A manuscript submitted to the 6th International Symposium on Fusion Nuclear Technology, April 7-12,
2001, San Diego, California

RADWASTE VOLUME IN LITHIUM AND FLIBE THICK LIQUID WALL AND COMPARISON TO CONVENTIONAL SW CONCEPTS

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

Among the advantages offered by the deployment of thick liquid walls (LW) in high power density reactors is the substantial reduction in radwaste volume and hazard that is mainly attributed to the extended lifetime of structural materials. In this paper, we quantitatively estimate the volume of the generated waste when different thick liquid walls are used. In particular, we make a comparison of the radwaste volume between lithium and Flibe as potential candidates for deployment as the thick liquid walls in high power density reactors (10 MW/m^2). In addition, the volume of the generated waste is compared to the corresponding volume in two conventional solid wall (SW) blankets with low wall load (LWL, 5 MW/m^2) and high wall load (HWL, 10 MW/m^2). In this assessment exercise, the blankets under consideration were optimized first such that adequate tritium breeding ratio (TBR) is obtained and the same level of magnet protection against radiation damage is reached. This initial optimization step was necessary to arrive at consistent comparisons. It is shown that using LWL conventional SW blanket generates ~10% more waste volume per unit height than that generated with the lithium LW concept while ~35% more waste volume is generated if the HWL conventional SW blanket is deployed. On the other hand, it is shown that the thick Li LW option generates total waste whose volume is a factor of ~1.3 larger than the one with the thick Flibe option which has superior neutron moderating capabilities compared to lithium.

RADWASTE VOLUME IN LITHIUM AND FLIBE THICK LIQUID WALL AND COMPARISON TO CONVENTIONAL SW CONCEPTS

M.Z. Youssef[1] and M.E. Sawan[2]
[1] 43-133 Engr. 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

1. INTRODUCTION

Recent studies in fusion technology [1-5] have focused on the deployment of thick liquid wall (LW) as a mean to protect solid structure from radiation damage and hence prolong components lifetime. In the APEX study [6-8] investigation is in progress to develop liquid wall concepts that have the capability for a high neutron wall load (~10 MW/m^2 maximum, 7 MW/m^2 average) and associated surface heat flux. A liquid wall concept is foreseen as a convective liquid layer introduced from the top through nozzles and flows poloidally driven by gravity and momentum. Both thin and thick LW concepts are considered in the study [9-10]. Because of the low atomic number of the candidate liquid walls (e.g. lithium), heat loads from X-rays are deposited over a measurable depth in the layer and thereby reduce the surface temperature [11]. The effect of the magnetic field on the flowing liquid layer and its impact on flow and heat transfer characteristics constitutes several design issues that are currently the subject of theoretical and experimental verifications within APEX activities [12-16].

In the present work, we present results on the advantages a thick liquid wall can offer in reducing the volume of disposed structural materials. It has been shown that a liquid wall of ~40 cm thick can reduce the damage parameters and activation in solid structure located behind the LW layer by ~ an order of magnitude [10]. The consequence is to increase component's lifetime, and hence decrease the frequency of component's replacement.

In a previous study [17], the radwaste volume and hazard in a thick LW concept (10 MW/m^2 wall load, 7 MW/m^2 average) were compared to the corresponding values in a conventional solid (SW) blanket subjected to a lower wall load (5 MW/m^2, 2.5 MW/m^2

average). Lithium was considered in both concepts as the breeder and the coolant with vanadium-alloy structure (V-4Cr-4Ti). In one case (denoted “Fixed Radii”), the plasma and FW radii were kept the same in both concepts with typical dimensions as those in ARIES-RS design [18]. In another case (denoted “Fixed Fusion Power”), the same fusion power was used and the plasma and FW radii were reduced by a factor of 2 in the LW concept and hence the wall load became twice as much as in the SW concept. It was shown that in both LW configurations, substantial reduction was achieved in radwaste volume and hazard.

In the present study, the “Fixed Radii” configuration was considered with Flibe (Li_2BeF_4) used as the coolant and breeder in the LW concept along with ferritic steel structure (Flibe/FS). Comparison is made to the corresponding waste volume when lithium/(V-4Cr-4Ti) is used instead, as reported in Ref. 17. Furthermore, a comparison is also made to the case where the conventional Li/V SW blanket is exposed to same high neutron wall load (10 MW/m^2) as the LW blanket. In the latter case, we assume that future advancement in material science could offer a material that can withstand as high a wall load as the LW concept.

In Section 2, we briefly summarize the results from the previous analysis [Ref. 17]. Comparison of the radwaste volume in the Li/V LW concept to the low- and high-wall load Li/V SW concepts is given is section 3. The impact of using Flibe in the LW concept instead of lithium on the volume of the generated waste is discussed in Section 4. The conclusions from the present study are given in Section 5.

2. RADWASE VOLUME WITH LITHIUM/V-ALLOYS BLANKET CONCEPTS

To have a consistent comparison of radwaste volume and hazard, the procedures followed [17] to assess radwaste volume are as follows: (1) vary breeding zone thickness such that TBR equal to or greater than 1.25 is obtained, (2) vary the shield thickness to achieve the same acceptable radiation damage level in the TF magnet while keeping the vacuum vessel (VV) and magnet thickness and composition the same, (3) estimate the lifetime of each component based on reaching 200 dpa damage limit, (4) based on a 30 years plant lifetime, estimate the frequency of replacement for each component, and (5) add volumes of all disposed components.

It was shown that the end-of-life fast neutron (E>0.1 MeV) fluence limit of 10^{19} n/cm^2 is the main driver for magnet shielding [17]. 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 (90% structure, 10% Li) is replaced at the 200 dpa damage limit. The rest of the structure is used as filler and is assumed to last the plant lifetime. The results shown here and in Ref. 17 assume that the 2% structure in the LW zone is replaced at the 200-dpa damage level. This structure contents account for the presence of nozzles, dividers, etc. to control the flow of the liquid in the LW concept. The radial build and the optimized dimensions of the blanket and shield on the inboard and outboard sides can be found in Ref. 17.

