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The Breeding Potential Of “Flinabe” And Comparison To “Flibe” In “CLiFF” High Power Density Concept

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ABSTRACT

Because of its low melting temperature (240^{o}C) and low vapor pressure, the molten salt LiF-NaF-BeF$_2$ (Flinabe) with ratio 1:1:1 has been suggested as the front flowing liquid layer, FFLL (2-cm thick) in the CLiFF high power density concept (7 MW/m^2 average neutron wall load, 10 MW/m^2 max.). However, because of its lower Li concentration relative to LiF-BeF$_2$ (Flibe, with ratio 2:1), its deployment as a breeder has been a concern. In this paper, we compare the local tritium breeding ratio (TBR) of Flinabe to Flibe in two arrangements: (1) as a FFLL and breeder in the blanket, and (2) as only the FFLL with LiPb/SiC conventional blanket following the FW. The impact of the choice of ferritic steel (FS) and SiC as the structural material on TBR was also examined. In addition, the paper discusses what constitutes a reasonable value for local TBR if all sources of uncertainties in the achievable and the required TBR are considered (e.g. modeling, nuclear data, burn up rate in the plasma, etc.)

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1. INTRODUCTION

Liquid Walls (LW) have been proposed as a means for protection of solid wall structural material from radiation damage in fusion reactors [1-4]. In the APEX study [5-7], LW concepts are under development for high power density application (neutron wall loads ~10 MW/m^2, surface heat flux ~2 MW/m^2). Although liquid walls have the potential for increasing the lifetime [8] of the structure located behind them by virtue of lowering the level of radiation damage in solid FW/Blanket system, there are several engineering issues that need to be resolved before LW concepts can be realized in fusion power plants. Among these issues are free liquid surface flow and its control, heat transfer characteristics in turbulent open flow, impact of magnetohydrodynamics (MHD) on the flowing conducting liquids, flow around and past penetrations, etc. [9-13]. Both thin (~2-4 cm) and thick (~40-50 cm) LW concepts are under investigation in APEX study [7,14-19]. More focus is currently directed toward thin LW concepts.

In the Convective Liquid Flow First Wall (CLiFF) concept, a thin liquid layer (2 cm) flows poloidally from the top in front of a solid wall. Several candidate liquids have been considered such as lithium, Flibe (Li_2BeF_4), Sn-Li (75:25), and Sn. The first three candidates are used as a front flowing liquid layer (FFLL) as well as breeder/coolant. For the latter (Sn), a conventional blanket such as LiPb/SiC or Flibe/SiC is placed behind the solid FW that is protected by the FFLL [8]. The choice of the structural material depends on the type of liquid wall and breeder and several combinations have been considered [19]. The key issue in this concept is the choice of the FFLL that should have a low vapor pressure (to lessen plasma contamination) and a low melting temperature to allow the blanket to operate at a wider temperature window for a favorable plant thermal efficiency.

The molten salt LiF-NaF-BeF$_2$ (Flinabe) with ratio 1:1:1 has been shown to have the above mentioned characteristics [20]. Flinabe has a low melting point of 240^{o}C [20]. This salt was originally considered for molten salt fission reactors but received less attention due to its poor neutron economy. It was also considered for other fusion applications [21] but its poor tritium breeding capability draw away the attention of research to other breeders with high potential for tritium breeding. In addition, the presence of sodium makes its activation in fusion environment a concern.

We show in this paper that Flinabe can indeed breed enough tritium and could meet tritium self-sufficiency condition when a neutron multiplier is used. With low melting point, low vapor pressure and the ability to breed enough tritium, Flinabe could be the best choice to deployment as a flowing liquid wall.

In Section 2, we discuss the breeding capability of Flinabe relative to other breeders without a multiplier. Comparison is made in particular to Flibe, which also has a comparable vapor pressure. In this regard, two arrangements are considered: (1) Flinabe as a FFLL and breeder in the blanket (90% breeder, 10% structure), and (2) as only the FFLL with LiPb/SiC conventional blanket following the FW. The impact of the choice of ferritic steel (FS) and SiC as the structural material on TBR was also examined. In Section 3 we briefly discuss the adequate values for tritium breeding ratio (TBR) such that tritium production is self-sustained in the D-T fuel cycle when all possible sources of uncertainties are considered. Conclusions from present work are given in Section 4.

