Activation Assessment for IFE Thin Liquid Wall Materials and Proposed Variations for Liquid Waste Minimization

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ABSTRACT

Heavy ion beam driven inertial fusion energy (IFE) power plants employ liquid wall materials to protect the structure against the energetic x-rays, ions, and debris emitted from the target following each shot. The objective of this assessment is to identify the radiological issues of the candidate liquid wall materials (Pb, LiPb, Sn, and Flibe) using the ARIES-IFE radiation chamber environment. The issues to be addressed include the radioactivity level and liquid waste minimization for waste management. Specifically, the liquids are evaluated with regard to the Class C limitation for waste disposal, a top-level requirement for all ARIES power plant designs. Two extreme cases were analyzed; the worst case is separation of the liquid wall material (highest radiation exposure) and the breeder (lowest radiation exposure), and the best case is the mixing of the two liquid streams. Both tangential and porous wall injection schemes were examined. Pb and LiPb are more radioactive than Sn and Flibe. For the liquid breeder system, the porous wall injection scheme with mixed liquid flows results in the lowest waste disposal rating and smallest waste stream.

I. INTRODUCTION

The most advanced approaches that have the greatest potential of meeting near term IFE requirements are utilizing indirect drive targets with heavy ion drivers and direct drive targets with laser drivers. The emphasis of the present study is on the heavy ion driver option and associated chamber technology. In heavy ion beam (HIB) designs, multiple beams focus at a central spot where DT targets, that are repetitively injected into the chamber at 4-6 times per second, are illuminated to initiate ignition and burn. It is widely recognized that liquid walls (LW) provide an attractive solution to the challenging material issues facing HIB applications. Thin or thick LWs could protect the solid walls against the highly energetic target x-rays and debris (carrying 30% of the energy yield) and therefore improve the reliability of the structural components. A chamber buffer gas is not essential as the LW slows down the target debris and helps mitigate the effect of the shock waves on the structure. It is estimated that for 460 MJ target yield and rep-rate of 4 Hz, approximately 3 MW/m^2 neutron wall loading is expected at the wall of a 6-m radius chamber[1]. During normal operation, the LW material passes through the chamber and gets irradiated for a period of time, then exits the chamber to spend a short time in the outer loop while being cooled and processed before returning back to the chamber. The cycle repeats for the entire plant life (~50 y). At the end of operation, the liquid is removed for disposal or reuse by the nuclear industry for similar applications. A safety concern regarding the use of LW for IFE applications relates to the activation of the thin film irradiated with the highest chamber neutron flux and the difficult of dealing with large amounts of radioactive waste after decommissioning the power plants.

The LW specifics are design dependent. Lead LW was proposed for the Prometheus solid breeder blanket design[2]. An alternate candidate for similar blanket concepts would be Sn. To simplify the design, a number of liquid breeder studies employed the same breeding material for the LW (LiPb[3,4], Flibe[5], and Li[6]). Just recently, two more liquid breeders were under consideration: $Li_{25}Sn_{75}$ and Flinabe ($NaF+LiF+BeF_2$). From the activation viewpoint, LiSn and Flinabe exhibit similar behavior to Sn and Flibe, respectively. No major activation problems were expected for the Li breeder. In this analysis, we considered two representative liquid breeders (LiPb and Flibe) and two LW materials (Pb and Sn) for liquid and solid breeder concepts, respectively. As discussed shortly, both tangential and porous wall injection schemes were investigated. Since the goal of the ARIES-IFE study is to define the design space rather than develop a point design, we examined two extreme activation cases: 1) separate LW material and tritium breeder, and 2) mix of the two liquid streams. This report highlights the LW and breeder cycles with emphasis on the activation issues associated with various routing of the flowing liquids and their residence times inside the IFE chamber. A paper[7] summarizing this work has been submitted to the 15th Topical Meeting on Technology of Fusion Energy to be held in Washington D.C. on November 17-21, 2002.

II. LIQUID WALL CYCLE AND SUPPLY METHODS

In this section, we describe the LW supply methods and the cycle that transfers the fusion energy deposited in the liquid to the power conversion system. By surveying the liquid supply options and chamber configurations, two supply methods seemed practical to consider for the thin LW: tangential injection and porous wall injection. A preset requirement judged necessary for the viability of the proposed methods is the ability of the thin liquid film to regenerate itself and cover the bare or thin spots within a fraction of a second before firing the next shot. Experiments are underway at the Georgia Institute of Technology[8,9] to access the feasibility of both methods.

