NUCLEAR PERFORMANCE OF THE THIN-LIQUID FW CONCEPT OF THE CLiFF DESIGN

Mahmoud Z. Youssef
43-133 Engr. IV Bldg.
School of Engineering and Applied Science
University of California-Los Angeles, UCLA
(310) 825-2879

Neil B. Morley
43-133 Engr. IV Bldg.
School of Engineering and Applied Science
University of California-Los Angeles, UCLA
(310) 206-1230

Dai-Kai Sze
Argonne National Laboratory,
ANL

ABSTRACT

The nuclear performance of the thin Convective Liquid Flow First Wall (CLiFF) concept is investigated. Liquid walls offer the advantage of protecting solid structure behind them from excessive damage from neutrons originated in the plasma and thus have the capability for high power density applications; the central research focus of the Advanced Power Extraction (APEX) study. In the present parametric and scoping work, several combinations of liquid breeder and structure type where investigated. The aim is to maximize local tritium breeding ratio (TBR), power multiplication, and ensuring that the vacuum vessel and toroidal coils are protected from excessive radiation. The candidate liquid breeders considered are Li, Flibe, and Sn-Li. Vanadium-alloy is deployed with Li while either Ferritic steel or SiC is deployed with Flibe and Sn-Li. Deployment of other refractory alloys and their impact on TBR was also studied. The introduction of a beryllium multiplier zone in the blanket was shown to enhance tritium production capability, particularly for those liquid breeders whose TBRs are marginal.

I. INTRODUCTION

Liquid walls (LW) concepts are the main focus of the APEX study.[1-2] The study aims at developing concepts that have the capability for a high neutron wall load and associated surface heat flux (>10 MW/m^2, >2 MW/m^2). Thin and thick LW concepts have different characteristics and offer several advantages for high power density application. Liquid-protected solid walls have been previously investigated.[3-7] The liquid layer copes with the high surface and neutron wall load and protects the blanket from excessive radiation damage. Because the liquid layer has low-atomic number, heat load from X-rays can deposit its energy over a measurable depth in the layer[8] and thereby reduce the surface temperature. The candidate liquid breeders considered are lithium, Flibe (Li_2BeF_4), and Sn-Li (75:25). The Gravity and Momentum Driven (GMD) thick LW concept has previously been discussed.[2,9-10] In the Convective Liquid Flow First Wall (CLiFF) concept, a thin liquid layer (3-4 cm) flows poloidally from the top in front of a solid wall.

In the present work we calculate the tritium production and heating rate profiles in CliFF design with the combination of Breeder/Structure Li/(V-4Cr-4Ti), Flibe/Ferritic Steel (FS), and Sn-Li/FS. For the latter two cases, SiC was also investigated for the structure. Also assessed is the impact of Li-6 enrichment on tritium breeding ratio (TBR) and power multiplication factor (PM). To predict the lifetime of the various components, the key damage parameters have been calculated at several locations in the system. The parameters considered are the DPA/FPY, and the helium production rate (appm/FPY). Since the TBR was found to be marginal in the case of Flibe and possibly with the Sn-Li breeder, the improvement in TBR upon the inclusion of a beryllium multiplier was also studied. The impact of utilizing other structural materials (TZM, Nb-1Zr, V-4Cr-4Ti) in the presence of a multiplier zone was also assessed.

II. CALCULATIONAL METHOD AND MODELING

The 1-D calculational model for CLiFF used in the present analysis is shown in Fig. 1. The model includes the geometrical details of the inboard (I/B) and outboard (O/B) sides to account for the geometrical effect on the key neutronics parameters under consideration. Liquid breeder of 2 cm-thickness is flowing poloidally from the top and covers a solid wall layer of 0.5 cm-thickness. The blanket and shield follow this solid wall. The dimensions shown and material composition volume fractions are those corresponding to the ARIES-RS design.[11] In this design, the blanket thickness (including the solid wall following the liquid layer) is 60 cm-thick on the O/B side and is 40 cm-thick on the I/B side. It consists of 90% liquid breeder and 10% structure. High-temperature (H.T.) shield follows the blanket and consists of 95% structure and 5% liquid (in the ARIES design, the volume fraction is 15% vanadium alloy, 80% Ferritic steel and 5% liquid breeder). Its thickness is 30.5 cm on the O/B side and 28 cm on the I/B side. After a 2 cm-thick gap, the low-temperature shield follows with a thickness of 30.5 cm (O/B) and 28 cm (I/B). It consists of 95% structure and 5% liquid breeder (in ARRIES design, the structure of the L.T. shield is Ferritic steel). In the present analysis, the material and configuration of the vacuum vessel (V.V.) and the TF coil are fixed in all the cases considered. The V.V. walls are made of Ferritic steel (2 cm-thick) with an interior zone of 80% 316SSLN and 20% water. The thickness of this interior zone is 26 cm (O/B) and 16 cm (I/B). The TF coil case is made of SS316LN and epoxy is used as the insulator.