2. FLINABE AND FLIBE BREEDING POTENTIAL IN CLIFF CONCEPT

A. Breeding without presence of structure or multiplier

We compared in Fig. 1 the TBR for Flinabe to other breeding materials in a blanket of 2 m-thickness without any structure or multiplier. Some of the breeders have different Li-6 enrichment to demonstrate its impact on local TBR. Also shown is the power multiplication, M, associated with each TBR value. This multiplication factor is defined as the ratio of total power generated in the blanket from neutrons and gamma rays energy deposition to the neutron power (14 MeV) incident on the FW. As shown, the TBR in Flinabe (natural Li) and its M are the lowest (TBR~1.1, M~1.15) among all breeders considered (including Flibe). Clearly TBR will decrease even further upon the inclusion of any amount of structure and penetrations. Natural lithium has the largest local TBR (1.85) as expected since it has the largest Li atomic density.

B. CLiFF configuration

The radial build of the CLiFF design concept is shown in Table I. One-dimensional model was used in the present analysis where both the inboard (IB) and outboard (OB) are accounted for in the geometrical model. The ANISN 1-D [22] code was used along with multigroup data based on the FENDL-2 library [23]. The plasma and FW radii are those used in the ARIES-RS design [24]. The FFLL is 2 cm-thick followed by 0.5 cm-thick solid FW and 60 cm-thick blanket on the OB side (40 cm-thick on the IB side). The vacuum vessel, shield and magnets are considered in the calculational model to account for neutron economy. The blanket consists of 90% breeder/coolant and 10% structure. The shield is composed of 95% structure and 5% breeder/coolant. Tritium breeding takes place in both the blanket and shield.

C. Tritium Breeding Without Beryllium

Figure 2 shows the attainable local TBR as a function of Li-6 enrichment when ferritic steel is used as the solid FW and structural material in the blanket and shield. The Flibe used has the composition LiF:BF_2 with ratio 2:1. When Flinabe is used as the FFLL and breeder/coolant, the attainable TBR is less than Flibe by ~ 15% (at natural Li) and by ~6% (at 90%Li-6). The TBR with Flinabe is less than 1.05 at all Li-6 enrichments. It is clear, therefore, that a neutron multiplier is needed to enhance the TBR with Flinabe. This is also true for Flibe whose maximum attainable TBR in this case is ~1.16 (at ~25%Li-6). One notes from Fig. 2 that TBR in Flibe maximizes at 25%Li-6 enrichment whereas it maximizes at ~50%Li-6 in the Flinabe case.

Figure 3 gives the values of local TBR as a function of Li-6 enrichment when SiC is used as the solid FW and structure in the FW/blanket/shield system. The TBR with Flinabe is also lower than those values found with the Flibe and the difference is comparable to the case with FS structure. Namely, the TBR is lower by ~13% (at natural Li) and by ~6% (at 90%Li-6). However, the features of TBR dependence on Li-6 is different than with the ferritic steel structure. The TBR in Flibe maximizes at natural Li while it maximizes at ~25%Li-6 in the Flinabe case. More importantly, the TBR with Flinabe in this case is always less than unity at all Li-6 enrichment. The use of beryllium multiplier is inevitable. Note from Figs. 2 and 3 that local TBR values with SiC structure are always less than with the ferritic steel by ~2-8% (Flibe) and by ~3-8%(Flinabe). This is due to the fact that some neutron multiplication through (n,2n) reactions take place in the constituents of ferritic steel (e.g. Fe, Cr, etc.) whereas no multiplication occurs in SiC.

D. Tritium Breeding With Beryllium

Significant increase in local TBR is achieved upon including a neutron multiplier zone in the blanket. This is shown in Fig. 4 where local TBR is calculated as a function of the thickness of the front beryllium zone. This zone consists of 60%Be, 30%breeder, and 10% structure. The results shown in Fig. 4 for Flinabe and Flibe are based on the values of Li-6 enrichment for which TBR reaches its maximum value (in the absence of Be) when either ferritic steel or SiC is used as structure.

For the same beryllium zone thickness, TBR in Flinabe is less than in Flibe by ~4-7% in the FS structure case and by~5-9% in the SiC case. To achieve the same TBR in Flibe, additional 3-4 cm of beryllium zone is needed with Flinabe (for both structures). For example, to achieve a TBR of 1.4, the required beryllium zone thickness $\Delta(Be)$, is shown in Table II. Note from the Table that replacing steel with SiC requires increasing the Be zone thickness by ~ 1 cm in order to achieve the same TBR. Since beryllium occupies ~60% of the multiplier zone, the effective beryllium thickness, $\Delta_e(Be)$, is less as shown in Table II.

