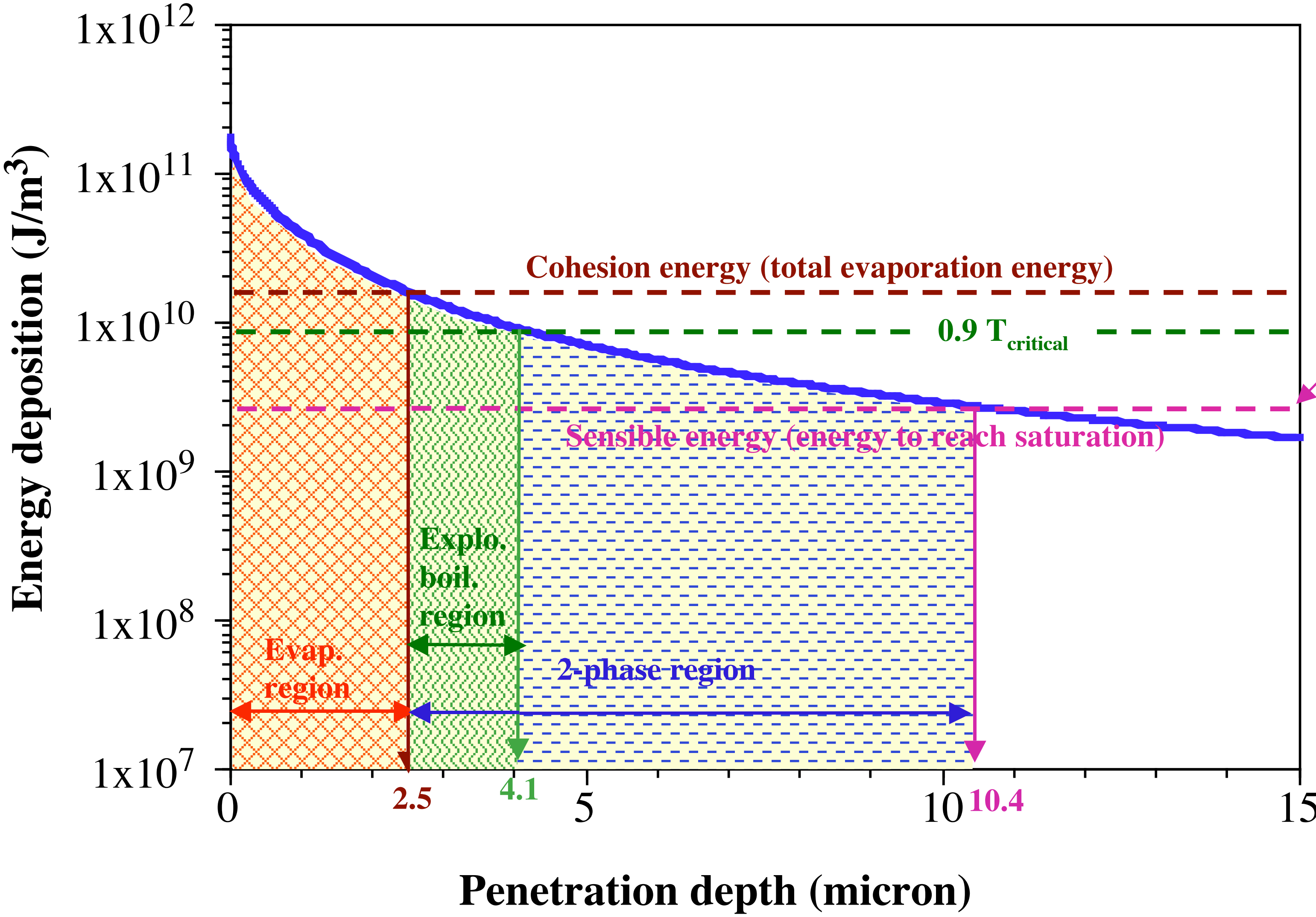
1. Pre-Shot Aerosol Parametric Design Window for Thin Liquid Wall

2. Scoping Liquid Wall Mechanical Response to Thermal Shocks

A. R. Raffray and M. Zaghloul
University of California, San Diego

ARIES Meeting
UCSD
San Diego, CA
January 8-10, 2003

Photon Energy Deposition Density Profile in Flibe Film and Explosive Boiling Region



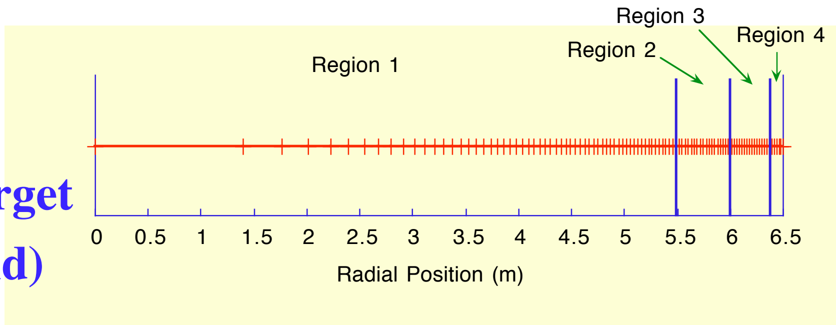
Sensible energy based on uniform vapor pressure following photon passage in chamber and including evaporated Flibe from film

