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

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Background

- The APEX study aims at exploring innovative blanket concepts that can cope with high power density fusion reactors

- The **thin Convective Liquid Flow First Wall (CLiFF)** concept is among the concepts investigated. Liquid walls offer the advantage of protecting solid structure behind them from excessive damage from 14 MeV neutrons

Objectives

Perform parametric investigation to determine the best combination of structure, liquid breeder, and multiplier to enhance tritium breeding while ensuring radiation protection to the superconducting magnet

Materials considered

Liquid breeder

Lithium, Flibe (Li_2BeF_4), and Sn-Li (75:25)

Structure:

Vanadium alloy, Ferritic steel (FS), and SiC

Multiplier: *Beryllium*

System Description and Calculated parameters

- 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.
- We calculate tritium production and heating rate profiles in CLiFF design with the combination of Breeder/Structure:
  Li/(V-4Cr-4Ti),
  Flibe/FS, Sn-Li/FS,
  Flibe/SiC, Sn-Li/SiC

Other Calculated Parameters

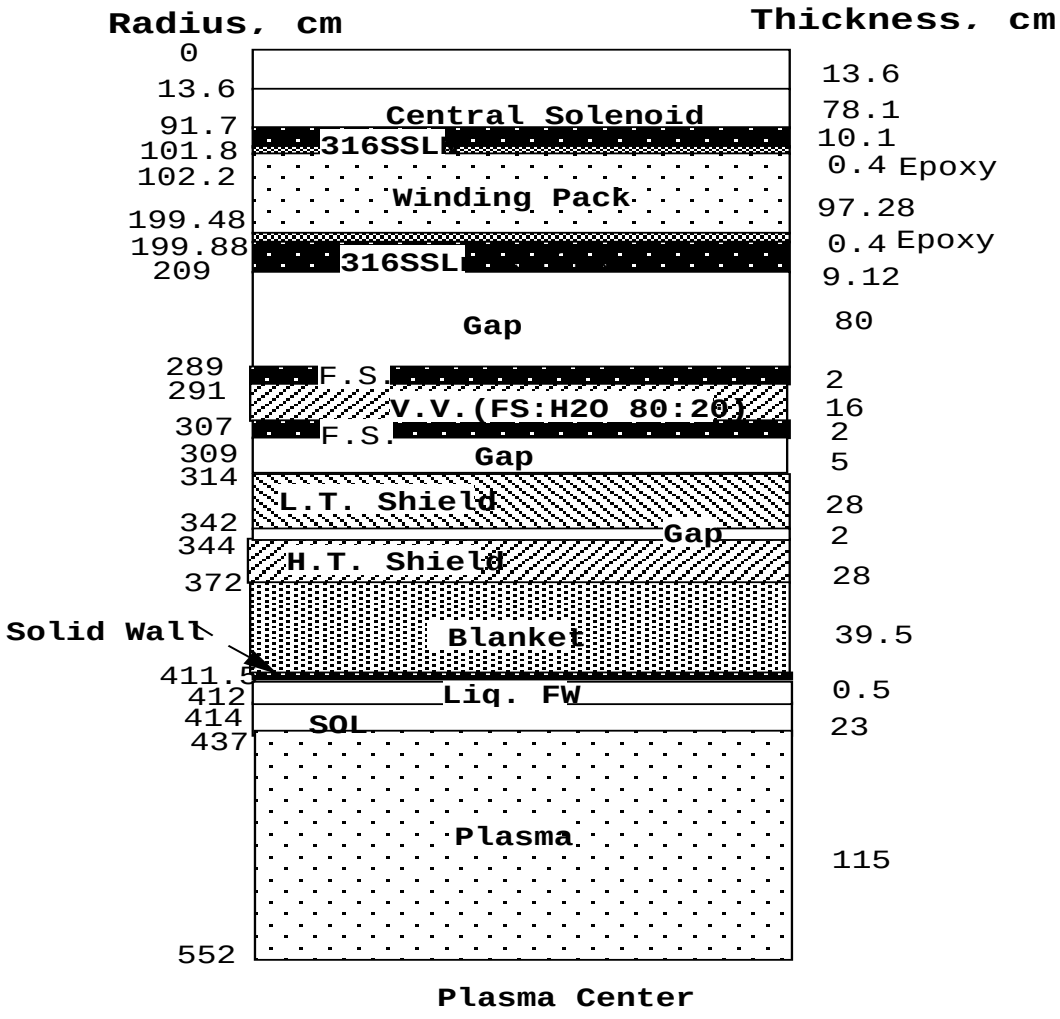
To assess the lifetime of the various components, the key damage parameters have been calculated at several locations in the system.