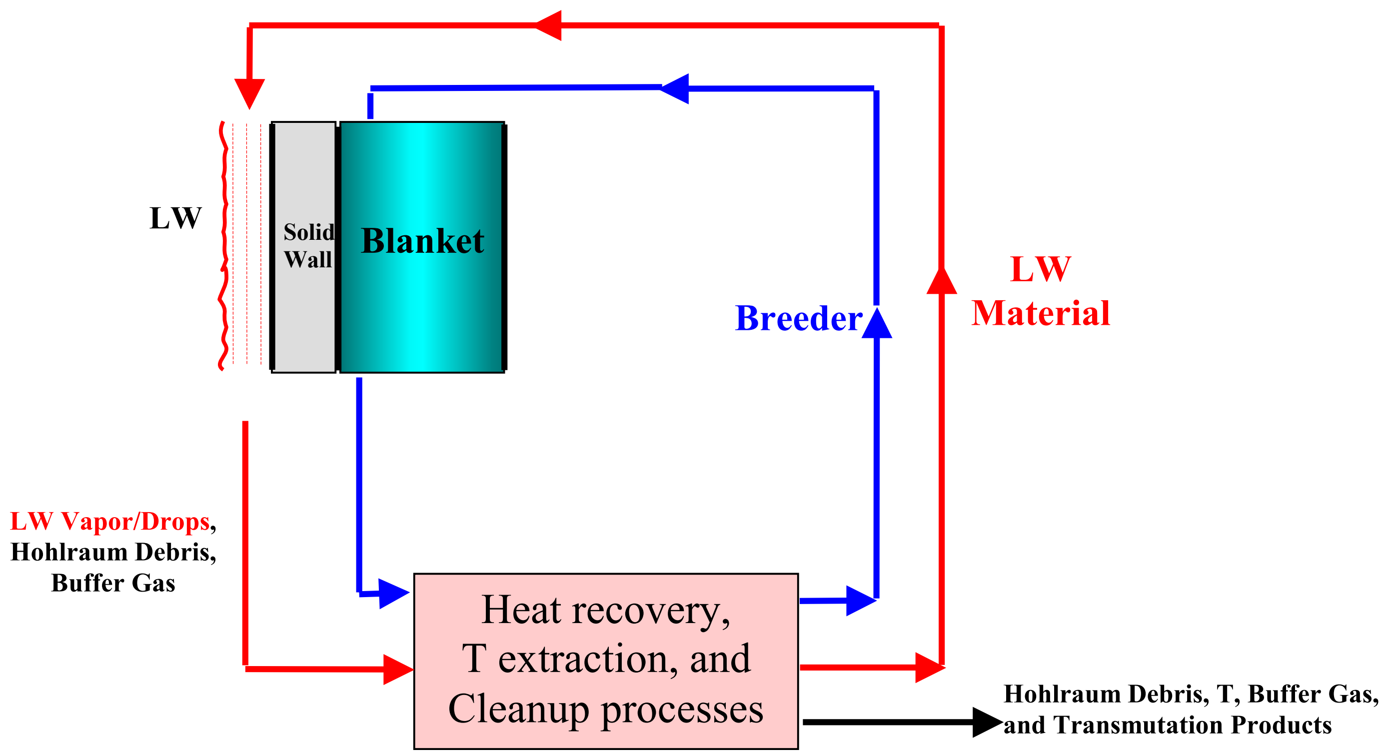

Figure 1. Liquid wall cycle for tangential injection scheme (no outside mixing of LW and breeding materials).

II.1 Tangential Injection Scheme

The flow schematic of the liquid is shown in Figure 1. Here, the LW does not mix with the breeder contained in the blanket, representing the worst activation case for the LW material. The assumption is that the LW fluid is injected tangential to the chamber wall, passes through the chamber while irradiated for a design-dependent period of time, then exits the chamber and remains only a short time in the outer loop for reprocessing before returning to the chamber.

II.2 Porous Wall Injection Scheme

The HIBALL[3], Osiris[5], and Prometheus[2] designs utilized this scheme to protect the solid wall. The liquid seeps through a SiC (or C) porous wall and maintains a wetted surface at all times. A supply channel (or bank of tubes) could provide the porous wall with the necessary liquid. Figures 2 and 3 illustrate the LW flow diagram for solid and liquid breeder blanket concepts, respectively. The design option of Fig. 3 employs the same breeding material for the LW. The case of different liquids would resemble the solid breeder case from the activation point for view. For liquid breeder blankets, it is highly recommended to route the liquid exiting the supply channel through the blanket to increase ΔT and enhance the thermal conversion efficiency.

