

Flibe Coolant Cleanup and Processing in the HYLIFE- II Inertial Fusion Energy Power Plant

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March 23, 2001

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Abstract

In the HYLIFE-II chamber design, a thick flowing blanket of molten-salt (Li_2BeF_4) called flibe is used to protect structures from radiation damage. Since it is directly exposed to the fusion target, the flibe will absorb the target debris. Removing the materials left over from target explosions at the rate of $\sim 6/\text{s}$ and then recycling some of these materials poses a challenge for the inertial fusion energy power plant. The choice of target materials derives from multi-disciplinary criteria such as target performance, fabricability, safety and environment, corrosion, and cost of recycle. Indirect-drive targets require high-Z materials for the hohlraum. Gold and gadolinium are favorite target materials for laboratory experiments but cost considerations may preclude their use in power plants or at least requires cost effective recycle because a year's supply of gold and gadolinium is estimated at 520 M\$ and 40 M\$. Environmental and waste considerations alone require recycle of this material. Separation by volatility appears to be the most attractive (e.g., Hg and Xe); centrifugation (e.g., Pb) is acceptable with some problems (e.g., materials compatibility) and chemical separation is the least attractive (e.g. Gd and Hf). Mercury, hafnium and xenon might be substituted with equal target performance and have advantages in removal and recycle due to their high volatility, except for hafnium. Alternatively, lead, tungsten and xenon might be used due to the ability to use centrifugation and gaseous separation. Hafnium or tantalum form fluorides, which will complicate materials compatibility, corrosion and require sufficient volatility of the fluoride for separation. Further complicating the coolant cleanup and processing is the formation of free fluorine due to nuclear transformation of lithium and beryllium in the flibe, which requires chemical control of the fluoride level to minimize corrosion. The study of the choice of target materials and the appropriate processing needs further study because we have not come up with choices which perform as well as gold and gadolinium and which have practical processes for recovery and recycle.

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1. Introduction

This report is based on two memos (Moir, 1996 and Moir, 1997), which were part of an industrial ecology study of inertial fusion energy (IFE) at UC Berkeley, Department of Nuclear Engineering (Lowenthal et al., 1999), although some recent material has been included. The inventory of flibe coolant must be processed to keep impurities from building up. The sources of impurities are target debris, transmutation products (principally tritium and helium), corrosion products, pump cover gases, in-leakage of air and water, and other minor sources. A schematic of the molten salt processing system for HYLIFE-II is shown in Fig. 1. The point of this note is to discuss the processes and equipment required so as to determine the cost and resulting impurity levels. Another purpose is to aid target designers in helping decide which materials are acceptable.

Most of the flow is simply recirculated to the chamber to form the thick-liquid blanket. A fraction (to be determined) of the recirculating flow is diverted to a salt clean-up system. About 20% of the flow is directed to the heat exchangers, first passing through a vacuum disengager for tritium recovery. The flow rate of the coolant to the heat exchangers of the balance of plant (BoP) is 10 and 20 m³/s for 2500 and 5000 MWth which corresponds roughly to an electrical power output of 1000 and 2000 MWe (Moir et al., 1994 and House, 1994). The total volume of flibe coolant is approximately 1200 m³ and 2000 m³ for the two plant sizes.

2. Choice of high Z hohlraum material

Target design studies have evaluated the performance of a number of material combinations and compared them to the standard choice of gold and gadolinium

in about equal amounts (Callahan-Miller and Tabak, 2000). The criteria for selecting hohlraum materials are many: target performance (which depends on

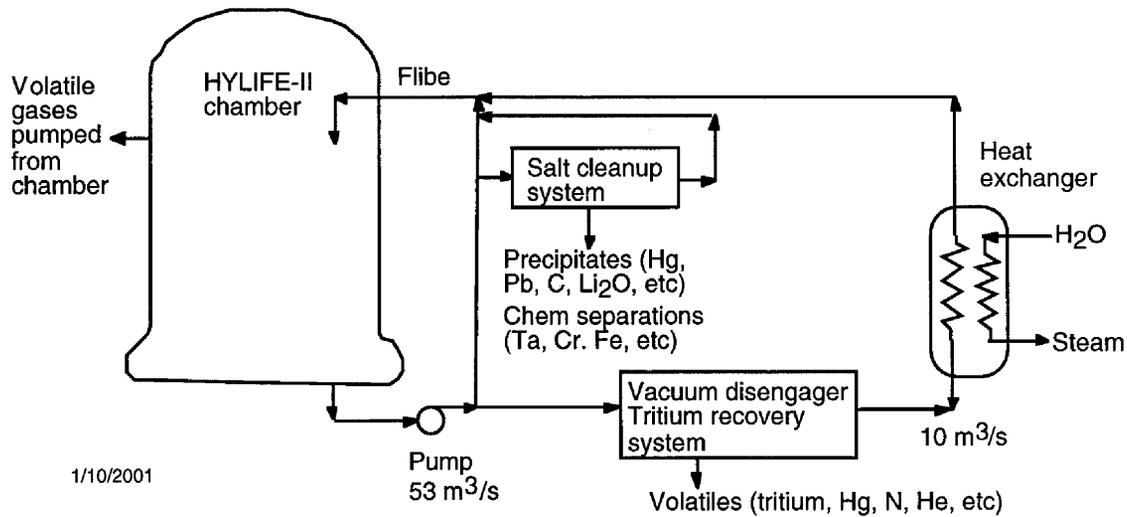


Fig. 1. Molten salt processing system for HYLIFE-II.