E. Effect of the Front Flowing Liquid Layer (FFLL) on TBR with Conventional Blanket

Another design option is to use Flibe or Flinabe as a FFLL while a conventional Li-Pb/SiC blanket is placed behind the 0.5 cm-thick SiC solid wall. We compared the potential for tritium breeding in this configuration with Flibe and Flinabe as FFLL.

Figure 5 depicts the variation in local TBR with Li-6 enrichment in the conventional Li-Pb/SiC blanket. For comparison, TBR for the cases where no FFLL is used (bare wall) and when Sn is used as a FFLL are also shown in Fig. 5. As expected, the inclusion of any liquid layer in front of the Li-Pb/SiC blanket tends to decrease TBR. The maximum attainable TBR is obtained in the bare wall case with 90%Li-6 enrichment. Neither Flibe nor Flinabe can reach this maximum value even when lithium in Li-Pb is enriched to 90%Li-6. However, using Sn as the FFLL has the least impact on TBR when the Li in Li-Pb is enriched to 90% Li-6. Also, the local TBR with Flinabe layer is less than with Flibe layer by ~3% at any level of Li-6 enrichment in Li-Pb. However, one can see from Fig. 5 that a local TBR of 1.4 can be attained with Flinabe when lithium in the conventional Li-Pb/SiC blanket has an enrichment of ~35%Li-6 or higher (~20%Li-6 with Flibe). Thus, tritium self-sufficiency is not a concern with Flinabe used as the FFLL as long as Li-Pb is highly enriched.

The advantage of this Flinabe/Li-Pb/SiC concept is the elimination of the need to use beryllium as a multiplier, as is the case with Flinabe/SiC (or Flinabe/FS) concept discussed earlier. However, using two types of liquid coolant may lead to complexity in the blanket design, large liquid waste, complex HX, tritium extraction and cleanup systems.

3. DEFINITION OF ADEQUATE TRITIUM BREEDING

A local TBR of 1.4 was chosen in previous Sections as a minimum value for which tritium self-sufficiency is not to be considered as a feasibility issue. In this Section, we justify this choice. The achievable TBR for a given FW/blanket concept is uncertain due to the uncertainty associated with the system definition (presence of divertor region, penetrations, etc) and the uncertainties in the prediction of the TBR. The latter includes the uncertainty associated with the geometrical modeling, calculation methods, and basic nuclear data. On the other hand, the required TBR must exceed unity by a margin that accounts for tritium losses and radioactive decay, tritium inventory in the plant components, supplying inventory for startup of other fusion plants etc. The main design factors affecting the required TBR are the doubling time, fraction of plasma burn-up, days of tritium reserves, residence time in plasma exhaust processing system. To attain tritium self-sufficiency, the calculated achievable TBR should be larger than the required TBR by enough margins to cover all uncertainties, tritium losses, doubling time, etc. In the following, assessment of the uncertainties involved in tokamaks (with solid breeders) is given based on published literature [25-27].

Achievable TBR (uncertainties):

1. Cross section data: 3-8%
2. Data processing: 4% (multi-group, MG), 2% (Monte Carlo, MC, point data)
3. Homogenization: 2-3%
4. Statistical errors in calculation: 2-3% (MG) , 1% (MC point data)
5. 1-D Vs. 3-D: ~4% (with adjustment to 1-D results)

: ~20% (without adjustment for penetrations and blanket coverage)

Sub-total uncertainties: 7-12% (MG), 6-10% (MC)

Sub-total uncertainties (worst): ~22% (without adjustment to 1-D results)

Required TBR (uncertainties)

1. Doubling time (5 years): 1%
2. Burn-up fraction of 5%: 4%
3. Days of tritium reserves (2 d): ~1%
4. Extraction inefficiency in plasma exhaust processing of 0.001: ~2%
5. Residence time in plasma exhaust processing (1d): ~1%
6. Blanket residence time (10 d): ~1%
7. Other parameters of fuel cycle: ~1.2%

Sub-total uncertainties: ~5% (Note: these uncertainties are design-dependent)

From the uncertainties listed above, the total uncertainty in TBR (square root of the squares sum) is 9-13% when MG method/data is used and ~8-11% when MC method/data is used. The worst uncertainty is obtained when no adjustment is made to 1-D results. In this case, the uncertainty in TBR is ~23%. Typical values for the required TBR in conventional solid breeder blankets range from 1.09-1.12 [25]. Notice that these values are design dependent. When using the maximum value of 1.12 as a reference, and accounting for the above cited overall uncertainties, we get:

1. Local TBR should be at least 1.35 when 1-D results are used with no adjustment)
2. Local TBR should be at least 1.25 when using MG method/data
3. Local TBR should be at least 1.23 when using MC method/data.