The parameters considered:

- DPA/FPY, helium production rate (appm/FPY).
- The improvement in TBR upon the inclusion of a beryllium multiplier (Flibe and Sn-Li).
- Impact of utilizing other structural materials (TZM, Nb-1Zr, V-4Cr-4Ti) in the presence of a multiplier.

Calculational Model

(1-D)

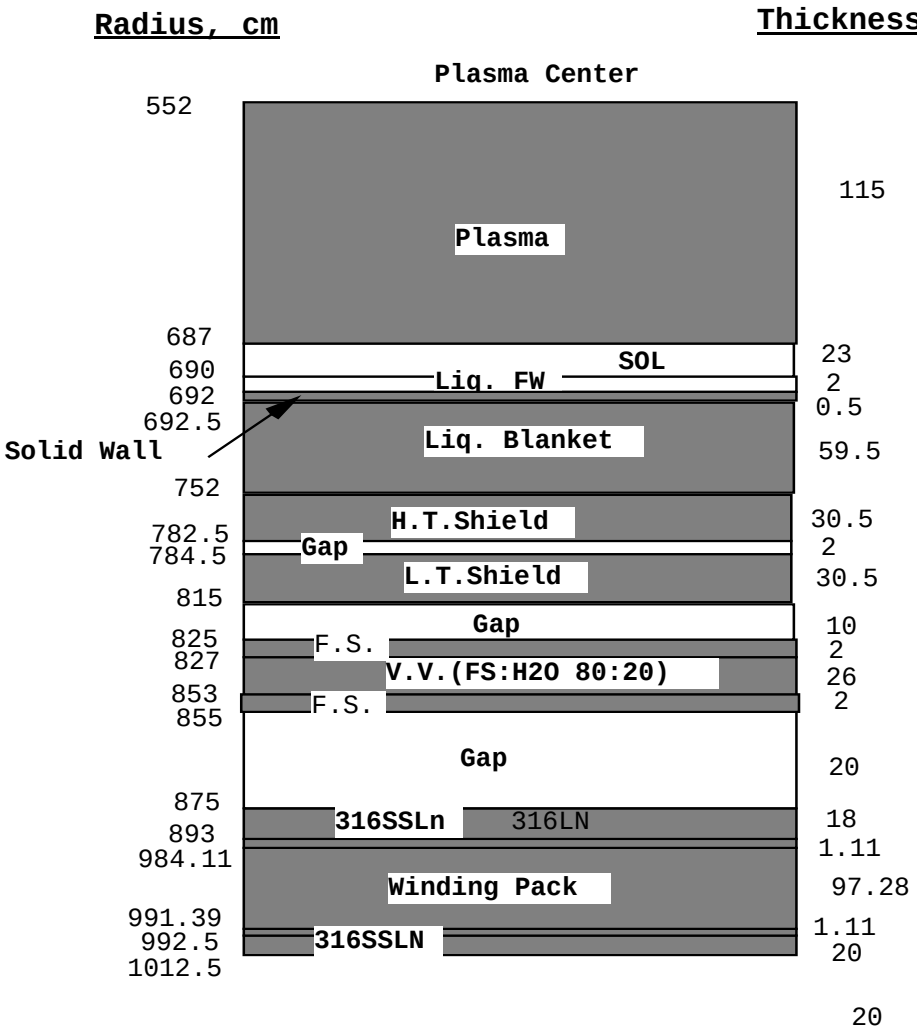


Radial Build of the CLiFF

Inboard

Calculational Model

(1-D)



Radial Build of the O/B CLiFF Concept

Outboard

Tritium Breeding Ratio *(No Beryllium Multiplier)*

- **In the Li/V and Flibe/FS cases Local TBR maximizes around 25%Li-6.**

- **TBR 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 but it keeps rising with Li-6 enrichment and at 90%Li-6 enrichment, the TBR reaches values larger than TBR with Flibe/FS, Flibe/SiC, and Li/V.**

Tritium Breeding Ratio *(No Beryllium Multiplier)*

(cont'd)