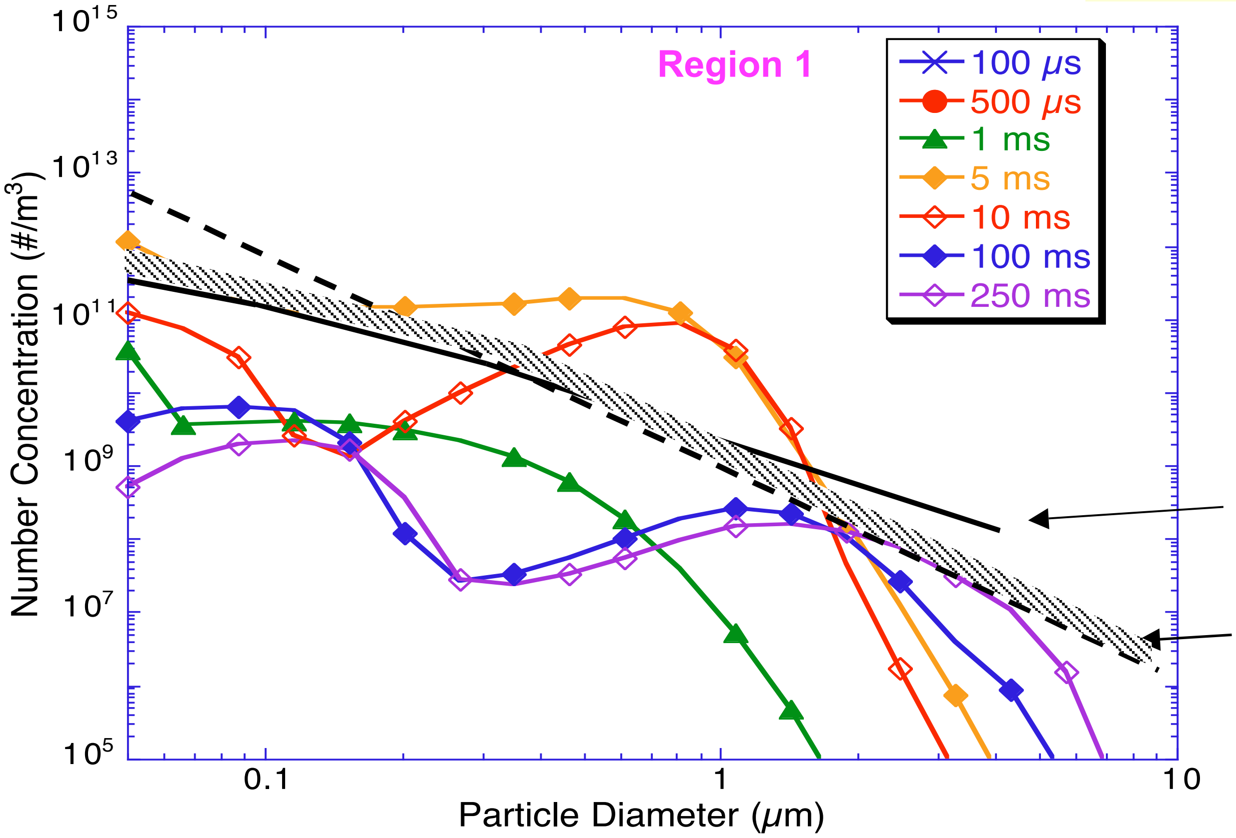
Bounding estimates of aerosol source term:

(1)Upper bound: the whole 2-phase region; (2)Lower bound: explosive boiling region

Analysis of Aerosol Formation and Behavior

- **Spherical chamber with a radius of 6.5 m**
- **Surrounded by liquid Pb wall**
- **115 MJ of X-rays from 458 MJ Indirect Drive Target**
- **Explosive boiling source term (2.5μm, lower bound)**



