for each allowable material combination a large variety of material arrangements (blanket designs) has to be analyzed. To reduce the number of necessary computations to manageable proportions we adopted the following strategy:

(1) start the optimization process with the well-defined and well-documented RTPR blanket/shield as described and analyzed in Ref. 1, and

(2) monitor initially only tritium breeding and total recoverable energy, because most other neutronics systems parameters scale approximately proportional to the radiation energy escaping from the blanket, i.e., inversely proportional to the total recoverable energy absorbed within the blanket/shield.

For convenience, the main neutronics features of the RTPR blanket/shield[1] as they pertain to our study, are briefly reviewed here. The total blanket/thickness is measured from the first wall radius (always at 50.0 cm) to the inboard Al_2O_3 insulation layer of the implosion heating coil and amounts to 38.9 cm for the original RTPR blanket. Its tritium breeding ratio is 1.11. The thermal efficiency of the blanket/shield assembly, $\eta_{B/S}$, is defined as the ratio of the total energy recoverable from the blanket via coolant channels to the total energy produced per fusion neutron, $\eta_{B/S} = E_{recover}/E_{total}$, and amounts to 0.95 for the original RTPR blanket design.

THE EFFECTS OF GRAPHITE AND BeO ON TRITIUM BREEDING AND $\eta_{B/S}$

In a postdesign assessment of the original RTPR blanket[2] a series of sensitivity analyses were performed indicating quantitatively how tritium breeding, blanket efficiency and other neutronics design parameters vary when certain design changes are performed. We use the results from these analyses as a starting point for desirable material and design changes. It is clear from Ref. 2 that a first step in thinning the RTPR blanket without substantial loss of tritium breeding could be the elimination of the second graphite region due to the low sensitivity of the breeding ratio to neutron moderation by the carbon in this region. However, such a modification increases the radiation heating in the copper coils substantially. In an attempt to compensate for this effect at least partially, we added a 2-cm-thick lead zone just inboard of the implosion coil to recover the gamma-ray energy otherwise leaking out of the blanket and heating the coils. In Ref. 2 it was also established that BeO acts as a better moderator than graphite in the RTPR blanket. Therefore, to compensate somewhat for the last neutron moderation by both graphite regions, and in a desire to further reduce the overall blanket thickness, we replaced the first graphite region with BeO and varied its thickness from six to zero cm. The effects on tritium breeding, as well as total recoverable and waste energies, are shown in Fig. 1 together with a schematic of the altered blanket. It is concluded that even with no BeO in the blanket, which makes an overall blanket/shield thickness of 21.8 cm, a breeding ratio of 1.10 can be obtained, rising to 1.19 with 6 cm of BeO. We feel that a tritium breeding ratio of 1.10 calculated with this one-dimensional model gives enough safety margin to account for possible neutron streaming effects which, in a two- or three-dimensional analysis, could further reduce the tritium breeding ratio,

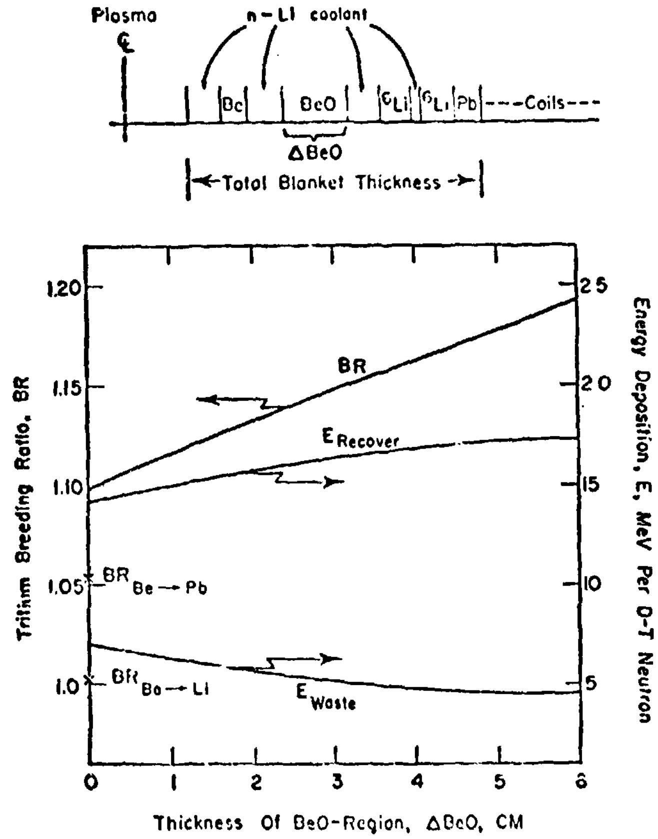


FIGURE 1. Tritium breeding and energy recovery of thin (21.8 cm with ΔBeO=0) RTPR blanket (MOD-1) vs thickness of beryllium oxide region.

