EXPERIMENTAL INVESTIGATION OF FREE LIQUID METAL JETS IN VACUUM:

PRELIMINARY RESULTS FOR IFE CHAMBER WALL PROTECTION APPLICATIONS

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ABSTRACT

Experiments are under way at UCLA to simulate the liquid slab jets of the HYLIFE-II Inertial Fusion Reactor. Measurements of surface ripple and break-up length are made based on photographic images of the jet flow, and velocity data is obtained from an orifice-type flow meter. The experiment can be run with a selection of nozzles and upstream conditioners in order to determine the optimum configuration for suppressing disturbances. Preliminary data, taken while verifying the operation of the experimental system, indicate that the slab jets issuing from a nozzle comprisedslot cut in an orifice plate this nozzle type contract out of their initial rectangular shape more rapidly than would be expected from surface tension forces alone. Subsequent data are expected to aid in the proof-of-principle for thick liquid cavity designs, provide insight into design requirements of such systems, and increase the fundamental understanding of turbulent liquid jet flow in vacuum.

I. INTRODUCTION

Wall protection and chamber clearing are two of the most critical issues facing designers of reaction chambers for Inertial Fusion Energy (IFE) power plants. With a repetition rate on the order of 5 to 20 Hz, depending on which of the many power plant design studies is consulted, IFE chambers must withstand rapidly repeated high energy bursts of X-rays, ionized target debris, and neutrons. Afterwards, such chambers must then return to a reasonably quiescent state before the next shot, 50 to 200 ms later, to allow propagation of the new target and driver beams

The use of liquids as a renewable first surface has been proposed since the beginning of IFE design studies in the early 1970s. The HYLIFE-II design study[1] utilizes an array of neutronically thick, molten-Flibe, slab jets which oscillate back and forth to form a pocket around the incoming fuel pellet (see Figure 1). The ends of the pocket are closed off with either a stationary array of slab jets, or a criss-crossing grid of smaller jets that allow penetration of driver beams. The HYLIFE-II concept provides protection of the first structural surface while allowing venting of ablated material to the reaction chamber. In addition, the incoming liquid pocket sweeps clear the majority of the droplets that may still be hanging in the reaction chamber. Cold Flibe sprays are used to condense any vapor not swept away by the incoming liquid.

The HYLIFE-II design relies on the use of fast, precise, oscillating liquid jets to make up the liquid pocket and end grids. The stability, surface roughness and breakup of such jets issuing into a vacuum environment has not yet been investigated to the point that the HYLIFE-II concept can be validated.

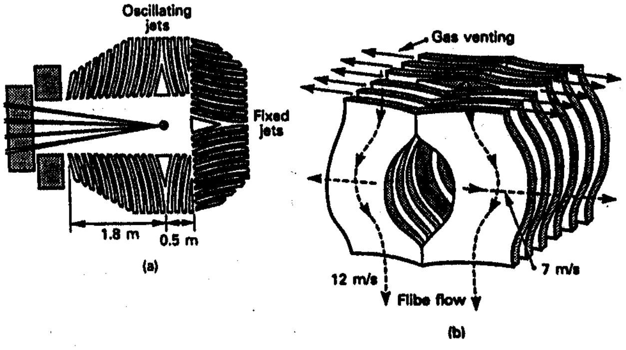

Figure 1: Schematic of the HYLIFE-II thick liquid jet wall protection concept, (a) top view, (b) perspective side view.

II. SIMILARITY OF PHENOMENA

The stability and breakup of liquid jets is a venerable subject area in fluid mechanics. We will not try to summarize the vast literature in this short paper, but instead cite some useful references in the area and mention some key points for consideration. Classical work on the breakup of cylindrical jets is summarized in McCarthy and Molloy[2]. A paper by Phinney[3] especially focuses on the area of turbulent jets in a low pressure atmosphere. A good summary of past research in the area of free sheet or slab jets is included in Cavanaugh and Peterson[4], where the problems of the HYLIFE-II jets are specifically addressed. The key points to be culled from these previous works can be summarized as follows:

