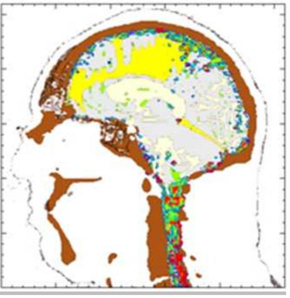
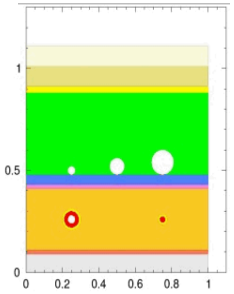
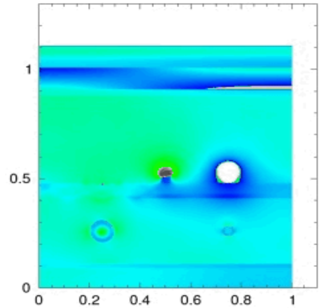
SAND2016-2111C

Virtual Simulation of the Effects of Intracranial Fluid Cavitation in Blast-Induced Traumatic Brain Injury







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Exceptional service in the national interest

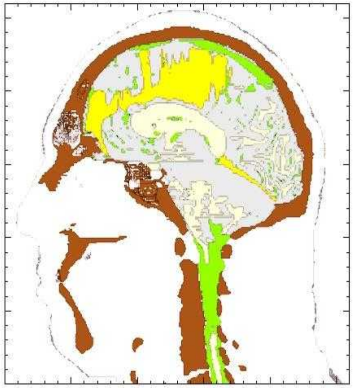
Blast-Induced Traumatic Brain Injury (TBI) Background

- Closed-Head Blast Injuries are leading cause of traumatic brain injury (TBI) in military personnel returning from combat [1]
  - Latest statistics show 333,000 US warfighters sustained TBI
- Objective: Primary Blast Injury (caused by direct blast exposure)
  - Investigate early-time wave intracranial wave mechanics leading to cavitation and traumatic brain injury
  - Previous work suggests shear stress and deviatoric shear energy correlate with localized brain injury identified in clinical TBI study
  - Separate work suggests intracranial cavitation may also cause brain injury
- Hypotheses: (1) Blast exposure induces intracranial fluid cavitation, (2) fluid cavitation, if it occurs, causes localized brain injury (3) the mechanisms of tissue damage, caused by cavitation bubble collapse, can be investigated on a microscale using a modeling & simulation approach
- Significance: Prediction, investigation, and identification of a new brain injury mechanism

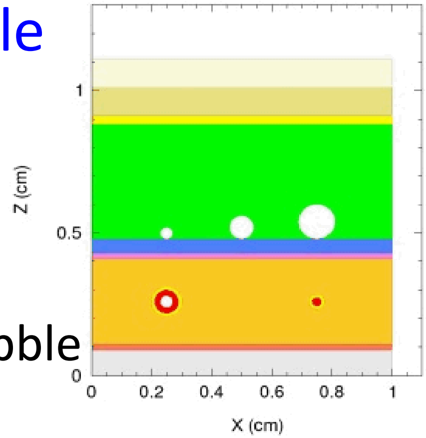
[1] Defense & Veterans Brain Injury Center TBI numbers: DoD numbers for traumatic brain injury, 2015.

Modeling Approach

- Simulate blast exposure to a macroscale model of the head to identify regions of the brain exposed to cavitation
  - Blast waves directed to the front, side and rear
  - Simulations predicted cavitation occurring in areas with high concentrations of CSF



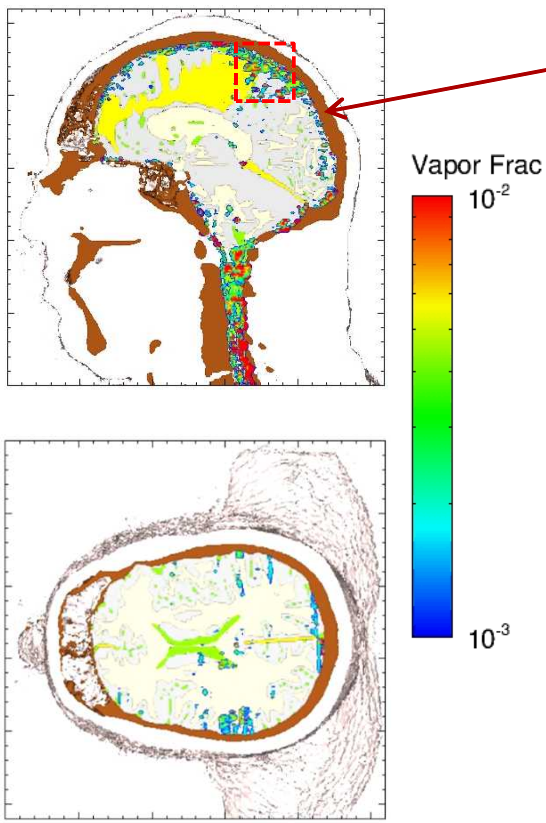
- Guided by the macroscale studies, conduct microscale investigations into the details of cavitation bubble collapse
  - Simulations assume the existence of cavitation bubbles
  - Investigate the tissue damaging mechanisms caused by bubble collapse
    - Examine the effects of the compressive wave strength, bubble diameter and internal bubble pressure



