Coolant Cleanup and Processes for Thick Liquid Walled IFE Power Plants

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Introduction

The present ARIES study is involved with IFE power plants which utilize thick liquid layers at the first wall (FW) to protect surfaces and to attenuate neutrons. Several liquid choices are possible, such as Li, LiPb, or molten salts such as Flibe (Li_2BeF_4) or Flinabe, a version which has Na added to reduce the melting temperature and vapor pressure. In this section we will limit discussions to Flibe, in particular the low viscosity formulation (LiF_2BeF_2) which has a melting temperature of 469^oC. As the liquid protective and attenuating layer flows through the reaction chamber while IFE targets are being imploded at a rate of 4-6 times per second, various impurities are caught up in it both from the fusion reactions as well as from the environment in which it exists. Specifically, these impurities are transmutation products such as tritium and helium, target and hohlraum debris, corrosion products, in-leakage of moisture and air, and other sources. These impurities cannot be allowed to accumulate for several reasons. They can create a radiation hazard in the event they are released, particulate matter can clog nozzles, and corrosion products can plate out in undesirable places where they can be troublesome. Therefore, online processing and filtration is mandatory to keep the liquid both physically and chemically suitable for continuous circulation.

Selection of Hohlraum Material

Selection of hohlraum materials must conform to the following criteria:

1) First and foremost, target performance
2) Fabricability
3) Activation and safety
4) Separability from Flibe
5) Cost of materials and the separation processes.

The preferred hohlraum material in present laboratory experiments is Au and Gd. However, power plants will require huge amounts (15-20 tonnes/y) of these expensive materials making them impractical to use. Other elements with high atomic numbers can be substituted. Among those selected by R. Moir[1] are Pb, W, Hg and Xe. Many other materials have been excluded for various reasons:

1) They form corrosive fluorides when reacting with Flibe
2) They have high melting temperatures forming powder precipitates
3) They are radioactive
4) They are costly.

Processes for the Separation of Materials

The four most suitable separation processes for liquids used in IFE power plants are filtration, distillation/evaporation/volatility separation (most attractive), centrifugal separation (acceptable) and reductive extraction using metal transfer (least attractive).
Non-soluble particulate matter such as C or BeO slag must be removed by filtration or by centrifugation. Particles that have the same density as Flibe cannot be removed by centrifuging, and therefore must be filtered out. However, particles that are either lighter or heavier than Flibe can be removed by a centrifuge. Filtration is important to prevent clogging of nozzles, in particular in the vacuum disengager, where the nozzles are 0.2 mm in diameter. Fine atomizing of the Flibe in the vacuum disengager is essential for recovery of tritium. Centrifugation is preferable to filtration because it is a continuous process causing little or no pressure drop. Online filters must be self-regenerating or regularly replaced to prevent loading up and creating a high pressure drop.

The distillation/evaporation/volatility separation process is the most attractive. In this process, the Flibe is sprayed in two series drop towers such that on the fall, tritium and other volatile materials diffuse out of the droplets. A vacuum system continuously pumps out the volatiles which pass through a series of baffles cooled to progressively lower temperatures. Baffles in the range of 500-100°C condense and collect Flibe; at lower temperatures of 100 to -50°C, Hg can be collected, and the only remaining gases such as T_2, H_2O, He, O_2 and N_2 pass through. Figure 1 shows the molten salt processing system for HYLIFE-II and Figure 2 shows a typical vacuum disengager[2].

Centrifugal separation is an acceptable process but is cumbersome because in involves rotating machinery and motor interfaces. Lighter than Flibe (e.g. C or BeO slag) or heavier than Flibe (e.g. Pb and W) can be separated in this way. Figure 3 is a schematic of a centrifuge.
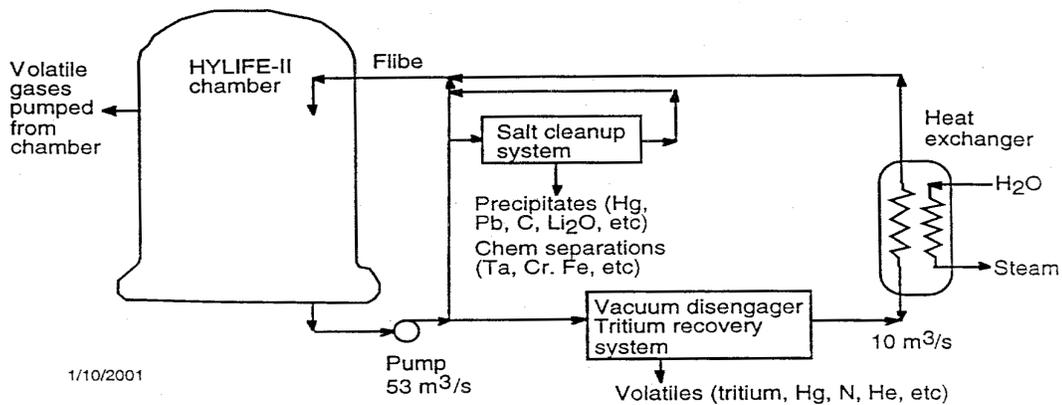