photon cross sections in the range of ~ 50 eV to ~ 3 keV), chemical compatibility with steel (Fe, Cr and Ni), separability from flibe, radio-toxicity, etc. The UC Berkeley industrial ecology study chose three candidates: Hg, Pb and Ta. To this list we could add more candidates, e.g., Gd, Xe, Hf, Bi, Rn. Photoelectric cross sections for some elements are given in Fig. 2. A mixture of two elements is used because the combination can fill holes in the opacity of a single element. As a result a mixture of two elements can re-emit more radiation back into the hohlraum interior than just one element. The wall absorption can be decreased as much as 28% for example with 50% Au + 50% Gd compared to 100% Au (Callahan-Miller and Tabak, 2000). The filler element might be lower in Z by ~ 15 and has a broad optimum around a 50-50 mixture but can be as low as 30-70 mixture (Larry Suter, 1996). The rare-earth elements (Lanthanides with atomic number between 58 and 71) appear to be the likely filler element. Table 1 gives results from the Callahan-Miller and Tabak, 2000 paper. The uranium and thorium cases are from Suter et al. (2000). It would appear a combination of several elements might be appropriate.

A two week inventory of gold at 350\$/oz would amount to \$20 M (520 M\$ for a year's supply). Au is not eliminated but cost is a negative factor. Radon (Rn) might be good for the Au substitute due to its extra high Z and ease of recovery due to it being a gas, but dealing with the alpha radioactivity seems to preclude its use. Fissionable materials like Th and U also seem to be precluded because of production of radioactivity but targets likely would perform better due to the

Table 1
Target performance of various wall materials

Material	$E_{\text{wall}}/E_{\text{wall AuGd}}$
Au/Gd (50:50)	1.00
Au	1.25
Pb	1.28
Hg	1.26
Ta	1.25
W	1.25
Pb/Ta (50:50)	1.08
Pb/Ta (70:30)	1.06
Hg/Xe (50:50)	1.18
Pb/Ta/Cs (50:20:30)	1.01
Pb/Ta/Cs (45:20:35)	1.01
Hg/Ta/Cs (45:20:35)	1.03
Hg/W/Cs (45:20:35)	1.04
Pb/Hf (70:30)	1.04
Pb/Hf/Xe (45:20:35)	1.00
Th/Bi/Ta/Sm/Cs	0.82
U/Pb/Ta/Dy/Nd	0.76

higher albedo from these higher Z materials. With thorium as the high Z material (30 μm layer at 10 mm radius) there would be about 1350 g/y (43.5 $\mu\text{g/s}$) production rate of ^{231}Pa (32,000 y, alpha emitter, from the n,2n reaction followed by beta decay), 450 g/y (14 $\mu\text{g/s}$) ^{230}Th (75,000 y, alpha emitter, from the n,3n reaction), and 450g/y of fission products for 1 GWe. The production rate of materials like these would be about the same but with about four times as many fission products with uranium. The actinide elements can be removed by reacting with beryllium. The hazard of these radioactive elements needs to be estimated and compared to the activation of other candidate materials such as Hg and Pb before they are dismissed out of hand because they might improve target performance. A survey of possible candidate high-Z target elements plus

lower Z elements down to Z=54 to fill the opacity hole are listed in Table 2. Once we know the criteria for selection and enough performance data we can choose a set of materials.

Preliminary screening (guessing) is used to eliminate many of the elements in Table 2 resulting in a reduced set in Table 3. Since this early work was done a computer code was used (Callahan-Miller and Tabak, 2000) to study albedo to help select the elements to use. This work should be extended.

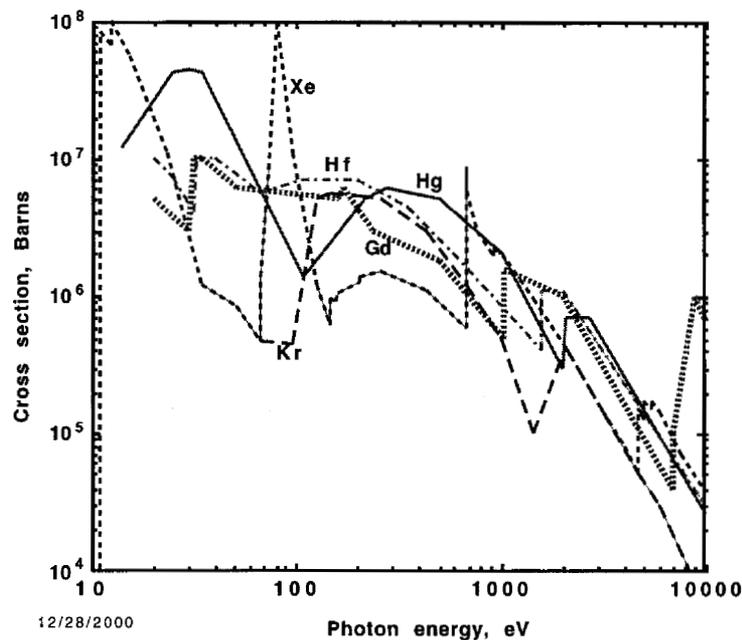


Fig. 2. Photoelectric cross-sections for some candidate target hohlraum wall materials.

It has been estimated that the wall absorption might increase by 28% for Pb compared to a 50% Gd and 50% Au mix giving a 13.5% decrease in target gain (Callahan-Miller and Tabak, 2000). A calculation shows a 13.5% decrease in gain from a gain of 60 at 5.5 MJ driver energy would result in an approximate 5% increase in cost of electricity for a 1 GWe plant. This is equivalent to a 130 M\$ capital cost increase (65 M\$ direct). We need to see if the added cost of the process equipment needed to process the second material is worth the expense. A legitimate question is, "how much effort at this stage of IFE development should we put into optimizing the target materials and studying the

processing?"

