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INJECTION FUSION ENERGY (HYLIFE) REACTION CHAMBER

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POTENTIAL DESIGN MODIFICATIONS FOR THE HIGH YIELD LITHIUM

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Introduction

Generation of electric power from inertial confinement fusion requires a reaction chamber. One promising type, the High Yield Lithium Injection Fusion Energy (HYLIFE) chamber, includes a falling array of liquid lithium jets as shown in Fig. 1. These jets act as: (1) a renewable first wall and blanket to shield metal components from x-ray and neutron exposure, (2) a tritium breeder to replace tritium burned during the fusion process, and (3) an absorber and transfer medium for fusion energy. Over 90% of the energy produced in the reaction chamber is absorbed in the lithium jet fall.

The effectiveness of the lithium jet fall for shielding allows the use of structural components without replacement over the entire 30-year expected lifetime of the chamber. These structural components are made from low-alloy, 2% Cr-1% Mo, ferritic steel that is compatible with flowing lithium, resistant to hydrogen (tritium) embrittlement, and produces few radioisotopes. The liquid lithium is circulated through 16 external loops, where both the tritium and the energy produced in the reaction chamber can be removed.

As originally conceived,¹ the HYLIFE chamber is pulsed every second by a 2700-MJ fusion reaction. A deuterium-tritium pellet is injected into the chamber and laser or heavy-ion beams initiate the fusion reaction. The fusion energy from the reaction is absorbed in the circulating liquid lithium.

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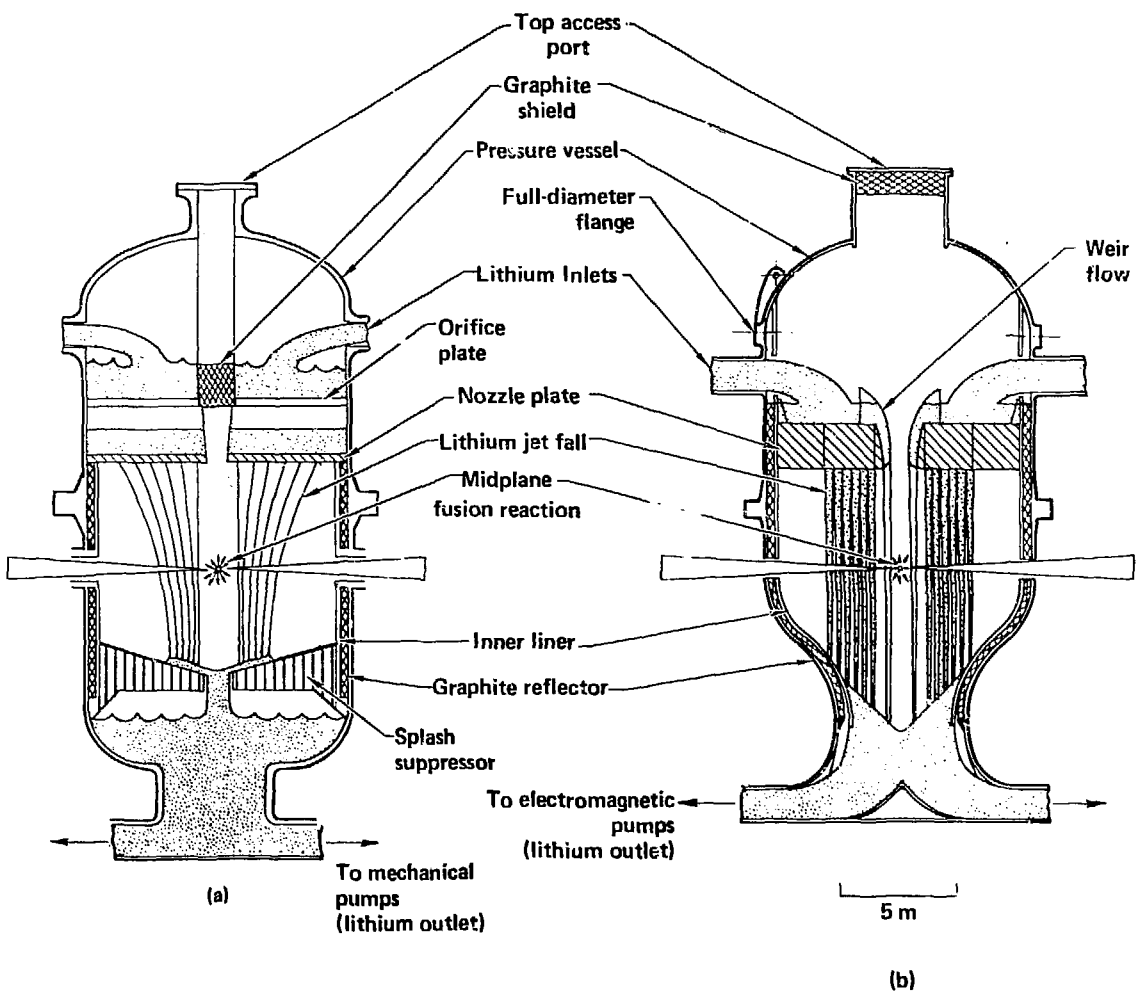


