HYLIFE-II INERTIAL CONFINEMENT FUSION POWER PLANT DESIGN

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The HYLIFE-II inertial fusion power plant design study uses a liquid fall, in the form of jets, to protect the first structural wall from neutron damage, x rays, and blast to provide a 30-y lifetime. HYLIFE-I used liquid lithium. HYLIFE-II avoids the fire hazard of lithium by using a molten salt composed of fluorine, lithium, and beryllium (Li_2BeF_4) called "Flibe". Access for heavy-ion beams is provided. Calculations for assumed heavy-ion beam performance show a nominal gain of 70 at 5 MJ, producing 350 MJ, about 5.2 times less yield than the 1.8 GJ from a driver energy of 4.5 MJ with gain of 400 for HYLIFE-I. The nominal 1 gigawatt electrical (GWe) of power can be maintained by increasing the repetition rate by a factor of about 5.2, from 1.5 to 8 Hz. A higher repetition rate requires faster re-establishment of the jets after a shot, which can be accomplished in part by decreasing the jet fall height and increasing the jet flow velocity. Multiple chambers may be required. In addition, although not adequately considered for HYLIFE-I, there is undoubtedly liquid splash that must be forcibly cleared because gravity is too slow, especially at high repetition rates. Splash removal can be accomplished by either pulsed or oscillating jet flows. The cost of electricity is estimated to be 0.09 $/kWh in constant 1988 dollars, about twice that of future coal and light-water-reactor nuclear power. The driver beam cost is about one-half the total cost.

1 INTRODUCTION

The use of jets to attenuate the blast in an ICF reactor design was first suggested by Burke *et al*[1]., using liquid lithium, and by Seifritz and Naegele,[2] using Flibe. The first complete inertial confinement fusion reactor design to use these principles of blast attenuation was first published by Monsler *et al.*[3] and a final report was published by Blink *et al.*[4] The design was called HYLIFE. The HYLIFE-I design in which molten salt jets composed of fluorine, lithium and beryllium (Flibe) is substituted for liquid lithium jets is called HYLIFE-II (Refs. 5 and 6). The design will work with minor modifications of the HYLIFE-I design (e.g., beam access) if targets having a yield of 1.8 GJ (a gain of 400 with a 4.5 MJ driver) can be obtained, as assumed in HYLIFE-I. Splash clearing, however, was never satisfactorily accomplished in HYLIFE-I. High gain (400) results from advanced targets and is beyond the state-of-the-art. Conventional targets are predicted to have gains of 70 at 5 MJ with projected beam parameters giving a yield of only 350 MJ. Such low yields (350 MJ rather than 2000 MJ) push the design to high repetition rates to obtain either the same power or higher driver energy and result in major departures from the HYLIFE-I design. Because, for any target design, the gain increases with driver energy, a larger yield can be obtained with higher driver energy, but drivers are expensive and the cost increases as the driver energy increases. The cost of electricity is expected to decrease as the repetition rate increases and eventually to rise again when pumping power becomes large. We find that this rise is above 10 Hz. We looked at three ways to obtain a higher repetition rate: use three chambers, pulse the flow, and use oscillating nozzles.

2 PLANT PARAMETERS

The plant parameters for the base case using pulsed flow (Ref. 7) for 1 GWe and a case at 1.9 GWe are shown in Table 1.

3 TARGET

The target is designed for heavy ions such as $^{200}Hg^{+}$ at 10 GeV. The gain depends on energy delivered to the target, beam radius (2 mm), and ion range (0.1 g/cm^2). Target gain curves for a zero-degree beam half angle are shown in Figure 1 (Ref. 8). We assume 30% of the energy, 5 MJ for example, is delivered on a long "foot" pulse of about 30 ns and 70% is delivered in the main pulse lasting about 8 ns.

