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NEUTRONICS ANALYSIS OF GRAPHITE-MODERATED SOLID BREEDER BLANKET DESIGNS FOR INTOR*

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Abstract

An in-depth analysis of the INTOR tritium-production-blanket design is presented. A ternary system of solid silicate breeder, lead neutron multiplier, and graphite moderator is explored primarily from safety and blanket tritium-inventory considerations. Lithium-silicate (Li_2SiO_3) breeder systems are studied along[2] with water (H_2O/D_2O) and Type 316 stainless steel as coolant and structural material, respectively. The analysis examines the neutronics effects on tritium-production regarding: (1) coolant choice; (2) moderator choice; (3) moderator location; (4) multiplier thickness; (5) ^6Li enrichment; and (6) ^6Li burnup. The tritium-breeding-blanket modules are located at the top, outboard, and bottom (outer) parts of the torus, resulting in a breeding coverage of ~60% at the first-wall surface. It is found that the reference INTOR design yields, based on a three-dimensional analysis, a net tritium breeding ratio (BR) of ~0.65 at the beginning of reactor operation, satisfying the design criterion of BR > 0.6.

Introduction

The various blanket concepts studied reprecented a number of combinatons of moderater type, and of breeder location with respect to the coolant. The nomenclature adopted to describe these concepts is listed in Table 1.

Table 1. Blanket Concept Nomenclature

Acronym	Concept Configuration
BIT/LM	Breeder In Tube/Liquid Moderator
BIT/SM	Breeder In Tube/Solid Moderator
BOT/NM	Breeder Out of Tube/No Moderator
BOT/LM	Breeder Out of Tube/Liquid Moderator
BOT/SM	Breeder Out of Tube/Solid Moderator

Neutronics effort in the U.S.-INTOR/blanket design study has been concentrated mostly on the BOT/SM blanket concept. This design concept has been developed to resolve two major problem areas associated with the BIT/LM and BOT/NM concepts: (1) potential high tritium inventory in BOT blanket designs; and (2) safety concerns regarding the presence of large amounts of water in BIT/LM blanket designs. An effort has, therefore, been placed on the development of a new BOT blanket design in which much of the solid breeder material is replaced by an effective solid moderator such as graphite and silicon oxide. This approach is promising for substantially reducing the breeder material inventory, and hence, the solubility tritium inventory in breeder blankets.[2]

All the scoping calculations were performed by ANISN[3], and the VITAMIN-C[4] and MACKLIB-IV[5] cross-section libraries were used for the transport and response rate calculations, respectively.

Effect of Moderator Location

The material choice for the first blanket zone is very important to breeding ratio for two reasons. First, this region is subjected to the highest neutron flux available for breeding. Second, this region interfaces with both breeding and nonbreeding zones. The overall system breeding performance is characterized to a large extent by this first zone in the blanket. Moderator materials such as graphite and water, if placed in this zone, impede the neutron current into the breeding area because they reflect a large fraction of neutrons back into the first-wall/multiplier/second-wall regions. As a result, in these regions a significant portion of neutrons will be lost parasitically due to the stainless steel structure.

The effect of the first zone moderator on BR has been examined, using the system dimensions and material compositions described in Table 2. Table 3 shows the BRs for the cases with and without the first moderator zone (moderator-0 in Table 2). Graphite and light water are considered in this analysis as the two representative solid and liquid moderators. In the H_2O moderator system, the blockage of neutron flow into the blanket, or the neutron reflection into the preceeding zones due to the presence of moderator-0 is very significant. The resultant BR is ~0.28 less than that for the case without the moderator in question. Most of the reflected neutrons tend to be absorbed in the stainless steel structural material, mostly in the armor. A similar trend is observed in the graphite systems.

The result suggests a blanket design where the first breeder zone is located as close as possible to the back side of the second-wall panel. In the following sections, the Zone 5 moderator is eliminated, and the thicknesses of the remaining moderator regions are adjusted as described in Table 2 in order to keep the total blanket thickness of 50 cm.

Effect of Coolant Selection

Table 4 compares three different combinations of water coolant choice: (1) D_2O coolant throughout the system (D_2O/D_2O; (2) D_2O coolant in the first wall only and H_2O in the rest of the system (D_2O/H_2O); and H_2O coolant throughout the system (H_2O/H_2O).

