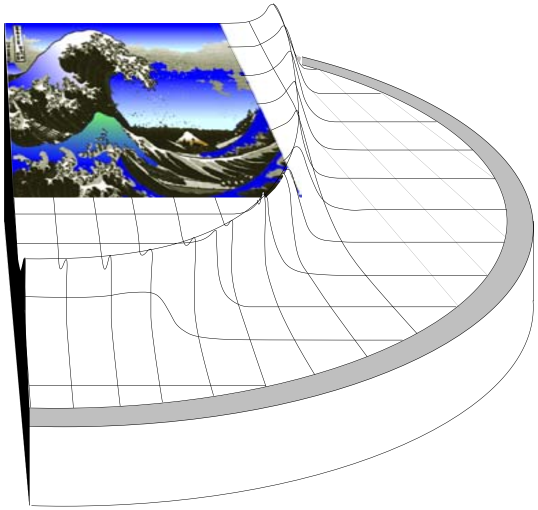
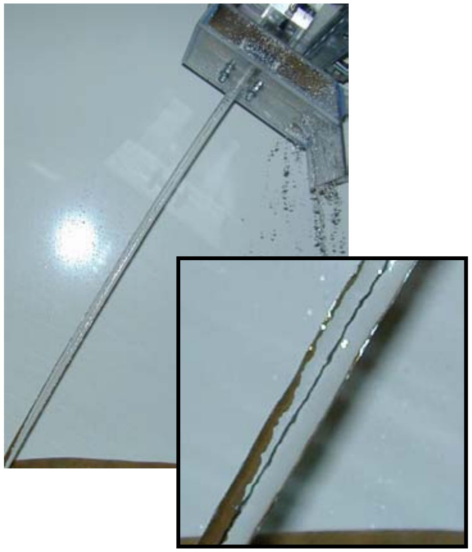
Jet disruption/recovery experiment

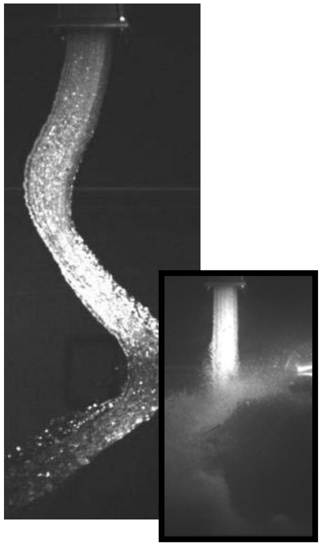


P.F. Peterson
Department of Nuclear Engineering
University of California, Berkeley