TBI Macroscale Modeling
260 KPa Blast Exposure: Cavitation Vapor Volume Fraction

<u>Frontal Blast</u>

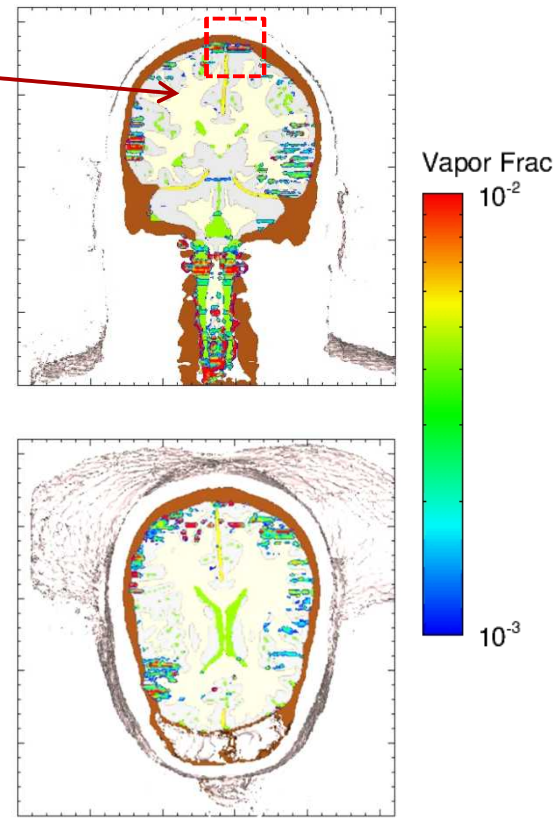
Blast Direction



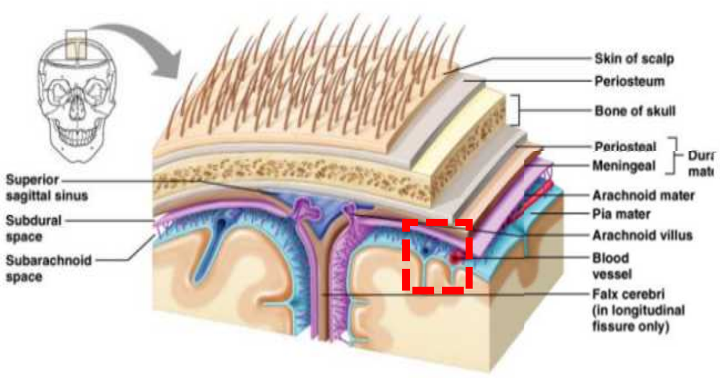
Note cavitation occurrence in Superior Sagittal Sinus

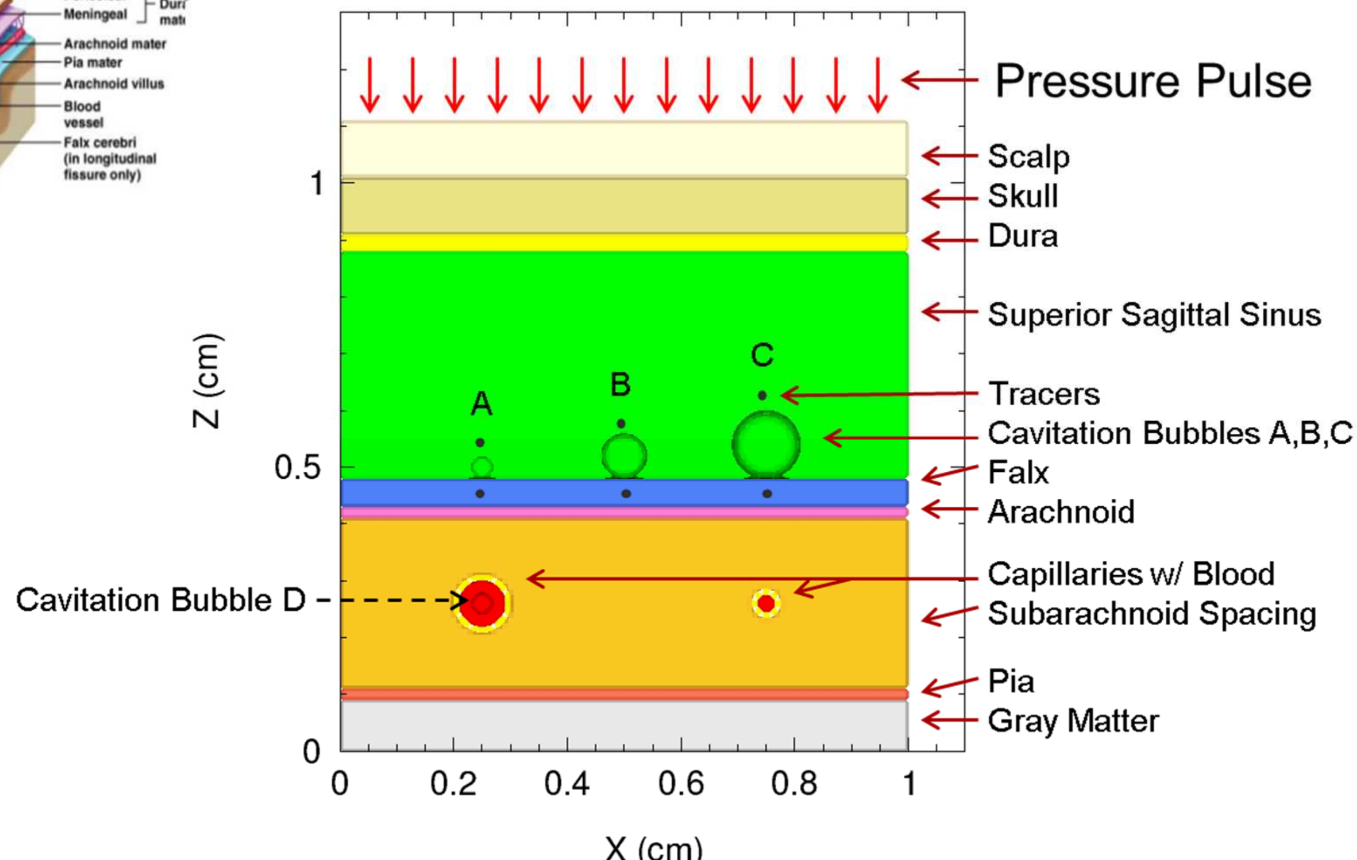
<u>Side Blast</u>

Blast Direction



Microscale Model of the Superior Sagittal Sinus (SSS)





Bubble Radii:
A: 0.2 mm
B: 0.4 mm
C: 0.6 mm
D: 0.2 mm

1 cm x 0.5 cm x 1.25 cm

Material Behavior

Material	Volumetric Response	Deviatoric Response
Scalp	Mie-Gruneisen EOS	Von Mises
Skull	Mie-Gruneisen	Von Mises
Dura	Mie-Gruneisen	Von Mises
Superior Sagittal Sinus	Tillotson-Brundage	-
Falx	Mie-Gruneisen	Von Mises
Arachnoid	Mie-Gruneisen	Von Mises
Blood Vessel	Mie-Gruneisen	Von Mises
Subarachnoid spacing	Tillotson-Brundage	-
Pia	Mie-Gruneisen	Von Mises
Gray Matter	Tillotson-Brundage	Viscoelastic
Blood	Tillotson-Brundage	-
Bubble contents	Sesame Tabular EOS	-

