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RESEARCH ON THE "HYLIFE" LIQUID-FIRST-WALL CONCEPT
FOR FUTURE LASER-FUSION REACTORS

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NOMENCLATURE

A_e	=	Wave envelope amplitude
A_o	=	Amplitude of the nozzle excitation
B_2	=	Coefficient of the second-order term
b	=	Sheet jet thickness (2h)
C_r	=	Wave speed
f	=	Forcing frequency
h	=	Sheet jet half-thickness (b/2)
k	=	Wave number, $2\pi/\lambda$
LT	=	Linear theory (constant U_o)
LTX	=	Approximate linear theory with variable velocity, $U(x)$
NT	=	Nonlinear theory (constant U_o)
NTX	=	Approximate nonlinear theory with variable velocity, $U(x)$
p	=	Pressure
r_d	=	Ratio of ambient density to liquid density, ρ_a/ρ
t	=	Time
U	=	Vertical component of mean jet velocity
w	=	Sheet jet width
x	=	Vertical coordinate
β_o	=	Wave-envelope temporal oscillation rate in the stable regime
η	=	Wave surface amplitude
λ	=	Wave length
ρ	=	Density
σ	=	Surface tension coefficient
ω	=	Complex frequency

Subscripts

a	=	ambient (or aerodynamic)
c	=	critical
i	=	imaginary part
o	=	at the nozzle exit (initial value)

LIQUID JET EXPERIMENTS: RELEVANCE TO INERTIAL CONFINEMENT FUSION REACTORS

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Summary

Early proposals for protecting the structural walls of a laser fusion reactor from the soft x-rays and pellet debris included the possibility of using thin liquid films on the walls facing the fusion microexplosion [1,2]. These wetted-wall concepts seemed to offer a simple method for extending the lifetime of the first structural wall. However, if the liquid layer were produced as a thin falling liquid film, our experiments showed that large waves would quickly develop in the film, leaving the wall regions behind the wave troughs essentially unprotected [3]. In addition, these wetted-wall concepts offered no protection against the fusion neutrons. In order to try to find a reactor design which offered protection against neutron damage, studies were undertaken at LLNL (the Lawrence Livermore National Laboratory) of self-healing, renewable liquid-wall reactor concepts.

In conjunction with these studies, we have run a series of small-scale water jet experiments over the past several years at UCD (University of California, Davis campus) to simulate the behavior of liquid lithium (or lithium-lead) jets in these liquid-wall fusion reactor concepts. The experiments were designed to simulate the time period between microexplosions. Extrapolating the results of these small-scale experiments to the large-scale lithium jets, we have tentatively concluded that the lithium jets can be re-established after the microexplosion, and with careful design the jets should not breakup due to instabilities during the relatively quiescent period between microexplosions.

Annular Jets or "Waterfall"

The original liquid-wall laser fusion reactor concept proposed by LLNL consisted of a near-vertical, annular lithium "waterfall" with nominal dimensions of about 4 meters inner diameter and 0.6 meters thickness at the midplane [4]. Our small-scale annular water jet experiments confirmed a theoretical model of Hovingh's which predicted negligible closure of the hollow annular region in the 8 meter fall distance of this reactor design [5]. Furthermore, a linear stability analysis of this annular jet geometry was performed by Esser, Paul, and Abdel-Khalik [6]. They concluded that the instabilities due to turbulent fluctuations would not cause the annular jet to break up in the fall distance of the reactor.

Although the annular lithium "waterfall" behavior between microexplosions appeared to be acceptable, the response of the liquid to the microexplosion was shown by Glenn and Young [7] to produce unacceptably large stresses and short lifetimes in the vacuum chamber wall for the high fusion energy yields desired (700 to 2700 MJ). Consequently, the LLNL studies shifted to alternative liquid jet concepts referred to as the HYLIFE (High-Yield Lithium-Injection Fusion Energy) reactor concepts [8,9].

Cylindrical Jet Array

The original HYLIFE design consisted of an annular array of cylindrical jets as shown in Figure 1a. This configuration allowed the plasma and lithium vapor to flow through the array, thus reducing the momentum imparted to the liquid and increasing the predicted chamber lifetime to 30 years [8].

For the time period between microexplosions, the key question regards premature breakup of the jets due to the various external disturbances and vibrations of the vacuum vessel and nozzle plate induced by the microexplosion. Almost all the available jet breakup data are for breakup in 1 atm ambient air with no forced vibrations other than the very low levels of natural disturbances in the various laboratories. Any premature jet breakup due to the "ringing" of the HYLIFE structure would be undesirable, since it would allow neutrons to stream directly to the chamber wall during the fusion burn.

The breakup of cylindrical jets of 12.7 mm diameter issuing vertically downward from long cylindrical nozzles was investigated in our water jet apparatus (Figure 2) at both 1 atm ambient pressure and at a reduced pressure of about 0.2 atm [10]. The nozzles were vibrated transversely using an electromagnetic shaker at frequencies in the range of 20 to 320 Hz and amplitudes from about 0.2 mm to 5 mm. This produced maximum wave amplitudes of the jet as large as 100 mm in our fall distance of about 0.9 m. Jet velocities from 1.25 to 5.0 m/s were investigated.

The range of parameters for our experiments is shown on the nondimensional plot of Figure 3. The upper boundary is at a ratio of fall distance to water jet diameter, L/D_0 , of about 70. This was fixed by the maximum fall distance available in our apparatus. The range of Weber numbers available was fixed by the range of velocities we could obtain.

In all but three of the approximately one hundred photographs analyzed, the jets showed no signs of breakup. This implies breakup lengths in excess of about 70 diameters even with forced transverse vibration. This is in general agreement with the (smoothed) data of others shown by the solid curves on Figure 3, where breakup (L/D_0) 's in the range of 60 to 100 were measured with no forced vibration. We can conclude that even in the presence of large transverse vibrations, the breakup length of our turbulent cylindrical jets was not reduced over the values found without forced vibrations. These conclusions only hold for the relatively low vibration forcing frequencies and transverse accelerations employed in our experiments to simulate the laser fusion reactor vibrations. At higher frequencies and accelerations, the vibrations can induce a jet "bunching" phenomenon which can lead to earlier breakup [11].

The few runs where jet breakup was observed at lower (L/D_0) 's occurred at very large nozzle forcing amplitudes (~ 4 mm) and at the reduced pressure of

about 0.2 atm. In these runs, the breakup was probably induced by air bubbles which tended to come out of solution and grow rapidly at the reduced pressure. This is a potential problem area for any fusion reactor employing liquid jets (or liquid film flows) if there are any significant amounts of helium or other gases in the liquid.