ARIES Town Meeting

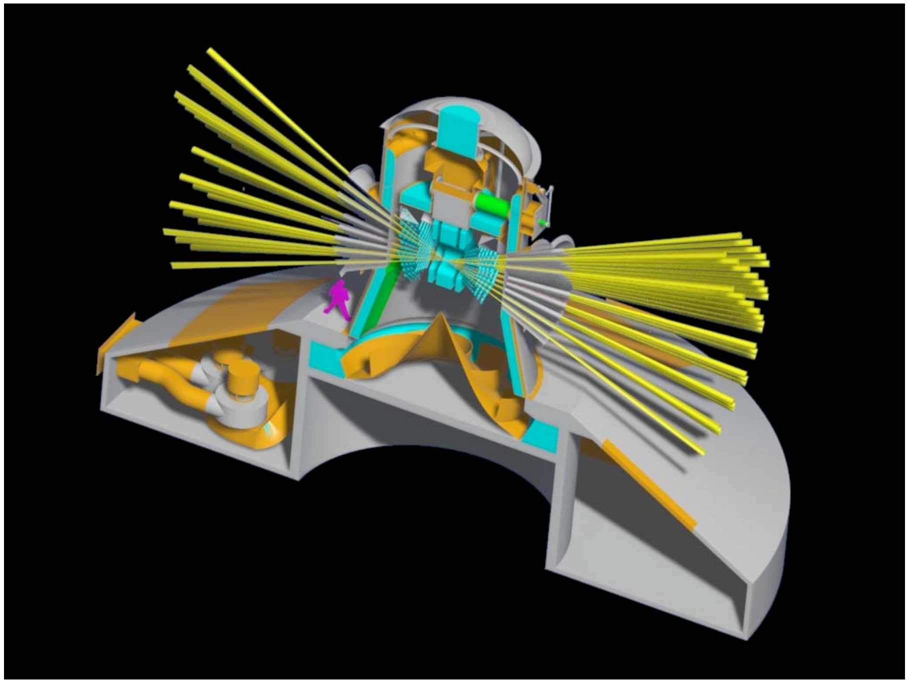
May 5-6, 2003



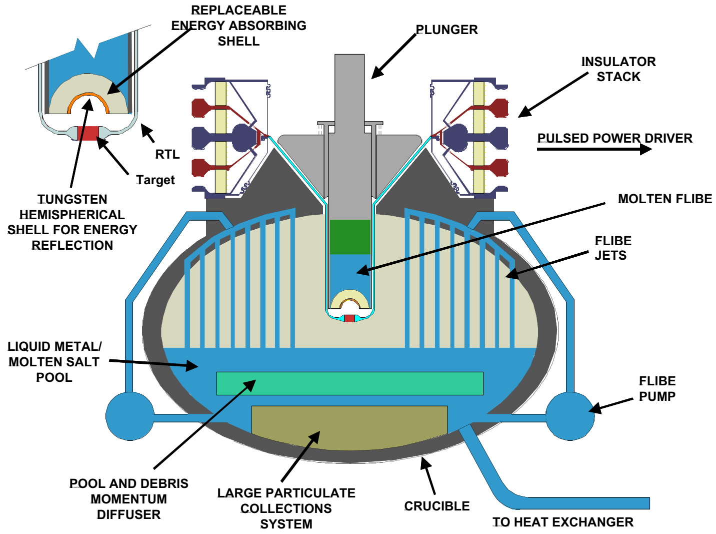


HYLIFE/Z Use Thick Liquid Chambers

- **Thick liquid jets shield chamber structures—fluid mechanics questions replace materials questions**
- **No blanket replacement required, increases availability**



HYLIFE RPD (Heavy Ions)



ZFE (Z-Pinch)

All IFE scientific topics can be identified and characterized by time scale and spatial location

Spatial Volume	**Time Scale (Phenomena Duration)**			
	Nanosecond **(Target Gain)**	Microsecond	Millisecond **(Rep. Rate)**	Quasi-Steady **(Safety/Reliab.)**
Capsule	Neutron/ion/ x-ray emission	Target debris expansion/ interaction with ablation debris, venting, impulse	Debris condensation	—
Hohlraum (if used)	X-ray and debris emission			—
Driver energy transport paths	Beam transport and focusing			Debris accumulation
Pocket Void/Vent Paths	—			—
External Condensing Region	—			—
Target-facing Surface Layers	X-ray deposition	Ablation/impulse	Liq. hydraulics/ solid thermal mechanics	Activation, neutron damage (solids), safety
Blanket (liquid/solid)	Neutron and gamma deposition	Neutron heating relaxation		
Final focus elements		—	—	Damage rate
Chamber structures		—	—	Safety, tritium, activation, corrosion
Coolant recirc./heat recovery loop	—	—	—	
Accelerator/laser systems	Driver physics	—	Driver rep. rate and reliability	
Target injection	—	—	Accel./heating	—
Target fabrication	—	—	—	Safety/reliability
Balance of plant	—	—	—	Safety/reliability

Liquid-protection fluid mechanics can be studied using simulant fluids in reduced scale facilities

A scaled IFE system behaves identically if initial conditions, boundary conditions and St, Re, Fr, I*, and We are matched...