The calculations were performed with ANISN code[12] along with 46:21 neutron-gamma multi-group cross section data library based on FENDL-1 data base[13] with an average neutron wall load of 10 MW/m^2. We note that the liquid FW/B is assumed to maintain its thickness in the poloidal direction (i.e. no account is taken for penetration) and therefore the 1-D model considered in the present work is appropriate under this assumption and for this scoping analysis.

III. CALCULATIONAL RESULTS

A. Tritium Breeding (No Beryllium Multiplier)

The local tritium breeding ratio (TBR) as a function of Li-6 enrichment for several combination of breeder/structure is shown in Fig. 2. In the Li/V and Flibe/FS cases, it maximizes around 25%Li-6. However, it keeps decreasing with Li-6 enrichment in the Flibe/SiC case. In the Sn-Li/FS and Sn-Li/SiC cases, the TBR is very low at natural Li-6 enrichment (~0.38 and 0.45 respectively) but it keeps rising rapidly with Li-6 enrichment. At 90%Li-6 enrichment, the TBR reaches values (1.26 and 1.23) larger than TBR with Flibe/FS, Flibe/SiC, and Li/V cases (1.1, 1.01, and 1.17) at this enrichment. The maximum local TBR is as follows: Li/V: 1.46 (25%Li-6), Flibe/FS: 1.16 (25%Li-6), Flibe/SiC: 1.13 (Nat. Li), Sn-Li/FS: 1.26 (90%Li-6), and Sn-Li/SiC: 1.23 (90%Li-6). Thus, with no neutron multiplier, the TBR in Sn-Li can be larger than the achievable TBR with Flibe. The local TBR for either Flibe/FS or Flibe/SiC is *marginal.* The local TBR with Li breeder is generally larger than with Flibe or Sn-Li (except Sn-Li with 90%Li-6).

B. Heating Rate Profiles and Power Multiplication

For illustration, the volumetric heating rate profiles (w/cm^3) in the O/B are shown in Fig. 3 for an average wall load of 10 MW/m^2 and for Li/V, Flibe/FS, and Sn-Li/FS cases. The maximum heating rates at various locations are given numerically in Table 1.

The maximum power deposition rate in the 2 cm liquid layer is the largest in the case Sn-Li (~97 w/cc) followed by Flibe (~70 w/cc) and Li (~52 w/cc). The maximum heating rate in the solid wall (0.5 cm-thick) following the liquid layer is the largest in the Flibe case (~72 w/cc) followed by the Sn-Li (~61 w/cc) and Li (~50 w/cc). In the blanket, the maximum heating rate is the largest in the Sn-Li case (~ 70 w/cc, features similar to the liquid layer) followed by Flibe (~57 w/cc) and Li (~45 w/cc) Generally, the heating rates in the layer/FW/Blanket are larger in the outboard side than in the inboard. However, the heating rates in the H.T shield, the L.T. shield, the V.V. walls, and the interior zone of the V.V. are larger in the inboard side than in the outboard. The heating rates at deep locations (i.e. in the V.V) with the Flibe breeder are an order of magnitude lower than with other breeders due to its superior attenuation characteristics relative to the other breeder. The largest heating rates across the shield and V.V. are in the case of Li breeder since the attenuation power of this breeder is the least compared to the other breeders (it was shown that Li is the least in attenuating the 14 MeV neutrons resulting in deep penetration for high energy neutrons [2,9].)

The total power deposited in all the components per unit height was calculated to be 7.9 MW/cm, 7 MW/cm, and 8.9 MW/cm for Li/V, Flibe/FS, and Sn-Li/FS cases, respectively. The corresponding power multiplication (PM) is 1.14, 1.02, and 1.29, respectively. Thus, the largest PM is with the Sn-Li breeder. The variation of the PM with Li-6 enrichment is shown in Fig. 4. The features of the PM curves and the TBR curves when Li-6 increases are revered; i.e. the PM minimizes with Li-6 enrichment at the values where TBR maximizes. The variation of the PM is less sensitive to Li-6 enrichment in the Li and Flibe cases than in the Sn-Li case where it drops from ~1.48 (natural Li-6) to ~1.29 (90%Li-6).