As was shown, TBR values larger than 1.35 (worst case given above) could be realized with Flinabe. To be noted that uncertainties (negative) that lead to reduction in TBR are considered in order to estimate a conservative minimum bound to the local TBR. If the uncertainties lead to increasing the TBR, design modifications such as reducing Be zone thickness and decreasing Li-6 enrichment can be made to avoid producing excessive tritium.

4. CONCLUSIONS

The molten salt LiF-NaF-BeF_2 (Flinabe) with ratio 1:1:1 has been suggested as the front flowing liquid layer, FFLL in the CLiFF high power density concept. Flinabe has intrinsic properties that favor its use as the FFLL. The concern raised with regard to its potential for tritium breeding has been examined in this paper and comparison was made to the Flibe (LiF:BeF_2, with ratio 2:1) in two arrangements: (1) as a FFLL and breeder in the blanket, and (2) as only the FFLL with LiPb/SiC conventional blanket following the FW. Two types of structure were also considered, ferritic steel (FS) and SiC.

In the first configuration and with FS structure, the local TBR in Flinabe is less than in Flibe by ~15% and by ~9% at natural Li and 90% Li-6 enrichment, respectively. The TBR maximizes at 50% Li-6 (Flinabe) and at 25% Li-6 (Flibe) with values ~1.04 and ~1.16, respectively. Using SiC as the structure material reduced TBR even further (~8%). A front beryllium multiplier must be introduced in the blanket for both breeders. Significant improvement in TBR is achieved with the Be zone. To achieve a TBR of 1.4, the required Be zone thickness is ~6 cm (Flibe) and ~10 cm (Flinabe) with SiC. This is equivalent to an effective thickness ~4 cm (Flibe) and ~6 cm (Flinabe) of solid Be zone. If a conventional LiPb/SiC blanket is employed, the local TBR with Flinabe FFLL is less than Flibe by ~3%. With this 2-cm thick layer, tritium self-sufficiency (TBR~1.4) can be achieved with LiPb enriched to ~35% Li-6 or higher. Thus, tritium self-sufficiency is not a feasibility issue for Flinabe if used as a FFLL and breeder (with Be multiplier) or as a FFLL only with enriched LiPb blanket. This was shown to be the case when account is made to all sources of uncertainties in the achievable and required TBR.

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FIGURES CAPTIONS

Fig. 1: Local Tritium Breeding Ratio (TBR) and Power Multiplication (M), in a 2-m Thick Blanket with no structure or Multiplier

Fig. 2: Local Tritium Breeding Ratio (TBR) in CLiFF concept as a Function of Li-6 Enrichment (Ferritic Steel Structure).

Fig. 3: Local Tritium Breeding Ratio (TBR) in CLiFF concept as a Function of Li-6 Enrichment (SiC Structure).

Fig. 4: Enhancement of Tritium Breeding Ratio (TBR) with increasing the thickness of the Beryllium Multiplier Zone.

Fig. 5: Impact of the Inclusion of Liquid Layer in Front of Solid Wall on Local TBR in the Conventional LiPb/SiC Blanket.

TABLE I
RADIAL BUILD OF THE CLiFF CONFIGURATION

Onboard Side		**Outboard Side**	
Zone	Inner Radius	Zone	Inner Radius
Central Solenoid	13.6	Plasma	437
Inner Casing[1]	91.7	SOL	687
Winding Pack[9]	101.8	Liquid FW[8]	690
Outer casing[1]	199.88	Solid FW[7]	692
Gap	209	Blanket[6]	692.5
V.V. Inner Wall[2]	289	HT- Shield[5]	752
V.V. [3]	291	Gap	782.5
V.V. Outer Wall[2]	307	LT-Shield[4]	784.5
Gap	309	Gap	815
LT-Shield[4]	314	V.V. Inner Wall[2]	825
Gap	342	V.V. [3]	827
HT- Shield[5]	344	V.V. Outer Wall[2]	853
Blanket[6]	372	Gap	855
Solid FW[7]	411.5	Inner Casing[1]	875
Liquid FW[8]	412	Winding Pack[9]	893
SOL	414	Outer Casing[1]	992.5
Outer Radius			1012.5