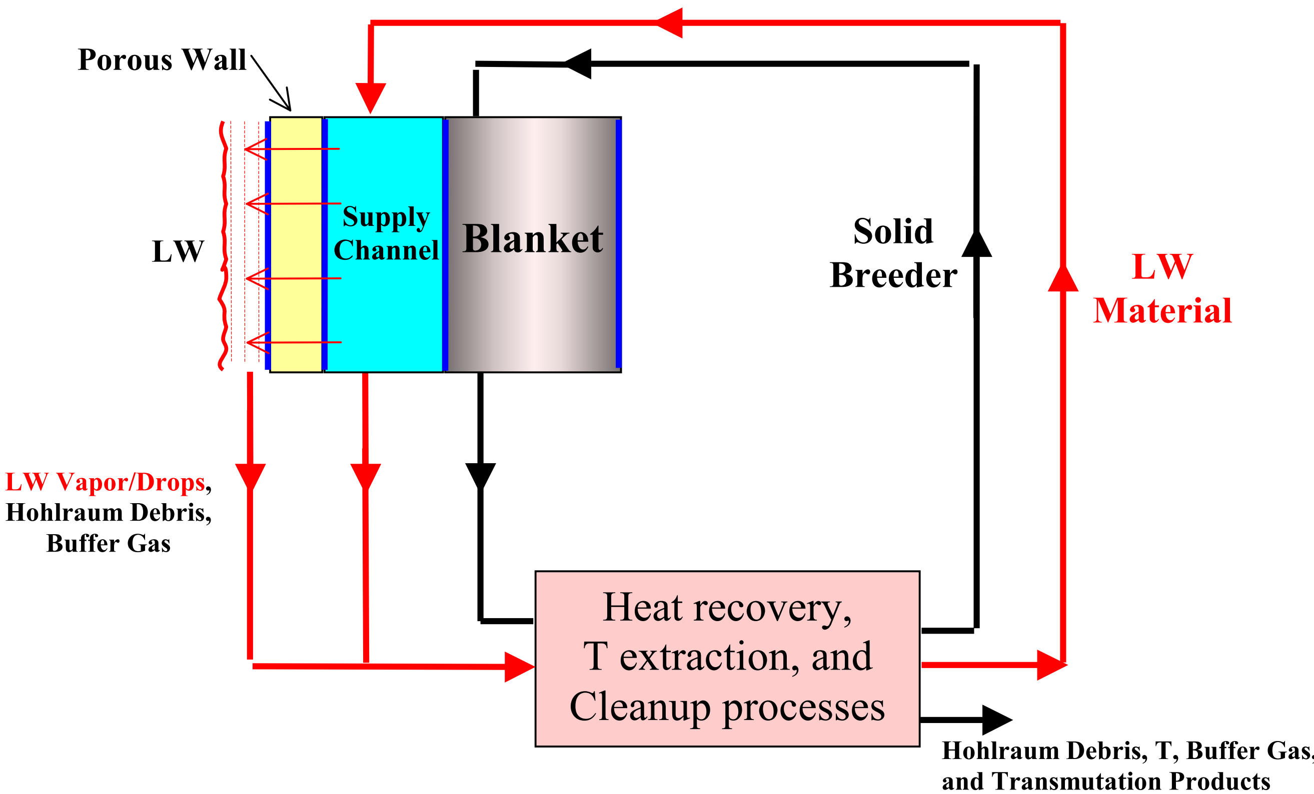

Figure 2. Flow diagram of liquid wall material seeping through porous wall from supply channel (no mixing of LW and breeding materials outside chamber).

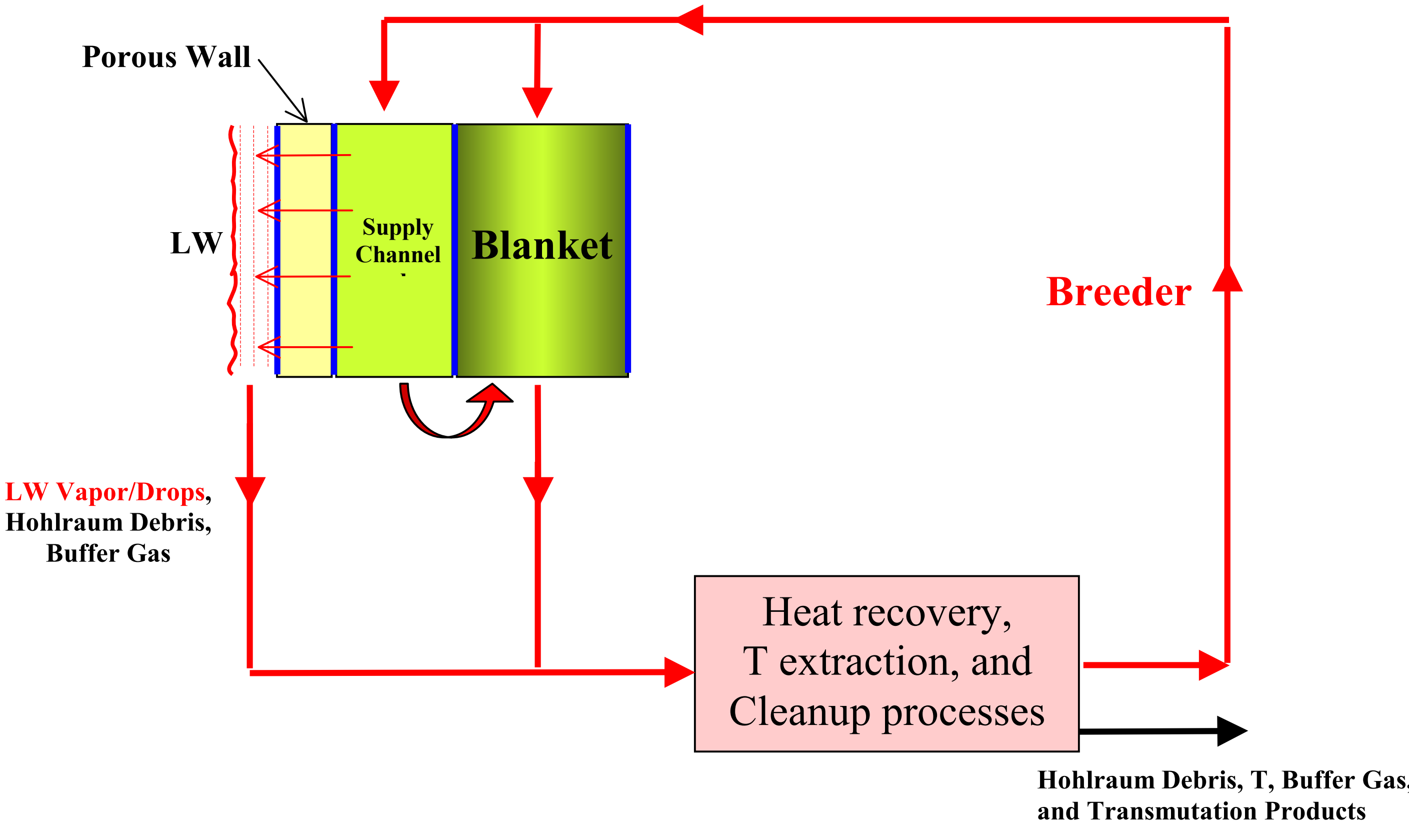

Figure 3. Porous wall injection scheme for liquid breeder blanket concept where LW and breeding materials mix inside and outside the chamber.