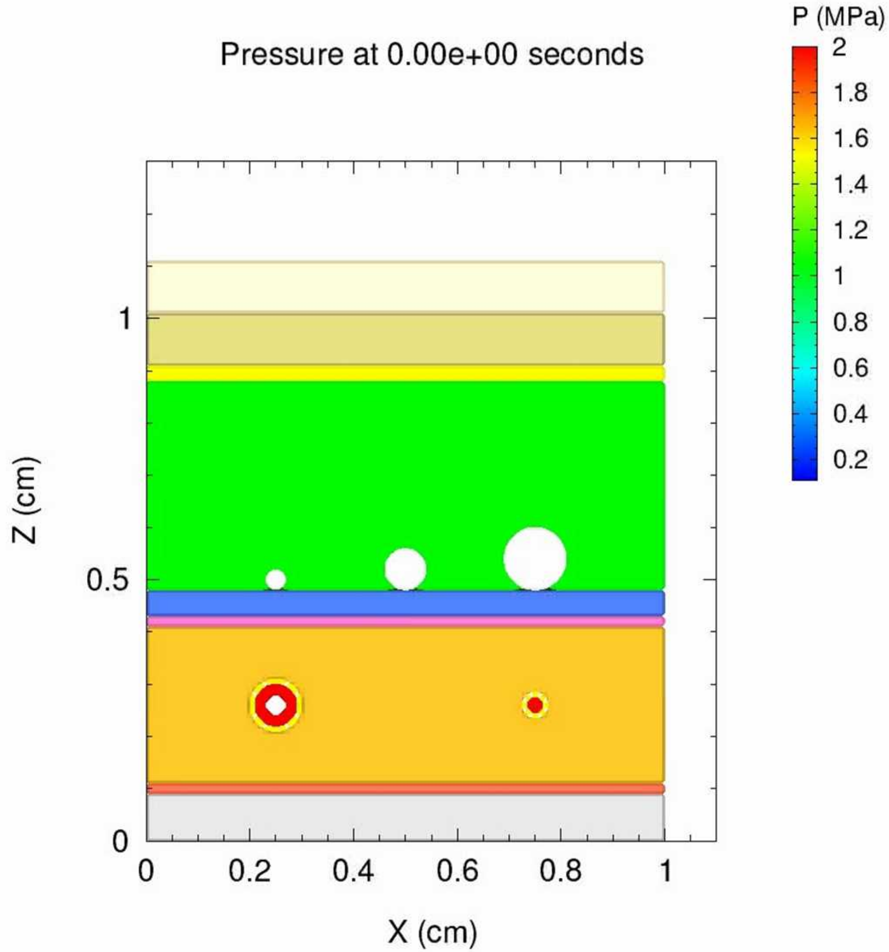
Soft tissues are represented by a Mie-Gruneisen equation-of-state (EOS) describing volumetric response and a linear elastic model describing deviatoric response

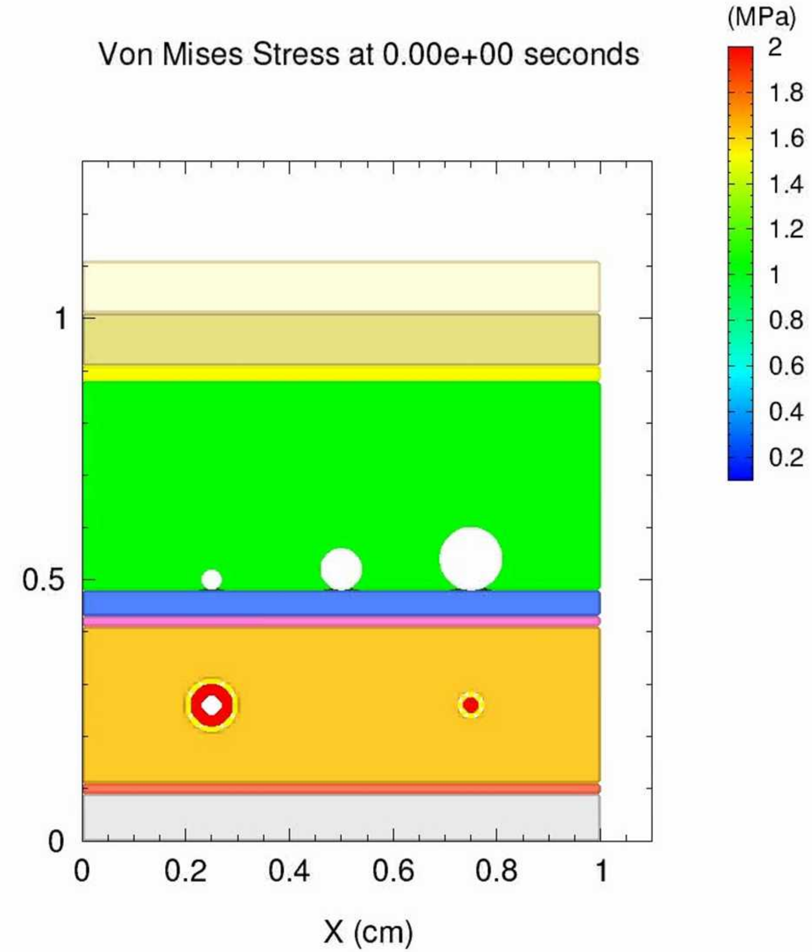
The Tillotson-Brundage EOS accurately captures the blood and cerebrospinal fluids' respective bulk properties under compression and their susceptibility to fluid cavitation when subjected to isotropic tension (i.e. tensile pressure)