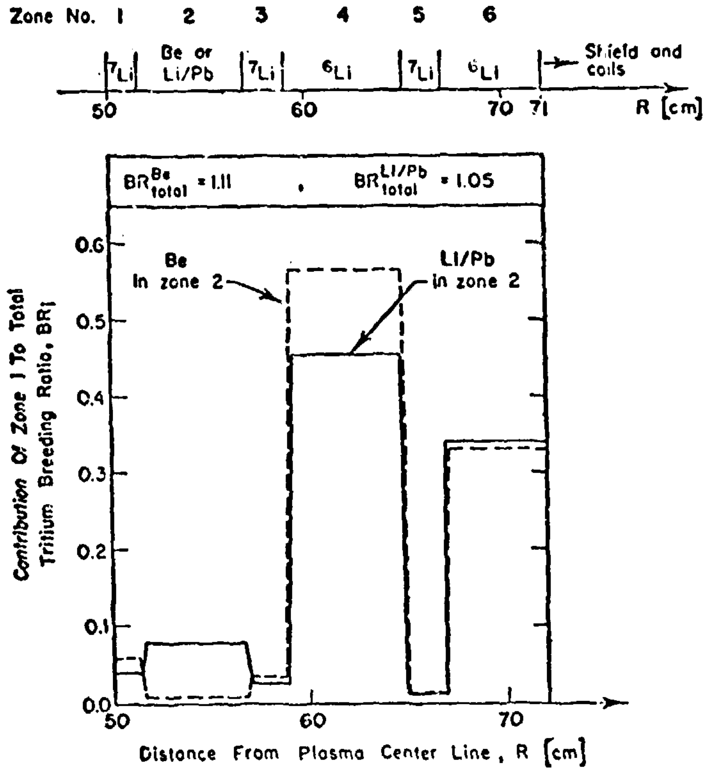


FIGURE 2. Breeding zones arrangement in MOD-2 blanket with contributions of individual zones to total tritium breeding for Be- and Li/Pb-multipliers.

but not below 1.0. It is seen from Fig. 2 also that the recoverable energy increases with increasing BeO thickness while the amount of waste energy decreases. However, at zero BeO thickness the blanket generates 66.8% as recoverable energy and 33.2% as waste energy, assuming that no further attempts are made to recover portions of this waste energy by additional design modifications.

From the above analysis it is quite clear that any design modifications outboard of the outermost tritium breeding zone (enriched ^{6}Li region) will influence the total tritium breeding ratio only very slightly but can dramatically change the amount of energy recoverable from the blanket. Hence, all materials outboard of the last lithium zone but inboard of the toroidal field coil act primarily as an energy absorber but cannot be used efficiently to breed tritium. This characteristic allows us to separate spatially the tritium breeding function of the blanket from its energy conversion function. Since the conversion of radiation energy into thermal energy is the general function of a radiation shield, we can view the entire blanket as a blanket/shield assembly where tritium breeding is accomplished with the innermost regions only, while the outer regions are just shielding. Based on this feature we can now divide our optimization process into two parts; first, an optimization of the inner breeding regions, and then a separate optimization of the outer shield regions of the entire blanket/shield assembly.

BREEDING-ZONE OPTIMIZATION

Concern over the availability and use of beryllium in the RTPR blanket has initiated additional modifications in the breeding zones of this blanket design (MOD-1). First, the 2.5-cm-thick Be region near the first wall acting as a neutron multiplier was replaced by lead, expecting that the fairly large (n,2n) and (n,3n) cross sections of Pb will assure some compensation for the eliminated neutron multiplication of the beryllium. Indeed, the total tritium breeding ratio is reduced by only 5% to 1.05 from the former 1.10 with beryllium as multiplier and no BeO moderator, as indicated in Fig. 1. Obviously, the secondary neutrons generated in lead have other spectral characteristics than those generated in beryllium. In a second computation the effect of replacing the neutron multiplier altogether with breeding material was investigated. We substituted natural lithium for the original metallic beryllium. The result is a breeding ratio of 1.01 (compare Fig. 1), which does not leave any margin for neutron streaming effects not incorporated in this analysis.

To eliminate any potential future problems associated with the use of Be in the RTPR blanket we decided to use Pb instead of Be as a neutron multiplier. In an attempt to increase the breeding characteristics of the thin MOD-1 blanket discussed above (containing Pb but no Be and no BeO), without substantially increasing the total blanket thickness, the pure liquid lead was replaced by a lithium/lead alloy (LiPb)[3] to increase the amount of breeding material (Li) without eliminating the neutron multiplier. However, since the blanket arrangement with a 2.5-cm-thick pure Pb neutron multiplier reached a tritium breeding ratio of only 1.01 (compare Fig. 1), we decided to increase the thickness of this multiplier zone to 5.5 cm. In addition, it was recognized earlier that in the MOD-1 blanket with no BeO (see Fig. 1) over 80% of the tritium production occurs in the two enriched ^{6}Li-zones (total of 4.8 cm thick) rather than the natural lithium coolant channels. Therefore, to enhance tritium production further, we also increased the total thickness of the two enriched ^{6}Li-zones to a total of 10.4 cm (5.7 + 4.7). The resulting arrangement of breeding zones in this new (MOD-2) blanket is shown in Fig. 2. Since this blanket uses a large amount of 95 atom-% enriched ^{6}Li we decided to replace the natural lithium coolant (zones 1, 3, and 5 in Fig. 2) with 99 atom-% enriched ^{7}Li which should be available in large quantities after the required enriched ^{6}Li is separated from n-Li (92.5 atom-% ^{7}Li and 7.5 atom-% ^{6}Li). The net effect on tritium production of replacing all natural lithium coolant with 99 atom-% enriched ^{7}Li was a decrease of the total tritium breeding ratio by only 1%.