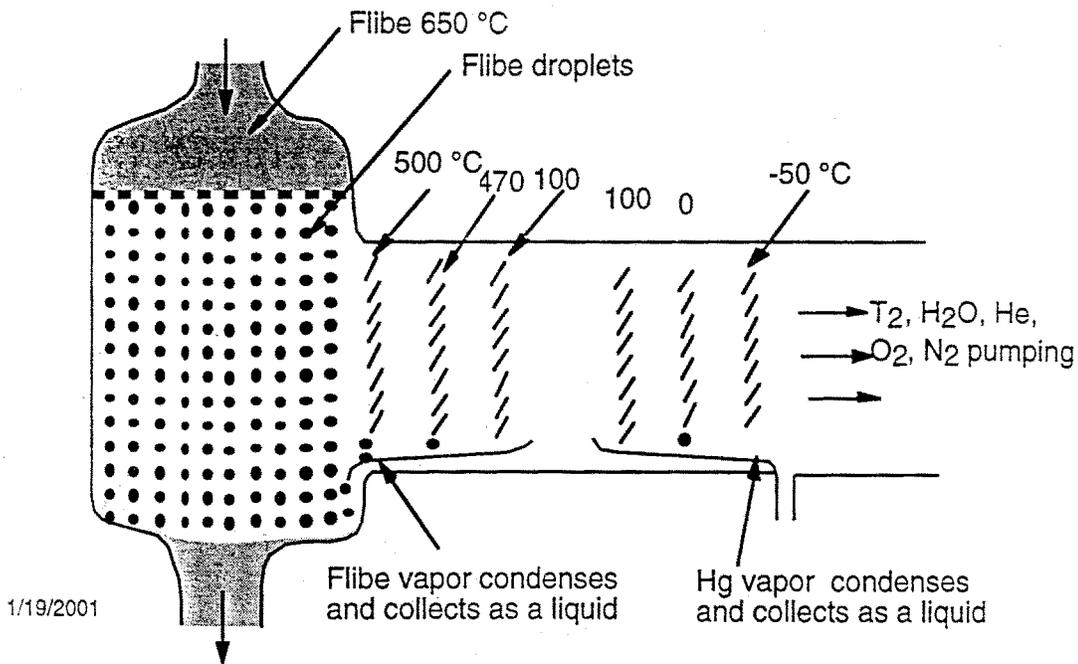Figure 1. Molten salt processing system for HYLIFE II.

Figure 2. Vacuum disengager modified to remove mercury vapor and other volatile materials from Flibe.

The least attractive of these processes is Reductive Extraction/Metal Transfer. Lanthanides such as Gd form stable fluorides that are soluble in Flibe and have low vapor pressure. Flibe is contacted with Be in a continuous process. Lanthanides preferentially transfer to Bi, then are separated by centrifugation. Figure 4 shows a schematic of a metal transfer process.