The large power multiplication in the case of Sn-Li breeder is due to the large gamma heating that is the consequence of the large Sn(n,gamma) reactions. This is advantageous from the viewpoint of improving the thermal efficiency of the system. The power multiplication with Flibe is only ~1.02 at 25% Li-6 enrichment. Coupled with the marginal local TBR value of 1.16 at this enrichment, it makes the Flibe to have the most unfavorable neutronics characteristics as far as tritium and power multiplication is concerned. As will be seen in Section D.1, the TBR can be drastically improved upon utilizing beryllium as a multiplier.

C. Damage Parameters

The structure damage parameters (DPA/FPY and helium production, appm/FPY) were calculated at several locations and are given in Table 3 with and without the liquid layer for the Li/V, Flibe/FS, and Sn-Li/FS cases. Several observations can be made: (1) The damage parameters in the solid walls of the O/B are larger than those found in the I/B, (2) the damage parameters in the V.V. walls and in the TF coil casing of the I/B are larger than the O/B ones, (3) damage parameters in the Li breeder case are larger in the V.V. walls and the TF coil casing than with Flibe and Sn-Li breeder, and (4) because the superior attenuation characteristics of Flibe relative to the other breeders, the damage parameters in the V.V. walls and the TF coil casing are about an order of magnitude less compared to the values found with the other breeders.

The inclusion of the 2-cm layer reduces the damage parameters in the first solid wall by 11-30%, depending on the response type under consideration. This is consistent with the estimated 10-fold thickness (the thickness required to reduce a response by an order of magnitude) discussed in Ref. 9.

The largest DPA rate in the bare solid wall is in the case of Sn-Li breeder on the O/B side (~152 DPA/FPY) followed by Flibe (~141 DPA/FPY) and Li (~138 DPA/FPY). The corresponding values in the presence of the liquid layer are: ~122 DPA/FPY, ~110 DPA/FPY, and 123 DPA/FPY, respectively. For a lifetime limit of ~200 DPA[14], the solid wall with the liquid layer can last for ~ 1.6 years with the Sn-Li and Li breeders and slightly longer (~1.8 year) with the Flibe breeder. This will require 19 and 17 replacements, respectively, during the 30 years plant lifetime. On the other hand, the accumulated DPA in the V.V walls over 30 years are 3 (considering the largest DPA rate with the Li breeder on the I/B side). This makes the V.V. a lifetime component (less than 200 DPA). Furthermore, the accumulated helium production over 30 years is ~ 0.9 appm, which is less than the limit of 1 appm for reweldability

D. Enhancing Tritium Breeding

1. Effect of Neutron Multiplier on Tritium Breeding Ratio. From Section II.A, it was shown that the maximum local TBR is: Li/V: 1.46 (25%Li-6), Flibe/FS: 1.16 (25%Li-6), and Sn-Li/FS: 1.26 (90%Li-6). Thus, with no neutron multiplier, the TBR in Sn-Li can be larger than the TBR with Flibe. The marginal TBR with Flibe can be improved upon including a beryllium multiplier in the blanket region.

The blanket region in the O/B (60 cm-thick) and in the I/B (40 cm-thick) was assumed to include a front multiplier zone consisting of 60% Be, 30% breeder, and 10% structure. The thickness of this zone was varied. The rest of the blanket zone (back blanket zone) is assumed to remain with the same composition (90% breeder, 10% structure). Fig. 5 shows the variation of TBR with the front multiplier thickness. The effectiveness of Be on improving TBR is apparent. For example, with natural lithium, the TBR increased from 1.14 to 1.63 in Flibe/FS case (~43% increase) while the TBR in Sn-Li/FS case increased from 0.38 to 0.92 (~142% increase.)

While the presence of beryllium improves TBR for either Sn-Li/FS or Sn-Li/SiC, local TBR is still marginal with natural lithium, even with Be present in the entire blanket. For the Sn-Li breeder, lithium must be enriched (to 90%Li-6) to achieve reasonable TBR values. As shown in Fig 2, TBR without Be multiplier is ~1.26 (Sn-Li/FS) and ~1.23 (Sn-Li/SiC) if Li is enriched to 90%Li-6. If penetrations are minimized, the blanket coverage is increased, and/or the structure contents is decreased, tritium self sufficiency can be achieved with enriched Sn-Li breeder without the need for beryllium to improve TBR. In fact, the rate of increase in TBR with increasing the Be zone thickness for either Sn-Li/FS or Sn-Li/SiC case is not as steep as in the natural Li case. The local TBR for Sn-Li/FS (90%Li-6) only increases from 1.26 to 1.31 (~4% increase) upon including 10 cm-thick Be zone. The corresponding increase in the Sn-Li/SiC (90%Li-6) case is ~5% (from 1.23 to 1.29).