Fig. 1. Comparison of the original and modified High Yield Lithium Fusion Energy (HYLIFE) converter.

Mechanical pumps are specified in the original HYLIFE version, as shown in Fig. 1(a). In this figure, lithium is first circulated into a pool above the orifice plate shown. It then rains down into a second pool and passes through a nozzle plate designed to produce the curved, free jet fall shown. The purpose of the orifice plate and the rain-down into the second pool is to isolate the pumps from pressure pulses in the upper portion of the chamber, and to assure that a uniform head of liquid lithium exists over the cross section of the nozzle plate. Variations of the liquid lithium head can cause the individual jets to coalesce in a curved fall. At the midplane, where the fusion reactions occur, the jet fall has an effective mean thickness of 1 m with a packing fraction of one-half.

The advantage of the jets over a solid annulus or several separate concentric annular rings is that high-pressure gases, generated by energy deposition during the fusion reactions, can vent through the interstices between the jets. Even though the energy deposition in the lithium closest to the fusion reaction is so large that these jets disassemble before the high-pressure gases can vent through the interstices, a circumferential density variation exists with the lowest value occurring in the regions of the interstices. These regions have lower resistance to gas flow so that the venting process is still enhanced. Less outward-directed momentum is produced, reducing the momentum transferred to the inner liner (first structural wall). The impact affects only the inner liner, so that a steady loading exists on the pressure vessel.

A splash suppressor is included in the original design to prevent the lithium from splashing back into the region of the microexplosions. It also creates a cavity below the suppressor, to isolate the mechanical pumps from the pressure pulses produced in the lithium by the fusion reactions. The lithium outlet contains a sufficient liquid head to prevent cavitation of the mechanical pumps used in the circulation loops.

Potential Design Improvements

Several design modifications [see Fig. 1(b)] potentially improve the originally conceived construction and operation of the HYLIFE chamber. The inlet nozzle plate that forms the flow pattern of the lithium jets

now includes an annular weir flow over the plate's inner radius. As a result, all of its parts are shielded adequately by lithium. The lithium flow is vertically downward, and the orifice plate is eliminated. The lower part of the pressure vessel is shaped so that the lithium now hits at an oblique angle to the vertical axis of the vessel. The liquid surface forms a cusp at the outlet, thus eliminating the need for a splash suppressor at the bottom. Electromagnetic (EM) pumps, instead of mechanical pumps, are used in the circulation loops, because they are less susceptible to damage by pressure pulsations produced in the lithium by the fusion reactions. The need for an open cavity to isolate the pumps from the fusion pulses is minimized. However, an open cavity is still retained at the bottom, adjacent to the sides of the pressure vessel. Lithium inventory in the loops is reduced because of the small, net positive suction head required by the EM pumps. The major disadvantage is that pumping power requirements are increased, mainly because of the lower efficiency of EM pumps relative to mechanical pumps.

Construction is simplified by the design modifications. For example, a full-diameter bolted flange, with gaskets, permits the remote disassembly and reassembly of components. Internal components may be attached to the upper head to simplify their assembly and disassembly.