- Infinitely wide, inviscid, sheet jets in vacuum are linearly stable to all small disturbances
- Turbulent fluctuations will contribute to surface roughness, and if sufficiently strong, primary breakup of the liquid jets in vacuum
- Relaxation of boundary layers after issuance from the nozzle can affect the surface roughness and breakup
- Nozzle design and upstream conditioning dramatically affect the average turbulent velocity, turbulent velocity fluctuation spectra[5], and large scale secondary flows, all of which in turn will affect the breakup behavior of a sheet jet

The most important scaling criteria for the jet breakup length is suggested by Phinney[3] to be the Weber number, $We = \rho V^2 D/\sigma$, where ρ, V, D and σ are the liquid density, average liquid velocity, appropriate length scale, and coefficient of surface tension respectively. He suggests (again, for a cylindrical jet) that the breakup is only weakly affected by the Reynolds Number, $Re = \rho VD/\mu$ where μ is the dynamic viscosity, provided that a sufficiently turbulent flow is reached. Ying and Abdou[6] support this assertion with their estimate that the surface ripple and droplet ejection caused by the turbulent eddies interacting with the jet surface will scale with the ratio $Re^{1/4}/We$. This is only valid near the nozzle exit where the turbulence behavior can be estimated using correlations for closed duct flow.

Cavanaugh and Peterson[4] mention the tendency of finite sheet jets to contract into a cylindrical shape. In this sense, all *finite* sheet jets are unstable and will begin to contract immediately after loosing contact with the nozzle. We define here a dimensionless number, which we call the *contraction number C*, that can be used to estimate the severity of the slab contraction effect. C is taken as the ratio of the distance ($s = Ft^2/2m$) through which a mass m can be accelerated by force F during the fall time t, to the half-length of the slab $w/2$. Using surface tension as the force and the amount of fluid in the (rounded-off) end of the slab as the mass, C is defined as:

$$C = \frac{8}{\pi}\frac{\sigma L^2}{\rho W D^2 V^2} = \frac{8}{\pi}\frac{L_D^2}{\beta \cdot \mathrm{We}}, \tag{1}$$

where L and W are the flow length and width of the jet, and L_D and β are the dimensionless length and aspect ratio. We see that if the dimensionless flow length and aspect ratio are kept constant, in addition to We, then C is automatically matched and the slab contraction should scale in simulation experiments. Note that any initial velocity in the lateral direction can be included as an additional term if the one wishes to make C more general.

Cavanaugh and Peterson[4] tabulate the important parameters of the HYLIFE oscillating jets (repeated here in Table 1), where it is seen that Re is quite high, indicating a highly turbulent flow. Equivalent parameters for the *MeSO-Jet* experiment at UCLA are also presented in the table. The advantage to using a LM over other test liquids like water is that similarity can be achieved at much lower flow rates and jet dimensions. Additionally, worries about cavitation due to jet ejection into a low-pressure atmosphere are reduced owing to the low vapor pressure on liquid metals. The main disadvantages, aside from some complications to the system design owing to LM use, are large increases in the required velocity and oscillation frequency. The high velocity will require a large driving pressure in the experimental apparatus. The high oscillation frequency may be impossible to attain experimentally. If so, only lower frequencies will be investigated in subsequent experiments.

Also needed for similarity is an appropriate nozzle design. The literature on HYLIFE-II, to our knowledge, does not contain a detailed description of the internal flow area of the nozzles, either oscillating or stationary. It is seen in McCarthy and Molloy[2] that, all other factors being equal, very different breakup behavior can be triggered by slight changes in the nozzle design. Hussain and Ramjee[5] suggest that compression nozzles, where the flow area constricts rapidly, can be effective in suppressing turbulent fluctuations perpendicular to the main flow direction. This can increase the lifetime of the jet if the dominant breakup mechanism is due to energetic turbulent eddies and turbulent boundary layer relaxation. However, the spacing between the HYLIFE-II oscillating jets allows

Table 1: Important parameters for HYLIFE-II oscillating jets and various simulation experiments (some data taken from Table 1 in Cavanaugh[2])

