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1. Abstract

The HYLIFE–II concept for IFE (inertial fusion energy) is based on nonflammable, renewable liquid-wall fusion target chambers formed with Flibe (Li_2BeF_4) molten-salt jets, a heavy-ion driver, and single-sided illumination of indirect drive targets. As a direct result of using thick renewable liquid walls, the predicted cost of electricity is reduced about 30% to 4.4¢/kWh at 1 GWe (3.2¢/kWh at 2 GWe). The development program for HYLIFE–II can be shortened and reduced in cost by not requiring expensive neutron sources to develop first-wall materials.

2. Description

HYLIFE–II is an inertial fusion power plant design[1] in which a 5-MJ heavy ion beam is focused onto a target to produce micro-explosions at a 6-Hz rate, with 350 MJ yield and 1000 MWe. The region where fusion reactions occur is surrounded by a neutronically thick liquid (0.5 m of Flibe), which has penetrations that allow only a few tenths of a percent of the neutrons to leak out (Fig. 1). Figure 2 shows the chamber[2] and pumps to circulate the liquid. These few leaking neutrons can be attenuated by adding an accurately placed liquid or solid near the target[3] (within 3 mm of the beam paths) to shadow-shield the beam ports from line-of-sight neutrons (Fig. 3). This idea is discussed more fully in Ref. 4.

The liquid, traveling at 12 m/s out of the oscillating (± 1.6°, 2 m long) deflectors, sweeps the target region clear of droplets during its 2-m travel. Figure 4 shows the incoming liquid is not perturbed by the prior shot because the liquid is contained within the deflector tubes, where the jets clear the central chamber of droplets that otherwise might interfere with the passage of the heavy ions to the target. (Chamber clearing is discussed more thoroughly in Ref. 1.) For example, recombination of the Flibe constituents has been shown theoretically to be sufficiently rapid that no significant free fluorine will be available to cause corrosion.

3. Design Function and Advantages

The design with liquid protection reduces stresses from pulsed loading and has a number of advantages over the solid first-wall designs. For example, the components are predicted to last the 30 year life of the plant with only 100 displacements per atom in 304 SS (with 0.55 m of Flibe [Li_2BeF_4] protection) and cyclic fatigue[2] included (see Fig. 5). The capacity factor is expected to be 10% higher (85% vs 75%) than for non-liquid-walled blankets, because no blanket replacement shutdowns are required. Without liquid protection, the wall load would be 15 MW/m^2 and the lifetime would be about 1 year. The component replacement, operations, and maintenance costs might be half the usual value (3% per year of direct cost vs 6%) because no blanket change-out costs or accompanying facilities are required. These combined savings might lower the cost of electricity by 30% to 4.4 and 3.2 ¢/kWh at 1 and 2 GWe (1993$), respectively. Table I gives a cost breakdown. The heavy-ion driver is the biggest single cost item (38% of the total). The cost of the liquid, its pumps, and its pumping power contribute about 12% to the cost of electricity, some of which is needed in any fusion power plant. In addition, the need for a high-intensity 14-MeV neutron test facility to develop first-wall materials is avoided or greatly reduced, saving billions of development dollars.

Nuclear-grade construction should not be needed, largely because the liquid attenuates neutrons resulting in less activation of materials. Upon decommissioning, the reactor materials qualify for shallow-burial disposal when constructed of 304 SS[5] with 0.8 m of Flibe protection (Fig. 6). There is 0.5 m of Flibe between the target and the first thin (2 mm) nonstructural wall at 3 m (Figs. 2 and 3). Before the double structural wall, there is another 0.5 m of Flibe. Each of these 25-mm-thick walls can handle the main stress and atmospheric load. The use of molten salt instead of molten Li and molten $Li_{17}Pb_{83}$ has several advantages: (1) it will not burn; (2) it has low vapor pressure, low corrosion rates; and (3) it has a low tritium solubility and therefore low tritium inventory. However, Flibe has 300 MCi of 2-hr half-life ^{18}F. Safety analyses have shown this large amount of activation does not require nuclear grade construction or an evacuation plan near the site because the ^{18}F is not in a volatile form (its form is LiF and BeF_2), and there is insufficient energy to disperse the activated material. Also its short half life permits decay to benign elements relatively quickly.[6]

4. Issues to Resolve

- Demonstrate that condensation of the evaporated liquid is quick enough to permit the required pulse rate without interfering with the passage of the beams to the target.
- Demonstrate that the incoming liquid clears the splashed liquid from a prior micro-explosion to not interfere with the passage to the beam target.
- Demonstrate that the moving parts that create the liquid configuration are reliable so as not to degrade the advantage of the liquid's life-enhancing features.
- Show through laboratory demonstrations if liquid jet configurations can be made to meet the conditions discussed above and can thereby achieve the stated advantages.