4 DRIVER INTERFACE ISSUES

The heavy ion beam and reactor chamber interface design are discussed more fully in a companion paper (Ref. 9). The driver is assumed to be a heavy-ion beam, although we also considered laser and compact-torus drivers. Because energy in a single beam is limited, 12 separate beams are assumed to provide the nominal 5 MJ total energy. These can be directed from two sides of the reactor or from only one side. The difficulty is to get a close-packed array with enough shielding. The beams are shown in Figure 2. A heavy-ion driver at 5 MJ, based on $^{220}Hg^{+}$ at 10 GeV, costs in the range of \$1 to 2 billion (10^9 dollars), a factor of 3 or more too high for good economics. Other drivers, such as a recirculating induction accelerator, with fewer components are possible. Another possibility is the mirrortron, which has the goal of shortening the heavy-ion beam lines by obtaining an average gradient an order of magnitude higher than is possible with induction accelerators (400 m long vs. 4000 m). Compact tori with acceleration and focusing require a much different target and transport system design and are interesting because of their order-of-magnitude lower cost (about \$100 M). However, they are speculative because the experimental parameters of compact torus accelerators are orders of magnitude away from what is needed. Laser drivers have been considered but are not leading candidates at this time because of high cost, low efficiency, and poor target performance, as well as the need to illuminate the target from many angles. Our back-up strategy to cut the driver's contribution to the cost of electricity is to either have one driver switched to up to four reactors, each of 1-GWe size, as in the HIBALL-II study (Ref. 10), or to increase

TABLE 1
Plant Parameters

	1 GWe	1.9 GWe
Driver energy	5 MJ	6.7 MJ
Target gain	70	100
Yield	350 MJ	600 MJ
Blanket multiplication	1.15	1.15
Repetition rate	8.2 Hz	8.2 Hz
Fusion power	2835 MW	5100 MW
Thermal power	3312 MW	5960 MW
Recirculating power	282 MWe	508 MWe
Pumping power	37 MWe	67 MWe
Beam electrical power	203 MWe	365 MWe
Auxiliary power	42 MWe	76 MWe
Net electrical power	1083 MWe	1949 MWe

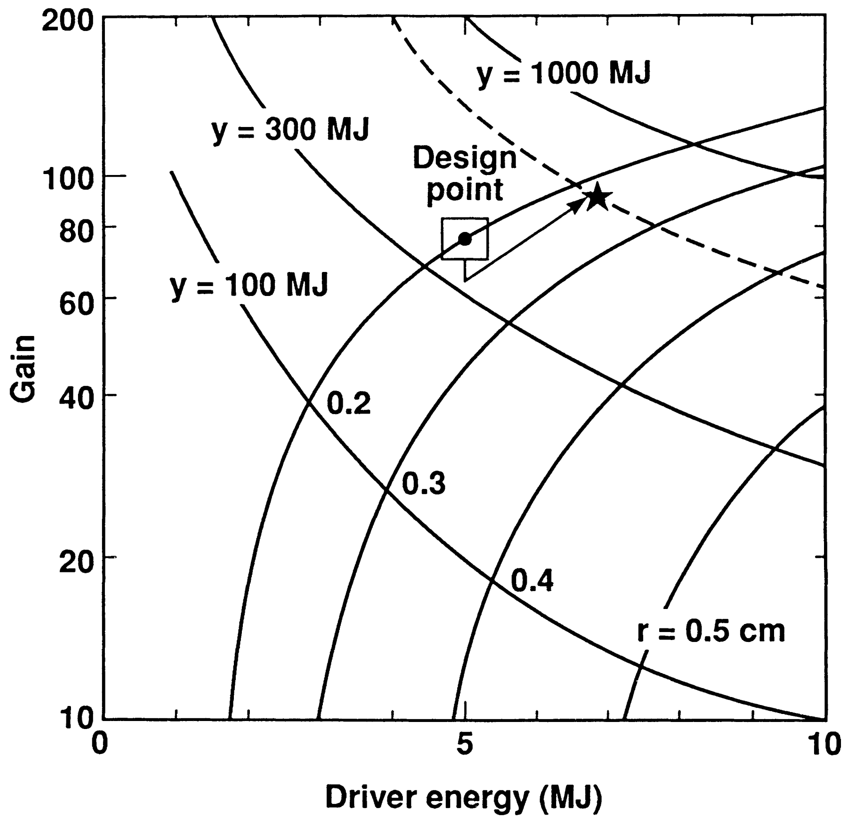

FIGURE 1 Target gain vs. driver energy. The beam spot size r is given as a parameter. The design point is 5 MJ, gain 70, range 0.1 g/cm^2, and spot radius 2 mm. The beam angle of about $\pm 9°$ will lower the gain. Increasing the driver energy to about 6.7 MJ will give a yield of 600 MJ for the 1.90 GWe case.