Jet Parameters	HYLIFE-II	Water	LM	MeSO-Jet (Goal)	MeSO-Jet (Current)
Thickness, D [cm]	7	1.85	0.45	0.45	0.20
Width, W [cm]	100	26.40	6.41	2.25	1.00
Velocity, V [m/s]	12	20	32	30	11
Flowrate, Q [l/s]	840	100	9.2	3.0	0.22
Dynamic Head [MPa]	0.15	0.21	4.6	4.1	0.55
Fall Distance, L [m]	2	0.53	0.13	0.13	0.06
Inter-Jet Spacing, S [cm]	5	1.32	0.32	0.32	0.14
Oscillation Frequency, f [Hz]	6	39	248	233	192
Oscillation Amplitude, A [cm]	9	2.38	0.58	0.58	0.26
Liquid Parameters					
Working Liquid	LiF-BeF$_2$	H_2O	Bi-Pb-In-Sn-Cd	Bi-Pb-In-Sn-Cd	Bi-Pb-In-Sn-Cd
Working Temperature [C]	660	5	60	60	60
Density [kg/m^3]	1963	1000	9160	9160	9160
Viscosity [10^{-3}·kg/m·s]	6.78	1.55	5.39[a]	5.39	5.39
Surface Tension [N/m]	0.193	0.075	0.407[b]	0.407	0.407
Dimensionless Parameters					
Reynolds Number, Re [10^3]	243	243	243	230	37
Weber Number, We [10^3]	103	103	103	91	5.4
Fall Length, $L_D=L/D$	28.6	28.6	28.6	28.6	28.6
Aspect Ratio, $\beta=W/D$	14.3	14.3	14.3	5.0	5.0
Contraction Number, C [10^{-3}]	1.4	1.4	1.4	4.6	76.4
Nozzle Compression Ratio, CR	1.7	1.7	1.7	1.7	1.7
Oscillation Amplitude, $A_D = A/D$	1.3	1.3	1.3	1.3	1.3

[a] Based on UCLA measurements using viscometer tubes.

[b] Inferred from data on 55.5w% Bi – 44.5w% Pb alloy. Measurements are underway for our specific alloy.

a compression ratio of only 1.7. Miles, Annese and Ingham [7] state that boundary layer separation in the nozzle should be avoided to ensure a stable jet. This is especially necessary on relatively thin lateral side walls of the nozzle, since separation may exacerbate the contraction of the slab. Other means to reduce the turbulent boundary layer effect, like suction at the wall, will be difficult to implement in a vacuum environment, although some sort of physical boundary layer cutting nozzle might be possible (see Wu, Miranda, and Faeth[8]).

III. LM EXPERIMENTS IN VACUUM

A. Description of Experimental Apparatus

A simplified schematic of the experimental apparatus currently in use at UCLA is given in Figure 2, corresponding to the last column in Table 1. After opening a control valve, the pressure differential between the upper reservoir and the vacuum chamber accelerates the fluid up to the desired speed, 0-11 m/s for these initial experiments. A pressure of about 0.45 MPa with respect to the atmosphere will be required in the upper reservoir to generate the maximum speed. The discharge will reach steady state by 2 s after initiation, and continue for at least 10 s where data can be taken. The control valve is then closed, before the LM level in the upper reservoir is exhausted, in order to avoid pressurization of the vacuum chamber. The LM in the lower reservoir is then recirculated to the upper reservoir, through a filter to continuously remove any oxide precipitate.

The nozzle for these preliminary experiments is a straight through slot in a plate with slightly rounded edges