III. REPRESENTATIVE RADIAL BUILD

The SiC-based LiPb-cooled blanket of ARIES-AT[10] has been considered as the baseline design for ARIES-IFE-HIB. The chamber radius (R_{fw}) should be 6 m or more based on ARIES-AT design rules (1000 ^{o}C max. SiC temperature, < 1 MW/m^2 surface heat flux, 200-300 ^{o}C ΔT for LiPb, 4-6 m/s LiPb velocity, and 1100 ^{o}C max. LiPb temperature). A representative radial build for the SiC/LiPb concept is displayed in Fig. 4 showing a thin liquid-cooled wall integrated with a liquid supply channel and liquid breeding blanket region. The 40-cm thick blanket system provides a tritium breeding ratio of 1.1 that satisfies the ARIES breeding requirement. The details of the wall concept considered for this analysis are shown in Fig. 5. The thin LiPb wall absorbs the prompt radiation from the target to form a short-lived vapor layer just above the surface. This vapor layer helps shield the later arrival of high-energy target debris. These target products transmit their thermal energy to the remaining liquid film and into the underlying porous SiC first wall. Behind the porous wall is the first wall film supply channel. This supply channel provides both fluid to migrate through the porous first wall and sufficient flow to cool the first wall and supply channel structure to maintain the proper operational temperature and thermal equilibrium.

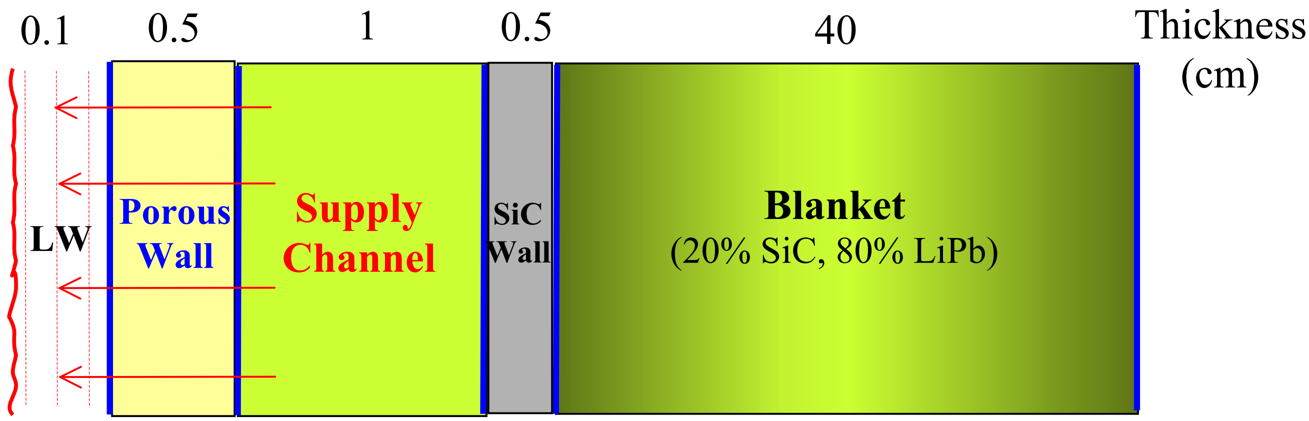

Figure 4. Representative radial build and typical dimensions of essential components for the porous wall injection scheme (not to scale).

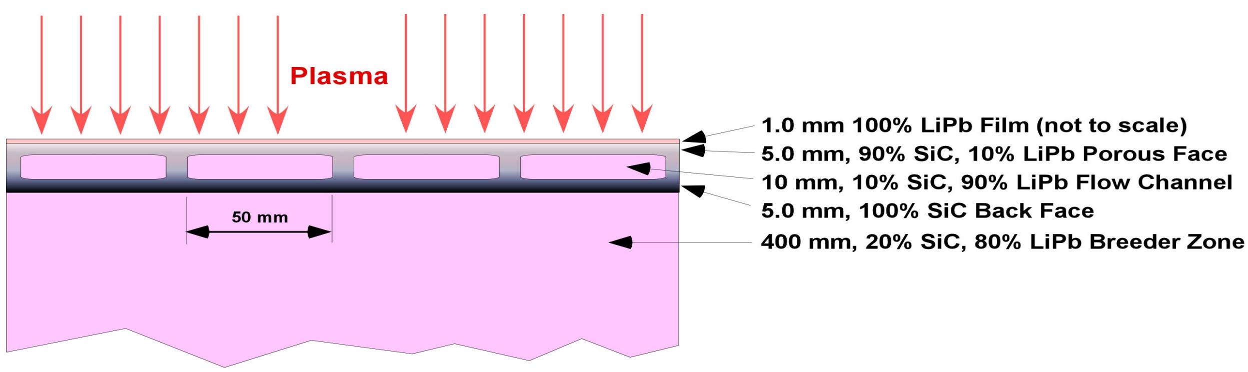

Figure 5. Schematic of thin liquid cooled wall with integral liquid breeding blanket (not to scale).

IV. IN- AND EX-CHAMBER RESIDENCE TIMES AND LIQUID VOLUMES

Definition of the power core configuration is necessary to determine the amount of coolant contained within the power core. The thin liquid protected first wall, supply channel, and blanket concept defined in Section III is generic and can be employed in a variety of reactor shapes and configurations. For this analysis, the chamber design chosen was that used in the Prometheus study[2], namely a right circular cylinder with radius R_{fw} and a height of R_{fw}, which is closed with hemispherical ends. This simple geometry is shown in Fig. 6. The first wall surface area for this geometry is $6\pi R_{fw}^2$. This first wall surface area with the radial build defined in Section III determines the coolant volumes within the power core. A first wall radius of 6 m results in a surface area of 680 m^2.