Table 2
Candidate elements for hohlraum walls

Z	Element	Comments	separation methods
96	Cm	makes fission products, unstable, alpha emitter	React with beryllium
95	Am	"	"
94	Pu	"	"
93	Np	"	"
92	U	"	"
91	Pa	"	"
90	Th	"	"
89	Ac	unstable, alpha emitter	"
88	Ra	alpha emitter	"
87	Fr	unstable	"
86	Rn	alpha emitter; short half-life too costly ~\$300/target	volatility
85	At	"	
84	Po	unstable, alpha emitter	
83	Bi		centrifuge
82	Pb		"
81	Tl		"
80	Hg		volatility, centrifuge
79	Au	too costly ?	centrifuge
78	Pt	too costly ?	"
77	Ir	too costly ?	"
76	Os	too costly ?	"
75	Re		"
74	W		"
73	Ta		TaF ₅ , volatility, electrochemical
72	Hf		HfF ₄ , electrochemical
71	Lu		reductive extraction/metal transfer = Bi extraction
70	Yb		YbF ₃ , Bi extraction
69	Tm		TmF ₃ , Bi extraction
68	Er		ErF ₃ , Bi extraction
67	Ho		HoF ₃ , Bi extraction
66	Dy		DyF ₃ , Bi extraction
65	Tb		TbF ₃ , Bi extraction
64	Gd		GdF ₃ , Bi extraction
63	Eu	too costly	EuF ₃ , Bi extraction
62	Sm		SmF ₃ , Bi extraction
61	Pm	unstable	PmF ₃ , Bi extraction
60	Nd		NdF ₃ , Bi extraction
59	Pr		PrF ₃ , PrF ₄ , Bi extraction
58	Ce		CeF ₃ , Bi extraction
57	La		LaF ₃ , Bi extraction

56	Ba		not volatility, not centrifuge, BaF ₂ ,chemically similar toLiF ₂
55	Cs		CsF, volatility,
54	Xe		volatility

Table 3

Reduced set of candidate elements for hohlraum walls

Z	Element	Comments	separation methods
83	Bi		centrifuge
82	Pb		"
81	Tl		"
80	Hg	low cost separation----->	volatility, centrifuge
75	Re		"
74	W		"
73	Ta		TaF ₅ , volatility, electrochemical
72	Hf		HfF ₄ , electrochemical
71	Lu		LuF ₃ , Bi extraction
70	Yb		YbF ₃ , Bi extraction
69	Tm		TmF ₃ , Bi extraction
68	Er		ErF ₃ , Bi extraction
67	Ho		HoF ₃ , Bi extraction
66	Dy		DyF ₃ , Bi extraction
65	Tb		TbF ₃ , Bi extraction
64	Gd		GdF ₃ , Bi extraction
62	Sm		SmF ₃ , Bi extraction
60	Nd		NdF ₃ , Bi extraction
59	Pr		PrF ₃ , PrF ₄ , Bi extraction
58	Ce		CeF ₃ , Bi extraction
57	La		LaF ₃ , Bi extraction
55	Cs		volatility, electrochemical, CsF
54	Xe	low cost separation----->	volatility

The lanthanides are not very volatile and form fairly stable fluorides. Recent advances in halide volatility separation of rare-earth elements need to be studied for applicability to the IFE case (Fray, 2000). The separation technology might be to contact the salt with bismuth and extract in a continuous flow centrifuge/contacter. These tend to be sized at ~ 1 l/min in present versions. They would have to be scaled up by a large factor making for a worrisome cost. The volatility and centrifuge processes look more attractive. Table 2 should be extended down to lower Z elements.

3. Process rates

Table 4 gives some target materials from several old sources. Some materials, such as ablaters, might have to be added if they can not be made of constituents of flibe or those given in the table. We consider for target debris 0.25 g of Pb, Hg or Ta as examples (a little inconsistent with Table 4, which uses 0.22 g). The processes we have in mind are chemical, electro-chemical, and physical. Hg and Pb do not form fluorides in flibe and are insoluble. They are heavy and centrifugation can separate them. Hg is volatile and can be separated by evaporation (distillation). Ta reacts with flibe forming TaF_5 , which is volatile. However, to make the reaction go, the fluoride content must be high making for excessive corrosion of the steel wall material. In the metallic form, the melting point of Ta is high. The form Ta would take is a powder precipitate, a difficult form to deal with, although centrifugation needs to be considered to see if filtration of the precipitate could be workable. For these reasons (corrosion and high melting point) Ta is not recommended for use in targets.

We consider various processing rates shown in Table 5 by processes to be discussed later. A reasonably small process rate of 1 liter/s will result in 1740 kg of radioactive mercury or other high Z material build up in the flibe to 700 ppm. The mercury recovered would then be reused in new targets. The issues involved with using radioactive mercury and other elements need study.