The HYLIFE cylindrical jets are expected to have fall distances to diameter ratios which fall in the region shown on Figure 3. This region can be seen to be below all the breakup data except those of Miesse and Vitman (shown by the dashed curves) where special nozzles were employed to induce early breakup for fuel atomization studies. We can conclude that the HYLIFE jets are unlikely to experience breakup due to transverse vibrations in the fall lengths in the reactor provided that gas bubbles are unimportant.

The cylindrical jet breakup data shown by the solid curves of Figure 3 were all taken using nozzles (usually hypodermic needles) with large L/D_0 's. For ease of comparison with these data, all of our experiments were run using long cylindrical nozzles with large nozzle length-to-diameter ratios of about 50. For our runs where the Reynolds numbers, $Re = \rho u D_0 / \mu$, were greater than about 2300, the flow issuing from these long nozzles was fully developed turbulent flow. McCarthy and Malloy [12] have shown that these turbulent jets tend to breakup sooner than laminar jets at the same Reynolds numbers. In the flow from a well-rounded short nozzle or orifice, the turbulence has no time to develop and the flow will be nearly laminar, resulting in longer breakup lengths. This is supported by the very long lengths to breakup measured by Chen and Davis [13] for high velocity, high Reynolds number flows from orifices (shown by the dotted curves of Figure 3). This suggests that the nozzle plate in the HYLIFE reactor should be designed with small L/D_0 nozzles to minimize the possibility of jet breakup.

A few experiments were run to see the effect of a collision between two adjacent cylindrical jets of different initial velocities due to transverse vibration [10]. As the wave amplitudes of the jets increased with fall distance, they would eventually collide as they grew more and more out of phase with one another. However, no jet breakup was observed even for jet velocity differences of up to a factor of 3. Consequently, velocity differences in the jet array such as might occur in HYLIFE due to a nonuniform liquid head above the nozzle plate should not cause serious jet breakup problems.

Rectangular Jet Breakup

An improved HYLIFE jet geometry employing an annular array of rectangular jets shown in Figures 1b and 4 was proposed in 1979. These rectangular or "sheet" jets provide more uniform shielding of the first structural wall and result in other design simplifications as well [9].

In order to investigate the breakup of these sheet jets, we fabricated a series of nozzles from round plexiglas tubing which tapered smoothly to a rectangular slit at the exit [14,15]. When these nozzles were vibrated transversely at an amplitude on the order of 1 mm, they produced relatively large amplitude waves on the sheet water jets. These waves can be seen in the edge-view photographs shown in Figure 5, where the wave amplitude is nearly 60 mm at the bottom of the left hand photograph. For these runs, Nozzle B produced a sheet jet with an initial half-thickness, $h_0 = 3.94$ mm and an initial width, $W_0 = 75$ mm.

These relatively thick sheet jets from Nozzle B did not break up in the available fall distance of 0.6 m. According to the linear theory [15,16] the

sheet jet on the left is in the unstable regime for the low forcing frequency of 20 Hz at 1 atm ambient pressure. It should ultimately break up at large fall distances, and it appears to be on the verge of doing so at the bottom of the photo.

For the higher forcing frequency of 50 Hz, the linear theory predicts that the jet will accelerate into the stable regime after a short fall distance of about 14.6 cm for 1 atm ambient pressure. The main part of the sheet jet then tends to flatten as can be seen in the right hand photograph. This is due to the fact that stabilizing surface tension forces dominate the destabilizing aerodynamic forces in the stable regime. However, this leaves large fluid "globs" at the edges essentially free-falling, since surface tension forces are insufficient to pull this fluid back toward the centerline. As the amplitude of the forced vibration was increased, these fluid globs become even larger. However, they did not appear to detach from the main sheet jet in the 0.60 fall distance of our apparatus.

The key question we wished to answer was what would happen in the HYLIFE reactor at low ambient pressures where the linear theory predicts that the sheet jets are always stable. To answer this question, we ran a series of tests at three ambient pressures using Nozzle A which produced a thinner sheet jet ($h_0 = 0.79$ mm, $W_0 = 78$ mm). Since the thinner sheet jet was demonstrated to break up in the 0.60 m fall length of our apparatus at 1 atm ambient pressure, we could examine the effect of ambient pressure on the breakup phenomenon.

The wave envelope amplitude divided by the initial forcing amplitude, A_e/A_0 , is plotted for these runs versus the fall distance, x , in Figure 6. For 1 atm pressure the data points show that the wave envelope amplitude increased to about $85 A_0$ at a fall distance of about 45 cm and then appeared to saturate (i.e., to remain constant). A careful examination of the flash photograph on a light table revealed that the main sheet of the jet actually was breaking up starting at about 45 cm. The fluid lumps or fragments were then just free-falling downward, giving the appearance of a constant amplitude.

Both the classical linear theory and a nonlinear theory developed by Asare [15,17] predict the initial near-exponential growth of the wave envelope for this 1 atm run reasonably well as can be seen from Figure 6. In addition, the nonlinear theory tends to peak just before the sheet jet breaks up. The nonlinear curve then plunges toward zero wave amplitude, implying that the nonlinear surface tension forces completely overcome the destabilizing aerodynamic forces. When this occurs, it is our hypothesis that the actual sheet jet must not be able to make these rapid adjustments, and begins to break up.

When the ambient pressure was reduced to 0.68 atm, the wave envelope amplitudes were reduced somewhat as shown on Figure 6. However, the sheet jet still exhibited the same unstable behavior as at 1 atm, leading to breakup at about 50 cm fall distance. When the ambient pressure was reduced further to 0.17 atm (the minimum possible in our apparatus), the wave envelope showed a very slow near-exponential growth, in reasonable agreement with the predictions of both the linear and nonlinear theories.

These theories predict that when the pressure is reduced to zero the sheet jets will be stable to all disturbance frequencies. For two sets of HYLIFE conditions at low lithium vapor pressures of 0.1 and 1 torr (13.3 and 133 Pa), the predictions of the nonlinear theory are plotted on Figure 7. Even though these cases are in the stable regime, the wave envelope grows initially due to the transverse momentum given to the fluid particles as they leave

the vibrating nozzle plate (i.e., not due to any instability). After reaching a maximum, the wave envelope is predicted to decrease in amplitude and increase in wave length due to the acceleration of the sheet jet downward. For an initial nozzle plate transverse vibration amplitude of 0.1 mm (greater than actually expected), the sheet jets should have maximum amplitudes of only about 5 mm.

From these experiments and theoretical predictions, we can tentatively conclude that the sheet jets in the HYLIFE reactor are unlikely to break up due to transverse vibrations. However, it is still necessary to run additional experiments at low pressure with longer fall distances in order to verify the behavior beyond the point where the wave envelope amplitude first crosses the zero value. In addition, experiments with forced vibration in the vertical direction should be run, since the nozzle plate will also vibrate in this mode.

