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Liquid wall options for tritium-lean fast ignition inertial fusion energy power plants

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Abstract

In an inertial fusion energy (IFE) thick-liquid chamber design such as HYLIFE-II, a molten-salt is used to attenuate neutrons and protect the chamber structures from radiation damage. In the case of a fast ignition inertial fusion system, advanced targets have been proposed that may be self-sufficient in terms of tritium breeding (i.e. the amount of tritium bred in target exceeds the amount burned). This aspect allows for greater freedom when selecting a liquid for the protective blanket, given that lithium-bearing compounds are no longer required. Materials selection may now be based upon other characteristics, such as safety and environmental (S&E), pumping power, corrosion, and vapor pressure, along with others. The present work assesses the characteristics of many single, binary, and ternary molten-salts and liquid metals using the NIST Properties of Molten Salts Database. As an initial screening, liquids were evaluated for their S&E characteristics, which included an assessment of waste disposal rating (WDR), contact dose, and radioactive afterheat. Liquids that passed the S&E criteria were then evaluated for required pumping power. The pumping power was calculated using three components: velocity head losses, frictional losses, and lifting power. The results of the assessment are used to identify those materials that are suitable for potential liquid-chamber fast-ignition IFE concepts, from both the S&E and pumping power perspective. Recommendations for further analysis are also made.

Keywords: Fast ignition; Liquid wall chambers

1. Introduction

The idea of inertial fusion energy (IFE) using fast ignition has been proposed as a method of achieving relatively high gain using ultra-powerful lasers to ignite the fusion fuel [1]. Advanced targets have been proposed that may be self-sufficient in tritium breeding [2]. These 'tritium-lean' targets contain ~0.5 tritium and 99.5% deuterium, but require a real densities (ρr) of 10–20 g/cm^2 compared with ~3 g/cm^2 for conventional hot-spot ignition. About 55% of the energy released by S. Atzeni's target is produced by D–T reactions, even though the majority of the reactions are D–D, which produces a new surplus of tritium [1–4]. Detailed description of Atzeni's target design,

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yield and output spectrum can be obtained from references [3,4]. For a 1 GWe power plant output, and because of the large yield (1330 MJ), these targets could be ignited at a repetition-rate of only 1.7 Hz. The low repetition-rate may help keep the pumping power significantly lower than in a traditional 5–10 Hz system.

Traditionally, when designing a thick-liquid protected IFE chamber such as HYLIFE-II [5], a major limitation to the choice of the liquid was the tritium-breeding ratio (TBR). The blanket was required to provide a TBR ≥ 1.1 so that tritium did not need to be added to the system during operation. Elimination of this requirement allows for greater flexibility in selection of a liquid than ever before. Materials selection may now be based upon other characteristics, such as S&E, pumping power, corrosion, and vapor pressure, along with others.

In this study we assessed the characteristics of single, binary, and ternary molten-salts as well as several liquid metals. Using the National Institute of Standards and Technology (NIST) Properties of Molten Salts Database [6], approximately 4300 molten-salts were included in the study. Two rounds of analyses were performed and are reported here. Assessments of the S&E characteristics and of required pumping power were performed for all materials for which density and viscosity data were available.

2. S&E assessment

Three assessments were done as part of the S&E study: a calculation of the waste disposal rating (WDR), an analysis of the radioactive afterheat in an accident scenario, and a calculation of the contact dose rate to determine if the material could be recycled. Our analyses assumed a total molten salt inventory of 1250 m^3, based in the HYLIFE-II design, with approximately 12.5 m^3 (1%) of the material in the chamber at any given time. A simple 1-D model was used to assess the neutron transport. The model consisted of a spherical thick liquid pocket inside the chamber (0.5 m distance from the target), a stainless steel type 304 first wall at a radius of 3.5 m, a liquid blanket and a second stainless steel shell with an inner radius of 4 m. All studies were done using the TART Monte Carlo code for neutron transport and the ACAB activation code [7,8]. Neutron irradiation was assumed to occur for 30 full-power years (no change-out of liquid was assumed).

