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Improvements to the HYLIFE-II Inertial Fusion Power Plant Design*

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ABSTRACT

If the present research program is successful, heavy-ion beams can be used to ignite targets and to produce high gain for yields of about 350 MJ. HYLIFE-II is a power plant design based on surrounding such targets with thick liquid (Flibe, Li_2BeF_4) so that the chamber and other apparatus can not only stand up to these 350 MJ bursts of energy but do so without replacing components during the plant's 30-year life. The capacity factor will be increased and the cost of component replacement will be decreased. Continuous improvements to the design are being made to increase safety, decrease the generation of radioactive material, and reduce the cost of electricity (COE). Improvements discussed in this paper decreased COE for each effect by the amount in parentheses: increased plant size (22%), increased capacity factor and reduced component replacement (20%), reduced remote maintenance equipment (3.2%), use of nonnuclear grade chamber, pumps and piping (2.9%), reduced tritium inventory by a factor of 2.4, reduced excess tritium production with attendant increase energy release in the blanket (1.8%), corrected treatment of Flibe inventory costs (3.4%).

INTRODUCTION

The inertial fusion power plant design¹ called HYLIFE-II is unique in its use of thick liquid to protect the reaction chamber structures to make them life-of-the-plant components. This design is predicated on success coming from the research program to get ignition and high gain in follow-on facilities to the Nova laser and in the program to develop a heavy ion driver. High gain (~ 70 at 5 MJ driver energy) in heavy ion targets is assumed². Ho³ discusses the latest target designs. Woodward, Logan and Moir;⁴ and Monsler and Meier,⁵ discuss a factory that makes low cost targets. Petzoldt and Moir⁶ discuss the system that accurately injects these targets into the reaction chamber about 5 times a second. The design is predicated on successfully developing heavy ion drivers that are low cost (< 500 M\$) and that can deliver its beams onto the target in small spot sizes (~ 2 - to 3-mm radius).^{7,8} Hoffman and Lee⁹ describe the power plant components that convert fusion energy into electrical power using modern supercritical steam conditions. Logan, Moir and Hoffman¹⁰ describe lowering the cost of

electricity (COE) and cost of hydrogen produced by electrolysis of water by driving multiple reaction chambers by a single heavy ion beam driver. Together, these references (Refs. 3-10) form a descriptive basis for a fusion power plant that will produce electricity at close to the cost that advanced light water fission plants are now projecting in sizes of 1 GWe and less for sizes much above 1 GWe (also lower cost than for coal plants).¹¹ This paper describes improvements being made since the publication of Ref. 1 and areas needing more work.

MECHANICAL DESIGN IMPROVEMENTS

Figure 1(a-e) shows the HYLIFE-II chamber with its molten salt pumps and liquid protection system. The cross-sectional area of the liquid was reduced from that of Ref. 1 to reduce the volume of liquid (a capital charge), the pumping power, and the number of pumps. This was accomplished by reducing the distance to the first liquid surface from 0.5 m to 0.3 m. It is believed that isochoric heating expansion following the shot and vapor

Figure 1(a). The HYLIFE-II chamber shown with the pumps that circulate the protecting liquid.

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Figure 1(b). An artist's view, showing the set of crossed jets of liquid that protect the beam port and the liquid that forms a pocket around the microexplosion.

Figure 1(c). Front view with the crossed jets of liquid removed showing the liquid pocket.

Figure 1(d). Cross section at the target elevation (aerial view), showing the open space for vapor venting and 0.5m of liquid to attenuate neutrons in all directions except the beam paths, Figure 1(e). The heavy ion target

venting will result in an acceptable increased outward motion of the liquid. The detailed venting paths shown in Fig. 1d have not been optimized. The other noticeable change since Ref. 1 is the illumination of the target from one side with a double-ended radiator (Fig. 1e). This configuration lends itself to a neutron attenuator shown as dashed lines in Fig. 1e and discussed below. A one-ended target design although seemingly formidably challenging to obtain adequate symmetry would have significant advantages such as: the attenuator needs tight tolerance only on one side rather than two sides, the beam power balance from one end to the other is avoided and fidelity of reproducibility from shot to shot (pulse shape) is less critical. The driver could lose one or two of its 12 beams and the target performance might still be acceptable although degraded, requiring an increased pulse rate.