The D_2O/H_2O system offers the best breeding performance, resulting in increases in BR by ~0.07 and ~0.06 relative to the D_2O/H_2O and H_2O/H_2O cases respectively. The difference in BR between the D_2O/D_2O and H_2O/H_2O systems reflects the difference in the neutron current into the blanket region, indicating that a reduced number of neutrons is available for breeding in the H_2O/H_2O system due to the increased parasitic absorption in the pre-blanket structure. In fact, for all the cases studied, the neutron multiplication in the pre-blanket regions remains almost constant (~0.29/DT).

Since the threshold energies of these neutron multiplication reactions are higher than those for effective neutron moderation by D_2O and H_2O, the neutron multiplication itself is not appreciably altered by the choice of coolant. The difference in the available number of neutrons in the blanket is therefore caused largely by the difference in the degree of the neutron spectrum softening, and hence, the degree of the neutron capture by the structure.

Another important aspect of the comparison of H_2O vs. D_2O coolants is the impact on the local tritium

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Table 2. Dimensions and Material Compositions Used for the BOT/SM Design Analysis

Component	Thickness (mm)	Composition
1. Armor	13.4	Stainless steel
2. First wall	3.0 3.0	Coolant Stainless steel
3. Multiplier	50.0	Lead
4. Second wall	2.0 1.5 1.0	Stainless steel Coolant Stainless steel
5. Moderator-0[a]	x_0	Moderator
6. BANK1 blanket	31.0	Li_2SiO_3[b]/SS/H_2O
7. Moderator-1[a]	x_1	Moderator
8. BANK2 blanket	29.7	Li_2SiO_3[b]/SS/H_2O
9. Moderator-2[a]	x_2	Moderator
10. BANK3 blanket	56.9	Li_2SiO_3[b]/SS/H_2O
11. Moderator-3[a]	x_3	Moderator
12. Blanket jacket	15.0	Stainless steel
13. Gap	30.0	Void
14. Shield jacket	15.0	Fe14Mn2Cr2Ni

[a] In presence of moderator-0: x_0 = 77 mm, x_1 = 80 mm, x_2 = 80 mm, x_3 = 56.5 mm.
In absence of Moderator-0: x_0 = 0 mm, x_1 = 105 mm, x_2 = 105 mm, x_3 = 83.5 mm.

[b] Li_2SiO_3: Density factor = 0.7.

Table 3. Effect of First Moderator Zone Upon Breeding Ratio

	C-Moderator	H_2O-Moderator
A. With First Moderator Zone		
BANK1-BR	0.475	0.429
BANK2-BR	0.229	0.090
BANK3-BR	0.139	0.043
TOTAL BR	0.844	0.563
B. Without First Moderator Zone		
BANK1-BR	0.458	0.532
BANK2-BR	0.306	0.254
BANK3-BR	0.187	0.060
TOTAL BR	0.952	0.846

Table 4. Effect of Coolant Selection Upon Breeding Ratio

	First-Wall/Blanket Coolants		
	D_2O/D_2O	D_2O/H_2O	H_2O/H_2O
BANK1-BR	0.320	0.469	0.458
BANK2-BR	0.344	0.338	0.306
BANK3-BR	0.276	0.203	0.187
TOTAL BR	0.940	1.010	0.951

producton and on the associated ^6Li burnup. Figure 1 compares the two coolant systems (D_2O/D_2O vs. H_2O/H_2O) in terms of the local $^6Li(n,\alpha)t$ reaction rate. For both systems, the local tritium production, particularly in the BANK1 and BANK2 regions, is significantly smeared out. This profile makes a vivid contrast to that of the BIT concept, in which the flux (or tritium production rate) is sharply depressed inside the breeder cylinders due to the self-shielding effect. The graphite moderator between the BANK1 and BANK2 breeder zones effectively supplies neutrons to both sides. Because of the neutron penetration deeper into the blanket region in the D_2O system, the maximum local burnup of ^6Li is ~25% less than the H_2O system. Such a reduced ^6Li consumption will have a significant impact upon the time-dependent breeding performance, in particular for systems based on natural lithium solid breeders.