*(1) 100% SS316 LN (2) 100% Ferritic Steel (**3**) 81% SS316, 19% water **(4)** Low-Temperature shield: 95% Structure, 5% Coolant/Breeder (5) High-Temperature shield: 95% Structure, 5% Coolant/Breeder (6) 90% Breeder/Coolant, 10% Structure. When a multiplier is used, the first 10 cm consists of 60% Be, 30% breeder, and 10% Structure (7) 100% Structure (8) Liquid Breeder (9) 18% epoxy, 19% Cu, 3% Nb-Sn, 17% Liquid He-4, 43% SS316 LW*

TABLE II

THE REQUIRED [$\Delta(Be)$] AND EFFECTIVE, [$\Delta_e(Be)$] THICKNESS OF THE BERYLLIUM ZONE TO ACHIEVE LOCAL TBR OF 1.4

Structure Type	Flibe		Flinabe	
	$\Delta(Be)$	$\Delta_e(Be)$	$\Delta(Be)$	$\Delta_e(Be)$
Ferritic Steel	~5.5	~3.3	~9.5	~5.7
SiC	~6.5	~3.9	~10.5	~6.3

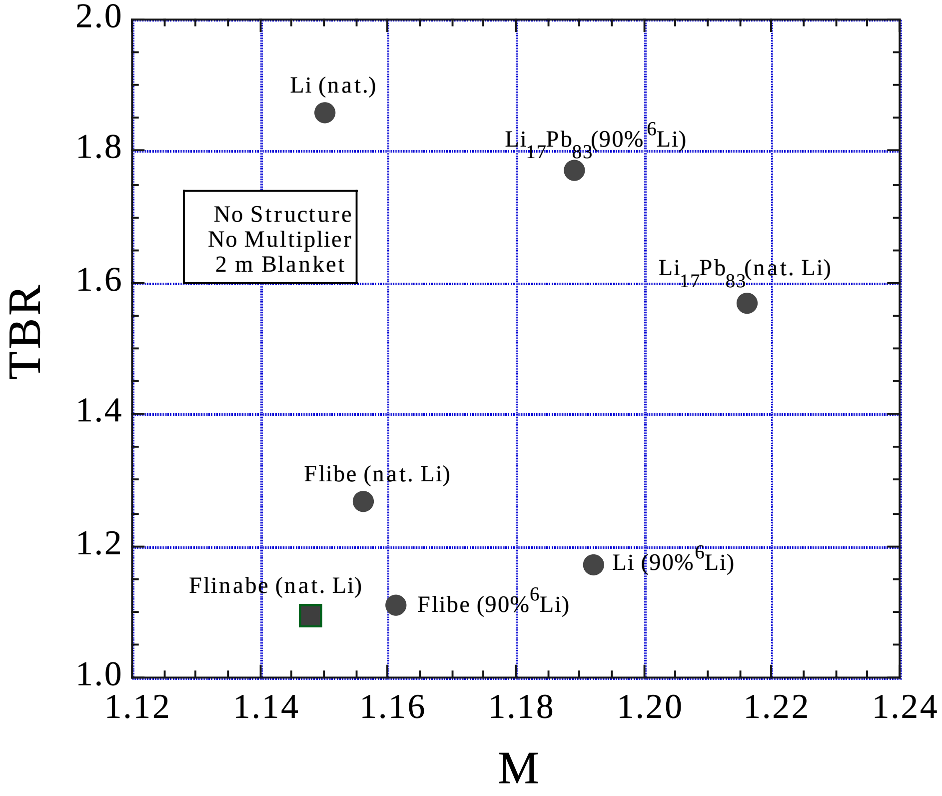

Fig. 1: Local Tritium Breeding Ratio (TBR) and Power Multiplication (M), in a 2-m Thick Blanket with no structure or Multiplier