The waste volume per unit height (m^3/m) for each component is shown in Fig. 1. The LW option with Fixed Radii generates a total waste volume that is ~10% less than the conventional SW concept for comparable machine size and twice as much thermal power. Note however that the FW/B waste volume in the conventional SW concept is ~4 times larger than in the LW Fixed Radii option. On the other hand, the LW option with Fixed Fusion Power generates less than half the total waste that is generated with the conventional SW concept due to the effect of machine compactness. The waste volume from the shield dominates the total waste volume (~50-63%). The disposed structure from the FW/B contributes ~22% to total waste volume in the conventional FW/B and ~6% in the LW options.

Figure 2 shows the waste volume per GW$_{th}$. This is a convenient measure that gives the volume of radioactive waste generated per unit thermal power produced. The waste volume per GW$_{th}$ is almost the same for both LW options. The FW/B structure waste volume per GW$_{th}$ in the conventional SW concept is larger than that in the LW concepts by a factor of ~7. However, the total structure waste volume per GW$_{th}$ in the conventional concept is ~2.14 larger than that in both LW options. A factor of 2 of this is attributed to the lower wall load. Thus, for a given fusion power, if one can design compact and smaller machines, one can realize an added attractiveness from the viewpoint of waste volume reduction.

3. WASTE VOLUME OF HIGH AND LOW WALL LOAD SW CONCEPTS AND COMPARISON TO LI/V LW CONCEPT

An interesting question is how the waste volume in the LW and SW concepts differ if both have a high wall load (max. of 10 MW/m^2) in the same configuration. For that purpose, we denote the high-wall load SW concept as SW HWL and the low-wall load (5 MW/m^2) solid wall concept as SW LWL. We compared the structure waste volume of these two conventional blankets to the thick (Li/V) LW concept.

The number of component replacement on the inboard (IB) and outboard (OB) side during the 30-year plant lifetime is shown in Fig. 3 and 4, respectively. The conventional SW HWL FW/Blanket has the highest replacement frequency. The lithium LW option has higher replacement frequency for the FW/B and R-shield than the conventional SW LWL FW/B.

Fig. 5 shows the structure waste volume per unit height. Waste volumes are comparable for the permanent components but are different for the replaceable FW/B and R-shield due to differences in structure content and frequency of replacement. The lithium LW option gives FW/B waste that is factors of ~4 and ~7 less than for the SW LWL and HWL blankets, respectively. The total waste volume with the SW LWL and SW HWL blankets is larger than with the lithium LW option by ~10% and 35%, respectively.

The structure waste volume per GW_{th} is much higher. The total structure waste volume per GW_{th} for the conventional SW LWL blanket is larger than with the Lithium LW option by a factor of ~2.14 as shown in Fig. 6 and discussed earlier (see Fig. 2) primarily due to its reduced thermal power. On the other hand, the total waste with the SW HWL option is larger than with the LW option by only ~30%.

It is interesting that structure in the replaceable components (FW/B, R-shield) of the SW HWL concept are replaced twice as much as compared to the SW LWL case by virtue of having twice as much wall load (i.e. twice as much waste volume, see Fig. 5). The waste volume/GW_{th} of these components are thus comparable, as shown in Fig. 6.

4. RADWASTE VOLUME IN LW CONCEPT WITH FLIBE AND COMPARISON TO CONCEPTS WITH LITHIUM

The analysis for the LW concept was extended to use Flibe instead of lithium as a breeder and coolant and ferritic steel (FS) as structure. The attenuation characteristics of Flibe for radiation are superior to lithium [10]. This impacts the structure lifetime and waste volume. Table I gives the radial build after the TBR and shielding optimization procedures referred to earlier. Because Li is superior to Flibe from tritium breeding viewpoint, the blanket thickness is smaller than the corresponding thickness with Flibe (17/32 cm IB/OB, as compared to 37/47 cm). On the other hand, the shielding thickness is larger with Li compared to Flibe for the same damage level in the TF coils (112/100 cm IB/OB, as compared to 79/65 cm). All components behind the Flibe liquid FW/B are permanent. The structure waste volume in the Flibe FW/B zone is twice that in the lithium FW/B due to its larger thickness needed to improve the TBR, as shown in Fig. 7. However, the total waste volume with lithium is larger than with Flibe by ~30% due to the much larger waste generated from the replaceable and permanent shield with the lithium option.

In the conventional Low WL and the High WL blankets, the waste volume generated in the FW/B zone is a factor of ~2 and ~4 larger than the corresponding volume in the Flibe LW option, respectively, as shown in Fig. 8. On the other hand, the total waste volume in the conventional Low WL and in the conventional High WL is larger than the corresponding volume in the Flibe LW option by ~40% and 75%, respectively. As for waste volume per unit power (see Fig. 9), the waste volume/GWth in the conventional Low WL FW/B is larger than the corresponding volume with the Flibe LW option by a factor of ~2.5 and by ~50% in the conventional Low WL and High WL options, respectively.

5. CONCLUSIONS

Structural waste volume was compared in a thick LW Li/V-4Cr-4Ti system with maximum neutron wall load of 10 MW/m^2 and in a conventional SW Li/V blanket with maximum neutron wall load of 5 MW/m^2. The comparison was made for two configurations, namely; (1) “Fixed Radii” where the LW and SW FW/B concepts have the same plasma and FW radii, and (2) “Fixed Fusion Power” where the LW FW/B has half the plasma and FW radii and hence twice the neutron wall load of the conventional SW FW/B. Shield optimization was performed to reach the same acceptable damage parameters in the magnet. The objective is to assess the advantage of using thick LW blanket option over convention SW system in reducing disposed waste volume.