These modifications, coupled with the inherent design flexibility of the HYLIFE reaction chamber, offer an improved promise for attaining economical fusion power.

Component Design Modifications

The simplicity and flexibility of the HYLIFE chamber design are key advantages over other proposed chambers. In the modified design, the pressure vessel contains only a nozzle plate, inner liner, and graphite reflectors.

Some components have not changed from the original design. The HYLIFE chamber permits the use of laser or heavy-ion fusion drivers, whichever prove to be the optimum choice. The driver beams enter horizontally into the chamber through openings in the pressure vessel, inner liner, and graphite reflectors. Fuel pellets are injected either horizontally next to one of the beams, or vertically through the top access port.

In the following paragraphs, we describe components that have changed from the original design as well as the characteristics of the modified HYLIFE chamber. Design parameters are compared in Table 1.

Nozzle Plate

The flow of liquid lithium is vertically downward in the modified design, with the jet cross section being generally rectangular as shown in Fig. 2. This geometry offers the advantages of simplicity, a more uniform shielding of the inner liner and other components, and an increased tolerance to the variation of liquid lithium head above the nozzle plate. Except for the driver beam injection areas, the inner liner is protected by a minimum of one meter of lithium at the midplane.

With vertical jets, the only effects of a change in liquid lithium head are the variations of jet velocity and cross-sectional area of the jets below the nozzle plate. The centerline location of each jet is independent of spatial or temporal changes in the liquid lithium head. Hence, the jets remain separate. In the original design, the jets had a radial velocity component, so that a variation in liquid lithium head could have caused the jets to coalesce. Hence, an orifice plate was required to assure that the jets did not coalesce as spatial or temporal changes in the liquid lithium head occurred. The modified nozzle-plate exit velocities of the jets and weir are 5.5 and 7.1 m/s, respectively.

Another difficulty in the original design was that the innermost zone of the nozzle plate was unprotected from the neutrons and x rays, a condition that may have required the periodic replacement or repair of this part of the nozzle plate. In the modified design, we have circumvented this problem by replacing the first inner row of jets with an annular weir flow over the inner radius of the nozzle plate. Now, all portions of the nozzle plate are shielded by one meter of lithium or more. The weir flow is split to allow horizontal injection of the driver beams.

Construction as well as strength must be considered in designing the nozzle plate. The nozzle plate consists of 33-mm-thick, extruded angle plates welded together. The part of the plate through which the jet fall passes contains essentially straight-through penetrations. The outer portion is of similar structure, except the bottom and top are closed by

Table 1. Comparison of parameters -- original and modified HYLIFE chambers.

Parameter	Original design	Modified design
Fusion energy yield per shot, MJ	2700	2700
Repetition rate, Hz	1	1
Lithium flow rate in fall, m ³ /s	93	130
Lithium flow rate for inner liner, reflector, and pressure vessel cooling, m ³ /s	36	18
Total lithium flow rate, m ³ /s	129	148
Lithium temperature (av), K	770	770
Temperature rise in lithium per shot, K	12	10
Pump efficiency	0.72 (mechanical)	0.40(EM)
Pumping power	20	45
Shielding at midplane, m of lithium	1.06(+0.54,-0.20)	1.00(+0.40,-0.02)
Packing fraction at midplane*	0.50	0.48
Jet cross section	Circular	Rectangular
Jet velocity at nozzle plate, m/s	4.4 (curved)	5.5 (vertical)
Annular weir velocity at nozzle plate, m/s	--	7.1
Pressure vessel:		
Inner radius, m	5.435	5.435
Wall thickness, mm	80	80
Nozzle plate thickness, m	0.4	1.8
Inner liner:		
Inner radius, m	5.000	5.000
Wall thickness, mm	35	35
Graphite reflector:		
Inner radius, m	5.085	5.085
Wall thickness, mm	300	300

*Packing fraction is defined as the ratio of liquid to total cross-sectional area in the region of the lithium fall.