Manuscript#273-Youssef-Fig. 2

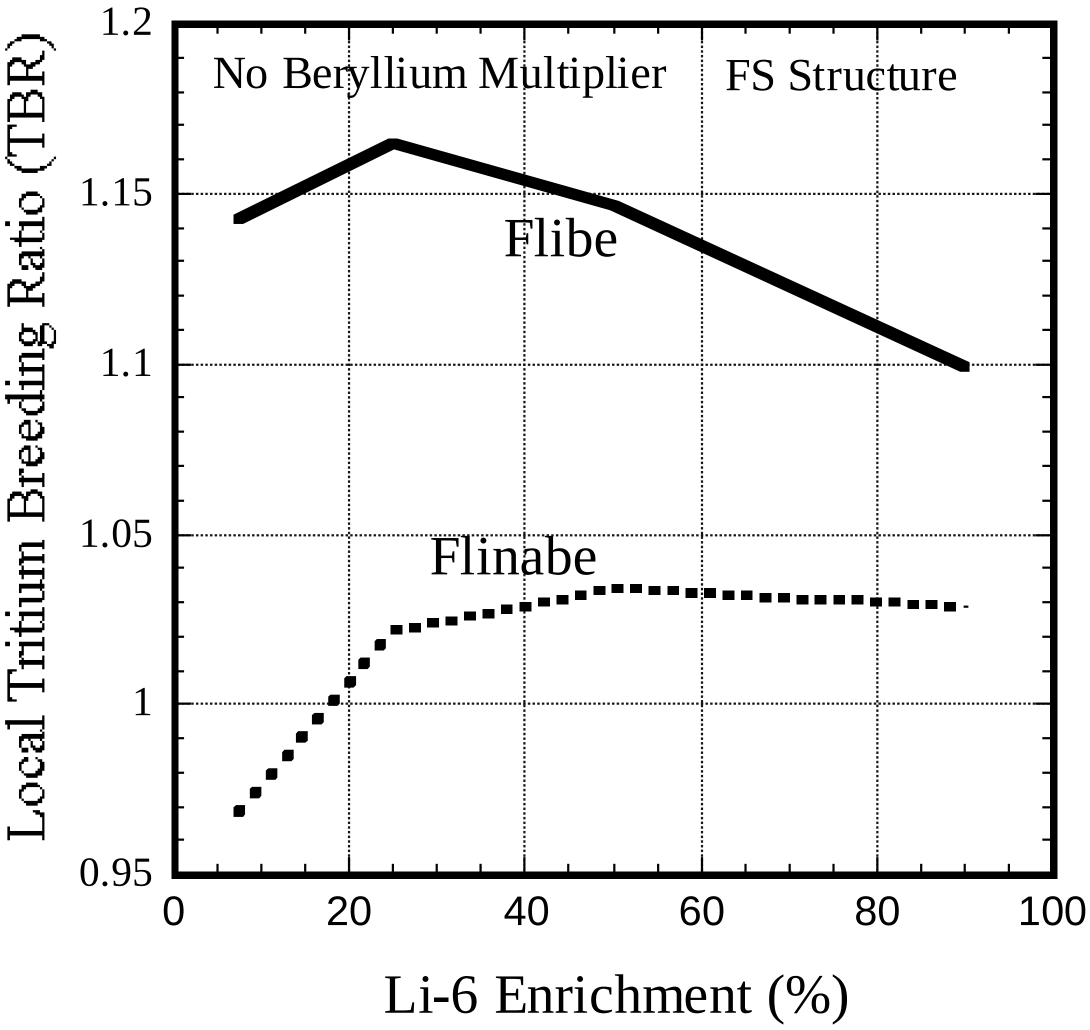

Fig. 2: Local Tritium Breeding Ratio (TBR) in CLiFF concept as a Function of Li-6 Enrichment (Ferritic Steel Structure).