Rectangular Jet Edge Convergence

As a rectangular jet falls, it not only accelerates but surface tension forces tend to change the cross-section from a rectangular shape toward a round shape. For a sheet jet with a width much larger than the thickness, this can be modeled as an accumulation of fluid in the two edges of the sheet as the edge fluid is accelerated toward the center by surface tension forces; i.e., the two edges grow in radius and also tend to converge toward the center of the sheet. This tends to produce a dumbbell shaped cross-section as shown as Figure 8.

In the HYLIFE reactor, there is already a significant reduction of the jet cross-sectional area due to the acceleration of gravity. This has been taken into consideration in the design of the rectangular jet array so as to give about one meter of total lithium thickness at the midplane of the reactor [9]. This thickness is required to give sufficient neutron shielding of the first structural wall and vacuum chamber so as to permit a 30 year lifetime.

The key question we asked ourselves was how large must the rectangular sheet jets be in order that the edge convergence have a negligible effect in reducing the total lithium thickness at the midplane. To answer this question, Monson first ran series of small-scale sheet-jet edge-convergence experiments using three nozzles A1, A2, and A3 [10]. These produced sheet jets with an initial thickness of 1.6 mm and initial widths of 5, 10, and 15 mm, respectively. He then measured the distance, L_c , to the first convergence point, converted it to the time to convergence, t_{c1} , and plotted this time versus the initial sheet jet velocity as shown on Figure 9.

We then developed a simplified theory to attempt to predict the time to edge convergence. We identified three significant times as shown on Figure 8: the time when the round edges first touch (Section C-C), the time when the two edges have merged (shown as section D-D) which we defined as the edge convergence time, and the time when the centers of the two edges would be at the same point or "collocated" (section E-E) if the two round edges simply merged together. In actuality, as the two round edges make contact, the conservation of mass and momentum causes the liquid to squirt out in a plane perpendicular to the original sheet jet; this is known as the Weber effect.

The predictions of our theoretical model can be seen to nicely bracket the data on Figure 9. The scatter in data is a result of the difficulty in identifying the edge convergence point accurately on these small scale experiments.

Using this theoretical model, we calculated the convergence point, L_c , for a wide variety of rectangular jets with initial widths and thicknesses which might be used in HYLIFE. The predictions shown in Figure 10 indicate that the rectangular jets proposed for the improved HYLIFE design will not converge significantly due to surface tension forces in the 5 m fall distance to the midplane nor in the 10 m fall distance to the bottom of the reactor.

Conclusions

The small-scale water jet experiments which we have run at UCD were designed to simulate the behavior of a variety of lithium (or lithium-lead) jet geometries during the time period between microexplosions. These results provide guidelines for the preferred geometry of rectangular, annular and cylindrical jets and for the design of the nozzle plate. The experiments have not revealed any problems which would prevent the successful operation of the HYLIFE liquid-wall reactor concepts. However, some additional vacuum experiments with somewhat larger diameter jets and longer fall distances are required to confirm these conclusions. In addition, experiments with vertical as well as transverse forced vibrations are recommended.

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References

1. L. A. Booth, "Central Station Power Generation by Laser-Driven Fusion" Nucl. Eng. and Design, Vol. 24, 263, North-Holland Pub. Co. (1973).
2. J. Hovingh, J. A. Maniscalco, M. Peterson, R. W. Werner, "The Preliminary Design of a Suppressed Ablation Laser-Induced Fusion Reactor", Proc. 1st Topical Meeting on the Tech. of Controlled Nuclear Fusion, Vol. 1, 96, San Diego, CA (1974).
3. M. A. Hoffman and W. W. Potts, "Experimental Behavior of Falling Liquid Films at High Surface Tension Numbers", Ind. Eng. Chem. Fundamentals, Vol. 18, No. 1, 27 (1979).
4. W. R. Meier and J. A. Maniscalco, "Reactor Concepts for Laser Fusion" Rpt. UCL-79654, Lawrence Livermore Laboratory (July 1977).
5. M. A. Hoffman, R. K. Takahashi, and R. D. Monson, "Annular Liquid Jet Experiments" ASME J. Fluids Engrg., Vol. 102, 344-349 (September 1980).
6. P. D. Esser, D. D. Paul, and S. I. Abdel-Khalik, "Stability of the Lithium 'Waterfall' First Wall Protection Concept for Inertial Confinement Fusion Reactors", Nuclear Technology/Fusion, Vol. 1, p. 285-294 (April 1981).
7. L. A. Glenn and D. A. Young, "Dynamic Loading of the Structural Walls in a Lithium-Fall Fusion Reactor", Fusion Eng. and Design, Vol. 54, 1-16 (1979).

8. M. J. Monsler and B. O. Jarman (eds.) "Laser Program Annual Report - 1978", UCRL-50021-78, Vol. 3, Ch. 9, Lawrence Livermore National Laboratory (March 1979).
 9. L. W. Coleman and J. R. Strack (eds.), "Laser Program Annual Report - 1979", UCRL-50021-79, Vol. 3, Ch. 8, Lawrence Livermore National Laboratory (March 1980).
 10. R. D. Monson, "Experimental Studies of Round and Sheet Jets With and Without Forced Nozzle Vibrations" M.S. thesis, Dept. of Mech. Engr., Univ. of Calif., Davis (December 1980).
 11. P. D. McCormack, L. Crane, and S. Birch, "An Experimental and Theoretical Analysis of Cylindrical Liquid Jets Subjected to Vibration", Brit. J. Appl. Phys., Vol. 16, p. 395-408 (1965).
 12. M. J. McCarthy and M. A. Malloy, "Review of Stability of Liquid Jets and the Influence of Nozzle Design", Chem. Engr. J., Vol. 7, 1-20 (1964).
 13. T. F. Chen and J. R. Davis, "Disintegration of a Turbulent Water Jet", J. Hydraulics Division, A.S.C.E., Vol. 90, 197-206 (1964).
 14. R. Takahashi, "Experimental Investigation of the Stability of Liquid Sheet Jets", M.S. thesis, Dept. of Mech. Engr., Univ. of Calif., Davis (December 1978).
 15. H. R. Asare, "Theoretical and Experimental Investigation of Water Sheet Jets Under Forced Vibration", Ph.D. thesis, Dept. of Mech. Engr., Univ. of Calif., Davis (November 1980).
 16. H. R. Asare, R. K. Takahashi, and M. A. Hoffman, "Liquid Sheet Jet Experiments: Comparison with Linear Theory", J. Fluids Engineering (accepted for publication).
 17. H. R. Asare and M. A. Hoffman, "Liquid Sheet Jet Experiments": Comparison with a Nonlinear Theory", Final Rpt. No. 6, Dept. of Mech. Engr., Univ. of Calif., Davis (December 1980).
- Figure 1. Comparison of (a) the original and (b) the modified HYLIFE reaction chamber.
- Figure 2. Schematic of the water jet apparatus, vacuum tank and forced vibration instrumentation.
- Figure 3. Cylindrical jet breakup data.
- Figure 4. Cross-sectional and elevation views of the modified HYLIFE nozzle plate.
- Figure 5. Edge views of the sheet jets from Nozzle B ($h_0=3.94$ mm, $U_0=2.05$ m/s, $p_a=1$ atm) for two conditions:
Left photo - $f=20$ Hz ($< f_c$), $A_0=1.6$ mm
Right photo - $f=50$ Hz ($> f_c$), $A_0=0.8$ mm
- Figure 6. Typical water sheet-jet experimental results.
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Figure 2. Schematic of the water jet apparatus, vacuum tank and forced vibration instrumentation.

