NEUTRONIC OPTIMIZATION OF A $LiAlO_2$ SOLID BREEDER BLANKET

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ABSTRACT

In this paper, a pressurized lobular blanket configuration is neutronically optimized. The blanket configuration features the use of beryllium and $LiAlO_2$ solid breeder pins in a helium-cooled cross-flow pattern. One-dimensional neutronic optimization calculations are performed to maximize the tritium breeding ratio (TBR). The procedure involves spatial allocations of Be, $LiAlO_2$, 9-C (low-activation ferritic steel), and He, in such a way as to maximize the TBR subject to several material, engineering and geometrical constraints. Consistent with all imposed engineering constraints, a TBR of 1.17 is achieved for a relatively thin blanket (≈43 cm depth).

I. INTRODUCTION

The development of blanket concepts based upon individual pods or canisters has been pursued since the early days of conceptual fusion designs.[1,2] Several perceived advantages have been considered for these designs. Results from a recent Blanket Comparison and Selection Study (BCSS)[3] have indicated that a combination of helium as a coolant and ceramic Li-bearing solid breeder can satisfy necessary neutronic and thermomechanical performance criteria. In a version of a GA blanket design,[4] the Li_2O ceramic breeder has been proposed in the form of clad plates. However, several critical areas remain unaddressed in the previous studies:

1. The plate cladding structure, with its thin dimensions, may not be tolerant to thermal and irradiation inelastic strains resulting in reduced lifetimes.
2. "Box-type" structures are generally prone to stress concentrations at corners, leading to early failure.
3. Even though Li_2O has a higher lithium atom density as compared to $LiAlO_2$, its swelling rate is about an order of magnitude larger.
4. With a greatly reduced structure-to-breeder ratio, the breeding ratio was found to be marginal.[4]

Recent efforts undertaken at CEA Saclay (France) have concentrated on clad breeder elements. This has been dictated by the desire to maintain a reasonable breeder geometrical integrity and a well controlled working temperature. Their studies of canister blankets with beryllium multiplier and solid breeder indicated that better tritium breeding is achieved when beryllium is mixed with the solid breeder.[5] The chemical compatibility problems, which are crucial for the viability of such a design, remain to be resolved.

The philosophy of the present design study follows the following lines:

1. A pressurized lobular configuration is used to allow for flat side plates as shown in Fig. 1. The configuration is well suited for tight-fitting locations, such as the in-board blanket.
2. Pressurized helium flows in the radial direction, achieving thermal homogeneity, as described in Ref. [6].
3. The use of beryllium in the front zone of the blanket is consistent with its high conductivity. The lower conductivity breeder material is used deep inside the blanket, where the nuclear heat generation is lower.
4. Beryllium and solid breeder pins are arranged such that helium cross-flow conditions are achieved. The small size of the pins ensures minimum temperature assymmetries. This is shown to result in minimal bowing and deflections within the blanket.[7]
5. The side plates are tapered from the back to the front in order to accommodate the high internal pressure (see Ref. [8]).

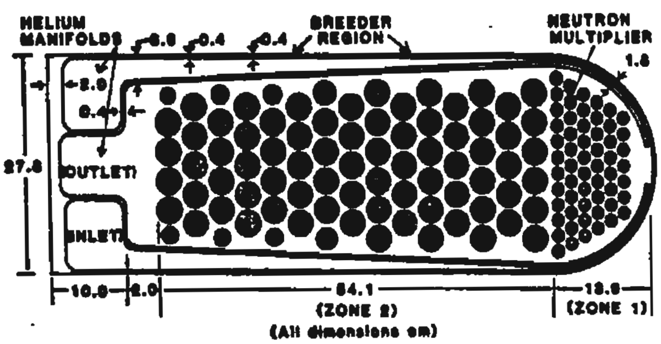

Fig. 1. Preliminary pressurized lobular blanket configuration.

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We present here the results of neutronic optimization calculations of a solid breeder blanket. The objective is to maximize the tritium breeding ratio by optimizing the spatial material allocations in the blanket, consistent with a number of engineering constraints. The materials used in the present analysis are given below:

1. Structural Material: Low activation material 9-C. This material, which is structurally equivalent to HT-9, has the following composition:[9]

   Cr = 11.81% C = 0.097% V = 0.28%
   W = 0.89% Mn = 6.47% Si = 0.11%
   N = 0.003% P < 0.005% S < 0.005%
   Fe = remainder