Two more parameters can be important:
Prandtl number (energy transport: MFE and wetted-wall IFE)
Hartman number (MHD: MFE)

Nondimensionalize incompressible-flow governing equations with appropriate scaling parameters:

$$\mathbf{v}^* = \mathbf{v}/U \qquad \nabla^* = L\nabla \qquad p^* = p/\rho U^2 \qquad t^* = ft \qquad r^* = r/L \qquad p_v^* = \frac{p_v L}{IU}$$

Giving the nondimensional incompressible-flow governing equations:

$$\nabla^* \cdot \mathbf{v}^* = 0 \qquad \mathrm{St}\frac{\partial \mathbf{v}^*}{\partial t^*} + \mathbf{v}^* \cdot \nabla^* \mathbf{v}^* = -\nabla^* p^* + \frac{1}{\mathrm{Re}} \nabla^{*2} \mathbf{v}^* + \frac{1}{\mathrm{Fr}} \frac{\mathbf{g}}{g}$$

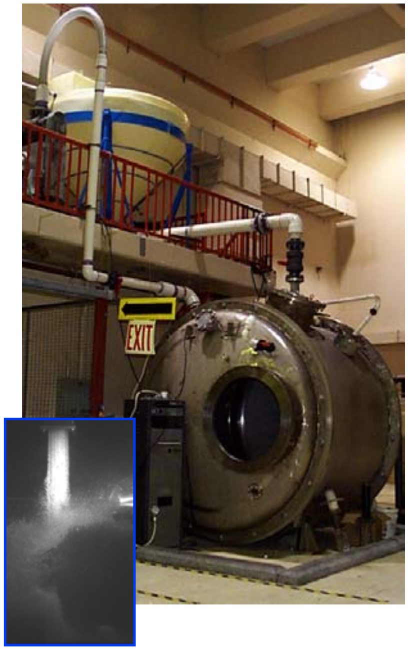
$$p^* - I^* p_v^* = \frac{1}{\mathrm{We}} \left(\frac{1}{r_1^*} + \frac{1}{r_2^*} \right)$$

Low temperature, easily handled simulant liquids (e.g. water, water-electrolytes and non-reactive liquid metals) provide a lower cost, higher flexibility avenue for exploring fundamentals of achievable liquid geometries with minimal experimental distortion

HIF fluid chamber fluid mechanics can be studied with increasing levels of integration in phased experiments

	HYLIFE	Single/Multiple Jet		Integral Experiments		
		Pre-IRE		IRE	ETF	DEMO
	RPD-2002	Single Jet	Partial Poc.	HITF	40%	90%
Geometric Scale	1	0.24	0.24	0.40	0.40	0.9
Target Yield (MJ)	400	—	—	—	34	301
Volumetric Flow (m3/s)	54.00	0.01	0.09	5.52	5.46	41.50
Oscillation Frequency (Hz)	6.0	26.5	12.2	9.5	9.5	6.3
Nozzle Velocity U (m/s)	12.0	12.7	5.9	7.6	7.6	11.4
Number of Jets	250	1	15	250	250	250
Typ. Jet Dimension D (m)	0.070	0.017	0.017	0.028	0.028	0.063
Pumping Power (kW)	24,700	2	12	513	1,000	17,082
Storage Tank Size (m3)	N/A	4	4	N/A	N/A	N/A
Jet Reynolds Number ReD	213,648	213,648	98,665	213,677	54,049	182,416
Jet Weber Number WeD	105,653	37,256	7,946	22,263	16,904	85,579
Froude Number FrH	7.3	34.4	7.3	7.3	7.3	7.3
Impulse Loading I*	1.23E-05	—	1.23E-05	1.23E-05	5.32E-05	1.23E-05
Neutron Heating N	7.35E-05	—	0	0	8.85E-05	7.50E-05
Working Fluid	Flinabe	Water	Water	Water	Flinabe	Flinabe

See: Meier, D.A. Callahan-Miller, J.D. Lindl, B.G. Logan, P.F. Peterson, "An Engineering Test Facility for Heavy Ion Fusion – Options and Scaling," *Fusion Technology*, Vol. 39, pp 671-677, 2001.



