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IMPACT OF NEUTRONICS CONSIDERATIONS ON THE SELECTION OF SOLID BREEDER AND MULTIPLIER MATERIALS AND CONFIGURATIONS *

Myungdal SONG, Mahmoud Z. YOUSSEF, Mohamed A. ABDOU and A. René RAFFRAY
University of California, Los Angeles, Los Angeles, CA 90024, USA

A large number of solid breeder materials have been proposed for fusion blankets. A study was performed to quantitatively compare the effect of solid breeder (SB) material choice on blanket attractiveness and to recommend priorities for focusing the solid breeder experiments. This paper summarizes the results of the extensive neutronics analysis which evaluated the achievable tritium breeding ratio (TBR) and the power multiplication factor (M) as key parameters. The study considered ten solid breeder materials (e.g., Li_2O, Li_2SiO_3, $LiAlO_2$), six neutron multipliers (Be, BeO, Pb, PbO, PbBi and and Zr_5Pb_3) and two coolants (helium and water). These breeder and multiplier materials were considered in six different design configurations which included homogenized breeder/multiplier mixtures and a separate multiplier zones.

The general conclusions which can be made from the TBR results are that: (1) Be exhibits the most superior performance among neutron multiplier (M) candidates; (2) Li_2O is the most attractive solid breeder candidate, showing the highest TBR for the unmultiplied, separate multiplier and homogeneous SB/M cases; (3) Li_2O is the only solid breeder with a plausible chance of performing satisfactorily without a multiplier; (4) the homogeneous SB/Be cases show exceptional TBR performance and should be considered in the test program, (5) multi-region solid breeder multiplier (SB/M) cases show still excellent TBR performance; and (6) the TBR with water coolant in all cases is 5–10% higher than with helium coolant.

The power multiplication results tend to vary in accordance with the TBR results and thus reinforce the above conclusions. There are two notable exceptions; the first is the case of Li_7Pb_2, which, although showing a high effective TBR of 1.22, exhibits a rather low M of 1.18. The other exception is that changes in ^6Li enrichment affect M only slightly in all cases. The overall M is actually decreased due to the decrease of the radiative capture reaction rate in the structure material used in the blanket utilizing highly enriched lithium.

1. Introduction

The primary functions of a fusion reactor blanket are to breed sufficiednt tritium and to maximize the blanket heat deposition per D–T fusion neutron [1]. In this study, TBR (tritium breeding ratio) and M (power multiplication) requirements are used for comparisons and optimizations of a large number of solid breeder candidate materials with respect to their properties and relative behavior under test condition. The Blanket Comparison and Selection Study (BCSS) [2] provided a fairly detailed assessment of various blanket concepts, but did not attempt a specific and consistent comparison among the solid breeder materials in a blanket design contest. In fact, there is a large number of potential solid breeder/multiplier materials with particular features and issues but it would be very expensive to consider all the options in experimental detail. In this study, ten solid breeder materials, six neutron multipliers and two coolants (helium and water) are considered. These breeder and multiplier materials are evaluated in six different design configurations which include homogenized breeder/multiplier mixtures and a separate multiplier zone.

The different solid breeder and neutron multiplier materials considered in this study are listed in table 1. The list includes all solid breeder materials currently seen as potentially attractive candidates. Except for Li_2O and Li_7Pb_2, all other solid breeders are ternary ceramics. Six multipliers are used as the neutron multiplier in combination with these solid breeders, that may require better neutronics performance. For most cases considered here, the multiplier is separate and in front of the breeder. However, for all the separate multiplier cases, a homogeneous mixture of solid breeder and beryllium multiplier is considered to examine the features of this approach. Since Be will chemically reduce the solid breeder material (although the rate might be

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Table 1

Solid breeder materials and cases considered

	Helium coolant				Water coolant	Helium coolant
	Without a multiplier (Case I)	Homogeneous SB/M (Case II)	Homogeneous multi-region (Case III)	With a separate multiplier [c] (Case IV)	With a separate multiplier [c] (Case V)	With a separate multiplier [d] (Case VI)
Li_2O	√	√[a]		√	√	√
Li_2ZrO_3	√	√[b]	√[b]	√		
Li_8ZrO_6	√	√[b]	√[b]	√		
Li_2BeO_3	√					
Li_7Pb_2	√					
$LiAlO_2$		√[a]	√[b]	√	√	√
Li_5AlO_4		√[b]	√[b]	√		
Li_2SiO_3		√[b]	√[b]	√	√	√
Li_4SiO_4		√[b]	√[b]	√		
Li_2TiO_3		√[b]	√[b]	√		

[a] Breeder/Be and Breeder/BeO.

