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APPENDIX D. THE LIFE IFE REACTOR CONCEPT

D.1 INTRODUCTION

The Cascade IFE reactor concept has received considerable attention because of the potential for very low activation, elimination of replaceable first walls, low cost and high efficiency.[D-1] In Cascade, solid granules flow in a rotating chamber which keeps the granules against the wall and the central region clear for target and beam injection. But using solid granules presents a number of problems: First, the granules will erode due to x-rays motion against each other and against fixed walls. Sudden X-ray deposition also gives rise to stress waves that can fracture the surface layer of granules. Lastly, the impulse from X-ray induced blowoff can cause the surface layer of granules to rebound into the chamber. If those granules are still in flight at the time of the next shot, they will be driven into the rest of the granule bed at very high velocity. There are also issues of granule fabrication, transport through the system, and heat transfer to the working fluid by radiation.

Many of these issues are eliminated by replacing the solid granules with a lithium-bearing flowing liquid. The liquid is self-healing, is easily transported through ducts and heat exchangers, and requires no fabrication facilities. It does, however, introduce a problem of vapor pressure in the chamber. This is a critical issue because the geometry of rotating chambers is suitable only for one or two-sided illumination, limiting drivers to heavy ion beams that require very low chamber pressures for propagation.

The idea of a liquid lithium rotating chamber has been examined before,[D-2] but appears to have been abandoned. As part of this study, we explored rotating chamber concepts using $Li_{17}Pb_{83}$ and Flibe (Li_2BeF_4). The former is especially attractive when it is also used as the target high-Z material. The latter has lower induced activity, but is a poor heat transfer material unless it is highly convective. The concept is called the LIFE reactor (Liner Inertial Fusion Energy).

D.2 DESCRIPTION OF THE CONCEPT

Figure D.1 shows the basic configuration for a lithium-lead blanket. The chamber rotates at 36 rpm, sufficient to provide about 1.5-g at the minimum radius. LiPb enters from fixed