Table 4
Input rates from targets and in-leakage

	In flibe removal by separation	From unburned targets removal by pumping
Tritium ^a	0.75 mg/shot 4.35 mg/s	1.2 mg/shot 7.0 mg/s
helium ^a	0.99 mg/shot 5.74 mg/s	0.85 mg/shot 4.9 mg/s
deuterium ^a	-----	0.79 mg/shot 4.58 mg/s
high Z material ^a	220 mg/shot 1.28 g/s	
H ^b membranes	0.05 mg/shot 0.29 mg/s	
O ^b "	0.04 mg/shot 0.23 mg/s	
C ^b "	0.075 mg/shot 0.44 mg/s	
Cr ^c	0.5 mg/s	
Fe ^c	1.8 mg/s	
Ni ^c	0.3 mg/s	
N ^d	0.12 mg	
O ^d	0.65 mg	
Ne ^d	0.065 mg	
N ^e	?	
O ^e	?	
H ₂ O ^f	?	

a-(Table II of Moir et al. 1994).

b-From membranes of targets assuming 6 membranes, 16 mm dia., 0.1 μm thick Mylar (C₁₀H₈O₄) membranes per target.

c-Corrosion products (see text).

d-transmutation products from fluorine, Latkowski private comm. 1/2001.

e-air leaks

f-water leaks

Table 5
Process rates

Process rate liters/s	Time to process total inventory	Inventory of high Z material	
		kg	wppm in flibe
10,000	120 s (2 min)	0.17	0.07
100	1.2×10^4 s (3.3 hrs)	17.4	7
1	1.2×10^6 s (14 days)	1740	700

4. Processes for removing high-Z materials

Three processes in order of decreasing simplicity and increasing cost will be discussed: distillation or volatility separation, centrifugation separation, and reductive extraction/metal transfer.

4.1 Distillation or volatility separation

The unusually high process rate of 10,000 l/s is the entire flow of flibe to the steam generators after passing through the vacuum-disengager, tritium removal system (Dolan and Longhurst, 1992). Tritium is removed by a volatility process whereby the liquid is sprayed in two, series flow "drop towers". The tritium diffuses out of small droplets and is pumped away. Volatile materials like Hg (and Xe or CsF) could also be separated from the liquid in this equipment. By installing cool plates, the Hg can be made to condense as a liquid and flow to a collection point as shown in Fig. 3.

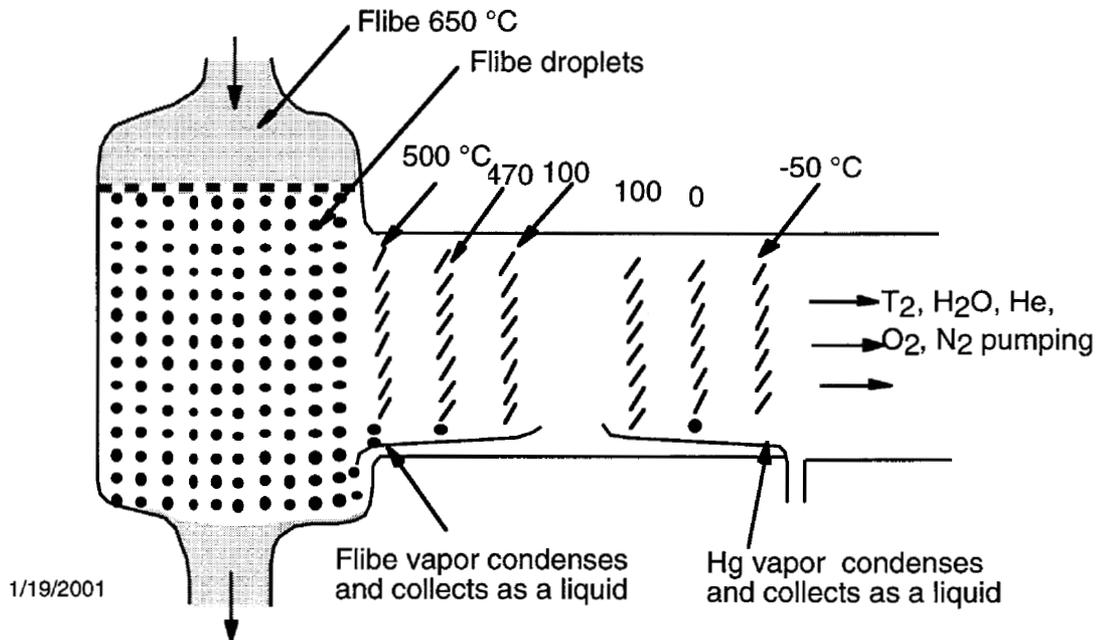


Fig. 3. Vacuum disengager modified to remove mercury vapor and other volatile materials from flibe.

The flibe itself has a relatively high vapor pressure and would be condensed first on a set of higher temperature plates held just above the freezing point of flibe (460 °C). [TaF₅ can also be separated by this volatility method. However, the flibe fluoride content would be so high that Cr and Fe would be fluoridized from steel as well. So the salt will be kept reduced and Ta would be in metallic form. As mentioned before Ta is not recommended.] The cost should be modest because much of the separation equipment is already in place for separating tritium. To be quantitative the evaporation rates need to be estimated. For Hg about 10 m² of condensing plates appears adequate. A small fraction of the 10,000 l/s flow rate would be adequate, for example, 1 l/s would probably do for Pb as will be discussed below.

4.2 Centrifugation separation

Another process is centrifugation as shown in Fig. 4.