[b] Breeder/Be only.

[c] Multipliers; Be, Pb, PbO, BeO, Zr_5Pb_3, PbBi.

[d] Heterogeneous multiplier case (see fig. 2).

acceptably slow once an initial BeO layer forms), BeO is also included as an alternative for the homogeneous mixture cases with Li_2O and $LiAlO_2$.

The material combination, SB/He/Be/FS, where FS denotes ferritic steel, was generically identified as attractive in the BCSS [2] and other studies. The BCSS $LiAlO_2$/He/Be/FS outboard blanket design is adopted here as a reference blanket configuration. The solid breeder or homogeneous solid breeder/multiplier mixture is in the form of flat plates with a thin HT9 cladding on each side. For cases with a separate multiplier region, an array of multiplier rods is placed in front of the breeder plates. The thickness of the breeder plates is calculated from the nuclear heating rate, the thermal conductivity and the maximum allowable temperature for the material. Since the volume fractions (and, hence, the plate thickness) are required for the nuclear heating rate calculation, a few iterations between the temperature and neutronics calculations are required in each case. The ^{6}Li enrichment, the multiplier region radial thickness for the cases with a separate multiplier region, and the ratio of solid breeder to multiplier volume fraction for the homogeneous mixture cases, are chosen based on optimization of the tritium breeding ratio.

2. Method of analysis

A one-dimensional poloidal cylindrical model (blanket surrounds the plasma) is used for this analysis with a 194 cm and 214 cm for the plasma and the first wall radius, respectively. The neutronics calculations were performed by the one-dimensional S_n code, ANISN [4], using 42 group (30n-12γ) cross-section library based on ENDF/B-V [5] data. The S_8–P_3 approximation was used. All results were normalized to a 5 MW/m^2 neutron wall loading.

The cases considered for analysis are in tables 1–3. Case I, the without multiplier case has two different breeder regions, breeder I and breeder II. Breeder regions I and II have the same materials, but their material volume fractions are different because of the inclusion of the structural elements holding the end walls in region II. For the homogeneous SB/M mixture cases, the breeder materials in region I and II are replaced by the SB/M mixture. The solid breeder and neutron multiplier are at 80% theoretical density. HT9 is used for the shield material and no coolant is included in the shield.

The difference between the homogeneous SB/M mixture, case II, and the homogeneous multi-region SB/M mixture, case III, is that the former case has two breeder regions and the latter case has three breeder regions. Actually the first breeder region of case II, homogeneous SB/M mixture, has been divided into two breeder regions for case III, multi-region SB/M mixture case, and then different volume fractions of solid breeder materials and multiplier materials were applied at the front two regions with no Be in the last region.

As shown in tables 1 and 3, six neutron multiplier materials were considered for the cases with a separate

Table 2

Breeder region thickness and volume fractions for the cases without a multiplier, the homogeneous SB/M mixture case and the homogeneous multi-region SB/M mixture case

	First wall		Blanket I			Blanket II			Plenum		Shield
Cases without a multiplier (Case I)											
Thickness	6 cm		45 cm			12 cm			22 cm		30 cm
	HT9	Helium	HT9	Helium	Breeder [a]	HT9	Helium	Breeder [a]	HT9	Helium	HT9
Li_7Pb_2	11.7%	88.3%	6.07%	7.43%	86.5%	26.7%	4.9%	68.4%	20%	80%	100%
Li_2O	11.7	88.3	7.0	9.3	83.7	14.2	6.28	79.5	20	80	100
Li_8ZrO_6	11.7	88.3	7.6	10.8	81.6	28.2	8.0	63.5	20	80	100
$Li_2Be_2O_3$	11.7	88.3	7.9	11.6	80.5	28.6	9.0	62.4	20	80	100
Li_2ZrO_3	11.7	88.3	7.3	10.2	82.5	27.9	7.7	64.4	20	80	100
Cases with a homogeneous SB/M mixture (Case II)											
			SB/M			SB/M			Plenum		Shield
Thickness	6 cm		45 cm			12 cm			22 cm		30 cm
Li_2O/Be	11.7	88.3	8.2	12.3	79.5	28.9	9.7	61.4	20	80	100
$LiAlO_2$/Be	11.7	88.3	8.3	11.8	79.9	29.0	9.2	61.8	20	80	100
Li_2O/BeO	11.7	88.3	8.1	11.9	80.0	28.7	9.0	62.3	20	80	100
$LiAlO_2$/BeO	11.7	88.3	7.9	11.5	80.6	28.6	8.9	62.5	20	80	100
Breeder [c]/Be	11.7	88.3	8.0	12.0	80.0	29.0	9.0	62.0	20	80	100
Cases with a homogeneous multi-region SB/M mixture case (Case III)											
			Blanket I & Blanket II			Blanket III			Plenum		Shield
Thickness	6 cm		45 cm			12 cm			22 cm		30 cm
Breeder [b]/Be	11.7	88.3	8.0	12.0	80.0	29.0	9.0	62.0	20	80	100

[a] 80% dense.