VHEX, a facility for partial-pocket experiments

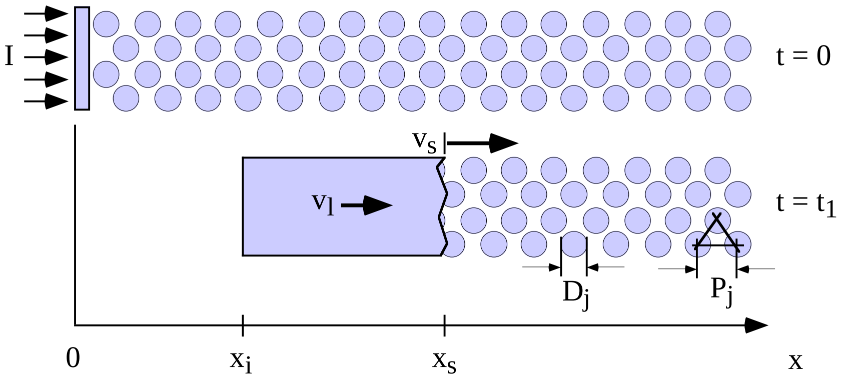
Z-IFE uses similar experiments, but explores different major design issues than HIF (protection of permanent electrode and insulator hardware from blast effects, versus restoration of precise liquid geometry/gas density)

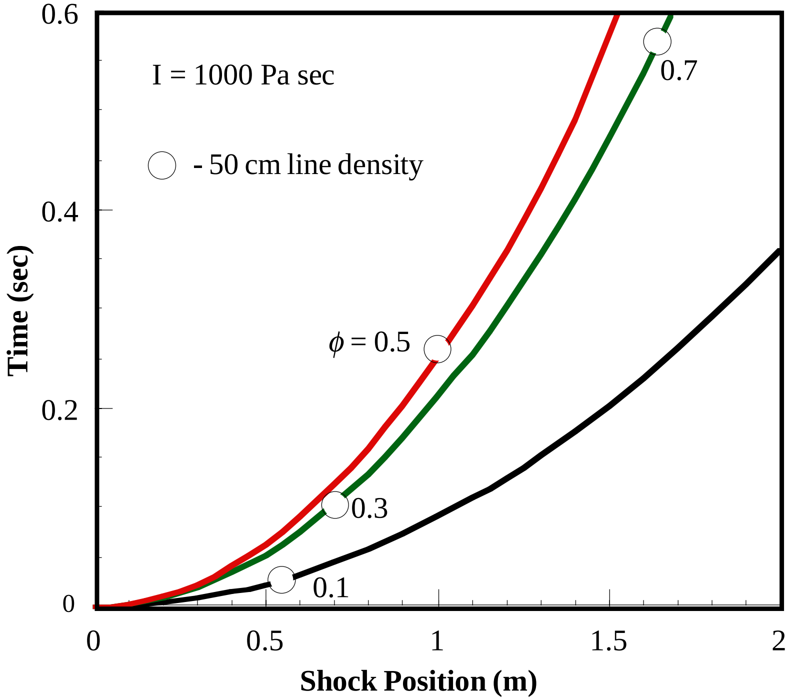
Porous Liquid Can Attenuate Shocks

- **Impulse from x-ray ablation and pocket pressurization generates shock**
- **Simple "snowplow" model gives shock transit time as function of liquid void fraction ϕ:**