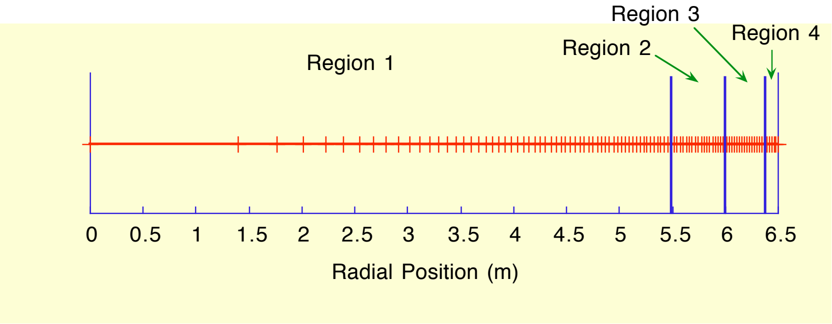


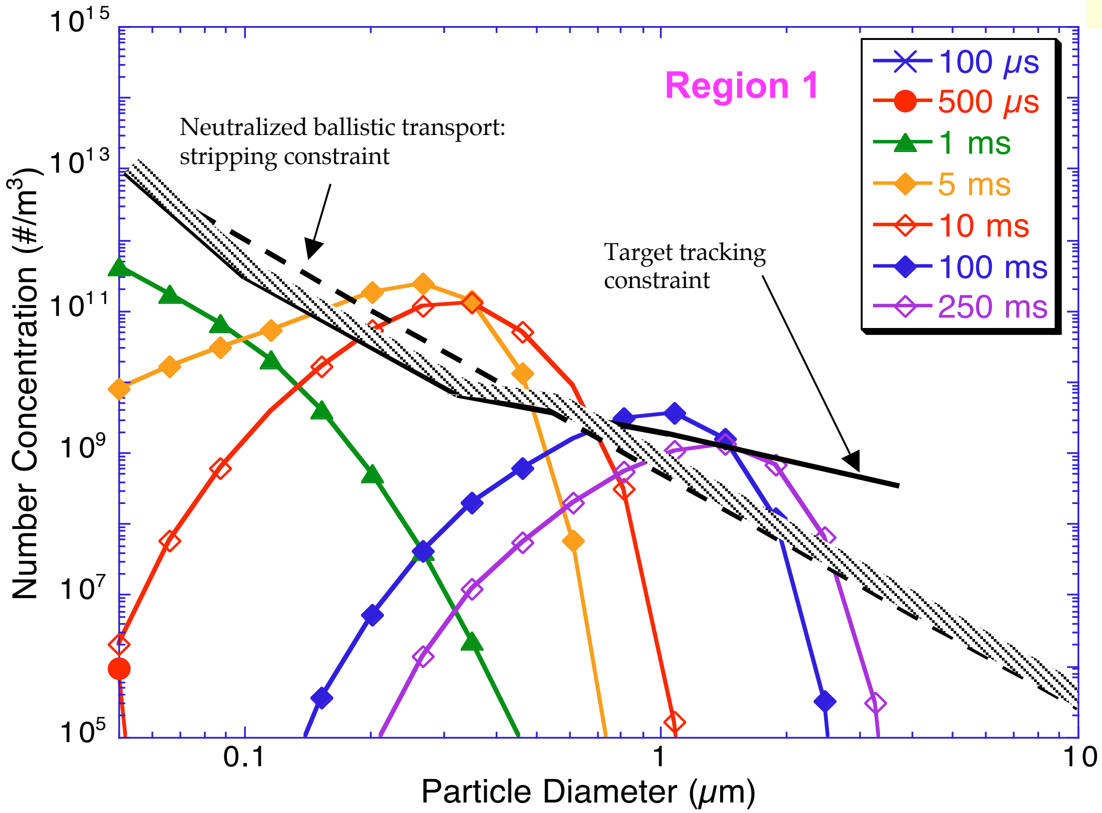
- **Appreciable # and size of aerosol particles present after 0.25 s**
  - **~10^7-10^9 droplets/m^3 with sizes of 0.05-5 μm in Region 1**
- **Preliminary estimate of constraints:**
  - Target tracking based on 90%beam propagation
  - Heavy ion driver based on stripping with integrated line density of 1 mtorr for neutralized ballistic transport

- From the analysis, aerosol formation could be a key issue and need to be further addressed
- Driver and target constraint also need to be more accurately defined

Analysis of Aerosol Formation and Behavior for Flibe

- **Spherical chamber with a radius of 6.5 m**
- **Spectra from 458 MJ Indirect Drive Target**
- **Explosive boiling source term (5.5 µm)**





- **Aerosol size and # after 0.25 s**
  - **10^7-10^9 droplets/m^3 with sizes of 0.3-3 µm**
  - **Exceeds driver limit**
- **Again, from this analysis, aerosol formation could be a key issue**
- **Needs to be addressed by future effort**

Concluding Remarks from Initial Aerosol Analysis and Parametric Design Window Study

- **High energy deposition rate of X-rays would lead to explosive boiling**
  - Provide bounding estimates for aerosol source term

- **Aerosol modeling analysis indicate substantial # and size of droplets prior to next shot for both Pb and FLiBe**
  - Preliminary estimates of constraints for indirect-drive target and heavy ion driver
  - Marginal design window (if any)

- **Future effort:**
  - Better understanding aerosol source term and behavior
  - Confirmation of target and driver constraints

