A Manuscript submitted to the 6th International Symposium on Fusion Nuclear Technology, ISFNT-6, April 7-12, 2002, San Diego, California, USA.

COMPONENT LIFETIME COMPARISON AND WASTE VOLUME IN CLiFF Sn/Flibe and Sn/LiPb BLANKETS

M.Z. YOUSSEF[1] and M.E. SAWAN[2]

[1] 43-133 Engineering IV Building, University of California, Los Angeles, 90095
Phone: (310) 825-2879 Fax: (310) 825-2599 E-mail:youssef@fusion.ucla.edu
[2] 1500 Engineering Drive, University of Wisconsin, Madison, 53706

Abstract

The thin Convective Liquid Flow First Wall (CLiFF) concept is one of the liquid FW concepts investigated in the Advanced Power Extraction (APEX) study for high power density application. Liquid tin has been suggested as the 2-cm thick front flowing liquid layer because of its low vapor pressure. Two choices were selected for the conventional blanket that follows the thin liquid wall, namely: (1) LiPb/SiC blanket, and (2) Flibe/SiC blanket. Lithium is enriched to 90% Li-6 in the first blanket option and to 25% Li-6 in the second option (with 10 cm-thick beryllium front zone). Because of the superior attenuation characteristics of Flibe over LiPb, this impacted the lifetime of the SiC structure used in both options. In this paper, we assessed the lifetime of the SiC structure in the FW/Blanket and the shield in both blanket options. The end-of-life limit of 200 dpa is assumed (corresponding to ~3% burn-up). The frequency of replacement of each component is estimated based on 30-year plant lifetime. Comparison is made for the waste volume of replaced components in each option. It is shown that the shield can last the plant lifetime in the Flibe blanket while part of the shield in the LiPb blanket will require replacement. The frequency of replacing the FW/Blanket with the LiPb blanket option is twice as much as in the Flibe blanket option. This is translated to a total volume of disposed structure at plant end-of-life from the entire FW/B/shield system that is larger by ~60%.

COMPONENT LIFETIME COMPARISON AND WASTE VOLUME IN CLiFF Sn/Flibe and Sn/LiPb BLANKETS

M.Z. YOUSSEF[1] and M.E. SAWAN[2]

[1] 43-133 Engineering IV Building, University of California, Los Angeles, 90095
[2] 1500 Engineering Drive, University of Wisconsin, Madison, 53706

1. INTRODUCTION

In the APEX study [1-3], liquid wall (LW) concepts are under development to cope with 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 [4-13]. The liquid protects solid walls behind it and thereby decreases their frequency of replacement. Several candidate liquid breeders have been considered such as lithium, Flibe (Li_2BeF_4), and Sn-Li (75:25) The Gravity and Momentum Driven (GMD) thick LW concept (~40-50 cm-thick) has previously been discussed [5, 12]. In the <u>C</u>onvective <u>Li</u>quid <u>F</u>low <u>F</u>irst Wall (CLiFF) concept, a thin liquid layer (2 cm-thick) flows poloidally from the top in front of a solid wall. The choice of the structural material depends on the type of liquid wall and breeder and several combinations have been considered [4].

Because tin has a low vapor pressure, it has recently been suggested as the front thin liquid layer. Since the primary function of this thin layer is to protect the solid wall located behind it from the large surface heat flux, the tritium breeding function was assigned to take place in a conventional blanket that follows a 0.5 cm-thick solid wall. The conventional blankets considered are (1) LiPb blanket and (2) Flibe blanket with SiC used as the structural material. Tritium breeding issue is not a concern for the first blanket choice since large tritium breeding ratio (TBR) can easily be realized with LiPb breeder/coolant. However, with Flibe breeder, beryllium is used as a neutron multiplier to improve the TBR and render enough margins to cover all sources of uncertainties.

The attenuation characteristics of Flibe are shown to be superior to LiPb [5]. Radiation damage parameters in solid structure, such as dpa, are much lower when Flibe is used as a breeder and coolant. This consequently reduces the number of components' replacements during plant lifetime (assumed to be 30 years). In this paper, we qualitatively assess the volume of the generated radioactive structure waste from the FW/blanket/shield system in the two blanket options after 30 years. The end-of-life limit of 200 dpa is assumed (corresponding to ~3% burn-up). This limit has been applied structural material in several design studies [17]. The shield thickness was varied to satisfy acceptable damage levels in the vacuum vessel and TF coil of the magnets during plant's lifetime.