The present design has increased attention to possible cyclic fatigue of the structural and moving parts. House¹² discusses this subject in more detail. His studies found the life of the parts to exceed 30 years, due to the low stress of the cycled parts. The emphasis on reliability and "no major parts change out in the life of the plant" philosophy results in our reducing the allocation for remote maintenance equipment cost from 100 to 50 M\$ which results in a 3.2% lower calculated COE. An availability study should be conducted comparable to a study started by Sawan and Sviatoslovski¹³ specifically for liquid protected designs including the availability requirements for the driver, the target factory, and the target injector. For an availability of 85%, the 15% downtime has to be distributed over all the components for both scheduled and unscheduled maintenance. Extra high availability is obtained for the target factory and target injector by redundancy, that is, having a spare system always ready. If we require an availability of 95% for the injector, it can be down only 2.5% of the time for scheduled maintenance and the same for unscheduled maintenance (or only 9 days per year).

As shown in Fig. 2, it may be possible to accurately place injected liquid near the target to attenuate (by two orders of magnitude) neutrons that would otherwise strike the beam ports. This attenuator concept¹⁴ might greatly increase the life of the final focus magnets and decrease activation of the beam lines. In addition to the reduced neutron flux, making the magnets especially radiation hardened might extend their life so that fewer scheduled change outs would be needed in the life of the plant. Further work will be needed to check out this idea.

CHAMBER CLEARING IMPROVEMENTS

Chamber clearing will be an important item to prove that inertial fusion can reliably shoot targets many times per second. In the central region incoming liquid will clear liquid debris from the prior shot. In the beam

region, in between the crossed jets shown in Fig. 1(b), we will rely on gravity clearing. As the pulse rate is lowered below 6 Hz to 4 Hz, for example, gravity clearing should be workable because the gravity drop distance becomes much greater than the spacing between the jets. In the region where the jets are vertical there may be a problem. If so, those jets could be redesigned to be placed at 45°. Experiments on making clean jets free of droplet formation at the nozzles will be needed, comparable to work discussed by Cavanaugh and Peterson.¹⁵ The beam lines are kept clear by use of fast rotating shutters. Reference 14 discusses beam path clearing of liquid debris. Experiments will be needed to demonstrate the rapid condensation predicted by theory.

SAFETY IMPROVEMENTS

In Ref. 1 the cost for the accounts 22.1 was 139.5 M\$ (the reactor chamber, the bypass pumps, and bypass pipes). The costs were multiplied by 1.5 because it was thought that these components had to be nuclear grade; however, the safety finding that nuclear grade was not needed was not folded into the cost. Using coal standards, these costs become 93 M\$, which lowers the cost of electricity by 2.9%.

One way to determine how much activation of structures in a nuclear system is permitted is to require that the material qualify for shallow land burial. The intruder dose has been calculated¹⁶ for various thicknesses of liquid and for thicknesses greater than 0.8 m of Flibe the intruder dose is adequately low for 304 stainless steel. Therefore, ordinary stainless steel used as the structural material will meet the qualifications for shallow land burial upon decommissioning. Essentially the only difference between 304 and 316 stainless steel we are concerned with is the absence of the Nb and Mo additives which activate badly. This nice finding means more study of 304 stainless steel should be made. A calculation of the curies of activation per unit thermal power for 304 stainless steel behind a thick Flibe zone versus time after shutdown should be made and compared to other blanket materials.

The present design has 140 g inventory of tritium in the steel walls of the bypass piping and the vacuum disengager piping. By lining the pipes with a thin liner and having a gas purge, Dolan¹⁷ has shown how to reduce this inventory by a factor of three, which reduces the calculated offsite dose to 5 mSv (5 rem). This would be a nice safety advantage obtained at little added cost.

