CONCEPTUAL DESIGN STUDY OF THE HYLIFE LITHIUM WATERFALL LASER FUSION CHAMBER

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PART A

FUSION CHAMBER DESIGN STUDIES

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1.0 INTRODUCTION

During FY 1978, the Energy Systems Group (ESG), formerly the Atomics International Division, of Rockwell International performed engineering analysis and design studies of laser fusion target chamber concepts in support of the System Studies for Laser Fusion Project at Lawrence Livermore Laboratory under LLL Purchase Order 8730803.

The FY 1978 ESG effort included a trade study of various types of liquid lithium falls: annular (single, multiple, and parabolic), jet (straight and parabolic), and helical. This study resulted in the selection by LLL of a parabolic jet fall as a preferred type.

Conceptual design studies of the target chamber defined the general configuration and dimensions of the chamber and the inlet plenum, orifice plate, and nozzle plate concepts required to generate the desired lithium jet fall. Preliminary studies were performed of the target chamber interfaces with the liquid lithium supply system, the laser system, the pellet injection system, and the target chamber mounting and support system. Preliminary analyses were made of means for providing a laser beam port through the main jet fall and of secondary lithium fall concepts to protect those regions of the chamber wall above and below the laser beam port.

Target chamber environmental effects resulting from typical thermonuclear burns were evaluated. A number of studies were conducted of the lithium wall interactions resulting from such effects and the resulting stress levels in the first metal wall. Preliminary calculations of the thermal stress in the first metal wall were also performed.

The outlet region of the target chamber was outlined conceptually, and preliminary design considerations were given to the annular graphite reflector regions of the target chamber and the associated liquid lithium coolant passages.

Ferritic steels, austenitic stainless steels, nickel alloys, titanium alloys and refractory alloys were reviewed as potential first wall/vessel materials. Based on mechanical strength, lithium compatibility, resistance to radiation damage, and cost, the family of ferritic steels was deemed best.

Data on radiation effects and corrosion in lithium were compiled and assessed for ferritic steels relative to expected service conditions. The fatigue behavior of 2-1/4 Cr - 1 Mo was reviewed, and a general consideration of erosion by impacting liquid lithium was made.

2.0 CHAMBER DESIGN

2.1 GENERAL DESCRIPTION

The thermal power of the HYLIFE power plant is generated in the fusion chamber. A DT pellet is injected into the chamber approximately once every second, where it receives the energy of two high-power laser beams. The resulting thermonuclear burn yields about 2700 MJ (2.56×10^6 Btu) of energy consisting of about 75% high-energy neutrons and hard x-rays, and 25% ionized pellet debris and soft x-rays. A lithium waterfall surrounds the pellet at the time of the thermonuclear burn and absorbs most of this energy. The neutrons and hard x-rays penetrate deeply into the lithium fall and are absorbed in all of the lithium in the target chamber. The ionized pellet debris and soft x-rays are absorbed in a very thin layer of lithium. A graphite reflector, at the sides of the chamber, reflects neutrons back into the chamber and improves the neutron economy. Some of the neutrons react with the lithium to form tritium, and some of these reactions produce additional neutrons. The tritium is eventually removed from the lithium to be used in the manufacture of more DT pellets. The additional neutrons contribute to the total energy per pulse that is 3175 MJ (3.01×10^6 Btu).

The lithium waterfall also serves to protect the target chamber structures from the radiations. The high-energy (~14-MeV) neutrons can cause atomic displacements and helium production. With a lithium thickness of about 1 m between the reacting pellet and the chamber structures, the material damage is less than currently accepted limits for 2-1/4 Cr - 1 Mo ferritic steel in a 30-year plant.

The establishment of a lithium fall about 1 m thick at the midplane, no closer than 0.5 m from the pellet, and having a fall height of 8 m, takes a lithium flow rate of about $129 \text{ m}^3/\text{s}$ (2.05×10^6 gpm). It is assumed that a new fall must be established following each pellet reaction--that is, the time to fall from the top to the bottom must not exceed the repetition period of about 1 sec.

The fall type may be a single annulus, a double annulus, or a large number of small jets. Studies have indicated that the jet fall is superior to the annular falls. A jet fall provides more surface to condense lithium vapor and, thus, prevents chamber pressure buildup. A jet fall also provides a gas path to allow expanding vapor to blow through the fall and thereby reduce pressure buildup.

The lithium flow rate required to re-establish the fall greatly exceeds the flow rate required to remove the thermal power. As a consequence, the average temperature rise of the lithium is about 12°C (22°F)--that is, the lithium is very nearly isothermal. This is advantageous in that thermal transients caused by splashing lithium are thereby minimized.

The target chamber is a vertical, cylindrical tank of height 23.5 m (77 ft) and inner diameter 10 m (32.8 ft). It consists of the lithium inlet and waterfall nozzle plate at the top, an outlet pipe and splash baffle at the bottom, and the first wall, graphite reflector, and pressure wall at the sides. The target chamber is shown in Figure 2.1.1. Its main features are described below.

Lithium enters the top of the target chamber in 16 pipes, 1.22 m (48 in.) in diameter. These empty into a pool above the orifice plate to a depth of about 1 m (3 ft). The orifice plate distributes the flow in the second pool, which supplies lithium to the perforated nozzle plate. The nozzle plate forms a large number of lithium jets which comprise the main lithium fall in the chamber. The upper and lower pools are provided with slosh baffles to control the movement of lithium.

The nozzles in the plate are set at various angles, so that the flow has parabolic trajectories that are generally inward. This creates a focusing of the flow at the mid-plane. The lithium head above the nozzle plate determines the jet initial velocity and, hence, the trajectory of each jet. It is for this reason that the distribution and sloshing of the lithium must be well controlled.

GETTER-ZIRCONIUM

LITHIUM INLET
16 REGD-48" DIA
(1.2 m)

GRAPHITE PLUG

SLOSH BAFFLE

Figure 2.1.1. HyLife Fusion Chamber

At the center of the upper pool and orifice plate is a vertical graphite plug. The purpose of the plug is to provide access to the inside of the chamber. There is a hole at the center of the nozzle plate just below the graphite plug. This allows the vapor pressure in the chamber to be nearly equal on both sides of the nozzle plate and thereby avoids disturbing the nozzle flow.

In addition to the main lithium fall, which is in the form of many round jets, there are other lithium flows in the chamber. One of these is a secondary lithium flow down the inside (pellet side) of the first wall. Others are secondary falls above and below the laser beam ports. Finally, there is the lithium cooling flow in the graphite reflector region between the first wall and the pressure vessel wall.

The first wall is 5 cm (2 in.) thick and is fabricated from 2-1/4 Cr - 1 Mo ferritic steel. The function of this wall is to contain the lithium flow as it falls from the inlet header and is disassembled by the pellet reactions. The graphite reflector has a total thickness of 30 cm (12 in.) and is clad with 2-1/4 Cr - 1 Mo. Its function is to reflect and moderate neutrons, thus improving the breeding ratio and neutron economy. The pressure vessel is 8 cm (3.1 in.) thick and also is constructed of 2-1/4 Cr - 1 Mo steel. It is a pressure vessel in the sense that it withstands atmospheric pressure on the outside, while the chamber alternates between a near-vacuum to an appreciable pressure following each pellet reaction.

The lithium outlet at the bottom of the chamber is a single pipe having a diameter of 5 m (16.4 ft). At the entrance to this pipe is a lithium pool. The pool must be protected from the direct action of the pellet reaction which could create shock waves that might damage the lithium pumps and piping. This protection is provided by a grid-like splash baffle a few meters above the pool. The splash baffle also minimizes the splashing of lithium brought on by both the fall itself and the force of the pellet reaction.

The target chamber has a support flange near its center of gravity, just above the laser beam ports.

A summary of the HYLIFE chamber parameters is given in Table 2.1.1.

TABLE 2.1.1
HYLIFE CHAMBER PARAMETERS

Pellet Power	2,700 Mwt
Electric Power	1,253 MWe
<u>Chamber Size</u>	
Height (overall)	32.4 m
Fall Height	8 m
Inner Diameter	10 m
Pulse Frequency	1 Hz
Fall Re-establishment Time	≤1 sec
Flow Rate (total)	129 m ³ /sec
<u>Mid-plane:</u>	
Annulus Inner Radius	0.5 m
Annulus Outer Radius	2.5 m
Jet Diameter	0.10 m
Number of Jets	1,200
Flow Rate	92.3 m ³ /sec
<u>Nozzle:</u>	
Annulus Inner Radius	0.5 m
Annulus Outer Radius	5 m
Velocity	4.4 m/sec
Pool Height	1.0 m
Jet Diameter (exit)	0.15 m
Nozzle Injection Angle (from vertical)	0°/45°

TABLE 2.1.1
HYLIFE CHAMBER PARAMETERS
(Sheet 2 of 2)

Orifice Plate:

Annulus Inner Radius	0.76 m
Annulus Outer Radius	5 m
Orifice Diameter	0.2 m
Number of Orifices	1,140
Pool Height	1.1 m

Top Penetrations

Number of Entering Lithium Pipes	16
Diameter	1.2 m

Chamber Pressure

Before Pulse	~0.1 torr
After Pulse	~2.0 atm

Lithium Temperature, Inlet	500°C
----------------------------	-------

Rise	12°C
------	------

Maximum Wall Temperature	550°C
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Wall Components

2-1/4 Cr - 1 Mo Steel, Graphite,
Lithium Coolant

First Wall Thickness	5 cm
Pressure Vessel Thickness	8 cm

3.0 FALL DESIGN

The following is a brief discussion of some of the more important considerations in the design of lithium falls in the target chamber of a laser fusion central power station.

3.1 SIZING THE LITHIUM WATERFALL

The lithium waterfall involves a massive flow of lithium on all sides of the fusion pulse. For a fall of a given thickness at the chamber midplane (the elevation of the pulse), it is desirable to minimize the radial distance to the fall. This minimizes the flow cross sectional area and, hence, the lithium flow rate. However, if the radial distance to the fall is decreased too much, the X-rays and debris which can vaporize several kilograms of lithium from the inner surface of the fall will generate a high pressure in the small volume available and may force the lithium fall into the first wall at a considerable velocity. Therefore, the annular geometry of the fall is a compromise between minimizing the flow rate and minimizing the pressure effects.

It is usually assumed that the fall must be re-established between pulses. That is, the new fall must drop to a level at or close to the base of the chamber before the next pulse occurs. It is desired to have the pulses occur at a rate of roughly one per second to achieve sufficient thermal power. If too high a chamber is selected, either the time of fall will be excessive or the nozzle exit velocity at the chamber top must be increased. In the latter case, both the flow rate and the pumping power must be increased. On the other hand, a chamber of low height will be subject to a greater neutron radiation damage, top and bottom, and greater vapor pressure on the lithium fall.

The equations relating the vertical fall parameters are shown in Appendix A.3.1.1.

The effect of re-establishment time on fall shape is shown in Appendix A.3.1.2.

3.2 SINGLE VS MULTIPLE FALLS

Fall designs of a wide variety were investigated. The simplest is a single annular fall that surrounds the target. The characteristics of even this fall are not yet entirely understood. For example, it is generally assumed that this fall will thin radially and retain uniform azimuthal continuity. In fact, there may be instabilities in the fall in space and time leading to poor first wall protection unless the nozzle design is performed with care.

An interesting modification of the single fall is the double annular fall. In this case, a second and smaller fall is established outside the main fall, starting at a lower height. A double fall has the advantages of reducing the flow rate and pumping power, and possibly mitigating the impact of lithium on the first wall. Studies have been made of up to five concentric, annular falls, but it is not clear that there are any advantages in having more than two falls. Reference 3.2.1

3.3 JET FALLS

Many studies have been made of falls comprised of a large number of closely packed round lithium jets. These jets are in the range of 10 to 20 cm in diameter and have a packing fraction of about 50% at the mid-plane. Multiple jet falls have several potential advantages. One is that the separation of the falls will tend to inhibit propagation of shock waves laterally through the lithium. Another advantage is that jet falls may provide a large lithium surface area upon which vaporized lithium may condense. This presumes that the surface area is sufficiently exposed to the vapor so that condensation can occur.