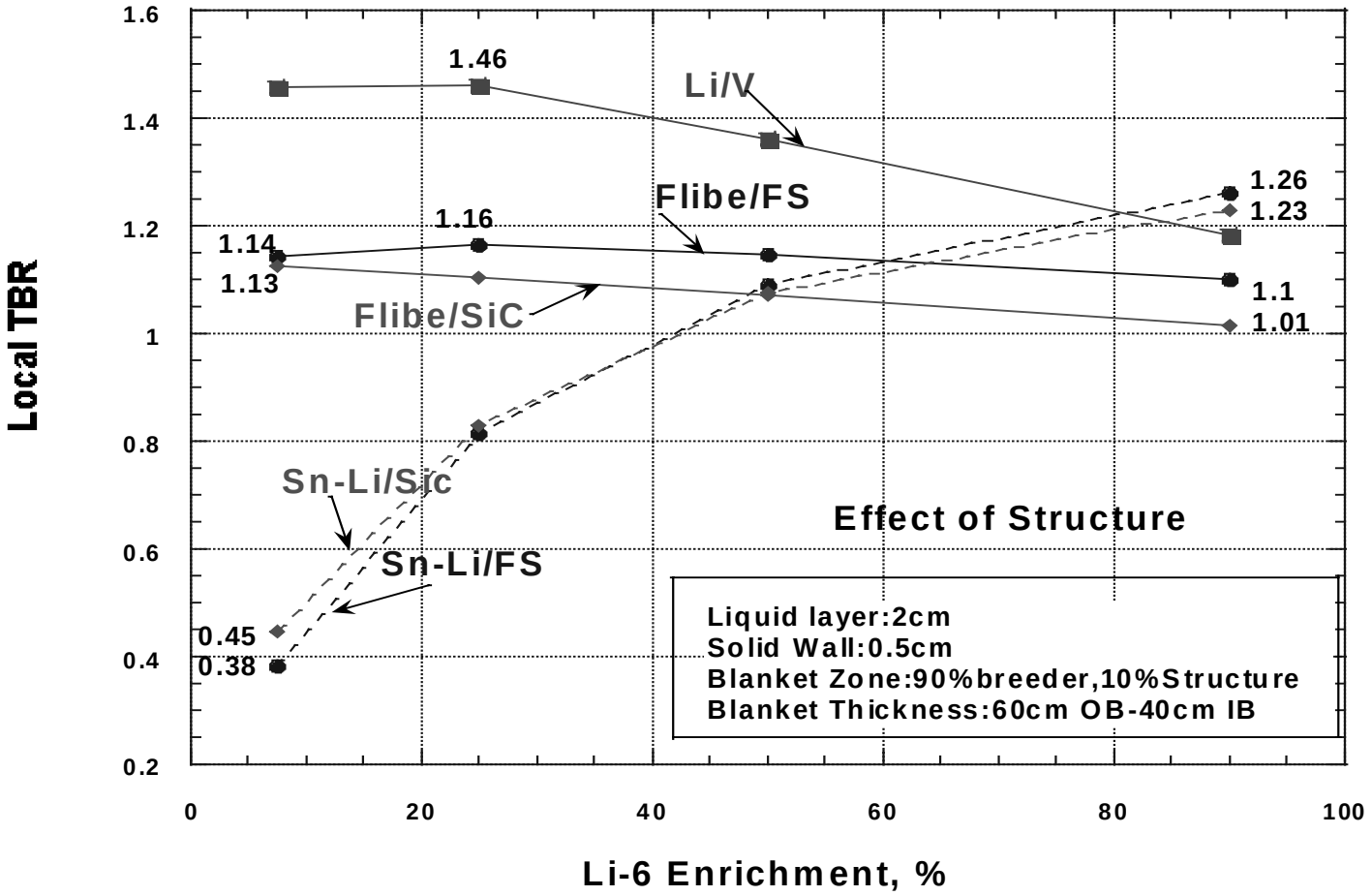
- **The maximum local TBR is as follows:**

  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), Sn-Li/SiC: 1.23(90%Li-6).

