ASSESSMENTS OF TRITIUM BREEDING REQUIREMENTS AND BREEDING POTENTIAL FOR THE STARFIRE/DEMO DESIGN

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(312)/972-4832/4835

ABSTRACT

This paper presents assessments of tritium breeding requirements and breeding potential for the STARFIRE/DEMO design. The assessment of breeding requirement is described based on two design considerations; i.e., (1) tritium inventory and doubling requirement; and (2) computational uncertainties associated with the breeding calculation. The lithium-containing materials considered include: solid Li_2O and $LiAlO_2$ and liquid lithium and 17Li-83Pb.

I. INTRODUCTION

The safety problems of liquid lithium received a great deal of attention in the past several years. The STARFIRE,[1] DEMO,[2] and INTOR[3] studies investigated breeder blanket concepts based on solid lithium compounds such as Li_2O, $LiAlO_2$, and Li_2SiO_3. Solid breeders appear now to be the leading candidates worldwide[3] for fusion blankets. However, the feasibility of solid breeders has not yet been established. Achieving adequate tritium breeding and acceptable tritium recovery from the blanket are the two most critical issues for solid breeders.

This paper presents a summary of the results of a study on the tritium breeding potential of candidate blanket materials. The study was carried out in the context of a Fusion Power Demonstration Plant (DEMO) project.[2] In Sec. II the determination of tritium breeding requirements for power reactor conceptual designs is discussed. Section III describes the geometrical models and computational methods used for the analyses. The results of neutronics analyses for breeder blanket concepts based on four candidate breeders, Li_2O, $LiAlO_2$, 17Li-83Pb, and lithium metal are discussed in Sec. IV. Conclusions are presented in Sec. V.

II. TRITIUM BREEDING REQUIREMENTS

The tritium breeding ratio (BR) is defined as $T_0 = N^+/N^-$, where N^+ is the rate of tritium production in the system and N^- is the rate of burning tritium in the plasma. T_0 must exceed unity by a margin (A) to cover: (1) losses and radioactive decay during the period between production and use; and (2) supplying inventory for startup of other fusion reactors. A detailed expression has been derived[4] to correlate tritium doubling time (t_d) to T_0:

$$T_0 = 1 + \left(I_0/\tau N^-\right) \cdot F\left(t_d/\tau\right) , \qquad (1)$$

where I_0 is the startup tritium inventory and F is a function of doubling time. τ is the mean decay time of tritium. The total tritium inventory is determined by the tritium inventories in the breeding blanket $\left(I_B\right)$, fueling and exhaust systems $\left(I_F\right)$, and storage $\left(I_S\right)$. At present, there are large uncertainties concerning the magnitude of the tritium inventory achievable in fusion reactor systems. The tritium inventory in the blanket will likely be <1 kg for liquid breeder systems, but may be between 1 and 10 kg or greater in solid breeders because their tritium release characteristics cannot precisely be quantified at present. The magnitude of I_F depends strongly on plasma-performance parameters such as the fractional tritium burnup in the plasma. I_S is determined by the startup inventory and the amount of fuel required in reserve, $I_{S,min}$ to guard against a temporary malfunction of the tritium recovery system.

Figure 1 shows the required BR as a function of t_d and the steady-state tritium inventory in the reactor system $\left(I_R = I_B + I_F\right)$. The analysis is based on a tritium burnup rate, N^- of 0.5 kg/d and $I_{S,min} = 0$. The required BR increases rapidly as I_R increases and as t_d becomes very short. For a fractional burnup of ~5% and doubling time of ~5 y, the required T_0 is ~1.05 assuming an I_R of ~30 kg. For a conceptual design, the goal for the BR (T_D) that must be achieved exceeds T_0 by an allowance (B) for the uncertainties in estimating T_0,

$$T_D = 1 + A + B . \qquad (2)$$

The sources of uncertainties are numerous, but can be broadly classified into three areas:

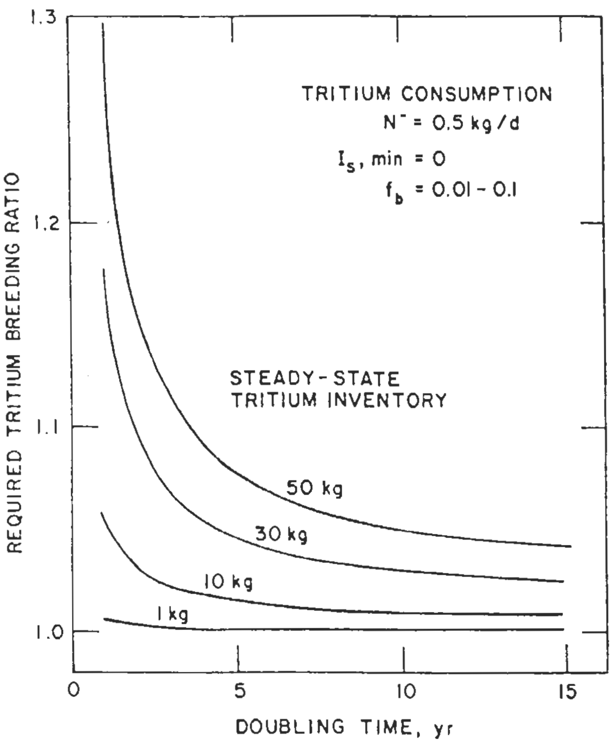

Fig. 1. TBR vs. doubling time.

(1) reactor design definition; (2) neutronics calculations; and (3) nuclear data. A few comments on these are in order.

The BR is sensitive to many of the design features of the fusion reactor. Some of the important features are: (1) the in-vessel components (e.g., limiter and divertor); (2) the bulk blanket design; (3) blanket penetrations (e.g., plasma-current drive and vacuum pumping); and (4) overall plasma characteristics and reactor configuration, including fusion neutron source distribution, shape of first wall, modularity of components, etc. Since the breeding potential for candidate breeding materials will be (and is already being) performed for various technology and design concept choices, we will require that T_D includes only 2% allowance for design definition. This is merely enough to account for those additional design details that cannot be developed at present for a given conceptual reactor design.

Neutronics calculations of the BR in a given system are subject to two types of uncertainties: (1) geometrical modeling of the fusion reactor configuration entails some approximations that are necessary to make the problem practical from viewpoints of computer storage and computing time; and (2) there are errors that are inherent in all calculational methods and codes for a variety of reasons such as those related to numerical techniques, averaging, and/or discrete treatment of continuous variables. Reducing errors due to calculations to <2% appears to be a very difficult goal.[5]

The third source of uncertainty in estimating T_0 comes from errors in nuclear data (e.g., cross sections and energy/angular distributions of secondary neutrons). These include errors arising from the accuracy of measurements, representation of parameters in data files, and processing of data into a form suitable for use in radiation transport codes. Over the past decade numerous studies have been conducted on the cross-section sensitivities to the fusion blanket performance. Judging from past experience and the estimated sensitivity of BR to variations in nuclear data, it is not unreasonable to require accuracies in nuclear data that result in an error in T_0 of no more than 1-2%.

From the above discussions, the allowance B in Eq. (2) is ~5 to 6%. Hence, the T_D required in a fusion reactor design must be ~1.1 (i.e., 1.05 plus ~5 to 6%) in order for the design concept to have a high potential of achieving self-sustaining DT fusion power economy. However, it appears somewhat premature to exclude blanket design concepts yielding BR's of 1.05 to 1.1 from the consideration. The viability of such blanket designs needs to be further investigated as more accurate evaluations on BR become possible.

III. GEOMETRICAL MODEL AND COMPUTATIONAL METHOD

Figure 2 illustrates a schematic view of the poloidal cross section of the DEMO reactor. This reactor system has been simulated by a 3-D Monte Carlo transport code, MORSE-CG. The spatial distribution of the source neutrons is assumed to be parabolic with an outward MHD shift of the magnetic axis of 0.26 m.