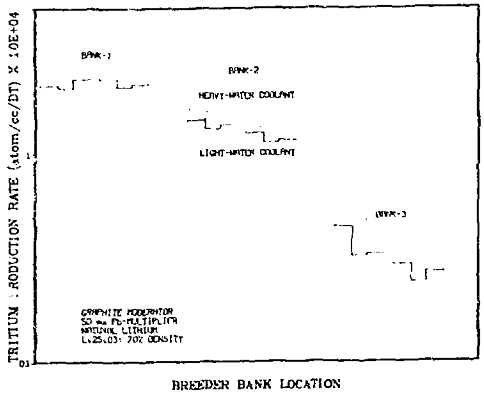

Fig. 1. Spatial variation of tritium production in BOT/SM design.

One conclusion to be drawn from the results presented in this section is that, although the D_2O/H_2O system results in the best breeding performance, the difference in BR is small when the actual blanket coverage of ~60% is taken into account. It is expected that the maximum difference in the net BR will be ~0.04 among the three systems. The final coolant selection will therefore be governed by other factors, such as material costs and the degree of design complexity for the dual coolant system of the D_2O/H_2O blanket design.

Effect of Moderator Selection

One of the most attractive solid moderators is SiO_2 because of its low tritium permeation. From the design standpoint the use of SiO_2 will eliminate a separate tritium barrier (e.g., stainless steel) between the breeder material and the moderator, so that the blanket design can be simplified. This simplication also increases breeding by eliminating additional nonbreeding material, although the analysis in this section assumes the same amount of stainless steel for all cases. In addition to SiO_2 and C, moderators of H_2O, D_2O, and a mixture of 50% C + 50% H_2O are included in the analysis for neutronics comparison.

The breeding performance of each moderator system is listed in Table 5 for D_2O and H_2O coolant systems. The use of SiO_2 in the D_2O-cooled blanket system is quite unattractive from the tritium-breeding standpoint. Obviously, the poor breeding performance is brought about by the inefficient neutron moderation in the D_2O-cooled blanket, followed by significant neutron leakage into the shield. With the H_2O coolant, the breeding capability of the SiO_2 moderator system is substantially improved. Most of the improvement comes from the more effective neutron capture by the BANK1 breeder and from reduced neutron leakage.

Table 5. Effect of Moderator Selection Upon Breeding Ratio

	D_2O Coolant Case		
Moderator	C	SiO_2	D_2O
BANK1-BR	0.320	0.239	0.413
BANK2-BR	0.344	0.222	0.487
BANK3-BR	0.276	0.274	0.264
TOTAL BR	0.939	0.735	1.169

	H_2O Coolant Case			
Moderator	C	SiO_2	H_2O	H_2O/C
BANK1-BR	0.458	0.405	0.532	0.539
BANK2-BR	0.306	0.249	0.254	0.352
BANK3-BR	0.187	0.193	0.060	0.093
TOTAL BR	0.952	0.847	0.846	0.983

Based on the results of Table 5, there seems to be an optimal point with respect to the neutron energy moderation power for maximizing the tritium fuel production. It is expected that an optimal tritium production will be found around the level of moderation power equivalent to that of the D_2O-coolant/D_2O-moderator system. There is no appreciable difference between the graphite and SiO_2 moderator systems regarding neutron multiplication capability in the preblanket region. The primary difference is the increased parasitic neutron loss in the SiO_2 moderator itself and the larger fraction of neutrons leaking into the shield.

Effect of Lead Neutron Multiplier Thickness

The objective of this section is to study the impact of lead thickness on BR. Figure 2 presents the variation of BR with lead thickness. Two classes of design, i.e., internally cooled multiplier design, and no-internal-coolant-multiplier design, are shown for two different coolants (H_2O and D_2O). The breeding performance constantly improves with thicker lead. In the case of the internally cooled multiplier design, the breeding enhancement with increased lead thickness is not as significant as for the other case. However, the difference in the coolant material choice becomes more significant. The breeding deterioration caused by the internal coolant flow of the H_2O reflects the nuetron spectrum softening due to the H_2O coolant, followed by the less-effective neutron amplification in lead.