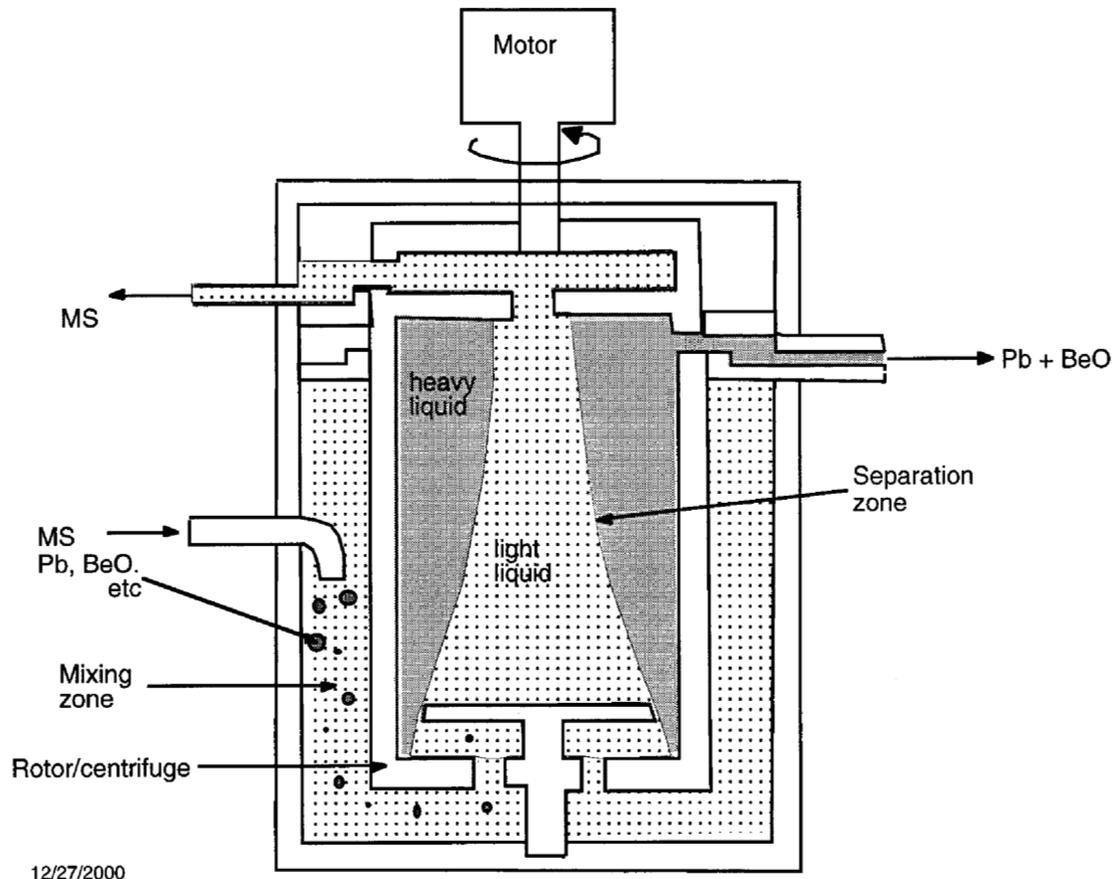


Fig. 4. Schematic illustration of a centrifugal separator design from a working ANL cadmium-chloride salt contactor (Chow et al, 1993).

A reasonable sized continuous flow centrifuge of 1 l/s would be adequate to process the 1240 m³ inventories in 13.9 days (1,200,000 s). For the 2 GWe case, 1.6 such units would be needed to process the 2000 m³ inventory in the same time. At a pulse rate of 5.8 Hz and 0.25 g/target the inventory would be 1,740 kg of heavy, high-Z target material in the flibe. This would be about 700 wppm for the 1 GWe case. The first stage of centrifugation would raise the concentration to the point where a small centrifuge could reduce the high-Z material to a pure metal stream.

4.3 Reductive extraction/metal transfer

The lanthanides form stable fluorides that are soluble in flibe and have fairly low vapor pressure. Since the vapor pressure is low, volatility does not work well

and because of solubility, centrifugation does not work. The next separation process to consider is called reductive extraction followed by metal transfer. This is a standard process in the salt pyroprocessing field for nuclear fuels. The salt is contacted in a continuous counter flow system with bismuth. The lanthanide fluorides preferentially transfer into the bismuth, which is heavy and can be separated by centrifugation. The flibe is of low solubility in Bi. The Bi containing the lanthanide fluoride is contacted with LiCl to transfer the lanthanide fluoride into the LiCl. The LiCl is contacted with Bi containing a small amount of Li. The lithium reduces the lanthanide fluoride, which can then be separated out as lanthanide elements. The process rate in this reductive extraction was 0.8 GPM (0.055 l/s) in the example worked out in (Haubenreich and Briggs, 1972). The process is shown in Fig. 5. A step would have to be added to remove the lanthanide element from the Bi-Li stream such as centrifugation assuming the solubility is low.

5. Impurity cleanup system (see Shaffer, 1971)

A clean up system to remove impurities will be needed in order to keep the flibe clean. These impurities are O, N, C, H₂O, corrosion products (Cr, Fe, Ni), and inert gases as well as target debris. The Ne, O, and N transmutation products from fluorine are already included in the impurities from other sources, except Ne which being a noble gas presents no problems and can easily be separated. N, H and inert gases should be removed along with the volatile high-Z elements within the tritium removal system. Cr, Fe, and Ni can be removed by reacting with beryllium contactors. We have an estimate of 2 μm/y as the dissolution rate of steel into the flibe based on some flow loop experiments (Keiser, DeVan and Lawrence, 1979). Experiments with high nickel alloys show nil dissolution rate. It could be that the Cr and Fe near the austenitic steel surface dissolve leaving an enriched Ni coating and greatly diminished further dissolution.