   The 9-C structural material is used for the lobe shell, and also for cladding the solid breeder material.
2. Solid Breeder Material: LiAlO$_2$, with variable enrichment of Li to be determined by the optimization study
3. Neutron Multiplier: Beryllium
4. Coolant: Helium
5. Shield-1: Water and ferritic steel Fe-1422
6. Shield-2: Water, ferritic steel Fe-1422, and B$_4$C

II. SYSTEM CONFIGURATION AND MODELING

The ANISN neutron transport code,[10] which utilizes the S-N method of solution to the transport problem, provides for approximate 1-D solutions for infinite slabs or cylinders. The actual blanket configuration, shown in Fig. 1, reveals more geometric details than can actually be modeled in 1-D calculations. For example, the solid breeder pins are also clad with the 9-C ferritic material. To determine such details, many engineering factors have to be considered. The final blanket configuration must result in acceptable neutronic and thermostructural performance. A basic consideration, however, is how to maximize the tritium breeding ratio by an appropriate spatial distribution of materials, without exceeding or conflicting with other engineering constraints.

A 1-D model is obtained by treating the various zones as cylindrical shells of infinite height. Materials are smeared within each zone according to their densities. This is consistent with a flat flux approximation, where self-shielding effects are neglected.

The neutron transport and gamma production cross sections were obtained as a coupled set of 46 neutron groups and 21 gamma groups produced by the AMPX modular code system[11] from the nuclear data in ENDF/B-IV. The cross sections were weighted with a 1/E spectrum for $E_n > 0.345$ eV, and with a Maxwellian distribution for $E_n \leq 0.345$ eV. The gamma interaction cross sections were uniformly weighted. Because of cost limits, the 46 neutron-group cross sections were collapsed to a smaller number of groups.

In the next section, we briefly describe the methodology adopted in this optimization study, outlining the basic principles of the technique. This is followed by the results of optimization studies, starting with modeling an idealistic system without any constraints. Finally, the results are presented for a nearly optimum system with all necessary engineering constraints.

III. THE SWAN OPTIMIZATION CODE

SWAN[12] is a code developed for the analysis and optimization of the nucleonic characteristics of CTR blankets. Any nuclear system that is described by the inhomogeneous linear transport equation can be analyzed by the SWAN code. SWAN is composed of two modules, ANISN and SWIF. SWIF is a code developed for perturbation calculations and optimization studies. The type of optimization problems that can be handled by SWAN can be characterized as follows.

Given the external source distribution

$$S(x) = S(\underline{r}, E, \underline{\Omega}) \tag{1}$$

and the atomic density distribution $N_i(\underline{r})$ for all I materials, the density of which are variables of the optimization, find the material density distribution that will extremize the functional $F_e(N_1, N_2, \ldots, N_I)$ subject to:

1. The constraints imposed by the density limits

   $$N_i^{min}(\underline{r}) \leq N_i(\underline{r}) \leq N_i^{max}(\underline{r}) \leq N_i^{0}(\underline{r}) , \tag{2}$$

   where these densities are assumed constant in each zone, N_i^{max} is the maximum allowable material density, and $N_i^{0}(\underline{r})$ is the natural material density at location $\underline{r}$.

2. The constraint on the total volume fraction available:

   $$\sum_{i=1}^{I} \frac{N_i(\underline{r})}{N_i^{0}(\underline{r})} = \text{const} \leq 1.0 \tag{3}$$

3. Preservation of the value of the constraints [denoted by the functional $F_c(N_1, N_2, \ldots, N_I)$] imposed on the problem.

The characteristic to be extremized (F_c) can be either of two general categories: a weight-type characteristic or a nucleonic characteristic. A weight-type characteristic is any characteristic expressible in the form

$$F_w(N_1, N_2, \ldots, N_I) = \sum_{i=1}^{I} \int d\underline{r} C_{w,i}(\underline{r}) \, N_i(\underline{r}), \tag{4}$$

to be referred to as a weight functional. A nucleonic characteristic is one expressible in the form of a bilinear functional:

$$F_b(N_1, N_2, \ldots, N_I) = \int dx \Big[\langle \phi, s_b^+ \rangle + \langle \phi_b^+, S \rangle - \langle \phi_b^+, H\phi \rangle\Big], \qquad (5)$$

(using the notation $\langle , \rangle$ for $\iint dE\, d\Omega$) where the flux $\phi = \phi(\underline{r}, E, \underline{\Omega})$ and the adjoint $\phi_b^+ = \phi_b^+(\underline{r}, E, \underline{\Omega})$ are the solution of, respectively, the linear Boltzmann equation and its adjoint.

The material densities for the nth iteration are obtained from the parameters in the (n-1) iteration as described in detail in Ref. [12].