Superior Sagittal Sinus Microscale Model

Intracranial Wave caused by 260 KPa Side Blast

5 kPa Internal Bubble Pressure and a 700 kPa Compressive Wave

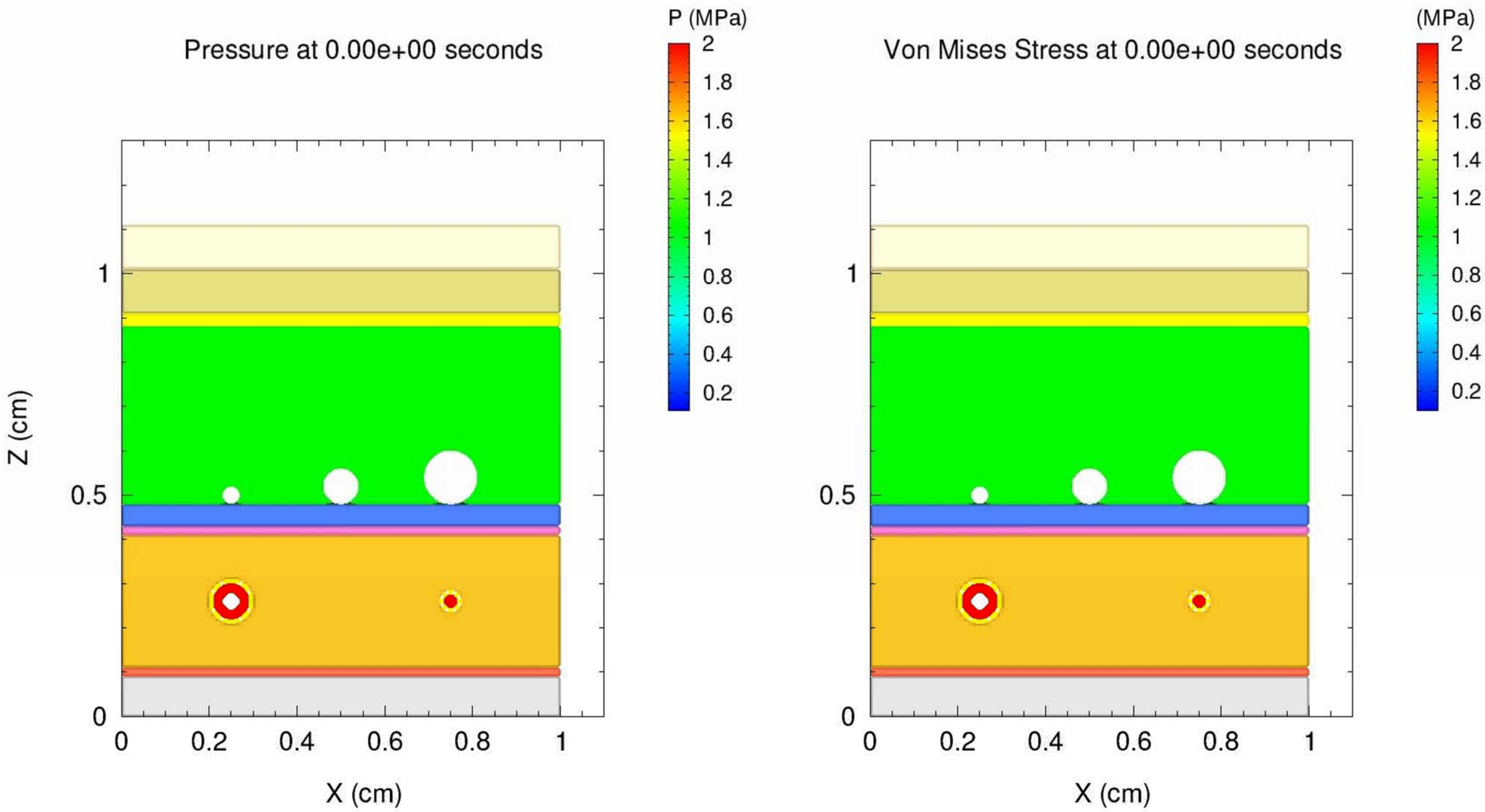




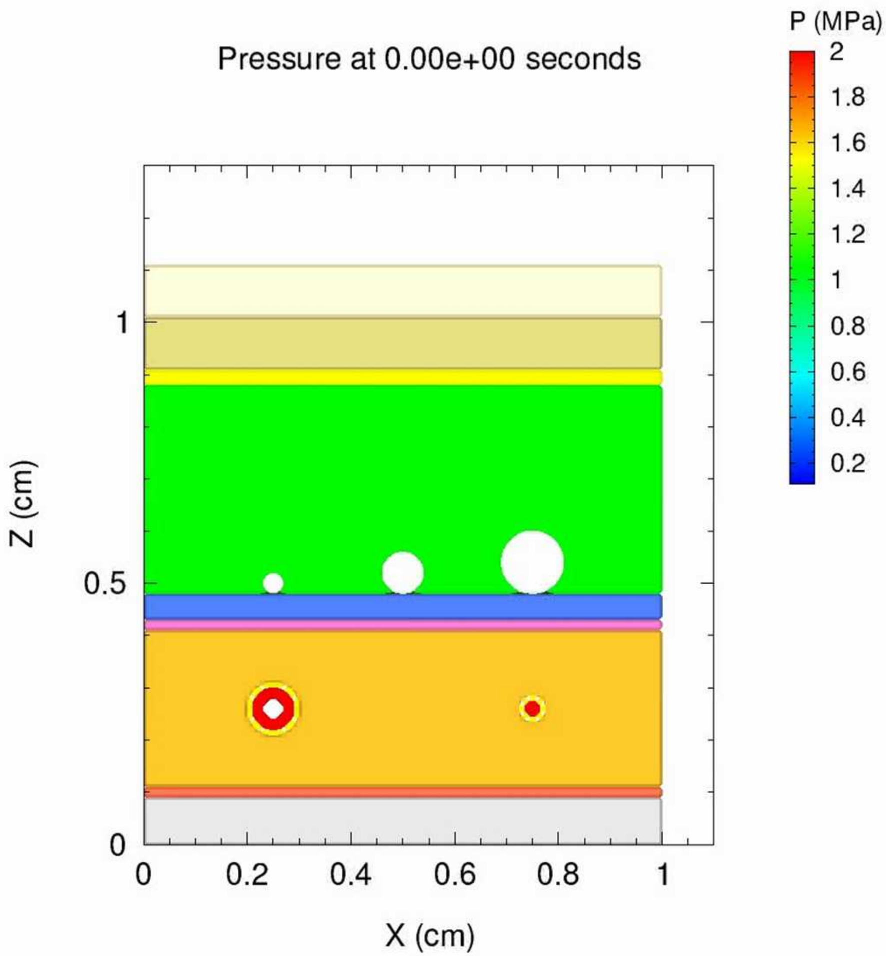
Superior Sagittal Sinus Microscale Model