Figure 3. Cylindrical jet breakup data.

Figure 5 Edge views of the sheet jets from Nozzle B ($h_0=3.94$ mm, $U_0=2.05$ m/s, $p_a=1$ atm) for two conditions:
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Figure 4. Cross-sectional and elevation views of modified HYLIFE nozzle plate.

Figure 6. Typical water sheet-jet experimental results.

Figure 7. Predicted behavior of lithium sheet jets.

Figure 8. Sheet-jet edge-convergence model.

Figure 9. Experimental results for sheet-jet edge convergence.

Figure 10. Predicted edge convergence behavior for lithium sheet jets.

Appendix A

Summary of Sheet Jet Stability Theory Results

The temporal solution to the constant-velocity nonlinear theory (NL) in the unstable regime ($f < f_c \approx \rho_a U_0^3 / 2\pi\sigma$) is of the form [15]:

$$\begin{aligned} \eta(x,t) = & \left(\frac{\pi f A_0}{\omega_i} \right) (e^{\omega_i t} - e^{-\omega_i t}) \cos(\omega_r t - kx) \\ & + \left(\frac{\pi f A_0}{2 \omega_i} \right)^2 B_2 (e^{2\omega_i t} + e^{-2\omega_i t}) \cos 2(\omega_r t - kx) \end{aligned} \quad (A-1)$$

The corresponding wave envelope equation is thus:

$$\frac{A_e(t)}{A_0} = \left(\frac{\pi f}{\omega_i} \right) (e^{\omega_i t} - e^{-\omega_i t}) + \left(\frac{\pi f}{2 \omega_i} \right)^2 A_0 B_2 (e^{2\omega_i t} + e^{-2\omega_i t}) \quad (A-2)$$

The temporal solution for the stable regimes is:

$$\begin{aligned} \eta(x,t) = & \left(\frac{2\pi f A_0}{\beta_0} \right) \sin(\beta_0 t) \cos(\omega_r t - kx) \\ & + 2 \left(\frac{\pi f A_0}{2 \beta_0} \right)^2 B_2 [\cos(2\beta_0 t) \cos 2(\omega_r t - kx) \\ & - \sin(2\beta_0 t) \sin 2(\omega_r t - kx)] \end{aligned} \quad (A-3)$$

The corresponding wave envelope equation is:

$$\frac{A_e(t)}{A_0} = \frac{2\pi f}{\beta_0} \sin \beta_0 t + 2 \left(\frac{\pi f}{2 \beta_0} \right)^2 A_0 B_2 \cos 2\beta_0 t \quad (A-4)$$

These equations can be transformed to the spatial forms by making the following substitutions [15]:

(a)	Replace	ω_i	by	$k_i U_0$
(b)	"	ω_r	by	$\omega = 2\pi f$
(c)	"	k	by	k_r
(d)	"	t	by	x/U_0

Note that $\beta_0 = 2\pi U_0/\Lambda$ where Λ is the wave length of the spatial wave envelope oscillation.

The values of the nonlinear second-order coefficient, B_2 , have been obtained from the approximate solution of a nonlinear, second order differential equation. Typical numerical values for B_2 for some of the experimental conditions of interest are listed in Table A-1. These values are the best average values over the liquid jet fall lengths of interest since B_2 is actually a slowly varying function of x and t .

Table A-1

Nozzle	U_0 (m/s)	p_a (atm)	f (Hz)	A_0 (mm)	B_2 (m^{-2})
A	5.0	1.0	30	0.2	- 98.7
	"	"	50	0.2	- 144.6
	"	"	70	0.08	- 168.3
	"	"	70	0.1	- 168.3
	"	"	70	0.2	- 172.7
	"	"	70	0.3	- 172.7
	"	0.68	50	0.2	- 122.0
B	2.05	1.0	20	1.6	- 3.49
	"	"	50	0.6	+ 99.2
	"	"	"	0.8	+ 99.2
	"	"	"	1.0	+ 99.4
	"	"	"	1.4	+ 99.4

Appendix B

Experimental Apparatus and Techniques

Robert D. Monson

ABSTRACT

This appendix describes the experimental apparatus and techniques used in the cylindrical and sheet jet experiments. The experimental apparatus is divided into three categories; water supply system, vacuum system and electronics system. Experimental techniques include equipment calibration and measurement methods.

Much credit and many thanks must go to Ron Takahashi for designing and building much of the equipment used in these experiments. The reader is referred to his thesis for design and construction details [14].

This appendix consists of three sections. Section 1 describes the cylindrical jet equipment and section 2 describes the sheet jet equipment. Equipment calibration and measurement methods are described in section 3.

1. Cylindrical Jet Equipment

The cylindrical jet equipment was the result of modifications to Takahashi's sheet jet equipment. The modifications (Figures B-1,2) included the installation of venturies, air traps, manometers, secondary valves, a feedthrough in the top lid, a nozzle holder and nozzles. The entire vacuum tank was inclosed in .5" plywood with a large Lexan (polycarbonate) window (to photograph through) for protection from an implosion.

The cylindrical jet equipment may be broken down into three subsystems. These are the water supply system, the vacuum system and the electronics system. A schematic of the cylindrical jet equipment is shown in Figure B-1 and Figures B-3 and B-4 are photos of the equipment.

1.1. Description of Water Supply System

Industrial water flowed into the system in a 2" (5.08cm) pipe and was regulated by the main valve. 10 meters downstream from the main valve the flow branched into two 1" (2.54cm) pipes. Each of the 1" pipes contained a Gerand venturi (connected to a water manometer for flow measurement) and a secondary valve (used to fine tune the flow rate). Figure B-2 shows the venturi - air trap - manometer system. Downstream from the secondary valves the 1" pipes connected to the top of a specially designed feedthrough fabricated in the UCD student/faculty shop. Next the water flowed through sections of flexible 1/2" (1.27cm) Tygon tube and then into the nozzles. The nozzles were 30 cm lengths of 1.27 cm inside diameter glass tubes held by an aluminum nozzle holder which was hung from the lid of the pressure vessel. The linkage which supported the nozzle holder insured that the nozzles were always vertical even when vibrated by the shaker. An accelerometer was mounted on one side of the nozzle holder and on the other side was a connecting rod to the shaker.