Corrosion Product Separation

The structural material of an IFE chamber will be steel. Ferritic stainless steel has been suggested, but austenitic steels such as 304 SS or 316 SS also have been considered. There is no data on the corrosion of ferritic steel with Flibe. However, S. Zinkle (ORNL) has suggested that the corrosion rates would be similar to 304 SS or 316 SS, i.e. corrosion will be dominated by Fe and Cr. Flow loop experiments at ORNL have estimated a corrosion rate of 2 μm/y for 304 SS with Flibe[3]. If we assume that the contact area between the Flibe and the steel is ~5000 m^2, The total dissolution rate will be 80 kg/y, of which 88% will be Fe, 9% Cr, 2% W, 0.3% V, 0.5% Mn and 0.08% Ta. All of these corrosion products can be removed by contact with Be. Assuming the Be is soluble in Flibe, metals will transfer to the Be and then will be removed by centrifugation.
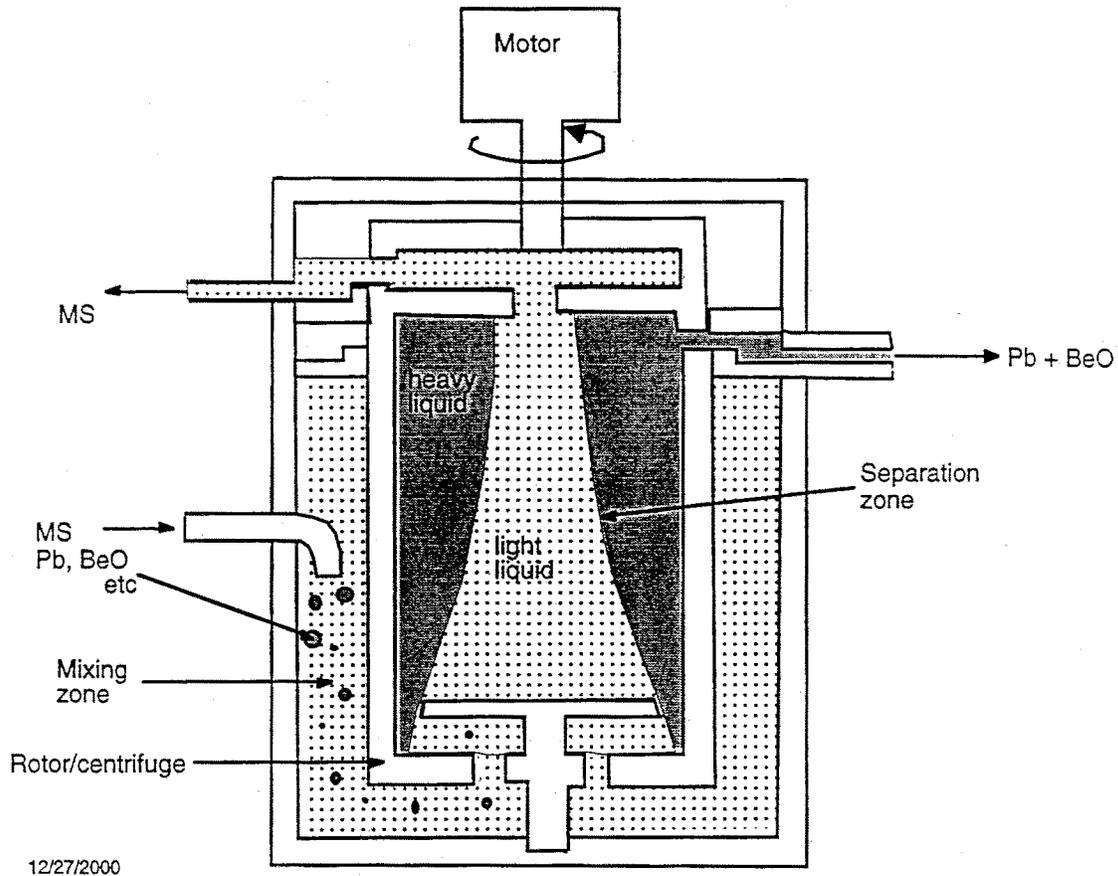
Figure 3. Schematic illustration of a centrifuge separator from a working model from ANL.