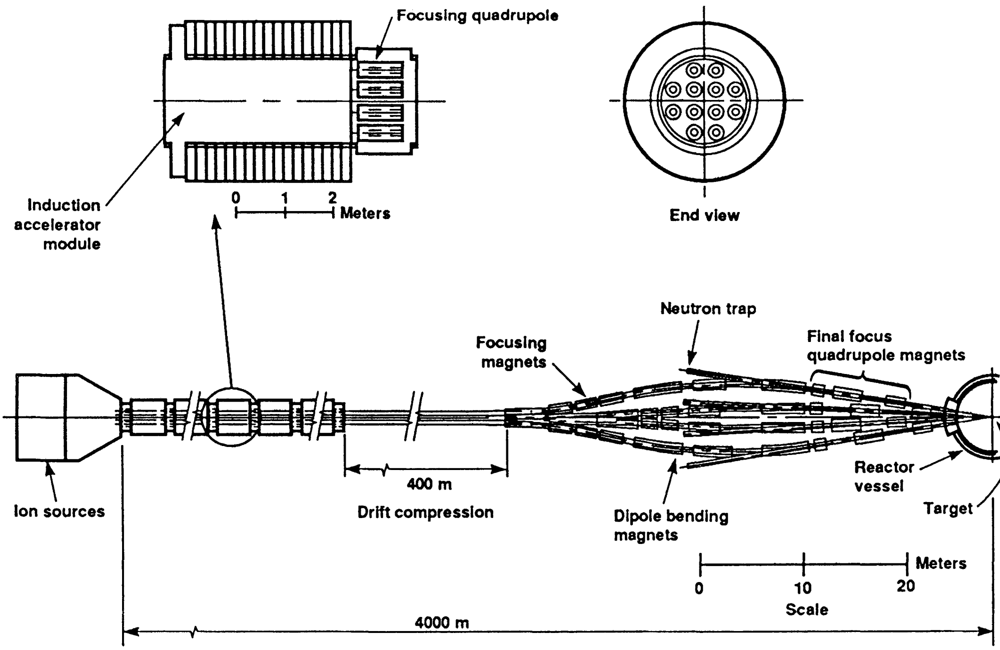

FIGURE 2 As an example we show a one-sided configuration of HYLIFE-II with 12 beams using heavy-ion induction linear accelerators. The length is approximately 4 km for charge +3 ions or three times longer for charge +1. The final beam focusing magnets (last 50 m) are in a very preliminary design stage. The half-angle encompassing all beams is ±9° for this array.

the power out of the reactor chamber to 4 GWe. The cost and complication of switching is probably acceptable when the total power is as high as 4 GWe, but is not acceptable at 1 GWe. A more modest suggestion is to increase the power in one chamber to 1.9 GWe, as shown in Table 1.

5 CHAMBER MECHANICAL DESIGN

A liquid fall is used to protect the first structural wall from neutron and blast damage. The liquid breaks up as a result of sudden neutron heating and the wall must be strong enough to contain the flying liquids (Refs. 11 and 12), and the gas pressure pulse.

5.1 *Steady Flow with Multiple Chambers*

The HYLIFE-I chamber shown in Figure 3 is a steady-flow chamber. The structural wall is protected by weir flow. This requires slow flow (10 m/s) and a long fall distance (about 5 m) to protect the nozzle parts from neutron damage by the curvature of the flow over the weir. The repetition rate is low (1.5 Hz) because of the long reformation