Another possible advantage of jet falls is that the lithium may enter over virtually the entire top of the chamber, thus providing protection which otherwise would be difficult to achieve. A corollary idea in the use of jet falls is that the falls can be parabolic instead of vertically downward. Lithium leaving near the center of the top may be directed downward while that leaving near the outer rim at the top may be directed inward--with the midplane fall being at the optimum distance from the target. Thus, parabolic jet falls would protect the top of the chamber while forming a fairly compact fall below. A disadvantage of jet falls is that the lithium is less compact, which tends to increase the flow rate for a given effective lithium protective layer.

A schematic of the various fall types studied is shown in Appendix A.3.3.1.

3.4 OVERALL FALL COMPARISON

A systematic comparison of many kinds of lithium falls and chamber designs was made to aid in the selection of a preferred reference design. Four basic fall types were considered which were: (1) vertical, (2) parabolic, (3) jet, and (4) helical.

The vertical falls were of the annular type and include three configurations: (1) single annulus, (2) double annulus, and (3) an annular design with five falls. In both of the multiple-annular falls, the additional falls were progressively larger in diameter and lower in height.

Two parabolic falls were considered. These were annular falls with the lithium diverging from the top center of the chamber. The two cases studied had one fall and three concentric falls. Another fall type was the jet fall. In this comparison, the jet fall was vertical. Finally, a study was made of a helical fall in which the lithium flow was caused to spiral down the inside of the first wall.

In order to evaluate the various fall types, the requirements were made as similar as practicable--for example, each chamber delivered the same thermal power. A number of design criteria were established so that each fall type could be judged, at least qualitatively.

Table 3.4.1 is a matrix which compares the various fall types with respect to a list of 22 requirements and criteria. Excluding the helical fall, which will be discussed later, the differences among the fall types are not great. The chamber size and neutron loading on the first wall are fairly similar. Flow rates tend to rise when either many vertical falls or an assembly of jet falls are used. This has an impact on the number and cost of pumps.

It is noted that all designs have lithium in contact with walls and structures which can lead to shock damage. Parabolic falls can be arranged to better protect the upper and/or lower structures. All of the falls, as presently conceived, lose all of their kinetic energy when they impact the bottom. The jet fall design has a particularly large lithium surface area which is an advantage because the lithium vapor can condense more easily. All of the falls have a rather small volume within (on the pellet side of) the fall. This is a disadvantage because there is a potential for lithium vapor pressure buildup that could cause damage.

The use of sprays of lithium has been proposed as a means of protecting metal surfaces from short-range radiations when they are otherwise inadequately protected. In most of the fall designs, the opportunity to use sprays is only fair because of the limited volume available in the chamber.

The peak vapor pressure that occurs in a given chamber depends on the pulse energy, the volume inside the fall, the effective lithium surface area, the use of sprays, and the amount of venting that can be

TABLE 3.4.1
FALL DESIGN COMPARISON

Criteria	Fall Types						
	Vertical (1)	Vertical (2)	Vertical (5)	Parabola (1)	Parabola (3)	Rod or Jet	Helical
1. Typical TN Burn (10^3 MJ)	4	4	4	4	4	4	0.4
2. Typical Rep Rate (Hz)	1	1	1	1	1	1	10
3. Typical Chamber Diam. (M)	10	10	12	10	10	10	15
4. Distance to Fall (M)	2.5	2.5	2.5	2.5	2.5	2.5	6
5. Wall Loading (MW/M^2)	1.3	1.3	0.9	1.3	1.3	1.3	0.03
6. Fall Thickness (M)	0.6	0.6	0.6	0.6	0.6	0.6	1.5
7. Lithium Transit Time (S)	1	1	1	1	1	1	30
8. Flow Rate (M^3/S)	118	111	189	107	82	138	25
9. Pump Power (MWe)	7.9	6.8	6.8	6.7	4.2	9.2	3.0
10. Lithium Contacts Wall?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11. Blanket Required?	Yes	Yes	Yes	Yes	Yes	Yes	No
12. Inherent Top Cover	No	No	No	Yes	Yes	No	Yes
13. Tendency to Splash	Yes	Yes	Yes	Yes	Yes	Yes	No
14. Fall Energy Recovery	No	No	No	No	No	No	Yes
15. Lithium Surface Area	Low	Med.	High	Low	Med.	High	High
16. Volume Inside Fall	Low	Low	Low	Low	Low	Low	High
17. Opportunity for Sprays	Fair	Fair	Fair	Fair	Fair	Fair	Good
18. Venting Possibilities	Poor	Fair	Good	Poor	Fair	Good	Fair
19. Peak Atm. Pressure	High	High	High	High	High	Low	Low
20. Optical Path Length	Low	Low	Low	Low	Low	Low	High
21. Optical Path Clarity	Fair	Fair	Fair	Fair	Fair	Good	Good
22. Water Hammer Effect	High	High	Med.	High	Med.	Low	Low

done. Among the various fall types, the jet design is best for reducing pressure buildup. One way to reduce pressure buildup is to use vents in the fall which will still attenuate neutrons as in a continuum but allow the vapor to expand beyond the fall. The jet fall has excellent venting capabilities.

The path length of the laser beam in the chamber must be considered. The greater the path length, the greater the chances are that the laser beam and/or the pellet will meet with interference. The falls all have a reasonably low path length. The inherent optical clarity in the chamber is important to the laser beam performance. The jet fall is superior in this respect because of its pressure suppressing characteristics.

The water hammer effect on walls and piping is lessened as the lithium flows are made more finely divided. A jet fall would have a minimum water hammer effect in comparison with other falls.

Some studies were made of helical falls in which the lithium spirals down the sides of the target chamber. The characteristics of helical falls differ from those of "free" falls and makes a direct comparison difficult. A helical fall could have a lower energy pulse and a higher repetition rate which could benefit the laser system. The lithium protective layer can be much thicker which not only protects the first wall and other structures better but eliminates the need for the graphite reflector and for one of the two metal walls.

In a helical fall, the lithium transit time is not 1.0 sec but more like 30 sec. This greatly reduces the flow rate and pump costs. The pump power is also reduced. A helical fall apparently provides a more uniform cover at the top and bottom of the chamber. There is relatively little tendency for the lithium to splash. The fall kinetic energy is

recovered at the bottom of the chamber. The volume inside the fall is large because the chamber is large and the lithium flows directly on the first wall rather than closer to the chamber center.

The chief question concerning the helical fall is whether the lithium flow, as it spirals down the wall, will remain intact and adequately protect the wall. With a transit time of 30 sec and a repetition rate of 10 pulses per second, the lithium flow may become unstable.

As a result of comparison studies such as given above, a preferred fall configuration was selected. The selected fall was actually a combination of the falls given in Table 3.4.1 and is a jet fall with inward parabolic flow. This fall gives the top and bottom of the chamber good protection and has a reasonable flow rate. It affords maximum protection against pressure buildup and lateral shock wave propagation.

3.5 JET FALL DESIGN

A number of jet fall designs were studied for various size reaction chambers. The problem was to simultaneously satisfy requirements for lithium thickness at midplane and flow re-establishment time within the geometric confines of the chamber. An example of such studies conducted is represented in Table 3.5.1 where fall heights of 10 m and 6 m were compared for varying flow and geometric parameters.

The approach taken was to first establish the fall velocity, space coordinates, and flow cross-section areas for a vertical jet and a slanted injected paraboloid jet. The jet re-establishment time then defined the initial injection velocity and nozzle pool head requirements which, together with the midplane inner and outer annulus radii and jet diameter, established the number of jets needed. The jet diameter at nozzle exit was then computed and with a given packing fraction, the injector plate outer radius determined.

TABLE 3.5.1
FUSION CHAMBER PERFORMANCE PARAMETERS
JET FALLS

	Units	Case			
		I	II	III	IV
Fall Height	M	10	10	6	6
Pulse Repetition Frequency	Hz	1.1	1.1	1.1	1.5
Re-establishment Time	Sec	.91	.91	.91	.667
<u>Mid-Plane</u>					
Annulus Inner Radius	M	1.0	.5	.5	.5
Annulus Outer Radius	M	3.0	2.5	2.5	2.5
Jet Diameter	M	.1	.1	.1	.1
Packing Fraction	-	.5	.5	.5	.5
Annulus Area	M ²	25.1	18.85	18.85	18.85
Number of Rods	-	1600	1200	1200	1200
Jet Spacing	M	.035	.035	.035	.035
Jet Pitch	M	.135	.135	.135	.135
Velocity	M/sec	11.9	11.9	7.96	9.57
<u>Nozzle Plate</u>					
Exit Velocity	M/sec	6.53	6.53	2.13	5.72
Head Requirement	M	2.17	2.17	.231	1.67
Exit Diameter	M	.133	.133	.193	.129
Entrance Diameter	M	.19	.19	.276	.184
Entrance Packing Fraction	-	.816	.816	.816	.816
Entrance Pitch	M	.2	.2	.290	.194
Plate Inner Radius	M	.5	.5	.5	.5
Plate Outer Radius	M	4.24	3.68	5.32	3.56
Fall Flow Rate	M ³ /sec	149.4	112.2	75.0	90.2
Reynolds Number/Nozzle	-	1.23×10^6	1.23×10^6	5.83×10^5	1.05×10^6

Cases I and II of Table 3.5.1 compared the effect of varying two inner annulus radii, $r_1 = 0.5$ m vs 1.0 m, for the same 10-m fall height. Case II ($r_1 = 0.5$ m) resulted in a smaller number of jets, 1,200 vs 1,600, and a smaller flow rate: 112 vs 149 m³/sec. Cases III and IV compared the effect of fall re-establishment time ($\tau = 0.91$ sec vs 0.667 sec) for a 6-m fall height. The Case III ($\tau = 0.91$ sec) resulted in a lowered flow rate requirement, 75.0 m³/sec vs 90 m³/sec. Studies such as these provided design guidelines for the jet fall parameters used in the present reference design of Figure 2.1.1.

The design parameters for the current reference chamber which has a radius of 5 m, a nominal fall re-establishment time of 1 sec, and a fall height of 8 m are given in Table 3.5.2. The inner annulus surface is formed by vertical jet falls while the outer jet annulus surface is established by paraboloid jets injected at a 45° angle with the vertical. The same axial initial velocity generated by the pool height was assumed for all jets which resulted in slightly different re-establishment times for jets that have different injection angles.

The analysis for the jet paraboloid fall is given in Appendix 3.5.1.

3.6 LASER FALL PENETRATION

The laser beams are conducted into the chamber through two 50-cm diameter opposite-facing ports at the chamber midplane. The pellets are injected through one of these ports.

It is planned to generate an unobstructed path through the lithium fall for both the injected target pellet and the laser beams while still providing the 1-m equivalent protection against neutron damage for nearly all portions of the wall.