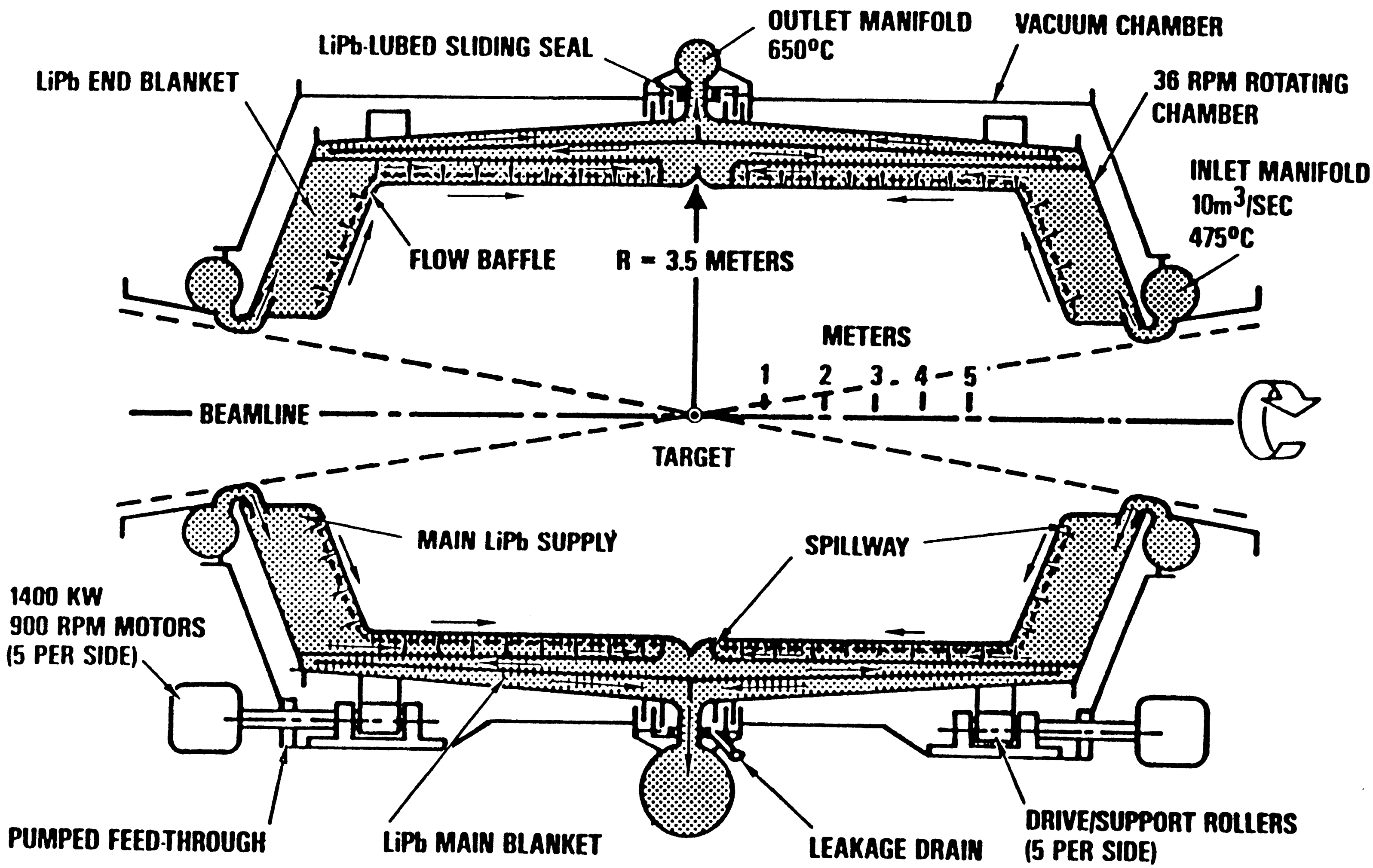

Fig. D.1. Cross section of the LIFE Reactor concept showing rotating blanket, turbulence-generating baffles, exit seal, and vacuum chamber.

manifolds at the ends into open weirs. A portion spills over the edge, protecting the end surfaces, while the rest makes up the end blanket and flows radially outward. Flow baffles allow liquid to jet to the surface, which generates the turbulence needed to prevent overheating (discussed below). All of the flow moves over the surface, picking up the X-ray and debris power, and is then directed radially outward by other baffles where it picks up the neutron heating and exits at the peak temperature. A low-pressure seal couples the rotating exit flange to a fixed outlet manifold. The rotating chamber is surrounded by a fixed chamber pumped down to moderate vacuum. The liquid flowing from the inlet manifold to the free surface of the end blankets seals the reactor chamber from the vacuum chamber. Ten 1400 kW (for LiPb) drive motors rotate the chamber. The chamber radius and aperture openings are scaled so that all of the liquid blanket will remain in the chamber if rotation were stopped.

D.3 STORED ENERGY AND PRESSURE

With a density of 9400 kg/m^3, lithium-lead can generate considerable pressure and stored energy in a rotating system. The pressure at a radius R_2 is easily derived and is given by

$$p_2 = \frac{\rho \omega^2}{3R_2}(R_2^3 - R_1^3) \tag{1}$$

where R_1 and R_2 are the inner and outer radii, respectively, of the liquid layer, ρ is the liquid density, and ω is the angular velocity in radians/s. In the reference design, for example, R_1 = 1.3 m and R_2 = 4.1 m in the ends. With ω = 3.4 rad/s, p_2 = 0.58 MPa (83 psi), which is high but tolerable. Most of this pressure is used up driving the liquid through the flow baffle restrictions. In the center section, R_1 = 3.5 m and R_2 = 4.5 m at the outlet manifold, giving p_2 = 0.4 MPa (55 psi). This pressure can be used to drive the LiPb through the heat exchangers and return ducting; no other pump is needed. The stored energy in the rotating system, which could be a safety concern, is given by

$$KE = \frac{\pi}{4}\rho L \omega^2 (R_2^4 - R_1^4) \tag{2}$$

where L is the axial length of the section with radii R_1 to R_2. With 3.4 rad/s, the stored energy is about 270 MJ. This could throw the LiPb up to a height of 9 meters. The dynamic pressure after thermalization associated with this energy are 0.8 MPa (115 psi) and 0.5°C. These values seem containable over local areas in expected reactor buildings. With Flibe, the stored energy, dynamic pressure, and temperature rise are reduced to 1/5 or less of the LiPb values: 57 MJ of rotational stored energy, 0.17 MPa (24 psi) dynamic pressure, and 0.04°C temperature rise. It is concluded that neither pressures from rotation nor stored energies are critical faults of the concept.

D.4 FIRST SURFACE BLOWOFF AND CONDENSATION

The maximum temperature at which the surface can operate is determined by the driver vacuum requirements. This depends on the vapor pressure of the liquid. Preliminary results from the ICF reactor study indicate that Flibe can operate at a surface temperature of 600°C; lithium-lead is limited to about 500°C.