Results from most recent analysis [17] indicated that the total waste volume from the machine (including magnets and VV) is dominated by waste from the shield (~50-63%). The FW/B contributes ~22 % to the total waste in the conventional blanket and ~6% in the two LW options. The structure waste volume per GW$_{th}$ is almost the same for both LW options. The waste volume per GW$_{th}$ of the conventional SW FW/B is larger than the blanket waste in both LW options by a factor of seven. However, the total waste volume per GW$_{th}$ in the conventional SW option is ~2.14 larger than the value in both LW options.

In the present work, we extend the analysis to include comparison of waste volume in thick Li/V LW option to both low wall load (LWL, 5 MW/m^2) and high wall load (HWL, 10 MW/m^2) conventional SW blankets. Using low wall low, LWL, conventional blanket generates more waste volume per unit height than that generated with the liquid wall (LW) concept by ~10%. Using high neutron wall load (HWL) conventional SW blanket generates more waste volume per unit height than that generated with the liquid wall (LW) concept by ~35%.

Other comparison made in the present work is comparing the waste volume in thick Flibe LW (with ferritic steel structure) to thick Li LW in the Fixed Radii configuration. It is shown that the thick Li option generates total waste whose volume is a factor of ~1.3 larger than with the thick Flibe option which has superior neutron moderating capabilities compared to lithium.

ACKNOWLEDGMENT

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

REFERENCES

1. N. C. Christofilos, Design for a high power-density Astron reactor, J. Fusion Energy, vol. 8 (1989) 97-105.
2. R.W. Moir, Liquid first wall for magnetic fusion energy configuration, Nuclear Fusion 37 (1997) 557-566.
3. R.W. Moir, Liquid wall inertial fusion energy power plants, Fusion Eng. & Des. 32-3 (1996) 93.
4. R.W. Moir, The logic behind thick liquid-walled fusion concepts, Nucl. Eng. Des. 29, (1995) 34-42.
5. R.W. Moir, Liquid first wall for magnetic fusion energy configuration, Nuclear Fusion 37 (1997) 557-566.
6. M.A. Abdou and the APEX, On the exploration of innovative concepts for fusion chamber technology, fusion engineering and design, vol. 54, issue 2 (2001) 181-248.
7. M.A. Abdou and the APEX, Exploring novel high power density concepts for attractive fusion systems, Fusion Engineering and Design, vol. 45 (1999) 145-167.
8. 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.
9. 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) 839-845.
10. M.Z. Youssef and M.A. Abdou, Heat deposition, damage, and tritium breeding characteristics in thick liquid wall blanket concepts, Fusion Engr. & Design 49-50 (2000) 719-725.
11. 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 Technolog*y*, **3**4 (1998) 697-705.

12. S. Smolentsev, B. Freeze, N. Morley, M. Abdou, Experimental study of turbulent heat transfer in supercritical open channel water flow, this issue, ISFNT-6, 2002
13. B. Freeze. M. Dagher, T. Sketchley, N. Morley, S. Smolentsev. M. Abdou, FLIHY experimental facilities for studying open channel turbulent flows and heat transfer, this issue, ISFNT-6, 2002
14. D. Gao, N. Morley, M. Abdou, V. Dhir, Numerical study of stability of liquid metal falling film flows in a varying spanwise magnetic field, this issue, ISFNT-6, 2002
15. H. L. Huang, A. Ying, S. Smolentsev, N. Morley, X.Y. Luo, M. Abdou, 3D MHD free surface fluid flow simulation based on magnetic-field induction equations, this issue, ISFNT-6, 2002
16. N. B. Morley and S. Smolentsev, Recent results from modeling and experiments for liquid wall fluid dynamics, this issue, ISFNT-6, 2002, Invited Paper
17. M.Z. Youssef, M.S. Sawan, and H. Khater, Comparison Of Radwaste Volume And Hazard In LW And Conventional SW Concepts, Proceeding of the 19th IEEE/NPSS Symposium on Fusion Engineering (SOFE), January 22-25, 2002, Atlantic City, NJ USA
18. F. Najmabadi, et al., Overview of the ARIES-RS reversed-shear tokamak power plant study, Fusion Engr. & Design, 38 (1997) 3-35.

FIGURES CAPTIONS

Fig. 1: Waste Volume Per Unit Height (m^3/m) in the Li/V Concepts (Ref. 17).

Fig. 2: Waste Volume Per Unit Power (m^3/GW_{th}) in the Li/V Concepts (Ref. 17)

Fig. 3: Frequency of Component Replacement in the Li/V Concepts (inboard) During the 30-year Plant Lifetime with Two Different Wall Loads for the Conventional Blanket.

Fig. 4: Frequency of Component Replacement in the Li/V concepts (inboard) during the 30-year Plant Lifetime with Two Different Wall Loads for the Conventional Blanket.

Fig. 5: Waste Volume per Unit Height (m^3/m) in the Li/V Concepts with Two Different Wall Loads for the Conventional Blanket

Fig. 6: Waste Volume per Unit Thermal Power (m^3/GW_{th}) in the Li/V Concepts with Two Different Wall Loads for the Conventional Blanket

Fig. 7: Waste Volume per Unit Height (m^3/m) in the Li/V and Flibe/Ferritic Steel Liquid Wall Concepts.