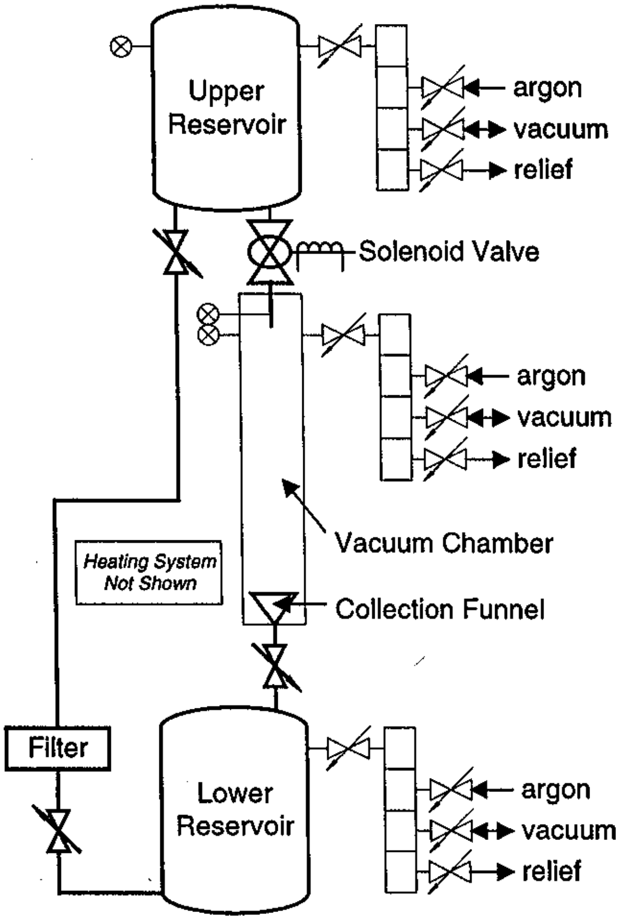

Figure 2: Simplified schematic of the MeSO-Jet experimental apparatus

on the liquid side, and square edges on the vacuum side. The slot dimensions are 2 mm deep by 10 mm wide by 6 mm long (see Figure 3). The rounded internal edge has a radius of 1 mm, which will hopefully reduce the most serious separation effects. This type of nozzle, however, represents a *worst case* scenario, one to which more elaborate and/or finely machined nozzles can be compared. The nozzle plate can easily be replaced with other plates with different nozzle geometry. The feed pipe, which extends through a vacuum bellows, can also be replaced with a rectangular channel or augmented with flow straighteners as the situation demands.

The performance of the jet is recorded with high-speed photographs using a digital camera with 512 x 512 pixel CCD and fast electronic LCD shutter. The vacuum chamber is an 80 cm long, clear lexan tube with a 10 cm internal diameter, allowing the lighting and camera to be outside the working vacuum. The photographs will be inspected using image analysis software to measure the size of surface disturbances, ejected droplets, relative slab contraction and ultimate breakup. The average jet velocity is determined from a pressure measurement on the internal side of the nozzle slot, which forms natural orifice flow meter. The discharge coefficient was determined from calibration tests with water. Vacuum measurements show that the chamber can be held at a few tens of Pascals.

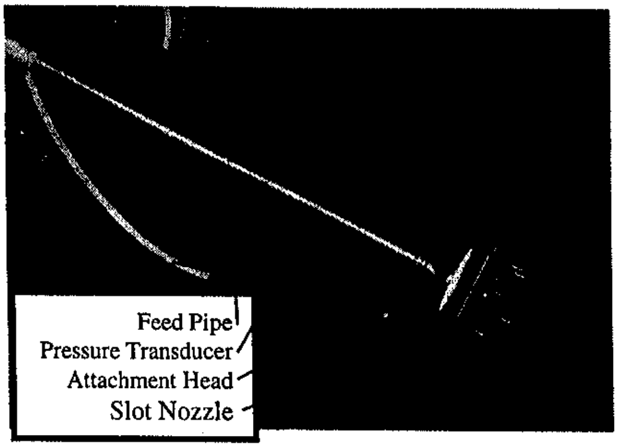

Figure 3: Slab jet nozzle assembly for the MeSO-Jet experiment at UCLA

B. Preliminary LM Jet Data

The test apparatus has been used to produce LM jets at several different speeds. Figure 4 shows pictures for three different runs with pixel size about 0.13 mm and the pictured length $L = 6$ cm. Looking from the flat side of the slab, it is apparent that the jets are contracting rapidly during their respective flight time through the pictured area. As expected the faster the velocity, the more contraction is reduced – the slab nature being maintained for a greater portion of the flow length. Also for the faster flows, wakes can be seen propagating in from the corners of the nozzle. This is due to the roughness of the nozzle corners and should be improved in subsequent nozzles.

The contraction numbers for these flows are C = 0.81, 0.17 and 0.096 respectively. For Figure 4-A, this C is close to unity and we expect the jet to contract as shown due to the surface tension force. Even at this low velocity, acceleration due to gravity changes the jet velocity by only 6%. The jet width near the bottom of this picture is about 2.8 mm, nearly the same as the inlet thickness D. Visual observations indicate that the slab has essentially reversed orientation at this point, *i.e.* the thin side has become the wide side, and vice-versa.