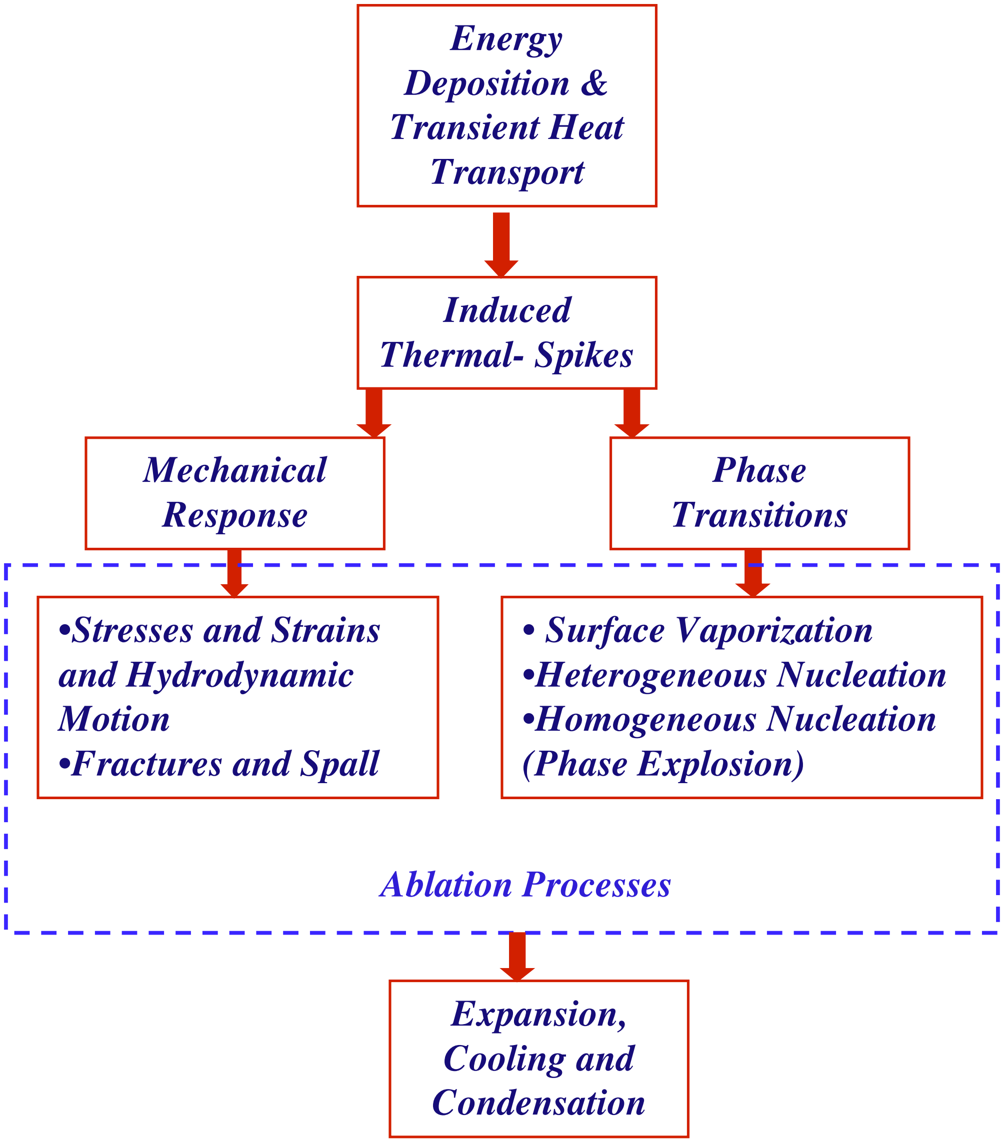
Proposed 2003 Effort on Wall Ablation as Aerosol Source Term

- **Integrated effect of liquid wall thermal and mechanical responses to X-ray energy deposition to provide bounding estimates of ablation as source term for aerosol analysis**
  - First principle consideration
  - Ablation depth of liquid wall
  - Form (vapor, liquid droplets) of the removed material

- **Thermal response previously estimated**
  - Explosive boiling is the key process

- **Investigation of liquid wall mechanical response to rapid x-rays energy deposition in analogy to thermal response analysis**
  - Spall strength of materials as compared to anticipated IFE shocks
  - Fracture or spall time scale
  - Droplets size and distribution
  - Consider Pb, FLiBe and Li as example liquid wall materials