Removal of Air and Moisture Leakage

Air leakage into the Flibe will be unlikely, since the Flibe pressure will always be higher. However, O_2 from air and moisture leaks will react chemically with Flibe in endothermic and exothermic reactions, forming BeO and corrosive HF. Moisture can be removed from Flibe in the vacuum disengager. Figure 2 shows cooled chevrons on which water vapor can condense and is drained away. In order to keep O_2 and moisture low in Flibe, continuous hydro-fluorination will have to be performed offline. This is a process called scrubbing, with 10% HF and 90% H_2 in Ni containers, because HF corrodes Fe-Cr containers. Continuous removal of corrosive HF by reaction with Be must be maintained. Here again the solubility of Be in Flibe has to be experimentally determined. The allowable buildup of HF and BeO dictates the size of the hydro-fluorination system, thus setting a limit on the water in-leakage in the power cycle.
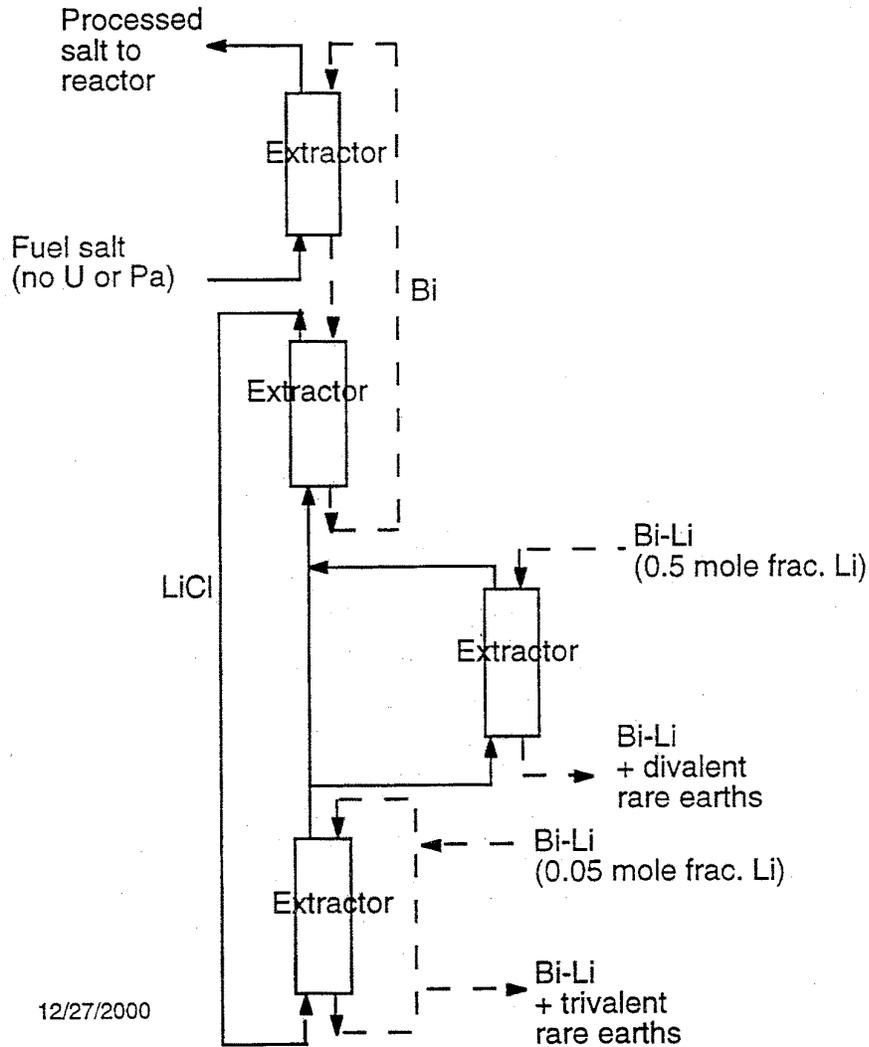
Figure 4. Metal transfer process for removal of rare earths from single-fluid MSBR fuel salt (Haubenreich and Briggs, 1972).

Separation Rates and Equipment Costs

As far as target and hohlraum materials go, Hg and Xe are the easiest and the cheapest to separate. The added cost of providing cooled chevron plates for condensing Hg and Xe would be minimal. T_2 recovery dictates that the whole Flibe inventory (10,000 l/s in HYLIFE II) must go through the vacuum disengager. At the same time, Hg and Xe will be separated. Although Flibe condenses at 470°C, Hg and Xe condense at much lower temperatures, 50°C and −107°C, respectively. The estimated cost of the vacuum disengager T_2 system is 60 M$, and the added cost of the volatile separator is <10 M$ at a process rate of 100-1000 l/s [1]. Separation of Pb or W will have to be done by centrifugation at a low rate of 1.0 l/s. The cost of such a system is estimated at 10 M$[1]. Reductive extraction of Gd at the very low rate of 0.1 l/s is estimated to cost ~20 M$[1].

Summary and Conclusions

- Flibe cleanup involves removal of target debris, transmutation and corrosion products, tritium, and air and moisture leakage into the coolant.
- Depending on the materials used in the target and the hohlraum, processes can be multifold, including filtration, vacuum disengagement, distillation, centrifugation and reductive extraction with metal transfer.
- Pb, W, Hg, and Xe hohlraum materials are insoluble in Flibe, do not form fluorides and are the easiest and cheapest to separate from Flibe.
- Tritium recovery from Flibe requires a large vacuum disengager system capable of handling ~10,000 l/s of liquid. At this rate, recovery of Hg and Xe is more than adequate.
- A centrifugal system with a rate of 1.0 l/s will be adequate for separating heavy metals such as Pb and W.
- The total cost of the system described above is ~100 M$.

References

1) R. W. Moir, "Flibe Coolant Cleanup and Processing in HYLIFE II Inertial Confinement Fusion Energy Power Plant", UCRL-ID-143228, March 23, 2001.

2) T. J. Dolan and G. R. Longhurst, "A Vacuum Disengager for Tritium Removal from HYLIFE II Reactor Flibe", Fusion Technology 21, 1949-1954 (1992).

3) J. R. Keiser, J. H. DeVan, and E. J. Lawrence, "Compatibility of Molten Salts with Type 316 SS in Lithium", J. Nucl. Materials, 85-86, 295 (1979).