  - **With no neutron multiplier, the TBR in Sn-Li can be larger than the achievable TBR with Flibe.**

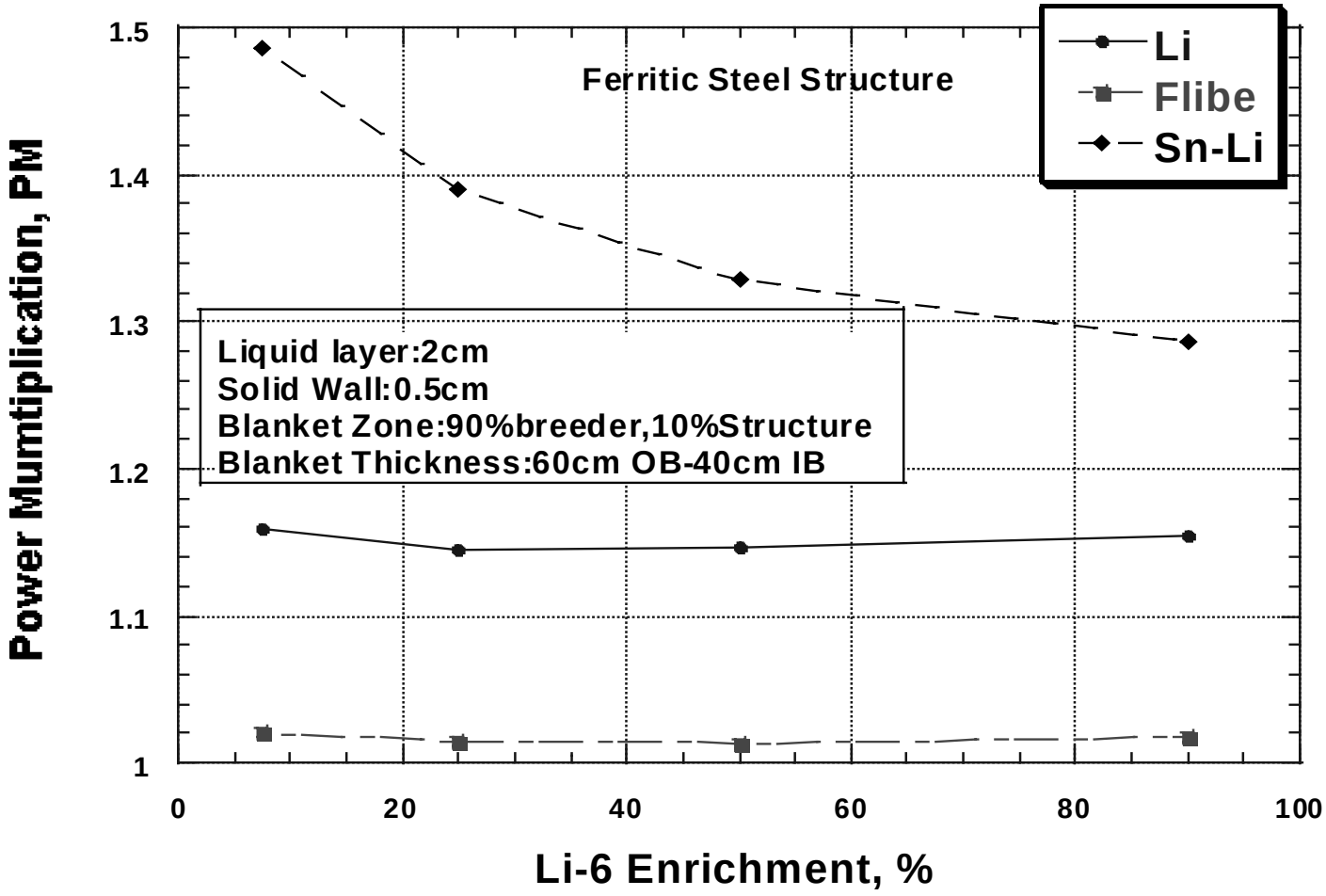
  - **The local TBR for either Flibe/FS or Flibe/SiC is *marginal.***

NO BERYLLIUM MULTIPLIER
Effect of Li-6 Enrichment on Local TBR with Various Structure
(CLIFF Configuration)



Power Multiplication

- ***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.***


Power Mumtiplication, PM
1.5
1.4
1.3
1.2
1.1
1
0
20
40
60
80
100
Li-6 Enrichment, %
Ferritic Steel Structure
Li
Flibe
Sn-Li
Liquid layer:2cm
Solid Wall:0.5cm
Blanket Zone:90%breeder,10%Structure
Blanket Thickness:60cm OB-40cm IB

Damage Parameters

- 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.