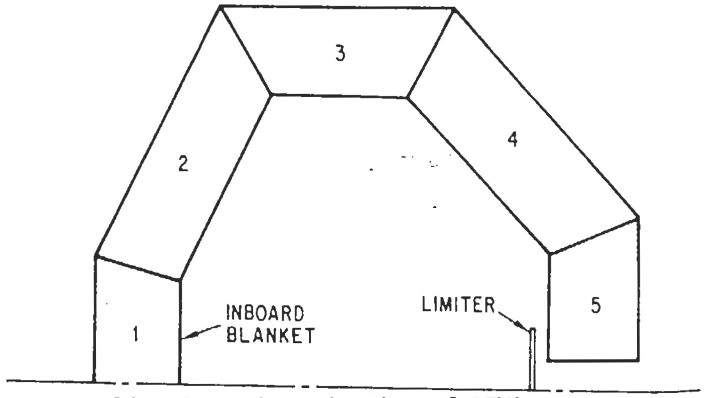

Fig. 2. Schematic view of DEMO blanket cross section.

In order to supplement the expensive 3-D Monte Carlo calculations, several 1-D analyses have been performed by using ANISN with the S_8-P_3 approximation. The geometrical model used for these 1-D analyses is an infinite cylinder where the plasma minor axis is chosen as the cylinder axis. The minor radius and the scrape-off size are assumed to be 2.08 m and 0.165 m respectively, and the neutron source is uniformly distributed in the plasma region.

Table I shows system dimensions and material compositions used for the neutronics analyses. The VITAMIN-C and MACKLIB-IV cross-section libraries were used for particle transport and reaction rate calculations, respectively. Both libraries were generated from the ENDF/B-IV data, and possess a 46-neutron and 21-gamma group structure.

TABLE I

System Dimensions and Material Compositions Used for Neutronics Analysis

Component	Thick. (mm)	Composition
Armor	10	100% structure
First wall	10	65% structure + 35% coolant
Blanket	680	Composition varies
Shield	300	90% Fe1422 + 10% H_2O

Recent experiments have shown that $^7Li(n,n'\alpha)t$ cross-section data in ENDF/B-V is substantially higher than that experimentally measured.[6] The maximum difference amounts to ~15%. In order to be consistent with these experimental results, the total tritium production rate reported here includes a correction of -15% for the $^7Li(n,n'\alpha)t$ reaction rate.

IV. TRITIUM BREEDING POTENTIAL

A. Li_2O Breeder Blanket Designs

1. Li_2O Blanket Designs Without Neutron Multiplier. Table II summarizes the results of a series of 3-D Monte Carlo calculations. In addition, Case A in the table shows the BR of full breeding coverage calculation by ANISN. This case is compared to the 3-D MORSE calculation given in Case B. The discrepancy between the two calculations is less than ~1% in the total BR.

The breeding potential in excess of 1.05 to 1.1, as in Case C of Table II, has several important design implications. For example, it can be utilized to eliminate tritium production in the inboard blanket and/or reduce the overall breeding blanket thickness. Based on a 1-D analysis a blanket thickness less than 0.4 m is sufficient to yield a net BR > 1.1 provided that the blanket is fully covered by the breeding material. Such a thin blanket design is attractive for reducing not only the required breeder inventory but also the associated tritium inventory. On the other hand, the elimination of tritium breeding in the inboard blanket (the Sector 1 region) results in a net BR of 1.055 as shown in Case D of Table II. As discussed in Sec. II this system does not meet the breeding goal of $T_D > 1.1$. However, it should be noted that the nonbreeding inboard blanket design has a quite significant impact on the required thickness for the inboard radiation shielding. A particular emphasis should be placed on solid breeder systems for which a large porosity must be accommodated for breeder materials in order to enhance the tritium extraction. Such an accommodation of breeder porosity will result in a thicker shield, leading to a costly degradation of the reactor power performance. In this regard Case D appears to deserve further investigation for more precise breeding evaluation. The effort is vital to the final decision as to whether the inboard blanket should be utilized for tritium production or not.