Intracranial Wave caused by 260 KPa Side Blast

100 kPa Internal Bubble Pressure and a 700 kPa Compressive Wave



Superior Sagittal Sinus Microscale Model



Results of Study:

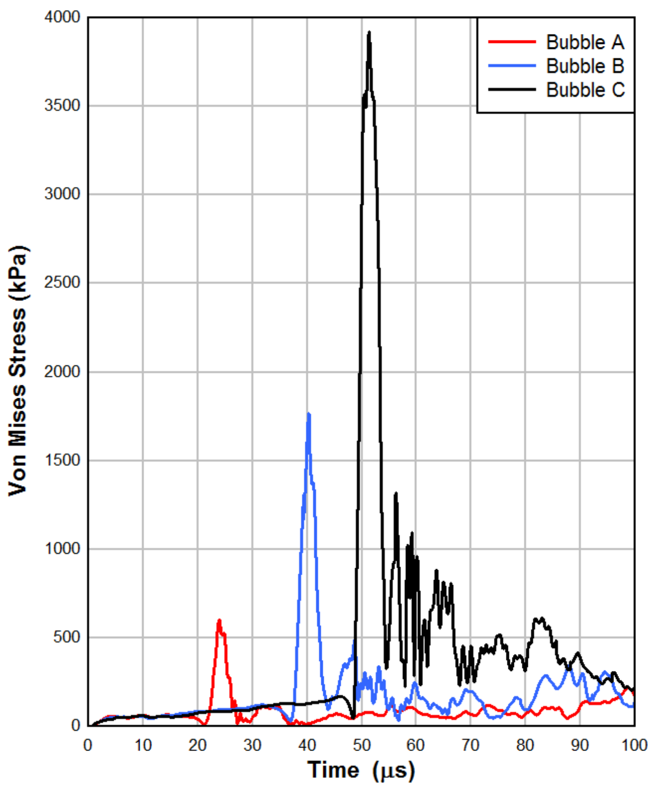
- Cavitation bubble collapse dependent on:
  - Strength of intracranial stress wave (related to blast strength)
  - Bubble diameter
  - Internal bubble pressure
- Effects of cavitation bubble collapse:
  - Generation of high pressure region around bubble site
  - Microjetting of fluid surrounding bubble in downstream direction
  - Significant levels of shear stress downstream from bubble
  - → Shearing of tissue downstream

Microscale Simulation Results

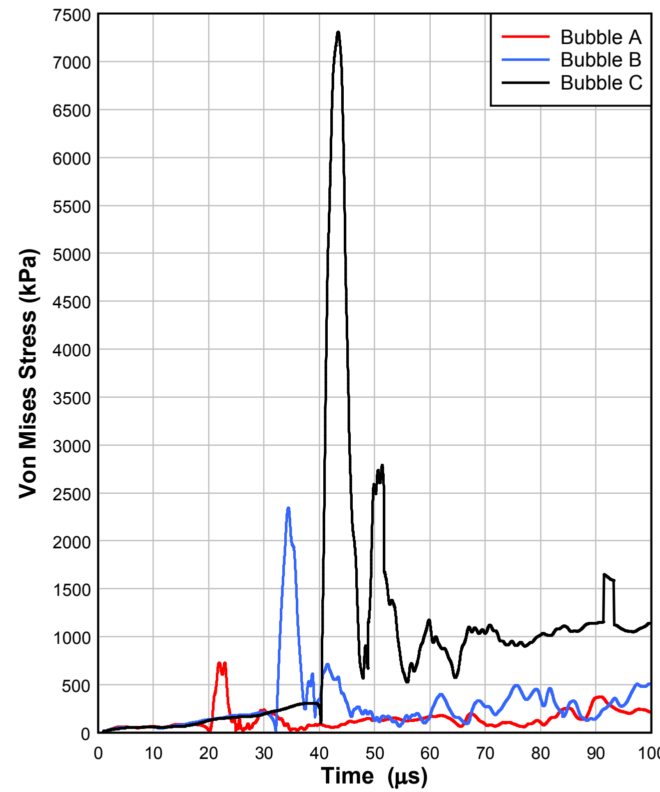
Effect of bubble size and compressive wave amplitude

- Spike indicates the collapse of the bubble and could lead to tissue damage
- Von Mises stress is greater as the bubble diameter increases
- As the compressive wave amplitude increases, the spikes in the downstream von Mises stress of each bubble increases

Downstream von Mises stress for bubbles A, B, & C with 5 kPa internal bubble pressure and a 400 kPa compressive wave



Downstream von Mises stress for bubbles A, B, & C with 5 kPa internal bubble pressure and a 700 kPa compressive wave