IV. OPTIMIZATION RESULTS

A. Preliminary Calculations

Preliminary calculations were first performed with slab geometry. In this case, we assumed 60% enrichment of the Li^6 in $LiAlO_2$ at 95% of the theoretical density. Volume fractions were taken as 0.4 for $LiAlO_2$, 0.18 for 9-C, and 0.48 for He. The first shield was assumed to be 95% Fe-1422 and 5% H_2O, while the second shield was assumed to contain the following materials: Fe-1422 = 45%, H_2O = 5%, B_4C = 50%. Reference calculations were performed using the S16-P3 approximation [10].

Because of the cost of optimization procedures, a smaller set of groups was used. A small library of 9 neutron groups and 3 gamma groups was created by collapsing the basic library of 46 n groups and 21 γ groups using flux weighting from preliminary blanket calculations. It was found that the TBR for the collapsed group procedure is within 10% of the uncollapsed case. Moreover, the relative spatial allocation of materials was relatively unaffected.

B. Stage I: Unconstrained Optimization at Maximum TBR

The objective of this phase of the study is to allocate various materials in fixed geometry in order to obtain the maximum tritium breeding ratio. The choice of materials is limited to $LiAlO_2$, 9-C, He, and Be within the blanket. The composition of the two shields was not changed however. The arrangement of materials is shown in Fig. 2.

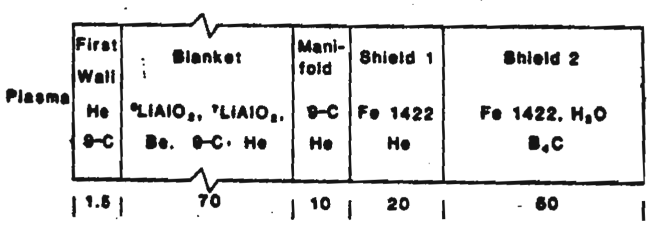

Fig. 2. A 1-D blanket model for maximum TBR.

Starting with a uniform distribution of materials in the blanket, the SWAN code calculates the effectiveness of each material at each spatial point. New material distributions are then calculated using the method of steepest descent. No constraint is imposed on the distributions except that the volume fractions must be positive and must add up to unity. The new material distributions are then used to calculate a new value of tritium breeding ratio and to generate new effectiveness functions. This iterative scheme is repeated until convergence is achieved.

First, it was found that the TBR was increased from 0.94 to 1.54, which is an increase of 64% due to the optimized allocations. Figure 3 indicates that the TBR is very sensitive to the location of Be. The material distributions, as shown in Fig. 3, display similar trends as the effectiveness functions. Be is shown to occupy the front zone of the blanket, with small contributions from other materials. Except for the front section, where Be is dominant, all other materials maintain a uniform distribution with the following ratios: (a) Breeder to structure ratio =4, (b) Li^6 enrichment of 60%. Nuclear heating, like most other reaction rates, was found to be high in the front, and decreases rapidly with depth. In $LiAlO_2$, the heating rate was found to be quite high in the front zone (126 W/cm^3).

C. Stage II: Optimization for a Two-Zone Constrained Blanket

Even though very high TBR values were obtained in the previous case (1.54 for He and 1.7 for a similar water-cooled case), the spatial allocation of materials was not subject to geometrical or engineering constraints. We then attempted to impose realistic constraints on the optimization. A two-zone blanket was first subjected to analysis and optimization where a beryllium zone was introduced behind the first

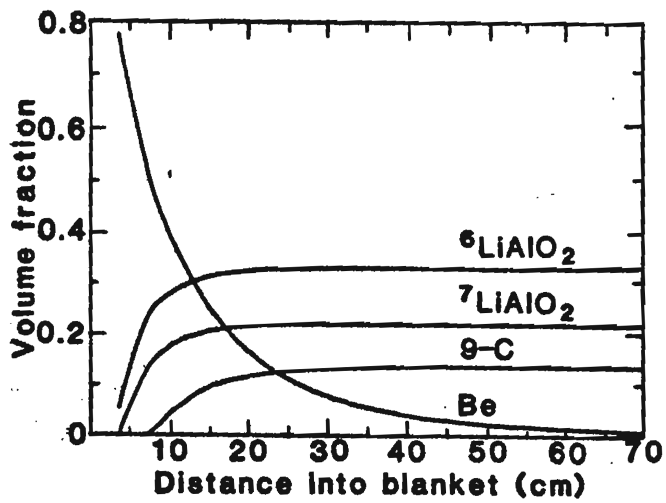

Fig. 3. Results of optimum material distributions for maximum TBR for He-cooled designs.

wall. This zone comprised 6 rows of 1.71-cm-thick unclad Be rods (0.3 cm rod spacing). The composition of this zone was not changed during subsequent optimization. The back zone of the blanket was a mixture of LiAlO$_2$, 9-C, and helium, with a fixed Li^6 enrichment of 60%. The structure to breeder ratio was varied and its effect on the TBR was studied. Calculations with the full 46 group library resulted in a TBR of 1.42, which is 8% lower than the 12 group results due to spectral differences.