- 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.

Damage Parameters *(cont'd)*

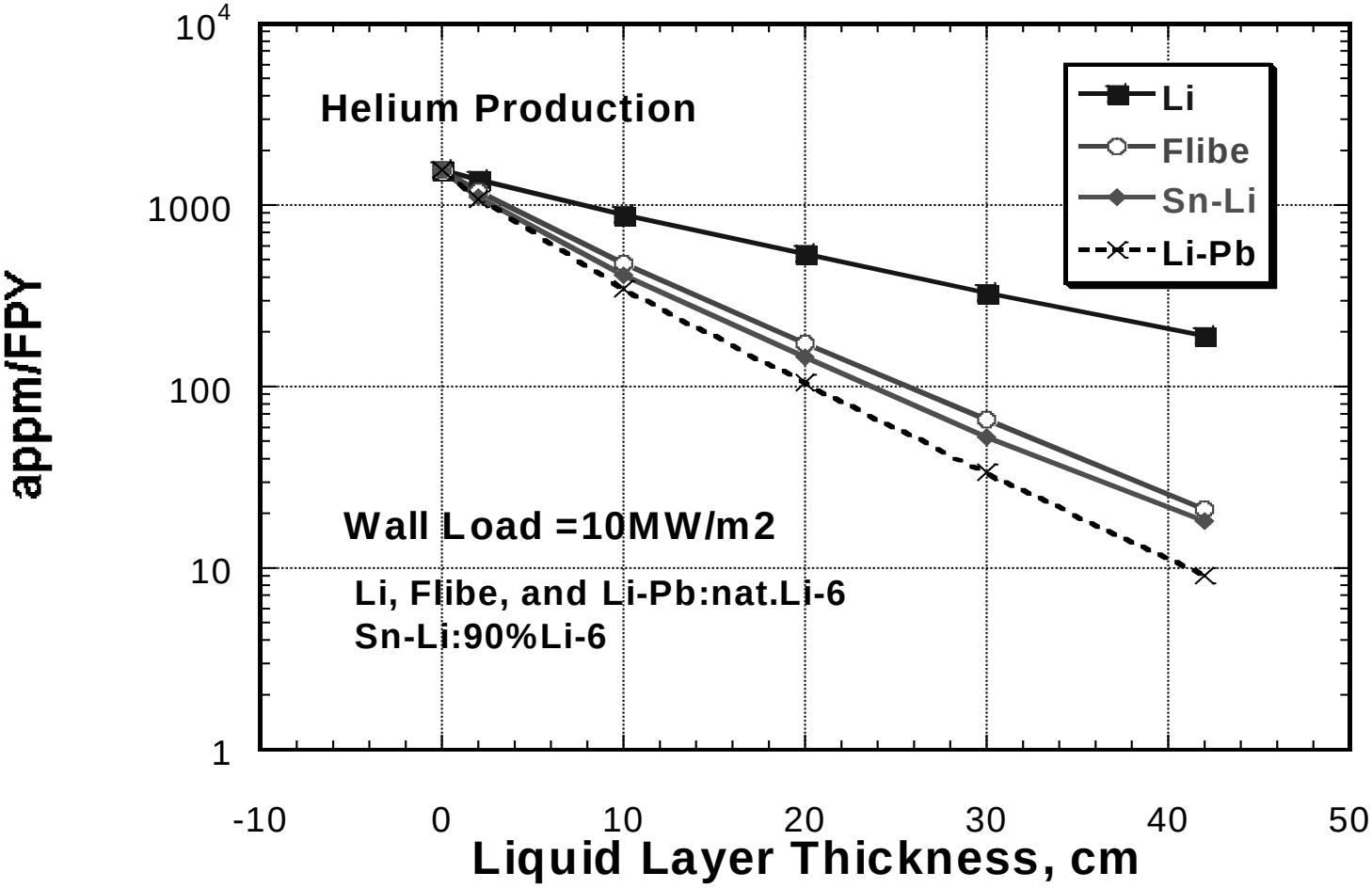
- For a lifetime limit of ~200 DPA, the solid wall with the liquid layer can last for ~ 1.6 years with the Sn-Li and Li breeders and slightly longer (~1.8 year) with the Flibe breeder. This will require 19 and 17 replacements, respectively, during the 30 years plant lifetime.

