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LAWRENCE LIVERMORE NATIONAL LABORATORY

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ABSTRACT

We present results of our reactor studies for inertial-fusion energy production. Design studies of liquid-metal wall chambers have led to reactors that are remarkably simple in design, and that promise long life and low cost. Variants of the same basic design, called HYLIFE, can be used for electricity production, as a fissile-fuel factory, a dedicated tritium breeder, or hybrids of each.

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1. INTRODUCTION

In terms of its impact on reactor design, an important feature of inertial fusion is that the confinement of the D-T fusion plasma is decoupled from the functions of the reaction chamber. Because the physics of energy absorption, implosion, ignition, and burn of this plasma are physically separable from the chamber conditions and structural requirements, there is an extraordinary degree of engineering flexibility.

The most challenging reactor design consideration is protecting the chamber wall from the various forms of rapid energy deposition. Diverse methods for providing this protection have led to a number of reaction chamber types: dry walls (includes both bare walls and sacrificial liners), magnetically protected walls, gas-filled chambers, wetted walls, and thick liquid-metal walls. A review of inertial fusion reactor design is given in Ref. 1.

In this paper we describe the high-yield lithium injection fusion energy (HYLIFE) chamber,² a concept which falls in the category of thick liquid-metal wall (LMW) chambers. HYLIFE has been studied at Lawrence Livermore National Laboratory (LLNL) in conjunction with university and industrial participation from Atomics International, Bechtel National, Energy Technology Engineering Center, Grumman Advanced Engineering, TRW and the University of California, Davis.³ We also describe how the basic HYLIFE design can be modified to form a suppressed-fission hybrid that supplies fissile fuel for light-water-reactors (LWRs).

2. THE LIQUID-METAL WALL CONCEPT

Before describing the HYLIFE concept itself, we review the generic features of LMW chambers.⁴ The dominant feature of the liquid-metal wall concept is the thick (0.5- to 1.0-m) free-flowing blanket of liquid metal used to protect the reactor structure. Using a layer of lithium or a lead/lithium eutectic allows most of the fusion energy to be absorbed before solid structural materials are encountered.

2.1 Attractive features

The attractive features of LMW chambers are:

- o Wall Protection. The structure is protected from all of the pellet debris, and all but the hardest x rays, over more than 98% of the solid angle.

- o Neutron Absorption. The neutrons are attenuated and moderated in the liquid metal^{5,6} before they reach a solid surface. Less than 5% of the neutron energy reaches the structure, with a highly degraded energy spectrum.

- o Long Life Structures. The lack of wall ablation, and the large attenuation and moderation of neutrons, allows chamber structures to be designed to last, without replacement, for the power plant's 30-yr lifetime.

- o Low Activation. Combining a long structural lifetime with a low-chromium, nickel-free steel should lead to a very low total activated structural mass.

- o Self-Renewing. The liquid wall is continuously self-renewing. If necessary, it can be entirely replaced between pulses.

- o Direct Energy Deposition. The energy from the fusion products (photons, ions, and neutrons) is deposited directly into the heat transfer medium, without first having to pass through a solid surface. The heat transfer medium is a liquid metal with high heat capacity and thermal conductivity.

- o Robustness. The LMW design is quite insensitive to the energy partition and energy spectra of x rays, ions, and neutrons.

- o Tritium Breeding. Using either lithium or a lead/lithium eutectic, sufficient tritium is bred in the LMW.

- o Beam Propagation. The low vapor pressures of liquid metals, at those temperatures that are interesting for energy conversion (400 to 500°C), span the pressure range of 10^{-4} to 10^{-1} Torr, favorable for the propagation of either laser or heavy-ion beams.

- o The LMW flow pattern can be directed so as to shield almost the entire chamber wall, leaving apertures just large enough to allow the pellet and driver beams to enter.

These positive features of LMW chambers give substantial advantages for the development of a power-producing technology.

2.2 Limitations

Of course, LMW chambers have limitations which must be minimized either by clever design or early attention to experimental development. Most of the limiting issues are specific to liquid-metal systems. They involve the following design aspects.

- o Flow Rates. High flow rates of liquid metal will result in high capital costs for pumps and piping and additional containment volume.

- o Liquid-Metal Hazards. A large inventory of liquid metal ($\sim 10^3 \text{ m}^3$) is required. Although this amount is comparable to the requirements for a liquid-metal fast breeder reactor, the size of SUPERPHENIX, the safety issues are different. The potential fire hazard and toxicity of lithium, in the unlikely event of a breach of containment, is an important safety concern.

- o Repetition Rate. The repetition rate of LMW chambers is limited by the injection time for a new LMW.

- o Chemistry. Since all the elements from the fusion pellets will end up in the liquid metal, along with corrosion products from the chamber and piping, extraction methods must be devised. Tritium extraction⁷ appears to be one of the easiest. Also, the corrosion rate may be enhanced by the presence of impurities.⁸

- o Secondary Loop. A secondary heat-transfer loop appears to be required to isolate the primary liquid-metal loop from the steam feedwater loop.