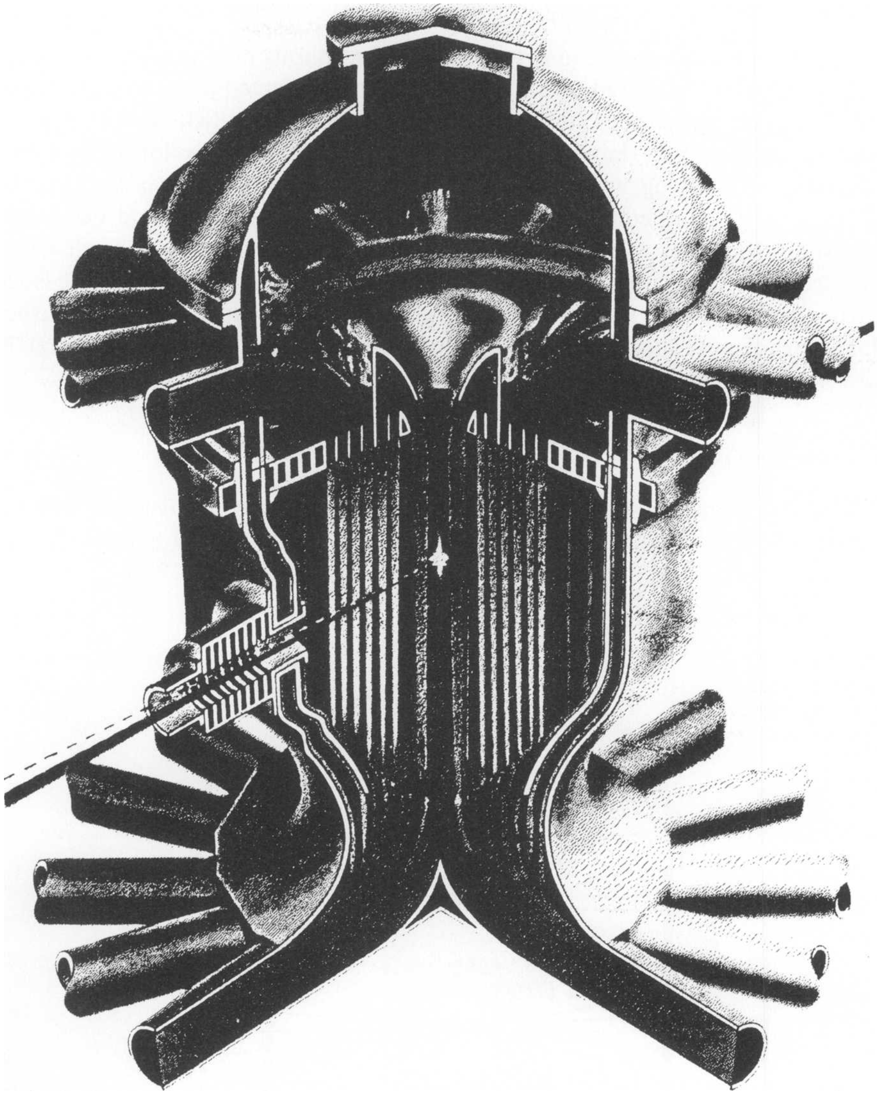

FIGURE 3 HYLIFE-I used steady flow.

time of the jet array. Splash is only partially cleared by gravity. The large distance above the target (over 8 m) would not be cleared.

To obtain enough power in HYLIFE-II, we considered using up to three 2.7-Hz chambers (1/3 GWe each). This system would have the complication of switching beams, high pumping power, high cost for a 1-GWe power plant, and still not be cleared of splash. The three-chamber design option was so undesirable it was dropped from further consideration.

5.2 Pulse Flow

The pulsed flow case shown in Figure 4 uses continuous flow everywhere except for a slug of liquid 0.3 m in radius and about 1 m long, injected at 12 to 16 m/s for 6 to 8 Hz. The high repetition rate is achieved by a short fall distance of only 2 m. A pulsed pump to inject the slug needs to be designed and developed to withstand cyclic fatigue. The slug will clear splash from the beam path near the target. It is vital that the trailing edge of the liquid slug be sharply cut off and not leave too many splash droplets in the beam path. Other pulsed jets may be needed to clear splash from the rest of the beam path. One issue that requires solution is the isochoric neutron heating of the top of one slug that reduces its velocity and diminishes the volume for the next shot (thereby possibly limiting the repetition rate to 4 Hz). Many issues need further thought.

5.3 Oscillating Flow

Another way to achieve a high repetition rate and short fall distance with splash clearing is to oscillate the jet nozzles horizontally, as shown in Figure 5 (Ref. 13). A

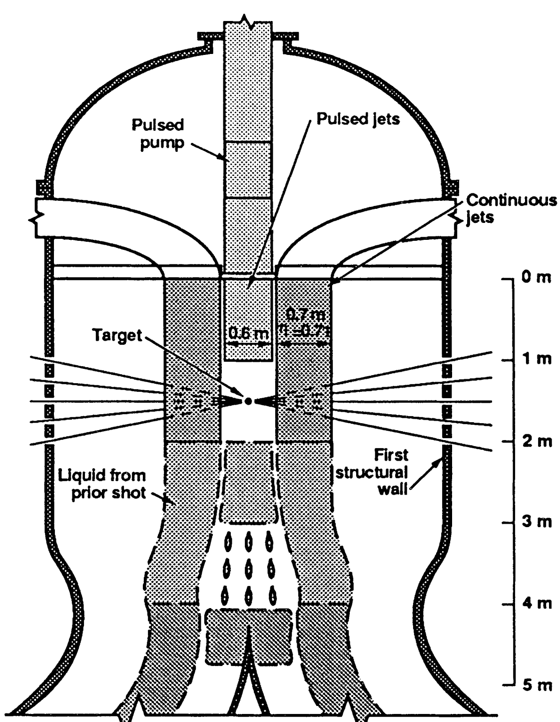

FIGURE 4 HYLIFE-II, pulsed flow. The flow speed for 8 Hz is 16 m/s with a 2-m fall height, giving a flow rate of 34 m^3/s.