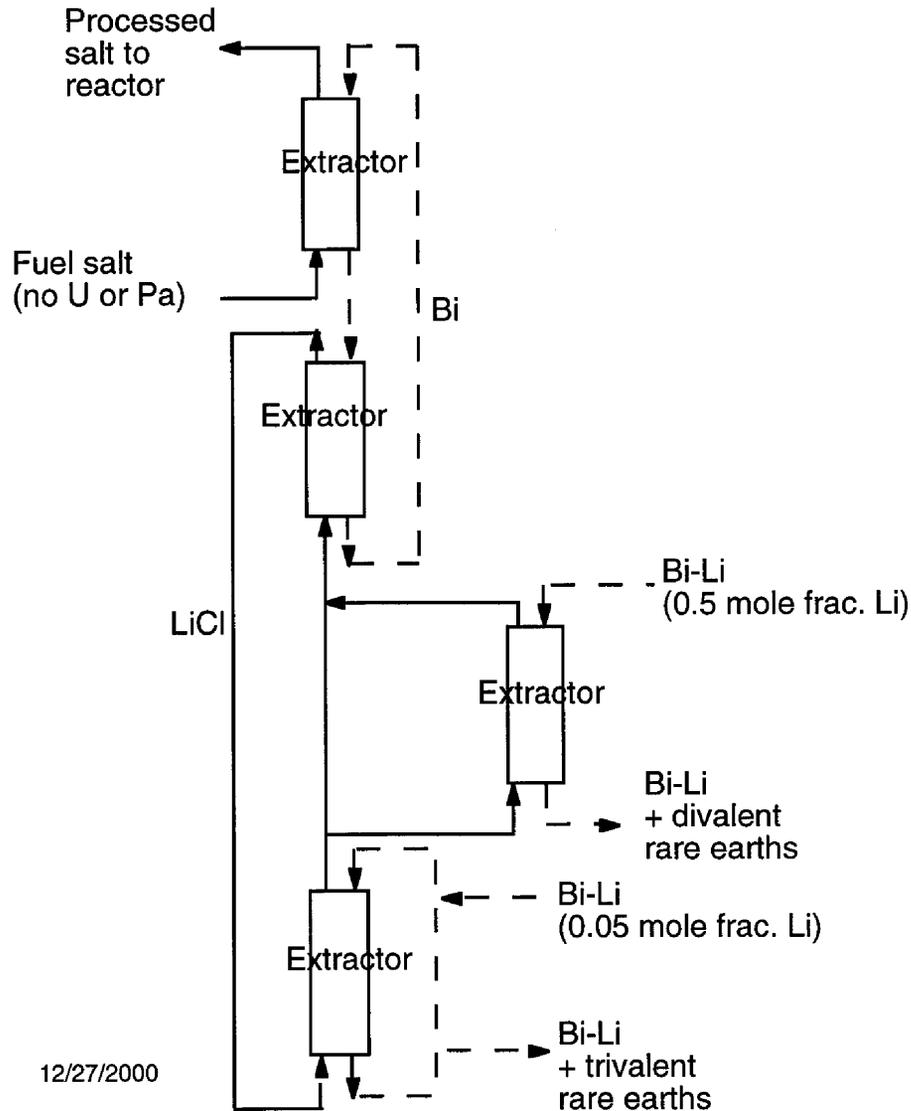
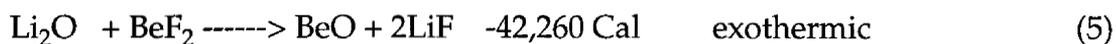
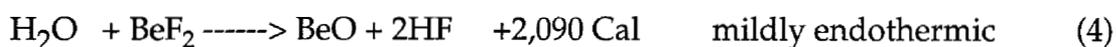
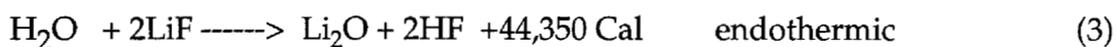


Fig. 5. Metal transfer process for removal of rare earths from single-fluid MSBR fuel salt (Fig. 11.5 from Haubenreich and Briggs, 1972).

This $2 \mu\text{m}/\text{y}$ will permit an estimate of the size of the removal system for the beryllium contactor system. The chemistry control of flibe due to production of free fluorine will increase this removal rate as discussed later. The area of wall exposed to the flibe is estimated at 5000 m^2 (2500 MWth at $1 \text{ MW}/\text{m}^2$ in the heat exchanges gives 2500 m^2). The 1240 m^3 of flibe if contained in a 1 m radius pipe (1 m dia probably should have been used for the example) on average would result in another 2500 m^2 giving a total of approximately 5000 m^2 . The dissolution rates

of structure are obtained as follows: $5000 \text{ m}^2 \times 2 \text{ } \mu\text{m}/\text{y} \times 8000 \text{ kg}/\text{m}^3 = 80 \text{ kg}/\text{y}$ (19% Cr, 70% Fe, 10% Ni, which works out to 2.5 mg/s or 0.5 mg/s Cr, 1.8 mg/s Fe and 0.3 mg/s Ni). The entries in Table 4 for steel constituents use these estimates.

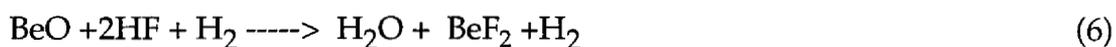
O₂ from air leaks and H₂O from steam generator leaks will chemically react with flibe:



The first three equations above show that the reaction products on the right should be in very low concentrations. The BeO reaction product in equation 4 should be in a small concentration and depends on the concentration of H₂O.