Section 2 describes the configuration of the CLiFF concept with discussion on the attainable TBR and magnet protection. Assessment of the radwaste volume and comparison between the two conventional blanket concepts that follow the flowing liquid layer are given in Section 3. Conclusions from the present study are outlined in Section 4.

2. CONFIGURATION AND IMPACT OF FLOWING LAYER ON TBR AND DAMAGE TO MAGNET

The configuration and radial build of the CLiFF design concept is shown in Table I. One-dimensional model was used in the present assessment with account made for the difference in the radial build on the inboard (IB) and outboard (OB) sides. The ANISN 1-D [14] code was used along with multigroup data library based on the FENDL-2 data [15]. The plasma and FW radii are those used in the ARIES-RS design [16].

The blanket thickness is ~40 cm and ~60 cm in the IB and the OB sides, respectively. The solid FW thickness is 0.5 cm on both sides. SiC composite is considered as the structural material in the solid FW, blanket, and shield whereas stainless steel-type material is used for the vacuum vessel (V.V.) and the magnet casing. The liquid flowing layer (liquid FW) is 2 cm-thick. The shield is considered to have a replaceable front part (R-shield) and a permanent part (P-shield). It is assumed that only 5% of the structure in the R-shield (95% structure, 5% coolant) will bear the structural load and is replaced at the 200 dpa damage limit. The rest of the structure is used as filler (shielding material) and is assumed to last the plant lifetime.

In the conventional Flibe/SiC blanket option, it is necessary to include a beryllium multiplier in the front zone of the blanket. The front 10 cm zone consists of 60%Be, 30%Flibe (breeder and coolant), and 10% SiC. The ratio of 2:1 of multiplier: coolant was shown to be an optimal ratio for both tritium breeding and cooling. In the conventional LiPb/SiC blanket option, however, there is no need to have a neutron multiplier since lead basically caries out this function and the local TBR is adequate, as discussed below.

Figure 1. shows the variation in the local TBR as a function of Li-6 enrichment in the two blanket options. Also shown is the attainable TBR in the case where the front flowing liquid layer is removed (bare FW case). This latter case is considered in order to assess the impact of the inclusion of the non-breeding 2 cm-thick Sn liquid layer on TBR.

In the LiPb/SiC blanket, the TBR is very sensitive to the Li-6 content in the presence of the Sn flowing liquid layer. TBR increases with Li-6 enrichment and reaches a value of ~1.52 at 90%Li-6. Increasing the Li-6 content tends to in increase the TBR through Li-6(n,α) reactions whose cross-section is large at low-energy neutrons that are slowed down by lead. The inclusion of the Sn layer adversely impacts tritium breeding since it limits the neutron multiplication effect caused by lead, particularly at low Li-6 enrichment (TBR is less by ~7% at 25% Li-6 and by ~0.3% at 90%Li-6). In the waste volume assessment given in section 3 we use 90% Li-6 enrichment for which the TBR is ~1.52 although lower Li-6 enrichment could give adequate local TBR (e.g. TBR~1.42 at 20% Li-6 enrichment).

In the Flibe/SiC blanket, TBR also increases at a lower rate with Li-6 enrichment in the presence of the Sn layer. At 25% Li-6 TBR is ~1.42 increasing to~1.46 at 90% Li-6. The inclusion of the Sn layer also decreases tritium breeding, particularly at low Li-6 enrichment, as shown in Fig. 1. In Section 3 we use a reference value of 25% Li-6 enrichment for which the TBR is ~1.42 (without Sn layer, it was shown that TBR with Flibe maximizes at 25% Li-6.)

Peak magnet radiation effects (at 10 MW/m^2 max. wall load) are shown in Table II. The End-of-life fast neutron fluence (E>0.1 MeV, *Limit: 1.00 x* 10^{19} n/cm^{2}) is the driving factor. In the Flibe/SiC blanket, the fast neutron fluence is slightly above the design limit whereas the corresponding value in the LiPb/SiC blanket is slightly below it. This marginal difference will not affect much the radwaste volume assessed in the following section with the assumption that the blanket/shield in both blanket options are optimized such that the TF coils are adequately protected.

3. RADWASE VOLUME IN THE Li-Pb/SiC AND FLIBE/SiC BLANKET OPTIONS

The peak end-of-life damage in the ferritic steel wall of the vacuum vessel is shown in Table III and is expressed in terms of accumulated dpa and helium production (appm) during the 30 year plant lifetime. The dpa values in both blanket options are less than the limit of 200 dpa in the IB and the OB sides. This makes the V.V. a lifetime component. Additionally, the accumulated helium production over 30 years is less than the limit of 1 appm for reweldability. This is a conservative limit for ferritic steel since it is more radiation-resistant than austenitic steel.