The WDR index has been used in order to classify the method of waste disposal needed [9]. If the WDR ≤ 1, the material can be disposed of via shallow land burial. Given the potentially large waste volumes involved, disposal via shallow land burial is a primary goal, and thus, liquids with a WDR > 1 were eliminated from consideration.

In the case of a severe accident, the radioactive afterheat of the liquid could heat the chamber wall and increase the quantity of material mobilized and released to the environment. Here, we compare the afterheat of the liquid to that from the chamber itself (assumed to be type 304 stainless steel, as in HYLIFE-II). In previous work [10], we calculated the temperature evolution of the HYLIFE-II first wall during a loss of coolant accident. It was obtained that the temperature of the wall reached a small peak above its operational temperature after approximately 15 min, and then starting decreasing through radiation heat transfer to the colder structures. It was observed that during the transient, the temperature of the wall remained well below the melting point of the steel ($T_{\mathrm{melt,\ SS304}} \sim 1400$ °C). For our safety screening, we calculated the values of radioactive afterheat for each candidate and compared those to the afterheat from the HYLIFE-II first wall during an accident scenario. Those liquids with an integrated afterheat value below that from the first wall at any given time during the first week of the accident, were declared as successful.

Finally, we require that candidate liquids would qualify for remote recycling. We assume that this requirement is satisfied if the component's contact dose limit is < 0.1 Sv/hr within 50 years of decay. While hands-on recycling is desirable, it requires a significantly lower contact dose rate of < 25 μSv/h, which may be overly restrictive.

In order to perform a preliminary screening of the initial 4300 molten-salts, we established allowable density limits for each element based upon the above S&E criteria. If all of the elements in a

Table 1
Maximum density an element can have in a liquid in order to be acceptable for use in thick-liquid protection of the fusion chamber

Element	Limit (g/cc)	Limiting Factor	Element	Limit (g/cc)	Limiting Factor	Element	Limit (g/cc)	Limiting Factor	Element	Limit (g/cc)	Limiting Factor
Li	1.10E+02	AH	V	3.78E+02	AH	Ru	7.41E−03	WDR	Tb	2.66E−05	WDR
Be	7.53E+03	WDR	Cr	1.41E+03	AH	Rh	3.54E−02	WDR	Dy	1.60E−04	WDR
B	9.49E+02	WDR	Mn	1.46E+01	AH	Pd	2.05E−03	WDR	Ho	3.75E−06	WDR
C	8.34E+01	WDR	Fe	4.54E+01	CDR	Ag	9.04E−05	WDR	Er	4.64E−04	WDR
N	4.78E−02	WDR	Co	7.13E−04	CDR	Cd	2.88E−02	WDR	Tm	1.35E−02	WDR
O	2.63E+01	WDR	Ni	1.02E−01	CDR	In	2.05E+01	AH	Yb	1.64E+01	WDR
F	1.05E+02	WDR	Cu	1.85E−01	CDR	Sn	1.63E+01	WDR	Lu	1.49E+01	AH
Ne	1.22E+01	WDR	Zn	2.29E+01	CDR	Sb	2.00E+00	AH	Hf	1.25E+01	AH
Na	5.11E+01	CDR	Ga	8.48E+00	AH	Te	9.69E−01	WDR	Ta	1.25E+00	AH
Mg	2.64E+01	AH	Ge	1.18E+02	AH	I	2.90E+01	AH	W	8.38E+00	WDR
Al	3.45E−02	WDR	As	2.51E+00	AH	Xe	9.83E−02	CDR	Re	4.93E−01	WDR
Si	6.90E+01	WDR	Se	5.51E−02	WDR	Cs	1.43E−02	CDR	Os	6.45E−03	WDR
P	3.72E+02	AH	Br	1.13E−01	WDR	Ba	8.66E−02	CDR	Ir	9.80E−05	WDR
S	2.06E+01	AH	Kr	2.63E−01	CDR	La	1.15E+01	WDR	Pt	7.33E−02	WDR
Cl	4.90E−02	WDR	Rb	3.11E+00	CDR	Ce	1.29E+01	WDR	Au	4.97E+00	AH
Ar	6.45E−02	WDR	Sr	7.29E+01	CDR	Pr	3.18E+01	AH	Hg	2.04E+02	AH
K	5.01E−02	WDR	Y	8.38E+00	AH	Nd	9.82E−02	CDR	Tl	3.35E+01	AH
Ca	1.34E+00	WDR	Zr	2.77E+00	WDR	Sm	7.78E−04	CDR	Pb	9.05E+00	WDR
Sc	5.09E+00	AH	Nb	1.81E−05	WDR	Eu	4.76E−05	CDR	Bi	5.15E−04	WDR
Ti	5.86E+01	AH	Mo	3.32E−04	WDR	Gd	9.26E−04	WDR			