Fig. 8: Waste Volume per Unit Height (m^3/m) in the Flibe/Ferritic Steel Concepts with Two Different Wall Loads for the Conventional Blanket

Fig. 9: Waste Volume per Unit Thermal Power (m^3/GW_{th}) in the Flibe/Ferritic Steel Concepts with Two Different Wall Loads for the Conventional Blanket

Table I: Radial Build of the Blankets Considered
(Measured from Center of Tokamak Torus)

	Inner Radii, cm		
	Conventional Solid FW/B ($5\ MW/m^2$)	Liquid FW/Blanket ($10\ MW/m^2$)	
		Li/V	Flibe/FS
Magnet	208.7	205	218
Gap	258.7	255	268
V.V.	263.7	260	273
Shield	283.7	280	293
Blanket	388.7	392	372
Solid FW	408.7	--	--
Scrap-off	409	409	409
Plasma	414	414	414
Scrap-off	690	690	690
Solid FW	695	--	--
Blanket	695.3	695	695
Shield	735.3	727	742
V.V.	825.3	827	807
Gap	855.3	857	837
Magnet	870.3	872	852
Outer Radius	920.3	922	902

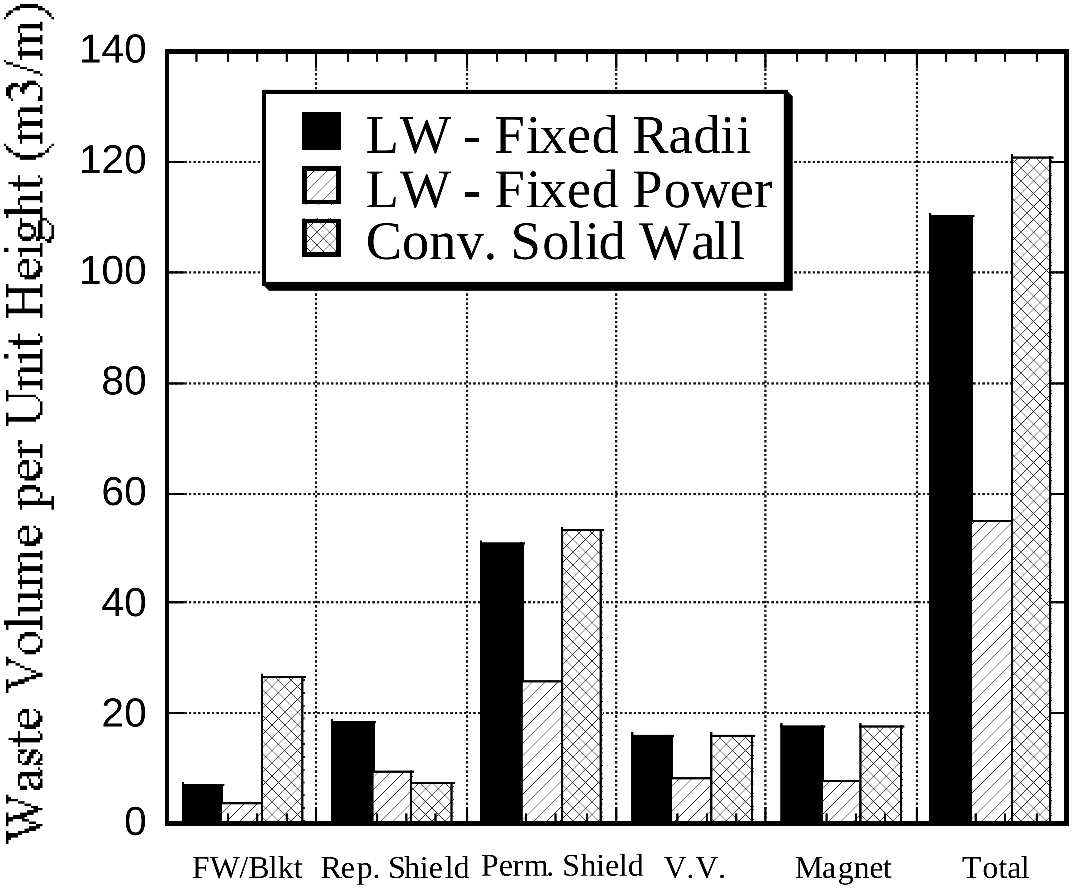

Fig. 1: Waste Volume Per Unit Height (m^3/m) in the Li/V Concepts (Ref. 17).

MS#271-Youssef-Fig. 2

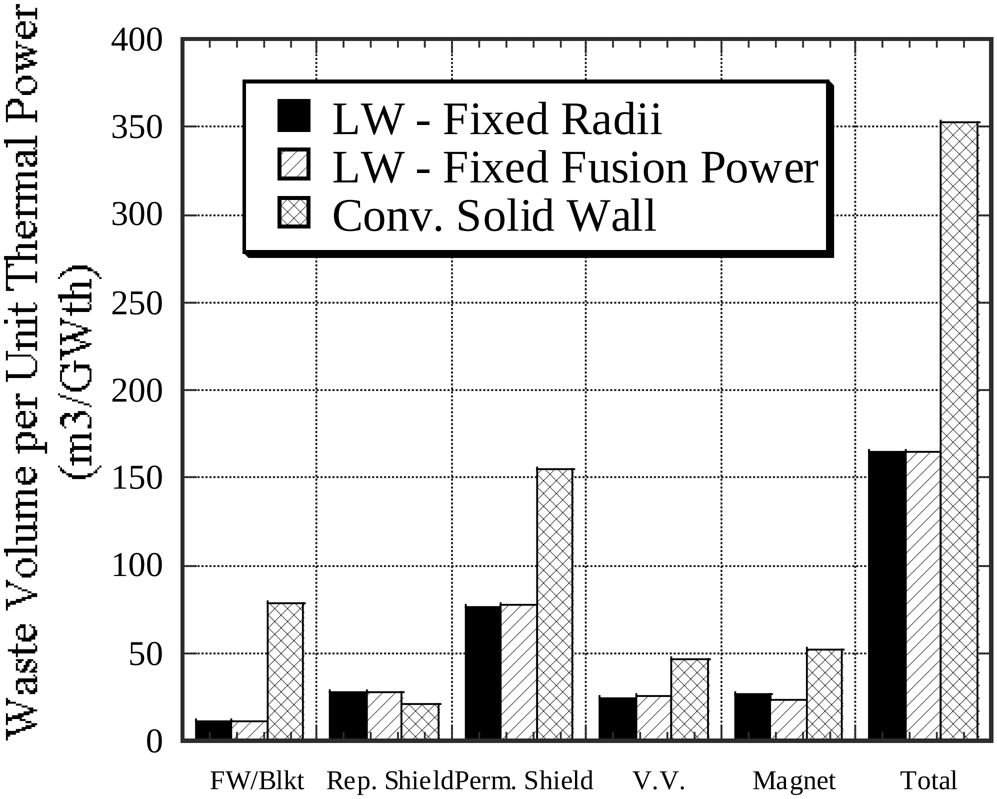

Fig. 2: Waste Volume Per Unit Power (m^3/GW_{th}) in the Li/V Concepts (Ref. 17)