As for the Flibe breeder there is a clear need for a Be multiplier. As shown in Fig. 2, local TBR is ~1.16 (Flibe/FS; 25%Li-6) and ~1.13 (Flibe/SiC; Nat. Li). The improvement in TBR for the Flibe/FS and Flibe/SiC cases is very similar when beryllium is utilized as a multiplier. With 10 cm thick Be zone, TBR in Flibe/FS (25%Li-6) case increases from 1.16 to 1.5 (~29% increase.) The corresponding increase in the Flibe/SiC (Nat. Li) is ~33% (from 1.13 to 1.5). The improvement in TBR with Be multiplier is more pronounced in the Flibe breeder than in the Sn-Li breeder. Note that in the presence of Be, the local TBR with Flibe (with either FS or SiC structure) is larger the TBR with Sn-Li (even at 90%Li-6; contrary to the case without Be). Also, the effect of Be is more pronounced in the Flibe/SiC case than in the Flibe/FS case.

From Fig. 5, the maximum attainable local TBR is achieved when the blanket is composed entirely of the beryllium zone. These maximum values are: Flibe/FS (25%Li-6) ~1.68, Flibe/SiC (Nat. Li) ~1.7, Sn-Li/FS (90%Li-6) ~1.39, and Sn-Li/SiC (90%Li-6) ~1.39. From practical viewpoint, and to minimize Be usage, the Be zone could be limited to 10 cm thickness. In this case the practical TBR values are: Flibe/FS (25%Li-6) ~1.5, Flibe/SiC (Nat. Li) ~1.5, Sn-Li/FS (90%Li-6) ~1.31, and Sn-Li/SiC (90%Li-6) ~1.29.

2. The impact of the Structure Contents on Local TBR. The following Flibe/FS and Sn-Li/FS reference cases were used to investigate the change in local TBR upon altering the structure volume fraction in the beryllium and the back blanket zones.
Liquid layer: 2 cm Breeder
Solid wall: 0.5 cm Ferritic Steel
Beryllium Zone: 10 cm (Flibe case), 20 cm (Sn-Li case) (60%Be, 30%breeder, 10%FS)
Back Blanket Zone: 50/30cm OB/IB (Flibe case: 90%Flibe, 10%FS)
40/20 cm OB/IB (Sn-Li case: 90%Sn-Li, 10%FS).

Fig. 6 shows the variation in TBR upon increasing the structure contents from 0% to 20% in both zones. Each incremental 5% increase in the volume fraction of the leads to 2-3% and 1.5-2.2% decrease in local TBR in the Flibe/FS and Sn-Li/FS cases, respectively.

3. Effect of the Type of Structure on Local TBR**.** The impact of considering other structural materials on local TBR was investigated by replacing the structural material with either W, V-4Cr-4Ti, TZM, Nb-1Zr, FS, or SiC, on one-to-one basis, in the reference Flibe and Sn-Li breeder systems mentioned above. Table 3 shows the achievable TBR in the case where the beryllium multiplier zone is included and in the case where this zone is replaced entirely with the non-multiplier back blanket zone.

While there is an increase in the TBR of 29%, 9%, 16%, 29%, and 34% upon the inclusion of the beryllium zone when the structure used is V-4Cr-4Ti, TZM, Nb-1Zr, FS, or SiC, there is an adverse effect on the local TBR when tungsten is used in the presence of beryllium. This latter combination leads to ~ 12% reduction in the local TBR. The neutron multiplication with W through the (n,2n) reactions, whose threshold energy is high (6.6 MeV), tends to compete with the Be(n,2n) reactions, whose threshold energy is relatively low (~ 2 MeV). Successive neutron multiplication takes place in Be which further moderates neutron to low energies where the Li-6(n,α) cross section is high. The presence of the W reduces this effect which in turn reduces the local TBR. The strong moderation of neutron energy in Flibe tends to improve the TBR. Note from Table 3 that the enhancement in TBR is more pronounced in the presence of Be when the structure is SiC and least pronounced when the structure is TZM.