Based on the thermal-hydraulic analysis, it is shown that a 70-mm thick multiplier is unacceptable since the maximum temperature exceeds 327°C of the lead melting point. The analysis is based on a 100°C outlet coolant temperature, with a lead/steel gap conductance of 4540 W/m^2-°K. For a 50-mm thick lead design, the maximum temperature has been found to be 289°C under the same coolant tenperature and gap conductance conditions.

These thermal-hydraulic results imply that the actual BR variation with lead thickness for realistic designs must be derived by constructing a design curve, which is equivalent to the no-internal-coolant curve (Fig. 2) for thicknesses <60 mm, and equivalent to the with-internal-coolant curve for thicknesses >60 mm. In such a case, the result of Fig. 2 suggests no practical advantage of having a multiplier thicker than ~60 mm for H_2O-cooled blanket designs.

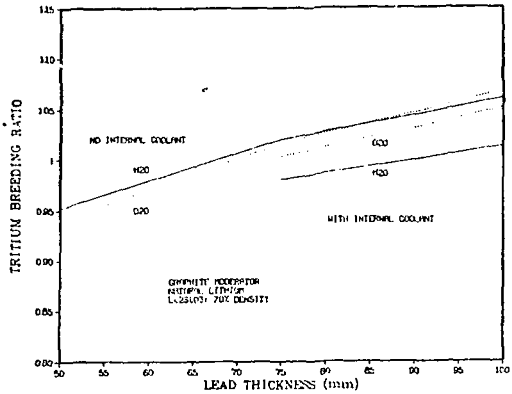

Fig. 2. Effect of lead Multiplier thickness for BOT/SM design.

Effect of ^6Li Enrichment

In general, tritium production in a breeding blanket that utilizes a ternary solid breeder along with a neutron multiplier relies largely upon the $^6Li(n,\alpha)t$ reaction. For example, most of the blanket designs studied so far produce typically 99% of the total tritium via the $^6Li(n,\alpha)t$ reaction. Such an extremely unbalanced ^6Li consumption, along with the fact that natural lithium contains only ~7.5% of ^6Li, may pose difficulty in maintaining a required BR. The high ^6Li burnup is of particular concern with the BOT/SM design, which contains a limited amount of breeder material. In addition, potential armor erosion during INTOR operation may significantly raise the ^6Li burnup rate from that anticipated at reactor startup. It is obvious that the ^6Li burnup problem can be alleviated by enrichment to include more ^6Li atoms in the system. However, the possible increase in BR or ^6Li burnup rate with the enriched breeder might bring about stoichiometric breeder instability as well as the associated increase in blanket tritium inventory.

For the H_2O-cooled BOT/SM blanket design, little incentive is found for enriching ^6Li more than ~30%. The breeding gain when the enrichment is raised from the natural abundance of 7.5% to 30% is ~0.09 for the 100% blanket coverage, being reduced to ~0.055 at a blanket coverage of 60%. In the case of the D_2O-cooled blanket, the breeding enhancement with enriched ^6Li is large, due to the increased effectiveness in absorbing neutrons that are not well moderated. The breeding improvements, as ^6Li content is varied from 7.5% to 70%, are ~0.16 for 100% coverage and ~0.10 for a 60% coverage.

Based on the results of ^6Li burnup calculations for several ^6Li-enrichment cases, the breeding calculation has been iterated. The breeding performance in the natural lithium system deteriorates substantially as ^6Li atoms are burned (from BR = 0.952 to 0.836 over the INTOR lifetime), while the enriched system is likely to maintain the initial BR (~1.04). As expected, the breeding in the BANK3 region slightly increases with ^6Li burnup, indicating that neutrons tend to penetrate deeper into the blanket. Based on the results in this section, the 30% ^6Li enrichment is chosen for the reference BOT/SM design.

Monte Carlo Analysis of the Reference BOT/SM Design

This section presents a three-dimensional tritium breeding analysis of the reference BOT/SM design for U.S.-INTOR based on a Monte Carlo method. Figure 3 shows the schematic of the model used for the analysis. For more detailed description of the reference design the readers are referred to Ref. 1. The physical breeding zone coverage amounts to 60% (sectors 1-4) of the total surface area. The analysis was carried out by the MORSE[6] code. The spatial distribution of the neutron source accounts for the plasma MHD shift. The computation was performed for a one-sixth segment of the torus.