Figure 2 analyzes the breeding characteristic of the MOD-2 blanket by zones. Although the change from Be to LiPb alloy in zone 2 increases tritium production in this zone substantially (from 0.007 to 0.077 per fusion neutron), the associated reduction of tritium breeding in zone 4 however (from 0.565 to 0.455 per fusion neutron) is still dominating. This effect indicates clearly that a good neutron multiplier in zone 2 is more beneficial to the total tritium production than additional breeding material. To find the optimum composition of Li and Pb for zone 2 we varied the lead content in this zone from zero to 100% by allowing mixtures of pure n-Li with LiPb alloy and pure Pb with LiPb alloy and then varying the volume fraction of LiPb alloy in the mix. Figure 3 shows how the total tritium production increases monotonically with increasing lead content to give a maximum breeding ratio of 1.06 for pure Pb in zone 2. This confirms the above indication that

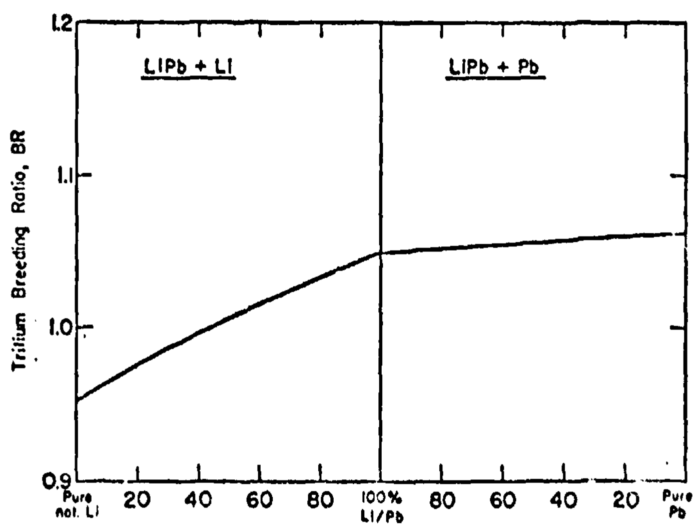


FIGURE 3. Variation of tritium breeding with varying composition of zone 2 in MOD-2 blanket.

the neutron multiplication by Pb in zone 2 is more beneficial than added breeding in this zone. In an attempt to strive for an optimum distribution of enriched ^{7}Li coolant channels with respect to tritium breeding in the MOD-2 blanket, we performed a series of additional computations whereby the enriched ^{7}Li of zone 3 was homogeneously distributed within the LiPb/Pb mixture of zone 2. The result was an increase of the total tritium production by 1.1 percent throughout. This breeding gain appears to be insufficient, however, to justify the added complexity of enriched ^{7}Li piping if such "homogenization" were attempted in practice.

As shown in Fig. 3, the total tritium breeding ratio for the MOD-2 blanket with pure Pb in zone 2 is 1.062, still short of our target value of 1.10. A sensitivity analysis of this blanket arrangement was therefore performed where the thickness of the Pb region (zone 2), the first enriched ^{6}Li region (zone 4), and the second enriched ^{6}Li region (zone 6) were varied successively and the change in total tritium breeding

