Comparison of Radwaste Volume and Hazard in Liquid Wall and Conventional Solid Wall Concepts

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***Abstract*—In this paper, we quantitatively assess the advantages offered by thick liquid wall (LW) concepts over conventional solid wall (SW) concepts in terms of the substantial reduction in radiation damage as well as activation to solid structure with subsequent reduction in radwaste volume and hazard. The conventional SW FW/blanket considered is made of Li/V with peak neutron wall load of 5 MW/m^2 (3.5 MW/m^2 ave.) and is compared to a thick liquid lithium with peak neutron wall load of 10 MW/m^2 (7 MW/m^2 ave.). "Fixed Radii" and "Fixed Fusion Power" configurations are considered. To have a consistent comparison, the two blankets were optimized first such that adequate tritium breeding ratio (TBR) is obtained and the same level of magnet protection against radiation damage is reached.**

I. INTRODUCTION

Thick liquid wall (LW) concepts under investigation in the APEX study [1-5] for high power density fusion reactors offer several advantages over conventional solid wall (SW) concepts, namely; (1) substantial reduction in radiation damage and hence extending solid components' lifetime, and (2) substantial reduction in activated structural components with subsequent reduction in radwaste volume and hazard. It was shown that a 40 cm thick LW leads to an order of magnitude reduction in the damage parameters and activation of the solid wall located behind it [5]. Studies on the deployment of liquid walls in fusion reactors for FW protection have been the subject of several investigations [6-9]. In the present work, we quantitatively address these advantages in a consistent manner. The conventional SW FW/blanket considered is made of Li/V-4Cr-4Ti with peak neutron wall load of 5 MW/m^2 (3.5 MW/m^2 ave.). This blanket is compared to a thick liquid lithium FW (with ~2% V alloy structure to account for nozzles, flow dividers, etc.) with peak wall load of 10 MW/m^2 (7 MW/m^2 ave.). In the two concepts, the plasma and FW radii are the same as in ARIES-RS [10]. This configuration is denoted "Fixed Radii" case. In another configuration (denoted "Fixed Fusion Power" case), the same thick liquid lithium FW is placed in a compact machine with plasma and FW radii reduced by a factor of 2 and same fusion power as the conventional blanket to achieve the 10 MW/m^2 peak neutron wall load.

For a consistent comparison of radwaste volume and hazard, the following procedure was followed: (1) vary breeding zone thickness such that a 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 a 200 dpa damage limit, (4) estimate the frequency of replacement for each component based on a 30 year plant lifetime, and (5) add volumes of all disposed components.

Section II gives the assessment of radwaste volume and hazard in the two configurations referred to earlier for the liquid Li/V FW concept and the conventional Li/V blanket. Concluding remarks are given in Section III.

II. RADWASTE VOLUME AND HAZARD IN THE LI/V LIQUID WALL AND SOLID WALL BLANKETS

A. *Waste Volume*

The radial build and composition of the LW blanket and the conventional SW blanket are shown in Table I after optimizing the two blankets for TBR and satisfying the same damage criteria in the magnets.

TABLE I
RADIAL BUILDS OF THE BLANKETS CONSIDERED
(MEASURED FROM CENTER OF TOKAMAK TORUS)

	Inner Radii (cm)		
	Conventional Solid Wall FW/Blanket	Liquid Wall FW/Blanket	
		Fixed Radii	Fixed Fusion Power
Magnet	208.7	205	1.5
Gap	258.7	255	--
V.V.	263.7	260	51.5
Shield	283.7	280	71.5
Blanket	388.7	392	189.5
Solid FW	408.7	--	--
Scrape-off	409	409	204.5
Plasma	414	414	207
Scrape-off	690	690	345
Solid FW	695	--	--
Blanket	695.3	695	347.5
Shield	735.3	727	379.5
V.V.	825.3	827	479.5
Gap	855.3	857	509.5
Magnet	870.3	872	514.5
Outer Radius	920.3	922	564.5

TABLE II
PEAK MAGNET RADIATION EFFECTS
(AFTER SHIELD OPTIMIZATION)