Although the target explosion imparts a sharp energy pulse to the front surface, blowoff and recondensation convert this to a quasi-steady power flow. With 1000 MW of surface energy (3000 MW total thermal power), at R = 3.5 m the power flux is 6.5 MW/m^2. With 400 MJ yield and 2400 MW fusion power, the interpulse time is 0.167 s. If the surface of the liquid were quiescent, LiPb temperature would rise a prohibitive 630°C in this interval. Turbulent mixing is required, and this can be accomplished with liquid jets created by baffles. This is shown in Figs. D.1 and D.2.

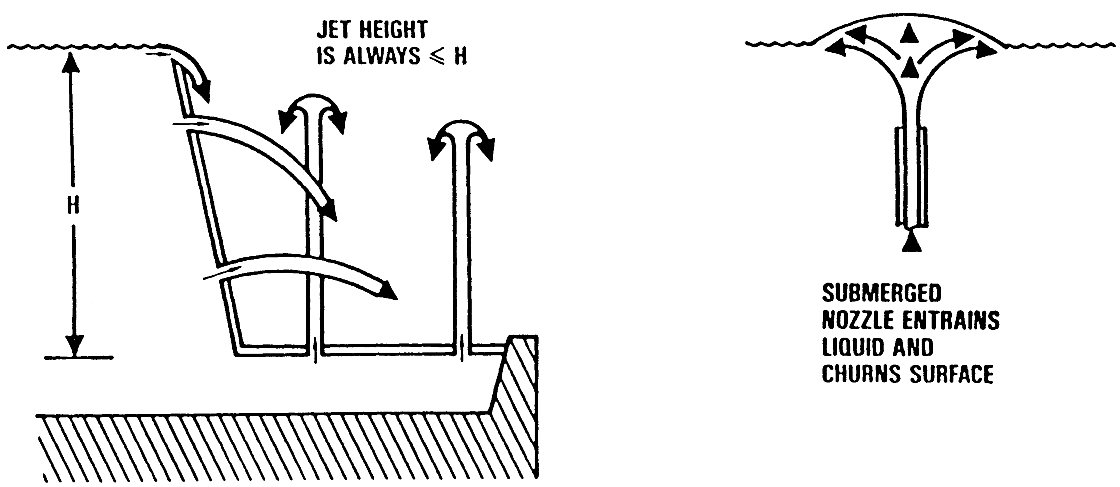

Fig. D.2. Conceptual depiction of turbulence mechanism.

Even though LiPb has a reasonable thermal conductivity, 15.1 W/m-K, turbulence is still needed at the heat fluxes encountered. With Flibe, K = 1.0 W/m-K, and conduction is negligible. However, because its viscosity is fairly low, it can handle these heat fluxes if turbulent. The Nusselt number, *Nu*, is a measure of the ratio of heat transfer with convection vs. that by conduction alone. To get rough estimates of surface temperature, the conduction equation can be used[D-3] with *NuK* replacing *K*:

$$\Delta T_s = 2q_s\sqrt{\frac{\tau}{\pi\rho C_p NuK}} \tag{3}$$

where ΔT_s is the temperature rise in time τ of an element of fluid on the surface when subjected to a steady heat flux q_s. For liquid metals, the Nusselt number is given by[D-4]

$$Nu = 5.6 + 0.165 Re^{0.85} Pr^{0.86} \tag{4}$$

where *Pr* and *Re* are the Prandtl and Reynolds numbers, respectively. Eq. (4) is valid for liquids metals, which have very low *Pr* values. Flibe, on the other hand, has a *Pr* value of 19. Here another expression for *Nu* is appropriate[D-5]

$$Nu = 0.036 Pr^{0.33} Re^{0.8} \tag{5}$$

In order to prevent surface overheating, Nusselt numbers must approach 300 for LiPb and 1000 for Flibe. These can reasonably be achieved in both cases with jet velocities in the 5 m/s range and jet characteristic dimensions of a few cm. Such velocities can be produced by the existing hydrostatic heads. The small, closely-spaced holes can be had with perforated plates of the type shown in Fig. D.1.

While Nusselt analysis can give a fair estimate of surface turbulence, a more detailed approach is to perform an analysis of entrained jets. A jet submerged a distance x below the surface will entrain liquid[D-6] and spread to a radial distance $b = 0.255x$. The jet diameter at x from a nozzle with diameter D is then $2b + D$. The velocity in the center of the jet falls off only linearly with distance:[7]

$$\frac{u}{u_o} = \frac{D}{x} \tag{6}$$

where $u(x)$ is the axial velocity, and u_o is that at the nozzle exit. The turbulent mixing length is $\lambda = 0.068b = 0.017x$. We can define a mixing time τ_m as the time an element of the jet is exposed to the surface heat flux:

$$\tau_m = \frac{\lambda}{u} = \frac{0.017x^2}{u_o D} \tag{7}$$

This time can be used in Eq. (3) to estimate surface temperature rise. Using the jet equations above, one can get a self-consistent design for the flow baffles. This is shown for Flibe in Table D.1.