[b] breeders; $LiAlO_2$, Li_5AlO_4, Li_2SiO_3, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3 and Li_8ZrO_6.

Table 3

Volume fractions for the cases with a separate multiplier region case the heterogeneous multiplier region case and water coolant in a separate multiplier case

	First wall		Multiplier [a]			Blanket			Plenum		Shield
Cases with a separate multiplier (Case IV)											
Thickness	6 cm		12 cm			32 cm			22 cm		
	HT9	Helium	HT9	Helium	Multiplier [b]	HT9	Helium	Breeder [c]	HT9	Helium	HT9
Li_2O	11.7%	88.3%	4.7%	41.3%	54%	14.4%	6.5%	79.1%	20%	80%	100%
Li_8ZrO_6	11.7	88.3	4.7	41.3	54	15.2	8.3	76.5	20	80	100
Li_5AlO_4	11.7	88.3	4.7	41.3	54	16.2	10.3	73.5	20	80	100
Li_2ZrO_3	11.7	88.3	4.7	41.3	54	14.7	7.3	78.0	20	80	100
Li_4SiO_4	11.7	88.3	4.7	41.3	54	15.7	9.3	75.0	20	80	100
Li_2TiO_3	11.7	88.3	4.7	41.3	54	14.2	6.3	79.5	20	80	100
Li_2SiO_3	11.7	88.3	4.7	41.3	54	15.9	9.6	74.5	20	80	100
$LiAlO_2$	11.7	88.3	4.7	41.3	54	14.7	7.3	78.0	20	80	100
Water coolant case (Case V)											
Thickness	0.8 cm		7.18 cm			Thickness [d]			4.0 cm		
	HT9	Water	HT9	Water	Multiplier	HT9	Water	Breeder [d]	HT9	Water	HT9
$LiAlO_2$	95%	5%	4.7%	5%	90.3%	14.7%	5%	80.3%	85%	5%	100%
Li_2O	95	5	4.7	5	90.3	14.7	5	80.3	95	5	100
Li_2SiO_3	95	5	4.7	5	90.3	15.9	5	79.1	95	5	100

[a] Total volume fraction of the heterogeneous cases is exactly the same as the homogeneous cases.

[b] 80% dense.

[c] 80% dense.

[d] Thickness: 31.08, 31.4, 30.14 cm for $LiAlO_2$, Li_2O and Li_2SiO_3.

multiplier region. All the cases except the beryllium multiplier have 35% ^{6}Li enrichment, therefore the comparison for different multipliers of each breeder material were investigated based on the same lithium enrichment, 35%. The multiplier has a 54% volume fraction at 80% theoretical density (TD). The breeder materials are assumed to also have an 80% theoretical density. In addition to the separate multiplier cases with helium coolant, water was considered as coolant for the case V, the water coolant for a separate multiplier case. Owing to the different amount of water coolant used for case V, each zonal volume (radial length in one dimensional arrangement) has been calculated again in order to keep the same atom densities of HT9, multiplier and breeder material.

Based on the homogenized separate multiplier cases, the 12 cm neutron multiplier region in case IV was divided into 12 regions of alternating beryllium and structure layers, for the case VI, the heterogeneous multiplier zone case. The thickness of each multiplier and structure layer was calculated by considering each multiplier's physical properties, melting temperature, thermal conductivities and allowable maximum temperature. Neutron multiplier materials considered for this case were Be, PbBi and Pb and helium was used as a coolant (41.3% in each layer).

3. Tritium breeding ratio (TBR)

In order to optimize the tritium breeding ratio (TBR), TBR values were calculated for each case for ^{6}Li enrichment varying from 7.5% to 90%. In addition, the thickness of the multiplier region was varied from 6 cm to 15 cm for the cases with a separate multiplier, and the volume fraction of breeder in the mixture was varied from 20% to 80% for homogeneous SB/M mixture cases.