TABLE 3.5.2
REFERENCE JET FALL DESIGN

Fall Height	8 m
<u>Re-establishment Time:</u>	
Outer Paraboloid	1.0 sec
Inner Vertical	0.99 sec
<u>Midplane:</u>	
Annulus Inner Radius	0.5 m
Annulus Outer Radius	2.5 m
Jet Diameter (Nominal)	0.1 m
Packing Fraction	0.5
Annulus Area	18.85 m^2
Total Area of Jets	9.43 m^2
Number of Jets	1200
Flow Rate	$93.2 \text{ m}^3/\text{sec}$
<u>Injector Exit Velocity:</u>	
Outer Paraboloid, V_o at 45°	4.37 m/sec
Inner Vertical, V_o	4.37 m/sec
Jet Diameter	0.15 m
<u>Annulus:</u>	
Inner Radius	0.5 m
Outer Radius	4.5 m

One solution to the problem uses the cross-sectional area reduction of the jet as it falls past the midplane. Thus, two rows of parallel jets, which are nearly touching at the injector exit, create a continuously widening gap which is several cm at midplane. However, the vertical narrow arch exposes a similarly shaped unprotected narrow gap of bare wall, both above and below the port in the chamber wall. Wall protection is accomplished by injecting crossed paraboloid lithium jets downward at the wall above the port and by providing a weir flow below the port. These added falls are fed by diverting a portion of the flow in the vertical coolant channels within the chamber wall. See Figures 3.6.1 and 3.6.2.

A second method for providing a small opening through the fall from the chamber port to the target is accomplished by injecting overlapping paraboloid jets downward from the injector. These jets are directed at such angles that they crisscross above and below the desired optical opening and form a small diamond-shaped projection at the wall. See Figure 3.6.3.

The detailed design for both fall penetration schemes have been addressed by both analytical and computer analysis and modeling. Further definition will be addressed during the next fiscal year.

4727-12

Figure 3.6.1. Chamber Wall Protection (Elevation) (Cathedral Opening)

4727-11

Figure 3.6.2. Chamber Wall Protection (Midplane - Plan View) (Cathedral Type Fall)

4727-2

Figure 3.6.3. Criss Cross Fall Schematic

4.0 INJECTOR DESIGN

The injector assembly consists of the following components:

- 1) Sixteen inlet pipe nozzles
- 2) Upper pool flow baffles
- 3) Orifice plate
- 4) Lower pool baffles
- 5) Nozzle assembly

The functions of the injector assembly are as follows:

- 1) The total lithium flow of $\sim 129 \text{ m}^3/\text{s}$ enters the top of the chamber in the 16 inlet pipes, each of which is 122 cm (48 in.) in diameter.
- 2) The lithium pours downward into a cavity that forms the upper pool of the injector.
- 3) The baffles in the upper pool minimize sloshing so that the pool depth is fairly constant.
- 4) The orifice plate provides a resistance to the flow and meters the flow as it enters the lower pool.
- 5) The orifice plate also provides for a discontinuity in the lithium flow so that the propagation of shock waves to the pipes and pumps is minimized.
- 6) The nozzle plate provides a resistance to the flow so that the lower pool is formed.
- 7) Baffles in the lower pool minimize slosh, maintain a fairly constant lithium head, and guide the flow to the nozzles.
- 8) The nozzle plate has a large number of 15-cm (6-in.) holes that direct the lithium fall in the general form of a converging annulus.

- 9) The nozzle plate is protected from neutron damage by having the jets emerge over nearly all of its surface.
- 10) The hole in the center of the nozzle permits pressure equalization to occur between the chamber and the nozzle plate pool.

4.1 ORIFICE PLATE

In order to provide pressure pulse isolation to the circulating pumps, the orifice plate injection design was introduced (Figure 2.1.1). It is positioned 1.0 m above the nozzle plate pool level and supports a pool of lithium above it. It meters the flow of lithium uniformly over the plate to the pool below through a series of orifices whose size governs the resistance needed for the metering. In addition, it provides the flow needed to cool the interior of the chamber wall through openings in the wall at the juncture of the plate and the wall. An analysis of the flow on the wall is given in Appendix A.4.1.1.

The orifice plate is an annulus of inner radius $r_1 = 0.77$ m and outer radius $r_2 = 5$ m. The graphite plug fits the inner circle. The height of the pool was calculated to be 1.1 m (see A.4.1.2 for detailed calculations). Figure 4.1.1 shows the orifice plate details and Table 4.1.1 lists the plate parameters. An analysis of the orifice plate performance is given in Appendix A.4.1.2.

4.2 FLOW BAFFLES

There are flow baffles in both the upper and lower injector pools. The baffles in the upper pool must withstand the lithium flow pouring in from 16 pipes. Gross movement of the lithium must be inhibited yet provision for lateral flow must be a part of the design. This is accomplished by using a coarse hexagonal-shaped honeycomb structure

Figure 4.1.1. Orifice Plate Geometry

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TABLE 4.1.1
ORIFICE PLATE PARAMETERS

Inner Radius	0.77 m
Outer Radius	5.0 m
Area	71.5 m ²
Void Fraction	0.50
Area of Orifices	35.8 m ²
Diameter of Each Orifice	0.20 m
Pitch (60° Triangle)	0.27 m
Number of Orifices	1140
Flow	129 m ³ /sec
Orifice Coefficient C	0.71
Head of Lithium	1.1 m
Plate Thickness	5.0 cm

which is positioned so its lower edge terminates above the top of the orifice plate and whose sides are perforated to promote dashpot-type flow between adjacent vertical flow passages.

The flow baffle above the nozzle plate also performs the functions of (a) inhibiting wave formation and turbulence caused by the rain of lithium injected by the orifice plate above, (b) distributing the liquid evenly over the nozzle plate entrance, and (c) providing a flow $L/D \geq 5$ so as to remove the turbulence at the nozzle entrance.

The basic hexagonal structure mentioned above is used except that the hexagonal grid is finer so that each flow channel feeds three nozzles. The baffle is positioned so that the lower edge is half a meter above the top of the nozzle plate, and its upper edge is 0.5 m above the mean pool surface and 0.5 m below the orifice plate.

4.3 NOZZLE PLATE

4.3.1 Annular Ring Nozzle

The final design of the injector system evolved through a series of preliminary designs covering first annular and then jet array falls. The annular ring nozzle was first studied for the annular falls discussed in Sections 3.1 and 3.2 where it was recognized that to satisfy the requirements would necessitate a smooth entry and a sufficiently long nozzle L/D to minimize turbulence in the emerging stream.

While the literature available discussed the stability of emerging jets in relation to jet L/D (examples: References 4.3.1.1 and 4.3.1.2), little information was available for application to the specific design of annular ring jets. The nozzle shape of Reference 4.3.1.3, Figure A.4.3.1.1, was selected as a model for the ring nozzle. It was immediately apparent

that the required nozzle length would be 2.0 m for a typical aperture. Ring annulus design was discontinued with the adoption of the jet array fall discussed next.

4.3.2 Jet Array Nozzle

The nozzle plate, located at the top of the chamber (Figure 2.1.1), is an annulus of inner radius 0.5 m and outer radius 5.0 m. The inner circle provides a means of relieving the chamber cavity pressure pulse buildup by permitting gas expansion into the space above the nozzle plate pool. A tapered pipe needed to contain the pool and to prevent spillage into the cavity slants back from the opening to allow free passage of pulse neutrons and radiation flux to impinge on the graphite plug above. The pipe is cut with 12-cm diameter holes to provide for gas flow.

The plate contains a hexagonal array of nozzle injectors set vertically at the inner radius ($r_1 = 0.5$ m) and gradually slanting to 45° at the outermost row ($r_2 = 4.5$ m). As previously mentioned in Section 2.1, slots are provided at the plate wall juncture to permit the thin (5 cm at midchamber) lithium auxiliary flow on the inner surface of the first wall.

The dimensions of the ASME vertical discharge nozzle are shown in Figure 4.3.2.1. They are based on the 8-m tall reference design which results in an exit diameter of 0.15 m (jet diameter = 0.10 m at mid-plane), and calls for a nozzle $L/D = 1.6$. Since a degree of uncertainty exists as to the need for this large L/D in a vertical free fall jet, it was reasoned that the nozzle bell entry dimensions could be decreased so as to provide more close packing of nozzles by mounting flow baffles in the lithium pool. Thus, the nozzle dimensions shown in the figure have an $L/D = 1.33$ and a resulting plate thickness of 0.20 m. Those nozzles which have their axes slanted to the vertical will, of course, show oval

JET NOZZLE PROFILE

Figure 4.3.2.1

projections at the plate exit and entrance. The entrance bell dimensions will also be modified for optimal spacing. The dimensions of a 45° slanted nozzle are shown in Figure 4.3.2.2.

Nozzle plate details are listed in Table 4.3.2.1.

SLANTED NOZZLE

FIGURE 4.3.2.2

SCALE :

9-21-78

TABLE 4.3.2.1
NOZZLE PLATE PARAMETERS

Inner Radius	0.5 m
Outer Radius	4.5 m
Number of Jets	1600
Jet Exit Diameter (Vertical)	15 cm
Nozzle Axis	
Inner Radius	90°
Outer Radius	45°
Plate Thickness	0.2 m
Jet Velocity	4.37 m/sec
Pool Height	1.1 m
Type of Nozzle	ASME Bell Entrance

5.0 CHAMBER WALL DESIGN

The chamber wall consists of three layers. The inner layer is the first metal wall or simply the first wall and has the basic functions of containing the lithium fall and the products of the fusion pulse. The middle layer consists of graphite, which has the function of moderating and reflecting the neutrons and thus improving the neutron economy of the chamber. The outer layer is the pressure vessel, which resists the steady external atmospheric pressure, resists the intermittent internal pressure, and supports the chamber as a whole.

5.1 FIRST METAL WALL

The first metal wall is made of 2-1/4 Cr - 1 Mo ferritic steel and is 5 cm (2 in.) thick. Radiation damage to this wall, which is the chief problem in most fusion concepts, was greatly reduced by the use of a nominal 1-m thickness of lithium in the fall. However, other problems arose that affected the mechanical design of the first wall. These problems involved the interaction between the fusion pulse and the lithium, followed by the interaction between the lithium and the first wall.

The problem first addressed was to determine a wall thickness which could withstand the 1-Hz impact of the disassembled lithium fall from a mechanical strength viewpoint. The maximum stress was assumed to be less than the allowable for 2-1/4 Cr - 1 Mo steel (~ 87 MPa). The model used in the analysis consisted of a thin ring section of the metal wall at the chamber midplane to which was transferred the momentum energy of the expanding lithium fall annulus (Figure 5.1.1). The detail of the analysis and subsequent mathematical treatment hinged on the approach taken in describing the fall at the moment of impact with the wall.

1.0
METER

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Figure 5.1.1. Lithium Fall Expansion

The first approach (described in Reference 5.1.1, Section 3) regarded the wall and fall as interacting spring mass systems, and the liquid was analyzed in one case as a continuum and in a second case as a sequence of droplets. The data on fall momentum/area and radial velocity distribution through the fall were supplied by LLL.

5.1.1 Fall Continuum Analysis

The detailed analysis is given in the Appendix A.5.1.1. A typical parametric curve plot of the ratio of wall stress/fall momentum ($\sigma/\bar{p}$) vs wall thickness for varying chamber radii is given in Figure 5.1.2 for the fall continuum case. A wall thickness of 15 cm and a chamber radius $R = 5$ m (Pt. A) results in a ratio $\sigma/\bar{p} = 1.6$.

The LLL curves for this size chamber showed a fall outer surface radial momentum $\bar{p} = 54$ Mg/ms (megagram/meter-second) and the resulting computed wall stress is, therefore, $\sigma = 1.6 \bar{p} = 86.4$ MPa (mega-pascals) which is an acceptable stress value.

5.1.2 The Fall as a Mass of Droplets

In the droplet approach (A.5.1.2), at the instant of wall contact, the fall was divided into zones of varying velocities using LLL-supplied data and the integrated effect for wall stress solved by a computer analysis (A.5.1.2.1). Figure A.5.1.2.2 shows the results plotted for wall stress vs wall thickness for varying chamber radii. A 15-cm thick wall at a chamber radius $R = 5$ m (Pt. B) resulting in an acceptable wall stress where $\sigma = 7.7$ MPa, less than the continuum case.