MS#271-Youssef-Fig. 3

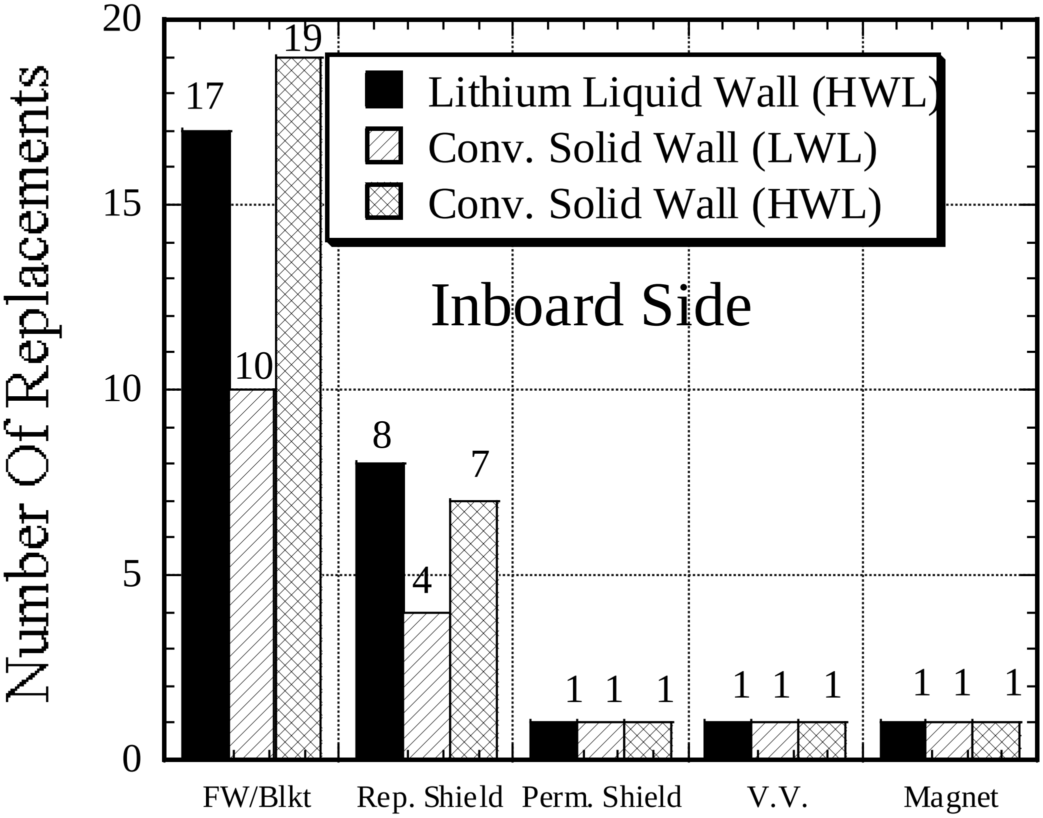

Fig. 3: Frequency of Component Replacement in the Li/V Concepts (inboard) during the 30-year Plant Lifetime with Two Different Wall Loads for the Conventional Blanket.