TABLE II

TBR's for Li_2O Blanket Designs

Case	Method	System	TBR
A	ANISN	Full breeding	1.184
B	MORSE	Full breeding	1.189
C	MORSE	Limiter	1.146
D	MORSE	Limiter, no inboard breeding	1.055

2. Li_2O Blanket Designs With Neutron Multiplier. Tritium breeding can be enhanced by use of a neutron multiplier. Table III shows the effect of a beryllium multiplier on BR for two different blanket material layouts. Both systems employ an 80-mm thick beryllium zone (100% of the theoretical density) without internal coolant, and an Li_2O breeder with 30% enriched ^6Li. System B yields a BR of about 1.34, which is about 0.15 greater than the case without a multiplier, whereas System A enhances the tritium production by more than 0.34. The substantial breeding enchancement in System A stems largely from the blockage of neutron reflection into the first wall region, thereby drastically decreasing the parasitic neutron loss in this pre-blanket region. In fact, the BR in the first zone alone (40 mm thick) in System A amounts to about 0.70, which is slightly below

TABLE III

Effect of Blanket Materials Layout on TBR

Material Layout	System A	System B
Zone 1 (4 cm)	Li_2O	Be
Zone 2 (4 cm)	Be	Be
Zone 3 (4 cm)	Be	Li_2O
Zone 4 (54.5 cm)	Li_2O	Li_2O
TBR	1.534	1.340

one-half of the total BR. In the case of System B a majority of the secondary neutrons generated by the Be(n,2n) reaction, which are more than in System A, tend to be lost in the pre-blanket region due to the strong neutron backflow. Although it is not shown here, the blanket designs based on the concept of System A can yield a continuously increasing BR with thicker multiplier while the designs based on the System B configuration show a maximum BR at a beryllium thickness of ~50 mm.

B. $LiAlO_2$ Breeder Blanket Design

Table IV summarizes the BR's for several $LiAlO_2$ blankets. The analysis is based on the 3-D model previously used for Li_2O systems. Case A is a full breeding blanket design which does not have limiter nor multiplier. The net BR of 0.883 indicates that the $LiAlO_2$ breeder (and possibly all ternary ceramic breeders) is not a viable candidate for fusion reactor application unless the breeding is assisted by use of a neutron multiplier. Case B replaces the first 8-cm zone of the Case A blanket by a 100% dense Zr_5Pb_3 multiplier as in the STARFIRE design. The resultant net BR is 1.084. The breeding margin is, however, not large enough to compensate for possible breeding losses due to limiter and nonbreeding sector implementation as shown in Case C. The breeding performance can be substantially improved when the Zr_5Pb_3 multiplier is replaced by either beryllium (Case D) or lead (Case E) of the same thickness. The relative breeding enhancement by use of such a multiplier can amount to ~0.08 in the net BR. However, as discussed earlier, the breeding margin shown in Cases D and E might not be sufficient for assuring $T_0 \geq 1.05$.

The sandwich-type breeder/multiplier design, System A, that was studied earlier for the Li_2O breeder (see Table III) was analyzed again, for α-$LiAlO_2$ using the 1-D model. Figure 3 examines the breeding enhancement for internally cooled multiplier designs based on the System A configuration. Three multipliers, beryllium, lead, and Zr_5Pb_3, are examined. In all cases, the multi

TABLE IV

Effect of Multiplier in $LiAlO_2$ Blanket Design

Case	TBR
Full breeding:	
A. No multiplier	0.883
B. With Zr_5Pb_3	1.084
No Sector 1 breeding/with limiter:	
C. With Zr_5Pb_3	0.978
D. With beryllium	1.062
E. With lead	1.055

plier region is represented by a homogeneous mixture of (90% multiplier + 5% 316 SS + 5% H_2O). When the net BR requirement ranges from T_D = 1.05 to T_D = 1.10 as discussed in Sec. II, one needs to have full BR's of 1.07-1.12 and 1.19-1.25 for (1) the limiter implementation; and (2) the implementation of limiter and non-breeding Sector 1 blanket. These breeding requirement bands are shown in Fig. 3. It is found that the $LiAlO_2$ blanket has the least viability for its fusion reactor application if the Zr_5Pb_3 multiplier is used. The $LiAlO_2$/Pb system does not seem to pose any serious breeding difficulty upon limiter implementation. It is expected, however, that this system can be considered viable only when the entire, or at least