Physical Processes in X-Ray Ablation



Energy Deposition & Transient Heat Transport

Induced Thermal- Spikes

Mechanical Response

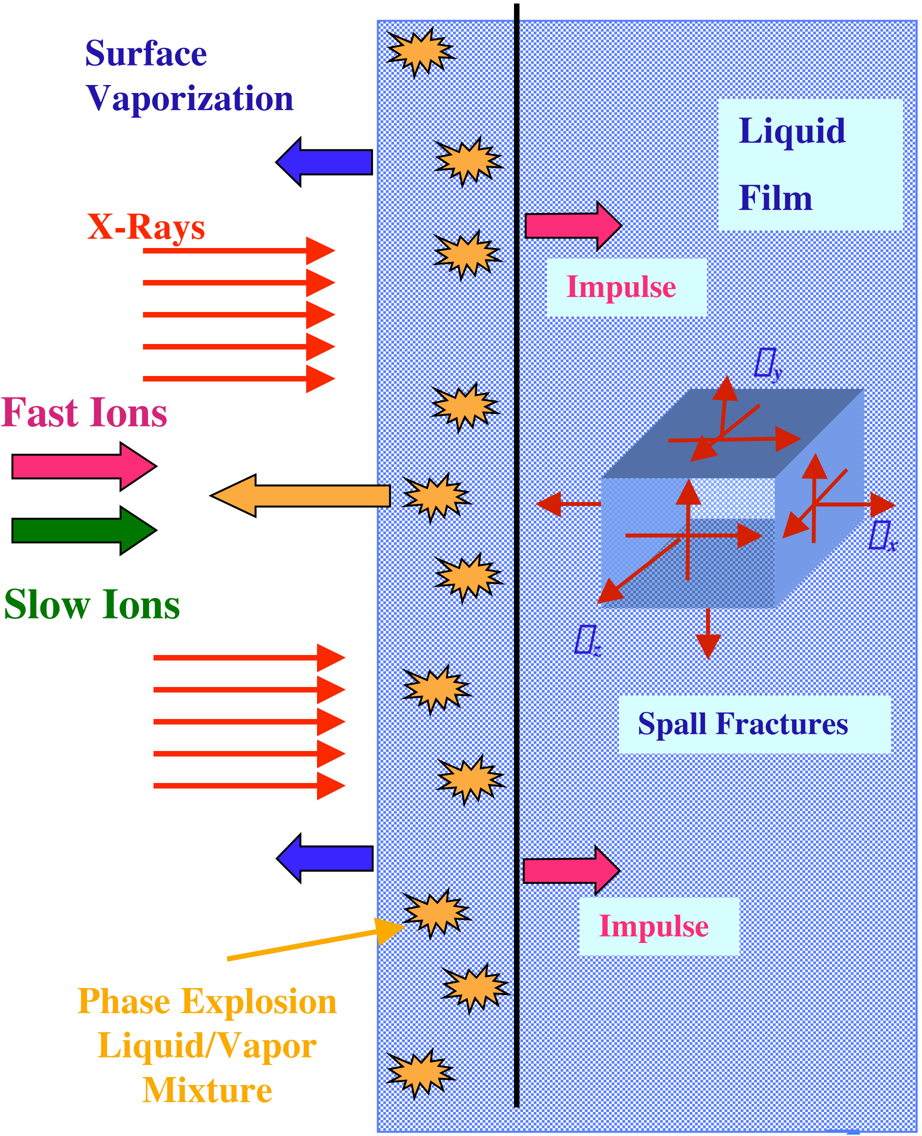
Phase Transitions

- *Stresses and Strains and Hydrodynamic Motion*
- *Fractures and Spall*

- *Surface Vaporization*
- *Heterogeneous Nucleation*
- *Homogeneous Nucleation (Phase Explosion)*

Ablation Processes

Expansion, Cooling and Condensation



Mechanical Response to Induced Shock

- **Rapid increase in internal energy due to x-ray energy deposition and/or ablation impulse creates high pressure within the material**
  - **Following the induced shock waves, rarefaction waves (producing tensile stresses) propagate from the surface into the bulk of the material.**
  - **If the magnitude of this 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**
  - **Small perturbations can lead to opening of voids and initiation of spall process**
  - **A reasonable prediction of the dynamic spall strength, time to failure, and some measure of the nominal fragment size created in the spall event are needed to characterize the spall process**
  - **An upper bound theoretical spall strength can be derived from intermolecular potential**

Theoretical (Maximum) Spall Strength Provides an Upper Bound Estimate in the Absence of Appropriate Spall Data

- **Based on intermolecular potential reflecting dependence on cohesive energy and bulk modulus with inherent energy balance**

  - Using a three-parameter potential such as the Morse potential

$$U(v) = U_{coh}\left[\exp\left(\frac{-2(v-v_0)}{a}\right) - 2\exp\left(\frac{-(v-v_0)}{a}\right)\right]$$

  - The cold pressure is given by:

$$P(v) = -\frac{dU}{dv} = \frac{2U_{coh}}{a}\left[\exp\left(\frac{-2(v-v_0)}{a}\right) - \exp\left(\frac{-(v-v_0)}{a}\right)\right]$$