For the cases without a multiplier, fusion D–T high energy neutrons enter the solid breeder region directly. The resulting neutron spectrum is harder than for the cases with a separate neutron multiplier. The ^{7}Li(n, n′α)t reaction is significant at high neutron energy. Therefore, as the ^{6}Li enrichment is increased, the tritium production from ^{7}Li is decreased, which tends to have a stronger negative effect on the total tritium production than the corresponding increase in tritium production from ^{6}Li. Note that the higher the initial T_7 (the part of the tritium breeding ratio due to tritium production in ^{7}Li), the sharper the decrease in T_7 as the ^{6}Li enrichment is increased. Fig. 1 shows that Li_2O exhibits the sharpest decline in TBR with increasing ^{6}Li enrichment.

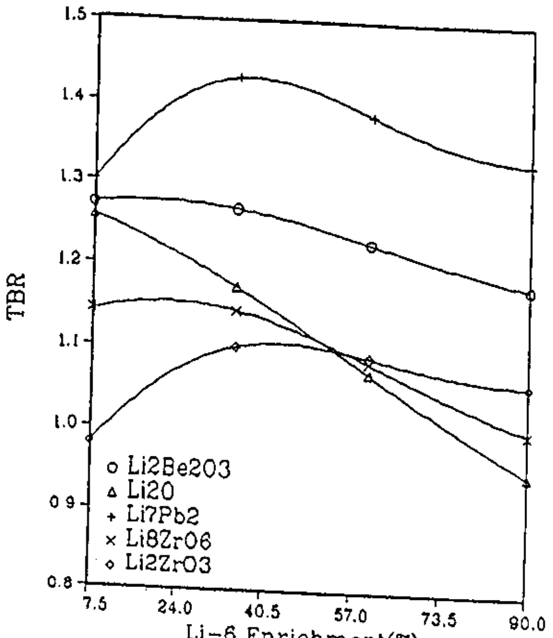

Fig. 1. TBR as a function of ^{6}Li enrichment for the cases without a neutron multiplier.

The Li_7Pb_2 and Li_2ZrO_3 breeders, however, exhibit an increase in TBR first and then a gradual decrease as ^{6}Li enrichment is increased. This is due to the high atom density of Pb and Zr in those breeder materials, and both elements have significant (n, 2n) reactions.

Four cases (Li_2O/Be, Li_2O/BeO, $LiAlO_2$/Be, and $LiAlO_2$/BeO) were considered as homogeneous mixtures of multiplier and breeder materials (Be was considered for other breeding materials). Increasing the breeder volume fraction beyond 20% decreases the TBR in all four cases. As illustrated in fig. 4 (in Section 5), this indicates that only a small amount of breeder material enriched to 60% ^{6}Li is required to achieve maximum tritium production. The Li_2O cases (Li_2O/Be and Li_2O/BeO) have a higher tritium production than the $LiAlO_2$ cases because the lithium atom density of Li_2O is larger than that of $LiAlO_2$. Also, the Be mixtures (Li_2O/Be and $LiAlO_2$/Be) show larger values of TBR than the BeO mixtures (Li_2O/BeO and $LiAlO_2$/BeO) because the atom density of beryllium is 1.7 times larger than that of beryllium oxide. The case with 20% breeder and 80% multiplier was selected as reference for all cases. Notice, however, that higher volume fraction of multiplier is needed only in the first blanket region closest to the first wall; at deeper re-

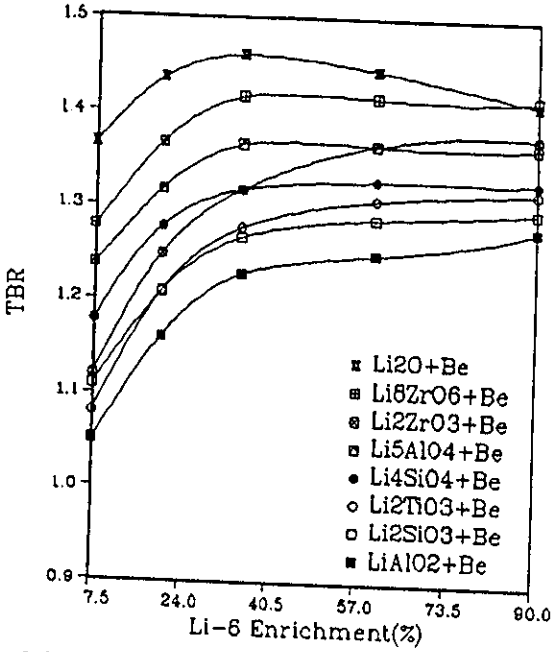

Fig. 2. TBR as a function of ^{6}Li enrichment for the cases with a separate multiplier (12 cm thick).

gions, the multiplier volume fraction can be substantially reduced without significantly affecting the TBR.