Manuscript#273_Youssef-Fig. 3

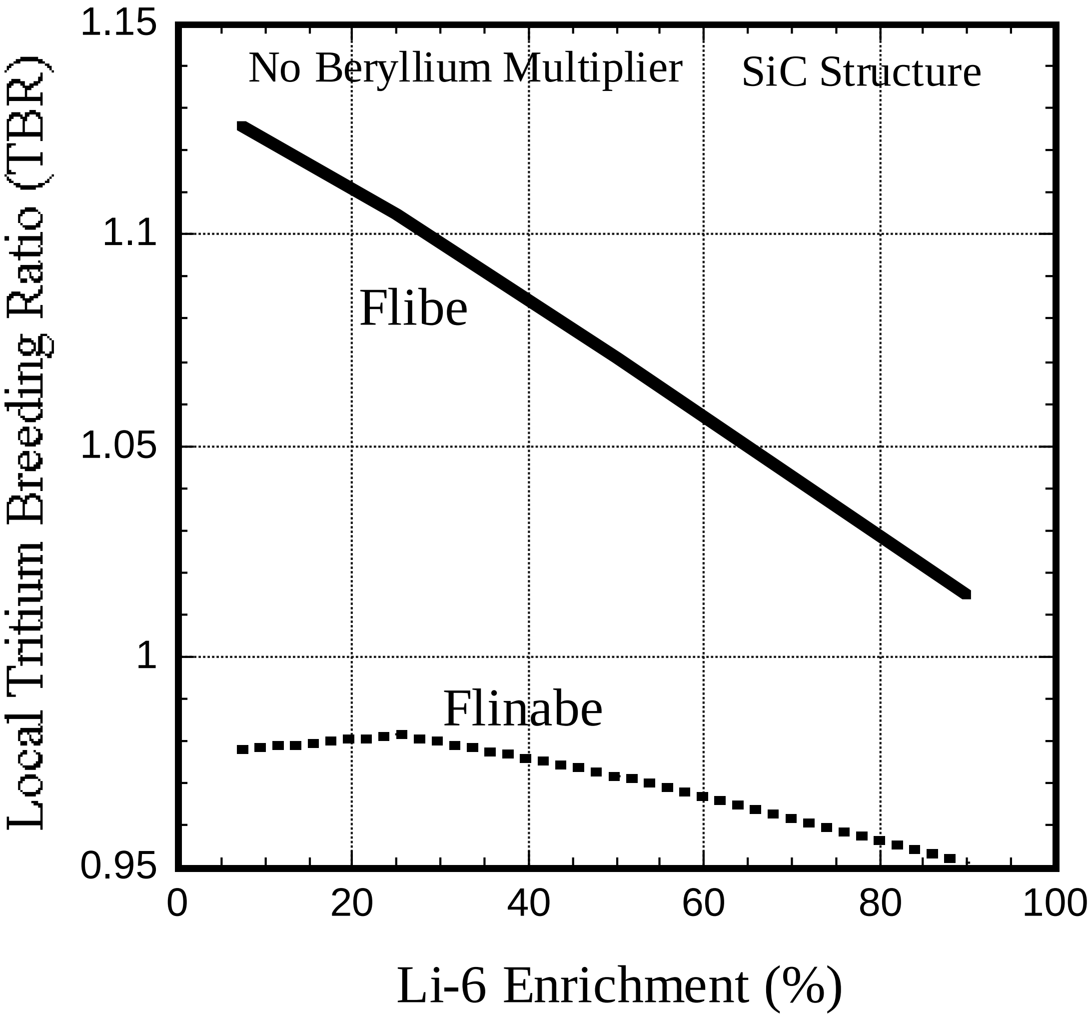

Fig. 3: Local Tritium Breeding Ratio (TBR) in CLiFF concept as a Function of Li-6 Enrichment (SiC Structure).