5.1.3 Liquid Shock Effect

During this period of analysis, LLL suggested a modification to the method used by AI for modeling the liquid fall first wall impact. It was suggested that at the moment of contact with the wall, an instantaneous

Figure 5.1.2. First Wall Stress (Continuum Model)

shock pulse would be generated within the liquid which would then be transmitted to the wall as a forcing function to be used in analyzing the subsequent wall displacement and stress. Details of the analysis are presented in Reference 5.1.3.1 and the Appendix (A.5.1.3.1).

In brief, the magnitude of the pressure pulse was calculated from the fluid velocity at the moment of wall contact. The time duration of the pulse was taken as equal to two traversals of the liquid annulus thickness. A second-order differential equation representing the motion of a pressure-loaded ring was then solved using Laplace transforms. The maximum displacement was found and the wall stress computed for three cavity pressure levels and two wall thicknesses. The results in Table 5.1.3.1 showed that the computed wall stresses were excessive. For example, an initial cavity pressure of only 1 atm (0.1 MPa) generated a liquid pressure pulse at the wall of 57.1 MPa, and a wall having a 25-cm thickness developed a stress of 168 MPa at its maximum displacement (double the allowable 87 MPa). In view of the high stresses reached in this model, other analytical approaches were formulated. One concept, for example, regards the wall as a moving boundary (Appendix A.5.1.3.2). However, LLL turned from annular falls to the jet fall primarily as a means of reducing the fall impact effects on the wall. Also, the initial cavity pressure level was re-evaluated by LLL and found to be much lower than had originally been estimated.

Thus, from mechanical stress considerations of annular lithium fall impact, a 15-cm wall was estimated as reasonably thick to stay within the allowable mechanical stress limitations.

5.2 GRAPHITE REFLECTOR

The first solid structure radially outward from the first structural wall is the graphite reflector (Figure 2.1.1). Its functions are to reflect, absorb, and attenuate the neutrons. Heat generated within

TABLE 5.1.3.1
FIRST WALL RESPONSE TO LIQUID PULSE

R = 5 m

P_c		V m/sec	P_0 MPa	$(\delta = .10 \text{ m})$		$(\delta = .25 \text{ m})$	
atm	MPa			$\frac{U \text{ max}}{m}$	$\frac{\sigma \text{ max}}{\text{MPa}}$	$\frac{U \text{ max}}{m}$	$\frac{\sigma \text{ max}}{\text{MPa}}$
1	.1	27.5	57.1	.013	419	.0052	168
10	1.0	86.8	181.0	.0412	1,328	.016	531
100	10.0	275.0	571.0	0.13	4,191	.052	1,676

the graphite is conducted to lithium coolant channels. The graphite reflector must retain its structural integrity over the system lifetime (30 years).

The design approach was to size the wall in the form of metal-clad blocks of dimension 15 cm in the radial direction, 30 cm in the circumferential direction, and 45 cm in height. The blocks are stacked in two concentric annuli--separated by three 5-cm lithium coolant channels external to and between the graphite annuli.

The optimum size of the blocks depends upon the system thermal, nuclear, and physical requirements. An initial survey of graphite structural material used in previous reactors (e.g., References 5.2.1 and 5.2.2) indicated that the graphite may undergo outgassing, swelling, and fracture in a nuclear environment and, therefore, the design will call for gas venting or gas gettering techniques, plus provisions for differential expansion and thermal contact between graphite and metal cladding wall. In addition, the structure will be subjected to vertical compressive loading from the system weight, plus thermal stresses and cyclic mechanical stresses in the radial direction.

5.3 PRESSURE VESSEL

The pressure vessel is made of 2-1/4 Cr - 1 Mo ferritic steel and has a nominal wall thickness of 8 cm (3.1 in.). It has a flange that rings the structure just above the two laser ports by means of which the pressure vessel and the rest of the target chamber can be supported. See Figure 2.1.1.

One function of the pressure vessel is to withstand the external atmospheric pressure while the internal pressure is a near vacuum. The minimum wall thickness is set by the collapsing pressure requirements.

Heat deposited by the nuclear radiations tends to set the upper limit on wall thickness in the pressure vessel. A wall that is too thick will have excessive temperatures and stresses. Heat generated in the pressure vessel is removed by a lithium flow that is between the outer graphite cladding and the pressure vessel.

There are 16 pipe penetrations at the top of the pressure vessel to admit the lithium flow, and there is one penetration at the bottom to discharge the lithium. Two 50-cm laser ports are at the midplane. Also, access to the chamber is provided at the top where the graphite plug and its containment are located. Thermal insulation of the calcium silicate type will be placed on all surfaces of the pressure vessel to a depth of ~30 cm.

The pressure vessel will be designed to meet the thermal, mechanical, and seismic stresses in accordance with the ASME Boiler and Pressure Vessel Code for nuclear structures (Section III, Class 1, High-Temperature Code).

5.4 CHAMBER WALL TEMPERATURES AND STRESSES

The high-energy neutrons and secondary gammas resulting from the fusion pulses are absorbed in the multi-layer chamber wall giving rise to what amounts to a steady generation of heat in these structures. This heat is removed by flows of lithium both between the first wall and the pressure vessel and on the inside (pellet side) of the first wall.

The generation of heat in such walls creates a temperature profile in the layer that is very nearly parabolic. The peak temperature is greater than the local temperature of the lithium by an amount that

varies as the power density, the square of the thickness, and, inversely, with the thermal conductivity. The thermal stress is very nearly proportional to this temperature rise.

Table 5.4.1 shows the energy deposited in the wall as provided by LLL for one particular wall geometry. A thermal and stress analysis (Figure 5.4.1) showed that the maximum metal temperatures in the first wall were far above the maximum allowable for 2-1/4 Cr - 1 Mo of 550°C (1022°F). Likewise, the stresses in the first wall were much higher than the allowables. It was concluded from this study that the first wall would have to be much thinner than the 15 cm used in this study and, furthermore, the cooling by the lithium would almost certainly would have to be done on both sides of the first wall. Calculations in which such cooling was done on both sides of the first wall showed that reasonable temperatures and stresses could be achieved if the first wall was about 5.0 cm thick. See Appendix A.5.4.1 for a detailed analysis. These are very preliminary results. Detailed stress analyses and trade studies need to be performed to determine more precisely the thickness constraints placed on the first wall by the heat deposition. It should be noted that the graphite reflector and the pressure vessel also are constrained by the heat deposition and the resulting temperatures and stresses.

As mentioned in Section 5.1, the mechanical loads on the first wall may require a considerable thickness. This is in contrast to heat deposition which dictates thin walls. Recent studies of jet falls indicate that the lithium pressures are less than at first believed and that mechanical loads will not require a very thick first wall.

5.5 COMPONENT VIBRATION RESPONSE

The fusion chamber will be disturbed by a periodic 1-Hz forcing function arising from the interaction of the lithium fall on the first

TABLE 5.4.1
ENERGY DEPOSITION IN WALL REGIONS

	MeV/ Fusion	Energy Fraction Deposited	Power Deposited in Region (MWt)
10 cm Lithium	0.465	0.0225	60.8
15 cm First Wall	0.56	0.0271	73.2
30 cm Graphite	0.091	0.0044	11.9
5 cm Lithium	0.13	0.00628	17.0
15 cm Pressure Wall	0.023	0.00111	3.0
Balance Target, Fall, etc.	_____	<u>0.939</u>	<u>2,535.0</u>
Total	20.7	1.0	2,700.9

q = 7Q
Q = 2700 MWt

HEAT TRANSFER EQUATIONS:

NODE 1:

$$Q_1 = q_1 \cdot Q_2$$

$$Q_1 = \frac{T_1 \cdot T_0}{R_1}$$

$$Q_2 = \frac{T_2 \cdot T_1}{R_2}$$

$$R_1 = \frac{\ell_1}{k_1 \cdot A_1}$$

$$R_2 = \frac{\ell_2}{k_2 \cdot A_2}$$

NETWORK ANALOGY

$$q_0 \sim 0 \text{ (ASSUMED)}$$

$$q_1 = \eta_1 Q$$

$$q_2 = \eta_2 Q$$

$$Q = \text{FUSION POWER}$$

$$T_0 = 500^\circ\text{C}$$

Figure 5.4.1. Thermal Analysis
(Typical Wall Geometry)

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wall and the pressure pulse on the nozzle plate. The problem is to determine the first flexural frequency of the main component parts of the chamber as a prelude to obtaining the total system response.

A rough analysis was made first of the chamber first wall using the radial expansion of a thin ring at midplane as a model. A 5-m radius wall (2-1/4 Cr - Mo) was found to have a natural frequency of $W_1 = 152$ cycles/sec.

A second analysis was made to determine the natural frequency of the nozzle plate. The model used was for a solid disk 0.2 m thick and radius = 1 m. The plate was assumed clamped at its circumference. The natural frequency was found to be $W_2 = 30$ cycles/sec. The frequency would decrease if provisions were made for the central hole and the nozzles. These frequencies are higher than the 1-Hz forcing function.

After the chamber system frequency is determined, an analysis of the system response to the 1-Hz and typical seismic disturbance can then be made and the structural components analyzed for stress limitations.

The details of the analysis are given in Appendix A.5.5.

5.6 SUPPORT FLANGE DESIGN

The support flange shown in Figure 2.1.1 provides the basic support for the chamber and its contents. It is a ring-shaped forging which is welded to the chamber wall at a position above the plane of the laser entry ports. The vertical thickness must be sufficient to take the static shear loads but, additionally, it must also be designed for bending stresses due to the chamber weight.

Other disturbances which act to load the flange include seismic and thermal stresses. The flange is near the target and will receive a portion of the neutron energy spectrum similar to that in the wall.

Therefore, means must be provided to remove the internally generated heat without exceeding the maximum design temperature for 2-1/4 Cr -1 Mo steel (550°C).

For the present, the analysis has considered only mechanical loads due to the loaded vessel weight estimated at 1.75×10^6 kg (3.9×10^6 lb). A 5-m radius vessel calls for a computed flange depth dimension of about 0.7 m and, from analogy with the Hanford Fuel Storage Facility, a corresponding minimum radial thickness of 0.3 m.

The shape of the flange shown in Figure 2.1.1 is in compliance with Section III, Class 1, Flange Code, while the radial thickness can be increased to provide for bolt holes and sufficient metal surface as required at the structural support interface.

5.7 SPLASH BAFFLE DESIGN

As shown in Figure 2.1.1, a splash baffle is incorporated in the chamber design, being located just above the pool at the bottom of the chamber. The splash baffle is a honeycomb structure made of 0.64 cm (1/4-in.) steel plate with the hexagons measuring 7.6 cm (3.0 in.) across. It measures 1.52 m (5 ft) deep at the first wall and 0.61 m (2 ft) deep at the center.

An important function of the splash baffle is to absorb the shock of the falling lithium and minimize the amount of lithium splash. The splashing of lithium is considered to be harmful in that droplets could interfere with the pellets and laser beams. The jet fall converges and impacts the splash baffle in a region roughly 4 m in diameter at the center. The lithium is held up momentarily then rains into the pool below the baffle.

Another function of the baffle is that it shields the lithium pool at the bottom from the direct action of the fusion pulse. It tends to prevent the propagation of shock waves through the lithium outlet pipe to the pumps. This is accomplished by both the presence of the lithium-filled baffle and by the discontinuity in the flow and is similar to the function of the lithium injector at the top of the chamber.

The convergent annular shape of the fall tends to protect the splash baffle from the effects of both the high-energy neutrons and the short-range radiations. The fall impacts the honeycomb structure edgewise so that the loads on the baffle are reduced. At this time it is not clear how much holdup of the lithium in the baffle is required. It can range from a mere splitting of the flow with very little holdup to considerable holdup with an intermittent pool formed on the concave upper surface of the baffle. If the amount of holdup is large, then some form of resistance such as an orifice plate will be incorporated in the splash baffle. These design considerations have not yet been resolved.