For the homogeneous mixture cases, only a slight increase in TBR is observed when the ^{6}Li enrichment is increased, with saturation occurring fairly rapidly. It should be noted that the maximum TBR values for the homogeneous 20/80 mixtures of Li_2O/Be (1.85) and $LiAlO_2$/Be (1.78) are much higher than for the corresponding breeder and separate multiplier cases when ^{6}Li enrichment was varied (1.46 for Li_2O + Be and 1.27 for $LiAlO_2$ + Be and the thickness of the multiplier zone is 12 cm, see fig. 2). Owing to the decrease of beryllium neutron multiplier volume percentage by the increase of the solid breeder volume percentage in the second solid breeder region, proportional decrease in TBR is observed.

For the separate multiplier cases, the fusion D–T neutron must pass through the neutron multiplier region before reaching the solid breeder; the resulting neutron spectrum entering the solid breeder region is much softer than the first wall neutron spectrum which leads to a noticeable reduction in the ^{7}Li (n, n'α)T reactions. However, this soft neutron spectrum increases the reaction with ^{6}Li to produce tritium from the ^{6}Li(n, α)T reaction. The TBR was calculated for different thicknesses of the neutron multiplier and a 60% ^{6}Li enrichment. The general trend is that the TBR increases as the neutron multiplier thickness is increased, until saturation is reached. Note, however, that the thickness of the multiplier region could not extend beyond 12–15 cm due to consideration of maximum allowable temperature for the multiplier. It should be emphasized that the beryllium effective density in the multiplier region corresponds to 43.2% (0.8 × 0.54) of the theoretical density. Optimization of the TBR incremental rate of change with increased Be thickness led to the selection of a 12 cm multiplier zone as a reference thickness for the TBR for all the separate multiplier cases. For a constant 12 cm neutron multiplier, the TBR was then calculated for different values of ^{6}Li enrichment as was shown in fig. 2. It is interesting to note that the "TBR versus Be thickness" and the "TBR versus ^{6}Li enrichment" sets of curves tend to follow the same pattern and that the material ranking is almost the same in both cases for all ^{6}Li enrichments and Be thicknesses (except for Li_2ZrO_3, whose particular behavior will be explained later), with Li_2O exhibiting the highest TBR and $LiAlO_2$ the lowest.

The ranking of the solid breeders in terms of achievable TBR can be explained by their respective Li atom density. It can be observed from fig. 2 that the saturation point, assumed here to correspond to 99% of the maximum TBR in each case, tends to occur at lower ^{6}Li enrichment as the lithium atom density of the material increases. It was shown that the ^{6}Li atom densities at saturation fall between the narrow range of 9×10^{21} cm^3 to 10×10^{21}/cm^3 for all the breeder materials considered, except for the Li_2ZrO_3 case which saturates at a higher ^{6}Li atom density due to its high density. The material with the highest total lithium atom density is Li_2O, which shows saturation in TBR at about 20% ^{6}Li enrichment. Note however that although the ^{6}Li atom density is about the same at saturation (although ^{6}Li enrichment is different) for the various cases, the TBR is different. This is mainly due to the differences in tritium production from ^{7}Li between the different cases and the differences in the neutronics characteristics of non-lithium atoms present (e.g., O, Zr, Si).

Another interesting point noted in fig. 2 is the behavior of Li_2ZrO_3, whose TBR tends to peak earlier than the other cases when varying the Be thickness and later than the other cases when varying the ^{6}Li enrichment. This is due to the high physical mass density of Li_2ZrO_3 (4.15 g/cm^3) and hence, to its relatively high Zr atom density. For the neutron spectra investigated, Zr has a large cross-section for (n, 2n) reactions and, in effect, acts as an additional neutron multiplier, causing the