1.2. Description of Vacuum System

The vacuum system was used to surround the water jet in a low pressure atmosphere.

The vacuum vessel was a 130 cm long by 30 cm diameter tube of Plexiglas with a lid covering the top and bottom. A feedthrough for the connecting rod was built into the wall of the vessel. The top lid had two feedthroughs, one for the water supply and another for the nozzle accelerometer cord. A Weksler vacuum gage was mounted on top of the lid and measured vacuum in inches of mercury. A 1" (2.54cm) PVC pipe which ran from the lid to an Ametek ejector pump provided the means for evacuating the vessel. The ejector pump created a vacuum when water supplied by a common garden hose flowed through it. Water was pumped out of the vessel and into the drain with a Sterling Speed-Trol pump via a 2" (5.08cm) pipe in the bottom lid.

1.3. Description of Electronics System

The purpose of the electronics system was to vibrate the nozzles and measure the amplitude of vibration.

A Hewlett-Packard function generator fed a sine wave into an MB Electronics power amplifier. The frequency of the sine wave was measured with a Hewlett-Packard counter. The amplified signal was used to drive an MB Electronics electromechanical shaker. An ammeter was used to guard against overdriving the shaker. Endevco accelerometers, one mounted on the nozzle holder and the other mounted on the face of the shaker detected the motion of the nozzle. Outputs from the accelerometers were fed into Umholtz-Dickie charge amplifiers. The charge amp signals were compared and checked for purity and absence of noise with a Tektronix two channel oscilloscope. The voltage from the charge amp connected to the nozzle accelerometer was measured with a Fluke digital voltmeter to determine the amplitude of vibration.

2. Sheet Jet Equipment

The equipment used in the sheet jet experiments was mostly the same as that used in the cylindrical jet experiments.

2.1. Description of Water Supply System

The sheet jet water supply system was different from that used in the cylindrical jet experiments in three ways. First, the venturies could not be used to measure the flow velocity because of the small flow rates involved. Instead, the time to fill a bucket held under the nozzle was measured and the jet's velocity was calculated. Second, one of the circular nozzles was replaced with a bypass hose. The jet velocity was varied by allowing more or less water thru the bypass hose. Third, the other nozzle was replaced with a slit nozzle fabricated out of Plexiglas in the UCD student/faculty shop. Figure B-5 shows a typical slit (or sheet) nozzle and below is a table of nozzle dimensions.

Nozzle	B_0 (cm)	W_0 (cm)	$\frac{L_{mezz}}{D_h}$
A1	.159	0.5	50
A2	.159	1.0	50
A3	.159	1.5	50

2.2. Description of Vacuum System

No low pressure sheet jet experiments were performed so the vacuum system was not needed. The Plexiglas tube, bottom lid, ejector pump and water pump were removed and replaced with a catching tank.

2.3. Description of Electronics System

The electronics system remained unchanged from the cylindrical jet experiments.

3. Equipment Calibration and Measurement Techniques

The accelerometer and venturies used in these experiments were calibrated to insure that the measurements were as accurate as possible. The calibration process and the various measurement techniques are described below. The error analysis is given in Appendix C.

3.1. Accelerometer Calibration and Amplitude Measurement

An Umholtz-Dickie System 76 amplifier and power supply was connected to an Umholtz-Dickie electromechanical shaker which had an internal accelerometer. The internal accelerometer was the standard used to calibrate two Endevco accelerometers. Two Umholtz-Dickie charge amps processed signals from the accelerometers.

The shaker's internal accelerometer was connected with a microdot cable to the first charge amp. The known sensitivity of 12.2 pC/g was dialed into the charge amp with the dial-a-gain knob. The accelerometer to be calibrated was mounted on the shaker table and connected with a microdot cable to the second charge amp. The shaker was then turned on and the output from the charge amps were compared with a Fluke digital multimeter. The dial-a-

gain knob on the second charge amp was turned until a setting was found which produced the same output as that from the first. The accelerometer's calibrated sensitivity was then read off the dial-a-gain knob. The shaker was vibrated over a wide range of frequencies and amplitudes and the whole process was repeated for the second accelerometer.

The results of the calibration are shown below

Accelerometer No.	Calibrated Sensitivity
LA 79	$150 \pm 2 \text{ pC/g}$
LA 81	$146 \pm 3 \text{ pC/g}$

It is possible to measure the amplitude of nozzle vibration with an accelerometer mounted on the nozzle holder. The motion of the nozzle was assumed to be

$$y(t) = -A_0 \sin(2\pi ft) \quad (\text{B-1})$$

therefore

$$\ddot{y}(t)_{\max} = 4\pi^2 f^2 A_0 \quad (\text{B-2})$$

or

$$A_0 = \frac{\ddot{y}_{\max}}{4\pi^2 f^2} \quad (\text{B-3})$$

where A_0 = amplitude of vibration and f = frequency of vibration. Frequency f was read off the Hewlett-Packard counter.

When the correct accelerometer gain in pC/g was dialed into the charge amp the output was scaled to

$$10\left(\frac{mV}{g}\right) = \frac{10mV}{980cm/s^2} \quad (\text{B-4})$$

Since the digital voltmeter used measured RMS voltage

$$\ddot{y}_{\max} = V_{rms} \frac{980}{10} \frac{cm/s^2}{mV} \sqrt{2} \quad (\text{B-5})$$

where V_{rms} = charge amp output in mV.

Equations (B-3) and (B-5) combine to give

$$A_0(cm) = \frac{98\sqrt{2}V_{rms}}{4\pi^2 f^2} \frac{(mV)}{(Hz)^2} \quad (\text{B-6})$$

A typical accelerometer conversion chart is shown in Figure B-6 *

3.2. Venturi Calibration and Measurement of Jet Velocities

Two Gerand 1"-648 brass venturies were used with water manometers to measure cylindrical jet velocities as shown in Figure B-2. The air traps were used to prevent mixing of flow water and manometer water. The Δp (in inches of water) at the pressure taps is given by $H = H_1 + H_2 - H_3$. It is important (for accurate measurement of H) that the water filled plastic tubes be void of air bubbles. Bubbles are easily removed by loosening the appropriate fitting between manometer and air trap (with flow through the venturi) and allowing the bubbles to pass into the air trap.

The venturi was calibrated by measuring the time to fill a large container with water under steady flow conditions while noting the corresponding H. The water was weighed and the velocity calculated. This was done at several flow rates and finally the velocity conversion charts in Figure B-7 were drawn for each venturi/nozzle.

The venturies could not be used with the sheet jet nozzles to determine jet velocity because of the low flow rates involved. The jet velocity was found by measuring the time to fill a small container, weighing the water and then calculating the jet velocity.