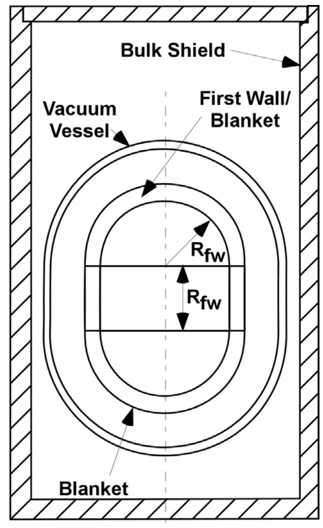

Figure 6. Representative power core geometry used for this analysis.

An analysis was conducted to validate the chosen thickness of 10-mm LiPb supply channel to handle the surface heat load and the nuclear volumetric heating. A surface heat of 570 MW was used per Perkins' calculation[11] for the HIB target assumed. A neutronics analysis determined there was an additional 130 MW deposited in the 5-mm porous SiC layer, an assumed supply channel thickness of 10 mm, and the 5-mm SiC backface structure. Table 1 illustrates the iterative analysis procedure used to determine the supply channel thickness and the coolant flow volume required to thermally balance the film and supply system. The supply channel must, at a minimum, provide enough flow to transmit the surface heat of 570 MW. This surface heat requires a minimum thickness of 5.8 mm in a channel that is 90% LiPb and 10% SiC structure. The flow channel was incrementally increased in thickness, accounting for the nuclear heating in each layer and the heat removal capacity of the supply coolant until the areas balanced. The preliminary data indicates that a minimum 7-mm thick supply channel would be sufficient having mass flow rate of 10,360 kg/s, 5 m/s velocity, 5 second residence time in the supply channel, and approximately 50 second time period spent outside the power core. At present, a 10-mm supply channel is being used in the conceptual design basis. A slower coolant velocity (~3.5 m/s) would thermally balance at the design basis supply channel thickness. A more detailed neutronics analysis can confirm the results when a firm target spectrum and blanket design is provided.

The breeder volume can be determined from the 400-mm thickness of the blanket and its radial position within the power core as defined in Section III. This established the blanket volume of approximately 340 m^3 and a liquid breeder volume of 272 m^3 (80% of the blanket volume) or 2400 tonnes. Approximately 1260 MW of thermal power is deposited in the blanket. Assuming the same coolant operating conditions and temperatures, a mass flow rate of 19,150 kg/s will pass through the blanket with an average residence time of 125 seconds. The blankets in the hemispherical ends will probably be thicker to more efficiently extract the thermal energy in these regions of lower neutron flux. Therefore the average blanket coolant residence time will likely increase to 140 seconds.

Table 1. Determination of Minimum Supply Channel Thickness and Coolant Volumes.

Lithium Lead Case

Delta Temperature Rise	350	Deg C	Wall Radius	6.000	m
Cp (LiPb)	188	J/kg-K			
LiPb Density @ 700 °C	8800	kg/m3			
Coolant Velocity	5	m/s			

Zone	Additional Width,mm	Layer MW	Cumultv MW	Delta Area, m2	Cumultv Area, m2	Layer Thkns,mm	Cumulative Supply Layer Thickness,mm	
Surface Heat from Perkins' data		570.0	570.0	0.197	0.197	5.80	5.80	
1 mm LiPb		7.3	577.3	0.003	0.199	0.07	5.88	
5 mm SiC90%,LiPb10%		35.0	612.3	0.012	0.211	0.36	6.23	
5 mm SiC100%		26.5	638.8	0.009	0.221	0.27	6.50	
Add in LiPb Flow Channel								
Thermal heat balance	0	0.0	638.8	0.000		0.00	6.50	
of nuclear heating and	1	6.1	644.9	0.002		0.06	6.57	
heat removal capability	2	12.2	651.0	0.004		0.12	6.63	
	3	18.4	657.2	0.006		0.19	6.69	
	4	24.5	663.3	0.008		0.25	6.75	
	5	30.6	669.4	0.011		0.31	6.81	
Note:	6	36.7	675.5	0.013		0.37	6.88	
Nuclear heating adjusted to	7	42.8	681.6	0.015	0.235	0.44	6.94	Thrml Balance
match additional 130 MW	8	49.0	687.8	0.017		0.50	7.00	
deposited in SiC layers and	9	55.1	693.9	0.019		0.56	7.06	
10 mm of LiPb and SiC	10	61.2	700.0	0.021	0.242	0.62	7.13	Design Basis

	7 mm thermal bal		10 mm design basis	
Total FW Sys Heat Load	681.640	MW	700.0	MW
Mass Flow Rate	10,359	kg/s	10,638	kg/s
Volume Flow Rate	1.18	m3/s	1.21	m3/s
Chnl Flow Area	0.235	m2	0.242	m2

Table 2. Summary of Heat Transport Coolant Masses.

