Liquid Wall Ablation under IFE Photon Energy Deposition at Radius of 0.5 m

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From the ARIES Town Meeting on Liquid Wall Chamber Dynamics

- **Liquid wall ablation due to explosive boiling and spalling presented then:**
  - **Overview of mechanisms**
  - **Estimates for specific cases with R=3.5 and 6.5 m**
  - **These cases are more representative of a wetted wall design**
  - **Action item to investigate a case simulating HYLIFE with thick liquid jets at ~0.5 m from the microexplosion**
  - **Such a case has been analyzed and is presented here**

Physical Processes in X-Ray Ablation

Energy Deposition & Transient Heat Transport

Induced Thermal- Spikes

Mechanical Response

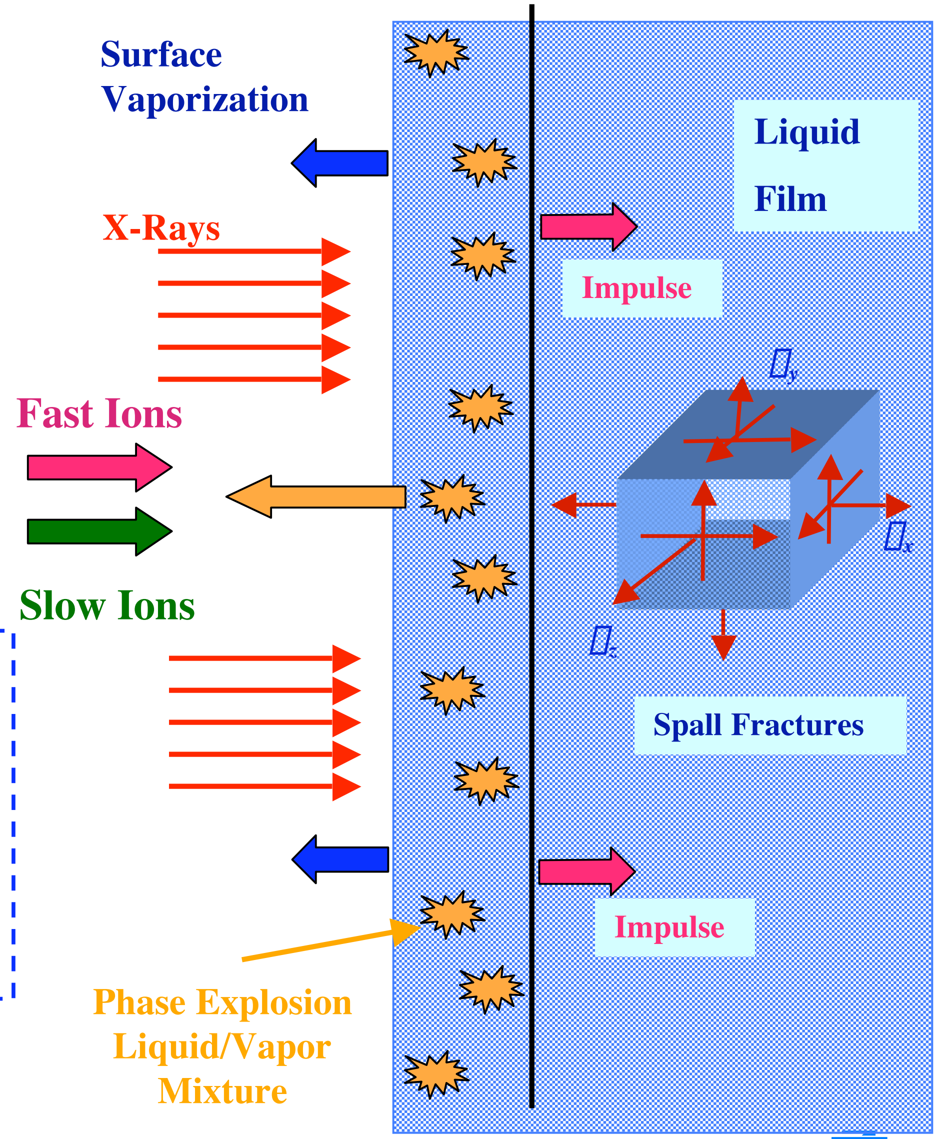
Phase Transitions

•Stresses and Strains and Hydrodynamic Motion
•Fractures and Spall

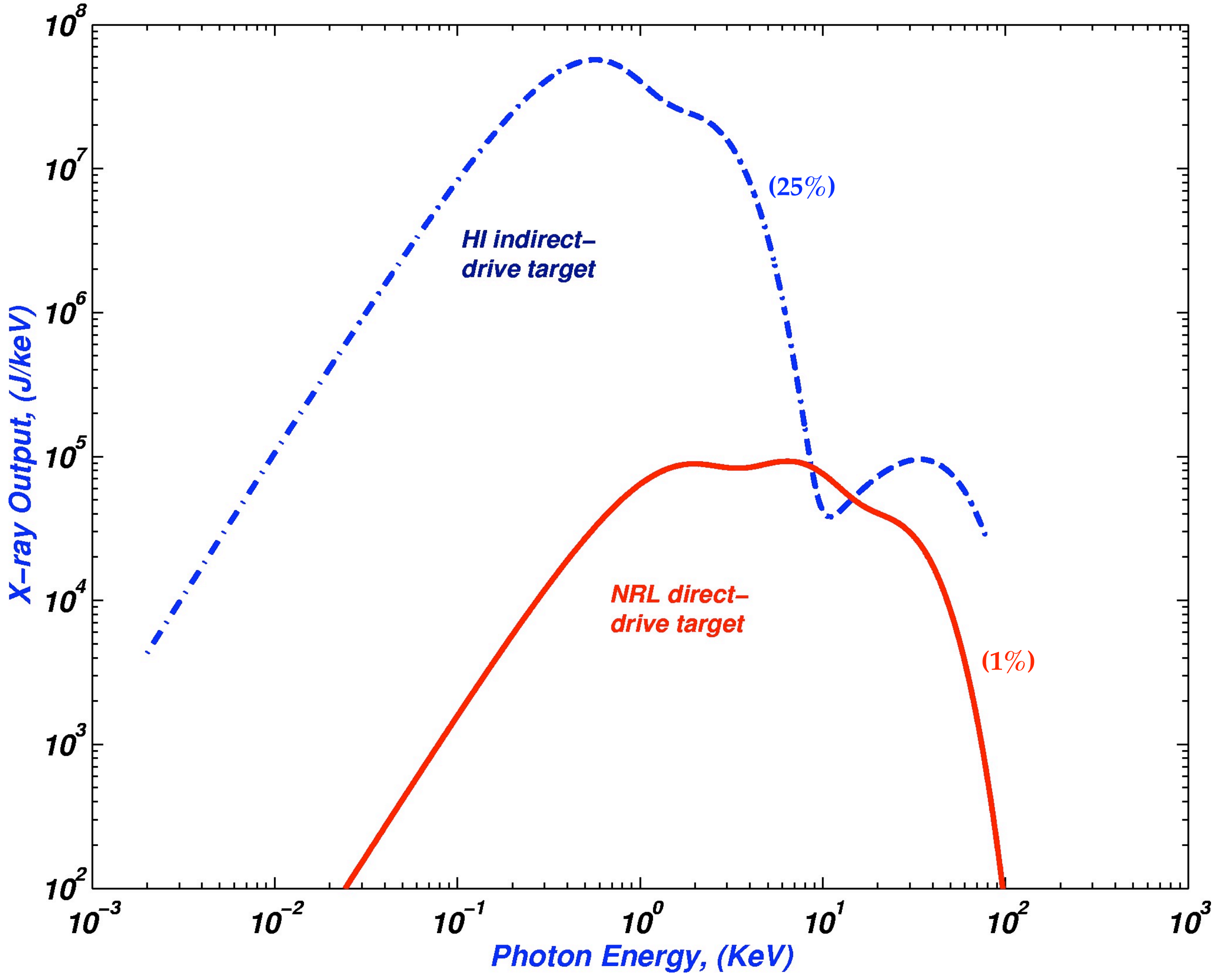
• Surface Vaporization
•Heterogeneous Nucleation
•Homogeneous Nucleation (Phase Explosion)