3.3. Measurement of Cylindrical Jet Wave Envelope

The envelope of the falling cylindrical jet was found by measuring a flash photo of the jet. The camera was a Minolta SRT 202 with a standard 50mm lens. The camera was positioned approximately 2 meters from the jet. The electronic flash was the Vivatar 252 (an automatic flash) and was the only source of light. The flash duration ranged from 1/1000 to 1/30,000 of a second according to the manufacturer; it was selected automatically by the flash. The film was Kodak Tri-x and it was printed and developed in the UCD mechanical engineering darkroom.

*The charge amps used had a maximum sensitivity setting of 100 pC/g. Since the accelerometers used had sensitivities greater than this, one tenth of the calibrated sensitivity was set on the dial-a-gain knob. This resulted in an output of 100 instead of 10 mV/g. This has been accounted for in Figure B-6.

The amplitude was measured as follows. Lines were drawn on the photo connecting the jet peaks through the centerline of the jet thus forming the wave envelope. A meter stick which was included in each photo and dividers were used to measure the envelope at various points along the jet. The jet envelope amplitude was taken as half the width of the envelope.

4. Equipment List

Equipment Description	Model	Serial No.
Gerand Venturi	1-648	8675
Gerand Venturi	1-648	8715
Endevco Accelerometer	2215M2	LA 79
Endevco Accelerometer	2215M2	LA 81
H-P Function Generator	200CD	S-6272
MB Electronics Power Amp	2250MB	510
H-P Counter	5221A	740-00877
Simpson Ammeter	370	
MB Electronics Shaker	PM-50	907
Umholtz Dickie Charge Amp	11	630
Umholtz Dickie Charge Amp	11	631
Fluke Digital Multimeter	8120A	20005
Tektronix Oscilloscope	565	004856
Sterling Speed-Troll Pump	WBDFV	V15166
Minoita 35mm Camera	SRT202	2362119
Minoita 50mm f1.7 Lens	Rokkor-X	4220531
Vivatar Flash	252	
General Radio Strobe	1531	

Figure B-1. Apparatus used in cylindrical jet experiments.

Figure B-1a. Dimensions of nozzle used in cylindrical jet experiments.

$$H = H_1 - H_2 + H_3$$

Figure B-2. Venturi - air trap - manometer system for measuring flow rate.

Figure B-3. Photo of cylindrical jet equipment showing venturiles, secondary valves and top lid.

Figure B-4. Photo of experimental apparatus.

Figure B-5. Slit nozzle for sheet jet.

Figure B-6. Accelerometer Conversion Chart

Figure B-7. Venturi Calibration Charts.

APPENDIX C

Sheet-Jet Edge Convergence and Breakup

Robert D. Meehan

(Chapter 3 of Reference [10])

C.1 Sheet Jet Background

A sheet jet may be loosely defined as a fluid jet with a nearly rectangular cross section. Many times sheet jets are used because a large fluid surface area is needed or because under the right conditions they readily break up. The HYLIFE reactor will take advantage of the large surface area (to condense lithium vapor) hopefully without breakup, and the better packing fraction (ratio of jet area to total area in a reactor cross section) than with cylindrical jets (e.g. see the nozzle plate in Figure 4).

One potential problem area for the HYLIFE application is the edge convergence phenomenon (sometimes referred to as the Weber effect). Edge convergence is the result of surface tension pulling the edges inward until the jet has taken on roughly a cylindrical shape. If there is no breakup, the inward momentum may cause the fluid to squirt out into a plane at 90 degrees from the original plane of the jet where once again surface tension pulls inward. Under certain conditions, as illustrated in Figure C.1 several convergence points may be observed. The length to each successive convergence point is labeled L_1 , L_2 , etc., and the breakup length is L_b .

Many breakup modes are possible with sheet jets. Dombrowski, Hasson and Ward (1960) (using water, glycerine-water, benzaldehyde, kerosene, alcohol, ethyl acetate, and mercury jets) and Clark and Dombrowski (1971) (using water, acetone, and glycerine-water jets) observed sheet jets which broke up before they converged for the first time. Sometimes the edges broke up first, and other times the edges remained intact even after the web between them had disintegrated. Binnie (1972), using an apparatus which kept the edges of his water jets touching side rails, observed the latter breakup mode. Takahashi (1978) and Asare (1980) also saw this type of breakup in water jets which they found was strongly affected by nozzle vibration amplitude and frequency. Another breakup mode is the kind observed in the water sheet jet experiments presented in this thesis. It is similar to cylindrical jet breakup. After the sheet jet has converged two or three times, it remains roughly cylindrical until it breaks up into drops. This is

the type of breakup indicated in the sketch of Figure 4.

The sheet jet work presented in this thesis is concerned with edge convergence and breakup. Water jets were used in these experiments with the intent of extending the results to the lithium jets of the JET III reactor. The nozzles were vibrated to see if this would affect convergence or breakup. Only turbulent jets were studied and all were at atmospheric pressure.

C.2. Sheet Jet Edge Convergence Theory

A simplified model of a converging sheet jet has been developed to predict the first convergence point, L_c . This is illustrated in Figure 8. The jet has three distinct parts: two cylindrical jet edges (which are pulled inward by surface tension) and the web connecting them. In this model, the fluid particles in the web have no inward velocity until they have been consumed by and become part of the edges, i.e., the web and the edges are assumed to be coupled only through mass conservation.

The position of the edge is given by $y(t)$, the distance measured from the edge of the nozzle to the center of the jet's edge. The edge has diameter $D(t)$ and web thickness $B(t)$. Beginning with the y momentum equation, assuming the angle θ is always small so that $\cos(\theta) \approx 1$

$$\frac{d}{dt}(\delta m_r \dot{y}) = F_y = 2\sigma \delta x \quad (1)$$

where the edge mass was assumed to be*

$$\delta m_r = \left(\frac{\pi}{4} D^2(t) - C_1 B(t) D(t) \right) \rho \delta x \quad (2)$$

Integrating (1) gives

$$\dot{y} \left(\frac{\pi}{4} D^2(t) - C_1 B(t) D(t) \right) \rho = 2\sigma (C_2 + k) \quad (3)$$

*Equation (2) was used instead of just $\delta m_r = \frac{\pi}{4} D^2(t) \rho \delta x$ so as to not require the entire edge mass to be moving at velocity $\dot{y}(t)$. It is reasonable to assume that the part of the web which has just become part of the edge is moving slower.

Since $y_0 = 0$, the integration constant $k = 0$. The constant C_1 was added for generality and is discussed below. Continuity of the edge requires (see sect. B-B, Fig. 6),

$$U_0 B_0 \left\{ 1 + \frac{D(t)}{r} \right\} = \frac{\pi}{4} D^2(t) U'(t) \quad (4)$$

this gives

$$D(t) = \frac{B(t)}{\pi} + \frac{1}{\pi} \sqrt{B^2(t) - 4B(t)U_0(t)\pi} \quad (5)$$

Continuity of the web requires

$$B(t) = \frac{B_0 U_0}{U'(t)} \quad (6)$$

Finally,

$$U'(t) = U_0 + gt \quad (7)$$

$$x(t) = U_0 t + \frac{1}{2} gt^2 \quad (8)$$

Equation (3) has been numerically solved along with (5)-(8) to give the profile of a converging jet. The constants C_1 and C_2 have been determined to be 8 and 9 respectively, by adjusting them in the convergence theory computer program until the computed results matched experimental convergence length data. The computer program is listed in Ref. [10].