	Supply Channel	Supply Channel and Blanket
Mass of Coolant in Supply Channel, tonnes	63	63
Mass of Coolant in Blanket, tonnes	–	2400
Mass of Coolant in Piping, tonnes	231	447
Mass of Coolant in IHX, tonnes	415	1251
Total Mass of Coolant, tonnes	709	4161

The determination of the coolant volumes outside the power core requires some definition of the power core and the heat transfer and transport system. The Prometheus power core[2] and heat transfer system definition was used for the model as it was designed to be as compact as possible while keeping the coolant piping lengths and Pb coolant volumes as small as possible. The Prometheus heat transport system is a close approximation for the LiPb system being considered. The bulk shield would be closely arranged around the vacuum vessel with an external radius of approximately 10.5 m for the LiPb blanket concept. Each of the six piping runs from the power core to the intermediate heat exchangers and back would be less than 30 m each way for a total length of 60 m including an allowance for pump volumes. The coolants from the first wall and blanket will likely be combined to reduce piping complexity. The pipes would be around 0.5-m diameter or less to keep the flow rate well below erosion limits (velocity < 4 m/s). Lithium lead intermediate heat exchangers (IHX) would be located in the area immediately outside the bulk shield. A rough estimate indicates the coolant would spend ~30 s in the piping and ~20 s in the IHX, totaling ~50 s outside the chamber. Table 2 shows the approximate coolant masses estimated for the major elements of the heat transfer system. The first column represents a design with separate coolant for the supply channel, such as the Prometheus design. The second column represents mixed flows of supply channel and blanket coolants combined to reduce the piping complexity and liquid waste stream.

V. ACTIVATION ASSESSMENT AND RESULTS

V.1 Assumptions, Model Description, and Irradiation History

The 14 MeV source neutrons interact with the target during burn. As a result, the neutrons moderate and lose a fraction of their original 14.1 MeV energy to the target materials. The computed neutron energy spectrum[11] for the 458 MJ HIB target is shown in Fig. 7, having an average neutron energy of 11.8 MeV. In this analysis, we assess the radioactivity of the LW and breeding materials only. Reference 12 addressed the activation of the target debris deposited in the LW. The sequence of the activation process begins with the liquid entering the chamber. During subsequent shots, the LW gets irradiated several times before leaving the chamber for reprocessing. The LW irradiation history can be represented as a pulsed history using the first wall neutron flux for an irradiation time parameterized between a single shot and 10,000 pulses. The actual in-chamber time is unknown as it depends on the complex evaporation and condensation processes. As Section IV indicates, the fast moving fluid of the supply channel spends ~ 5 seconds inside the chamber. The in-chamber residence time of the slowly moving breeder is estimated to be ~140 seconds using the blanket parameters and dimensions. It is assumed that all liquids spend 50 s outside the chamber for tritium extraction and heat recovery. The reuse of the liquid continues for the entire life of the plant (~50 y) with 85% availability.

The liquid is modeled by considering a given control volume as it circulates throughout the system. The irradiation history of the control volume is represented as a pulsed history with many pulses, depending on the residence time. Mixing of the same LW and breeding materials in various subsystems (e.g. in the heat exchanger and cleanup system) is assumed to take place at the end of plant operation. This is a conservative assumption, as in reality a given control volume does not necessarily follow the same flow path each time through the chamber. The activation model explicitly included the effect of the 85% system availability.

The waste disposal rating (WDR) of the liquid was computed using the ALARA pulsed activation code[13] and the FENDL-2 175 neutron group transmutation cross section library[14]. The neutron flux throughout the chamber was calculated with the DANTSYS[15] discrete ordinates transport code and the FENDL-2 175 neutron 42-gamma group coupled cross section library[16]. To exclude the geometric effect, a unified radial build was utilized for all LW and breeding materials despite the compatibility problems and differences in physical properties that may call for dimensional and structural changes. The computational model included the essential components that influence the analysis, namely the porous wall, supply channel, and blanket as arranged in Figure 4. As Table 3 indicates, impurities were included for all liquids and breeding materials.

V.2 Waste Disposal Limits

As a top-level requirement for the ARIES power plants, all components should meet both Fetter's[17] and 10CFR61 NRC[18] waste disposal limits for Class C low-level waste. A computed volumetric average WDR ≤ 1 at the end of a 100-year institutional control period at the disposal site means the component qualifies for shallow land burial as a low-level waste (LLW). The Nuclear Regulatory Commission (NRC) waste classification is based largely on radionuclides that are important to fission facilities. In fusion power plants, the isotopes are different because of the different materials being considered and the different transmutation products that are generated. In the early 90's, Fetter et al. performed analyses to determine the Class C specific activity limits for all long-lived radionuclides of interest to fusion using a methodology similar to that used in 10CFR61. Although Fetter's calculations carry no regulatory acceptance, they are useful because they include fusion-specific isotopes. The ARIES approach requires all components to meet both NRC and Fetter's limits until the NRC develops official guidelines for fusion waste. We take the following approach to report the WDR: we evaluate the WDR for both Fetter's and NRC limits and report the highest value.

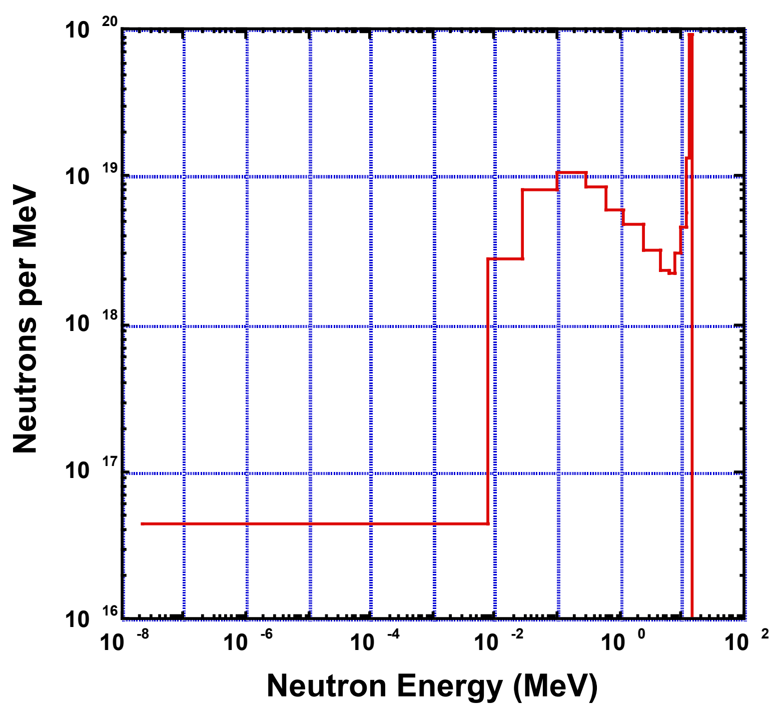

Figure 7. Neutron spectrum for 458 MJ HIB target.