MS#271-Youssef-Fig. 4

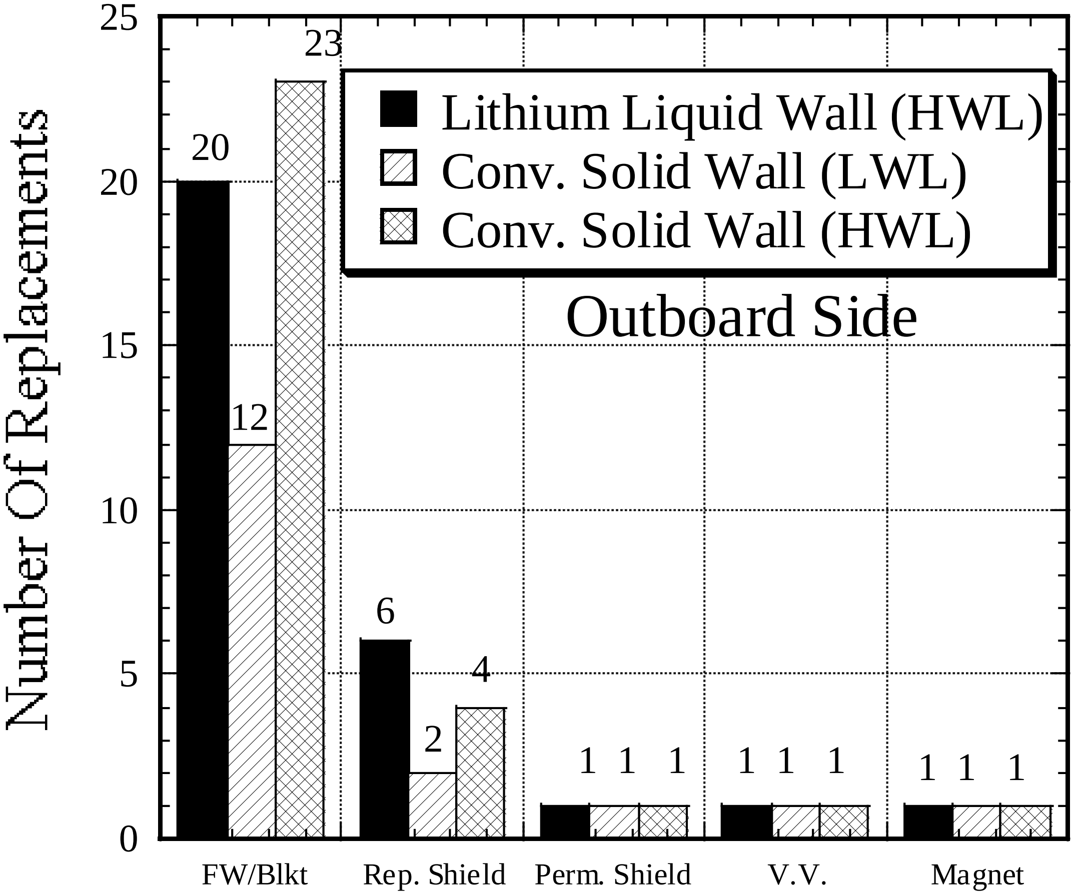

Fig. 4: Frequency of Component Replacement in the Li/V concepts (inboard) during the 30-year Plant Lifetime with Two Different Wall Loads for the Conventional Blanket.

MS#271-Youssef-Fig. 5

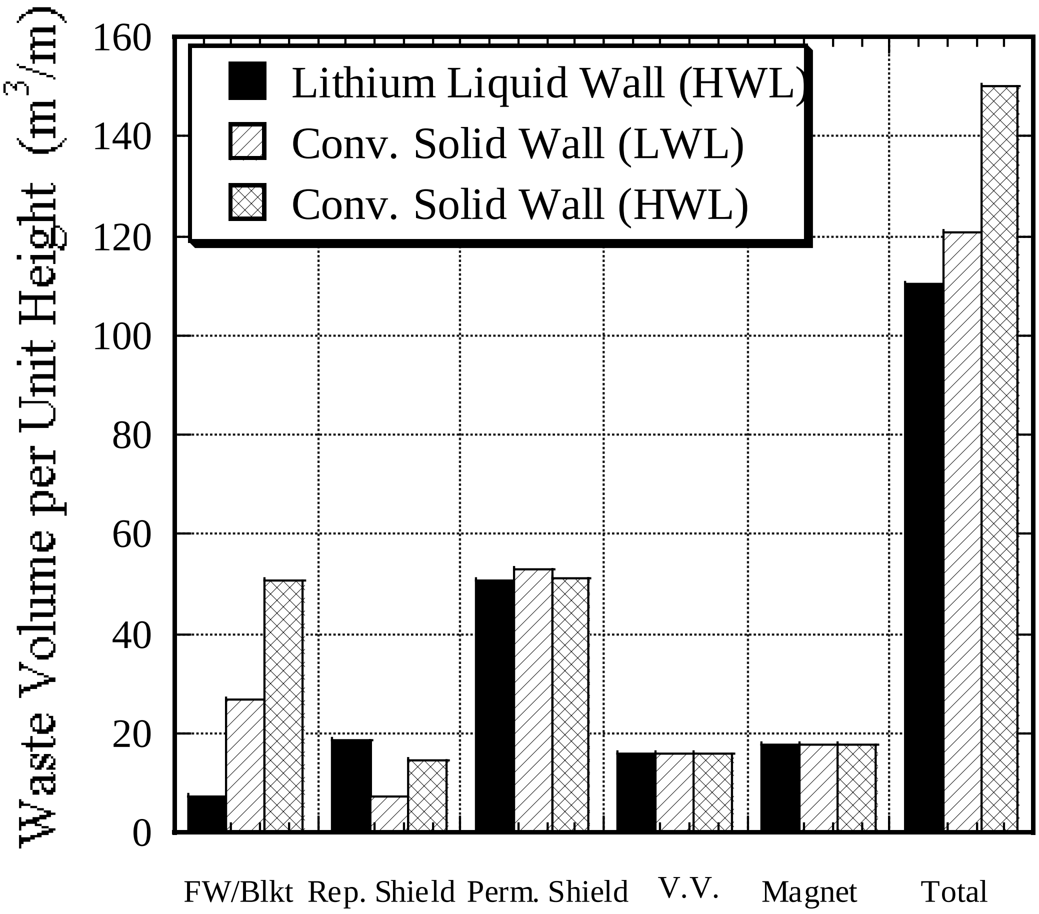

Fig. 5: Waste Volume per Unit Height (m^3/m) in the Li/V Concepts with Two Different Wall Loads for the Conventional Blanket