We need to study high Z target materials that are used to line the hohlraum. Tobin¹⁸ studied Pb and Ta but not the presently preferred Hg. Because Hg is volatile we need to see if beams will propagate through its vapor and if the Hg can be removed in the vacuum disengagers along with the tritium removal at an acceptably rapid rate.

Figure 2. Cross section of HYLIFE-II chamber showing a 30-cm neutron attenuator to shield the beam ports from line-of-sight neutrons. The enlarged view of the target shows the attenuator and the region of shadow shielding. The liquid jet attenuator is flowing down between all six beam pairs.

ECONOMIC IMPROVEMENTS TO COMPETE WITH ALTERNATIVES (Advanced Fission, Coal)

One of the most important changes to improve the COE would be to increase the power output. The high driver cost makes the COE especially sensitive to power output. In Ref. 1 we treated a 1 GWe and a 2 GWe case. The COE went from 5.0¢/kWh to 3.9¢/kWh (a 22% reduction). The trend in fission plants is to build ever larger units to obtain lower cost power. For example, there are two 1.45 GWe fission plants being built in Japan. It is more straightforward to scale up an inertial fusion plant to large sizes, for example, 2 GWe, by a combination of increased yield and pulse rate, than for a tokamak, where the heat load on the divertor surfaces are already difficult to deal with at smaller powers. Fission plants have increased safety problems (criticality and afterheat removal) at ever higher powers due to the larger core size.

The tritium breeding ratio (TBR) in HYLIFE-II is calculated to be 1.17 but only needs to be slightly over unity, perhaps 1.02 will do. If we add an energy producing absorber such as Mn to the molten salt, we can increase the energy output. Surrounding the target with a multiplier material might also be considered. Adding 12 mol%¹⁹ MnF₂ to Flibe reduces the TBR from 1.17 to 1.02 and raises the blanket energy multiplication factor, M, from 1.18 to 1.265.²⁰ This produces 63.7 MWe more power at a cost of 4.4% less per kWh (4.72 vs. 4.93¢/kWh). When the power is kept fixed by dropping the driver energy from 5 MJ to 4.66 MJ, the COE drops by 1.8% to 4.84¢/kWh. This change is worth while if the cost and adverse effects of adding MnF₂ are small. The final costs given in table I differs somewhat from this and other variance examples but the percentage changes are small.

The estimated cost (102.6 M\$) of the Flibe in the reference design was in error for two reasons: (1) Since this coolant is delivered to the site near the beginning of plant operations and few indirect charges are appropriate, its cost should be multiplied by an indirect cost factor closer to unity (1.2 perhaps) rather than 1.936. This would result in a COE reduction of 2.0%. (2) The cost estimate of 42\$/kg in 1990 dollars was based on a calculated cost ten years ago that had two math errors in it. Simply correcting these errors would give 24.3\$/kg in 1990\$ for a reduction of cost of electricity of 2.2%. Both these corrections would give a 3.4% cost of electricity reduction. A better cost estimate for Flibe should be made accounting for the reduced use of beryllium in industry and the increased regulations for its use.

Table I gives the summary of the capital cost and the cost of electricity²¹ for the improved HYLIFE-II along with the improvements discussed in this paper. The driver energy was 5 MJ (6.5), gain 70 (90), pulse rate 6.4

Hz (7.5) for a power of 1000 MWe (2000 MWe values in parentheses). The COE went from 6.5 to 4.4¢/kWh for a 32% decrease at 1000 MWe and from 4.5 to 3.2 ¢/kWh for a 29% decrease at 2000 MWe. These cost savings come from the direct advantage of liquid protection of walls, reduced activation, and reduced tritium inventory (only the target factory has to be constructed to nuclear certified standards), a high performance modern steam plant, and a low cost driver (direct cost ~500 M\$).