For the experimental conditions of Figure 4-B and C, the contraction numbers and 3D flow calculations indicate

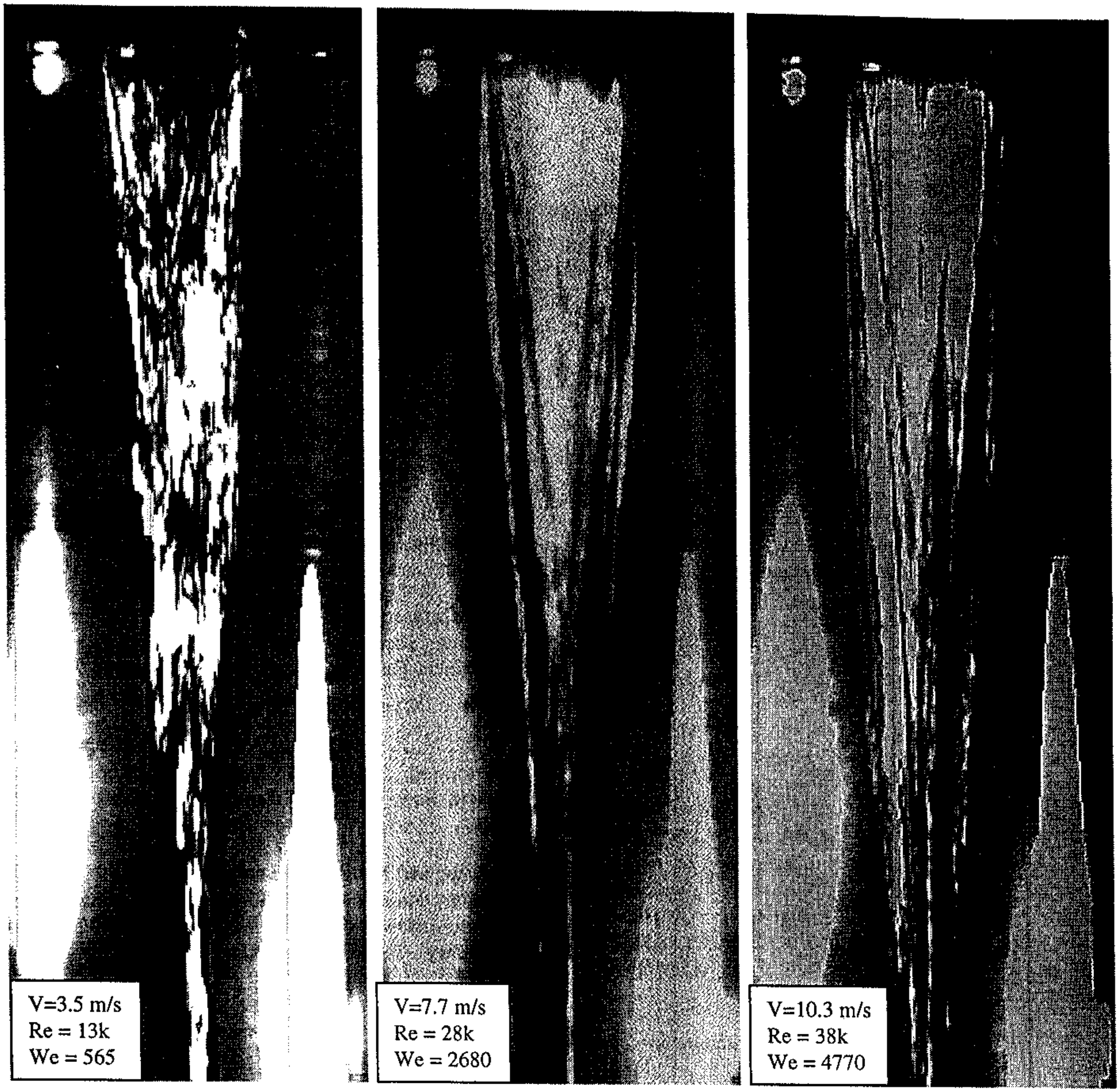

Figure 4: LM slab jets (initially 2 mm deep x 1 cm wide) at various velocities. Pictured length is 6 cm.