	Liquid wall FW/Blanket		Conventional Solid Wall FW/Blanket
	Fixed FW Radii	Fixed Fusion Power	
End-of-life fast neutron fluence (E>0.1 MeV), n/cm^2 Limit: 1.00 x 10^{19}			
Inboard	1.00 x 10^{19}	9.63 x 10^{18}	7.83 x 10^{18}
Outboard	1.00 x 10^{19}	9.86 x 10^{18}	7.87 x 10^{18}
End-of-life insulator dose, Rads (Limit: 1.00 x 10^{11})			
Inboard	1.60 x 10^{10}	1.48 x 10^{10}	1.45 x 10^{10}
Outboard	1.33 x 10^{10}	1.22 x 10^{10}	1.19 x 10^{10}
End-of-life Cu stabilizer dpa (Limit: 6 x 10^{-3})			
Inboard	4.33 x 10^{-3}	3.92 x 10^{-3}	3.24 x 10^{-3}
Outboard	4.26 x 10^{-3}	3.92 x 10^{-3}	3.19 x 10^{-3}
Peak winding pack power density, mW/cm^3 (Limit: 2)			
Inboard	0.76	0.72	0.62
Outboard	0.61	0.55	0.49

Table II gives the peak magnet radiation effects after shield optimization. As shown, the upper limit for the end-of-life neutron fluence is not exceeded. This fluence is the dominant factor in determining whether or not magnet protection criteria are satisfied as compared to other damage parameters.

We assumed that a structural component should be replaced once the damage limit of 200 dpa is reached. The frequency of a component replacement is estimated based on a plant lifetime of 30 years. Note that the shield is considered to be composed of a replaceable front part (R-shield) and a permanent part (P-shield) that stays the lifetime of the plant. It is assumed that only 5% of the structure in the replaceable 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. Also, three cases were considered in estimating the waste volume in the LW concept. They are: (1) no structure is assumed in the LW zone, (2) 2% structure in the LW zone is assumed to last the lifetime of the plant, and (3) 2% structure in the LW zone is replaced at the 200 dpa damage limit. The results shown here correspond to the last case.

Figures 1 and 2 show the frequency of component replacement in the inboard and outboard regions, respectively. The LW options have the same replacement frequencies for the FW/B and the structure in the R-shield since the neutron wall load is fixed in these options. These frequencies are higher than in the conventional SW concept. This is expected since the LW concepts are subjected to twice as much wall load as in the conventional SW concept. Note that the frequencies of replacement for these parts are larger in the outboard side as compared to the inboard side.

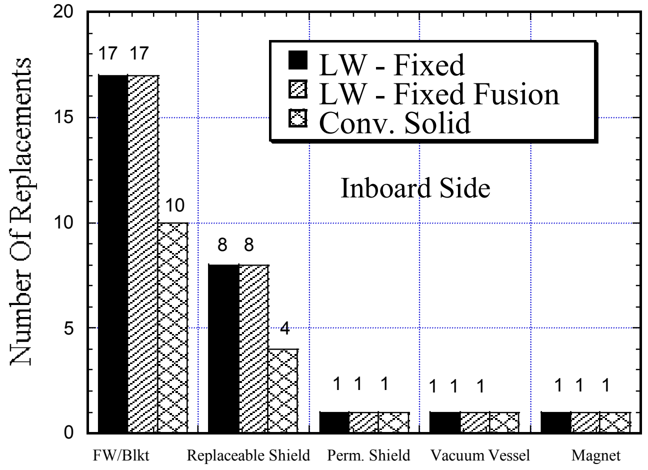

Fig. 1. Frequency of component replacement in the Li/V concepts (inboard).

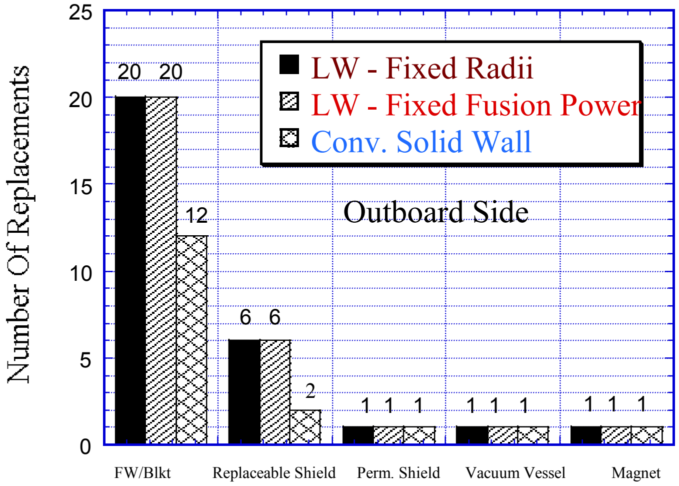

Fig. 2. Frequency of component replacement in the Li/V concepts (outboard).