Factor limiting element density: WDR, waste disposal rating; CDR, contact dose rate; AH, radioactive afterheat.

Table 2
Comparison of pumping power from flibe in the original HYLIFE-II design and some alternative examples using FI concept

Material	Thickness (m)	Velocity head (MW)	Friction losses (MW)	Lift power (MW)	Total (MW)
Flibe (HYLIFE-II)	0.50	8.86	7.84	10.98	27.69
Flibe	0.45	0.15	1.83	4.68	6.66
Flinabe	0.50	0.20	3.61	5.00	8.81
LiPb	0.97	7.38	17.38	35.66	60.41
Li	1.05	0.53	1.17	2.05	3.75
LiSn	0.50	0.69	4.18	16.99	21.86

particular material were below these limits, the material passed the S&E assessment. Table 1 shows the acceptable quantities of each particular element in a molten-salt, and which criterion limits the acceptability. For example, the allowable densities of Li, Be and F are all much higher than their relative densities in flibe, and thus, flibe would be an acceptable liquid. After assessing S&E characteristics, approximately 200 liquids remained—mostly single-salts and binaries. These were then evaluated for required pumping power.

3. Pumping power assessment

When considering a molten-salt for thick-liquid protection of a fusion chamber, the pumping power needed to pump the volume of material through the chamber is a critical characteristic for materials selection. Pumping power must be sufficiently low in order to maximize net electric power generated from the fusion plant. In the case of the HYLIFE-II design, three components to pumping power must be considered: velocity head, frictional/minor losses in pipes, and lifting power.

3.1. Velocity head

The liquid wall must be thick enough to provide adequate shielding to chamber structures. Knowing that an equivalent thickness of flibe (34 BeF_2–66% LiF) will provide adequate shielding by limiting neutron damage to less than 100 displacements per atom (DPA) after 30 years of continuous irradiation, we determined the thickness of each molten-salt that would result in an equivalent DPA.

Starting from the first principles relation for power, we derived the relation for the velocity head pumping power, as a function of the inner radius of the molten-salt pocket, the thickness of the liquid wall, the liquid density (in kg/m^3), and the frequency of shot repetition. Detailed equations used throughout this section are described in [11].

3.2. Frictional/minor losses

The pumping power needed to overcome frictional losses in the pipes was calculated for each liquid as a function of the density, the volumetric flow rate and the frictional head loss. The frictional factor is calculated using the Reynolds number as explained in [12]. The frictional losses for the original HYLIFE-II design as described by Palmer House are 7.84 MW [13]. Use of the high yield Atzeni target significantly reduces the required flow rate. This is mostly due to the lower repetition rate, which reduces the liquid velocity. The softer spectrum of the Atzeni target also leads to a thinner pocket (45 vs. 56 cm) and the overall frictional losses are only 1.83 MW.