As for the Sn-Li breeder, the reference case system has a 20 cm thick beryllium zone (90%Li-6, TBR=1.36). Table 4 is similar to table 3 and gives the achievable TBR with and without the beryllium multiplier zone. As shown, there is only an improvement in the TBR (of ~8-9% increase) upon the inclusion of the beryllium zone when the structure used V-4Cr-4Ti, FS, or SiC. The presence of beryllium in this case has an adverse effect on the local TBR when tungsten, TZM, or Nb-1Zr alloys are used as the structural materials. The decrease in the local TBR is ~10% in the TZM and Nb-1Zr cases, but as large as ~30% in the case of tungsten. Note that neutron multiplication through (n,2n) reactions takes also place in Mo, and Nb (main constituents of TZM and Nb-1Zr, respectively) at high threshold energies, but to a lesser extent than multiplication in W. Since Sn-Li is not as a good moderator to neutrons as Flibe is, the impact of the competition between neutron multiplication in beryllium and in W, Mo, or Nb are more pronounced. Since much less (n,2n) reactions take place in V and Ferritic steel alloys, the utilization of beryllium with these structural materials improves the local TBR by ~8%.

The adverse effect of the presence of a beryllium multiplier zone when tungsten is used as the structural material is further investigated in Sn-Li breeder reference case (20 cm Be zone, 90%Li-6) by gradually increasing the volume fraction of Be in the beryllium multiplier zone up to 60%. The variation of local TBR with this increase is shown in Fig. 7. The TBR drops from a value of 1.244 (0% Be) to 0.872 (60% Be). When the Be fraction is low, the TBR decreases by ~ 3-4% for every 10% increase in Be fraction. This decrease is larger (~6-10%) at larger Be fraction.

IV. CONCLUDING REMARKS

In the CLiFF design, a thin liquid layer of thickness ~2 cm is flowing in front of a solid wall. During the initial phase of the design, several liquid breeders (Li, Flibe, and Sn-Li) were explored. Vanadium alloy was used with Li while Ferritic steel (FS) is deployed with Flibe and Sn-Li. Without a multiplier, the maximum local TBR is ~1.5 [Li(25%Li-6)/V], 1.16 [Flibe(25%Li-6)/FS] and 1.26 [Sn-Li(90%Li-6)/FS]. Power multiplication with Flibe is marginal and is the largest with Sn-Li (PM~1.4) which is advantageous from enhancing the total power removed from the system. Thus Flibe showed the least favorable neutronics characteristics from TBR and PM viewpoints. However, the damage parameters at the vacuum vessel (VV) and TF coil case are about an order of magnitude less with Flibe breeder due to its superior attenuation power. The inclusion of the 2-cm layer reduces the FW damage parameters by 11-30%. For 10 MW/m2 average wall load, the accumulated DPA in the VV over 30 years is 3, which makes the VV a lifetime component.

In the second phase of the design, Flibe and Sn-Li with SiC structure were studied. The maximum attainable TBR was explored under various parameter variations and the following were established:

(1) Without a beryllium multiplier, local TBR for either Flibe/FS or Flibe/SiC is *marginal* (TBR~1.14 and 1.13, respectively, at natural Li*)*. Flibe/SiC combination gives lower TBR at all Li-6 enrichment. It decreases with Li-6.whereas it peaks around 25% Li-6 enrichment in the case of Flibe/FS (TBR ~1.16). Beryllium multiplier must be deployed to achieve tritium self-sufficiency with Flibe.

(2) Without Be multiplier, local TBR for either Sn-Li/FS or Sn-Li/SiC increases drastically with increasing Li-6 enrichment (maximizes at 90%Li-6). TBR can reach values larger than Flibe/FS or Flibe/SiC cases. The effect of increasing Li-6 enrichment is more pronounced in the Sn-Li system than in the Flibe system. The attainable values at 90%Li-6 are: TBR ~1.26 (Sn-Li/FS) and ~1.23 (Sn-Li/SiC). This values may be appropriate for meeting tritium self sufficiency condition if penetrations are minimized, blanket coverage is maximized and/or lesser amount of structure is used.

(3) In the presence of beryllium, the local TBR with Flibe is larger than TBR with Sn-Li (even at 90% Li6). Effect of Be is more pronounced in the Flibe system

than in the Sn-Li system and it is more pronounced in the Flibe/SiC case than in the Flibe/FS case.