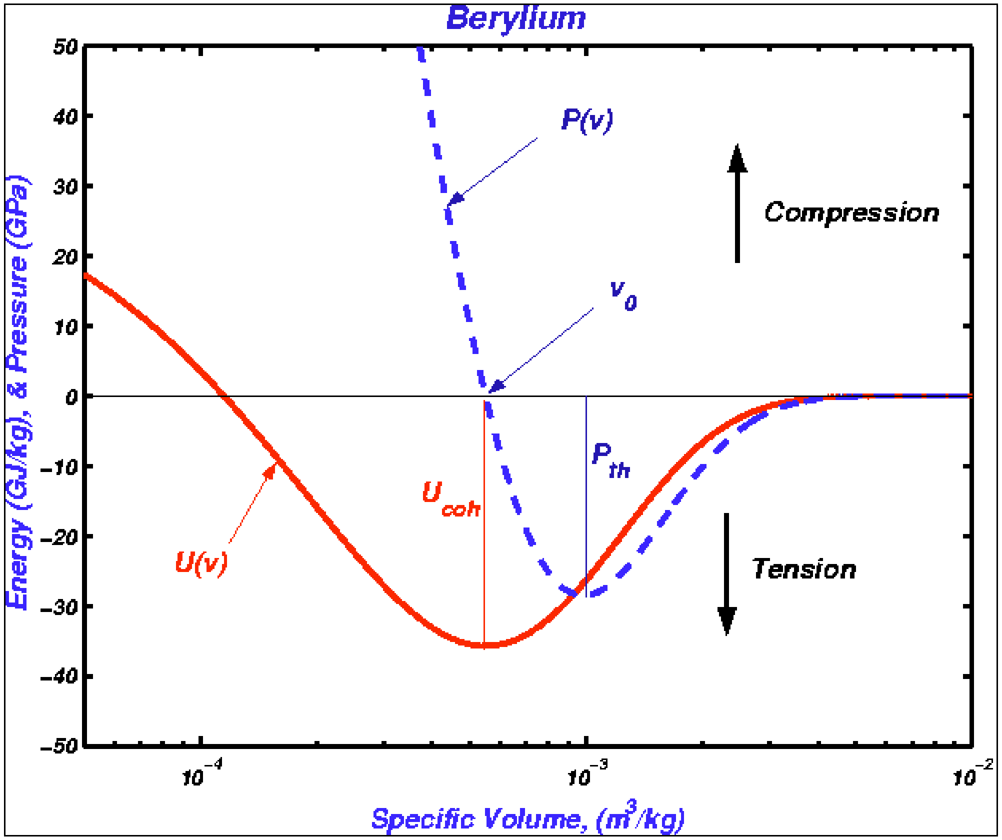
U_{coh} = Specific cohesive energy

$v = 1/\rho$ = Specific volume

v_0 = Specific volume at zero pressure

$a=(2v_0\, U_{coh} / B_0)^{1/2}$

B_0 = Bulk modulus



Theoretical spall strength, P_{th}, given by minimum of P(v):

$$P_{th} = \sqrt{\frac{U_{coh}\, B_0}{8\, v_0}}$$

Spall Strength is Highly Temperature Dependent

- **Using the Soft Sphere EOS to Estimate Temperature-Dependent Spall Strength**

$$U(v,T) = U_{coh} + N K_B T \left[\frac{3}{2} + C_n \rho^{n/3} \left(\frac{\varepsilon}{K_B T} \right) + \frac{1}{6} (n+4) Q \rho^{n/9} \left(\frac{\varepsilon}{K_B T} \right)^{1/3} - \rho^m \left(\frac{\varepsilon}{K_B T} \right) \right]$$

$$P(v,T) = \frac{N K_B T}{V} \left[1 + \frac{1}{3} n C_n \rho^{n/3} \left(\frac{\varepsilon}{K_B T} \right) + \frac{1}{18} n(n+4) Q \rho^{n/9} \left(\frac{\varepsilon}{K_B T} \right)^{1/3} - m \rho^m \left(\frac{\varepsilon}{K_B T} \right) \right]$$

n, m, Q, ε and σ are adjustable parameters to satisfy the available experimental data