The waste volume per unit height (m^3/m) for each component is shown in Fig. 3. 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.

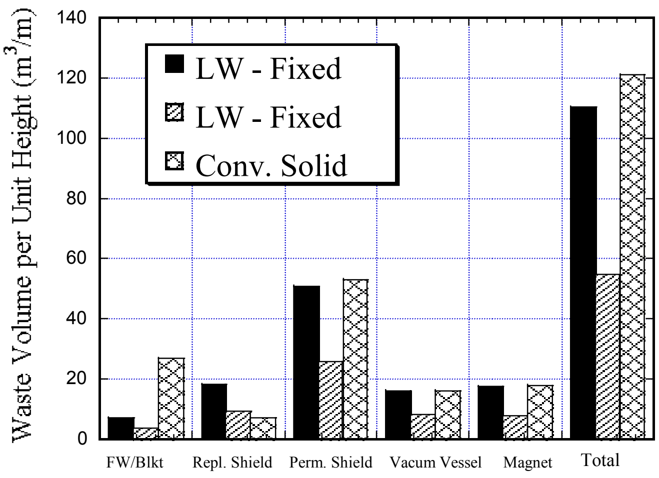

Fig. 3. Waste volume per unit height (m^3/m) in the Li/V concepts.

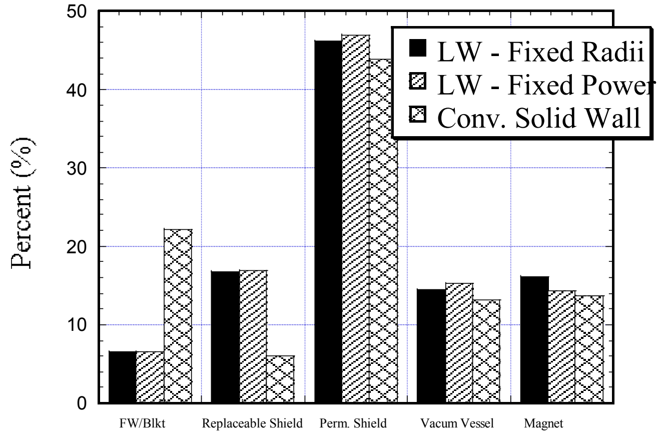

Fig. 4. Percentage of replaced structure volume from each component to the total volume of disposed structure in the Li/V concepts.

The waste volume from the shield dominates the total waste volume (~50-63%). The disposed structure from the FW/B contributes ~22% of the total waste volume in the conventional FW/B and ~6% in the LW options (see Fig. 4).

A good figure-of-merit for comparison is the waste volume per unit thermal power. This is depicted in Fig. 5. 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 SW 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.

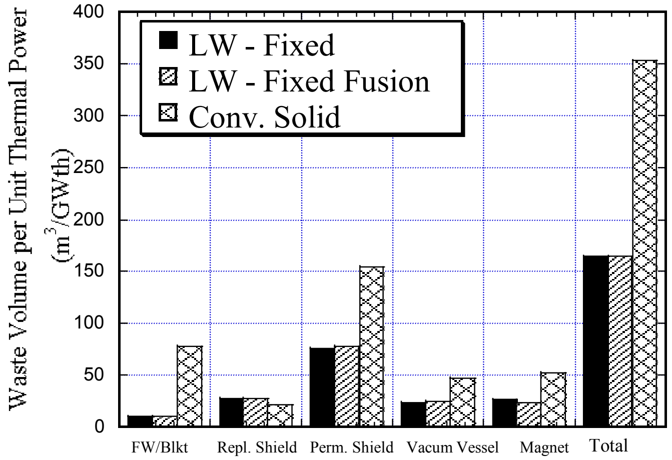

Fig. 5. Waste volume per unit thermal power (m^3/GW_{th}) in the Li/V concepts.

B. *Waste Disposal Rating, Activity, and Decay Heat*

The waste disposal ratings (WDR) of the concepts considered are shown in Fig. 6 based on Fetter's limits [11]. The WDR depends primarily on the total fluence level that each component is exposed to. The results for the two LW options are almost identical. As shown in Fig. 6, the WDR values for the LW and conventional SW concepts are comparable because the replaceable components are replaced at the same fluence (dpa level) and the permanent components are designed to the same fluence or cumulative damage level. All components are classified as Class C low-level waste. Hence, regarding radwaste, the main attractiveness of LW concepts is the reduction of waste volume while the WDR remains nearly the same.