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CONTINUITY:

$$A_o V_o = AV$$

(1)

ANNULUS AREA

$$A = 4\pi (R_o - R) R_o$$

(2)

$$A_o = 2\pi R_o t_o$$

(3)

VELOCITY

$$V = \sqrt{V_o^2 + 2gh}$$

(4)

$$R_o = k t_o$$

(5)

RESULTS IN:

$$\frac{R}{R_o} = 1 - \frac{V_o}{2k\sqrt{V_o^2 + 2gh}}$$

(6)

Figure A.3.1.1. Fall Profile Parameters

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Figure A.3.1.2. Fall Repetition Rate and Profiles

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Figure A.3.3.1. Fall Types

A.3.5.1 Equations for Jet Paraboloid Fall

Trajectory Analysis (See Figure A.3.5.1.1)

a) $t = 0, x = 4.5, y = 8$

b) $t = 1, y = 0$

c) When $y = 4, x = 2.5$

Vertical Component

$$\ddot{y} = -g \quad \dots(1)$$

$$\dot{y} = -gt - V_0 \sin \theta \quad \dots(2)$$

$$y = -\frac{gt^2}{2} - (V_0 \sin \theta) t + 8 \quad \dots(3)$$

Horizontal Component

$$\ddot{x} = 0 \quad \dots(4)$$

$$\dot{x} = V_0 \cos \theta \quad \dots(5)$$

$$x = - (V_0 \cos \theta) t + 4.5 \quad \dots(6)$$

must find V_0, θ

Use Cond. (b) in (3)

$$0 = -4.91 - V_0 \sin \theta + 8$$

or

$$V_0 \sin \theta = 3.09 \quad \dots(7)$$

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Figure A.3.5.1.1. Paraboloid Fall Trajectory

Cond. C satisfies (3) and (6) for same t:

thus (3) becomes

$$0 = -4.91t^2 - (V_0 \sin \theta) t + 4 \quad \dots(8)$$

Substitute c in (6)

$$2.5 = - (V_0 \cos \theta) t + 4.5$$

or

$$(V_0 \cos \theta) t = 2.0 \quad \dots(9)$$

Substitute (7) in (8):

$$0 = -4.91t^2 - 3.09t + 4$$

$$0 = t^2 + .629t - 0.815$$

$$t = - \frac{.629 \pm \sqrt{.629^2 + 4(.815)}}{2} = \underline{.642 \text{ sec}} \quad \dots(10)$$

t = time to reach midplane

Find θ :

Substitute into (9) V_0 from (7) & t from (10):

$$\frac{3.09}{\sin \theta} (\cos \theta)(.642) = 2.0$$

$$\cot \theta = 1.00$$

or

$$\tan \theta = 1.00$$

$$\theta = \underline{\pi/4 \text{ rad}}$$

$$\sin \theta = \cos \theta = 0.707$$

Find V_0 from (7):

$$V_0 = \frac{3.09}{\sin \theta} = \frac{3.09}{0.707} = \underline{4.37 \text{ m/sec}}$$

Find X_3 :

Substitute $\theta = 45^\circ$, $t = 1$, $V_0 = 4.37$ in (6):

$$X = -4.37 (.707)(1) + 4.5$$

$$X = \underline{1.41 \text{ m}}$$

Find V_x and V_y and θ at midplane:

Substitute in (2):

$$t = 0.642 \text{ sec}, V_0 = 4.37 \text{ m/sec}, \theta = 45^\circ$$

$$\dot{y} = V_y = -9.81(.642) - 4.37 (.707) = \underline{-9.39 \text{ m/sec}}$$

Substitute in (5):

$$\dot{x} = V_x = -4.37 (.707) = \underline{-3.09 \text{ m/sec}}$$

$$\tan \theta_m = \frac{V_x}{V_y} = \frac{3.09}{9.39} = 0.329$$

$$\theta_m = \underline{18.2^\circ}$$

$$V_m = \sqrt{(9.39)^2 + (3.09)^2} = \underline{9.89 \text{ m/sec}}$$

Number of rods: N

Calculated from midplane:

Assume P.F. = .5

Area of annulus at midplane:

$$A = \pi(R_2^2 - R_1^2) = \pi(2.5^2 - .5^2) = 18.85\text{m}^2$$

$$\text{Area of jets} = (\text{P.F.})(A) = (.5)(18.85) = 9.43\text{m}^2$$

$$\text{Area/jet} = \frac{\pi d^2}{4}$$

Let $d = 0.10\text{m}$ at midplane

Thus

$$\text{Area/jet} = \frac{\pi}{4} (.10)^2 = .00785\text{m}^2$$

$$N = \frac{\text{Area of jets}}{\text{Area/jet}} = \frac{9.43}{.00785} = \underline{1,200}$$

Full Flow Rate

$$Q = AV, \text{ midplane}$$

$$A = \text{Area of jets} = 9.43\text{m}^2$$

$$V = V_m = 9.89 \text{ m/sec}$$

$$\therefore Q = (9.43)(9.89) = \underline{93.2 \text{ m}^3/\text{sec}}$$

Vertical Jet (inner row)

Head requirement: h

Assume head is determined by V_0 of outer row:

$$V_0 = \sqrt{2gh} = 4.37 \text{ m/sec}$$

$$h = \frac{V_0^2}{2g} = 0.973 \text{ m of Lithium}$$

$$\ddot{y} = -g$$

$$\dot{y} = -gt - C_1$$

$$\text{when } t = 0, \dot{y} = -4.37 \text{ m/sec}$$

$$\therefore \dot{y} = -gt - 4.37 \quad \dots(11)$$

$$y = \frac{g}{2}t^2 - 4.37t + C_2$$

$$\text{when } t = 0, y = 8$$

$$\therefore y = \frac{-g}{2}t^2 - 4.37t + 8 \quad \dots(12)$$

Find midplane velocity, $\dot{y}_m$

Substitute in (12): $y = 4$ and find t :

$$4 = -4.91t^2 - 4.37t + 8$$

$$0 = -4.91t^2 - 4.37t + 4$$

$$0 = -t^2 + .89t - .815$$

$$t_m = \frac{-.89 \pm \sqrt{(0.89)^2 + 4(.815)}}{2} = .562 \text{ sec}$$

Substitute t in (11):

$$\dot{y}_m = -9.81(.562) - 4.37 = \underline{-9.88 \text{ m/sec}}$$

Time to reach bottom: vertical jet

Substitute y = 0 in (12):

$$0 = -4.91t^2 - 4.37t + 8$$

$$0 = t^2 + .89t - 1.63$$

$$t = \frac{-0.89 \pm \sqrt{(0.89)^2 + 4(1.63)}}{2} = 0.907 \text{ sec}$$

Geometric Contraction

From continuity:

$$Q = AV = \text{Constant}$$

$$Q = (AV)_{\text{midplane}} = (AV)_{\text{nozzle}}; \frac{D_1}{D_2} = \sqrt{\frac{V_2}{V_1}}$$

$$V_m = 9.88 \text{ m/sec}, V_o = 4.37 \text{ m/sec}$$

$$\text{Jet diameter midplane} = 0.10$$

$$\therefore \text{Jet diameter at nozzle exit} = (.10) \sqrt{\frac{9.88}{4.37}} = \underline{0.15m}$$

Minimum nozzle plate r_2 :

Based on jet drain = 0.15m at plate exit:

$$\text{Assume P.F. at nozzle plate exit} = 0.4$$

$$\text{Area jets} = (\text{P.F.})(\text{area nozzle plate})$$

$$N \frac{\pi d^2}{4} = (\text{P.F.}) \pi (r_2^2 - r_1^2)$$

$$N = 1200, d = 0.15, \text{P.F.} = .4, r_1 = 0.5$$

$$(1200) \frac{\pi}{4} (.15)^2 = 0.4 \pi (r_2^2 - .5^2)$$

$$r_2 = 4.14 \text{ m, minimum}$$

$\therefore$ set $r_2 = 4.5\text{m}$ to allow for extra area

A.4.1.1 Flow of Lithium on First Wall

5 cm Lithium Layer on First Wall

Analysis

Area at midplane:

$$A = \pi(R_2^2 - R_1^2)$$

$$R_2 = 5.0\text{m}, R_1 = 4.95\text{m}$$

$$A = \pi(5^2 - 4.95^2) \approx 1.56\text{m}^2$$

$$h = .973\text{m}$$

Assume Free Fall:

From A.3.5.1, Vertical Jet

$$V_m = 9.88 \text{ m/sec}, V_o = 4.37 \text{ m/sec}$$

Flow Rate

$$Q = AV = (1.56)(9.88) = \underline{15.4 \text{ m}^3/\text{sec}}$$

Area at nozzle plate

$$A_n = A_m \frac{V_m}{V_o} = 1.56 \left(\frac{9.88}{4.37} \right) = \underline{3.53 \text{ m}^2}$$

$$A = \pi(R_2^2 - R_1^2) = 3.53, R_2 = 5.0\text{m}$$

$$\therefore \text{ Inner radius of annular fall} = \underline{4.89\text{m}}$$

A.4.1.2 Orifice Plate Analysis

Assume following dimensions:

$$R_1 = 1.5\text{m}, R_2 = 5\text{m}$$

$$Q = \text{flow rate} = 129 \text{ m}^3/\text{sec}$$

$$\text{Plate area} = \pi(R_2^2 - R_1^2) = \pi(5^2 - 1.5^2) = 71.5\text{m}^2$$

$$Q = CA_o \sqrt{2gh} \quad \dots(1)$$

$$A_o = \text{Area of all orifices}$$

$$h = \text{head, m}$$

$$C = \text{Orifice coefficient}$$

Assume packing fraction = 0.5

Assume 60° triangular pitch

$$A_o = 0.5 (71.5) = 35.8\text{m}^2$$

$$\text{Orifice diameter} = d = 0.2\text{m}$$

$$a = \text{orifice area} = \pi/4 d^2 = \pi/4 (.2)^2 = 0.0314\text{m}^2$$

For a 60° triangular pitch

$$P.F. = 0.907 \left(\frac{d}{p}\right)^2 \quad \dots(2)$$

Solving (2) for (d/p) :

$$d/p = (.5/.907)^{1/2} = 0.742$$

and pitch:

$$p = \frac{d}{.742} = \frac{.2}{0.742} = 0.269\text{m}$$

Number of Orifices

$$N_o = \frac{A_o}{a} = \frac{35.8}{0.0314} = 1,140$$

Head Requirement

$$C = .71 \text{ for } d/p = 0.74 \text{ (Crane Catalog, Page A-20)}$$

Substituting in (1):

$$129 = (.71)(35.8) \sqrt{2 \times 9.81h}$$

$$h = \underline{1.15\text{m}}$$

4727-9

Figure A.4.3.1.1. ASME Nozzle

A.5.1 FIRST STRUCTURAL WALL INTERACTION

The problem is to determine the response of the containment vessel wall resulting from the impact of the lithium.

One of the difficulties is that the condition of the lithium, at the instant of impact, is not known. It is unknown whether the lithium may be considered to be a continuum with uniform velocity or in some more disorganized form, such as droplets.