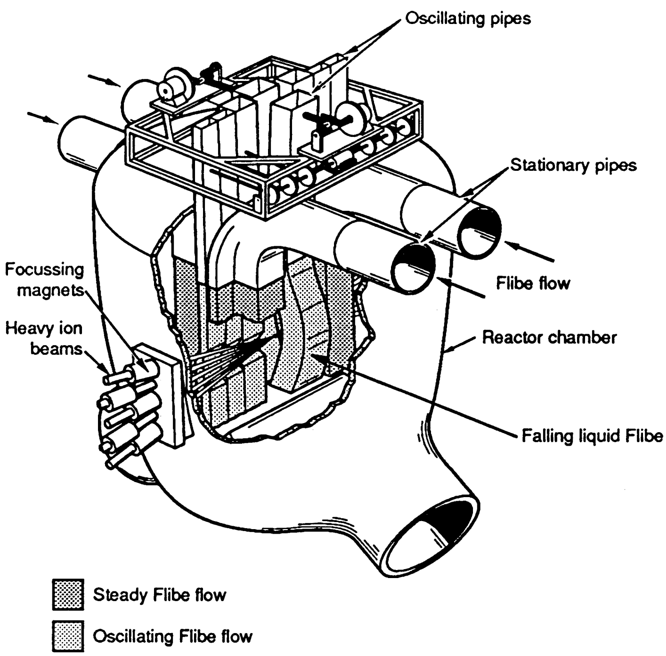

FIGURE 5 HYLIFE-II, oscillating flow.

pocket is formed in the flow where a target is injected and the microexplosion occurs. The oscillating flow sweeps splash liquid from the target region. The beam path can be cleared with more oscillating flows or with pulsed flows of liquid. It will be necessary to design mechanical moving parts, including bellows, to allow nozzles to oscillate at up to 8 Hz through a motion of up to ± 0.1 m. Fatigue and vibration will be design problems.

5.4 Jet Design, Clearing, and Condensation

Steady horizontal and vertical, neutronically thick, liquid jets shown in Figure 6 will clear the beam path and protect the beam ports from radiation damage. The spacing between these jets should be less than S ($S = 0.5\ \mathrm{gt}^2$), where S is the distance liquid droplets or splash can fall by gravity between shots. For 8 Hz, $S = 7.7$ cm. If splash starts with an upward velocity, the distance S must be cut by up to a factor of four. With this system, splash is not cleared from all regions of the beam.

The energy from the 350 MJ microexplosion will evaporate about 8.8 kg of liquid Flibe. The density of the vapor cloud when it has filled the chamber is about $10^{18}/\mathrm{cm}^3$, assuming 8.8 kg at 5000 K in a 5-m-high chamber with 3-m radius. By the time of the next shot (0.125 s for 8 Hz) the density must drop from $10^{18}/\mathrm{cm}^3$ to about $3 \times 10^{13}/\mathrm{cm}^3$ in 0.125 s for propagation of heavy ions, a factor of 3×10^4. The vapor pressure and density for propagation is discussed in Ref. 9 and references cited therein.

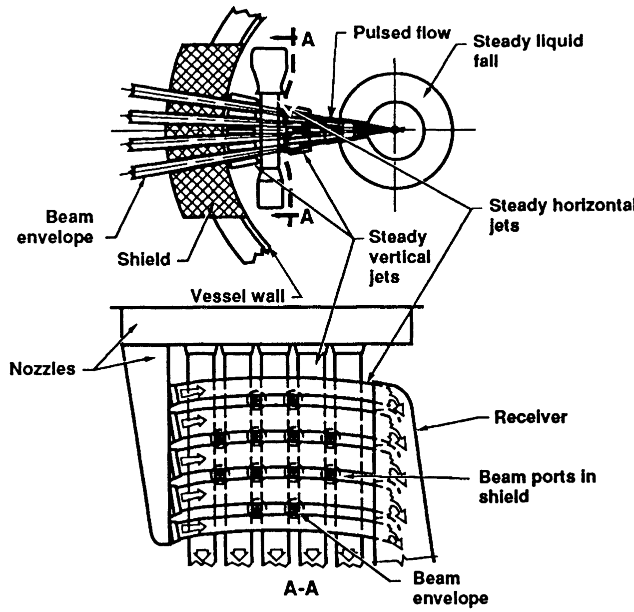

FIGURE 6 Thick horizontal and vertical liquid jets protect the beam ports from radiation and help clear splash liquid for the next shot.