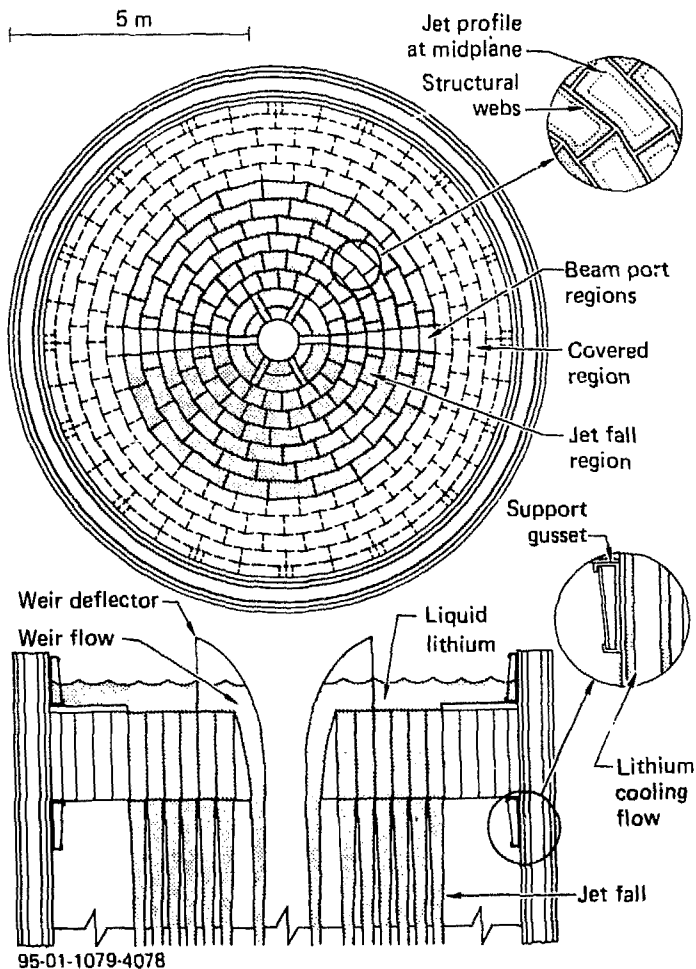


Fig. 2. Cross section and elevation views of the modified nozzle plate.

flat plates to prevent the through-flow of lithium and to give additional strength. Some circulation does occur in the outer region to keep the maximum metal temperatures below 800 K. This circulation is directed to the inner liner, reflector, and pressure vessel to cool them as well.

The nozzle plate is simply supported from the inner liner by a series of gussets. Its central hole equalizes pressure from the fusion reaction on the top and bottom. Also, it makes the center of the chamber accessible, if pellets are injected from above, and it eliminates shielding problems by accommodating the weir flow. Circulative cooling around and through the gussets keeps peak temperatures below 800 K.

The impact loads for the modified HYLIFE reaction chamber were determined with the hydrodynamic analysis method of Glenn and Young.² These loads occur as the lithium in the jet fall hits the lower surface of the nozzle plate, following an upward acceleration after each fusion pulse. To determine their value, the appropriate pressure history of the jet impact is integrated with time and applied over the area of the jet fall to obtain an impulse. To keep dynamic stresses below allowable limits in the plate and in its supports, the vertical thickness of the nozzle plate was set at 1.8 m.

Calculations, using one-dimensional wave propagation theory,³ show that the dynamic stresses produced by the jet-fall impact on the individual steel angles of the plates are acceptable. Thermal stresses that result from the temperature gradient through the angle plates are well below the allowable design stress.⁴

Pressure Vessel and Inner Liner

Essentially all the cyclic impulse loads from the fusion reactions are absorbed by the liquid lithium fall, inner liner, and nozzle plate. Any cyclic stress imposed on the upper head is small, because flow through the central hole in the nozzle plate is restricted and the gas dissipates throughout the entire upper cavity inside the pressure vessel. Consequently, the pressure vessel need only withstand the steady loads that stem from component weight and the static pressure difference across the vessel wall. Stresses produced by component weights do not exceed 7 MPa, which is well below allowable limits. Since the static

pressure in the HYLIFE chamber is at a near vacuum, we selected a wall thickness of 80 mm to prevent the pressure vessel from buckling. Thus, the pressure vessel is able to withstand the effects of 30 years of service without replacement.