5. Conclusions

An ongoing study of the HYLIFE–II design has resulted in considerable improvement and more can be expected. The close coupling of the driver and target requires an integrated design with special emphasis on the driver interface with the chamber and target. The most significant uncertainties are target performance and driver cost.

6. References

1. Moir, R. W. *et al.*, "HYLIFE–II: A Molten Salt Inertial Fusion Energy Power Plant Design-Final Report, " *Fusion Technology* **25**, 5–25 (1994).
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Figure Captions

Fig. 1. Liquid jets injected through oscillating deflectors periodically forms a pocket around the target and micro-explosion and crossed jets of liquid protect the beam ports from neutron damage.

Fig. 2. The HYLIFE–II fusion chamber. Oscillating Flibe molten salt jets create periodic pockets in the liquid for targets. Arrays of bypass pumps produce the required circulation rate of Flibe to speed chamber clearing.

Fig. 3 (a) Cross section at the target elevation (aerial view), showing the open space for vapor venting from the pocket and 0.5 m of liquid to attenuate neutrons in all directions except the beam paths. (b) A typical heavy ion target is shown with a special neutron attenuator that can shadow-shield the beam ports.

Fig. 4. The liquid from the oscillating nozzle deflectors shown at different times to illustrate the effect of sweeping the chamber clear of droplets and placing liquid between the shot point and the end of the deflectors to protect them. The 2-m-long deflectors move through ±1.55° or ± 54 mm. The outward shot induced velocity of the liquid is about 5 m/s. Notice that there is a possibility of injecting targets downward between the deflectors.

Fig. 5. Structural material lifetime versus density times the thickness of the liquid protecting the structural material for 304 and 316 SS. The useful lifetime in years is limited by "displacements per atom," assumed to be 100 dpa for austenitic stainless steels.

Fig. 6. Intruder lifetime dose versus thickness of the liquid protecting the structural material. If the intruder dose is less than 5 mSv/y or 0.5 rem/y (defined as the safe lifetime dose), the material qualifies for shallow land burial.

Table I. Plant Cost Breakdown

		1000 MWe Case (millions 1993$)		2000 MWe Case (millions 1993$)	
Acct	Item	R+D+TF[1]	BOP	R+D+TF[1]	BOP
20	Land and land rights		11.7		11.7
21	Structures/improvements	62.4	77.7	94.5	108.2
22	Reactor plant equipment				
22.1	• Reactor chamber	32.2		56.8	
	• Bypass pumps	61.2		95.9	
	• Bypass pipe	10.2		16.1	
22.2	Flibe coolant	34.0		60.7	
22.3	Vacuum system (in 22.5)				
22.4	Target factory and equipment	56.4		65.6	
22.5	Tritium management system	55.9		92.4	
22.6	Shielding (in Acct. 21)				
22.7	Heat transport system				
	• Coolant piping		7.4		14.3
	• Coolant valves and bellows		16.4		31.8
	• Pump and motors		39.1		75.8
	• Coolant cleanup		17.0		33.0
	• Steam separators		10.3		20.0
	• Water loop piping		0.2		0.2
	• Steam generators		73.3		142.1
22.8	Remote maintenance equip't	50.0		75.8	
23	Turbine plant equipment		197.2		344.7
24	Electric plant equipment		62.2		108.7
25	Misc. plant equipment		23.9		41.7
26	Main heat rejection system		32.9		57.7
27	Driver equipment[2]	579.5		652.3	
	Total direct cost	941.8	569.1	1210.3	989.9
			1510.9	2200.2	
	Indirect cost factor	1.936	1.936	1.936	1.936
	Subtotal	1823.3	1101.8	2343.1	1916.4
	Total Capital Cost		2925.1		4259.5
	Capital cost/kWe		2925		2130
	COE for capital[3] (¢/kW/hr)	2.37	1.43	1.52	1.24
	COE for O&M/SCR[4]/Fuel	0.38	0.23	0.24	0.20
	Total COE		4.4		3.2

[1] Reactor + Driver + Target Factory.