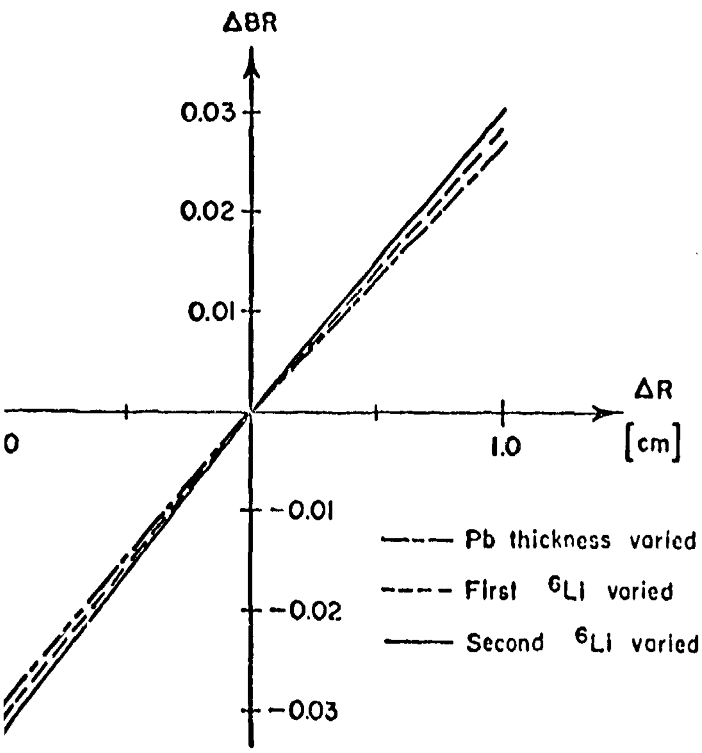


FIGURE 4. Sensitivity of total tritium breeding to zone thickness variations in MOD-2 blanket.

monitored. The results are plotted in Fig. 4, where ΔBR is defined as

$$\Delta BR = BR_{\text{altered design}} - BR_{\text{MOD-2 with PB in zone 2}}.$$

Maximum variation on these zone thicknesses were held to $\Delta R = \pm 1$ cm, and Fig. 4 indicates that all three zone thickness variations produce approximately the same BR within the limits of $\Delta R = \pm 1$ cm. Therefore, total tritium production is enhanced almost equally by equal thickness increases of either the Pb multiplier zone or any one of the two enriched ^{6}Li breeding zones. Based on this analysis we increased the total thickness of both, the Pb as well as the enriched ^{6}Li slightly to push the total tritium breeding ratio over 1.10. From a coolant technology point of view it becomes now desirable to redistribute the lithium-7 coolant channels so that the material arrangement shown in Fig. 5 results (MOD-3). The total tritium breeding ratio of the MOD-3 blanket shown in Fig. 5 is 1.172. It appears then that we overshot our target breeding ratio of 1.10 by about 7% possibly due to synergistic effects excluded from the results of the foregoing sensitivity analysis (Fig. 4).

In an attempt to tune the high MOD-3 breeding ratio closer to 1.10 we performed a final sensitivity analysis to obtain guidance to perform a maximum blanket thinning with an allowed loss of 7% tritium breeding. Figure 6 displays the results of this two-step procedure. From the first part it became clear that a thinning of either one of the two Pb zones in the MOD-3 blanket produces the smallest loss in tritium production

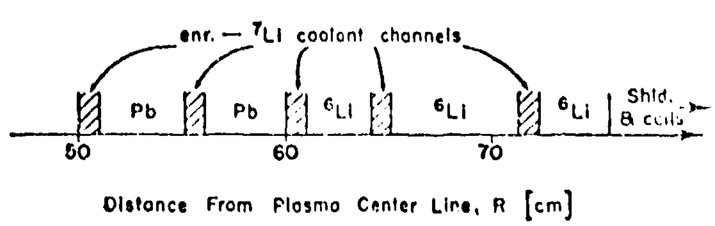


FIGURE 5. Schematic of breeding region of MOD-3 blanket.