Manuscript #273-Youssef-Fig. 4

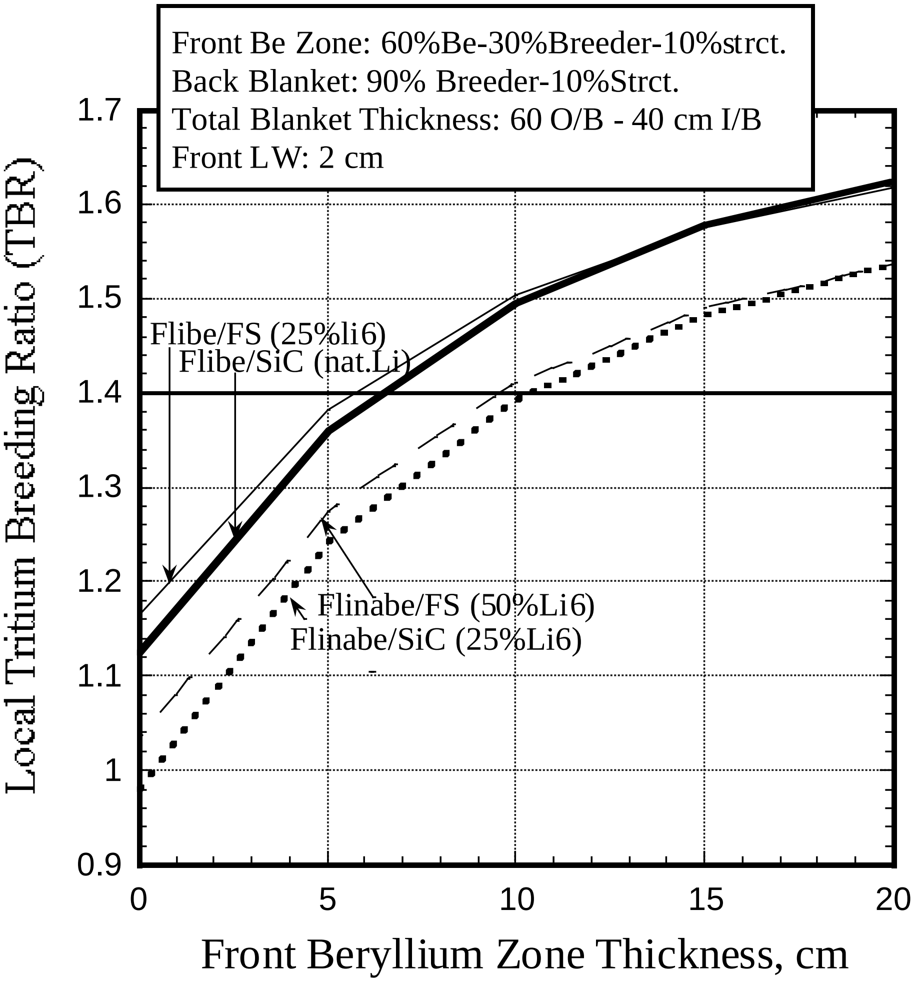

Fig. 4: Enhancement of Tritium Breeding Ratio (TBR) with increasing the thickness of the Beryllium Multiplier Zone.

Manuscript#273-Youssef-Fig. 5

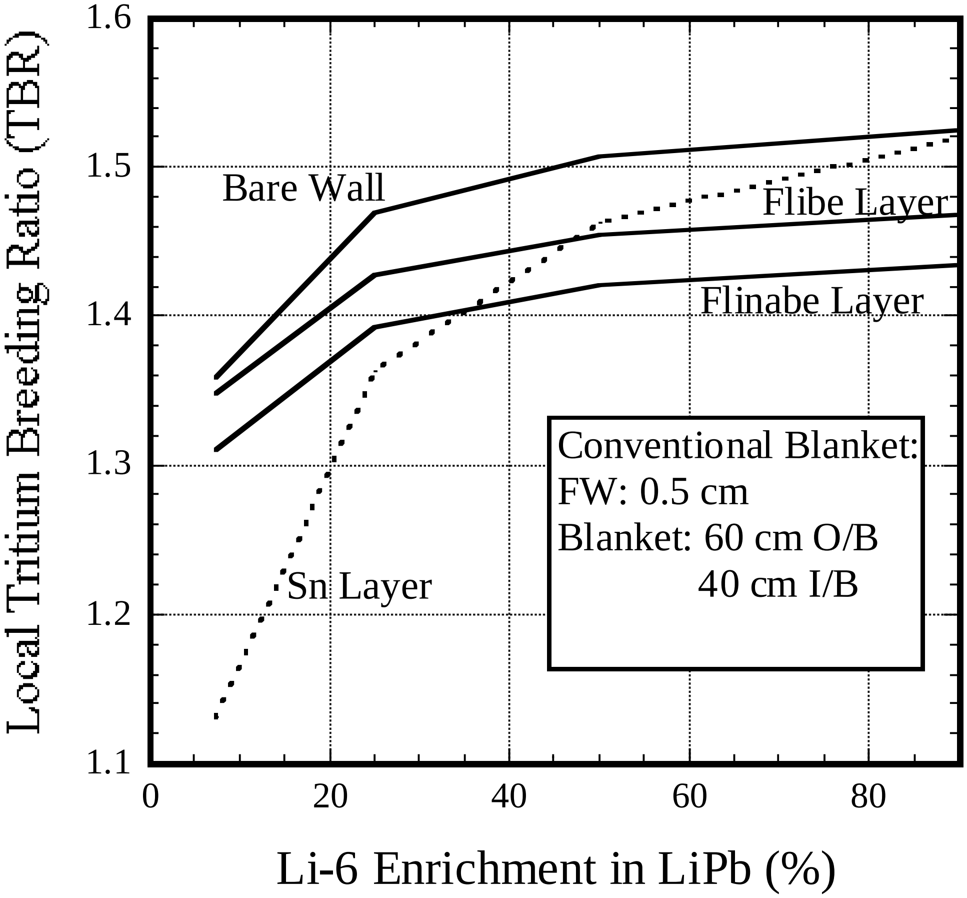

Fig. 5: Impact of the Inclusion of Liquid Layer in Front of Solid Wall on Local TBR in the Conventional LiPb/SiC Blanket.