The nuclear heating was found to be high in the front of the second zone, with a cell average value of 65 W/cm^3. However, averaging over separate materials showed even higher values reaching 98.8 W/cm^3 in LiAlO$_2$ alone. These high heating rates have led to temperatures well above the 1100°C limit set for LiAlO$_2$. This in turn led to the next and final optimization step which is to include temperature limits as well as density constraints.

D. Stage III: Final Optimization of a Thin Blanket

The previous optimization studies are quite idealistic, since materials compositions have been continuously changed throughout the blanket. This is an impractical situation and one should account for simplicity of manufacturing as well as engineering assembly. For these reasons, we chose to arrange the pins into one neutron multiplier zone and two tritium breeding zones. Even though this arrangement does not result in a "theoretical" maximum TBR, it produces a near-optimum value.

Nuclear heating and rod temperature limits were considered as drivers for the blanket arrangements. Based upon the results of previous stages, a three-zone arrangement was set.

Zone 1: 6 rows of bare Be rods (1.7 cm o.d.)
Zone 2: 5 rows of LiAlO$_2$/9-C rods (1.22 cm o.d.)
Zone 3: 5 rows of LiAl02/9-C rods (3.22 cm o.d.)

The cladding thickness was chosen as 0.1 cm, with a nominal gap thickness of 0.01 cm. The distance between adjacent pins was taken as 0.3 cm. Thermal and mechanical considerations for these choices can be reviewed in Refs. [6-7]. The final blanket configuration is shown in Fig. 4.

Throughout all previous optimization studies, the breeder density was taken as 95%. However, modeling of tritium transport indicated that such a high density may result in unacceptable tritium inventory.[13] Consequently, the density of LiAlO$_2$ was reduced to 85% of the theoretical density. Furthermore, the total blanket depth was reduced to about 0.5 m, including helium gas manifolds, so that modules can fit either in the out-board or in in-board sections of the tokamak. With all imposed constraints and the reasonably short blanket modules, it was found that the tritium breeding ratio is 1.175.

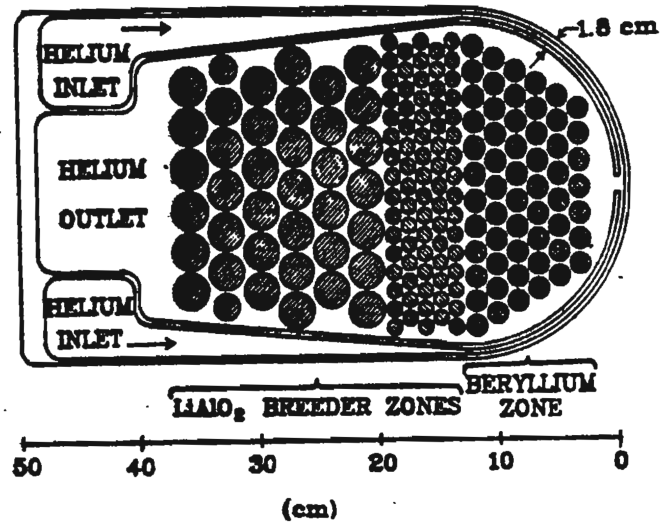

Fig. 4. Final configuration of optimized reference blanket.

For a 14.1 MeV neutron incident on the first wall, the integrated values of nuclear heating were calculated as follows:

First wall	2.45 MeV
Beryllium	5.25 MeV
LiAlO$_2$	8.85 MeV
9-C cladding	1.52 MeV
Manifold section	0.54 MeV
Shield-1	2.20 MeV
Shield-2	0.34 MeV
TOTAL	21.15 MeV

As can be seen, the heat generated in the first wall, Be, LiAlO$_2$/9-C, and manifold section is 18.61 MeV, yielding an energy multiplication factor of 1.32. The actual volumetric heat distribution in the blanket is shown in Fig. 5. It is to be noted that the maximum values for LiAlO$_2$ heat generation rate is 179 W/cm^3, while that for Be is 35 W/cm^3. However, when averaging is performed over rod dimensions, the following maximum values are obtained:

Beryllium	35 W/cm^3
LiAlO$_2$ (1.22 cm o.d.)	127 W/cm^3
LiAlO$_2$ (3.22 cm o.d.)	21 W/cm^3

These values were found to result in acceptable temperature distributions within the breeder and Be rods.[6]

The distribution of tritium production in the LiAlO$_2$ throughout the blanket is shown in Fig. 6. It was found that the average tritium production rate is 4.31x10^{-5} wppm/s (1359 wppm/yr). However, 76% is produced in the first breeder zone and only 24% is produced in the back breeder

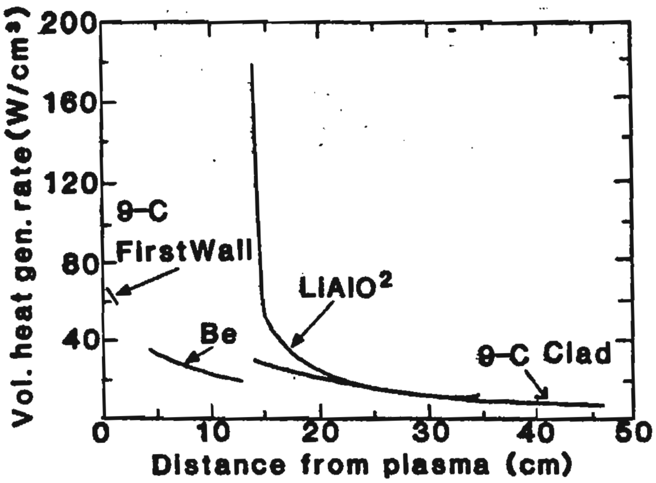

Fig. 5. Distribution of volumetric heat generation rate within the reference blanket.

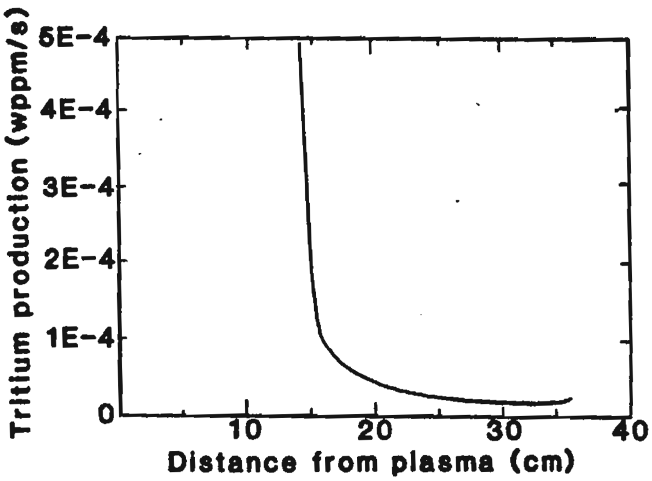

Fig. 6. Distribution of tritium production within the reference blanket.

zone. Nearly 99% of produced tritium was in Li^6 reactions. Tritium was also found to be produced in beryllium, with an average rate of 122.8 appm/y, and a maximum value of 204.5 appm/y. Burnup calculations are not included. However, the reaction profiles are expected to remain nearly similar to those presented here, with a gradual shift into the blanket with accumulated fluence.

Helium was found to be produced in all blanket materials. However, the production rate of helium in LiAlO$_2$ was found to be exceptionally high, reaching a maximum of 85,000 appm/y. Displacement damage rates in the first wall, LiAlO$_2$ breeder, and the 9-C cladding were calculated, giving a maximum first wall value of 64 dpa/y.

V. CONCLUSIONS AND RECOMMENDATIONS

The present calculations have shown the viability of a pin-type solid breeder blanket for tritium breeding. Engineering materials and geometrical constraints were all considered self-consistently, without a sacrifice of tritium self-sufficiency. Moreover, the final reference blanket is quite thin, with a total depth of 46.3 cm including the manifolds and first wall zones. The amount of breeder material is small, since the solid breeder zone is only 21.8 cm. It was also found that all reaction rates display a steep dependence on distance into the blanket. Thus, across the breeder zone only, the tritium production rate decreases by a factor of 25, the heating rate by a factor of 16, and helium production by a factor of 26. As in many other blanket designs, this behavior is a result of the nature of the fusion reaction, producing neutrons that impinge on one side of the blanket. The volume utilization of the blanket is less than optimal, and consequently, the design can be further improved. A double optimization for a maximum TBR and energy multiplication factor can improve the overall performance of the blanket.

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