Three points have been defined for the inward moving edges as is shown in sections C-C, D-D and E-E of Figure 8. The first point, called touch, happens when all of the web has been consumed and the edges touch. This occurs when

$$\frac{2y(t) + D(t)}{W_0} = 1 \quad (9)$$

The second point, called converge, takes place when the two edge areas have moved into a larger circle of equal area. This occurs when

$$\frac{y(t)}{.5W_0 - .21D(t)} = 1 \quad (10)$$

The point called collocate occurs when the centers of the edges have moved to the centerline of the jet, or when

$$\frac{2y(t)}{W_0} = 1 \quad (11)$$

These three points were defined because of the uncertainty in measuring L_c experimentally and to aid in the evaluation of equation (4). It was hoped that the experimentally measured convergence point would lie between the touch point and the collocate point, ideally at the convergence point.

Finally, it should be pointed out that this model has limitations. It is probably best suited for very wide jets before they converge to the touch point. This is because there is no allowance for interaction between the two edges once the touch point is reached. The model will be discussed further in section C.4 along with the presentation of the experimental results.

Binnie (1972) has also developed a convergence theory for sheet jets. There are two fundamental differences between his model and the one developed here. First, Binnie did not assume θ (defined on Fig. 8.1) was small and consequently ended up with θ terms in his equations. Second, he allowed the edge velocity to be greater than the web velocity thus retaining a rectangular cross section for the converging jet while satisfying continuity. The complex nature of his equations required measurement of θ , $\frac{d\theta}{dx}$ (which was found to be difficult), and y (usually from photos) in order to determine the edge mass (and therefore the edge width) and the edge velocity.

C.3. Experimental

Three different slit nozzles were used in these experiments. All three had the same exit thickness of 0.159 cm and exit widths of .5, 1.0 and 1.5 cm. All nozzles had a length to hydraulic diameter ratio of 50. The nozzles were vibrated at frequencies of 0, 20 and 70 Hz at amplitudes of .01, .02 and 0.04 cm. Jet velocities ranged from 86 to about 787 cm/s. All runs were at atmospheric pressure, the fluid was water, and the jets were turbulent. Convergence length and breakup length were measured with a meter stick. The jet was illuminated with a strobe light while measuring the breakup point. For more details of the experimental techniques, see Appendix B. The data are tabulated in Ref. [10].

C.4 Sheet Jet Edge Convergence Results

Figure 9 shows the edge convergence experimental results and the edge convergence theory for each nozzle. The vertical axis is time to convergence, $t_c = U_0 \sqrt{U_0^2 + 2gL_1}/g$, for the data (in milliseconds). Initial jet velocity in m/s is plotted on the horizontal axis. The curves labeled collocate, converge, and touch refer to the conditions of equations (11), (10) and (9), respectively.

The data for each nozzle roughly follow their corresponding theoretical converge curves. This was expected since the C_1 and C_2 coefficients were determined with these data as discussed in section C.2. It should also be noted that the scatter in the data is confined (except for two points) between the collocate and touch curves. These curves were used to put upper and lower limits on the predicted convergence time t_c . Such limits are useful since visually determining the convergence point is sometimes difficult. Refer to the error analysis in Ref. [10] for a discussion of the uncertainty in measuring the convergence length.

Fig. C.2 shows how well the edge convergence theory can predict the entire profile of a sheet jet in addition to the convergence point. The computer solution is drawn onto the photo showing both the total jet width and the web width. There is excellent agreement between the total jet width predicted and the photo. The web width, however, was predicted to be too large. The failure of the theory to predict web width can be explained by reexamining the sheet jet model of Figure 8. In section B-B there is a sharp corner at the intersection of the edge and the web. In reality surface tension would tend to round out this corner, thus a photo of a sheet jet would show a smaller than predicted web width.

As a final evaluation of the edge convergence theory, a similar photo comparison was made of a jet with significantly larger dimensions than the jet of Figure C.2. The photo was Binnie's (1972) Figure 5 ($W_0 = 61\text{cm}$, $B_0 = 0.038\text{cm}$, $U_0 = 212\text{cm/s}$). Again there was good agreement between theory and the total jet width, with theory predicting the jet to be wider than it actually was in the photo. For example, at the convergence point ($W_0 \approx 0$) in Binnie's photo, theory predicted a width of about 4.5cm.

Finally, the slit nozzle was vibrated to see if edge convergence would be affected. There was no observable change in convergence length at any jet velocity due to nozzle vibration for frequencies of 20 and 70 Hz, and for amplitudes up to 0.04cm.

C.5 Sheet Jet Breakup Results

Results of the sheet jet breakup length measurements are shown in Fig. C.3. The data are compared to Phinney's and Grant and Middleman's breakup curves for turbulent cylindrical jets (see references). L_b/D_{nom} , breakup length divided by flow diameter is plotted on the vertical axis. Flow diameter is the diameter of a circle which has the same area as the exit area of the slit nozzle. The square root of the Weber number based on D_{nom} and $\bar{U}$ ($\bar{U} = L_p/t_p$, average velocity to breakup) is plotted along the horizontal axis. Flow diameter was used instead of hydraulic diameter because it more closely represents jet diameter just before breakup. The average velocity to breakup was used rather than initial velocity to account roughly for acceleration of the jet (the curves are correlations of horizontal jet breakup data).

The mode of breakup was similar to cylindrical jet breakup. After the sheet jet had converged two or three times, it becomes roughly cylindrical until breaking up into drops (Figure C.1. This may be why the data agree quite well with the turbulent cylindrical jet breakup correlations. Sheet jet data were compared to cylindrical jet theory because there is no theory or correlation for the breakup of sheet jets after several edge convergences. Fig. C.3 suggests that this particular mode of the breakup of sheet jets formed by long nozzles is similar to cylindrical jet breakup and that cylindrical jet correlations may be used to estimate sheet jet breakup length. We have no evidence that this is true for the other modes of sheet jet breakup discussed in section C.1.

The slit nozzles were vibrated to see if this would affect breakup length. There was no change in breakup length at any jet velocity due to nozzle vibration for frequencies of 20 and 70 Hz, and for amplitudes up to 0.04cm.