Table 4

TBR and M for the different neutron multiplier cases [a] with different coolants

Helium coolant cases (Case IV)	Be	Pb	PbBi	Zr_5Pb_3	PbO	BeO
Li_2O	1.45 [b] (1.41) [c]	1.39 (1.20)	1.37 (1.12)	1.32 (1.13)	1.29 (1.20)	1.17 (1.31)
Li_8ZrO_6	1.41 (1.34)	1.35 (1.16)	1.32 (1.11)	1.29 (1.08)	1.25 (1.16)	1.13 (1.24)
Li_5AlO_4	1.37 (1.40)	1.31 (1.18)	1.29 (1.10)	1.24 (1.11)	1.21 (1.19)	1.08 (1.29)
Li_4SiO_4	1.32 (1.39)	1.29 (1.10)	1.25 (1.09)	1.19 (1.10)	1.17 (1.17)	1.05 (1.28)
Li_2ZrO_3	1.32 (1.41)	1.29 (1.11)	1.23 (1.12)	1.19 (1.03)	1.17 (1.11)	1.05 (1.19)
Li_2TiO_3	1.27 (1.40)	1.23 (1.18)	1.21 (1.09)	1.15 (1.10)	1.13 (1.18)	1.02 (1.29)
Li_2SiO_3	1.26 (1.38)	1.23 (1.17)	1.20 (1.08)	1.14 (1.09)	1.12 (1.17)	1.01 (1.27)
$LiAlO_2$	1.21 (1.40)	1.19 (1.19)	1.15 (1.09)	1.13 (1.11)	1.09 (1.19)	0.98 (1.29)
Water coolant cases (Case V)	Be	Pb	PbBi	Zr_5Pb_3	PbO	BeO
Li_2O	1.55 [b] (1.45) [c]	1.44 (1.22)	1.38 (1.14)	1.35 (1.21)	1.32 (1.22)	1.20 (1.33)
Li_2SiO_3	1.37 (1.41)	1.29 (1.16)	1.22 (1.13)	1.21 (1.11)	1.18 (1.18)	1.06 (1.29)
$LiAlO_2$	1.34 (1.43)	1.28 (1.20)	1.20 (1.13)	1.20 (1.19)	1.16 (1.21)	1.04 (1.31)
Helium coolant cases (Case VI)	Be	Pb	PbBi			
Li_2O	1.42 [b] (1.42) [c]	1.40 (1.19)	1.39 (1.11)			
Li_2SiO_3	1.25 (1.38)	1.24 (1.15)	1.23 (1.08)			
$LiAlO_2$	1.20 (1.39)	1.20 (1.16)	1.19 (1.08)			

[a] 35% ^6Li enrichment.

[b] TBR (tritium breeding ratio).

[c] M (power multiplication).

TBR curve to saturate earlier with increasing Be thickness and later with increasing ^6Li enrichment.

Table 4 shows the effect on the TBR of using different neutron multipliers with the different solid breeder blanket regions. Beryllium has the highest capability of breeding among the six neutron multiplier materials. However, BeO exhibits about 80% of tritium breeding capability compared with Be itself, and PbO does about 90% of breeding capability with Pb itself. This is due to the atom density of lead in PbO is higher than that of Beryllium in BeO. As shown in table 4, the effect on the TBR of water coolant in all cases has 5–10% higher TBR than the helium coolant case, but the order of tritium breeding capability is still the same as the helium coolant case. Table 4 also shows that the difference in TBR is less than 3% between the separate, one region multiplier case (Case IV) and the heterogeneous (and more realistic) multiplier case (Case VI).

As a sensitivity analysis for the cases with a separate multiplier, a sandwich-type geometry was considered, in which another breeder zone which is highly enriched in ^6Li is placed in front of the neutron multiplier zone. This geometry provides better TBR performance since the low energy neutrons scattered back from the multiplier region to the first wall are absorbed in the ^6Li in the front breeder zone. It is also probable that this will reduce the (n, γ) reaction (caused by low energy neutrons) in the first wall, which is a strong source of activation, thereby reducing the first wall activation. Two cases were considered, one exhibiting a high TBR (Li_8ZrO_6) and the other a low TBR ($LiAlO_2$). The TBR was calculated for different values of the front breeder region thickness, ranging from 0.2 cm to 4 cm (with a 0.54 volume fraction of 80% dense solid breeder). The back breeder region thickness was adjusted to keep the total breeder thickness the same as before. The effect on the TBR of adding this front layer is similar for both the $LiAlO_2$ and Li_8ZrO_6 cases where an increase in the TBR occurred. This tends to indicate that such a change of geometry will similarly increase the TBR for all the candidate materials. To maximize the TBR, the thickness of this layer should not exceed the mean free path of the high energy neutrons that contribute to the (n, 2n) reaction in the multiplier zone. Beyond a certain thickness of the first breeder region, the TBR starts to decrease.