This density reduction can come about by condensation of the vapor on the liquid jets and on the droplets left from the explosion (Ref. 14). One strategy is to inject "cool" Flibe at 873 K in a spray of droplets in the vicinity of the beam paths. According to our calculations, this injected spray can provide enough condensation area without depending on the explosion itself making enough small droplets of the liquid in the chamber. Our present model indicates the temperature in the cloud drops quickly ($\ll 1$ ms) to 5000 K. Below 5000 K, radiation is slow and conduction and convection bring the temperature to about 1500 K when the liquid surface and cloud temperature are equal, after about 1 ms. After this time, condensation proceeds at the rate heat can be transported from the liquid surface into the cool liquid interior. Although we predict condensation will be fast enough to allow an 8-Hz repetition rate, we recommend a definitive experiment on condensation with Flibe because of the complication of condensation of Flibe dissociation products, etc.

6 NEUTRONICS

Neutronics analyses of the HYLIFE-II reactor concept (Ref. 15) give a tritium breeding ratio (TBR) of 1.17 and a system energy multiplication factor of 1.15. The main safety issues for HYLIFE-II are the large shallow burial index (106) and the requirement to contain 99.9964% of the ^{18}F inventory to prevent its release to the public. Although fluorine is very chemically active, in the form of Flibe it is well tied up and not volatile. Therefore special nuclear certification such as the ASME ("N-stamp") is not needed.

7 TRITIUM SYSTEMS

Practically all of the tritium gas emitted by exploding targets will be removed by the vacuum pumping system, but almost none of the tritium bred in the Flibe will diffuse out of the Flibe droplets (Ref. 16). At a fusion power of 2835 MWth with a breeding ratio of 1.17, the tritium production rate in the Flibe is 1.16×10^{21} atoms/s. The corresponding radioactivity production rate is 4.8 MCi/d, of which most will be recycled in new targets. The fraction of tritium removed from Flibe by the primary loop vacuum disengager (wherein a fine spray of Flibe droplets permits tritium to diffuse out and be pumped) is about 99%. The fraction of tritium leaking through the intermediate heat exchange (IHX) per pass of the coolant through the IHX is 6.5%, according to detailed calculations of mass transfer during turbulent flow in the IHX. The fraction of tritium removed from the $NaBF_4$ intermediate coolant by the gas exchanger is greater than 99%. Because data on tritium behavior in $NaBF_4$ are lacking, the fraction of tritium leaking from the $NaBF_4$ through the stream generator tubes is conservatively assumed to be about 1%. For these conditions, the tritium leak rate is held to less than 40 Ci/d, which satisfies the safety goal for routine releases.

The tritium removal system could be very large because the intermediate coolant flow rate is very large. The blast chamber and Flibe piping should be double-walled, to prevent significant tritium leakage under normal and off-normal conditions. Beryllium metal will be used to neutralize free fluorine liberated in the Flibe by nuclear reactions. The greatest need for future work is to design the vacuum disengager and gas exchanger to quantify the size, power dissipation, and cost associated with achieving 99% efficiencies.

8 MATERIALS AND MOLTEN SALT TECHNOLOGY

8.1 Compatibility and Corrosion

We chose a high-nickel steel for our vessel material and pipes. A 316-stainless steel will work with adequately low corrosion rates, and modified Hastelloy N (a high-nickel steel) will work even better. In the future we might consider the use of carbon-carbon composites for the vessel material because graphite is compatible with the molten salt if tritium retention is not too serious. Pyrolytic graphite has low retention but porous forms of graphite have higher retention. The use of a graphite vessel will reduce activation, increase tritium breeding, and reduce the heat leak to the shield.

8.2 *Chemical Kinetics of Dissociated Flibe*

We know that, when Flibe is dissociated into its constituents by the microexplosion, about 9 kg of Flibe is raised to 5000 K. (Recent investigations not folded into this work suggest this temperature may be as much as ten times higher.) These constituents will reform Flibe and not other species. That is, Flibe is stable under radiation and the recombination reaction is strong; however, based on preliminary study, we believe that the recombination is sufficiently fast so as not to be a limiting factor in the condensation of Flibe vapor on liquid droplet surfaces. An issue with condensation is that the constituents of Flibe must chemically recombine and stick on striking the droplet surfaces. Too low a sticking ratio will slow condensation. We think LiF will have a sticking coefficient of at least 0.5. We are concerned that the BeF_2 may bounce off liquid surfaces many times before sticking and joining the bulk liquid. If the small sticking coefficient is not limiting, we have shown all other processes are fast enough to permit a repetition rate as high as 8 Hz. This is an area for further study, and a definitive experiment is needed.