$$t = \frac{\phi(1-\phi)\rho x_s^2}{2I}$$

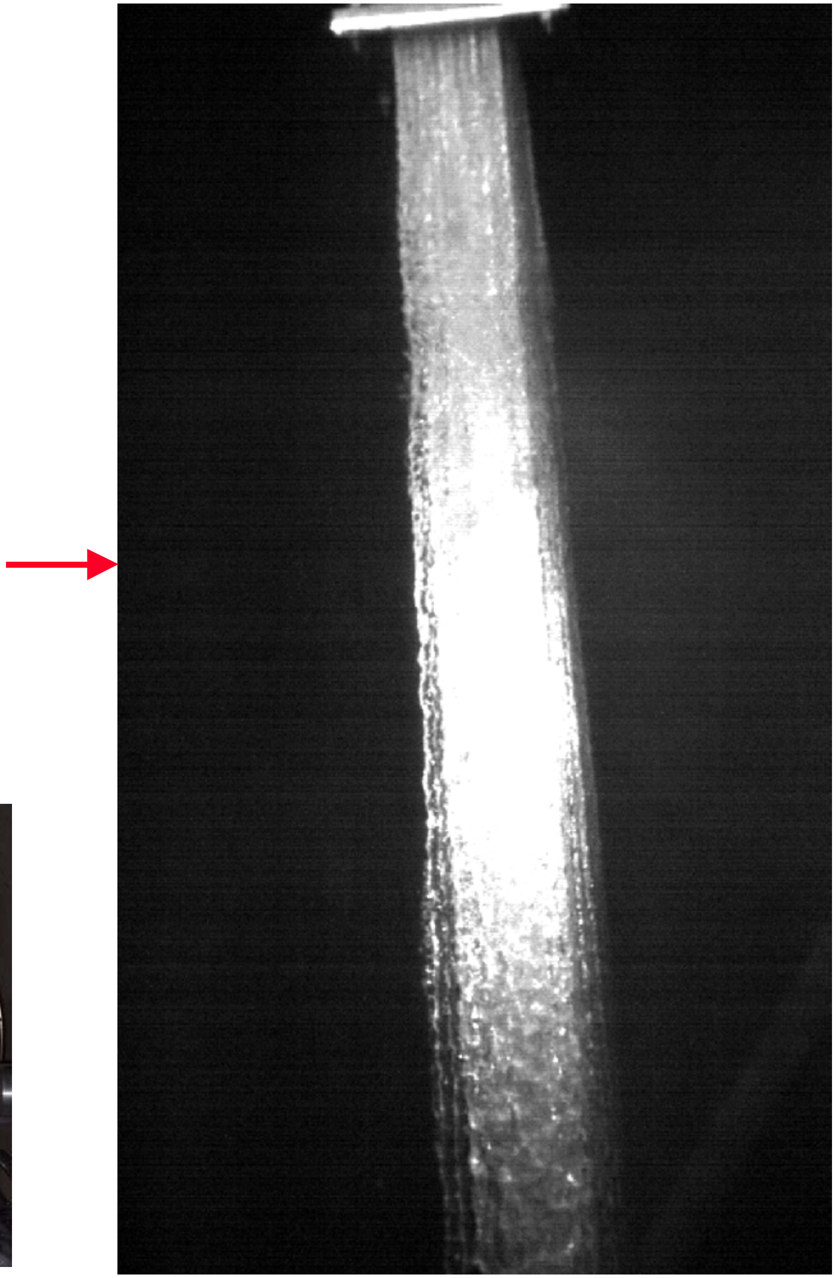
- **Shocks require > 100 ms to arrive at outside of porous pocket liquid**
- **Caveat: pocket openings may collimate high-velocity liquid**