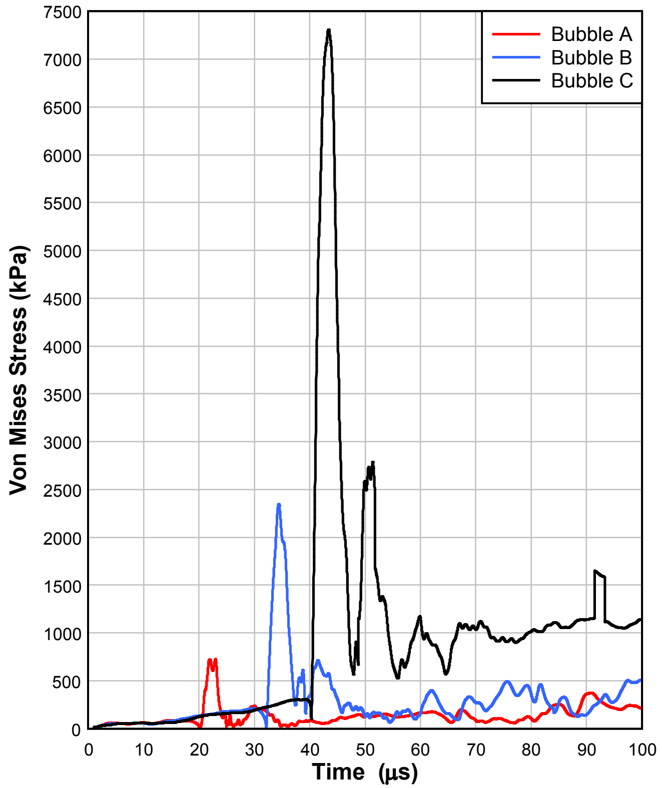


Microscale Simulation Results

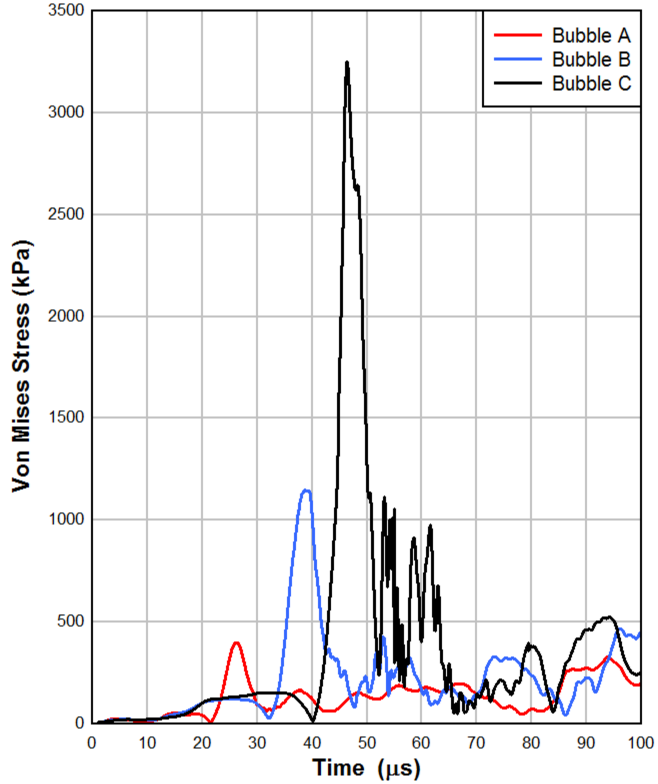
Effect of bubble size and internal bubble pressure

- Spike indicates the collapse of the bubble and could lead to tissue damage
- Von Mises stress is greater as the bubble diameter increases
- A higher internal bubble pressure results in lower downstream von Mises stresses

Downstream von Mises stress for bubbles A, B, & C with 5 kPa internal bubble pressure and a 700 kPa compressive wave



Downstream von Mises stress for bubbles A, B, & C with 60 kPa internal bubble pressure and a 700 kPa compressive wave



Microscale Simulation Results

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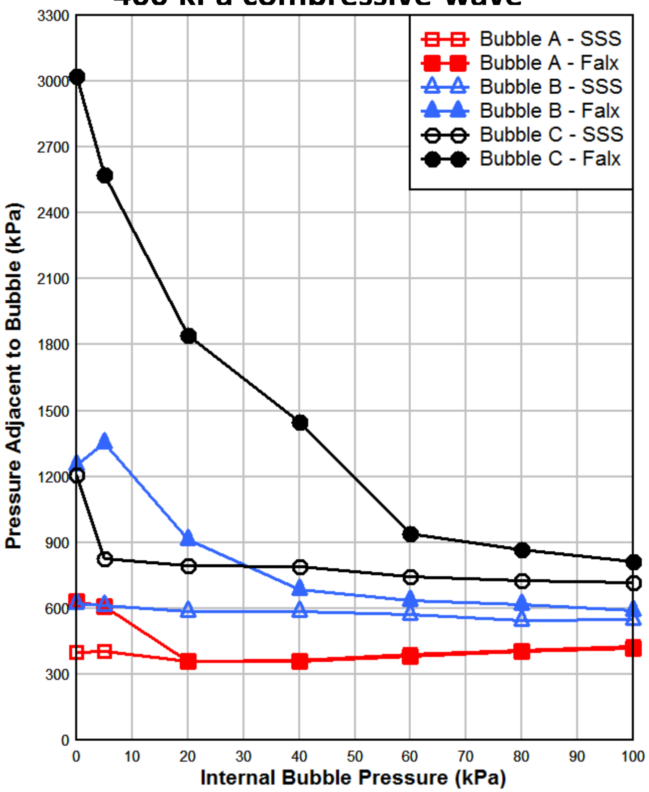
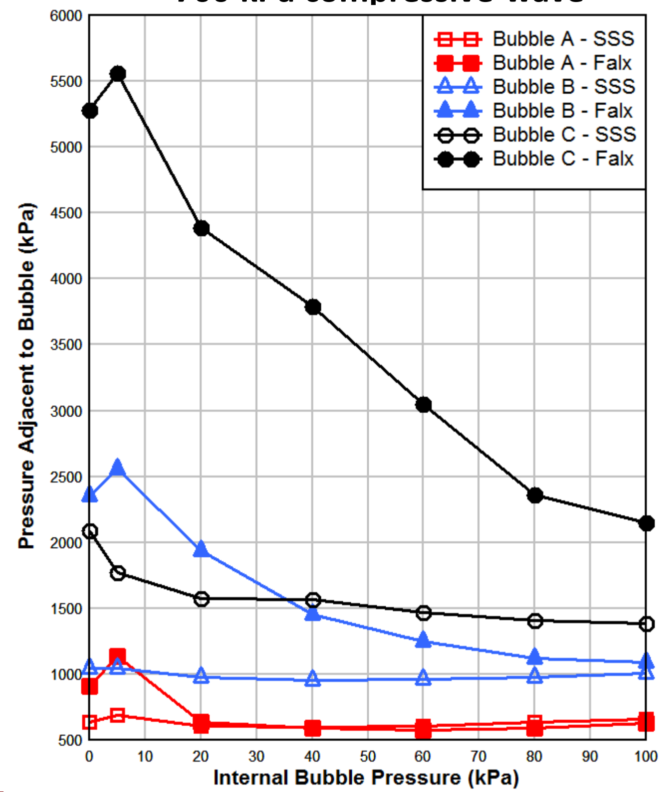
- Downstream pressures (in the Falx) due to bubble collapse greater than the upstream pressure (in the SSS) indicates microjetting
- Pressure generated from bubble collapse is greater as the bubble diameter is increased
- As the compressive wave amplitude increases, the upstream and downstream pressure increases as well
- Differences in pressures increase with reducing internal bubble pressure