The peak damage rate in the SiC structure and expected lifetime of the FW/blanket and shield are shown in Table IV expressed in terms of dpa/FPY and FPY, respectively, for both blanket options. As shown, the lifetime of the shield in the Flibe/SiC blanket option is ~118 and ~526 FPY in the IB and OB side, respectively. Thus, the shield is considered as a permanent component when Flibe is used as the breeder/coolant in the FW/B/shield system. On the other hand, the corresponding lifetime in the LiPb/SiC blanket option is ~17 (IB) and 47 FPY (OB). This will necessitate replacing part of the shield (R-shield) in the inboard side once during the plant lifetime. Clearly the lifetime of the FW/Blanket is much shorter but still the Flibe/SiC blanket option offers longer lifetimes than those found in the Li-Pb/SiC blanket option. Note that the lifetime of the FW/blanket is shorter on the outboard side than on the inboard due to neutron wall load peaking that reaches its maximum at the outer side in the mid plane. The reverse is true for the shield component as a result of using thicker OB blankets.

The superiority of Flibe over Li-Pb as an attenuator can be seen from Table V [Ref. 5]. Damage to a ferritic steel-type structure is estimated as a function of the thickness of a front liquid flowing layer. The thickness required to reduce a particular damage parameter by an order of magnitude is estimated and is shown in Table V. Flibe is the best attenuator for the dpa damage parameter while Li-Pb is the best attenuator for helium and hydrogen production. Lithium does not have the attenuation capability of the other liquid breeders. Lithium and Li-Pb have the same poor attenuation characteristics for dpa.

Based on the above discussion and the results shown in Table IV, the frequency of component's replacement in the both the inboard and outboard side is estimated during the 30 year plant lifetime and the results are shown in Fig. 2 and Fig. 3, respectively. Frequency of replacement that is equal to unity implies that the component lasts the plant lifetime and is removed after 30 years for disposal.

As shown in Figures 2 and 3, the shield in the Flibe/SiC blanket option will last the plant lifetime while part of the shield (R-shield) in the Li-Pb/SiC blanket option will require one replacement in the inboard side during plant lifetime (frequency of replacement=2). The frequency of replacing the FW/blanket itself is nearly twice as much in the Li-Pb/SiC blanket as in the Flibe/SiC blanket.

From the frequency of component's replacement shown in Figs. 2 and 3, the total radwaste volume per unit height has been estimated in the two blanket options and the results are shown in Fig. 4. Note that the total structure waste volume is estimated as the sum of the structure content of each component multiplied by the number of times this component is replaced during the plant lifetime. Due to the higher frequency of replacement in the Li-Pb blanket option, the total SiC waste volume in the FW/blanket/shield system is lager than in the Flibe blanket option by ~60%. For the solid FW and for the Blanket, this excess in structure waste volume is larger (~65% and ~63%, respectively) as shown is Fig. 4. Note that the increase in the overall waste volume is lower than in the individual solid FW and blanket since the volume of the shield is relatively larger than the volume of these two components in a realistic fusion reactor.

4. CONCLUSIONS

Liquid tin has been suggested as the 2-cm thick front flowing liquid layer in CLiFF concept for high power density application. Two choices were selected for the conventional FW/blanket that follows the Sn liquid layer, namely: (1) LiPb/SiC blanket, and (2) Flibe/SiC blanket.

Because of the superior attenuation characteristics of Flibe over LiPb, this impacted the lifetime of the SiC structure used in both options. It is shown that Flibe is the best attenuator for the dpa damage parameter while LiPb is the best attenuator for helium and hydrogen production. In the present work, we assessed the lifetime of the SiC structure in the FW/Blanket and the shield in both blanket options. The end-of-life limit of 200 dpa is assumed (corresponding to ~3% burn-up).

The frequency of each component replacement is estimated based on 30-year plant lifetime. Comparison is made for the waste volume of replaced components in each option. It is shown that the shield can last the plant lifetime in the Flibe blanket while part of the shield in the LiPb blanket will require replacement. As for the FW/blanket, the frequency of its replacement in the LiPb blanket option is twice as much as in the Flibe blanket option. While the LiPb blanket option offers the advantage of not having a beryllium zone as is the case with the Flibe blanket option, the generated SiC waste with LiPb breeder is larger than in the Flibe blanket option by ~65% (solid FW), by ~63% (blanket zone) and by ~60% (the entire FW/B/Shield system). Note that there is no need to use beryllium multiplier in the LiPb blanket option since the TBR is already large at 90% Li-6 enrichment whereas the TBR in the Flibe blanket only improves upon including the Be multiplier zone.