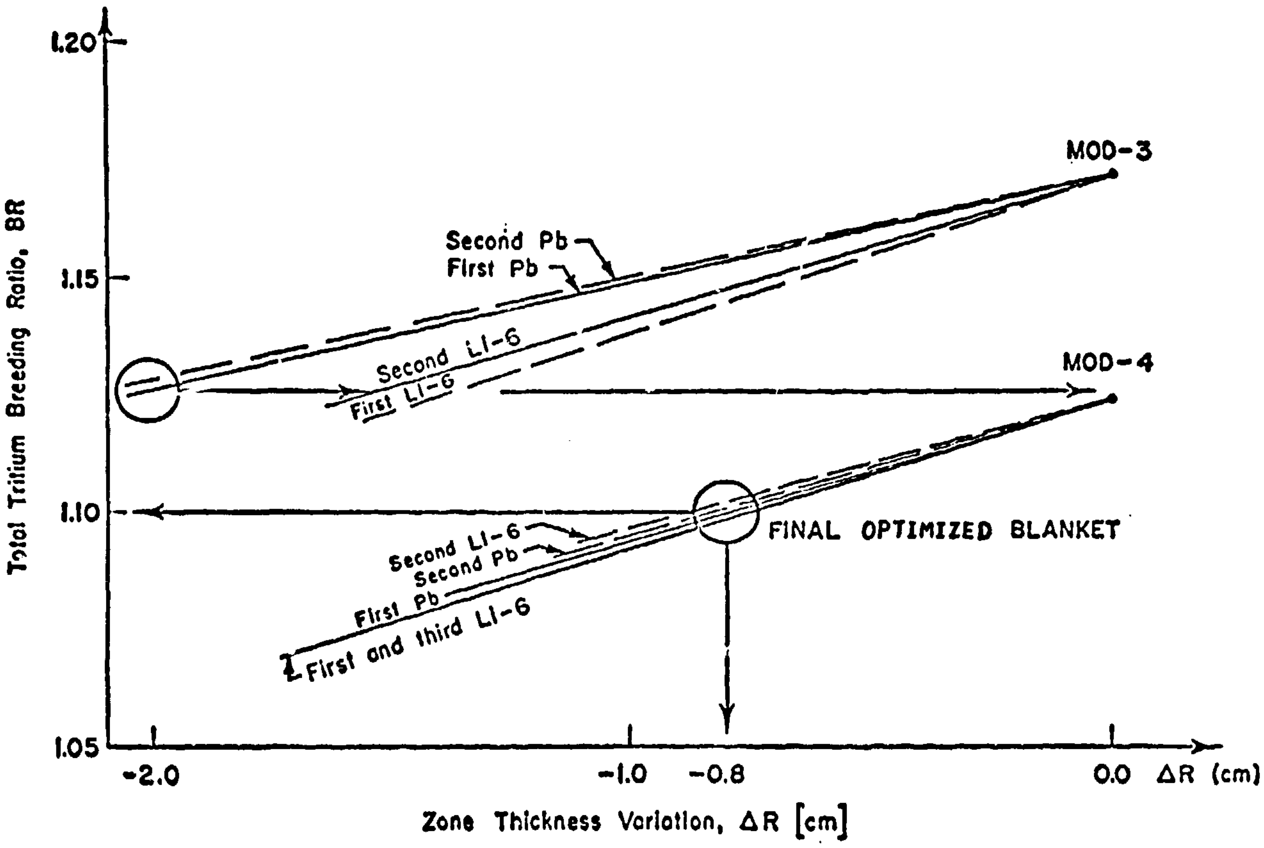


FIGURE 6. Sensitivity of the total tritium breeding ratio of MOD-3 and MOD-4 blankets to reductions in individual zone thicknesses.

(compare Fig. 6): for $\Delta R = -1.0$ cm a ΔBR of minus 0.022 results, as compared to a ΔBR of - 0.032 if one of the enriched ^{6}Li zones is thinned by 1 cm. This result is somewhat surprising because for the MOD-1 and MOD-2 blankets we found that the neutron multiplying properties of Be or Pb were of higher benefit to the total breeding ratio than the breeding properties of natural lithium. However, the MOD-3 blanket arrangement is significantly different from its forerunners, and the above high sensitivity to lithium refers to enr.-^{6}Li rather than natural Li. Therefore, as an initial adjustment to the MOD-3 blanket we reduced the thickness of each of the two Pb multiplier zones by 1.0 cm to reach a breeding ratio of 1.124. With this new (MOD-4) blanket then the same sensitivity analysis was performed varying each of the five zone widths individually. The results of this second step are also shown in Fig. 6. As a conclusion, we can thin the MOD-4 blanket further by 0.8 cm to reach our target breeding ratio of 1.10. Another, more general conclusion can also be drawn from this last sensitivity analysis: the MOD-4 as well as the final optimized blanket employ a well-balanced material arrangement for tritium breeding purposes in the sense that the sensitivities to design changes are approximately equal for all five significant zones:

$$\frac{d(BR)}{dR_i} \approx \text{constant for all } i,$$

where R_i denotes the thickness of each individual zone i (neutron multiplier as well as breeding material). For that reason we claim that the breeding part of the new blanket/shield design is an optimized and well-balanced design.

SHIELD ZONE OPTIMIZATION

In the previous sections we arbitrarily defined the shield zone of a blanket/shield assembly as consisting of those materials outboard of the tritium breeding zone but still inboard of the first coil, insulators, and other components further away from the plasma, against excessive radiation. Obviously, the tritium breeding zone has also a substantial shielding function, but, in most cases this is insufficient so that additional shielding material must be added. For example, the breeding zone of the MOD-5 blanket absorbs 70.9% of the total energy deposited in blanket, shield, and coils. The additional shielding required to meet our target specifications must be designed so that 15 to 25% of the total energy is deposited in it to obtain a thermal efficiency for the entire blanket/shield assembly of $\eta_{B/S}$ = 0.85 to 0.95. A more precisely specified requirement for $\eta_{B/S}$ is possible only as the result of a detailed systems optimization which incorporates total energy balance and plasma engineering considerations. Nevertheless, it should be pointed out that the requirement of $0.85 < \eta_{B/S} < 0.95$ for a reactor concept which operates normal-conducting magnets is much less demanding than usual specifications of $\eta_{B/S} > 0.99$ for fusion reactors operating with super-conducting magnets.

Most of the radiation shielding function in the original reference RTPR blanket (MOD-0) was carried out by the vast amounts of graphite in this design (compare Ref. 1). The extremely good neutron moderation properties of graphite can be obtained only by other very low atomic number materials such as H, He, Be, B, etc., most of which cannot be used for currently studied fusion reactor designs from other than neutronics reasons. Also, the graphite in the MOD-0 blanket has been interspersed with the breeding zones to boost tritium production from thermal neutrons in ^{6}Li. With the new concept, separating breeding and shielding functions spatially, we need to investigate new materials for the shielding part of the blanket/shield assembly.