Table 3. Composition of Liquid Wall and Breeding Materials (in wt.%)*.

	$Li_{17}Pb_{83}$	Pb	Sn	Flibe	Flinabe
Density (g/cm^3)	8.8 @ 700°C	10.3 @ 1000°C	6 @ 1000°C	2 @ 600°C	2 @ 420°C
Li				14.04	6.051
Be				9.114	7.857
C				*91	*91
O				*987	*987
F				76.86	66
Na					20.043
Mg				*5.5	*5.5
Al				*77	*77
Si				*27	*27
S			*50		
Ti				*19	*19
Cr				*9	*9
Mn				*11	*11
Fe	*10	*10	0.015	*139	*139
Co			*50		
Ni	*2	*2	*50	*13	*13
Cu				*7	*7
Zn	*10	*10	*50		
As			0.05		
Ag	*5	*5			
Cd	*5	*5			
Sn	*5	*5	99.825		
Sb			0.04		
Pb	99.2925	99.992	0.05		
Bi	*43	*43			

* indicates wppm.

V.3 Tangential Injection Results

For the tangential injection scheme with separate flows displayed in Fig. 1, it is assumed that the highly activated liquid film is segregated from the bulk blanket coolant/breeder that exhibits a lower activity. The residence time of the flowing liquid inside the high radiation zone of the chamber is parameterized to cover a wide range from a fraction of a second (one shot) to about an hour (> 10,000 shots). We quantified the impacts of the in-chamber residence time and exposure (or irradiation) time on the WDR of the candidate LW coolants (Pb, LiPb, Flibe, and Sn). Figures 8 and 9 display the increase in WDR with time for the extreme case of no transmutation product removal. When inspecting both figures, several observations are made:

- For all coolants, the WDR saturates at an in-chamber residence time of ~40 minutes that corresponds to ~10,000 shots.
- Lead and LiPb are more radioactive than Flibe and Sn having a WDR of 81, 69, 9, and 6, respectively, at the end of life.
- Pb/LiPb and Flibe/Sn films generate high-level wastes (WDR >1) at short residence times of 2-3 s and 20-25 s, respectively, if recycled for the entire plant life (40 FPY @ 85% availability).
- Pb/LiPb and Flibe/Sn begin generating high-level wastes after 2-3 y and 14-16 y, respectively, if the in-chamber residence time exceeds 40 minutes.

In practice, a coolant cleanup system[19] that is judged essential for the HIB concept to remove the target debris could also filter out a large fraction of the transmutation products (^{208}Bi from Pb, ^{14}C from Flibe, and ^{108m}Ag, ^{121m}Sn, and ^{126}Sn from Sn). If successful, the cleanup process could prolong the 2-25 s residence time and 2-16 y exposure time identified in Figs. 8 and 9, allowing the reuse of the coolant indefinitely without a time constraint. The accuracy of this statement depends on the efficiency of the cleanup system. The next question is how to deal with the filtered-out, highly radioactive materials? This issue along with a proposed solution will be discussed shortly.

Table 4. Waste Disposing Rating for the Porous Wall Injection Scheme for Designs Employing Solid and Liquid Breeders.

No mixing with solid breeder	WDR
Pb	14
Sn	0.9
Mixing with liquid breeder	
LiPb	10
Flibe	0.8

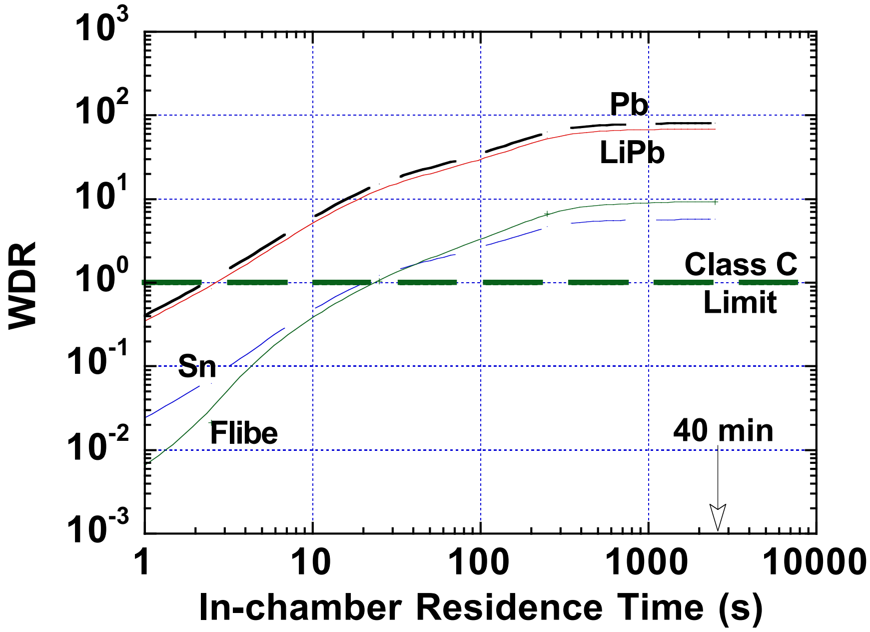

Figure 8. Variation of liquid film waste disposal rating with in-chamber residence time for 47 y of operation without removal of transmutation products.