8.3 *Choice of Target Material*

We chose tantalum for use in the target because it is relatively high Z ($Z = 73$) and is soluble in Flibe. We can make coatings by chemical vapor or liquid deposition. Many other high-Z materials we could have chosen, such as lead and tungsten, would precipitate on the walls of the vessel and pipes, making recovery difficult and causing other problems.

9 BALANCE OF PLANT

The balance-of-plant is discussed by Hoffman (Ref. 7). The low-viscosity composition of Flibe that melts at 733 K (460°C) was chosen. The inlet and outlet temperatures of the Flibe from the intermediate heat exchanger are 923 K (650°C) and 873 K (600°C), respectively. Our use of molten salt relies heavily on early work on molten-salt reactors at ORNL (Ref. 17). The intermediate coolant $NaBF_4$ was chosen (Ref. 18) in part because of its tendency to hold up tritium in the form of T_2O and retard its passing on into the steam system and hence to the environment.

10 SAFETY AND ENVIRONMENT

An outstanding feature of the HYLIFE-II reactor is its favorable safety characteristics (Ref. 19). Safety and environmental goals for HYLIFE-II include:

- Offsite dose from severe accident less than 2 Sv (200 rem) for passive safety
- No N-stamp requirement for most components, requires less than 0.25 Sv (25 rem) offsite dose

- Working area dose rate less than 50 μSv/h (5 mrem/h) for a low occupational risk
- Dose from routine atmospheric effluents less than 50 μSv/y (5 mrem/y)

To evaluate the potential to meet these goals, the consequences of a severe accident involving blast chamber failure and breach of containment are studied, including the effects of activation products, tritium, and beryllium toxicity. HYLIFE-II has no large sources of energy available to disperse radioactive materials. The tritium inventory in the Flibe could be kept very low (about 1 g). The dominant activation product is about 300 MCi of ^{18}F (half-life 110 m). A very small fraction (6×10^{-6}) of the Flibe activation products would be mobilized, because the microexplosion vaporizes about 9 kg from the 1500 t of Flibe. Only a fraction of the mobilized vapor would escape from a hole in the blast chamber, and only a fraction of that from a hole in the containment building. The ^{18}F offsite dose from a severe accident (breaching both the blast chamber and the containment) would be less than 0.2 mSv (20 mrem). Thus, N-stamp requirements can be avoided in the main reactor components, and the passive safety goal can be met.

If the maximum vulnerable tritium inventory in the target factory and tritium handling systems were less than 2.5 kg, then the maximum offsite dose from its release would be less than 0.25 Sv (25 rem), and the N-stamp requirement could be avoided for those systems as well. Some contact maintenance should be feasible on the $NaBF_4$ secondary loop, but not on the Flibe primary loop (unless a very effective impurity removal system were operating and activated impurities did not plate out on pipe walls). Activation of metallic impurities in the Flibe from a $NaBF_4$ secondary coolant leak from corrosion products, from target materials, or from a MoF_6 corrosion inhibitor (if used) could result in high dose rates. The occupational risk goal can be met if personnel do not work in the primary coolant loop area. The routine effluent goal is met provided the tritium removal systems in the primary and intermediate coolant loops are made large enough. After 30 y of operation with a 50-cm-thick Flibe jet curtain, the dose rate from the blast chamber (made of high-nickel steel such as Hastelloy or stainless steel) would be too high for shallow land burial.

11 ECONOMIC ANALYSIS AND SYSTEMS ISSUES

The SAFIRE economics and systems analysis code was used to study some trends in HYLIFE-II (Ref. 20). Some but not all of the algorithms in SAFIRE were changed to model the chamber and IHX using Flibe instead of lithium; therefore the trends are only suggestive. The cost of electricity calculated for various values of net power and for various driver cost multipliers is shown in Figure 7.