Ablation Processes

Expansion, Cooling and Condensation

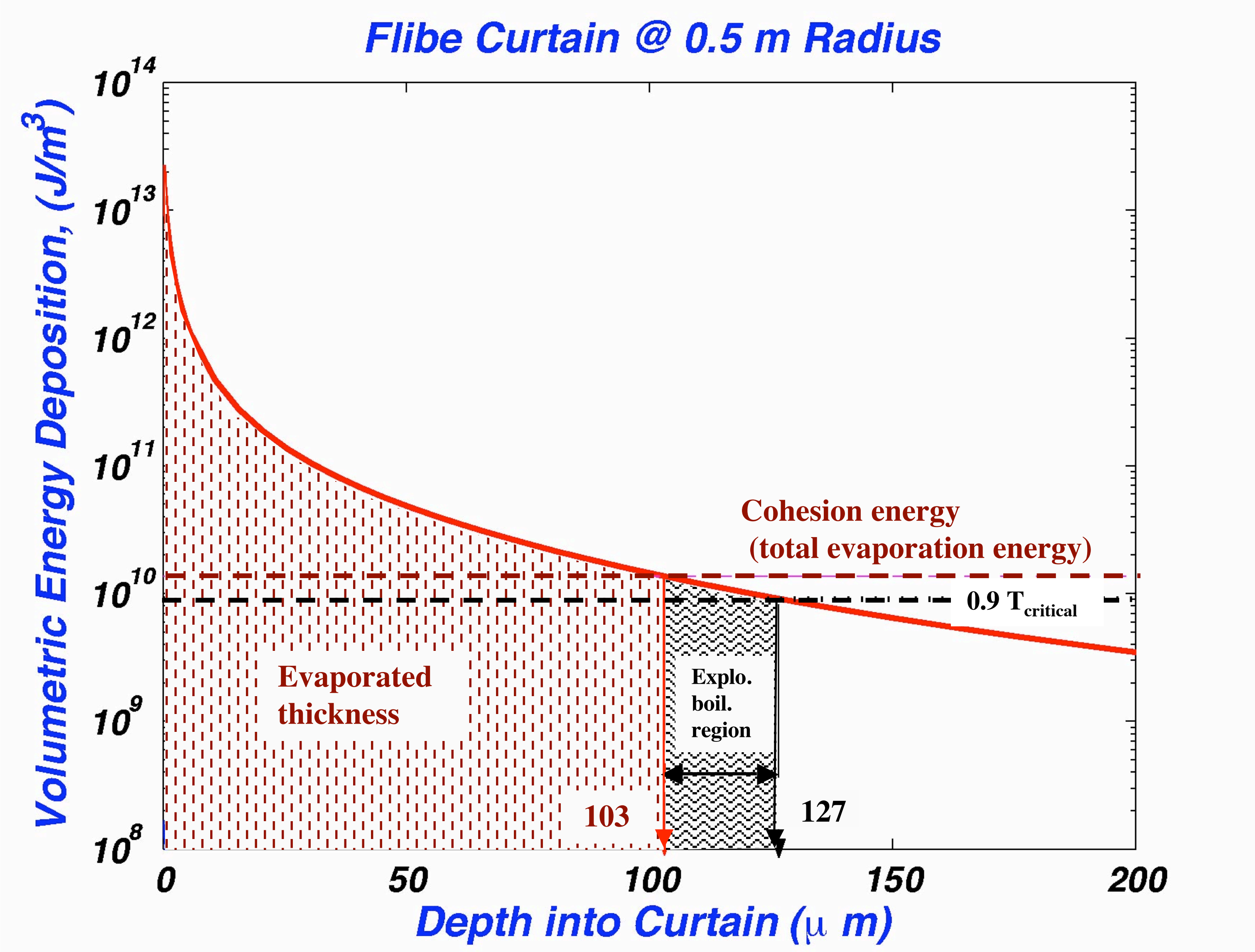


Analysis Based on Photon Spectra for 458 MJ Indirect Drive Target



- High photon energy for indirect drive target case (25% compared to 6% ion energy))
- More details on target spectra available on ARIES Web site: http://aries.ucsd.edu/ARIES/

Photon Energy Deposition Density Profile in Flibe Film and Explosive Boiling Region (for $R_{chamber}$=0.5m)



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Summary of Explosive Boiling Results for Different $R_{chamber}$'s

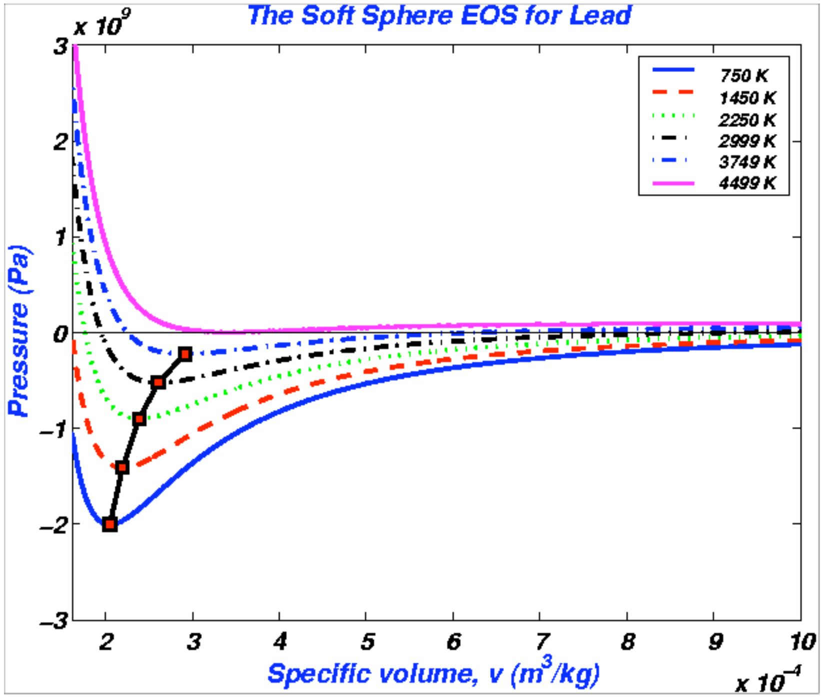
Explosive Boiling Ablated Thickness/Total Mass for:

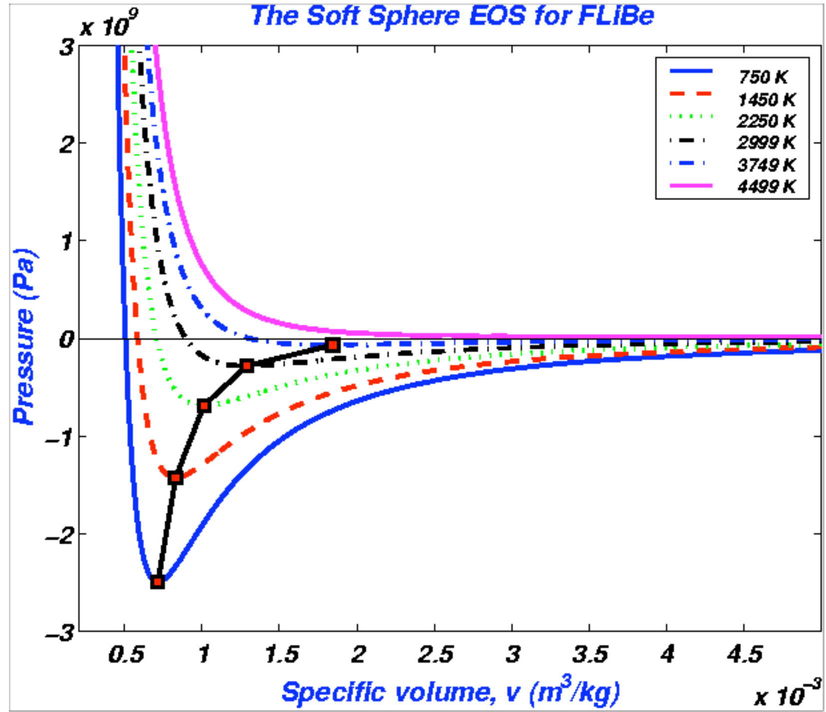
	Flibe	Pb
$R_{chamber}$= 6.5 m	4.1 □m/4.2 kg	2.5 □m/13.8 kg
$R_{chamber}$= 3.5 m	10.9 □m/3.4 kg	3.83 □m/6.2 kg
$R_{chamber}$= 0.5 m	127 □m/0.79 kg	

Mechanical Response to Induced Shock

- **Rapid increase in internal energy due to x-ray energy deposition and ablation impulse creates high pressure within the material**
  - **The induced shock wave propagates through the liquid:**
    - **If there is a stiff back wall, the shock wave gets reflected back to the free surface(as a pressure wave) where a rarefaction wave is produced (creating tensile stresses) and propagates back through the material. The process is repeated until the wave is dampened out.**
    - **For the realistic case of a non-perfectly stiff wall, the reflected wave (pressure or rarefaction) depends on the shock impedances of the two materials.**
    - **If there is a free surface at the back of the jet, a rarefaction wave is created there, propagating back through the liquid. The extent of this process and of its repetition depends on the dampening (or decaying) of the shock.**
  - **If the magnitude of the rarefaction wave is greater than the tensile strength of the material, fracture or spall will occur establishing a new surface.**
- **Evolution of spall in a body subject to transient stresses is complex**
  - **Material dependent: brittle, ductile or liquid**
  - **Affected by perturbations**
  - **Upper bound theoretical spall strength derived from intermolecular potential**

Temperature-Dependent Spall Strengths of Example Materials





T (K)	Pb (GPa)	Li (GPa)	Flibe (GPa)
750	-2.0014	-1.4401	-2.4914
1450	-1.4098	-0.8950	-1.4212
2250	-0.8981	-0.4267	-0.6848
2999	-0.5221	-0.1010	-0.2814
3749	-0.2235	Gas	-0.0657

Parameters of Different IFE Reactor Design Studies & Pressure Pulse Profile

Parameters	Prometheus-L	Osirus	Hiball	Present Study				
Liquid/Structure	Pb/SiC	Flibe/C	Pb-17Li/SiC	Pb/SiC		Flibe/SS		Flibe
X-ray yield (MJ)	31	129*	95	115		115		115
Closest distance from target (m)	5	3.5	5	6.5	3.5	6.5	3.5	0.5
Vaporized mass (kg/m^2)	0.0125	0.0278	0.0234	0.026	0.04	0.008	0.022	0.251
Reactive impulse** (Pa-s)	22	59.0	60	15.2	23.31	17.3	45.77	525.6

* X-ray and debris

** Ablated material velocity ~ sonic velocity ~ 586/2094 m/s for Pb/Flibe at T_{crit} (~5100/4500 K)

- The pressure wave is steady (no change in shape)
- Parameters of different IFE reactor design studies and the present study are comparable
- Osirus profile scaled according to the relative impulses and used for the present analysis.