The above estimates might change, based on the criterion used to determine the lifetime of the SiC composite structure. If He or burn up is the limit for lifetime, LiPb will be better shield than Flibe and conclusions for blanket waste volume could be reversed. The limiting factor for SiC lifetime is under investigation and input from materials community is envisioned [17].

ACKNOWLEDGMENT

This work is funded by the US Department of Energy under the Advanced Power Extraction Study (APEX) contract # DE-FG03-86ER52123

REFERENCES

1. M.A. Abdou and the APEX Team, On the Exploration of Innovative Concepts for Fusion Chamber Technology, Fusion Engineering and Design, vol. 54, issue 2, 2002, pp. 181-248.
2. M.A. Abdou and the APEX Team, Exploring Novel High Power Density Concepts For Attractive Fusion Systems, Fusion Engineering and Design, vol. 45, 1999, pp. 145-167.
3. M. A. Abdou, et al., On the Exploration of Innovative Concepts for Fusion Chamber Technology, APEX Interim Report**,** Vol. I & Vol. II, UCLA-ENG-99-206, UCLA-FNT-107, University of California, Los Angeles, November, 1999.
4. M.Z. Youssef, N.B. Morley, and D-K Sze, Nuclear Performance of the Thin-Liquid FW Concept of the CLiFF Design", Fusion Technology, Vol. 39 Number 2, part 2, 2001, pp. 839-845.
5. M.Z. Youssef and M.A. Abdou, Heat Deposition, Damage, and Tritium Breeding Characteristics in Thick Liquid Wall Blanket Concepts, Fusion Engineering and Desig*n*, 49-50, 2000, pp. 719- 725.

6. M.Z. Youssef, N. Morley, A. El-Azab, X-Ray Surface and Volumetric Heat Deposition and Tritium Breeding Issues in Liquid-Protected FW in High Power Density Devices, Fusion Technology, **3**4, 1998, pp. 697-705.
7. A. Ying, N. Morley, S. Smolentsev, K. Gulec, and P. Fogarty, Free Surface Heat transfer and Innovative Designs for Thin and Thick Liquid Walls, Fusion Engineering and Design, 49-50, 2000, pp. 397-406.
8. A. Ying, N. Morley, K. Gulec, B. Nelson, M.Z. Youssef, M.A. Abdou, Concept Description and Thermalhydraulics of Liquid Surface FW/Blankets for High Power Density Reactors, Fusion Technology, 34(N3), 1998, pp. 855-862.
9. N. C. Christofilos, Design for a High Power-Density Astron Reactor, J. Fusion Energy, 8, 1989, pp. 97-105.
10. R.W. Moir, Liquid First Wall For Magnetic Fusion Energy Configuration, Nuclear Fusion, 37, 1997, pp. 557-566.
11. R.W. Moir, Liquid Wall Inertial Fusion Energy Power Plants, Fusion Engineering and Design, 32-3, 1996, 93.
12. R.W. Moir, The Logic Behind Thick Liquid-Walled Fusion Concepts, Nucl. Eng. Des. 29, 1995, 34-42.
13. R.W. Moir, Liquid First Wall For Magnetic Fusion Energy Configuration, Nuclear Fusion, 37, 1997, pp. 557-566.
14. W. W. Engle, ANISN: A one dimensional discrete ordinates transport code with anisotropic scattering, Report K-1693, Union Carbide Corporation, 1967.
15. A.B. Pashchenko, "Completion of FENDL-1 and Start of FENDL-2," INDC(NDS)-352, IAEA Nuclear Data Section, International Atomic Energy Agency, March 1996.
16. F. Najmabadi, et al., Overview of the ARIES-RS Reversed-Shear Tokamak Power Plant Study, Fusion Engineering and Design, 38, 1997, 3-35.
17. S. Zinkle, private communication, Oak Ridge National Laboratory, United States, 2001.