Pressure adjacent to bubble vs internal bubble pressure of three different bubble sizes for:

400 kPa compressive wave



700 kPa compressive wave



Results Suggest a Scaling Relation

- Cavitation bubble collapse → Microjetting
  - Microjetting perforates membranes (disruption of neuronal function)
  - Propose relation for pressure resulting from bubble collapse:

$$P_{collapse} = \mathcal{F}(\rho, c, R, \dot{P}_{comp})$$

  - Microjetting occurs for bubbles with:
    - Radius > R_{crit} (critical radius)
    - Internal Pressure < P_{crit} (critical internal pressure)
  - Critical pressure & bubble radius:

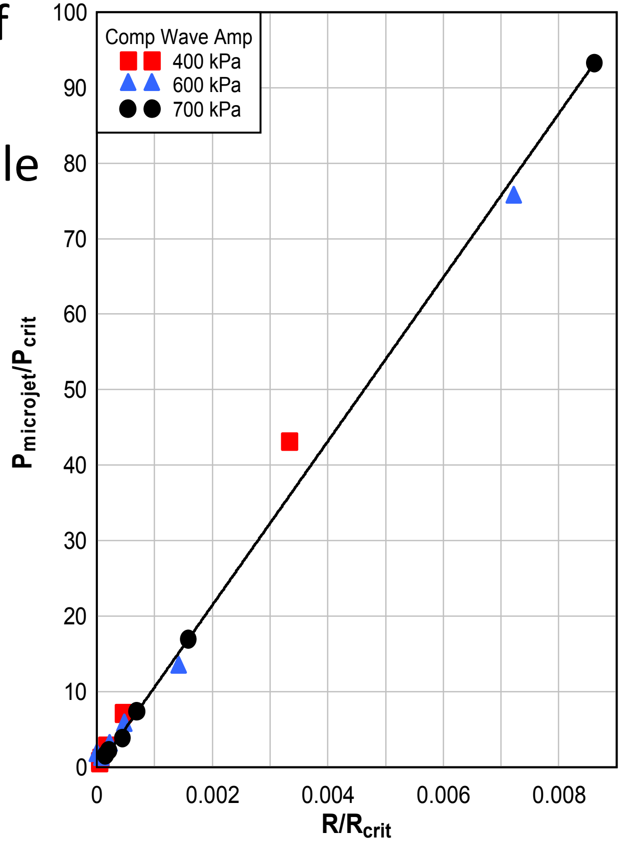
$$P_{crit} = \rho c^2 \qquad R_{crit} = \frac{\rho c^3}{\dot{P}_{comp}}$$