that there should be little lateral motion due to surface tension during the flight time, and not such dramatic width contraction as seen in the figures. One might suspect that contracting streamlines cause a separation of the flow from the lateral walls as the flow enters the nozzle, and so imparts a non-zero initial velocity that causes the rapid contraction. But the photographic images indicate that the width of the fast flows initially *increases*, likely due to pressurization of the liquid in the nozzle, before contracting rapidly near the end of the 6 cm pictured length. This would seem to indicate that there is no separation nor initial inward velocity.

We note that (for the faster flows) the left side of the jet, where the nozzle was (unintentionally) more rounded, retained its position for a greater length of the flow than did the more squared-corners of the right hand side. Our definition of the contraction number uses the radius of curvature of a completely rounded corner ($r_c = D/2$) to determine the surface tension force. It is possible that sharp square corners, which have smaller radii of curvature, will cause a stronger initial force of contraction, and subsequently faster contraction times. However this seems unlikely to cause such dramatic deviation from our calculated results.

No breakup or ejection in the first 6 cm ($L_D = 28$) is observed for these *Re* and *We* numbers once the flow has reached its steady state following the initiation of the jet discharge. Wave structures about 0.3 mm thick can be seen streaming out of the nozzle. This size is 15% of the jet thickness, and represents a sizeable surface ripple. It remains to be seen how much these waves can be reduced by a better nozzle design.

It should be understood that the nozzle described in this paper is obviously not ideal, and will be used as a benchmark for upcoming modification of nozzle geometry and upstream conditioning.

IV. FUTURE PLANS

The experimental apparatus will be modified by replacing the upper reservoir with a larger volume, higher pressure tank capable of withstanding 5 MPa of pressurization. This higher pressure will allow higher velocity jets to be produced, and so more prototypic *Re* and *We* numbers. A number of nozzles will be tested, including arrays of jets with the precise knife-like separator edges and smooth compression. Alternate nozzles shapes and upstream flow conditioners will be employed as needed to determine if the HYLIFE-II requirements can be met for stationary jets.

The nozzle must be better braced against unwanted vibrations, which we are already seeing in these experiments. Modification of the apparatus to oscillate the nozzles in a controlled manner, parallel to the long edge of slab, is planned for later this year. Nozzle vibration will be measured with an accelerometer attached to the end of the nozzle apparatus.

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REFERENCES

1. R. W. Moir, et al., "HYLIFE-II: A molten-salt inertial fusion energy power plant design–final report," Fusion Technol., **25**, 5, (1994).

2. M. J. McCarthy and N. A. Molloy, "Review of stability of liquid jets and the influence of nozzle design," Chem. Engr. J., **7**, 1 (1974).

3. R. E. Phinney, "Breakup of a turbulent liquid jet in a low-pressure atmosphere," AICHE Journal, **21**, 996 (1975).

4. C. J. Cavanaugh and P. F. Peterson, "Scale modeling of oscillating sheet jets for the HYLIFE-II inertial confinement fusion reactor," Fusion Technol. **26**, 917 (1994).

5. A. K. M. F. Hussain and V. Ramjee, "Effects of the axisymmetric contraction shape on incompressible turbulent flow," J. Fluids Engr. Trans. ASME, **98**, 58 (1976).

6. A. Ying and M. Abdou, "Scaling criteria for IFE liquid wall protection scheme simulation," In Proceedings of the 4th International Symposium on Fusion Nuclear Technology, Tokyo, Japan, April 1997. To appear in Fusion Engr. Des., (1998).

7. R. R. Miles, C. R. Annese and J.G. Ingham, "Verification of the hydraulic design of the FMIT liquid lithium target," in Proceedings of the 10th IEEE Symposium on Fusion Engineering, Vol. 2, 1120 (1983).

8. P. K. Wu, R. F. Miranda and G. M. Faeth, "Effects of initial flow conditions on primary breakup of non-turbulent and turbulent round liquid jets," Atom. and Sprays, **5**, 175 (1995).