C.6 Applications to HYLIFE Reactor Conditions

As discussed in Ref. (10) lithium jets will fall about 10 meters in the HYLIFE reactor. The sheet jet experiments discussed above indicate that the sheet jet breakup length for this particular edge-convergence mode is not affected by nozzle vibrations and can be predicted by turbulent cylindrical breakup correlations. Using typical HYLIFE reactor conditions (Fig. C.4) and Phinney's equation, the sheet lithium jets should remain intact for 150-165 meters. This is much longer than the 10 meter fall distance in the reactor.

As we have seen from the above discussions, sheet jets experience a phenomenon known as edge convergence which cylindrical jets do not. If the lithium sheet jets converge too much, parts of the wall might be exposed to and damaged by radiation. In order to predict the profile of such a jet, the edge convergence theory was developed in section C.4. This was used to produce the nozzle design chart in Figure 10. The dashed lines are an extrapolation of the theory necessitated by a break down of the model. The point to which the curves were extrapolated was found by first drawing the curves on log-log graph paper, noting that they were approximately straight lines and then extending them to an aspect ratio of 1 (i.e. a square jet).

Figure 10 shows that the first convergence point (L_{c1}) of a 30x90 cm lithium jet is much greater than 10 meters, or well beyond the bottom of the reactor. An earlier proposal to use 10x30 cm jets would have resulted in severe edge convergence effects since an L_{c1} of only about 5 meters is predicted.

The edge convergence theory was used to calculate the profile of a 30x90cm lithium jet. This profile is shown in Figure C.5. At the reactor midplane ($x = 5$ meters) the jet width has been reduced by about 19%. As a second case, the convergence theory was used with surface tension set to zero. Calculations indicate that the midplane jet width is reduced by 17% indicating that acceleration of gravity accounts for most of the thinning of the jet; this second case is not shown on Fig. C.5 because the profile is so close to the first case.

Asare, H.	1980	"Theoretical and Experimental Investigation of Water Sheet Jets Under Forced Vibration," Ph.D. Thesis, Department of Mechanical Engineering, University of California, Davis.
Binne, A. M.	1972	"The Stability of a Falling Sheet of Water," Proc. R. Soc. Lond., 326, 149-163, Great Britain.
Chen, T.-F.
Davis, J. R.	1964	"Disintegration of a Turbulent Water Jet," J. Hydraulics Division, A.S.C.E., Vol. 90, 175-206.
Clark, C. J.
Dombrowski, N.	1971	"The Dynamics of the Rim of a Fan Spray Sheet," Chem. Engr. Sci., Vol. 26, 1949-1952.
Crane, L.
Birch, S.
McCormack, P. D.	1964	"The Effect of Mechanical Vibration on the Break-Up of a Cylindrical Water Jet," Brit. J. Appl. Phys., Vol. 15, 743-750.
Doebelin, E. O.	1966	<u>Measurement Systems</u> , McGraw-Hill, New York.
Dombrowski, N.
Hasson, D.
Ward, D. E.	1960	"Some Aspects of Liquid Flow Through Fan Spray Nozzles," <u>Chem. Engr. Sci.</u> , Vol. 12, 35-50.
Gavis, J.
Modan, M.	1967	"Expansion and Contraction of Jets of Newtonian Liquids in Air: Effect of Tube Length," <u>Phys. Fluids</u> , Vol. 4, 487-497.
Grant, R. P.	1966	"Newtonian Jet Stability," <u>A. I. Ch. E. J.</u> , Vol. 12, No. 4, 669-678.
Hoffman, M. A.	1979	"Research on the "HYLIFE" Liquid - First - Wall Concept for Future Laser-Fusion Reactors," Final Report No. 4, Dept. of Mech. Engr., University of California, Davis Campus.
Hoffman, M. A.
Takahashi, R. K.
Monson, R. D.	1980	"Annular Liquid Jet Experiments," <u>Trans. of the ASME</u> , Vol. 102, 344-349.

- 1977 "Waves on Water Jets," J. Fluid Mech., Vol. 83, Part 1, 1977.
- 1977 "Conceptual Design of a Laser Fusion Power Plant," UCRL-9650, Lawrence Livermore Laboratory.
- 1968 "Review of Stability of Liquid Jets and the Influence of Nozzle Design," Chem. Engr. J., Vol. 7, 1-20.
- 1976 "Conceptual Design Considerations and Neutronics of Lithium-Fall Laser Fusion Target Chambers," UCRL-80782, Lawrence Livermore Laboratory.
- 1966 "Correlation of Experimental Data on the Disintegration of Liquid Jets," Industrial and Engineering Chemistry, Vol. 47, No. 9, 1690-1701.
- 1976 "A Study of a Disintegration of a Liquid Jet in an Air Flow," Proc. The First International Conference on Liquid Atomization and Spray Systems, The Fuel Society of Japan, 29-36.
- 1975 "Break Up of a Turbulent Liquid Jet in a Low-Pressure Atmosphere," A. I. Ch. E. J., Vol. 21, No. 5, 996-999.
- 1979 "Potential Design Modifications for the High Yield Lithium Injection Fusion Energy (HYLIFE) Reaction Chamber," UCRL-82895, Lawrence Livermore Laboratory.
- 1975 "The Instability of Capillary Jets," J. Fluids Mech., Vol. 68, Part 3, 447-495.
- 1978 "Experimental Investigation of the Stability of Liquid Sheet Jets," M.S. Thesis, Department of Mechanical Engineering, University of California, Davis.

- Vennard, J. K. 1975 Elementary Fluid Mechanics John Wiley & Sons, New York
- Vitman, L. A. 1967 "Calculation of the boundary layer length of a disintegrating liquid jet of drops and of heat transfer and evaporation of VO_2 -droplets" Meda, Pergamon Press Oxford, U.K. 1967

Figure C.1 Actual (l) and idealized (r) sheet jet behavior.

Figure C.2 Actual and Theoretical profile of a sheet jet.

Figure C.3. Sheet jet breakup data compared to cylindrical jet theory.

HYLIFE Reactor
Reference Design Conditions

Initial Sheet Jet Thickness (B_0)	30 cm
Initial Sheet Jet Width (W_0)	90 cm
Initial Cylindrical Jet Diameter (D_0)	30 cm
Initial Jet Velocity (U_0)	5 m/s
Density of Lithium	489 kg/m ³
Surface Tension	.35 N/m
Mean Temperature of Lithium	800 K
Chamber Radius	5 m
Chamber Pressure	13-130 Pa
Fusion Energy Yield per Shot	27 MJ
Repetition Rate	1-10 Hz
Resonate Frequency of Nozzle Plate	70 Hz
Max. Vibration Amplitude of Nozzle Plate	0.1 cm

Figure C.4 HYLIFE reactor reference design conditions.

SHEET LITHIUM JET PROFILE

Figure C.5 Expected profile of a sheet lithium jet
 ($U_0 = 500 \text{ cm/s}$, $B_0 = 30 \text{ cm}$, $W_0 = 90 \text{ cm}$)