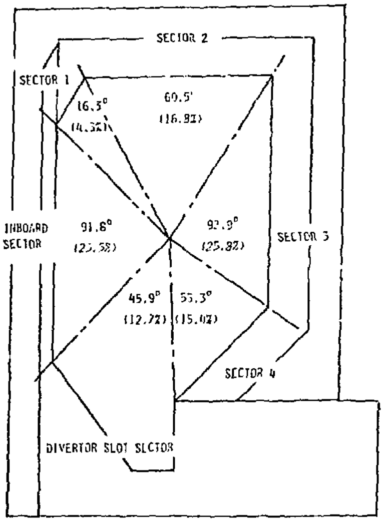

Fig. 3. Schematic of model for Monte Carlo analysis.

The breeding zone is divided poloidally into four subzones (sectors 1-4). Each sector has been further divided into three layers of BANK1 (inner), BANK2 (middle), and BANK3 (outer) regions. The inboard nonbreeding blanket has a stainless steel armor of 1.5 cm, followed by a 0.6-cm thick first wall zone (same as the outboard wall design). A 16.4-cm thick inboard blanket with a material composition of 90% stainless steel + 10% H_2O follows the first wall. In order to improve the statistics of the Monte Carlo analysis, each blanket subzone of breeder or moderator region is homogeneously mixed.

Table 6 summarizes the individual zone BRs together with the sector and bank layer BRs. A comparison is also made with the one-dimensional analysis case. Within an error estimate of ~1%, the total BR for the reference BOT/SM is ~0.66. This BR is close to that anticipated from the one-dimensional analysis for a blanket coverage of ~60%. The neutron multiplication in the lead region amounts to 0.22. This neutron multiplication indicates that ~70% of the source neutrons have passed through the outboard preblanket regions, when compared to the multiplication of ~0.32 in the one-dimensional analysis. However, the neutron loss in the nonbreeding zone, particularly in the divertor region is significantly higher than that expected from its physical coverage or from that due to the toroidal geometry effect.[7] It appears that while neutrons are bounced back and forth between the breeding and nonbreeding regions, they tend to be more effectively absorbed in the nonbreeding zone. In fact, the largest breeding loss (relative to the one-dimensional case) can be seen in the first two banks which are quite sensitive to the nuclear characteristic of the inboard region.

Table 6. Tritium Breeding Analysis by Monte Carlo Method[a]

Zone Breeding Ratio		Sector Breeding Ratio	
SECTOR 1/BANK1	0.0199	SECTOR 1	0.0261
BANK2	0.0053	SECTOR 2	0.1843
BANK3	0.0008	SECTOR 3	0.3007
SECTOR 2/BANK1	0.1077	SECTOR 4	0.1482
BANK2	0.0543		
BANK3	0.0222	Layer Breeding Ratio	
SECTOR-3/BANK1	0.1714		
BANK2	0.0894	BANK1	0.3890
BANK3	0.0400	BANK2	0.1908
SECTOR 4/BANK1	0.0899	BANK3	0.0795
BANK2	0.0419		
BANK3	0.0164	1-D Layer Breeding Ratio	
TOTAL:	0.6592		
T_6:	0.6520	BANK1	0.6348
T_7	0.0072	BANK2	0.3218
Ratio of 3-D/1-D = 0.6102		BANK3	0.1237
		TOTAL:	1.0803

[a] Number of neutron histories = 20,000.

The BR of 1.08 for the 100% breeding coverage corresponds to a Li_2SiO_3 breeder inventory of ~72 MT or a pure lithium inventory of ~6 MT. These figures are compared, for instance, to those of the STARFIRE design[2] (net BR = 1.04) in which the α-$LiAlO_2$ breeder and lithium inventories are estimated to be ~605 MT and ~64 MT, respectively. Although STARFIRE is substantially larger than INTOR, the difference in the lithium inventory shown here is more than the difference in the reactor size, and stems largely from the diffference in the blanket design concept.

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