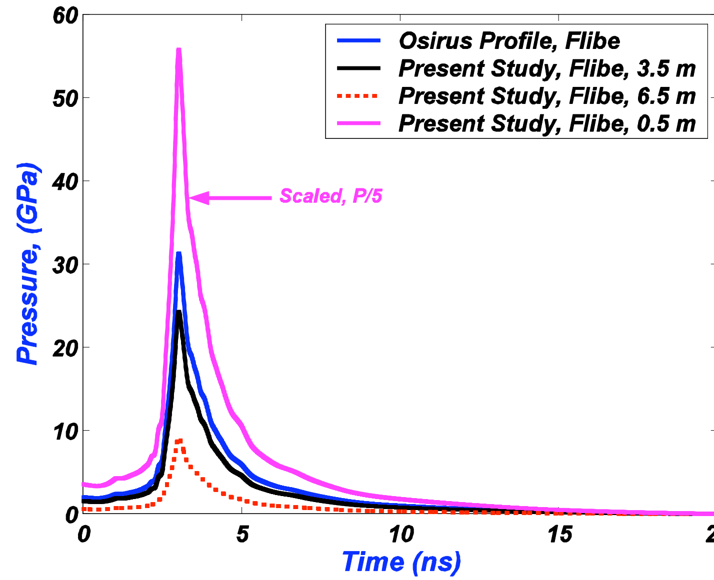


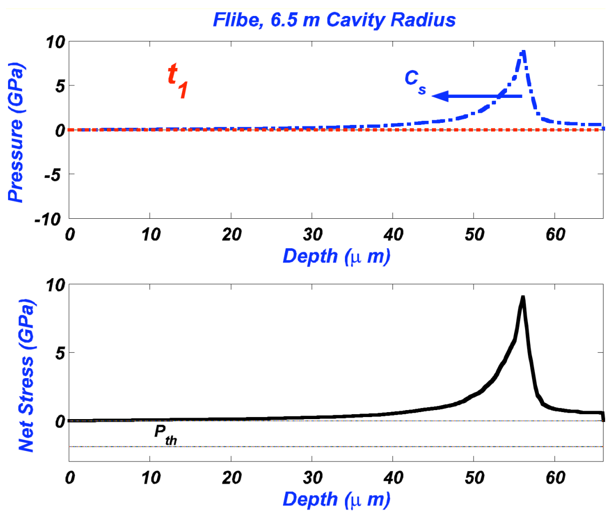
Illustration of Spalling Following a Pressure Wave Propagation in a Thin Flibe Layer on a Perfectly Stiff Wall

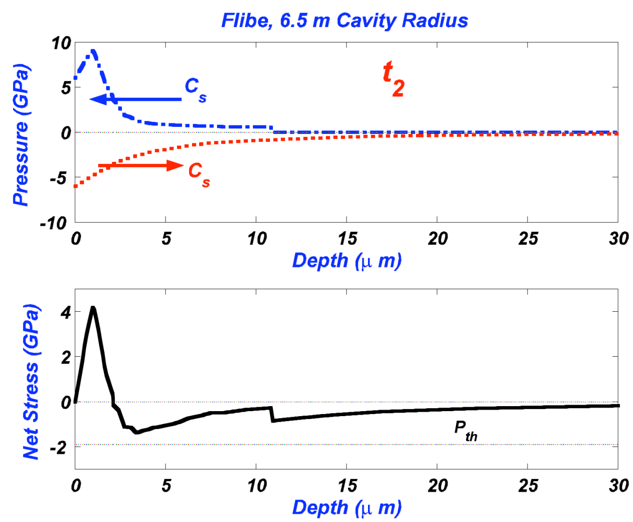
□□2000 kg/m3, *C_s□3300 m/s,* *T_{in} = 885.7 K,* *P_{th} = -1.887 GPa*