[2] R. L. Bieri, "Parametric Studies for Recirculating Induction Accelerators as Drivers for Heavy-Ion Fusion," published in the Proceedings of the 1993 Particle Accelerator Conference, Washington D. C., May 17-20, 1993.

[3] The assumed availability was 85%, the capital rate for noninflating dollars was 9.66%.

[4] Scheduled component replacement and operations and maintenance annually costed at 3% of direct cost.

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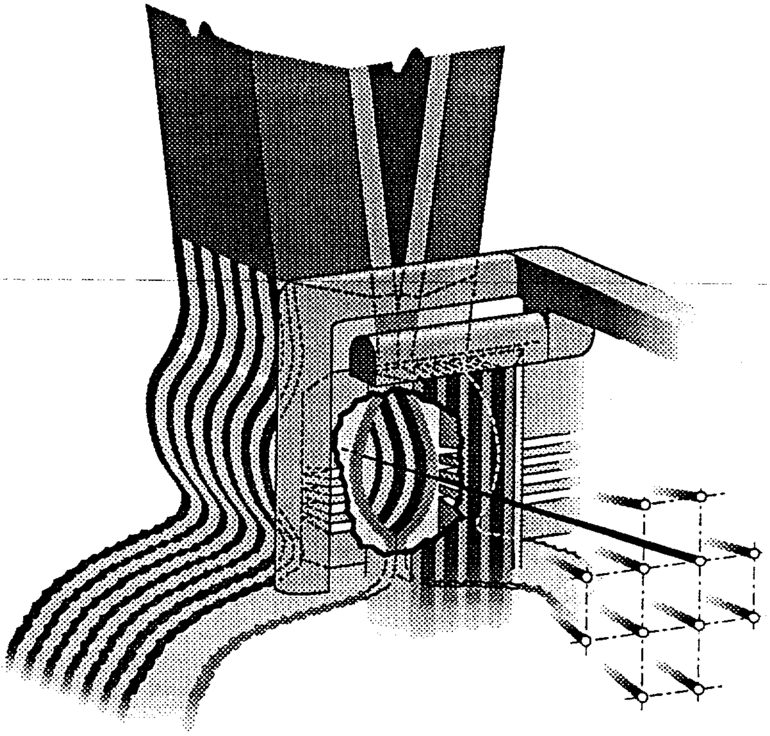
1984 words (1284 not counting table or fig captions)
1284 total not counting table or fig captions
100 for 1 table
600 for 6 figures
1984 total 1900 allowed; 84 over



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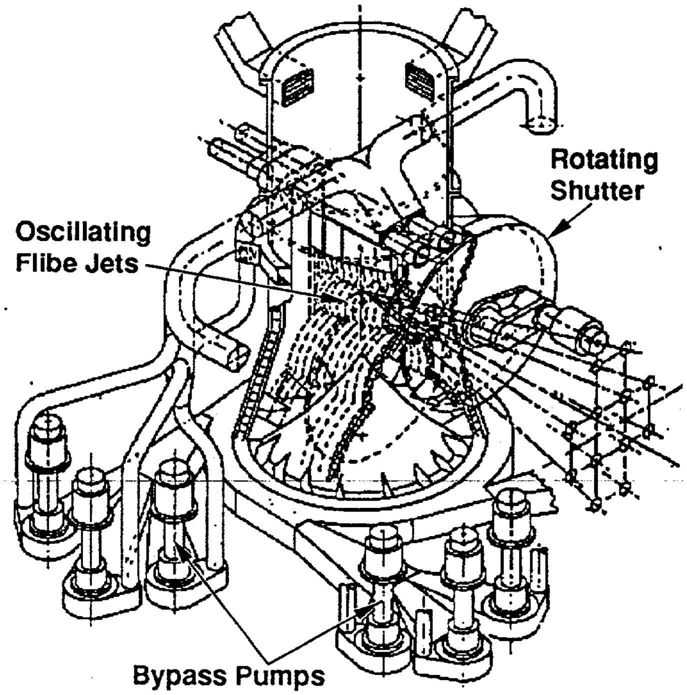