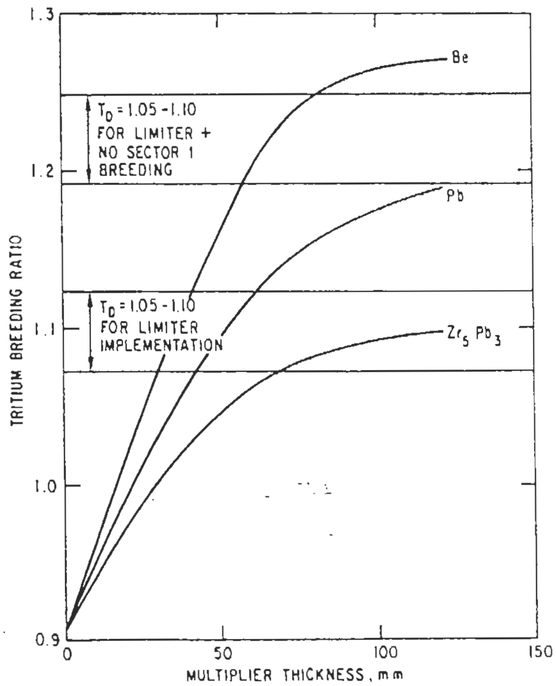

Fig. 3. Effect of neutron multipliers for $LiAlO_2$ blanket regions.

a part of the inboard blanket is utilized for the tritium production. The $LiAlO_2$/Be blanket design has the least impact on the design constraints in terms of the self-sufficient fuel production. Approximately 8 cm thick beryllium will suffice the breeding criterion to incorporate the limiter as well as the nonbreeding Sector 1 blanket. If the Sector 1 blanket is fully utilized for breeding this system requires a multiplier zone thickness of only ~4 cm for T_D = 1.10 and ~3 cm for T_D = 1.05.

The observations made above strongly suggest that if $LiAlO_2$ (or ternary ceramics, in general) is a favorable choice as the fusion breeder material, the co-use of a beryllium multiplier will certainly be the most promising and viable design option to be selected.

C. 17Li-83Pb Breeder Blanket Designs

Liquid 17Li-83Pb is one of the most attractive tritium breeding materials in that a substantial neutron multipliation can take place in the breeder itself through the Pb(n,2n) and Pb(n,3n) reactions. The resultant neutron spectrum is generally quite soft, implying great potential for tritium production by the $^6Li(n,\alpha)t$ reaction. The lithium density in 17Li-83Pb is, however, very low compared to other breeders. As a result the content of ^6Li or the enrichment of ^6Li in 17Li-83Pb plays the most important role in the tritium-breeding performance in 17Li-83Pb blanket designs.

Table V lists the BR's for several 17Li-83Pb blanket designs studied based on the 3-D model. The blanket composition is neutronically assumed to be a homogenous mixture of 85% 17Li-83Pb + 10% Fe9Cr1Mo + 5% H_2O, implying a separate coolant concept. The 17Li-83Pb breeder is enriched to 90% of ^6Li. The full breeding blanket can yield a BR of 1.483. By comparing Case B to Case A, one finds that the presence of the limiter opening results in a breeding loss of ~5.5% in BR. The Case C blanket which incorporates the limiter as well as the nonbreeding inboard (Sector 1 only) blanket can still yield an excellent net BR of 1.259. However, Case D of Table V shows that the complete elimination of tritium production from Sector 1 and Sector 2 blankets results in a BR of only 1.002. It appears more attractive, therefore, to utilize the breeding margin in Case C for reducing the thickness of blanket Sectors 2-5. According to a tritium accummulation analysis, it is found that the Case D blanket requires minimum blanket thicknesses of only 30 and 34 cm in order to realize net BR's of 1.05 and 1.10, respectively.

TABLE V

TBR's for 17Li-83Pb Blankets

Case	Method	System	TBR
A	MORSE	Full breeding	1.483
B	MORSE	Limiter	1.405
C	MORSE	Limiter, no Sec. 1 breeding	1.259
D	MORSE	Limiter, no Sec. 1 & 2 breeding	1.002

So far the coolant has been assumed to be H_2O. There are several other candidate coolant materials that are considered for use with the liquid breeder material. They include sodium, 17Li-83Pb itself, and helium. Table VI lists tritium BR's for the 17Li-83Pb breeder blanket designs using these coolants, based on the 1-D model. In all the cases examined the increase in ^6Li enrichment always results in a substantial improvement of the breeding performance and the choice of coolant becomes less important in terms of tritium production. The selection of coolant, therefore, can be made for such a high enrichment system, based on design considerations other than the neutronics performance. Thus, a great degree of design flexibility can be afforded to the relevant technical areas such as thermal-hydraulics and mechanical designs.