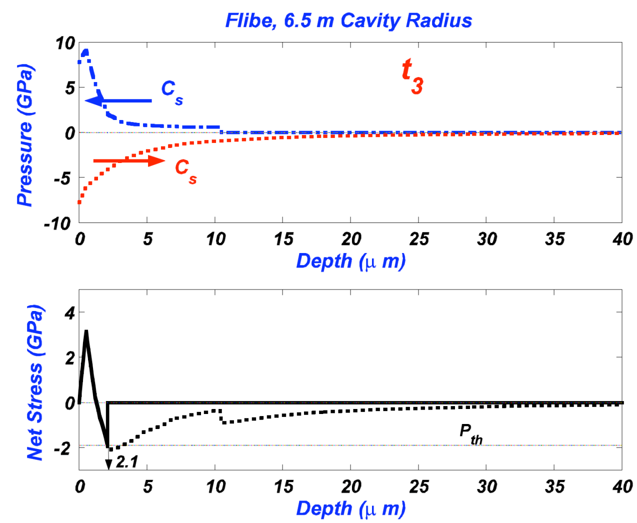
1. For a perfectly stiff wall, the pressure wave is reflected from the wall and returns to the free surface as a pressure pulse

2. $P_{free\text{-}surface} = P_{chamber}$ and the pressure pulse arriving at the free boundary must be reflected back as a tensile wave