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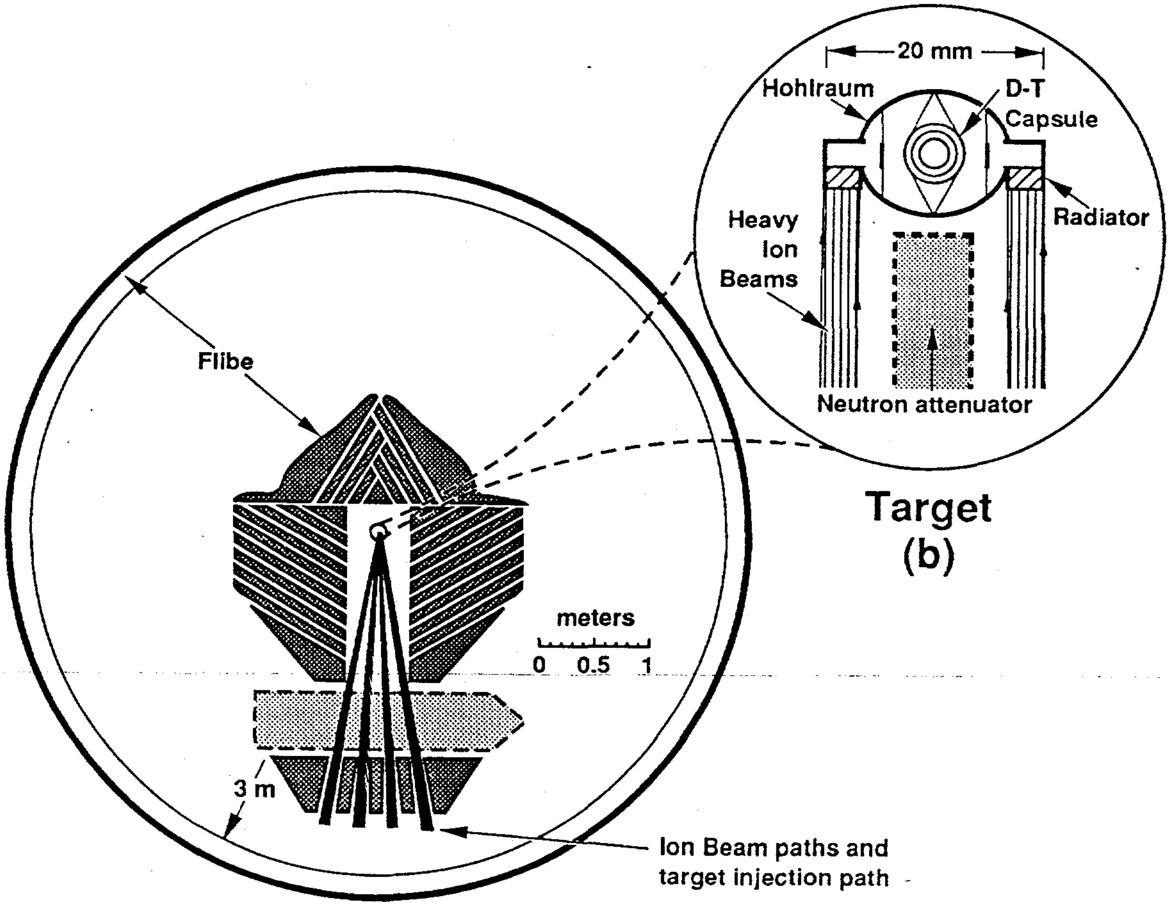


Target
(b)

Cross Section through liquid
Top View
(a)