BEAM TRANSPORT THROUGH CHAMBER TO TARGET, BEAM FOCUSING AND TARGET GAIN

Transport of the beam to the target is more of an economical issue than a technical issue. Beam emittance, space charge, space charge neutralization and momentum spread will determine the focal spot size. The spot size can be reduced as in any optical beam design by choosing a larger diameter of the focusing array (spot size $\propto L/d$). Shortening the focal distance L and increasing the diameter of the focusing magnet will decrease the spot size. HYLIFE-I and HIBALL-II had an 8 m distance from the face (end) of the last focal magnet to the target. In HYLIFE-II we made an effort to reduce the distance to 5 m. It may be possible to further reduce this distance to close to 4 m with careful design owing to the shielding properties of the liquid protecting the walls and beam ports (Fig. 2).

The diameter of the beam in HIBALL-II at the face of the last focal magnet (8 m from the target) was 0.26 m. The diameter of the beam at the face of the last focal magnet in HYLIFE-II (4 m from the target) was 0.14 m as shown in Fig. 2. The effect of increasing the diameter of the beam means more neutrons leak out. Another effect is as the beam array (12 with HYLIFE-II) is spread further apart, the gain decreases. In HYLIFE-II the gain decreases 16% from a beam array with no spread. The neutron attenuator¹⁴ is predicted to cut the neutron dose to the beam ports by about 2 orders of magnitude which, all things being equal, should permit a larger beam diameter at the focal magnet, if necessary. These two effects are working in opposite directions, that is, larger beam diameter at the focal magnet results in a smaller spot size and higher gain but this same larger beam diameter results in a larger array of beams and a lower gain. A trade-off study will be needed to determine the optimal arrangement of beams (array) and the optimal beam diameter.

The spot size, therefore gain, does not have a very sensitive effect on cost of electricity in heavy ion power plants because the recirculating power fraction is low. If we increase the spot size but also increase the beam energy enough to compensate to maintain the same yield and then increase the pulse rate slightly, the same total power is maintained. The COE at a gain of 71.4 and spot size of 2 mm radius is 4.9¢/kWh. The COE goes up

Table I. Plant Cost Breakdown

Acct	Item	1000 MWe Case (millions 1993\$)		2000 MWe Case (millions 1993\$)	
		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, BP pumps, pipe				
	• Reactor	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	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 ² (¢/kWh)	2.37	1.43	1.52	1.24
	COE for O&M/SCR ³ /Fuel	0.38	0.23	0.24	0.20
	Total COE		4.4		3.2

¹Reactor + Driver + Target Factory.

²The assumed availability was 85%, the capital rate for noninflating dollars was 9.66%.

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

2.1% at 2.5 mm (gain is 66), 5.6% at 3.0 mm (58.3), 8.4% at 3.5 mm (53), 12.2% at 4.0 mm (47.3), and 16.3% at 4.5 mm (42.2). By looking at the decrease in gain for any other reason one can see the effect on COE. The gain dropping from 71 to 50 will increase the COE by 10%. A target designer might ask how many more MJ's of driver energy do I need to obtain the needed symmetry by, for example, increasing the size of the hohlraum. Suppose 7 MJ were needed instead of 5 MJ to produce 350 MJ yield for a gain of 50, then the same power results by raising

the pulse rate from 6 to 6.2 Hz and the COE would increase from 4.93 to 5.4¢/kWh or a 9.8% increase. This is a serious cost increase but possibly tolerable. If the above cases were optimized, the cost increases would be somewhat lessened. The economic model used for these estimates has the same assumptions as Ref. 1. More recent economic model improvements will likely change these results only slightly.

CONCLUSIONS

An ongoing study of the HYLIFE-II design has resulted in considerable improvement and continuation of this effort can be expected to make more improvements to the basic design. The interactiveness of the driver and target design requires an integrated design with special emphasis on the driver interface with the chamber and target. The most significant uncertainties are of course target performance and driver cost.

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