BeO is the more stable oxide in flibe compared to Li₂O as shown in equation 5.

The moisture content in flibe is removed in the following reaction:



This moisture-removal process (scrubbing) is done off-line with 10% HF + 90% H₂ (hydro-fluorination). The H₂O is volatile and removed as a vapor in a getter bed. The added H₂ serves to prevent corrosion of Ni containers. Ni can resist corrosion by HF + 90% H₂, but Cr and Fe cannot, so this scrubbing process needs to be done in a off-line nickel system. 304 or 316 SS may be acceptable because the Cr and Fe quickly becomes depleted near the surface and "looks"

like a nickel container for practical purposes (Keiser, DeVan and Lawrence, 1979). In order to keep the oxygen content of the salt low we will need a continuous hydro-fluorination step. This will have to be sized and costed. The size of the hydro-fluorination system and allowed buildup concentration of HF and BeO will result in calculating a maximum size water leak rate for which we would continue operating the system until a shut down period to plug the leak. It may very well be possible to avoid the clean up process shown in Eq. 6 by simply removing H₂O in the vacuum disengager because the reactions are endothermic but where would the HF come from? Adding HF would make the system too corrosive.

One idea behind chemistry control when using flibe in fusion systems is to continually remove HF by reaction with beryllium. If beryllium is soluble in flibe even at extremely small concentrations, then the HF can be easily removed by the reaction



Even if beryllium is not soluble in flibe it can be finely dispersed by adding beryllium and/or lithium to targets, which upon exploding become vaporized and dispersed. Lithium fluoride is more stable than beryllium fluoride so adding lithium is a way to provide beryllium as can be seen from the following equation



Experiments are needed to determine the solubility of beryllium in flibe and if it is too low to determine the effectiveness of dispersing beryllium in flibe.

The steam generators, which are double-walled, could have an inert gas between the water tubes and the flibe tubes so that in-leakage to the flibe would be primarily inert gas with the little water vapor that remains in the inert gas from water tube leaks. The present design calls for double-wall steam generators so that cracks will not propagate all the way through but has no purge system for the space between the walls.

6. Removal of solid particulates

The removal of nondissolved material such as C and BeO (slag, precipitates) will require special attention. The amount of this material should be minimized as clogging of the spray system can be a problem where we have many small holes of 0.2 mm dia in the vacuum disengager tritium removal system. This spray system is part of the tritium removal system. In essence, this spray system can be considered a filter needing periodical servicing. Alternatively, a filter system can be installed on a slip stream with the filter size smaller than the 0.2-mm diameter of the spray system. The centrifuge will or could be used to separate particulates that are heavier (precipitates) or lighter (flotsam) than flibe ($\rho=2050 \text{ kg/m}^3$). The specific gravity of C and Li_2O are close to that of flibe but BeO is about 3.0.

7. Cost of processing and cost of materials

The tritium processing system using vacuum disengagers has been estimated to cost 60 and 100 M\$ (1995\$) direct for 1 and 2 GWe, respectively. There have been several reports written on this system, for example (Longhurst and Dolan, 1993). Many of the volatility separation processes discussed later can use much of this equipment so the added cost should be modest. The cost of the flibe cleanup system currently being used in the systems code is 19 and 37 M\$ direct for 1 and 2 GWe, respectively, with little or no basis nor any studies carried out or reports written.

A cost estimate first requires a process description with flow sheets and specifications. Lacking these we attempt to put bounds on the cost. We also assume the process equipment will fit into buildings and facilities with remote equipment that is already present and covered in the tritium process systems, the salt cleanup system and the target fabrication system. We assume the form of the material that is useable is liquid Hg, solid or liquid Pb, gaseous Xe or solid lanthanide in elemental form.

The volatility system should cost a fraction of the vacuum disengager tritium system of \$60M. Lets assume \$10M as an order of magnitude. The cost is likely to scale as a power of process rate, PR. Perhaps $C \sim PR^{0.6}$. The nominal process rate is 100 l/s. The centrifuge system is likely to cost about the same at a process rate of 1 l/s. The reductive extraction might cost more than twice this much at a process rate of 0.1 l/s. The low process rates imply a high inventory. These rough order of magnitude estimates are summarized in Table 6. The volatility process is so simple it might cost less than the 10 M\$ estimate, the centrifuge process seems about right and the reductive extraction has a number of extra steps and might be more than the 20 M\$ estimate. The sense of these order of magnitude estimates is that the 10 M\$ might be 3 to 30 M\$. More refinement is needed and much caution to the reader is recommended.

Table 6

Process cost estimates

(order of magnitude)

Process	Cost est.	Process rate, PR	Cost scaling	Inventory / concentration / holdup time
Volatility, Hg	$\$10^7$	100 l/s	$(PR)^{0.6}$	0.17 kg/7 wppm/3.3 hr
Centrifugation, Pb	$\$10^7$	1 l/s	$(PR)^{0.6}$	1740 kg/700 wppm/13.9 d
Reductive extraction, Gd	$\$2 \times 10^7$	0.1 l/s	$(PR)^{0.6}$	17,400 kg/7000 wppm/139 d
Volatility, Xe	$\$5 \times 10^6$	1000 l/s	$(PR)^{0.6}$	0.017 kg/0.7 wppm/20 min.