MS#271-Youssef-6

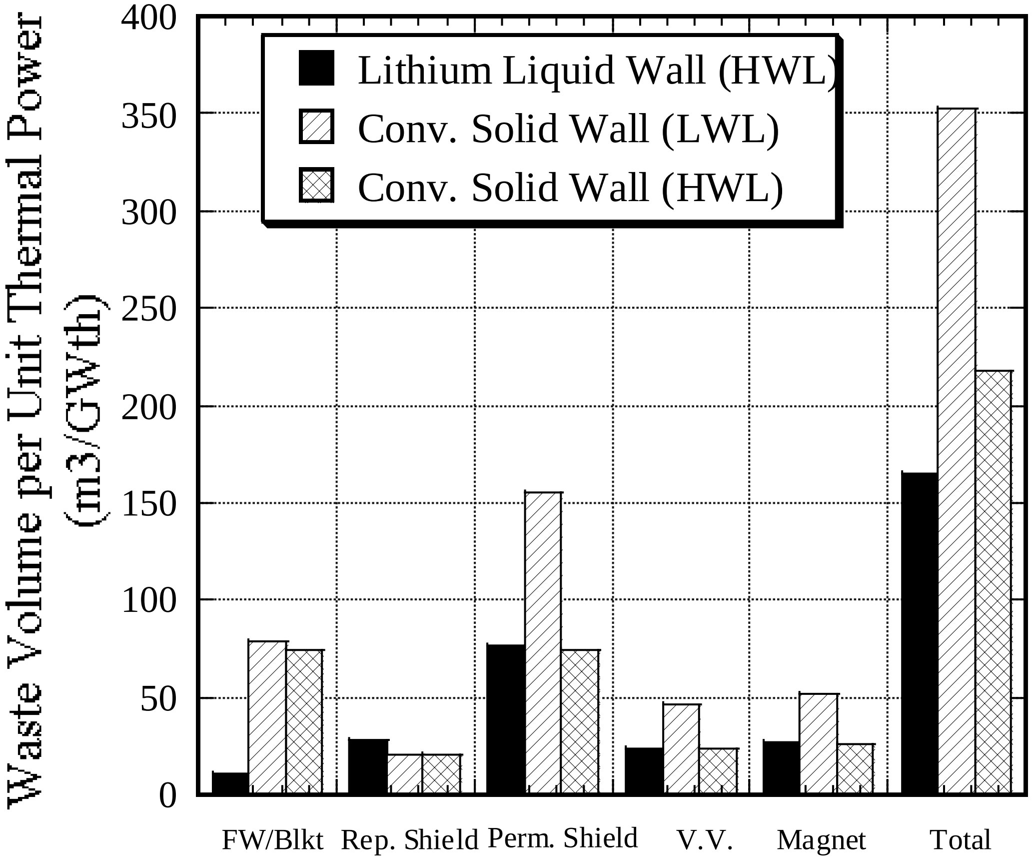

Fig. 6: Waste Volume per Unit Thermal Power (m3/GWth) in the Li/V Concepts with Two Different Wall Loads for the Conventional Blanket

MS#271-Youssef-Fig. 7

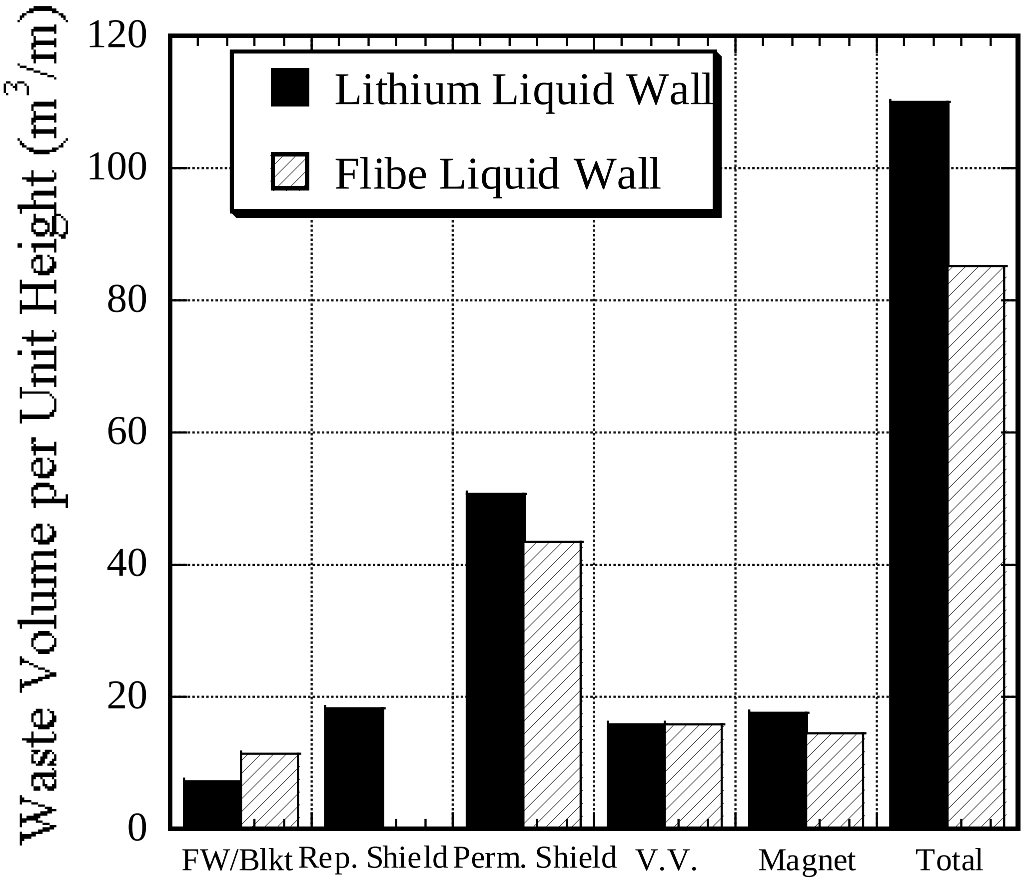

Fig. 7: Waste Volume per Unit Height (m^3/m) in the Li/V and Flibe/Ferritic Steel Liquid Wall Concepts.