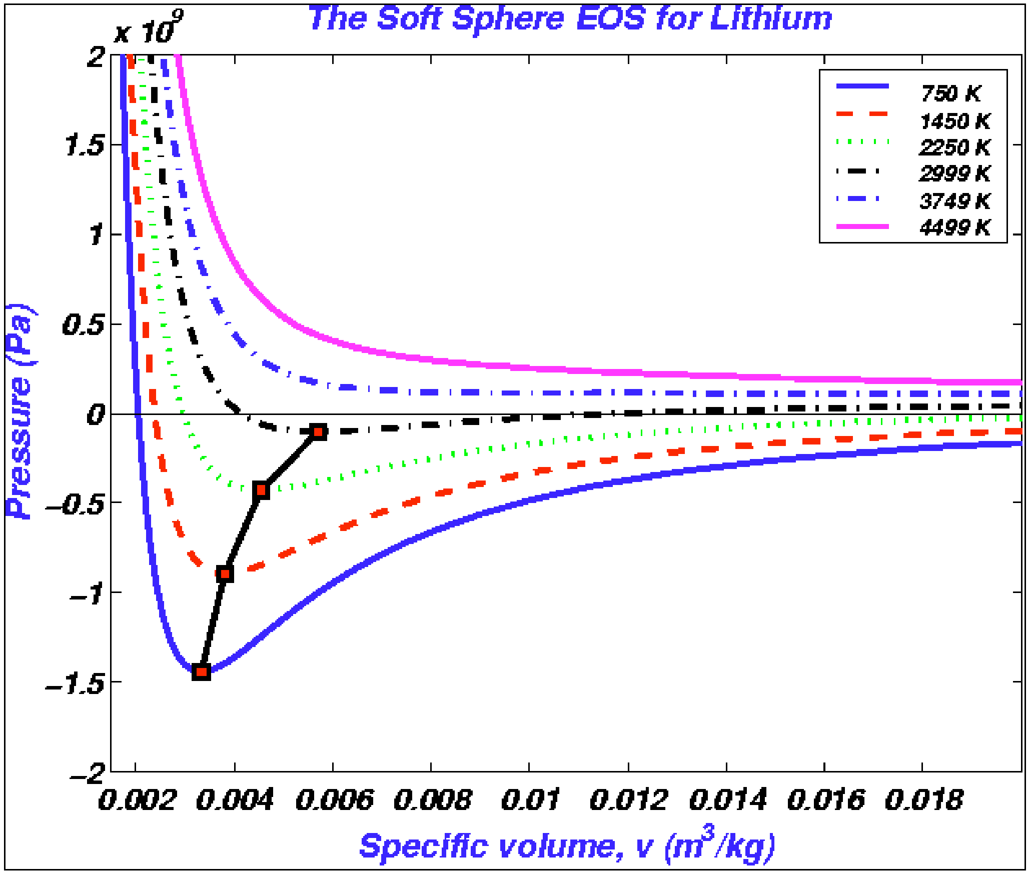
N: Number of molecules,

V: Specific volume,

$\rho = N \sigma^3 / (2^{1/2}) V$,

σ: the sphere diameter,

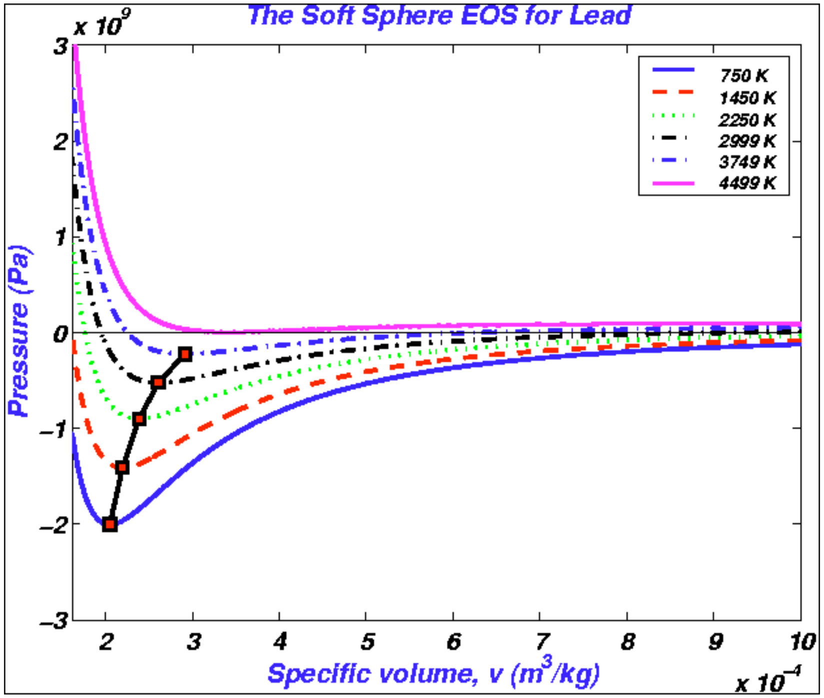
C_n: *FCC Madelung constant.*

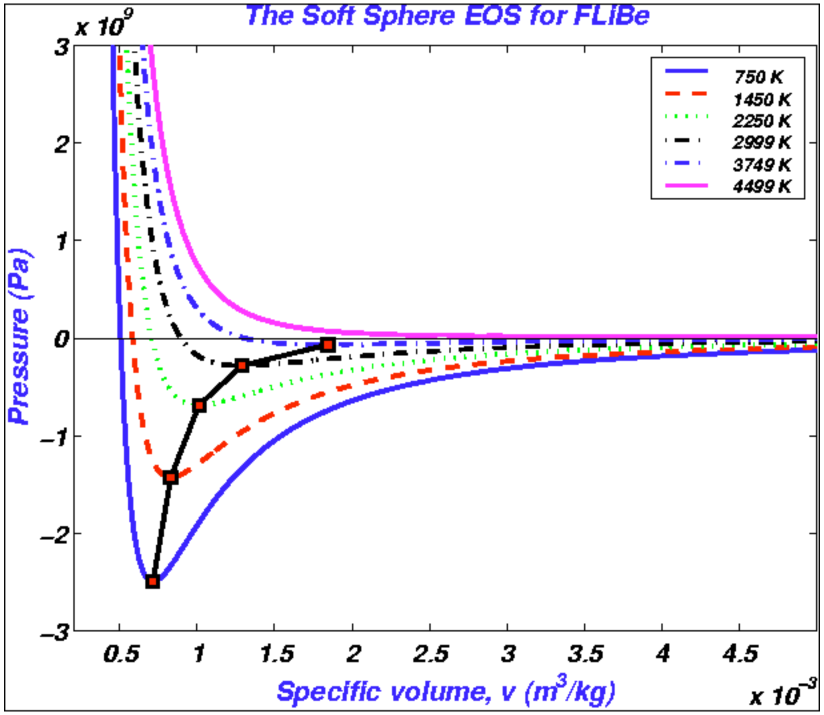


- **Theoretical spall strength is then calculated from:**

$$\frac{d\,P(v,T)}{d\,v} = 0.$$

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

Comparing Spall Strengths of Liquid Walls to Estimated Tensile Stress Resulting from Thermal Spike and Ablation Impulse