The maximum attainable local TBRs in the presence of Be are: *Flibe (Nat. Li)/SiC ≈ 1.7,Flibe (25%Li6)/FS ~ 1.68, Sn-Li (90%Li6)/SiC ≈ 1.39, Sn-Li (90%Li6)/FS ~ 1.39.* However, under practical condition, a 10 cm thick Be zone would be enough. In this case, the attainable TBR are: *Flibe(25%Li6)/FS ~1.5,Flibe(Nat. Li)/SiC ~1.5, Sn-Li (90%Li6)/FS ~ 1.31,Sn-Li(90%Li6)/SiC ~ 1.29.* The impact of using other structural material on TBR was also studied. The materials considered are: W, V-4Cr-4Ti, TZM, and Nb-1Zr. The presence of Be in the Flibe blanket has an adverse effect on local TBR when the W structure is used everywhere. Likewise, the presence of Be in the Sn-Li blanket has an adverse effect on local TBR when the structure is made of W, TZM, or Nb-1Z.

Table 1: Maximum Heating Rate (w/cc) in Various Components (CLiFF Concept- 10 MW/m2)

Component	**Li/V (25%Li6)**	**Flibe/FS (25%Li6)**	**Sn-Li/FS (90%Li6)**
Liquid Layer I/B	44.834	59.881	83.219
Liquid Layer O/B	52.204	70.628	97.344
Solid Wall I/B	39.613	56.196	48.519
Solid Wall O/B	50.054	71.550	61.416
blanket I/B	36.235	46.676	62.337
blanket O/B	45.448	57.424	69.707
HT shield I/B	11.270	2.7330	3.2243
HT shield O/B	6.7865	0.70014	1.1116
LT shield I/B	1.3389	0.24382	1.0042
LT shield O/B	0.60495	0.041149	0.29418
VV walls I/B	0.28866	0.044834	0.25488
VV walls O/B	0.098266	0.0055581	0.052204
VV I/B	0.33779	0.046062	0.27637
VV O/B	0.11055	0.0058038	0.057731

Table 2: Displacement Rate (DPA/FPY) and Helium Production Rate (appm/FPY) in the CliFF Concept with 2 cm Liquid Layer (10 MW/m2)

	With Liquid Layer					
Comp-onent	**Li/V (25%Li-6)**		**Flibe/FS (25%Li-6)**		**Sn-Li/FS (90%Li-6)**	
	DPA	He-4	DPA	He-4	DPA	He-4
Solid Wall*	96	335	83	924	97	822
Solid Wall**	123	454	110	1301	122	1151
VV*	0.11	0.03	0.01	2.9-3	0.08	3.3-3
VV**	0.03	5.7-3	1.4-3	2.4-4	0.01	3.0-4
TF Coil*	1.9-3	1.8-3	2.0-4	2.1-4	9.1-4	2.4-4
TF Coil**	7.0-5	6.4-5	2.7-6	2.7-6	1.5-5	3.6-6
	Without Liquid Layer					
Solid Wall*	112	420	114	1400	125	1280
Solid Wall**	138	542	141	1808	152	1653
VV*	0.12	0.03	0.01	3.0-3	0.09	3.9-3
VV**	0.04	6.1-3	1.6-3	2.9-4	0.02	3.6-4
TF Coil*	2.6-3	1.9-3	2.4-4	2.5-4	9.7-4	2.8-4
TF Coil**	9.3-5	6.9-5	3.2-6	3.2-6	1.6-5	4.2-6

* Inboard ** Outboard

Table 3: The Local Achievable TBR with and without a Beryllium Multiplier Zone with Various Structural Materials- Flibe Breeder

Structure Type	**With Be-Zone**	**Without Be-Zone**	**Change in TBR**
W	0.887	0.954	-12%
V-4Cr-4Ti	1.535	1.189	29%
TZM	1.184	1.065	8.7%
Nb-1Zr	1.131	0.928	16%
Ferritic Steel	1.504	1.165	29%
SiC	1.483	1.105	34%

Table 4: The Local Achievable TBR with and without a Beryllium Multiplier Zone with Various Structural Materials- Sn-Li Breeder

Structure Type	**With Be-Zone**	**Without Be-Zone**	**Change in TBR**
W	0.872	1.244	-30%
V-4Cr-4Ti	1.379	1.275	8.2%
TZM	1.122	1.254	-11%
Nb-1Zr	1.069	1.185	-10%
Ferritic Steel	1.356	1.259	8%
SiC	1.346	1.230	9%