Extensive shield optimization studies have been performed for the ANL Tokamak Experimental Power Reactor design[4] which propose laminates of stainless steel (SS) and boron carbide (B_4C) as a most effective radiation shield which is optimized for minimum thickness. Based on these results and some additional calculations, we arrived at the MOD-5 shield assembly shown in Fig. 7 (top schematic) which has been optimized to give a total blanket/shield thermal efficiency of about 90%. It should be pointed out that two enriched-^{7}Li coolant channels are inserted in this 12-cm-thick shield to extract the absorbed energy (approximately 22% of total). Also shown in Fig. 7 are variations of this optimized shield which achieve total blanket/shield thermal efficiencies ranging from 0.87 to 0.93. In Fig. 8 we plotted $\eta_{B/S}$ vs the total thickness of the blanket/shield assembly where only those (optimized) designs are chosen from Fig. 7 which achieve the highest $\eta_{B/S}$ for a fixed thickness. It is interesting to note from Figs. 7 and 8 that the effectiveness of shielding added to the outside of the B/S assembly diminishes rapidly as the entire assembly gets thicker and $\eta_{B/S}$ approaches 1.0. Also, the specific arrangement of these outside materials becomes less important.

SUMMARY

A schematic of the optimized complete blanket/shield assembly is shown in Fig. 9. Within a total thickness of 36 cm the target breeding ratio of 1.10 is achieved as well as a blanket/shield thermal efficiency of 90%. Also, this new design uses only materials of which the thermal, mechanical, electric, and magnetic properties are well understood and within technically and economically feasible bounds. Beryllium and graphite are totally eliminated.

Although all computations were performed in one-dimensional cylindrical geometry a very detailed model with 44 separate material zones was employed which allowed a realistic inclusion of the effects of structural materials (Nb walls of varying thicknesses) and insulators (Al_2O_3). A detailed description of the 44-zone geometry and all isotopic material compositions are contained in a separate LASL report. Figure 10 shows the radial distribution of the total heating rates throughout the optimized blanket/shield assembly.