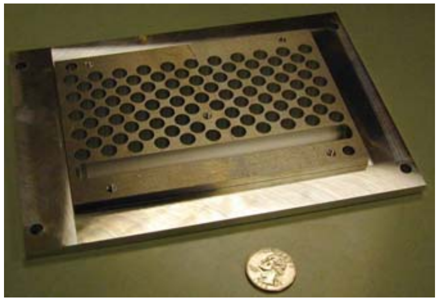


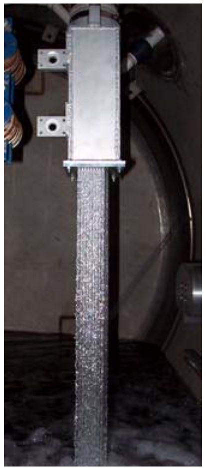


Porous liquid structures can mitigate shocks

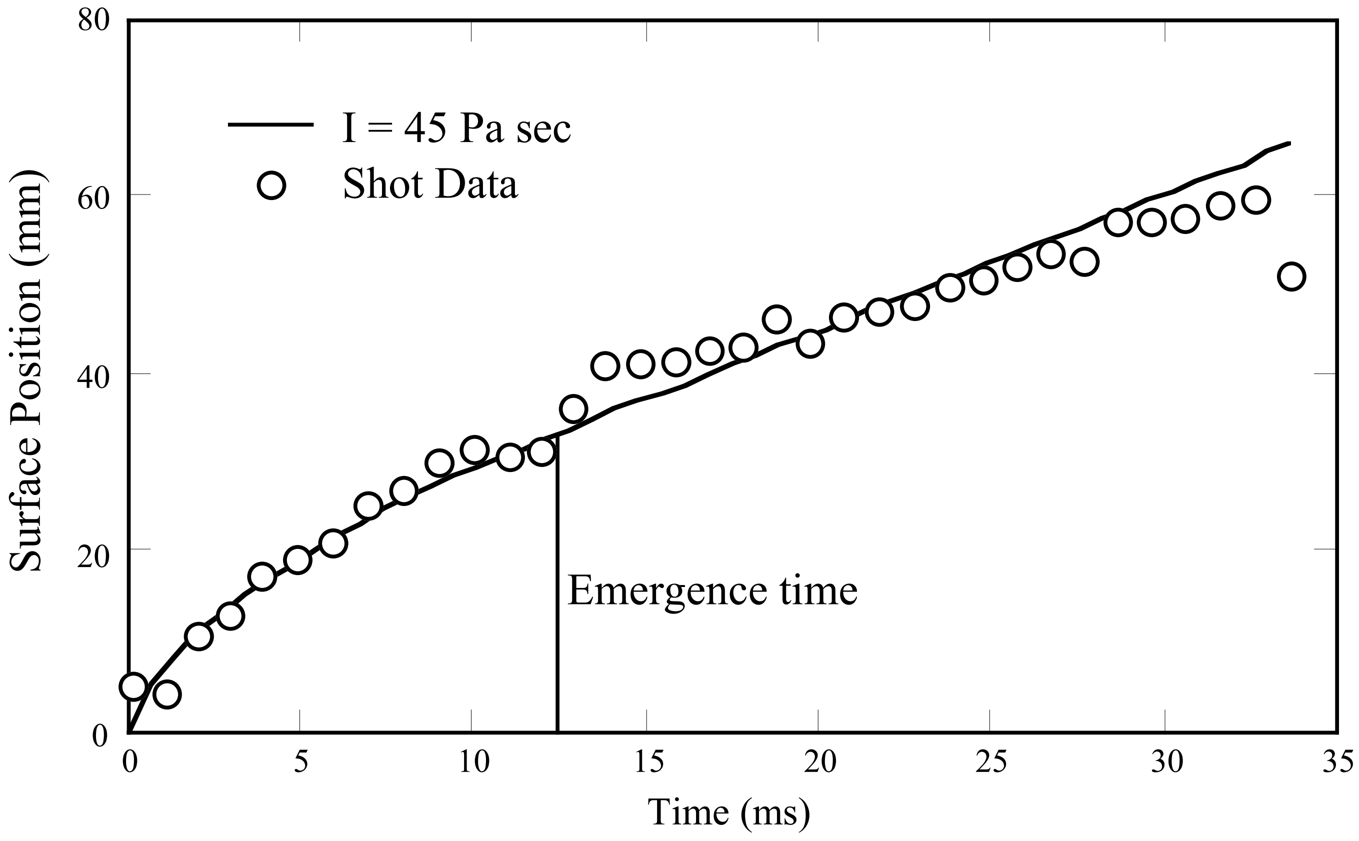
- Scaled partial-pocket experiments simulate HYLIFE
  - **1/4 geometric scale**
  - **1/4 pocket thickness**
  - **~100 Pa-sec scaled impulse**
- Current issues
  - **Incomplete powder burn (~10%)**
  - **Upgrade to exploding bridge-wire detonators**