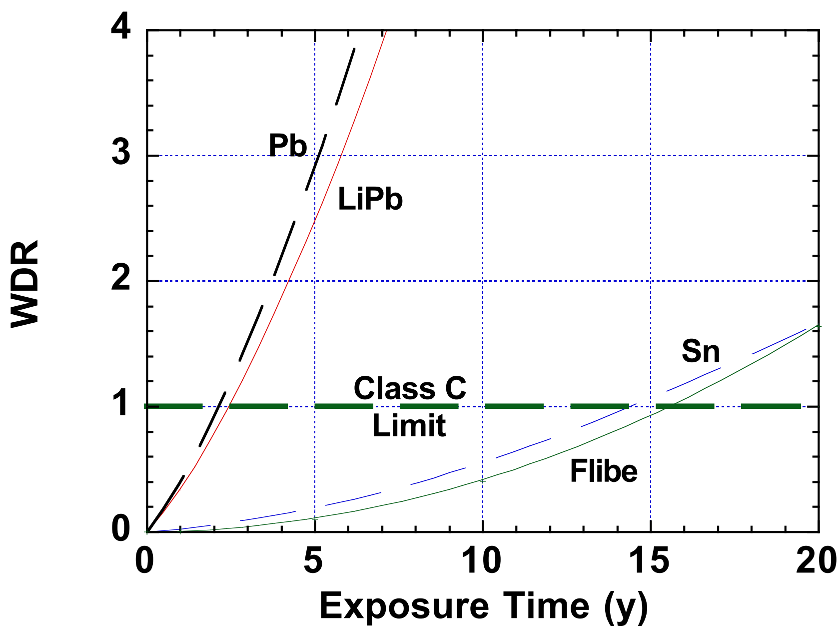

Figure 9. Increase of liquid film waste disposal rating with operation time assuming ~40 min in-chamber residence and no online removal of transmutation products.

V.4 Porous Wall Injection Results

We summarize the results of the porous wall injection scheme in Table 4. Pb or Sn could be the materials of choice for the liquid walls of solid breeder blankets (such as Prometheus[2]) while LiPb and Flibe could serve the dual purpose of liquid wall and breeder for liquid breeding blankets (such as HIBALL[3], LIBRA[4], and OSIRIS[5]). The reported results pertain to ~ 40 min in-chamber residence time and 40 FPY plant lifetime. The concluding remarks for the solid breeder system include:

- LW controls the volumetric average WDR (86% from LW and 14% from supply channel).
- Pb generates HLW.
- No waste disposal problem identified for Sn even in the absence of a transmutation product removal system.

The case where the same liquid breeder is employed for both LW and blanket results in the lowest WDR achieved in our study. Interesting features include:

- The blanket controls the volumetric average WDR.
- Insensitive WDR to the in-chamber residence time.
- LiPb generates HLW.
- No waste disposal problem identified for Flibe even in the absence of a transmutation product removal system.

VI. POTENTIAL SOLUTION FOR HIGH-LEVEL WASTE

Most of the cases analyzed so far generate tonnes of high-level wastes that violate the low-level waste requirement for ARIES fusion power plants. It seems likely that we can satisfy the Class C LLW requirement for all liquids by filtering out online a small amount of highly radioactive elements (^{208}Bi, ^{108m}Ag, ^{121m}Sn, and ^{14}C). As an alternative to near-surface geological burial, the multi-thousand tonnes-processed liquid can then be released to the nuclear industry for similar applications. Admittedly, some elements will be difficult to separate from the bulk liquid using current technology due to the nearly identical physical and chemical properties. One could rely on advanced, extrapolated technology and hopefully, the economical and technological limitations associated with the readily available separation processes (the isotopic one in particular) will be surmountable in 50 y before the commercialization of fusion power plants.

A novel strategy to avoid the deep geological burial of the filtered out solid HLW has been outlined in Reference 20. The concept requires fusion devices to burn their own HLW in a specially designed burning module, attempting to transmute the majority of the long-lived radionuclides into short-lived or preferably, stable isotopes. It remains to be seen if the added design requirements can be accommodated easily in fusion devices and if the cost of the proposed system can be much less than disposal in HLW repositories.

VII. CONCLUSIONS

We discussed in detail the waste management of the candidate liquids for both tangential and porous wall injection schemes. We also assessed the impact of the in-chamber residence time on the liquid activity. Our results indicate that the activation responses increase with the residence time of the liquid film in the chamber and saturate at ~40 minutes. In most of the cases, the candidate liquids generate tonnes of high-level waste unless the in-chamber residence time is limited to 25 seconds or less, the exposure time remains below 16 years, and/or the transmutation products are continuously removed online. Lead and lithium lead are more radioactive than Flibe and Sn. The main contributors to the WDR of Pb, Sn, and Flibe are ^{208}Bi, ^{108m}Ag, and ^{14}C, respectively. The Class C low-level waste requirement could be met by filtering out small amounts of transmutation products and using the original liquid for the plant life. At the end of operation, the liquid can then be either disposed of as low-level waste or preferably, released to the nuclear sector for use in similar applications. The long-lived transmutation products removed during the cleanup process are classified as high-level waste. An approach that requires fusion devices to burn their own waste has been proposed to avoid the deep geological burial of the high-level waste. For liquid breeder systems, it is highly recommended to utilize the same breeding material for the liquid film to minimize the liquid inventory and waste stream.

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