- 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.

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

Helium Production Rate Rate (appm/FPY) in the Solid Wall (FS) as a Function of the Liquid layer Thickness

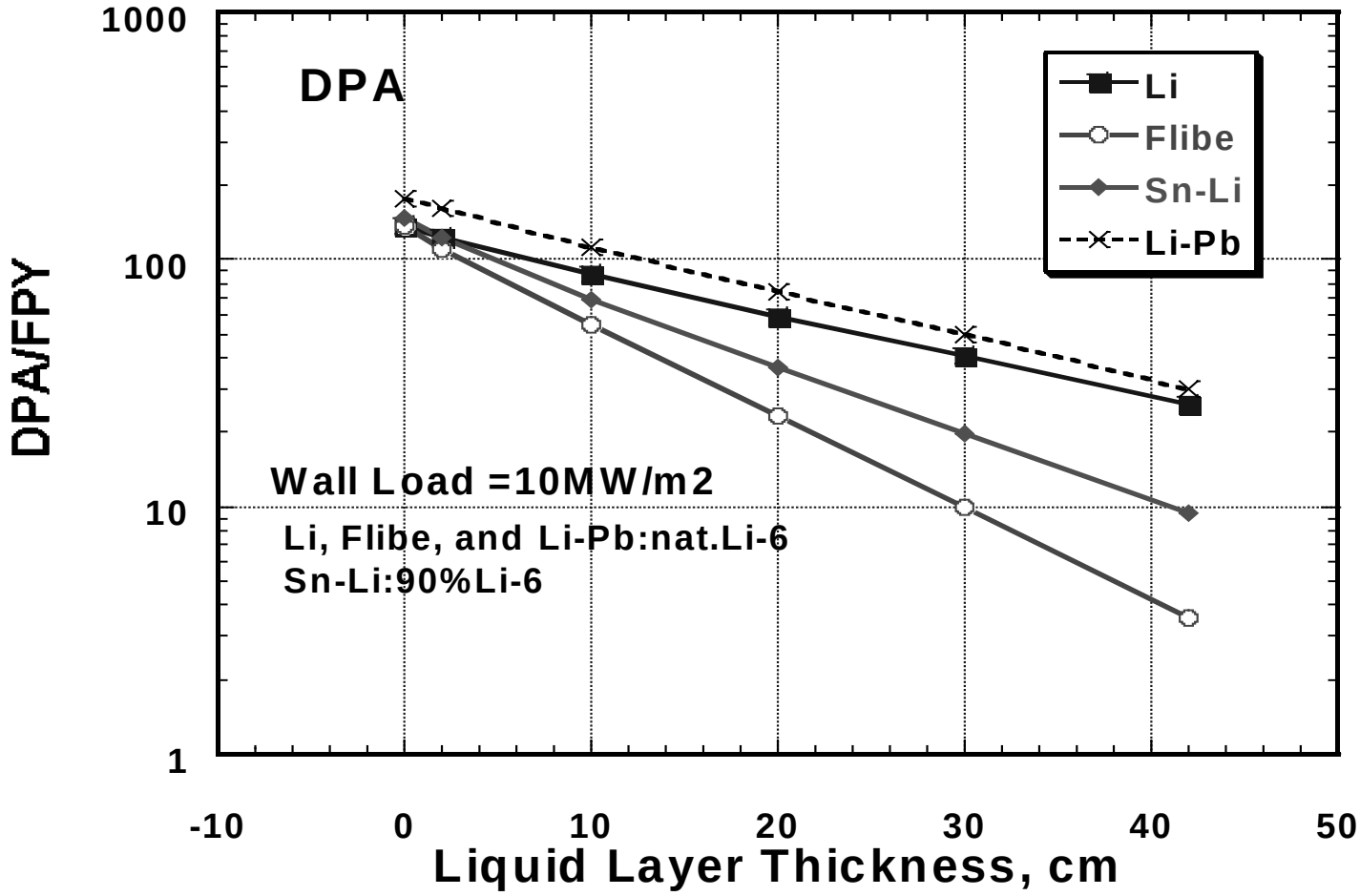


The 10-Fold Thickness* of Several Liquid Breeder First Wall

Parameter	Li/FS	Flibe/FS	Li-Sn/FS	Li-Pb/FS
DPA	~58	~26	~36	~56
Helium Production	~46	~22	~21	~18
Hydrogen Production	~44	~22	~22	~19