TABLE VI

Effect of Coolant Choice in 17Li-83Pb Blankets

^6Li (%)	TBR			
	Helium	H_2O	Sodium	17Li-83Pb
7.5	0.840	1.248	0.852	0.881
50.0	1.331	1.418	1.325	1.363
90.0	1.427	1.450	1.419	1.452

D. Liquid Lithium Breeder Blanket Designs

Recently somewhat less attention has been called to liquid lithium systems because of the perceived problems associated with the use of liquid lithium in the fusion environments. Major problems concerning the use of lithium breeder/coolant include: (1) reactivity of lithium with air and water, leading to possible lithium fire; (2) compatibility with structural material; and (3) MHD effects created by the strong magnetic field. Yet, liquid lithium appears one of the best breeding materials to use in fusion reactors from the neutronics standpoint. In addition, lower blanket tritium inventories are expected to result from continuous processing of liquid lithium breeder/coolant as compared to solid breeder blankets.

Table VII presents a 3-D analysis of liquid lithium blanket designs along with the reference 17Li-83Pb designs for the sake of comparisons. Two blanket systems were studied: Case A, full breeding blanket without the limiter penetration; and Case B, no inboard breeding (breeding in Sectors 2 through 5 only) with the limiter penetration. It is found that the liquid lithium can yield self-sufficient tritium for Case A and a BR slightly less than 1.1 for Case B. It is expected that small breeding in the inboard blanket might be required in order to assure $T_0 \geq 1.05$ in the liquid lithium blanket designs. The breeding potential is not as much as that of the 17Li-83Pb systems. Normally liquid lithium systems are characterized by the much harder neutron spectrum than 17Li-83Pb systems. In fact, the result of Table VII shows that the contribution of $T_7[^7Li(n,n'\alpha)t]$ to the total BR amounts to almost 30% in the lithium blankets compared to that less than ~1% in the 17Li-83Pb systems. Every tritium production reaction by ^7Li releases one secondary neutron, substantially moderated in energy, that can be utilized for inducing the $^6Li(n,\alpha)t$ reaction. In consequence, the ^6Li enrichment (or ^7Li reduction) in liquid lithium systems generally does not increase, but instead decreases the BR because the loss in T_7 is larger than the gain in $T_6[^6Li(n,\alpha)t]$. In fact, the tritium production in liquid lithium systems has been shown to be optimized at the natural lithium composition.[7]

TABLE VII

A Comparison of TBR in Liquid Lithium and 17Li-83Pb Blankets

	Lithium (Nat. Li)	17Li-83Pb (90% ^6Li)
A. Full Breeding		
	1.247	1.483
B. Limiter + no Sector 1 breeding		
	1.088	1.260

It should be noted that the breeding evaluation presented here for liquid lithium systems remains to be further refined as more accurate lithium reaction cross-section data become available. The correction method used for the T_7 evaluation might result in an unduly underestimated BR for such a hard (or fast) neutron spectrum system.

CONCLUSIONS

The magnitude of the TBR required in fusion reactors to achieve a given doubling time cannot be precisely defined because of present uncertainties in the magnitude of tritium inventory in the blanket. Present estimates of the achievable TBR for various blanket concepts suffers from uncertainties due to incomplete design definition and deficiencies in calculational methods and data. Using semi-quantitative judgments on tritium inventory and design, methods and data uncertainties, the breeding potential was evaluated for a number of blanket concepts. Enriched 17Li-83Pb offers the highest potential and liquid lithium and Li_2O blankets present medium risk. Ternary ceramics cannot provide a TBR > 1 without use of a neutron multiplier. It appears that the breeding margin of these ceramics becomes adequate only when the best non-fissionable neutron multiplier (beryllium) is used with them.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy.

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