3.3. Lifting power

Lifting power is needed to get the liquid that has been sprayed to the bottom of the chamber back up to the top of the chamber. It is calculated using a 10.5-m distance from the bottom of the chamber to the top of the jets. For the original HYLIFE-II design, the lift power was 10.98 MW. Using the values for the tritium-lean target results in a significant drop in the lifting pumping power to

Table 3
Liquids that passed all assessments

Molten-salt composition			Mol%			Molten-salt composition			Mol%		
BeF_2	LiF	~	34	66	0	$NaPO_3$	Na_2SO_4	~	75	25	0
BeF_2	LiF	~	50	50	0	$NaPO_3$	$Na_4P_2O_7$	~	75	25	0
BeF_2	LiF	~	75	25	0	$NaVO_3$	~	~	100	0	0
BeF_2	NaF	~	30	70	0	$NaVO_3$	V_2O_5	~	20	80	0
BeF_2	NaF	~	50	50	0	$NaVO_3$	V_2O_5	~	80	20	0
BeF_2	RbF	~	50	50	0	Na_2CO_3	~	~	100	0	0
$CaSO_4$	Na_2SO_4	~	10	90	0	Na_2SO_4	~	~	100	0	0
$CaSO_4$	Na_2SO_4	~	30	70	0	Na_2S_3	~	~	100	0	0
$CaSO_4$	Na_2SO_4	~	55	45	0	Na_2S_4	~	~	100	0	0
FeS	~	~	100	0	0	Na_2S_5	~	~	100	0	0
HgI_2	~	~	100	0	0	Na_2WO_4	~	~	100	0	0
LiF	~	~	100	0	0	$Na_4P_2O_7$	~	~	100	0	0
LiF	NaF	BeF_2	33.3	33.3	33.4	$Na_4P_2O_7$	WO_3	~	34	66	0
LiF	NaF	BeF_2	31.5	31	37.5	$Na_4P_2O_7$	WO_3	~	65	35	0
LiF	NaF	BeF_2	63	5	32	RbF	~	~	100	0	0
LiF	NaF	~	60	40	0	RbI	~	~	100	0	0
LiF	RbF	~ ~	43	57	0	Rb_2CO_3	~	~	100	0	0
LiI	~	~	100	0	0	TlI	~	~	100	0	0
Li_2CO_3	~	~	100	0	0	V_2O_5	~	~	100	0	0
Li_2CO_3	Na_2CO_3	~	10	90	0	PbF_2	~	~	100	0	0
Li_2CO_3	Na_2CO_3	~	40	60	0	Rb	~	~	100	0	0
Li_2CO_3	Na_2CO_3	~	60	40	0	LiPb	~	~	100	0	0
Li_2CO_3	Na_2CO_3	~	90	10	0	Na	~	~	100	0	0
Li_2WO_4	~	~	100	0	0	Li	~	~	100	0	0
$NaBF_4$	~	~	100	0	0	Hg	~	~	100	0	0
$NaBF_4$	NaF	~	92	8	0	Ga	~	~	100	0	0
NaF	~	~	100	0	0	LiSn	~	~	100	0	0
NaI	~	~	100	0	0	In	~	~	100	0	0
$NaPO_3$	~	~	100	0	0						

4.68 MW (for flibe). In this case, the reduction is due entirely to the reduced flow rate.

3.4. Pumping power results

Sixty-six liquids were analyzed for the total pumping power needed to keep the salt flowing through the chamber at the correct frequency. Acceptable pumping power was assumed to be less than or equal to 80 MW, though the exact value is subject to debate. Nine liquids failed the pumping power requirement. Seven of them are high viscosity boron containing compounds. The other two are BeF_2 and Tl_2S, which are also very viscous substances. Materials that fared well in the pumping power assessment usually contained Li, Na, or Rb. Some other materials also passed, but on a less frequent basis. Examples of pumping power results for some typical candidates in fusion systems are shown in Table 2.

4. Conclusions

Upon conclusion of the numerical analysis, approximately 57 liquids passed all evaluations. Most of these salts contain elements such as Na, Li, Be, B, F, and O. Other elements were present in lesser frequency. These liquids are presented in Table 3. It is recommended that further analysis be done on these liquids. Future assessments may include corrosion, surface tension, and/or vapor pressure studies. After additional screening, perhaps 6–12 materials might remain. A detailed analysis of these materials then could be conducted to assess their potential use in a thick-liquid, fast ignition inertial confinement fusion energy concept.

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