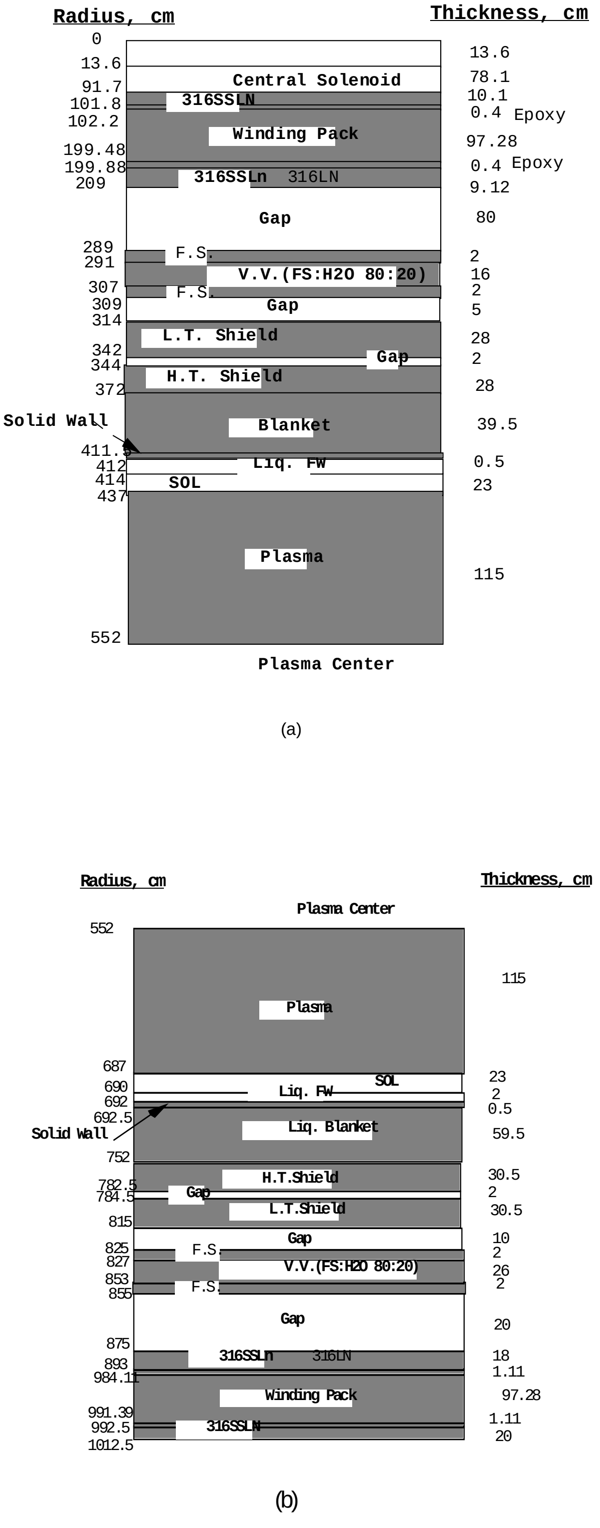

Fig. 1: The Radial Build of the Cliff Concept: (a) Inboard Side, (b) Outboard Side

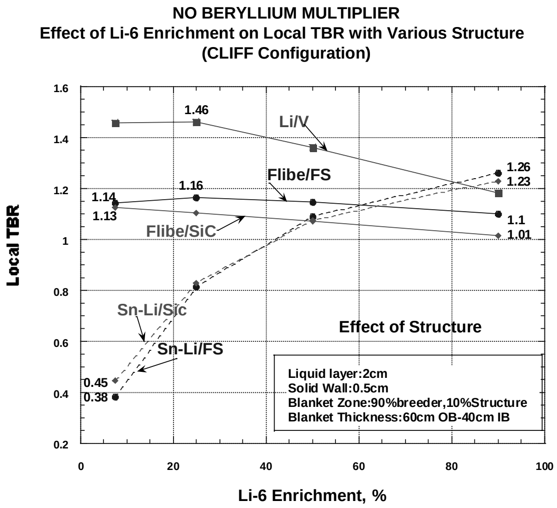

Fig. 2: The Tritium Breeding Ratio (TBR) for Several Breeders as a Function of Li-6 Enrichment

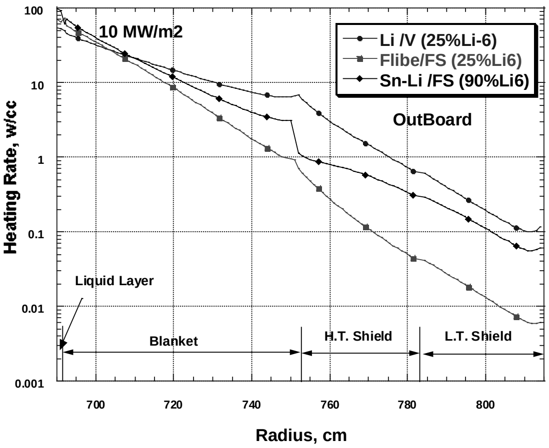

Fig. 3: The Heating rate Profiles in the Outboard for Several Breeders in the CLIFF Concept