The activity and decay heat per MW_{th} are comparable for the LW and the conventional SW options for the permanent components (see Figures 7 and 8). Large differences occur for

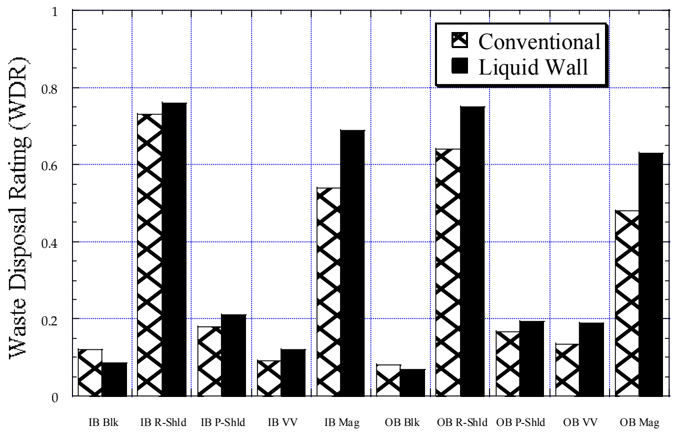

Fig. 6. Waste disposal rating (Fetter's limits) in the Li/V concepts.

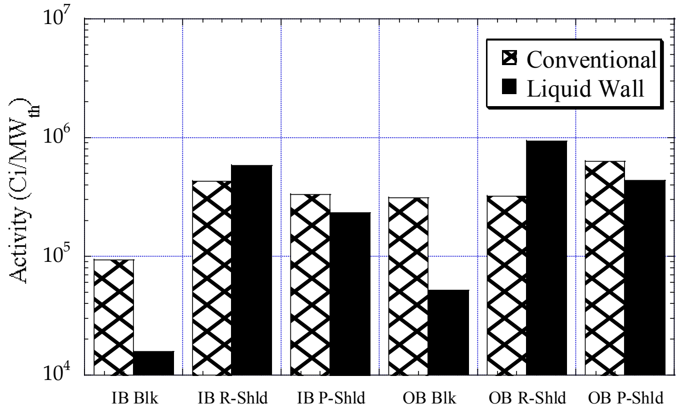

Fig. 7. Activity at shutdown in Li/V concepts.

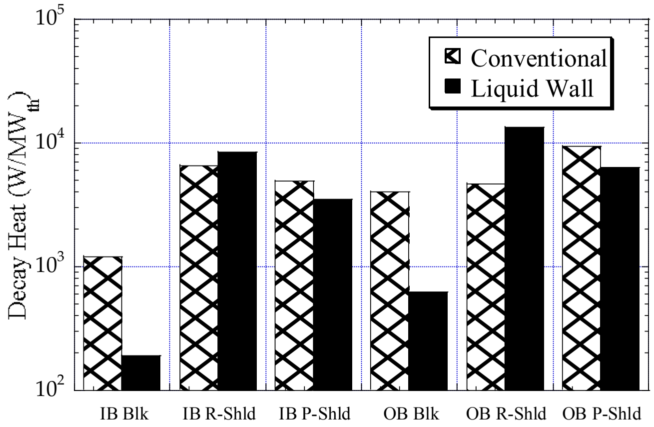

Fig. 8. Decay heat at shutdown in Li/V concepts.

the replaceable shield, which has larger volume in the LW option due to the poor shielding by the LW. In addition, values in the FW/B zone of the SW are much higher due to the much larger structure content.

III. CONCLUDING REMARKS

Structural waste volume and hazard were 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 have the same plasma and FW radii, and (2) "Fixed Fusion Power" with the LW FW/B having half the plasma and FW radii and hence twice the neutron wall load of the conventional SW FW/B. Shield optimization was performed to satisfy the same acceptable damage parameters in the magnet. The objectives are to quantify the advantage of using the thick LW blanket option over a conventional SW system in reducing disposed waste volume and its hazard.

The analysis indicates 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% of the total waste volume in the conventional SW 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 that 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. Regarding waste disposal rating (WDR), the results for the two LW options are identical. The WDR values for the LW and conventional SW concepts are comparable. All components are classified as Class C low level waste. Values for activity and decay heat per MW$_{th}$ are comparable for the LW and conventional SW blanket options for the permanent components. However, values in the FW/B zone of the SW are much higher due to the much larger structure content.

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