Figure Captions

Figure 1: Variation in the Local Tritium Breeding Ratio (TBR) as a function of Li-6 Enrichment

Figure 2: Frequency of Component's Replacement during 30 years plant lifetime (Inboard)

Figure 3: Frequency of Component's Replacement during 30 years plant lifetime (Outboard)

Figure 4: Radwaste Volume per Unit Height (m3/m) after 30 years plant lifetime

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% SiC, 5% Coolant/Breeder (5) High-Temperature shield: 95% SiC, 5% Coolant/Breeder (6) 90% Breeder/Coolant, 10% SiC, In Flibe blanket, a 10-cm-thick zone is included (7) 100% SiC (8) Liquid Tin (9) 18% epoxy, 19% Cu, 3% Nb-Sn, 17% Liquid He-4, 43% SS316 LW

TABLE II: PEAK MAGNET RADIATION EFFECTS

	Flibe Blanket	**Li-Pb Blanket**
End-of-life fast neutron fluence, E>0.1 MeV,n/cm^2 Limit: 1.00 x 10^{19}		
Inboard Outboard	1.02 x 10^{19} 4.65 x 10^{17}	9.14 x 10^{18} 2.81 x 10^{17}
End-of-life insulator dose[(1)], Rads, Limit: 1.00 x 10^{11}		
Inboard Outboard	4.90 x 10^{9} 6.40 x 10^{7}	1.10 x 10^{10} 5.26 x 10^{7}
End-of-life Cu stabilizer dpa, Limit: 6 x 10^{-3}		
Inboard Outboard	2.19 x 10^{-3} 2.80x 10^{-5}	2.18 x 10^{-3} 1.59 x 10^{-5}
Peak winding pack power density, mW/cm^3 , Limit: 2		
Inboard Outboard	0.19 0.002	0.61 0.002

(1) Polyimid insulator is considered with thick inter-laminar shear under compression. Its end-of-life dose limit is shown to be 1.00 x 10^{11} Rads.

TABLE III: PEAK END-OF-LIFE DAMAGE IN THE FERRITIC STEEL WALL OF THE VACUUM VESSEL

	Flibe Blanket	**Li-Pb Blanket**
Displacement per atom, dpa		
Inboard Outboard	0.091 0.017	0.122 0.028
Helium production, appm		
Inboard Outboard	0.163 0.029	0.104 0.014

TABLE IV: PEAK DAMAGE RATE (DPA/FPY) AND EXPECTED LIFETIME FOR SIC STRUCTURE*

	Flibe Blanket			
	Inboard		**Outboard**	
	dpa per FPY	Lifetime FPY	dpa per FPY	Lifetime FPY
FW/Blk	73.2	2.73	89.6	2.23
Shield	1.7	***118***	0.38	***526***
	Li-Pb Blanket			
	Inboard		**Outboard**	
	dpa per FPY	Lifetime FPY	dpa per FPY	Lifetime FPY
FW/Blk	127.8	1.57	146.3	1.37
Shield	12.4	***16.1***	4.3	***47***

*Based on 200 DPA lifetime Limit

TABLE V: THE 10-FOLD THICKNESS* OF THE FLOWING LIQUID LAYER [REF. 5]

Damage Parameter	**Lithium**	**Flibe**	**Sn-Li**	**Li17-Pb83**
dpa	~58	~26	~36	~56
Helium Production	~46	~22	~21	~18
Hydrogen Production	~44	~22	~22	~19

* Thickness required reducing a response by an order of magnitude

TABLE VI: PEAK DAMAGE RATE (DPA/FPY) AND EXPECTED LIFETIME FOR SIC STRUCTURE*

	Flibe Blanket			
	Inboard		**Outboard**	
	dpa per FPY	Lifetime FPY	dpa per FPY	Lifetime FPY
FW/Blk	73.2	2.73	89.6	2.23
Shield	1.7	***118***	0.38	***526***
	Li-Pb Blanket			
	Inboard		**Outboard**	
	dpa per FPY	Lifetime FPY	dpa per FPY	Lifetime FPY
FW/Blk	127.8	1.57	146.3	1.37
Shield	12.4	***16.1***	4.3	***47***