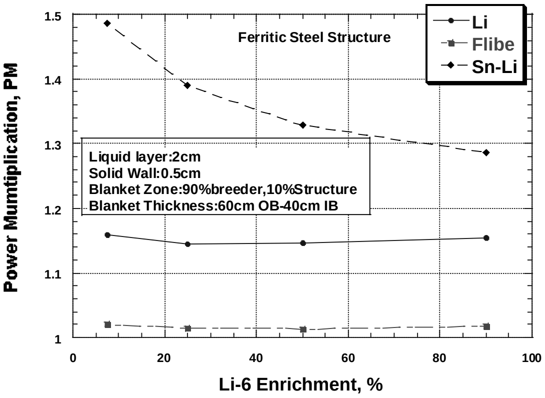

Fig. 4: The Power Multiplication, PM, as a Function of Li-6 Enrichment for Various Breeders

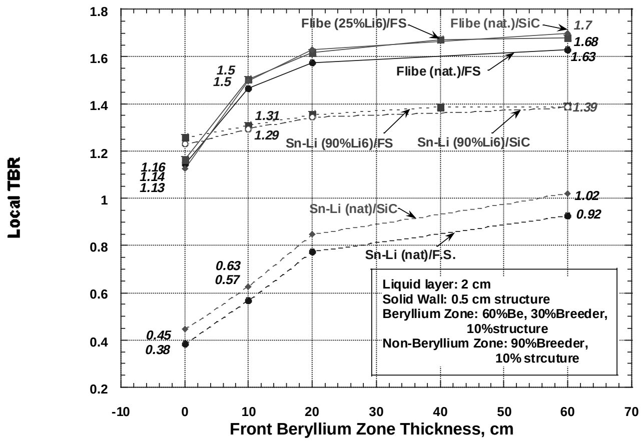

Fig. 5: Impact of Increasing the Thickness of Beryllium Multiplier Zone on Local TBR

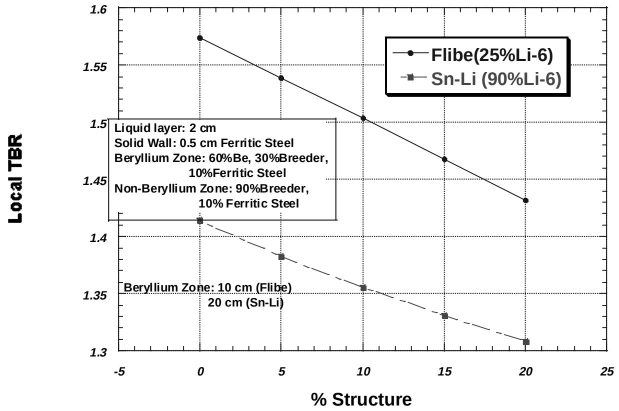

Fig. 6: The Variation of the Local TBR with the Structure Content

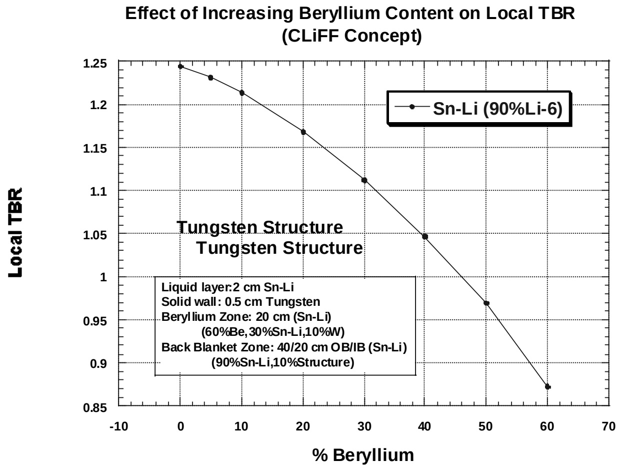

Fig. 7: The Effect of Increasing the Beryllium Volume Fraction on Local TBR in the Presence of Tungsten Structure- Sn-Li Breeder

ACKNOWLEGMENTS

This work is supported by the U.S. Department of Energy under grant #DOE-FG03-86ER52123

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