The table shows a design having jets flowing radially inward toward the surface. There are a number of other possibilities, of course. For example, louvers directing the jets to flow near-tangentially could increase turbulence even more.

Table D.1. Flow Baffle Design for Flibe

Allowable ΔT	75°C
Surface Heat Flux	6.5 MW/m^2
Flibe Volume Flow	4.2 m^3/s
Initial Jet Velocity	8 m/s
Baffle Nozzle Hole Diameter	1.0 mm
Hole C-C Spacing	17.6 mm
Hole Depth Below Surface	23 mm
Number of Holes	710,000
Surface Fluid Mixing Time	0.5 ms

D.5 VAPOR CONDENSATION

As shown above, the cool, turbulent liquid surface can condense hot vapor directed to it up to a heat flux of several MW/m^2. The question remains about the pumping rate of the vapor on to the liquid surface. The analysis below for Flibe, the worst case, shows that pumping is rapid and not a constraint to condensation.

The pumping speed of the vapor is given by[D-8]

$$S = \frac{62.5\ A}{\sqrt{M}}\sqrt{\frac{T}{298}} \quad l/s \tag{8}$$

where A is the liquid surface area in cm^2, $M = 14$ is the average molecular weight for dissociated Flibe, and T is the gas temperature in K, estimated to be 10,000 K. For a volume to be pumped, V, the pumpdown time over a pressure ratio p_1/p_2 is

$$\tau = 2.3\frac{V}{S}\log\frac{p_1}{p_2} \tag{9}$$

Density can be substituted for pressure in Eq. (9) by noting that the remaining vapor expands adiabatically and therefore $p \sim n^{\gamma}$, where $\gamma = 1.67$ for a monatomic gas. With a cylindrical chamber of 3.5 m radius and a length of 10 m, pumping from of 10^{23} m^{-3}, which exists just after a shot, to 10^{18} m^{-3}, needed for beam penetration for the next shot, requires 24 ms, a small fraction of the interpulse time. We conclude that blowoff vapor can be condensed in the time available.

D.6 ROTATING SEAL

A sliding seal is required between the rotating reactor chamber and the outlet manifold (no seal is needed at the inlet manifold because the inlet flow is onto a free surface). Figure D.3 shows the seal concept. The sliding seal is large, about 9 m in diameter, but can be segmented, and some leakage is allowed. The segmented seal slides against the outlet flange and is lubricated by the lithium-lead or Flibe. Metal O-rings, which can roll, seal the housing and allows the segmented seal to wear. Labyrinth seals contain any leakage so that it can be collected at the bottom of the reactor chamber and pumped back into the main f ow.

D.7 ROUGH COSTING

This concept is at a very early stage of development. Nevertheless, some rough costing is in order as part of the evaluation. The rotating chamber and flow baffle material is V-15Cr-5Ti, which is very expensive ($350/kg), but is compatible with hot LiPb. Less critical structures