3. If the net tensile stress > the spall strength of the material, rupture occurs establishing a new surface





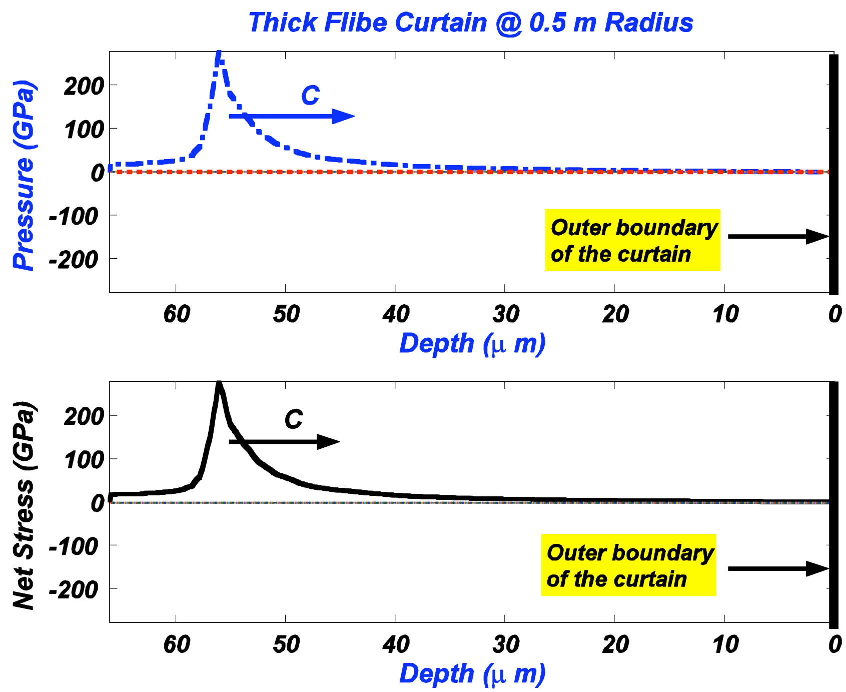


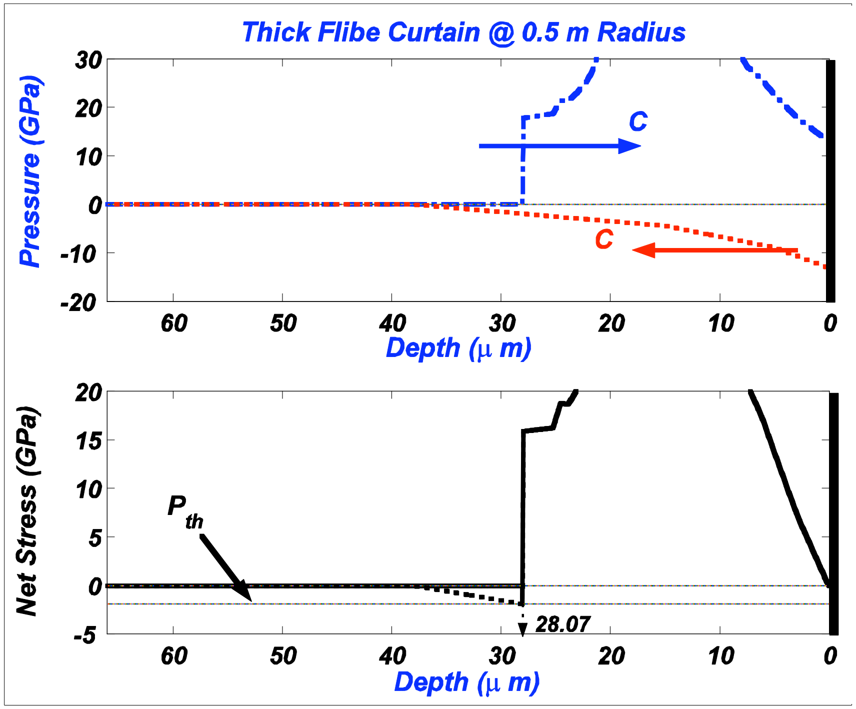
Spalled Thickness □2.1 μm & Spall Time ($t_3 - t_1$) □16.9 ns

Spall time from the beginning of the pressure pulse = 2 L/C_s+ (t_3-t_1)□200 ns for a 0.3 mm flibe layer

Illustration of Spalling in the Case of a Thick Free Jet at R=0.5 m from Microexplosion

- From Janatzen & Peterson (*), the peak pressure in the wave would decay rapidly over the first few mm's of depth. Accordingly, for thick liquid jets, only a small fraction of the total thickness would experience high stresses.
- However, the theoretical spall strength of flibe is about 2 orders of magnitude lower than the magnitude of the initial shock for this case and even a "dampened" shock could result in spalling depending on the conditions (jet thickness,…)
- As an illustration, a conservative estimate of spalling was made under a worst case scenario of a steady pressure wave (i.e. no change in shape as assumed before) for a liquid jet with no back wall





(*) C. Janatzen, P. F. Peterson, "Scaled impulse loading for liquid hydraulic response in IFE thick-liquid chamber experiments," Nuclear Instruments and Methods in Physics Research A, 464 (2001) 404-409.

Summary of Ablation Results

		Flibe	Pb
Explosive boiling thickness (μm)	R=0.5 m	**127**	