- o Irradiation Geometry. The LMW chambers are attractive if the liquid wall can be parted in just a few places to admit the driver beams and pellet.

The conceptual design, summarized in the next section takes maximum advantage of the attractive features, and is constrained by the engineering limitations just stated.

3. THE HYLIFE SYSTEM

The HYLIFE chamber, shown in Fig. 1, is designed to operate with yields of a few thousand megajoules at rates of a few Hertz. A lithium energy-conversion blanket, consisting of a dense array of 20-cm-diam jets, is continuously injected into the chamber. Figure 2 shows a cross section through the chamber midplane. The jet array provides an effective blanket thickness of 0.74 m between the fusion pellet and the inner steel wall. The 14-MeV neutron flux is significantly reduced, allowing a chamber with a 5-m-radius inner wall to operate for 21 full-power years (30 years at 70% availability). The power density within the reactor vessel is very high, approaching that of a fission reactor. A common low alloy ferritic steel (2.25 Cr-1 Mo) is used throughout. The tritium breeding ratio is controllable⁹ between 1.0 and 1.7.

The array lithium jets also gives an effective shock isolation from the effects of the fusion pulse. Since the hot gas merely blows through the jets, this configuration minimizes the wall stress due to the impact of lithium accelerated by high-pressure blowoff gas, caused by x-ray and debris energy deposition. A substantial fraction of the fluid kinetic energy, resulting from the neutron absorption, is dissipated in the liquid-liquid interactions among colliding jets. Finally, the enormous surface area of the fluid acts as an effective condensation pump for the lithium vapor.

The HYLIFE power plant requires 12 pumps to inject the liquid lithium into the 5-m-radius chamber. The power necessary for the lithium recirculation pumping is 26 MW (electric), only 2% of the gross electric power. The power plant characteristics are given in Table I.

3.1 Radiation damage

The liquid-metal wall attenuates and moderates the neutron flux and thereby reduces the radiation damage due to helium production and atomic displacements in a steel wall. For example, Fig. 3 shows the effects of one meter of lithium on the neutron spectrum incident on the first structural wall located 5-m from the pellet. The 14 MeV

Fig. 1 In the HYLIFE chamber an array of liquid-metal jets forms a renewable first wall and blanket.

Fig. 2 Cross section of the HYLIFE chamber showing the entrance of the driver beams through the jet array.

Table 1. Summary of HYLIFE power plant characteristics.

<u>System Parameters</u>		<u>Lithium Array Geometry</u>	
Fusion power, MW_t	2700	Number of jets	175
Gross thermal power, MW_t	3172	Midplane jet diameter, m	0.20
Gross electric power, MW_e	1237	Midplane packing fraction	0.57
Net electric power, MW_e	1004	Array inner radius, m	0.52
Net system efficiency, %	32	Array outer radius, m	1.82
Tritium breeding ratio	1.0 to 1.7	Effective array thickness, m	0.74
<u>Laser and Pellet Parameters</u>		<u>Flow Parameters</u>	
Beam energy, MJ	4.5	Midplane jet velocity, m/s	13.3
Pellet gain	400	Array flow rate, m^3/s	72.2
Yield, MJ	1800	Total flow rate, m^3/s	108.9
Repetition rate, Hz	1.5	Total pumping power, MW_e	26.0
Laser efficiency, %	5	Total lithium inventory, m^3	1850
Laser power consumption, MW_e	135	Number of lithium loops	12
Fusion energy gain	20	Li outlet temperature, °C	500
		Li temperature rise/pulse, °C	18
<u>Fusion Chamber</u>			
Radius, m	5		
Height, m	8		
Material	2.25 Cr-1 Mo

Fig. 3 Moderation of the neutron spectrum by a one-meter-thick, liquid-lithium blanket.

flux is reduced by a factor of ~ 200 , and the total neutron energy flux (MW/m^2) is reduced by a factor of ~ 20 .

The LMW thickness must be set so that the total accumulated atom-parts-per-million (appm) of helium and displacements per atom (dpa), after 21 full-power years, are each less than the prescribed damage limits for the particular material. The lifetime of a 2.25 Cr-1 Mo ferritic steel wall as a function of the thickness of lithium protection is shown in Fig. 4. The 5-m radius and fusion power of 2700 MW correspond to the HYLIFE parameters. Estimated damage limits for helium production and displacement damage of 500 appm and 165 dpa respectively were used in this example. From the figure, we can see that a lifetime of 21 full-power years might be reached, with a total LMW thickness of < 80 cm.