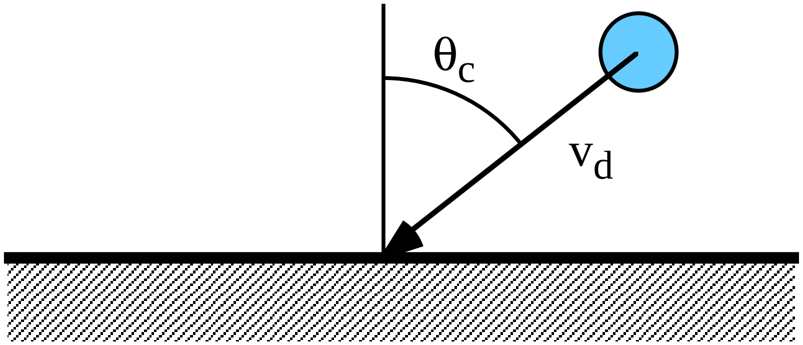


VHEX experiments have confirmed the snowplow model for shock propagation in voided liquids



Droplet erosion must be considered

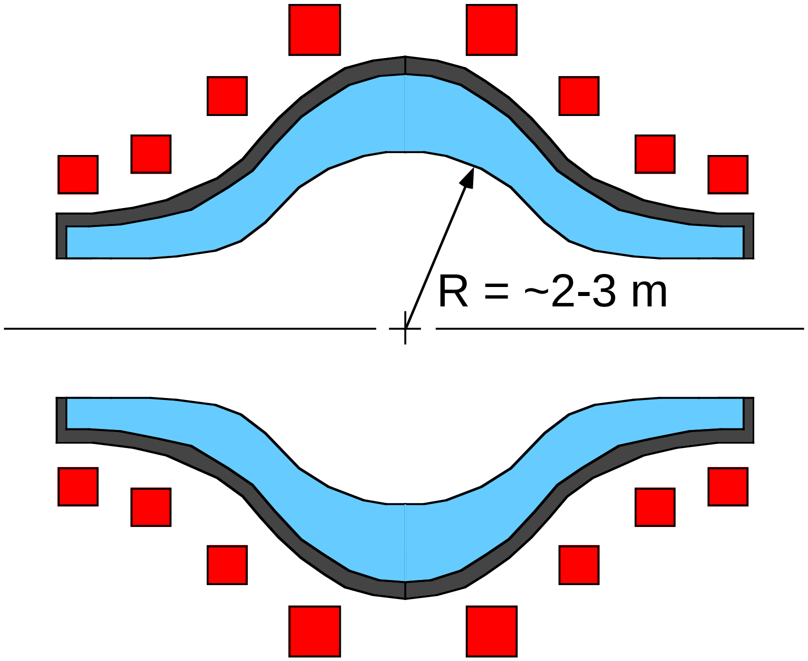
- **Peak substrate stress from droplets is proportional to**
  - **Liquid density (flibe:** 1992 kg/m^3)
  - **Liquid sound speed (flibe:** 3310 m/s)
  - **Liquid velocity**
- **Droplet erosion control will require further study**
  - **Mitigation by liquid films, other methods**

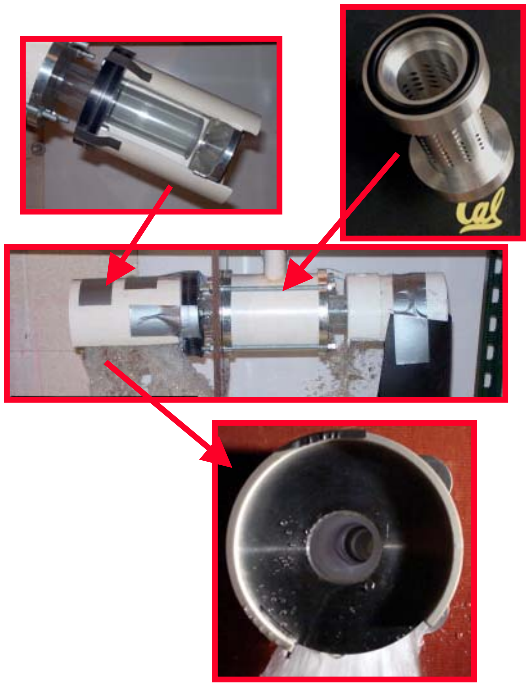


$$\Delta P_{WH} = \rho_o C_o v_d \cos(\theta_d)$$

Modular solenoid HIF chamber could potentially use a large-scale vortex flow

- **Issues:**
  - Using injection and suction to maintain vortex flow on substrate with non-uniform radius
  - Response of liquid layer to x-ray ablation (surface waves, substrate stresses, droplet ejection)
  - Effects of turbulent surface renewal on surface temperature and condensation