*Based on 200 DPA lifetime Limit

MS#272-Youssef-Fig. 1

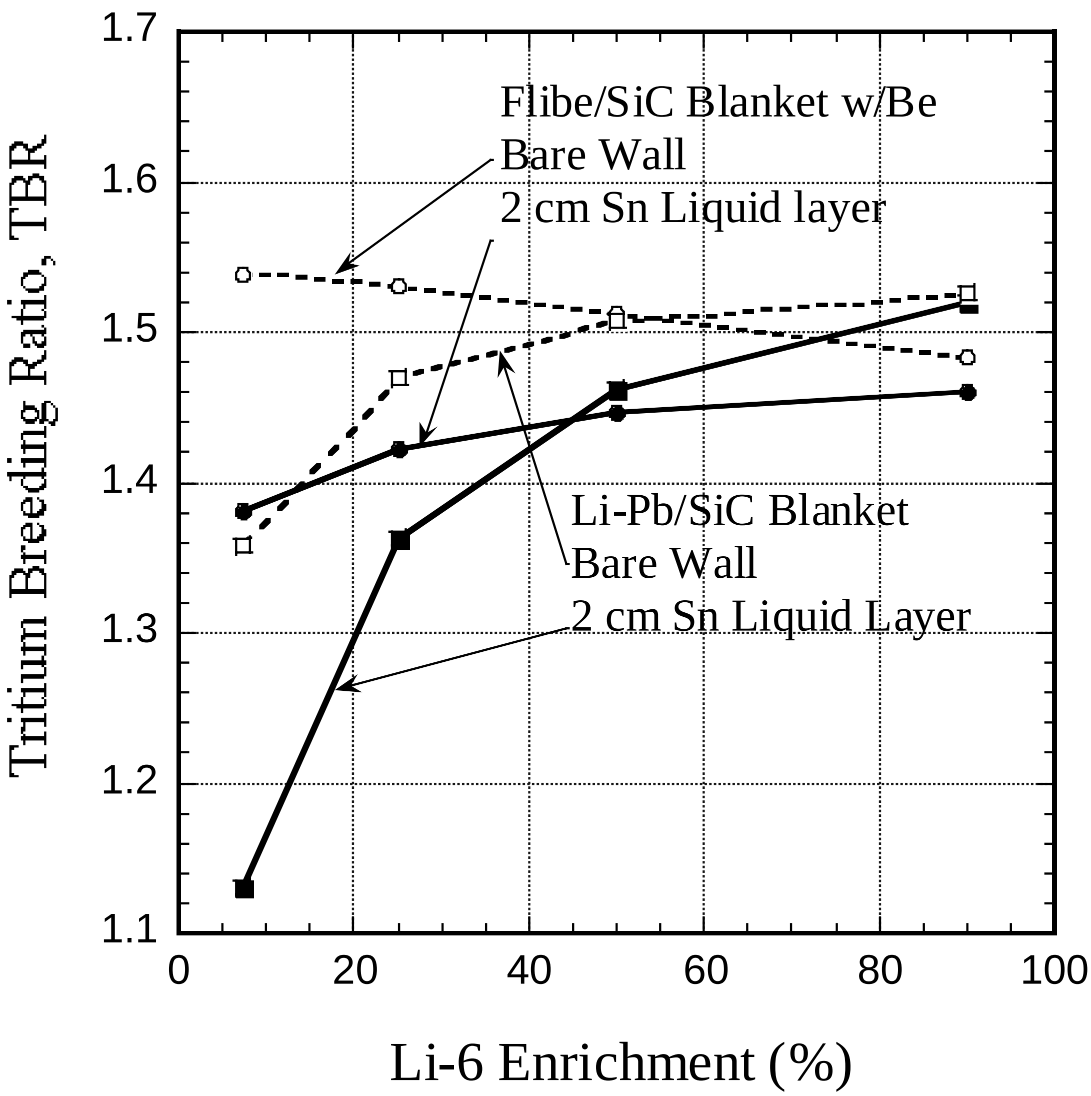

Figure 1: Variation in the Local Tritium Breeding Ratio (TBR) as a function of Li-6 Enrichment