Another liquid-metal candidate for the effective protection of the structural wall from radiation is the eutectic $\text{Pb}_{83}\text{Li}_{17}$ (Ref. 5). If lead-lithium were to be used, only half the thickness would be needed for the same level of protection as that provided by a given layer of lithium. However, its density is ~ 19 times that of lithium, so the net effect will be nearly a factor of ten increase in the pumping power requirements.⁴

3.2 Control of wall stress

Three major classes of wall stress in LMW chambers are: 1) a steady thermal stress arising from the temperature distribution in the wall, 2) a transient stress, due to the pressure of expanding plasma on the wall,¹⁰ and 3) a transient stress, from the impact of liquid metal¹¹ on the wall due to sudden energy deposition in the LMW by neutrons.

In an earlier concept,¹² when radiation damage was the only concern, the protection provided by a liquid-lithium annulus was thought to be adequate. It was later realized^{13, 14} that the hot, high-pressure plasma in the center would push the LMW rapidly outward and deliver a catastrophic impact to the wall. The essential innovation was to divide the LMW into an array of jets, as shown in Fig. 2. Having alternate regions of liquid and vapor serves several functions. First, the hot

Fig. 4 Lifetime of the first-structural-wall as a function of the thickness of lithium protection.

plasma created in the center of the cylindrical LMW can vent through the jets. As it expands it will cool by radiative heat transfer to the liquid, in a way that minimizes the momentum transferred to the LMW.

The second benefit of breaking the LMW up into an array of jets lies in reducing the impulse delivered to the wall by the impact of liquid, which has been accelerated by the deposition of neutron environment. The liquid-liquid collisions among disassembled jets promote significant energy dissipation. The collisions of two-phase flows are directly analogous to the compression of porous media. The reduction of the impulse due to this disruptive process has been calculated by Glenn¹¹ for model cases with cylindrical annuli and concentric annuli, with various layer and gap thicknesses. The results, for LMWs with 6 to 10 gaps, show a factor of 3 reduction in impulse.

Finally, the hoop stress in the cylindrical wall is dramatically reduced if the fluid interaction time can be made greater than the wall response time. This can be assured if the liquid impact is in the form of a compacting two-phase flow (a rain of droplets), rather than being a sharp impulsive slap from a homogeneous liquid layer. For HYLIFE, the stress from the two-phase impact is only 4% of the impulsive stress. In absolute terms, a pressure pulse of ~ 3 atm, lasting for ~ 15 ms, results in a stress of ~ 30 MPa in a 0.1-m-thick wall at a distance of 5 m. This illustrates how the design of the geometric configuration of the LMW can be altered to control the structural wall stress, in order to contain very high yields, in chambers of an economic size.

4. THE HYBRID OPTION

The basic HYLIFE concept can be utilized in the design of a fusion-fission hybrid. The HYLIFE-hybrid concept, studied by TRW¹⁵ is shown in Fig. 5. The protective lithium region thickness is reduced to 60 cm and instead of using natural lithium, the lithium is denatured to $\sim 0.15\%$ ^6Li . This is necessary to reduce the tritium breeding ratio to ~ 1.0 and allows the excess neutrons (from $^7\text{Li}(n,n'\text{T})\alpha$ reactions) to reach the fertile fuel region which is behind the first-structural-wall.

Fig. 5 The HYLIFE hybrid, a suppressed-fission breeder, would produce fissile fuel for LWRs.

The fertile fuel, in the form of thorium metal balls, is contained in steel tubes and cooled by liquid sodium. Provisions for adding and removing the balls without shutting down the reactor allow for frequent reprocessing. The fissile ^{233}U concentration is kept low, $\sim 0.4\%$. The combination of a soft neutron spectrum due to the moderating effects of the lithium jets and the low fissile concentration effectively suppress fast and thermal fission. Such suppressed-fission hybrid has significant safety advantages over fast-fission hybrids, and it simplifies after-heat cooling and containment systems.

The 2220 MW_t (fusion power = 1500 MW) HYLIFE-hybrid produces 3545 kg of ^{233}U per year assuming a plant capacity factor of 70%. This is enough fissile fuel to supply the makeup fuel for ~ 15 LWRs of equal thermal power. This high support ratio makes system electricity cost relatively insensitive to uncertainties in fusion performance and cost. It also allows a large commercial impact at an early date.

5. TRITIUM PRODUCTION

By adjusting the concentration of ^6Li , the tritium breeding ratio in HYLIFE can be varied from 1.7 down to 1.0. The excess tritium could be needed as start-up inventory for fusion reactors, make-up fuel for reactors that are unable to achieve a tritium breeding ratio of 1.0, or to meet the tritium needs of military programs. At breeding ratio of 1.7, the excess tritium production rate is 23.5 kg/GW_t·yr at 70% capacity factor.

6. CONCLUSION

In our reactor studies at LLNL we have attempted to exploit the flexibility afforded by the separability of the physics of generating the fusion energy from the engineering of a reactor to absorb, remove and convert that energy. This flexibility allows us to innovate in an attempt to increase component lifetime, reduce radioactive hazards and inventory, simplify operation and maintenance and reduce costs.

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