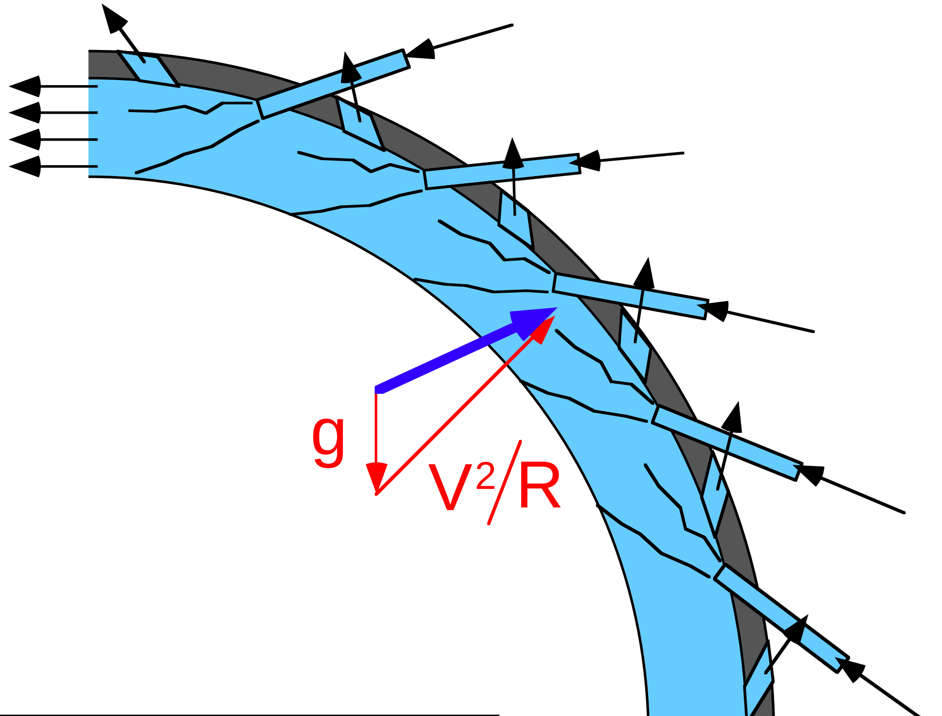




Vortex generation has been demonstrated experimentally

Fluid injection and suction can be used to control vortex layer momentum

- Injected jets add momentum to vortex layer
  - entrainment process equilibrates jet flow with layer flow, converts jet kinetic energy to turbulent kinetic energy, and
  - enhances free surface heat transfer
- Issues
  - Optimize momentum injection
    - overcome gravity ($\Delta H = V^2/2g$)
    - optimize pumping power/ average fluid residence time
  - Control surface waves at large and small length scales
    - include effects of target-induced impulse loads



Example parameters:
R = 2.5 m, t = 0.5 m, W = 6.0 m
for $U^2/gR = 2$, then U = 5.0 m/s
potential energy effect
$\Delta U = (2gH)^{1/2} = (4gR)^{1/2} = 10$ m/s
total liquid volume
$V = 50\ m^3$
bottom to top residence time
$\pi R/U = 1.5$ sec

Conclusions

- Thick liquid pockets experience very large impulse loads (~1000 - 4000 Pa-sec for HIF)
  - Accelerates inner liquid layer to high velocities (1 cm --> 50 - 200 m/s)
  - Initial kinetic energy must be dissipated, and momentum redistributed into larger liquid mass to give reasonable velocities
  - Potential for generation of high-velocity liquid droplets and slugs exists
  - Voided bulk liquid appears to respond according to the snowplow model
- Effects of x-ray impulse loads to vortex flows also needs study
  - May generated large-amplitude waves, liquid ejection, and substrate damage