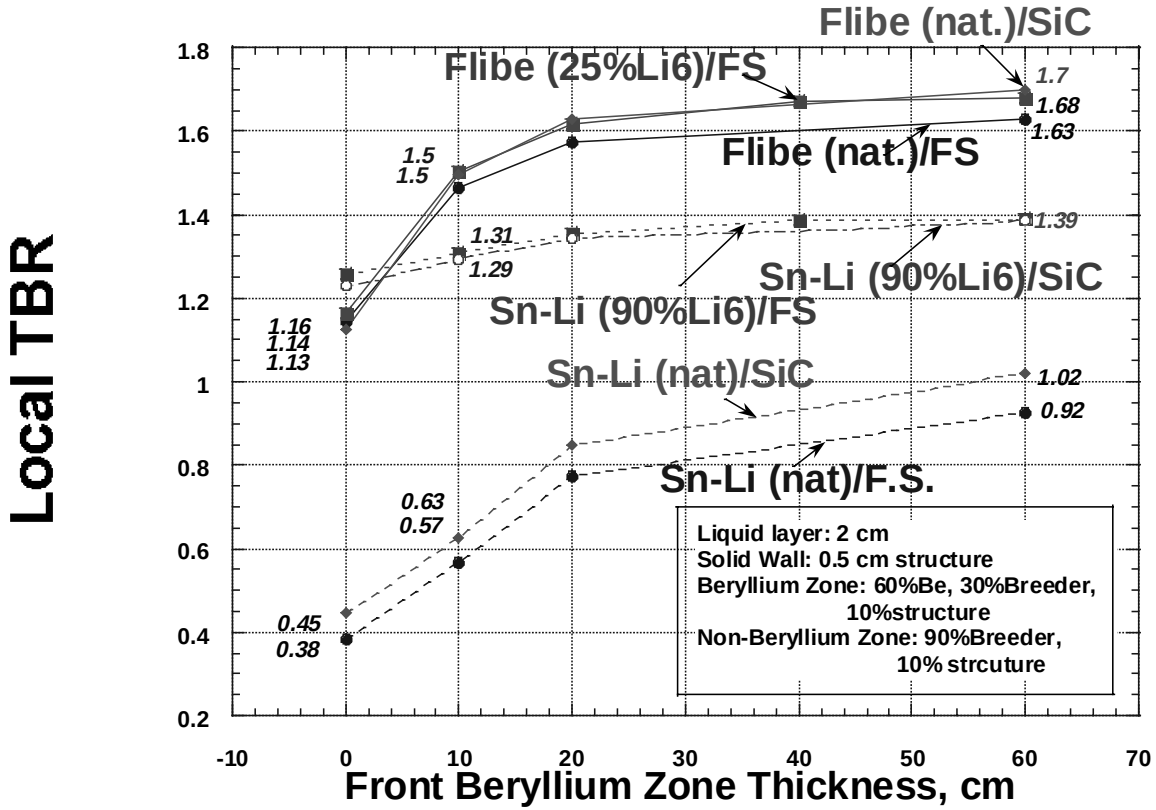
- *The thickness (cm) required to reduce a response by an order of magnitude*

DPA Rate (DPA/FPY) in the Solid Wall (FS) as a Function of the Liquid Layer Thickness



Enhancing Local TBR

Effect of Increasing the Thickness of Beryllium Zone on TBR



Sn-Li Breeder:

- While the presence of beryllium improves TBR for either Sn-Li/FS or Sn-Li/SiC, local TBR is still marginal with natural lithium. For the Sn-Li breeder, lithium must be enriched (to 90%Li-6).
- 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.

- 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

Flibe Breeder:

- Flibe breeder needs for a Be multiplier to improve TBR.

- The improvement in TBR for the Flibe/FS and Flibe/SiC cases is very similar when beryllium is utilized as a multiplier.