A.5.1.1 Full Continuum Analysis

If we consider the continuum model, then the simplest solution is to assume that the lithium strikes the wall with a uniform velocity and that the wall is initially rigid. This results in the formation of a step pressure pulse on the wall having a magnitude of PCV where

$$\begin{aligned} \rho &= \text{density of the lithium} \\ &= 465 \text{ kg/m}^3 \end{aligned}$$

$$C = \text{speed of sound in lithium (4328 m/s)}$$

$$V = \text{velocity with which the lithium strikes the wall.}$$

The response of the wall to this step pulse is dependent on the length of time the pulse is active. The maximum response will occur when the pulse duration is equal to $\tau/2$ where

$$\tau = \text{the period of the containment vessel.}$$

Since the loading is axisymmetric, we are concerned with only the extensional modes of the structure and, therefore, the period may be calculated as

$$\tau = 2 \sqrt{\frac{(1-\nu^2) \rho_s R^2}{E}} \quad \dots(1)$$

$$\rho_s = \text{density of steel} = 7.9 \times 10^3 \text{ (kg/m}^3\text{)}$$

$$E = \text{Young's modulus of steel} = 175 \text{ gpa}$$

$$R = \text{radius of the vessel (m)}$$

$$\nu = \text{Poisson ratio}$$

For the case in question, the pulse duration will be much smaller than $\tau/2$, being limited to the time required for a compressive shock wave to twice traverse the thickness of the lithium. Thus

$$t_1 = \frac{2l}{c}$$

where: l = thickness of lithium at the wall

When the pulse width is less than $\tau/2$, the vessel's maximum response will occur after the pulse is past. This maximum response may be calculated from:

$$\sigma = 2\sigma_0 \sin\left(\pi \frac{t_1}{\tau}\right) \text{ for } 0 \leq t_1/\tau \leq 1/2 \quad \dots(2)$$

σ = Stress (MPa)

$$\sigma_0 = (\rho CV) \frac{R}{h}$$

The time at which this maximum stress occurs is t_m and t_m is found to be:

$$t_m/\tau = (1 + 2 \frac{t_1}{\tau})/4$$

Although there is no clear agreement at LLL as to the impact velocity of the lithium, it appears from the work thus far done that $V = 50$ m/s is a reasonable figure. Based on this and a 5-meter radius vessel, we obtain:

$$\sigma = \frac{2(100.63)5}{h} \sin\left(\pi \frac{t_1}{\tau}\right)$$

$$t_1 = \frac{2 \times .3}{4328} = 9,138 \text{ ms}$$

$$\tau = 6.4 \text{ ms}$$

$$\text{and } \sigma = \frac{68.6}{h} \text{ MPa}$$

For a wall thickness of 250 mm, the maximum stress is seen to be:

$$\sigma_{\max} = 274 \text{ MPa}$$

The time at which this stress occurs is 1.67 ms. This is well above the maximum allowable stress of about 70 MPa (based on fatigue considerations).

The results obtained in the above analysis may be thought of as an upper bound. This is so because the pulse was permitted to act to its fullest extent before the vessel wall was allowed to move.

In actuality, this does not happen, because the wall will begin to move at the instant that the lithium strikes it. As the wall moves, the pressure is somewhat relieved, thus ultimately producing a smaller stress.

To calculate this effect requires a coupled model of the vessel and the lithium. This was done, in a simplified way, by utilizing a lumped parameter model and solving the resulting coupled differential equation by means of the normal modes technique. The response equation thus obtained was implemented into a computer program which then calculated the resultant maximum hoop stress. The results of the computer runs are presented in the curves of Figure 5.1.2.

Examination of these curves indicate that this approach yields a reduction in stress from the previous upper bound calculation by a factor of about 2.5.

One of the difficulties with this model is that, being a lumped parameter system, it cannot build up the shock pulse as rapidly as we would expect it to.

This second approach may be then considered to be a lower bound on the stress.

This lower bound solution could be improved by introducing a continuum model for the lithium side while maintaining the lumped parameter description of the vessel.

A.5.1.2 Droplet Analysis

Another approach is to assume that the lithium strikes the wall as a sequence of droplets. The assumption is that the momentum of each of the droplets is transferred to the wall of the vessel instantaneously upon impact, thus imparting a velocity to the vessel.

The hoop stress response may be obtained from

$$\sigma = \frac{E \tau}{2\pi \rho_s R} \left[\sum_{i=1}^N G_i \sin 2\pi \left(\frac{(t - t_i)}{\tau} \right) \right] \quad \dots(3)$$

where:

G_i = the momentum/unit area of each droplet

t_i = the arrival time of each droplet

N = total number of droplets

A velocity distribution suggested by LLL is shown in Figure A5.1.2.1. A computer program was written to solve Equation 3 for several values of vessel radius and wall thickness based on the distribution of Figure A5.1.2.1. It was assumed that each droplet was 2 mm thick. The results are shown in Figure A5.1.2.2.

Figure A.5.1.2.1. Fall Velocity Distribution

4727-1

4727-10

Figure A.5.1.2.2. Stress vs Wall Thickness and Chamber Radius

A.5.1.3 Wall Response to Pressure Pulse

The radial displacement of a cylindrical wall is given by

$$\ddot{U} + \frac{E}{\rho R^2} U = \frac{P(t)}{\rho \delta} \quad (1)$$

(See Table A.5.1.3.1 for Nomenclature)

The pressure pulse is given by

$$P(t) = [H(t) - H(t - \tau)] P_0 \quad (2)$$

The pressure pulse magnitude is given by

$$P_0 = \rho_L C V \quad (3)$$

where V = annulus velocity at the wall and is a function of the initial cavity pressure, P_c .

$$V = 0.0868 P_c^{1/2} \quad (4)$$

The wall stress is given by

$$\sigma = \frac{E}{R} U \quad (5)$$

The solution to Equation 1 is obtained by using Laplace transforms and taking the inverse resulting in

$$U = \frac{B}{\omega^2} \left\{ (1 - \cos \omega t) - H(t - \tau) \cdot [1 - \cos \omega(t - \tau)] \right\} \quad (6)$$

where

$$B = \frac{P_0}{\rho \delta}, \quad \omega = \sqrt{\frac{E}{\rho_s R^2}} \quad (7)$$

The time to reach maximum displacement is obtained by setting dU/dt from (6) equal to zero: For 5 m radius, this occurred at $t = 1.79 \times 10^{-3}$ sec and the maximum displacement is given by

$$U_{\max} = 2.28 \times 10^{-11} \frac{P_0}{\delta} \quad (8)$$

where $P_0 = N/m^2$, δ = wall thickness, meters.

The maximum stress is given by

$$\sigma_{\max} = 0.734 \frac{P_0}{\delta} \quad (9)$$

Table 5.1.3.1 shows the results for three cavity pressures and two wall thicknesses.

TABLE A.5.1.3.1

NOMENCLATURE

Pressure: $1 \text{ MPa} = 10^6 \text{ N/m}^2 = 10 \text{ atm} = 147 \text{ psia}$

U = wall radial displacement, m

$\ddot{U}$ = wall acceleration, d^2U/dt^2 , m/sec^2

E = wall modulus of elasticity, $1.61 \times 10^{11} \text{ N/m}^2$

ρ_s = wall density, $7.67 \times 10^3 \text{ kg/m}^3$

R = chamber wall radius, 5 m

$\mathcal{L}f(t) = \int_{-\infty}^{+\infty} e^{-st} f(t) dt$, Laplace Transform

δ = wall thickness, m

$P(t)$ = time variation of pressure, N/m^2

τ = duration of liquid pulse, sec

σ = wall stress = $\frac{E}{R} U$, N/m^2 , MPa

P_c = chamber cavity pressure, atm, N/m^2 , MPa

P_0 = liquid pulse pressure, atm, N/m^2 , MPa

ΔR = annulus thickness, m

c = speed of sound in lithium, 4,328 m/sec

ρ_L = lithium density, 481 kg/m^3

$$1 \text{ Newton} = 1 \text{ kg} \cdot \text{m}/\text{sec}^2$$

t = time, sec

$$\omega = \text{frequency} - \text{sec}^{-1}$$

$H(t)$, $H(t - \tau)$ = unit step

s = Laplace transform variable

A.5.1.3.2 Moving Boundary Analysis

A means of reducing the magnitude of a pressure pulse due to lithium fall impact with the wall is obtained by regarding the wall as an instantaneous moving boundary as shown in Figure A.5.1.3.2.1.

A second order differential equation describes the radial wall motion while a second order partial differential equation (wave equation) describes the fluid motion. The pressure pulse is a function of the spatial derivative of the fluid wall interface.

The simultaneous solution of the three equations will provide a history of wall displacement, U , and stress generation, $\sigma = \frac{E}{R} U_{\max}$.

MOVING BOUNDARY SCHEMATIC

BOUNDARY CONDITIONS:

$$x=0, \dot{z}=u$$

INITIAL CONDITIONS:

$$t=0, z=0, u=0, \dot{u}=g \frac{\partial z}{\partial t} = -V$$

WALL

$$\ddot{u} + \frac{E}{R^2 \rho_w} u = \frac{P}{h \rho_w}$$

LIQUID

$$\frac{\partial^2 z}{\partial t^2} = c^2 \frac{\partial^2 z}{\partial x^2}$$

$$P = \rho_l c^2 \frac{\partial z}{\partial x}(0, t)$$

FIGURE A.5.1.3.2.1

A.5.4.1 Thermal Stress Analysis

First Wall

Slab Geometry

$$\sigma = \frac{\alpha E}{1-\nu} (\Delta T)_{\max} \quad (1)$$

Assume $T_{\max} = 550^{\circ}\text{C}$

$$E = 174 \text{ GPa} \times \frac{10^4 \text{ atm}}{\text{GPa}} \times \frac{14.7 \text{ lb/in}^2}{\text{atm}} = 2.56 \times 10^7 \text{ lb/in}^2$$

$$\alpha = \text{therm coeff. of exp.} = 14.0 \times 10^{-6}/^{\circ}\text{C}$$

$$\nu = \text{Poisson's ratio} = 0.293$$

$$\sigma = 10,000 \text{ lb/in}^2, (2\text{-}1/4 \text{ Cr} - 1 \text{ Mo})$$

Subst. in (1)

$$10,000 = \frac{(14.0 \times 10^{-6})(2.56 \times 10^7)}{1 - 0.293} (\Delta T)_{\max}$$

$$\Delta T_{\max} = 19.7^{\circ}\text{C}$$

Slab with Two-Sided Cooling

$$\Delta T_{\max} = \frac{QL^2}{2k} = T_0 - T \quad (2)$$

a) Assume:

$$\bar{Q} = 2.38 \times 10^{-6} \text{ Mw/cm}^3 = \text{average first wall heating}$$

$$k = 0.33 \times 10^{-6} \text{ Mw/cm} \cdot ^\circ\text{C}$$

$$\Delta T = 19.7^\circ\text{C}$$

Subst. in (2)

$$19.7 = \frac{2.38 \times 10^{-6} L^2}{2(0.33 \times 10^{-6})}; L = 2.33 \text{ cm}; 2L = 4.66 \text{ cm}$$

b) Assume: Midplane: $Q_{\max} = 2.18 \bar{Q} = 5.19 \times 10^{-6} \text{ Mw/cm}^3$

$$19.7 = \frac{5.19 \times 10^{-6} L^2}{2(0.33 \times 10^{-6})}$$

$$L = 1.58 \text{ cm}; 2L = 3.16 \text{ cm}$$

Repeat

$$\text{Assume: } \Delta T_s = \frac{\Delta T_{\max}}{0.7}$$

then

$$\Delta T_s = \frac{19.7}{0.7} = 28.1^\circ\text{C}$$

$$\text{a) } 28.1 = \frac{2.38 \times 10^{-6} L^2}{2(0.33 \times 10^{-6})}$$

$$L^2 = 7.80$$

$$L = 2.79$$

$$2L = \underline{5.59} \text{ cm}$$

$$b) \quad 28.1 = \frac{5.19 \times 10^{-6} L^2}{2(.33 \times 10^{-6})}$$

$$L^2 = 3.57$$

$$L = 1.89$$

$$2L = 3.78 \text{ cm}$$

714-F.60/jmh

A.5.5 Vibration Analysis

1. Injector Plate - Natural Frequency

Formulas for Stress and Strain,
Rork, Page 272, 4th ed

Edge Fixed:

$$f(\text{cycles/sec}) = 9.66 \left(\frac{Et^3}{wr^4} \right)^{1/2} \quad (1)$$

t = thickness

w = weight/area

r = radius

E = Young's modulus

$$t = .2\text{ m} = 7.88\text{ in.}$$

$$r = 5\text{ m} = 137\text{ in.}$$

$$w = \frac{W}{A} = \frac{V\rho}{A} = \frac{(\pi r^2 t)\rho}{\pi r^2} = \rho t$$

$$\rho = 7.7 \times 62.4 = 480.5\text{ lb/ft}^3 \times \frac{1\text{ ft}^3}{1728\text{ in}^3} = 0.278\text{ lb/in}^3$$

$$w = \rho t = \left(0.278 \frac{\text{lb}}{\text{in}^3} \right) (7.88\text{ in}) = 2.19\text{ lb/in}^2$$

$$E = 2.56 \times 10^7\text{ lb/in}^2$$

Subst. in Equation 1:

$$f = 9.66 \left(\frac{2.56 \times 10^7 \frac{\text{lb}}{\text{in}^2} \times (7.88 \text{ in})^3}{2.19 \frac{\text{lb}}{\text{in}^2} \times (137 \text{ in})^4} \times 386.4 \frac{\text{in}}{\text{sec}^2} \right)^{1/2}$$

$$= 38.9 \text{ cycles/sec}$$

Cylinder

For a long cylinder, assume breathing mode of a thin ring at midplane.