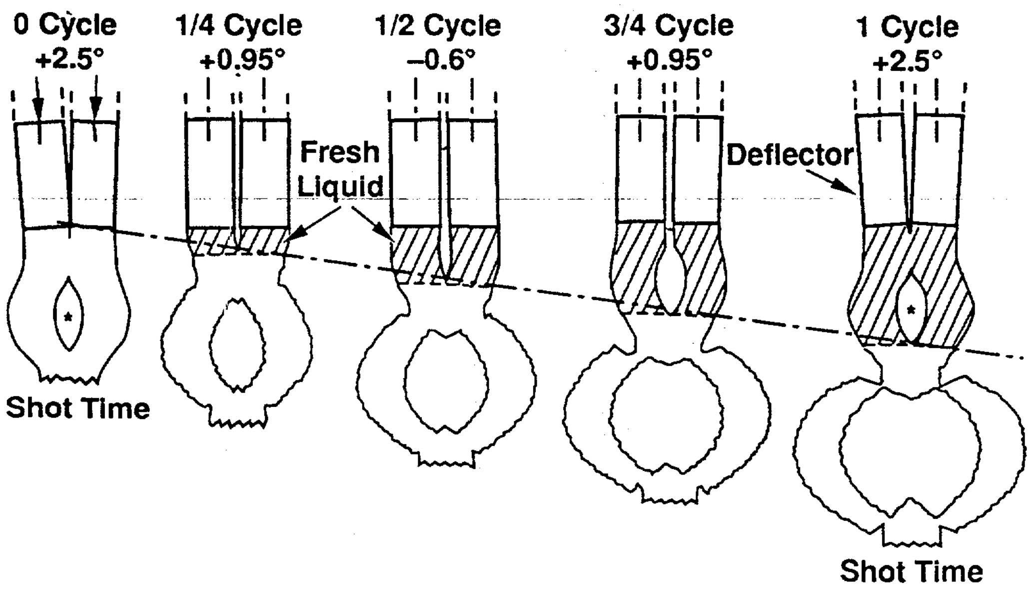
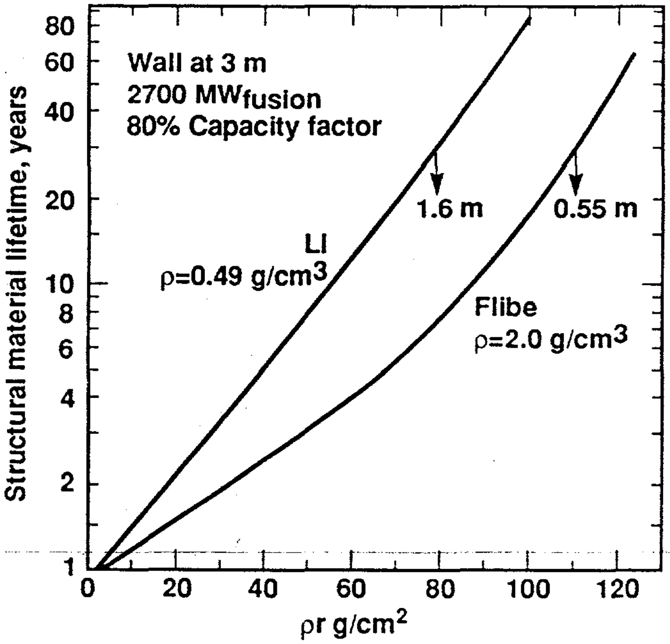

0 Cycle
+2.5°
1/4 Cycle
+0.95°
1/2 Cycle
–0.6°
3/4 Cycle
+0.95°
1 Cycle
+2.5°
Fresh
Liquid
Deflector
Shot Time
Shot Time

Fig 7


Wall at 3 m
2700 MWfusion
80% Capacity factor
Li
ρ=0.49 g/cm3
1.6 m
0.55 m
Flibe
ρ=2.0 g/cm3
Structural material lifetime, years
80
60
40
20
10
8
6
4
2
1
0
20
40
60
80
100
120
ρr g/cm2

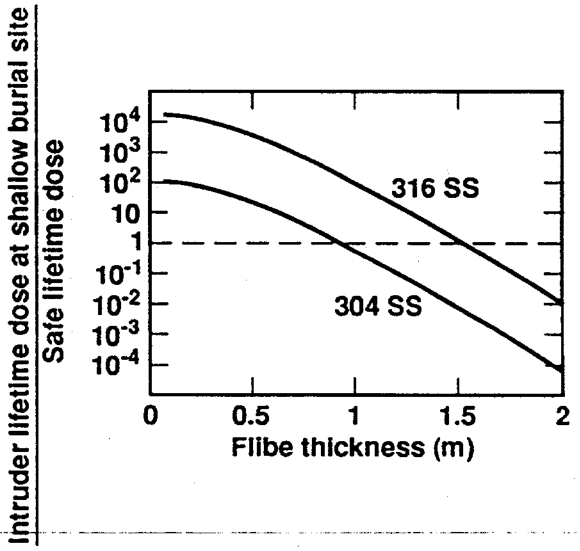

Intruder lifetime dose at shallow burial site / Safe lifetime dose
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
0
0.5
1
1.5
2
Flibe thickness (m)
316 SS
304 SS

Fig [illegible]