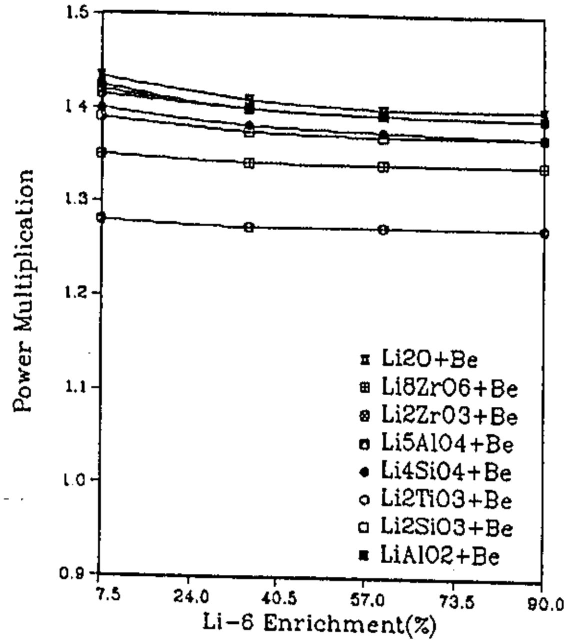

Fig. 3. Power multiplication as a function of ^{6}Li enrichment for the cases with a separate multiplier.

4. Power multiplication and heat generation

Fig. 3 shows the variation of power multiplication (M) with ^{6}Li enrichment for the cases with a separate multiplier region. Changes in the ^{6}Li enrichment only slightly affect M in all cases. This feature was also found for the cases without a multiplier. When the ^{6}Li enrichment is increased, M in the breeder region increases due to the exothermic ^{6}Li(n, α) reaction. However, the radiative capture reaction rate in the structure, which has a larger Q value than that of ^{6}Li(n,α), decreases. Therefore, the overall M is actually slightly decreased. However, M increases as the Be region thickness is increased due to the increase in secondary neutron production from beryllium neutron multiplier region. In agreement with these results, M, for the homogeneous breeder/multiplier mixture cases, decreases proportionally with increasing breeder volume fraction and shows a slight decrease with increasing ^{6}Li enrichment. Also, table 4 shows the variation of power multiplication (M) with different multipliers, water coolants, and heterogeneous neutron multipliers. The effect on the power multiplication of water coolant is that all cases have 2–4% higher M than the helium coolant case. Also, the effect of the heterogeneous multiplier design was very small even though the peak heating could be lower in value than the homogeneous cases. For the $LiAlO_2$ and Li_8ZrO_6 sandwich cases, M decreases with an increase in the front breeder region thickness as the number of fast neutrons reaching the multiplier is reduced. Note that for all the cases, the relative M rankings tend to remain the same for all values of ^{6}Li enrichment and of Be volume fraction.

5. Summary

Because of the importance of achieving tritium self-sufficiency in the D–T fuel cycle, the TBR is the major neutronics criterion, followed by power multiplication, which is the basic power parameter.

It is important to stress the difference between the 1-D neutronics calculations performed in this study and more accurate 3-D neutronics calculations. The 1-D calculations typically overestimate the actual TBR by about 15–20% because of the assumptions of full coverage, fully homogeneous regions, and equal inboard and outboard blanket thickness. Consequently, the 1-D results were reduced by 15% to obtain *effective* TBR values in fig. 4, which shows a bar chart of the optimum effective TBR (assumed to be 99% of the maximum effective TBR value) for the different solid breeder cases. To satisfy the tritium self-sufficiency criterion within the given uncertainties, the effective TBR can be ranked in the categories shown in Table 5.

From fig. 4, and based on the above criteria, all the without-multiplier cases except Li_2O and Li_7Pb_2, and all the BeO and PbO multiplier cases except Li_2O are rejected. The unmultiplied $Li_2Be_2O_3$ case, the separate multiplier cases with $LiAlO_2$, the homogeneous $LiAlO_2$/BeO mixture case, all the Zr_5Pb_3 multiplier cases, except Li_2O, all the PbBi and Pb cases except Li_5AlO_4, Li_8ZrO_6 and Li_2O are in the high risk category. The separate beryllium multiplier cases with Li_2SiO_3, Li_2TiO_3, Li_4SiO_4, Li_5AlO_4, Li_2ZrO_3, the separate Pb multiplier cases with Li_5AlO_4, Li_8ZrO_6 and Li_2ZrO_3, the separate PbBi with Li_5AlO_4, Li_8ZrO_6 and Li_2O, the separate PbO or Zr_5Pb_3 with Li_2O, and the homogeneous Li_2O/BeO mixture case are in the medium risk category. Finally, the Li_7Pb_2 case without

Table 5

Effective TBR	Calculated TBR (1-D)	Response
< 1.05	< 1.24	rejected
1.05–1.10	1.24–1.29	high risk
1.10–1.20	1.29–1.41	medium risk
> 1.20	> 1.40	low risk