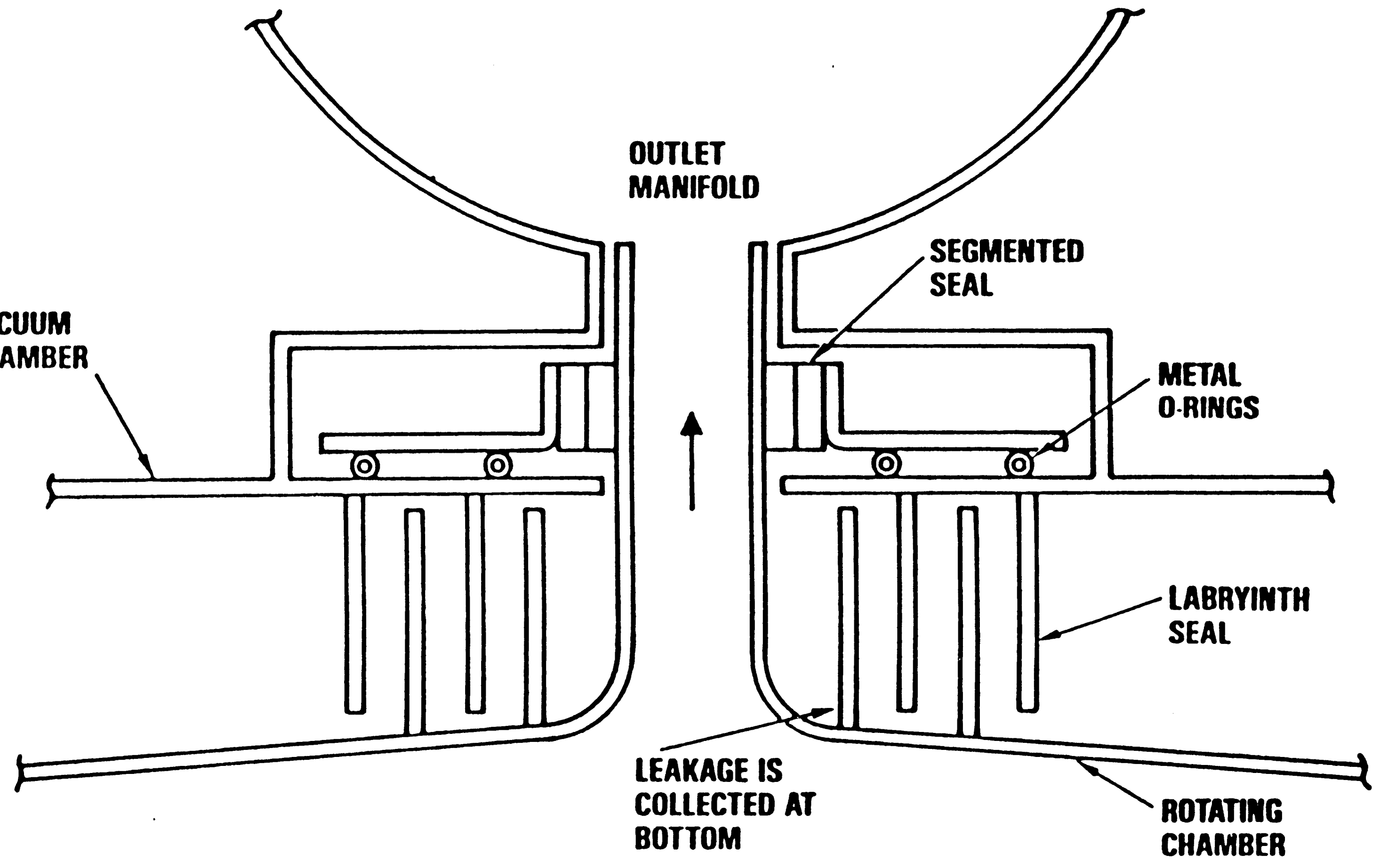

Fig. D.3. Sliding seal concept.

are of stainless steel ($50/kg). The outer shield is an aluminum water tank. The blanket coolant mass is increased 30% to account for that in manifolds and heat exchangers. A hotwell is provided below the reactor to store the molten coolant during service periods. Direct installed costs for the primary components are shown in Table D.2. Although these costs are very inexact, it is seen that large errors could occur and costs would still remain moderate.

Table D.2. Cost Estimate ($ Millions)

	LiPb	Flibe
Rotating Chamber	16	10
Blanket Coolant	17	66
Vacuum Chamber	3	3
End Plates/Manifolds	10	10
IHX	18	24
Water Shield	5	5
Drive Motors	2	1
Hotwell	3	2
Total	74	121

D.8 SUMMARY

This work has shown that a rotating reactor chamber with a liquid blanket can be designed with sufficient turbulence in the free surface to remove the heat generated by target explosions. Because it is viscosity rather than thermal conductivity that limits heat removal, both lithium-lead and Flibe can be used. Although LiPb has a fairly high rotational stored energy, it translates into a moderate dynamic pressure and thermalized temperature rise. The stored energy in Flibe is actually quite low and poses no problem. A rough cost estimate shows that the primary reactor components are not very expensive.

The LIFE reactor concept appears to be an improvement over the Cascade concept in that granule refurbishing is eliminated, the blanket is self-healing, and heat transfer to the power conversion system is by convection rather than radiation. One disadvantage is the lower operating temperature compared to the ceramic granules in Cascade. However, one can still expect power conversion efficiencies in the 45% range.

The LIFE reactor is but one of several concepts that have been explored in the this study. It was decided not to pursue it further mainly because of concern with large rotating machinery and the large amount of stored energy with lithium-lead. Rotating machines of this scale exist today; therefore this concern is somewhat unfounded. The rotational stored energy issue has been shown above to be a minor one, especially with Flibe. Therefore, this concept can still serve as an important fallback position.

D.9 REFERENCES FOR APPENDIX D

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