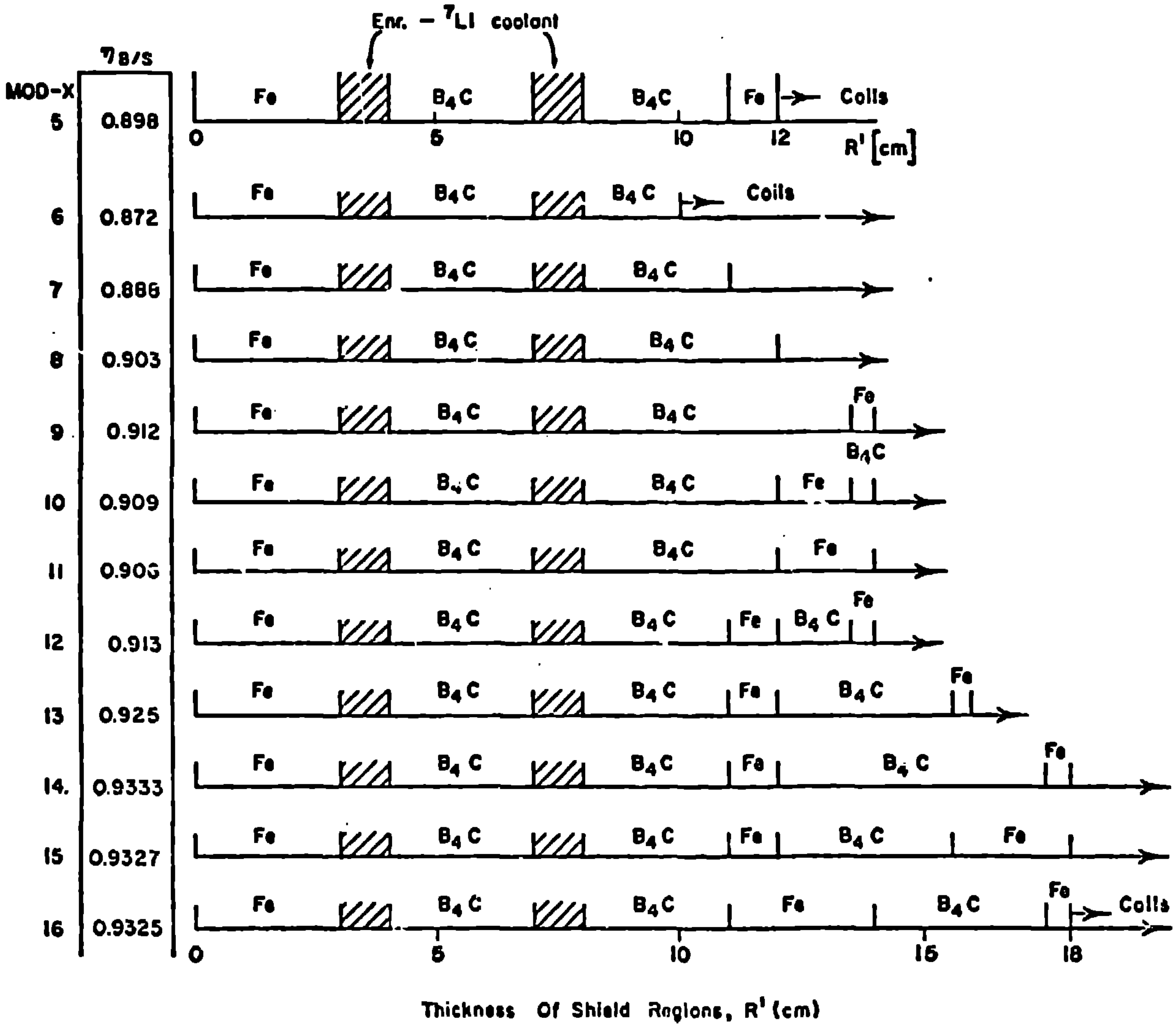


FIGURE 7. Schematic of optimized shield regions (MOD-5 is used in new RTPR blanket) with variations, indicating total blanket/shield thermal efficiencies $\eta_{B/S}$.

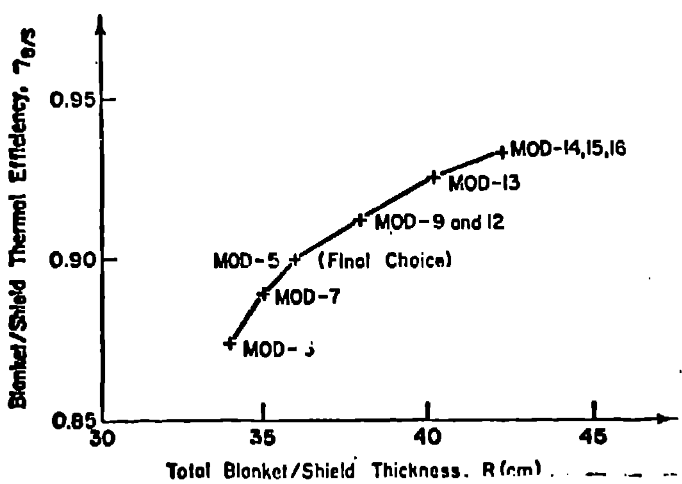
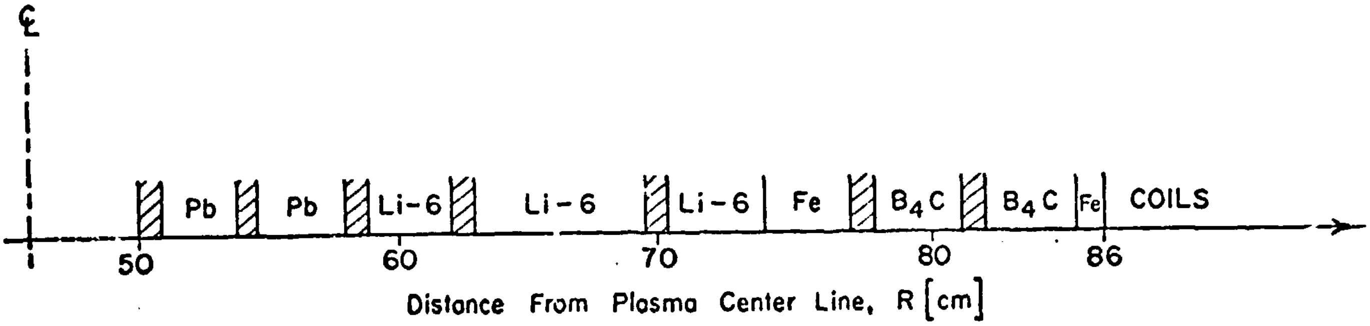


FIGURE 8. Thermal efficiencies for several optimized blanket/shield assemblies vs total B/S-thickness.

Based on these heating rates Court and Krakowski[5] performed a detailed heat transfer analysis for the pulsed operation of a fusion reactor with this blanket/shield design. Figure 11, borrowed from Ref. 5, gives an illustration of the radial temperature profile throughout the optimized blanket/shield for three different plasma conditions. This confirms that our requirement (4) of acceptable temperature distribution is also met by the new design.



Total Blanket/Shield thickness = 36 cm $\begin{cases} 24 \text{ cm breeding zone} \\ 12 \text{ cm shielding zone} \end{cases}$

Tritium breeding ratio, BR = 1.10

Blanket/shield thermal efficiency, $\eta_{B/S} = 0.90$

Li-6 ≙ 95 at.-% enriched ^{6}Li, stagnant

Pb ≙ liquid lead, ρ = 10.5 g/cm^3

▨ ≙ Lithium coolant, 99 at.-% enriched ^{7}Li

Structural walls of 1 to 2 mm niobium

FIGURE 9. Schematic of optimized blanket/shield model.