- The improvement in TBR with Be multiplier is more pronounced in the Flibe breeder than in the Sn-Li breeder. In the presence of Be, the local TBR with Flibe (with either FS or SiC structure) is larger than the TBR with Sn-Li (even at 90%Li-6)

The Maximum And Practical Attainable Local TBR

- The Max. 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, *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,*

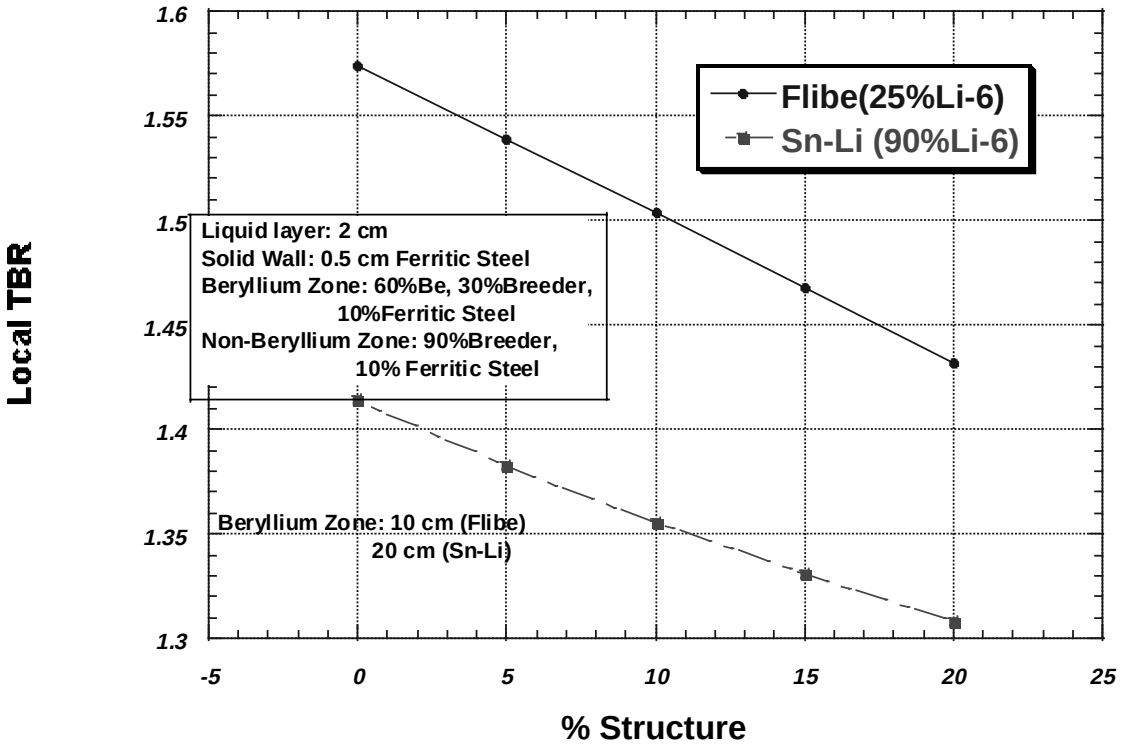
Sn-Li/FS (90%Li-6) ~1.31, *Sn-Li/SiC (90%Li-6) ~1.29.*

The Impact of the Structure Contents on Local TBR.

Reference Cases

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 (90% breeder, 10% FS)
40/20 cm OB/IB

- **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.**



Effect of the Type of Structure on Local TBR

- Investigate the impact on TBR when replacing structural material in the references cases above, on one-to-one basis, by:

  W,
  V-4Cr-4Ti,
  TZM,
  Nb-1Zr,
  FS, or
  SiC.

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%

Flibe Breeder:

- While there is an increase in the TBR 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 (~12% decrease in TBR).

- The neutron multiplication with W through the (n,2n) reactions competes with the Be(n,2n) reactions, whose threshold energy is relatively low (~ 2 MeV).

- 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.

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%

- There is only an improvement in the TBR (of ~8-9% increase) upon the inclusion of the beryllium zone when the structure used is V-4Cr-4Ti, FS, or SiC.

- The presence of beryllium 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.

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.

- Flibe without multiplier 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.

Without Beryllium Multiplier:

Flibe (No Be):

- Local TBR for either Flibe/FS or Flibe/SiC is *marginal at natural Li enrichment.*
- 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.

- Beryllium multiplier must be deployed to achieve tritium self-sufficiency with Flibe.

Sn-Li (No Be)

- 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.

With Beryllium Multiplier:

Flibe (with Be):

- Local TBR 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 Max. 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, *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, *Sn-Li/SiC (90%Li-6) ~1.29.*

- 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.