	R=3.5 m	**10.9**	**3.8**
	R=6.5 m	**4.1**	**2.5**
Spallation thickness (μm) (for a wetted wall assuming a perfectly stiff wall except for R=0.5 m which is for a thick free jet case)	R=0.5 m	**28 from free surface at rear of jet**	
	R=3.5 m	**4.1**	**1.8**
	R=6.5 m	**2.1**	**1.1**
Total fragmented thickness (μm)	R=3.5 m	**15.0**	**5.6**
	R=6.5 m	**6.2**	**3.6**

Summary

- The energy deposition density is increased substantially for the R=0.5 m case (compared to the previous R=3.5 and 6.5 m cases)
- The resulting $\delta_{expl.boil.}$ for flibe is 127 μm for the case analyzed corresponding to an ablated specific mass (kg/m^2) and impulse (Pa-s) more than one order of magnitude higher than the 3.5 m case
- The resulting shock wave through the thick liquid jet could decay relieving the spalling concern. The extent of the shock dampening and the possibility of spalling depend on the conditions (impulse, jet thickness, local spall strength…).
- For the conservative assumption of a steady pressure wave through the jet to the rear free surface, the rarefaction wave generated would cause local spalling at about 28 μm from the rear surface
- This could affect the formation and behavior of aerosols in the chamber if this fractured layer at the back of the jet finds a way out of the pocket
- However, the dynamic processes occurring are quite complex and should be further assessed through a combination of modeling and scaled experiments