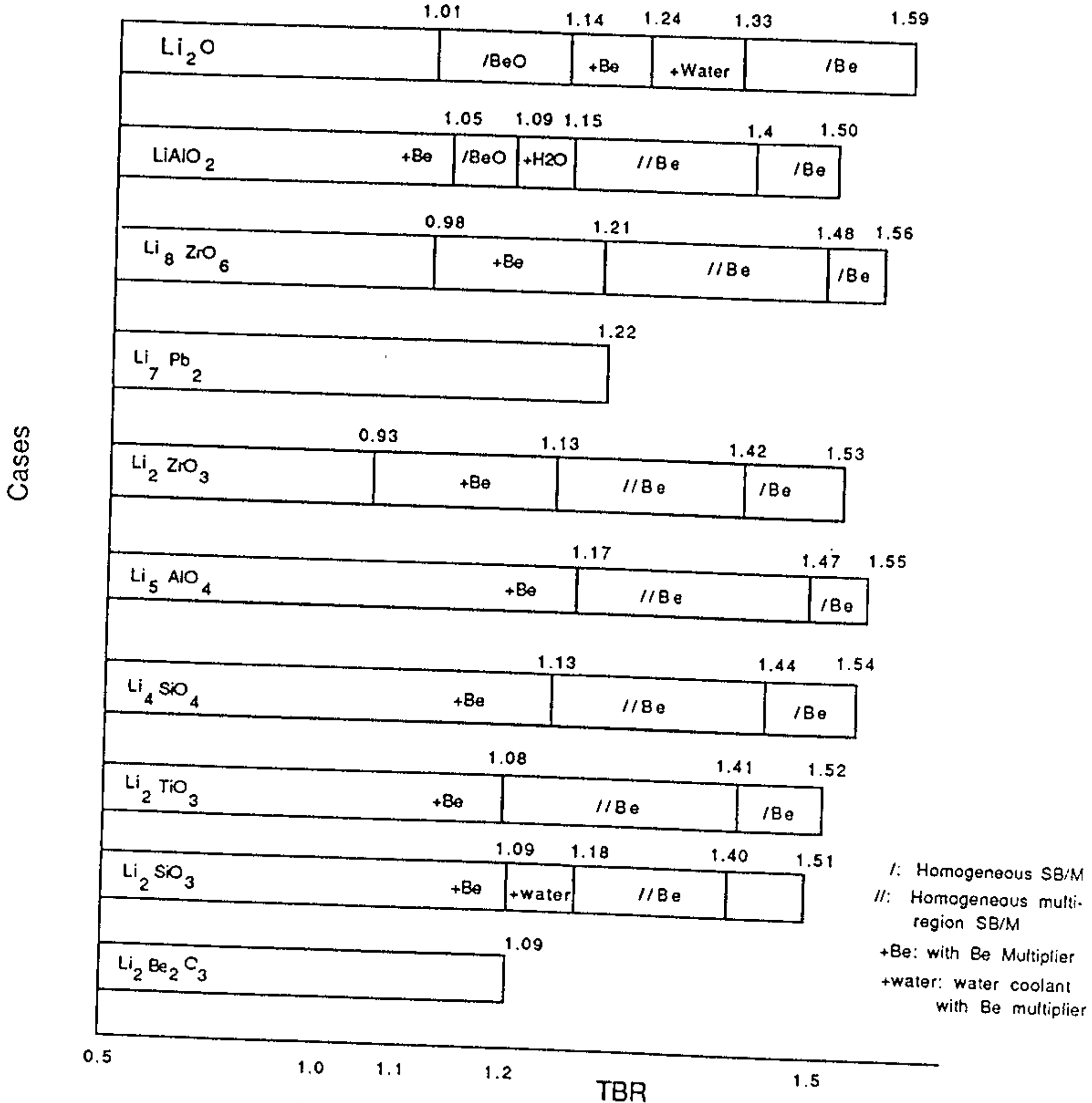

Fig. 4. Effective TBR for the different cases considered.

a beryllium multiplier, the separate beryllium multiplier cases with Li_8ZrO_6 and Li_2O, the separate Pb multiplier with Li_2O, all the homogeneous multi-region SB/M cases, and the homogeneous $LiAlO_2$/Be and the Li_2O/Be cases are in the low-risk category.

Since the homogeneous $LiAlO_2$/Be case is acceptable, it is anticipated that all homogeneous mixtures of ternary ceramics (which usually have higher Li atom densities than $LiAlO_2$) with beryllium would be acceptable from a TBR consideration.

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