The cost breakdown is given in Table 2 for a case with a 5-MJ driver operating at a 7.5 Hz repetition rate and 1 GWe power. The cost of electricity is about 0.27 $/kWh for current dollars or 0.09 $/kWh for noninflated constant 1988 dollars. If the driver direct cost were to be multiplied by 0.5 or 0.0 the cost of electricity would drop as shown in Figure 7. Reducing the net power to 500 MWe has a major

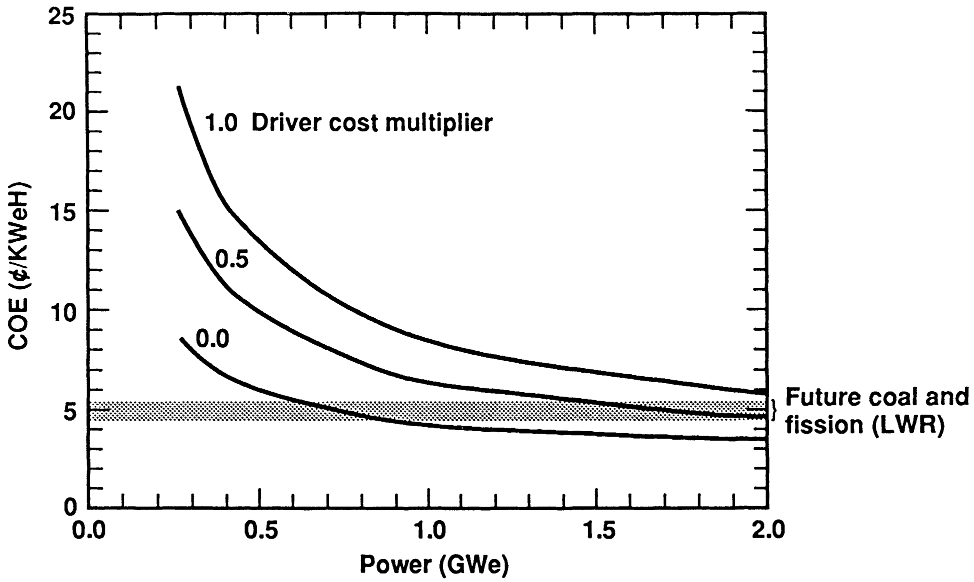

FIGURE 7 Cost of electricity in constant 1988 dollars vs power. The importance of driver cost reduction and increasing plant size are shown.

cost penalty, especially for the costly driver cases. For comparison we show the future coal and light-water reactor (LWR) nuclear power costs of 0.04 to 0.05 \$/kWh. Future coal and nuclear costs might be increased because of CO_2 mitigation, waste disposal, and fuel breeding.

12 SUMMARY AND CONCLUSIONS

In the design known as HYLIFE-II, we have substituted Flibe for lithium and modified the HYLIFE-I design to obtain repetition rates up to 8 Hz. We examined pulse and oscillating flow concepts to obtain this high repetition rate and to remove splash liquid from the beam lines before the next shot. Condensation is predicted to reduce the Flibe vapor to low enough values to permit an 8-Hz repetition rate. The fire hazard has been eliminated and safety requirements met (but shallow burial upon decommissioning is not achieved).

At present, the design and performance of the system depend on many assumptions that must be verified by future analysis and experiment before we can have a high level of confidence in the predicted performance. Some of the key issues include verifying splash removal techniques, tritium removal effectiveness and permeation rates, condensation phenomena and sticking coefficients, heavy-ion accelerator technology and cost reduction, and beam propagation. To be competitive with future coal and LWR nuclear power, the cost of electricity needs to be reduced by about factor of 2, which might be accomplished by a combination of driver cost reduction and increased plant power.

TABLE 2
Plant Cost Breakdown

Acct.	Item	Cost (million $)	
20	Land and land rights		5.0
21	Structures and improvements		280.2
22	Reactor plant equipment		551.4
	Tracking, align systems	30.4	
	First wall systems	1.6	
	Tritium extraction systems	4.6	
	Blank and shield	32.5	
	Heat transport system	80.4	
		149.5	
23	Turbine plant equipment		229.8
24	Electric plant equipment		90.9
25	Miscellaneous plant equipment		59.5
26	Main heat rejection equipment		41.1
27	**Drive equipment**		**1397.3**
28	Target factory equipment		128.8
	Total direct cost		**2783.9**
91	Construction services		556.8
92	Home office engineering and services		417.6
93	Field office engineering and services		278.4
94	Owner's cost		194.9
95	Project contingency		423.2
	Total overnight cost		4654.7
		Current $ 1996	Constant $ 1988
96	Escalation during construction	1502.2	0.0
97	Interest during construction	1955.1	434.8
	Total capital cost	8112.0	5089.5
	Cost of electricity (¢/kW h)		
	Capital	21.12	6.79
	Fuel	0.03	0.01
	O & M	6.97	2.24
	Total	28.11	**9.04**

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