A 140 day, 17,000 kg inventory of Gd, for example at 880 \$/kg, would be about \$15 M. If Gd were important to have as a target material, a higher process rate would be important to minimize the inventory and therefore the cost of Gd. Assuming that other costs, such as buildings and remote equipment, doubles the costs in Table 6 (40 M\$ direct for Gd) and assuming an annual operating cost of

0.12 times the capital cost (the plant averaged annual operating cost is assumed to be 0.06 times the direct cost of components, but the chemical separation plant will be more operations intensive), then we get 2.4 M\$/y to process 39 tons of heavy high Z target material. Adding capital charges of 4 M\$/y (10% of 40 M\$) give a total direct annual cost of 6.4 M\$ or 164\$/kgHM (HM= heavy metal). It would be about twice this for the rare earth lanthanides.

For comparison, 1200 \$/kgHM is a typical cost for aqueous processing of nuclear fuels and \$350 \$/kgHM for pyroprocesses. Typical throughput of a plant to process the fuel from 20, 1-GWe nuclear plants might be 100 tons/y for aqueous processing. A pyroprocessing plant is economical in sizes several times smaller. We can see the throughput of the processing plant to process target material and that to process fission fuel is comparable.

As stated earlier, adding Gd to the hohlraum material results in a 13.5% increase in gain. This would result in an approximate 4.7 % decrease in cost of electricity for a 1 GWe plant. This is equivalent to a 130 M\$ capital cost decrease (65 M\$ direct). Said another way, the added cost to manufacture targets with Gd or some substitute (including recovery ready for remanufacturing) can cost up to 130 M\$ (~65 M\$ direct cost). However, the cost cited above for Gd removal was 40 M\$ direct. Clearly, we should be concerned about the cost of using Gd.

The clear implication of the above process costs are the simplest, lowest cost process should be selected. Volatility of Hg should be used and Gd avoided. The extra yield from targets may not be worth the extra cost unless other more easily separable materials can be found.

The energy production per unit target material throughput is $(1000 \text{ MWe} / [0.25 \text{ g} \times 10^{-6} \text{ tons/g} \times 5.8 / \text{s} \times 3600 \text{ s/hr} \times 24 \text{ hr/day} =) 8000 \text{ MWe-days/ton}$. At 38.8 tons/y the annual cost of new material with no recycle would be, 337 k\$, 580 k\$, 8.5 M\$, and 50 k\$, for Hg (costing 8.70 \$/kg), W (15 \$/kg), Ta (220 \$/kg), and Pb (\$1.30/kg). Compared to the annual value of electricity produced of about 370

M\$ we can see these costs are insignificant and recycle would only be employed for reasons other than cost of materials (e.g. to minimize radioactive waste inventory). By comparison gold at 350 \$/oz or \$12,300/ kg would cost 478 M\$ for a years supply with no recycle. Gd would be \$40M. We could use gold but would have to recycle it.

8. Safety and environment considerations

There are three main measures for the safety and environmental (S&E) acceptability of target materials [Latkowski et al. Oct 2000 and Mar 2000]. First, an accident in the target fabrication facility, for example, must produce a site boundary (1 km) dose of less than 10 mSv (1 rem), including any tritium release. Second, the large throughput of target material (~ 50 tonnes/year), suggests that materials must be selected so that they can be recycled. Third, it is desirable to select target materials that may be disposed of as Class C (eligible for shallow land burial) waste at the end-of-life of the power plant. If, however, recycling is performed on a weekly basis, then it may be sensible to allow this material (volume < 0.1 m³) to exceed the Class C limits. This issue is still under debate in the S&E community.

9. Alternatives to flibe systems

Alternative liquids to flibe are lithium, lithium-lead (Li₁₇Pb₈₃), and tin-lithium (Sn₈₀Li₂₀). Alternatives to flibe have a serious pumping power problem with a thick layer of liquid (Moir, 2000). Nevertheless, we include a discussion of alternatives. Design modifications might overcome the high pumping power of alternative liquids. Hg could be used with the alternatives. It is soluble and its high vapor pressure would allow easy separation by volatility process discussed above. Pb is also soluble in Li but its removal is not so easy. Centrifugation would be difficult because of the Pb is in solution rather than an immiscible heavy liquid. Selective freezing will not freeze out Pb because its freezing point is much higher than that of Li. There is not much problem with letting the Pb

simply accumulate until separation becomes practical by freezing out the Li in order to raise the concentration of Pb in the remaining liquid. Corrosion enhancement by the Pb additive must be considered.

In the case of LiPb, the use of Pb in the targets would not even be a contaminant and no extraction would be needed. The use of Hg, which is soluble in LiPb, would allow easy separation by volatility if desired. Hg should also work with SnLi.

Separation of elements with Z about 15 lower than Pb or Hg, i.e., the Lanthanides must be considered if target designs call for them. Their solubility is quite low in Li and LiPb (this needs to be confirmed) which might permit them to be easily removed by centrifugation for concentrations above their solubility limits.

10. Conclusions

A flibe coolant clean up and processing system has been described. The plant design and especially the target design need to take into account the process system. Target materials will need to be processed for recycle. Target fabrication needs to be considered when choosing target materials and processes. We are looking for practical materials to substitute for those used in present experiments, Au and Gd. A combination or "cocktail" of several materials might do the job. Many materials can be eliminated based on prohibitively expensive materials or processing steps. The favored materials are those that can be separated by the simple volatility process. There is a worry about using Pb, which can be separated by centrifugation but attack of metal surfaces may be a feasibility problem. We recommend further studies to find a combination of three materials, each of which can be easily separated. Hg, Xe and a third element as yet to be specified are recommended for target materials. Processing is needed for chemistry control of corrosion and target debris and impurity clean up.

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