The pressure vessel itself consists of two parts: a main body and a detachable head that is sealed and bolted to the main body by a full-diameter flange. The inner liner may be attached to, and supported from, the head to simplify remote assembly and disassembly of components. During disassembly, we use a manipulator to unbolt the flange, after which the head, inner liner, and nozzle plate may be lifted out of the pressure vessel and moved to a separate hot cell for further disassembly, replacement, or repair. The total mass of these pieces is 500 Mg, which is within the capacity of today's large cranes. The head also contains a small access port, lined with graphite, which can be utilized for in-place inspection and repair. The graphite liner, which is supported by a niobium platform and is internally cooled by circulating lithium, shields the access port.

The main body contains ducts for injection of the driver beams, and its lower portion is contoured to minimize lithium splash. The ducts, which are attached with seals and bolted flanges, may be removed remotely with a manipulator before disassembly of the vessel's internal components. All seals are located above the vessel's lithium liquid level, exposing them to lithium vapor only and thus maximizing their lifetime. A space separates the lithium liquid below the end of the inner liner from the vessel and offers a mechanism to reduce effects of the fusion-reaction pressure oscillations in the pump region. This mechanism, coupled with the low splash from the contoured lower part of the body, allows us to eliminate the splash suppressor of the original design.

A 300-mm-thick graphite reflector (Fig.1) is attached to the inside surface of the pressure vessel wall. It is encased in a thin-metal container and is cooled on both sides, as well as internally, with lithium.

A 35-mm-thick inner liner is positioned inside the reflector and may be attached to the top head for easy removal. This liner is the most

highly stressed component and is presently designed to last the entire 30-year life of the reaction chamber. It can be replaced, if necessary, with little expense as compared to replacing the pressure vessel. The inner liner is also cooled on both sides; however, its cooling is not coupled to the reflector cooling. In this way, the cyclic pressure waves passing through the inner liner are transmitted neither to the reflector nor to the pressure vessel.

The inner liner's thickness is dictated primarily by temperature and stress considerations. As the thickness increases, the temperature in the liner increases. The allowable design stress decreases, as does the stress due to lithium impact induced by the fusion pulses. An optimum thickness exists where the margin of safety is at a maximum. Other types of inner liner designs are being considered that may increase the margin of safety.

Lithium Circulation

The circulation system consists of 16 separate loops, each containing an electromagnetic (EM) pump. Inlets and outlets are 1.2-m-diam pipes, equally spaced around the circumference of the pressure vessel. All joints are welded, and no valves are present in the loops. The inlets are located above the lithium pool, so that if a pump failure occurs in one loop, the other loops can continue to operate normally (see Fig.1). Efficiency of the EM pumps is anticipated to be 40%.⁵

Characteristics of the lithium fall and cooling streams inside the chamber are listed in Table 2. The channels between the inner liner and reflector, as well as between the reflector and the pressure vessel, each contain two lithium fluid streams (separated by a space) on the walls. This arrangement reduces the required flow rate of lithium without appreciably increasing the temperature rise in the lithium as it passes through the chamber. Further, the space prevents direct transmission of impact forces from the fusion reaction to either the reflector or the pressure vessel. The reflector is cooled internally to keep the maximum temperature in it below allowable limits.

The major disadvantage of the revised design is that the pumping power increases from 20 to 45 MW. But 45 MW is still only 3.6% of the

Table 2. Characteristics of the lithium circulation in the modified HYLIFE chamber.