MS#271-Youssef-Fig. 8

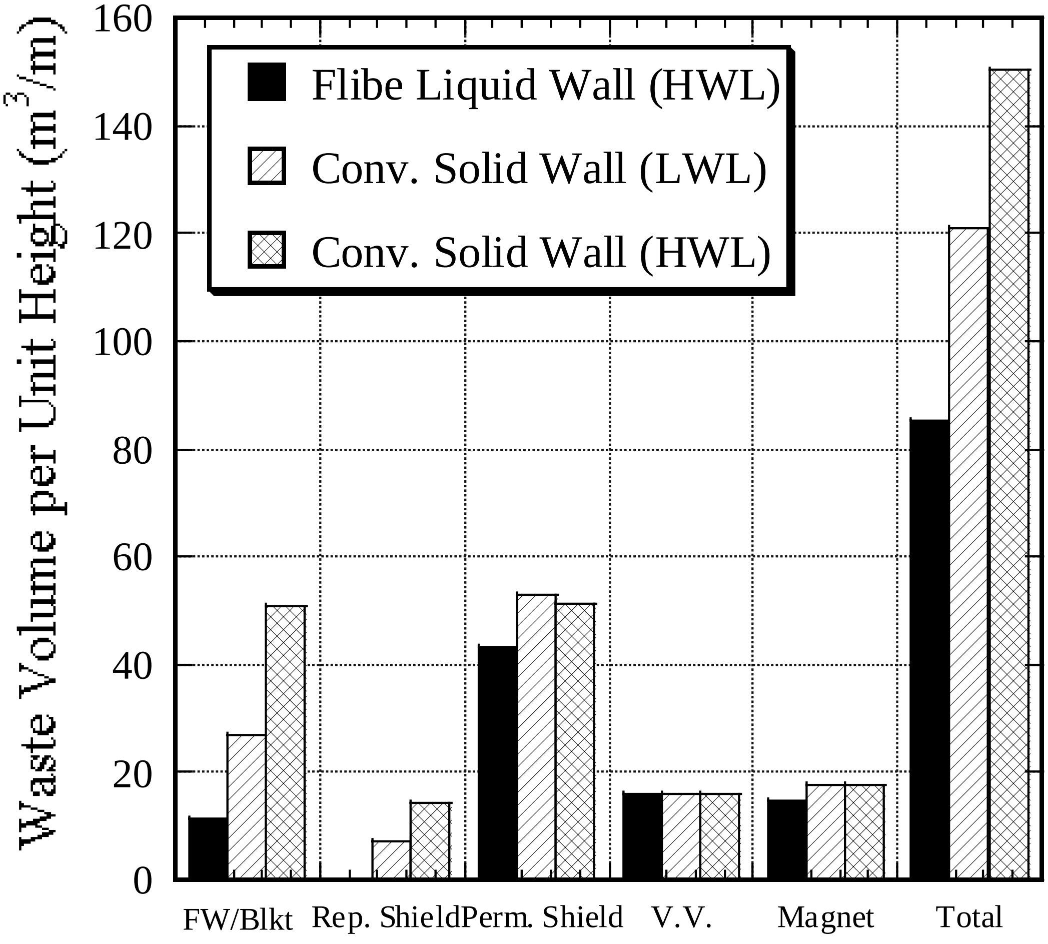

Fig. 8: Waste Volume per Unit Height (m^3/m) in the Flibe/Ferritic Steel Concepts with Two Different Wall Loads for the Conventional Blanket

MS#271-Youssef-Fig. 9

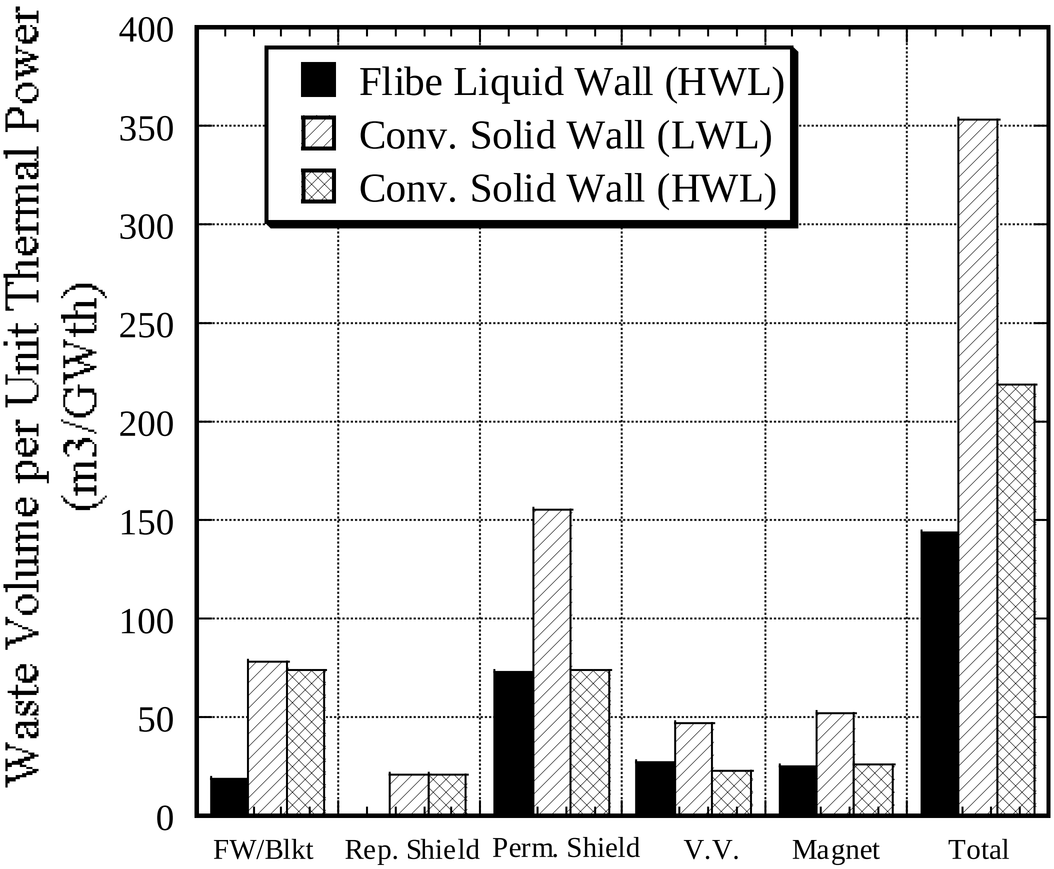

Fig. 9: Waste Volume per Unit Thermal Power (m^3/GW_{th}) in the Flibe/Ferritic Steel Concepts with Two Different Wall Loads for the Conventional Blanket