From "Shock and Vibration handbook", Harris and Crede, Pages 7-35.

R = cylinder radius

$$\omega = \sqrt{\frac{Eg}{\gamma R^2}}, \text{ rad/sec}$$

$$E = \text{Young's modulus} = 2.56 \times 10^7 \text{ lb/in}^2$$

$$g_c = 386.4 \text{ in/sec}^2$$

$$\gamma = 0.278 \text{ lb/in}^3$$

$$R = 5 \text{ m} = 197 \text{ in.}$$

Subst. in above equation for frequency

$$\omega = \sqrt{\frac{2.56 \times 10^7 \frac{\text{lb}}{\text{in}^2} \left(386.4 \frac{\text{in}}{\text{sec}^2} \right)}{\left(0.278 \frac{\text{lb}}{\text{in}^3} \right) (197 \text{ in})^2}}$$

$$= 957.5 \text{ rad/sec} = 152.3 \text{ cycles/sec}$$

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PART B
MATERIALS CONSIDERATIONS

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1.0 INTRODUCTION

The purpose of the materials effort was (1) to make preliminary recommendations of construction materials for the first wall and vessel of a laser fusion system employing a protective lithium fall and (2) to review the expected performance of those materials based on estimates of the operating environment. Ferritic steels are the best candidates for a first wall and vessel (as will be described below), but information on their behavior is limited. Hence, it is sometimes necessary to review data on other steels to make qualitative judgments about the expected behavior of ferritic steels.

Four major aspects of materials behavior were reviewed: (1) radiation effects, (2) fatigue in the absence of radiation, (3) corrosion in lithium, and (4) erosion. They are not intended to be conclusive, but to serve as an introduction to the application of ferritic steels appropriate to the current state of the HYLIFE design. Several important aspects remain to be explored, including the effects of radiation and corrosion on fatigue and limitations imposed by current engineering practice of ferritic steels. Although the evolution of the HYLIFE design has reduced the concern over erosion by impacting lithium, the review serves as a warning of the potential consequences.

2.0 SELECTION OF FERRITIC STEELS

The choice of a structural material is based on the criteria of (1) mechanical strength; (2) compatibility with lithium; (3) resistance to radiation damage; (4) cost; and (5) limited use of scarce or imported elements. The present reference operating temperature of the first wall is 500°C. The alloy families that could possibly be used for the first wall are ferritic steels, austenitic stainless steels, nickel-base alloys, titanium alloys, and refractory alloys based on molybdenum and niobium.

Table 1 gives a qualitative assessment of these alloy families relative to the criteria stated above and shows that ferritic steels are attractive candidates for a first wall material. Therefore, this family of alloys will be explored for the purpose of identifying one or two prime candidates.

TABLE 1
QUALITATIVE ASSESSMENTS OF ALLOYS*

Alloy Family	Mechanical Strength	Lithium Compatibility	Resistance to Radiation Damage	Cost
Ferritic Steels	S	S	Probably S	L
Austenitic Stainless Steel	S	Probably I	Probably I	M**
High-Nickel Alloys	S	P	Probably S	M**
Titanium Alloys	S	S	Probably S	H
Refractory Alloys	S	S	Probably I	H

*S = Satisfactory, I = Inadequate, P = Poor, L = Low, M = Medium, H = High
 **High fraction of imported elements, Cr and Ni, in alloys

2.1 DESCRIPTION OF FERRITIC STEELS

The ferritic steels under consideration are those with chromium contents from 2% to 12%. Within this range are those steels with the best combination of properties. Table 2 lists these and their nominal compositions in weight percent.

TABLE 2
COMPOSITION OF FERRITIC STEELS

Steel	Fe	Cr	Composition (wt %)					Si	Other
			Mo	Ni	C	Mn			
2-1/4Cr - 1Mo	Bal	2.25	1.0	-	.15	.45	.50		
2-1/4Cr - 1Mo-Nb	Bal	2.25	1.0	-	.09	.50	.35		1.0 Nb
2-1/4Cr - 1Mo-Ni-Nb	Bal	2.25	1.0	.65	.06	.75	.30		0.75 Nb
5Cr - 1/2Mo	Bal	5.0	0.5	.23	.10	.50	.30		0.1 Co
9Cr - 1Mo	Bal	9.0	1.0	-	.15	.45	1.0		
9Cr - 2Mo-V-Nb	Bal	9.0	2.0	-	.10	1.0	.30		0.5 Nb 0.35 V
12Cr - 1Mo-V-W	Bal	12.0	1.0	.50	.20	.55	.30		0.3 V 0.5 W

The most common steel is 2-1/4 Cr - 1 Mo which is used extensively in this country for heat exchangers and steam generators. The version of this steel stabilized with Nb is used in Europe and Japan in both fossil and nuclear systems. The 5 Cr - 1/2 Mo and 9 Cr - 1 Mo steels see service in the chemical process and petroleum industries because of their corrosion resistance. The 9 Cr - 2 Mo-V-Nb and 12 Cr - 1 Mo-V-W steels possess high strength and good corrosion resistance at elevated temperature. They are relatively new and are used in Europe for steam generators.

2.2 COMPARISON OF STRENGTH

Table 3 gives some allowable operating stresses for these steels based on ASME codes or calculated on the basis of available creep-rupture data. Type 316 stainless steel is shown for comparative purposes. The 5 Cr - 1/2 Mo is the weakest, and the 9 Cr - 1 Mo steel offers no significant strength advantage over the 2-1/4 Cr - 1 Mo steel. They are also both more expensive than 2-1/4 Cr - 1 Mo. The 9 Cr - 2 Mo-V-Nb and 12 Cr - 1 Mo-V-W are the strongest of the lot, surpassing even Type 316 stainless steel.

TABLE 3
ALLOWABLE STRESS VALUES FOR 100,000 HOURS AT 538°C (1000°F)

Alloy	Stress	
	MPa	ksi
2-1/4 Cr - 1 Mo	43	6.3
2-1/4 Cr - 1 Mo-Nb*	46	6.6
5 Cr - 1/2 Mo	39	5.6
9 Cr - 1 Mo	59	8.5
9 Cr - 2 Mo-V-Nb	121	17
12 Cr - 1 Mo-V-W	124	18.0
316	106	15.4

*Similar stress values are expected for the 2-1/4 Cr - 1 Mo-Ni-Nb steel.

3.0 RADIATION EFFECTS IN FERRITIC STEELS

The major potential effects of radiation on the first wall are dimensional instability due to swelling and high-temperature embrittlement due to the accumulation of helium. Some data on the swelling behavior of three steels, 2-1/4 Cr - 1 Mo, 9 Cr - 2 Mo-V-Nb and 12 Cr - 1 Mo-V-W are extant. There are no available data on the effect of radiation on the ductility of these alloys as yet. We may infer some trends in this regard based on the behavior of other alloys.

3.1 SWELLING

Ni-ion irradiations have been performed on 2-1/4 Cr - 1 Mo at 625°C to produce a damage of 140 dpa.¹ Swelling, as measured by electron microscopy was 0.1%. Ni-ion irradiations have also been performed on 9 Cr - 2 Mo-V-Nb and 12 Cr - 1 Mo-V-W (commercially known as EM12 and HT9) over the temperature range 450°C to 650°C producing damages up to 260 dpa.² The peak swelling temperatures were determined to be 550°C for EM12 and 500°C for HT9. The swelling values obtained after 260 dpa at peak swelling temperatures were 1.5% for EM12 and 3.7% for HT9.

However, neutron irradiation temperatures generally correlate to an ion irradiation temperature about 100°C higher. Therefore, the expectation is that little swelling will occur in either of these alloys under neutron irradiation at 500°C because little swelling occurs above 600°C during ion irradiation. The situation is essentially the same for 2-1/4 Cr - 1 Mo, although the damage is not as high.

Considering a first wall protected by 40 cm of lithium, a loading of 3 MW/m² will produce about 9 dpa/yr. After 30 years of operation at a 70% plant factor, the accumulated dpa will be 190. The data above indicate that this will not produce any swelling at 500°C.

3.2 HELIUM EMBRITTLEMENT

Atomics International has studied the effect of helium on the tensile properties of alloys by injecting helium into miniature tensile specimens by alpha-particle irradiations. Results on Type 405 stainless steel, a ferritic Fe-13 Cr alloy, show that 40 appm helium does not have an effect on total elongation at 500°C.³ The value of total elongation with or without helium lies between 40% and 50%. This value is maintained at 750°C in the absence of helium but drops to about 20% with 40 appm helium.

By comparison, Type 316 stainless steel with the same helium content loses ductility more rapidly with increasing temperature until at 750°C the value of total elongation is down to about 10%.⁴ Type 316 stainless steel irradiation at ORNL in the High Flux Isotope Reactor and tensile tested at 550°C retained a total and uniform elongation of 0.7% while containing 3,160 appm helium.⁵ If we can extrapolate the superior ductility retention of a ferritic steel to a high helium regime, we can expect EM12 of HT9 to retain several percent elongation at 500°C with 1,900 appm helium. This is equivalent to about 30 years of first wall operation as described above. Current design minimums for uniform elongation in the LMFBR program range from 0.2% to 0.5%. Ferritic alloys thus appear able to perform satisfactorily although experimental verification is needed.

4.0 FATIGUE OF 2-1/4 Cr - 1 Mo STEEL

One of the leading candidate steels for the first wall and vessel is 2-1/4 Cr - 1 Mo based upon its wide use. It is useful to examine the fatigue behavior of this alloy for tentative design purposes.

An extensive program of fatigue testing and data analysis is in progress as part of the LMFBR steam generator program.⁶⁻⁸ Fully reversible continuous cycle fatigue tests have been performed in the temperature range of 427°C to 593°C for up to 10^8 cycles. The test specimens were hourglass in shape and subjected to push-pull forces. Figure 1 shows the fatigue curves for specimens either continuously cooled from 900°C or cooled with a 2-hour isothermal interruption at 700°C. The fatigue behavior is the same for both treatments.

Figure 2 shows a series of design fatigue curves constructed according to ASME methods.³ The strain range refers to the absolute value of the strain in a cycle; one-half of the strain is tensile and one-half compressive. These curves are applicable for an atmospheric environment at strain rates $\geq 4 \times 10^{-3}$ /s and frequencies between 1 and 20 Hz.