MS#272-Youssef-Fig. 2

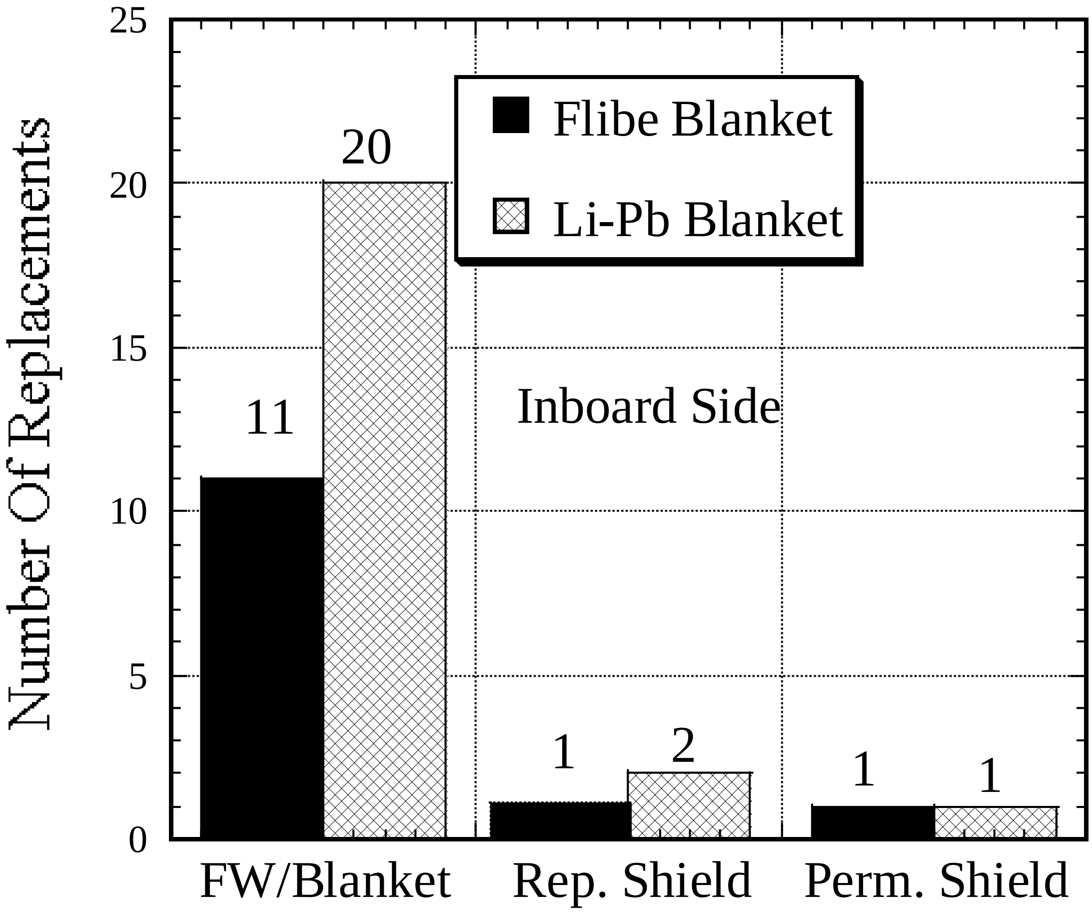

Figure 2: Frequency of Component's Replacement during 30 years plant lifetime (Inboard)