- **Assuming rarefaction wave of same order as shock wave (P):**

  - Ablation thickness from explosive boiling, □~ 2.5/4.1 □m for Pb/FLiBe)
  - Time scale of X-ray energy deposition ~1-10 ns
  - Ablated material velocity, v ~ sonic velocity ~ 586/2094 m/s for Pb/FLiBe at T_{crit} (~5100/4500 K)
  - Density, □ ~ 11,300/1590 kg/m^3 for Pb/FLiBe

  - P ~ □□ □v/□t ~ 1.7 / 1.4 GPa for Pb/FLiBe

T (K)	Pb (GPa)	FLiBe (GPa)
750	-2.0014	-2.4914
1450	-1.4098	-1.4212
2250	-0.8981	-0.6848
2999	-0.5221	-0.2814
3749	-0.2235	-0.0657

- **Based on these estimates, pressure and corresponding tensile stress > spall strength**
- **More detailed analysis required**

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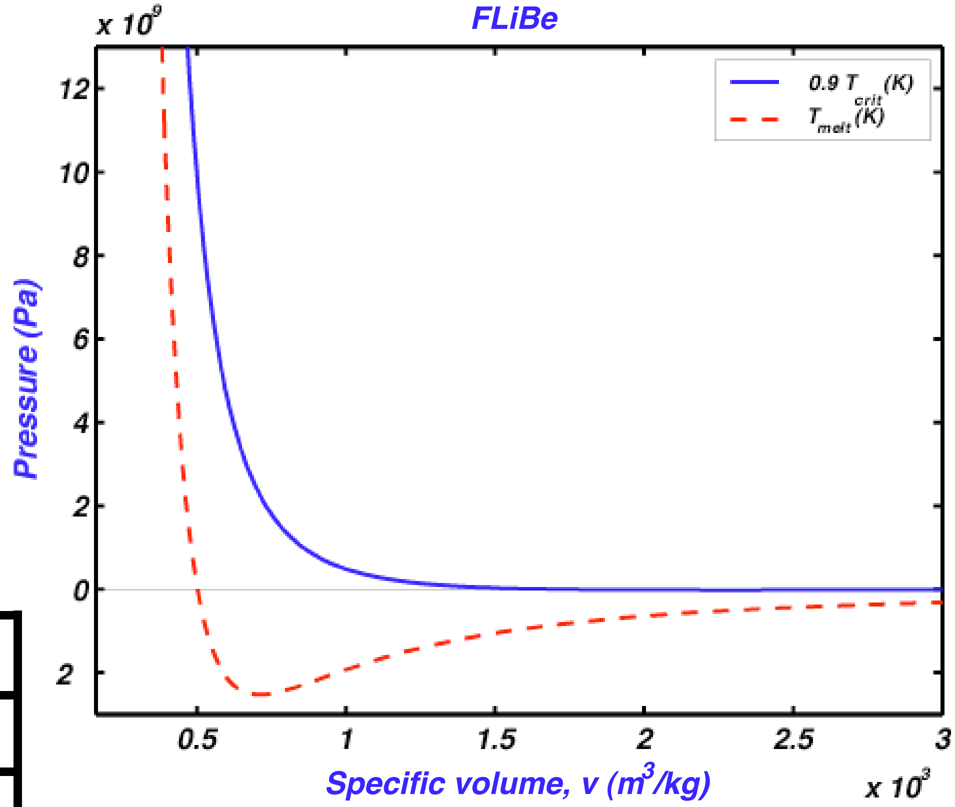
Comparing Spall Strengths of Liquid Walls to Estimated Tensile Stress Resulting from Thermal Spike and Ablation Impulse

- Melting point isotherm show specific volume at zero pressure

- Corresponding specific volume at explosive boiling surface (0.9 Tcrit) yields estimate of pressure at surface interface surface

- P ~ 5.8 / 9.7 GPa for Pb/FLiBe

T (K)	Pb (GPa)	FLiBe (GPa)
750	-2.0014	-2.4914
1450	-1.4098	-1.4212
2250	-0.8981	-0.6848
2999	-0.5221	-0.2814
3749	-0.2235	-0.0657



- Based on these estimates, pressure and corresponding tensile stress >> spall strength

- Reinforces need for more detailed analysis

Future Effort

- More detailed characterization of spalling
  - Spall time scale effect
  - Droplets size and distribution
  - Form (vapor, liquid droplets) of the removed material
- Refine estimate of shock and rarefaction pressure in liquid wall under X-ray energy deposition
- Integrate thermal and mechanical responses of liquid wall to obtain better estimate of aerosol source term