A strain range value of 10^{-3} at 538°C is associated with an initial tensile stress of 87.2 MPa (12,650 psi). At this temperature, the cyclic stresses necessary to produce a given strain range will not materially change until near the end of life. The yield strength of 2-1/4 Cr - 1 Mo at 538°C is 163 MPa (23,600 psi) so that a strain range of 10^{-3} is within the elastic range.

The implication of this information for first wall performance is critically dependent on whether or not the impact of lithium following an explosion produces shock loading. If shock loading does not occur, then it appears possible to design a structure capable of enduring cyclic loading for 10^9 cycles. If analysis indicates that shock loading will occur, then considerable uncertainty is introduced owing to the paucity of data on shock-loading fatigue.

Figure 1. Total Cyclic Strain Range vs Cycles to Failure for 2 1/4 Cr - 1 Mo Steel Tested at Several Temperatures

Figure 2. Proposed ASME Design Fatigue Curves for 2 1/4 Cr - 1 Mo Steel in the Annealed Condition.

Not considered in the fatigue life predictions are the effects of lithium (corrosion and erosion) and radiation. Some estimates can be made on the effect of radiation, but this may not be possible for lithium. Also, high-cycle fatigue life is significantly reduced by increments of plastic strain that may be randomly introduced during operation of a component, such as could be caused by emergency conditions, earthquakes, etc.

5.0 BEHAVIOR OF FERRITIC STEELS IN LIQUID LITHIUM

5.1 DATA FROM DYNAMIC SYSTEMS

There are only meager corrosion data of these steels in a liquid lithium environment typical of laser fusion power plant operating conditions. The limited test data on 2-1/4 Cr - 1 Mo-Nb steel were developed with a thermal convection loop at 600°C, which showed that the stabilized 2-1/4 Cr - 1 Mo ferritic steel is significantly better than 304L SS or 321 SS in clean lithium ($v = 3-4$ ft/min).⁹ The corrosion rates obtained are shown in Table 4. Oxygen and nitrogen levels were 46 and 48 ppm.

TABLE 4
CORROSION OF FERRITIC STEELS AT 600°C

Material	Corrosion Rate
2-1/4 Cr - 1 Mo-Nb steel	2.3 $\mu\text{m}/\text{yr}$ (0.09 mil/yr)
304L SS	14 $\mu\text{m}/\text{yr}$ (0.55 mil/yr)
321 SS	14 $\mu\text{m}/\text{yr}$ (0.55 mil/yr)

In addition, the extent of localized corrosion attack was also less for the 2-1/4 Cr - 1 Mo-Nb relative to that found for the austenitic stainless steels. It must be noted that the stabilized 2-1/4 Cr - 1 Mo

used in these tests had a rather low carbon concentration ($C = 0.05\%$) and a high Nb concentration ($Nb = 0.70\%$), which probably enhanced its corrosion resistance. An increasing carbon content in steels increases the corrosion rate and the grain boundary attack by liquid lithium.^{10,11,13,14,15,16} Nb stabilization also improves corrosion resistance of steels in liquid lithium.^{12,13,14,15,16}

Consequently, the low corrosion rate found for this Nb-stabilized 2-1/4 Cr - 1 Mo may not be generally representative of the standard unstabilized 2-1/4 Cr - 1 Mo steel. The corrosion rate of the standard unstabilized 2- 1/4 Cr - 1 Mo steel is expected to be higher because: (1) the C concentration is higher (maximum 0.15%), and (2) absence of Nb stabilization of C.

The importance of Nb stabilization is evident in Figure 3 which shows the stability of various carbides with temperature.¹⁴ The shaded area indicates the uncertainty associated with the computation of ΔF for Li_2C_2 . At the typical design temperature of a laser fusion reactor ($T \sim 500^\circ C$), NbC is the most stable carbide in the stabilized 2-1/4 - 1 Mo ferritic steel. Mo_2C and Fe_3C in the unstabilized 2-1/4 Cr - 1 Mo steel are unstable with respect to Li_2C_2 .¹⁴ These observations lead to the conjecture that unstabilized 2-1/4 Cr - 1 Mo would corrode at a higher rate than the stabilized 2-1/4 Cr - 1 Mo steel. However, testing is needed to develop the corrosion data for the 2-1/4 Cr - 1 Mo steel.

5.2 DATA FROM STATIC TESTS

Some static screening tests were performed on Cr-Mo ferritic steels in liquid lithium at $500^\circ C$ for 1 month.² As shown in Table 5, the results indicated: (1) high Cr concentration in the steels increased the corrosion rates in liquid lithium, (2) high Si concentration also increased the corrosion rate, and (3) the low weight gain of the 1/2 Cr - 1/2 Mo

Figure 3. Stability of Carbides with Temperature

steel is consistent with the observation that pure iron has good corrosion resistance against attack by liquid lithium. It must be noted that these rates may have been affected by the presence of dissimilar metals, since an austenitic stainless steel test container was used.

TABLE 5
CORROSION OF FERRITIC STEELS IN STATIC LITHIUM
AT 500°C FOR 1 MONTH
(Container Material: Austenitic Stainless)

Alloy	Av. Corrosion Rate mg/cm ² /month (mpy)		Metallographic Examination
1/2 Cr - 1/2 Mo	+0.10	(0.06)	Slight surface grain boundary broadening
5 Cr - 1-1/2 Si - 1/2 Mo	-1.07	(0.65)	No attack
7 Cr - 1/2 Mo	-0.77	(0.47)	No attack
9 Cr - 1 Mo	-0.44	(0.27)	No attack
12 Cr - Ni (410 SS)	-1.08	(0.67)	Intergranular attack (1 mil)
12 Cr - Al (405 SS)	-2.53	(1.66)	Slight pitting
18 Cr - Ni (430 SS)	-3.08	(1.92)	No attack
28 Cr - Ni (446 SS)	-2.69	(1.70)	Slight surface roughening

5.3 SUMMARY

Based on the limited data available, the behaviors of ferritic steels in liquid lithium can be summarized as follows:

- 1) Stabilized Cr - Mo ferritic steels are more resistant to liquid lithium corrosion than low C or stabilized austenitic stainless steels.
- 2) Fe₃C and Mo₂C in Cr-Mo steels (without stabilization) are thermodynamically unstable in liquid lithium at temperatures typical of laser fusion design temperatures.
- 3) Ferritic steels with low Cr and Mo concentrations (e.g., 2-1/4 Cr - Mo, 1/2 Cr - 1/2 Mo) and low in other elements (e.g., Si, Mn, etc.) are more resistant to lithium corrosion.

6.0 EROSION OF METALS BY IMPACTING LITHIUM

Analysis of early versions of the lithium fall system indicated that part of the lithium will impact the vessel wall during each explosion. Although the exact nature of the liquid, either as a continuum or as drops and the velocity with which it impacts the wall, cannot be ascertained from the analysis, it appeared that erosion of the first wall by repeated impacts of the liquid lithium presented a potential problem. A literature search was undertaken to review erosion theories that could be used to predict the severity of erosion in a laser-fusion vessel.

The type of erosion that most closely approximates the situation in the fusion vessel is rain erosion. Rain erosion has been extensively studied because of the severity of this phenomena on aircraft and missiles. However, until quite recently, most studies were done for materials selection and only compared the relative erosion rates of these materials. Also there was, and still is, no standardized rain erosion test. Some experiments used rocket-powered sleds traveling through a man-made rain field, others used a rotating arm with a sample on the end that impacted a liquid jet, and still others used vibratory methods. Impact velocities ranged from a several tens of m/sec to the supersonic range (1700 m/sec). Most of the theories were based on the mechanical and physical process of erosion and were from a dynamic or continuum mechanics' point of view.

More recently, theories have been advanced that attempt to correlate resistance to rain erosion to some strength parameter of the material such as hardness, tensile strength, fracture energy, Young's modulus, or combinations of these parameters.^(17,18,19,20,21) Due to considerable scatter in the data, a significant correlation with any of the parameters in the models is not possible. As a result, there is considerable disagreement as to the merit of any particular model.

Experimental and computer studies of the nature of the liquid-solid interaction have also been undertaken.^(22,23) Also a considerable number of studies have used high-speed photography to elucidate the nature of the liquid-solid interaction. Progress is being made on both the theoretical and the basic experimental fronts with respect to the fundamental understanding of the processes involved in erosion and the ability to predict the behavior of an alloy in an erosive environment.

For the present study, the model developed by Springer and Baxi⁽²¹⁾ is being used to predict the degree of erosion that might be expected in a laser-fusion vessel. This model predicts the number of impacts needed to initiate erosion, i.e., the incubation period, and the mass removal rate during the linear portion of erosion. It does not, however, predict the end of the linear portion of erosion and the steady-state mass removal rate. A schematic erosion curve is shown in Figure 4. The model of Springer and Baxi⁽²¹⁾ is as follows:

$$n_i = \left(\frac{4}{\pi d^2} \right) 3.7 \times 10^{-4} \left(\frac{S}{P} \right)^{5.7} \quad \text{and} \quad (1)$$

$$\alpha = \left(\frac{\pi P_s d^3}{4} \right) \frac{(0.023)}{(3.7 \times 10^{-4})^{0.7}} \left(\frac{P}{S} \right)^{3.99} \quad (2)$$

where d = drop diameter

n_i = impacts per unit area at end of incubation (See Figure 4)

α = mass loss per impact (See Figure 4)

P = water hammer pressure

$$= P_L C_L V / (1 + P_L C_L / P_S C_S) \quad (3)$$

$$S = 2\sigma_u (b-1)/(1-2\nu_s) \quad (4)$$

Figure 4. Schematic of Experimental Erosion Results and Model Solution.

$\rho_{L,S}$ = density of liquid and solid, respectively

$C_{L,S}$ = speed of sound in liquid and solid, respectively

V = impact velocity of drop

σ_u = ultimate tensile strength

ν_s = Poisson's ratio for the solid

$$b = b_2 / \log_{10}(\sigma_u / \sigma_1) \quad (5)$$

b_2 is defined by the expression 10^{b_2}
= number of cycles in a fatigue σ - N curve
corresponding to "knee" in the curve.

σ_1 = endurance stress level in the fatigue curve.

The constants 3.7×10^{-4} and 0.023 in Equations (1) and (2) were determined from experimental data on a number of different materials. The mass loss per unit area is given by

$$m = \alpha(n - n_i) \text{ for } n_i < n < n_f, \quad (6)$$

and

$$m = 0 \quad \text{for } 0 < n < n_i \quad (7)$$

Results of these calculations are given in Table 6 where the mass loss has been converted to depth of erosion. For velocities less than 50 m/sec, there is no predicted erosion for any drop size, as the incubation period is not exceeded. At higher velocities, however, the erosion depth either exceeds or is a large fraction of the proposed vessel wall thicknesses.

The configuration of the lithium fall in the HYLIFE Power Plant design has been significantly improved from previous versions so that erosion is no longer a primary concern. However, the potential severity is present and design care must be exercised in this regard.

TABLE 6
DEPTH OF MASS LOSS AS A FUNCTION
OF DROP DIAMETER AND VELOCITY AT 500°C

Drop Diameter (m)	$T = m/\rho_s (m)$						
	V = 25	V = 50	V = 75	V = 100 (m/sec)	V = 150	V = 200	V = 275
0.001	-	-	0.04	0.14	0.75	2.37	8.44
0.002	-	-	0.08	0.29	1.50	4.74	16.88
0.01	-	-	0.40	1.44	7.48	23.69	84.40
0.10	-	-	4.00	14.44	74.82	236.93	844.01
0.20	-	-	7.95	28.89	149.63	473.86	1688.02
0.30	-	-	11.93	43.33	224.45	710.79	2532.03

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