	Fluid temp rise through chamber, K	Lithium flow rate, m ³ /s	Fluid velocity at nozzle plate lower surface, m/s	Fluid velocity at midplane, m/s	Radial thickness at nozzle plate lower surface, mm	Radial thickness at midplane, mm
Annular weir flow	11.3	8.5	7.1	11.4	316	198
Jet fall	11.3	121.5	5.5	10.4	300	189-215
Inside inner liner wall cooling	6.9	3.4	6.2	10.8	17	10
Outside inner liner wall cooling	5.0	3.4	6.2	10.8	17	10
Inside reflector wall cooling	8.4	3.4	5.2	10.8	17	10
Outside reflector wall cooling	4.7	3.7	6.2	10.8	17	10
Inside pressure vessel wall cooling	1.2	3.7	6.2	10.8	17	10
		147.6				

gross electric power. Most of this increase is associated with the change from mechanical to electromagnetic pumps. Although mechanical pumps are desirable because of their efficiency, their ability to withstand pressure pulsations transmitted through the liquid lithium from the fusion reactions is questionable. The internal rotating parts of mechanical pumps are particularly susceptible to failure from repeated fluid impact and local cavitation caused by these pressure pulsations. We circumvented the problem by using EM pumps, in which the fluid essentially flows through a straight channel. Large EM pumps that have flow rates of 8-10 m³/s are required for the circulation loops, but they need development; however, smaller-sized pumps (0.1-0.2 m³/s) are utilized in numerous applications today.⁵

Material Considerations

Materials in the HYLIFE chamber must be compatible with hot flowing lithium and they must be composed of isotopes that keep activation to a minimum. The 2½% Cr-1% Mo, low-alloy ferritic steel appears to be the best choice of material in satisfying these criteria, with adequate strength at operating temperatures of up to 800 K. Whitlow et al,⁶ report that the weight loss of this alloy is about 1/3 that of 300-series stainless steel when in contact with flowing lithium at 810 K. The hot lithium attacks the metal at the grain boundaries, producing exposed grains at the surface. Selle and Olson⁷ suggest that material dissolution increases as the nickel and chrome increase. The alloy chosen for the HYLIFE chamber contains no nickel and only 2½% chrome.

The absence of nickel is also an advantage with respect to activation, because no ⁵⁸Co or ⁶⁰Co isotopes are generated. These cobalt isotopes have long half-lives and their presence complicates the shielding of components in the lithium circulation loops. If nickel were present in the structural components, it would be leached out and activated to form cobalt isotopes that could then be deposited throughout the lithium circulation loops.

We performed activation calculations of the steel, using the TARTNP (50-group), two-dimensional neutronics code in conjunction with the Fusion Reactor Isotope Production (FRIP) code.⁸ Results, showing total

curies from all activation products present at shutdown and total gamma energy emission rate for the modified HYLIFE chamber, are listed in Table 3.

Induced activity in terms of bulk curies is an important consideration for long-term storage and other environmental effects. But it is less germane for the technical design of the chamber containment than is the gamma energy's output rate. In comparison with the original design, removing the splash suppressor at the bottom of the modified HYLIFE chamber reduces the bulk of activated material. A small decrease in activation also results from replacing the two-plate injection configuration of the original chamber with a single injection plate.

Conclusions

Potential improvements in the modified HYLIFE reaction chamber include:

- Elimination of the orifice plate.
- Vertical flow in the jet fall, which permits substantially larger variation of liquid lithium head above the nozzle plate.
- Replacement of mechanical pumps by EM pumps, because the EM pumps are less susceptible to failure caused by pressure pulsations from the fusion reactions, and they allow a reduced lithium inventory.
- Addition of a full-diameter flange in the pressure vessel, which permits the remote disassembly and reassembly of components.
- Reduced activation by eliminating the splash suppressor at the chamber bottom.
- Improved shielding of components.

The modified design can accommodate laser or heavy-ion beams to initiate the fusion reactions. It contains no moving solid parts and offers the advantage of a renewable, fluid first wall and blanket. Structural components, designed with presently accepted techniques and limitations, can survive the expected 30-year life of the chamber without replacement.

Table 3. Activation of components in the modified HYLIFE reaction chamber.

	Total Ci at shutdown, Ci/kW _{th}	Total gamma energy emission rate, γ-MeV/kW _{th} -h
Pressure vessel	0.9	4.1×10^{13}
Nozzle plate	1.1	7.3×10^{13}
Inner liner	6.3	3.8×10^{14}
	<hr/>	<hr/>
Totals	8.3	4.9×10^{14}

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