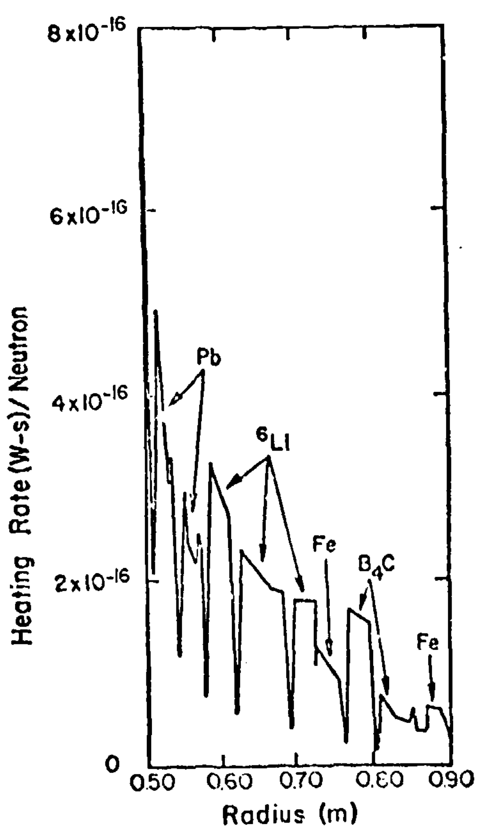


FIGURE 10. Radial distribution of total (neutron + secondary gamma) heating rates in optimized blanket/shield per fusion neutron.

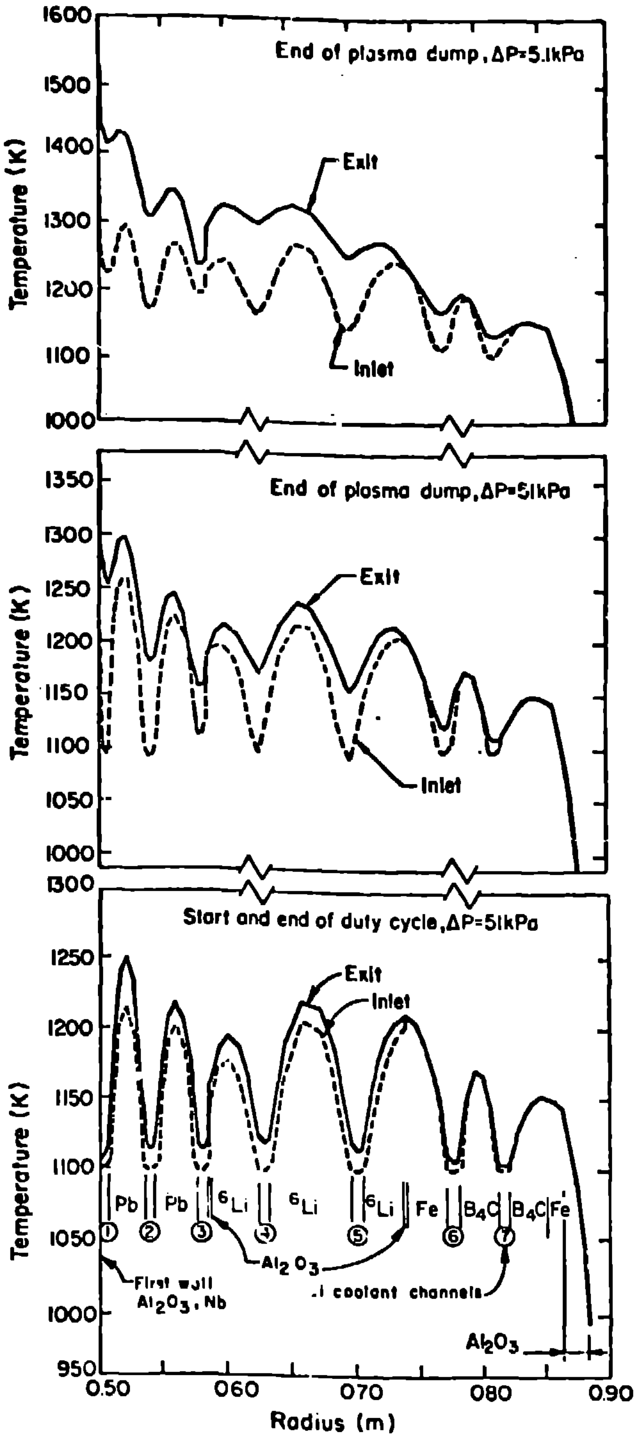


FIGURE 11. Radial temperature distributions throughout the optimized blanket/shield for varying plasma conditions.

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