MS#272-Youssef-Fig. 3

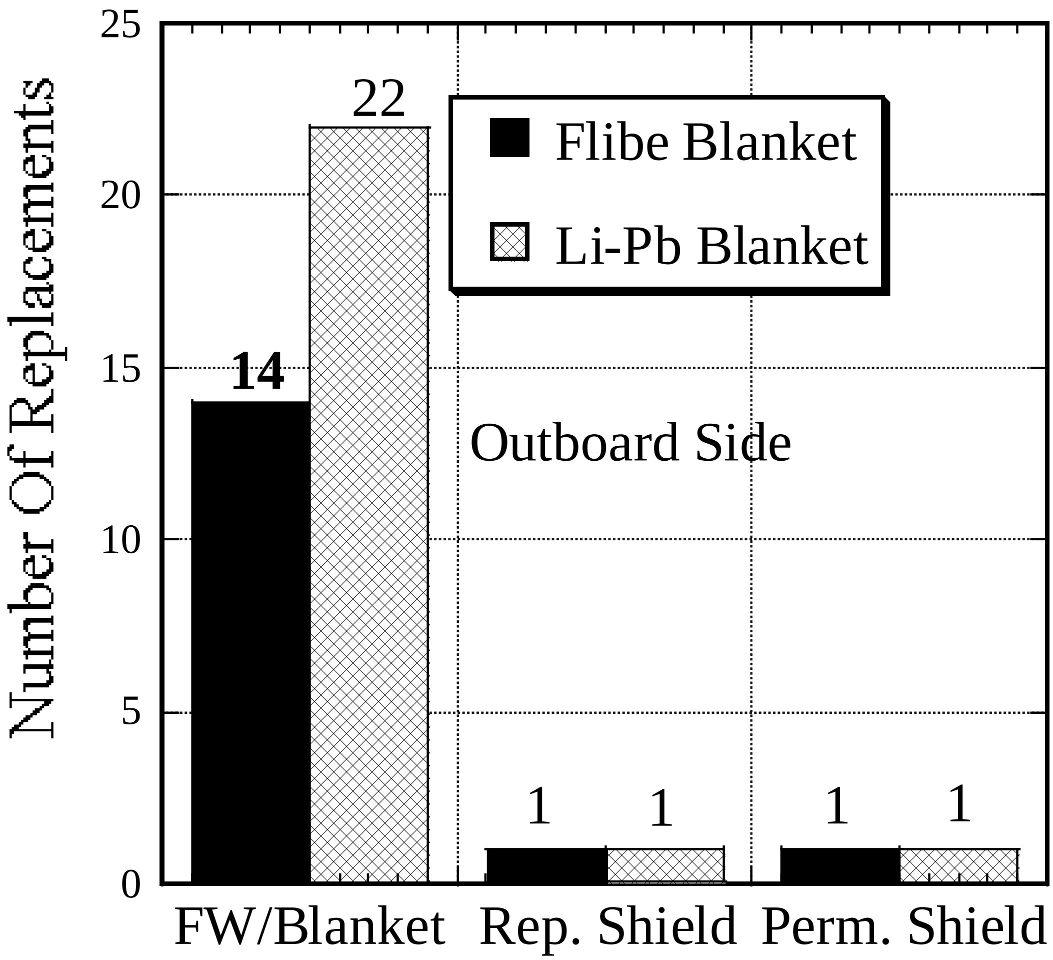

Figure 3: Frequency of Component's Replacement during 30 years plant lifetime (Outboard)

MS#272-Youssef-Fig. 4

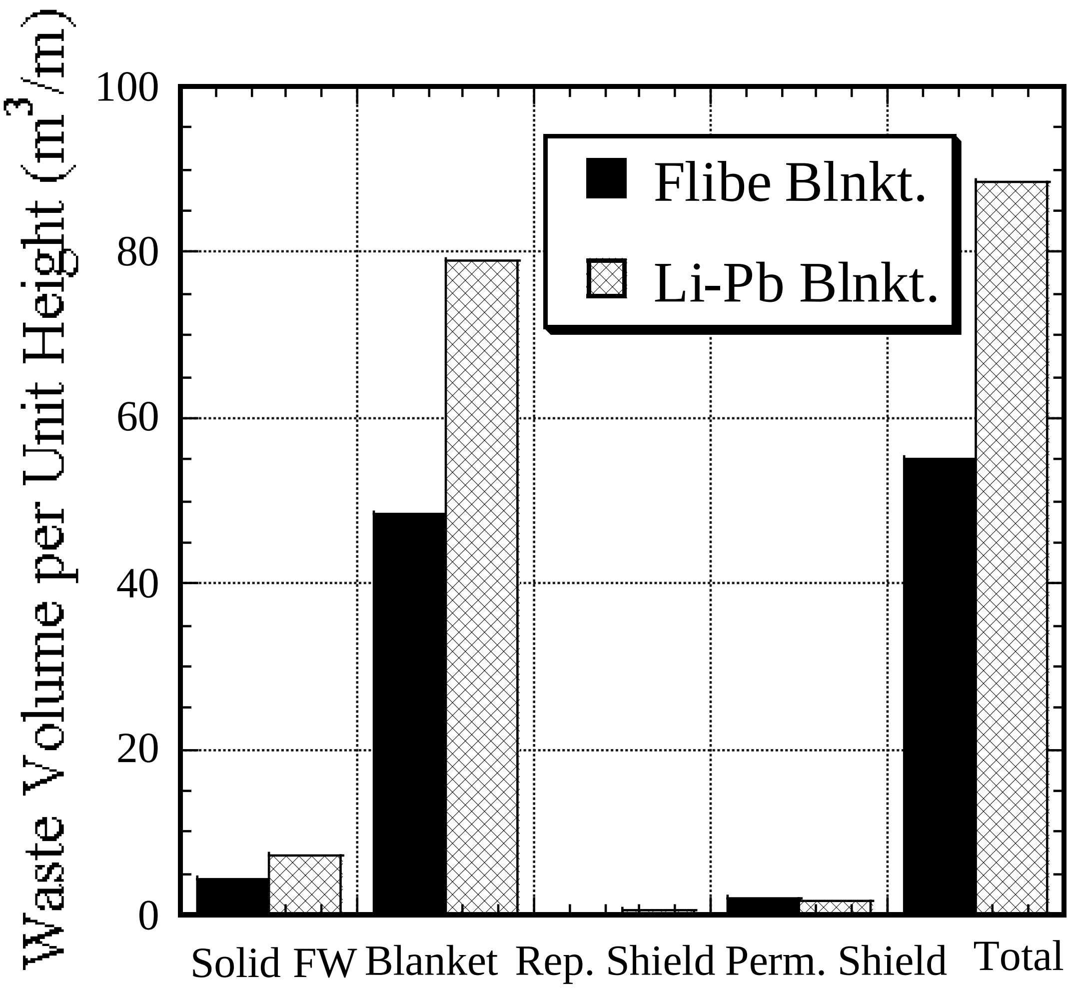

Figure 4: Radwaste Volume per Unit Height (m^3/m) after 30 years plant lifetime