ρ = bubble gas density

c = bubble gas sound speed

R = bubble radius

$\dot{P}_{comp}$ = compressive wave amplitude rate

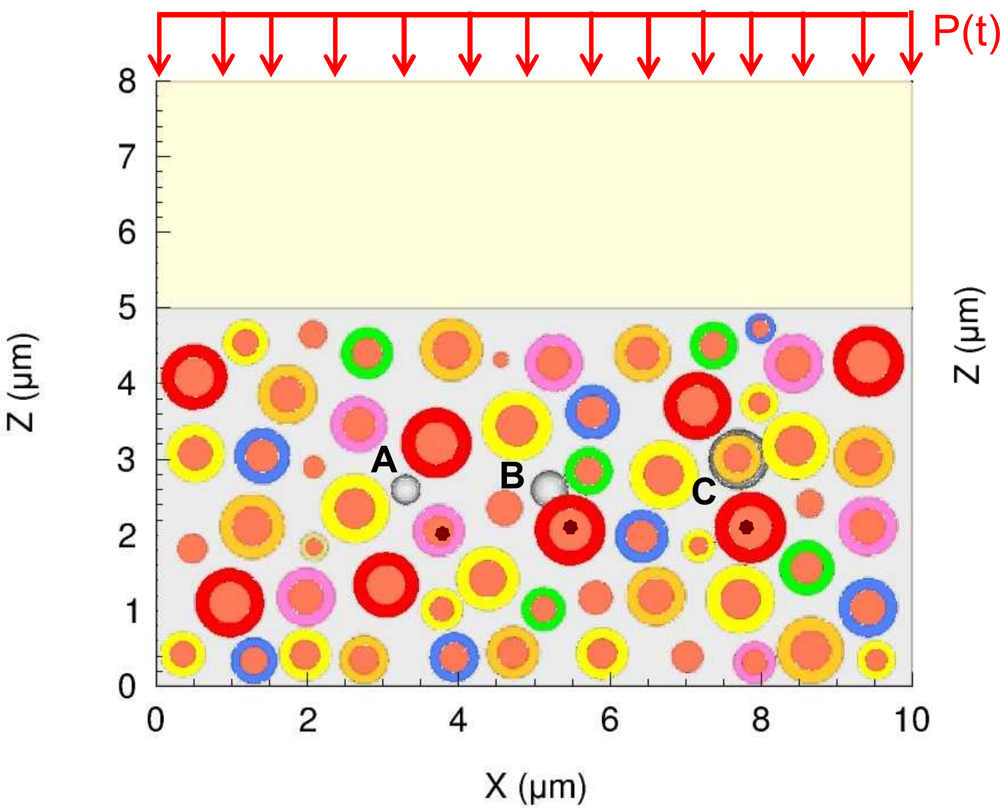


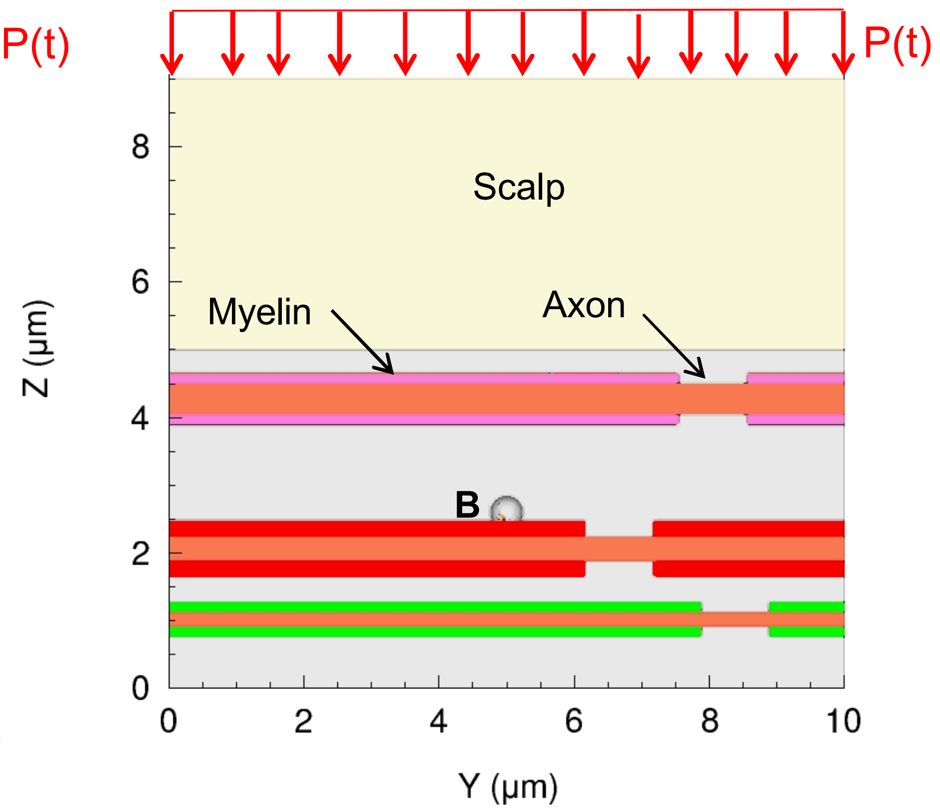
Remarks

- Constructed microscale model of Superior Sagittal Sinus region (predicted to experience significant fluid cavitation)
  - Effects of bubble collapse are dependent upon cavitation bubble size, internal bubble pressure, and compressive wave amplitude
  - The effects of bubble collapse are (1) generation of a high pressure region downstream from the bubble and (2) a significant increase in von Mises (shear) stress at the downstream site.
  - We expect these stresses to cause potential tissue damage
- Currently investigating cavitation within the white matter axon fiber bundle tracks

Microscale model of the White Matter Axon Fiber Bundle

- Currently investigating cavitation bubble collapse within the white matter axon fiber bundle tracks and potential damage to myelinated axons
  - Examining bubble collapse with and without the presence of propagating compressive waves





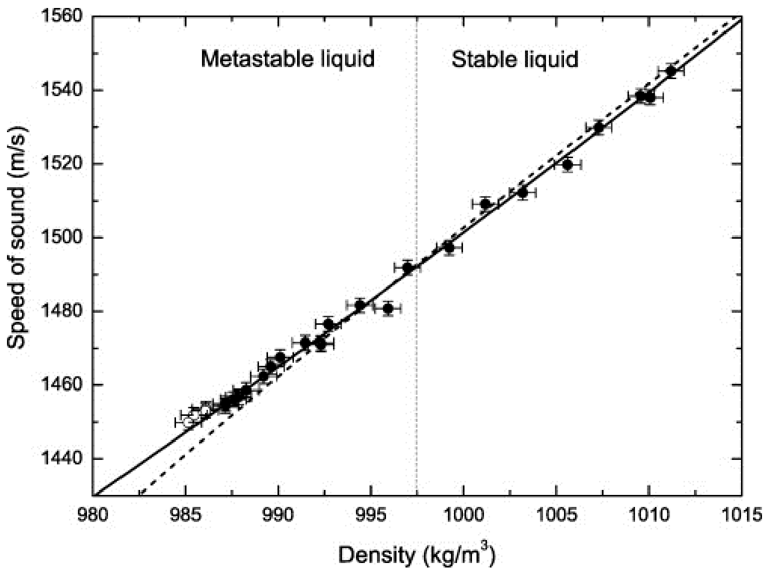
Questions?

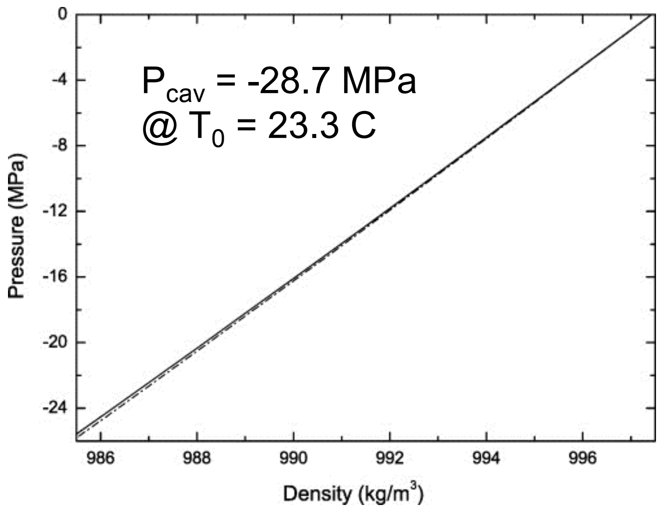
Supplemental Slides

Material	Density (g/cc)	Bulk Modulus (MPa)	Young's Modulus (MPa)	Poisson's Ratio
Scalp	1.20	34.8	16.7	0.42
Skull	1.21	4762	8000	0.22
Dura	1.133	73.3	22	0.45
SSS	1.00385			
Falx	1.133	105	31.5	0.45
Arachnoid	See Pia properties			
Blood Vessel	See Dura properties			
Subarachnoid Spacing	See SSS properties			
Pia	1.133	38.33	11.5	0.45
Gray Matter	1.04	2371	-	0.49
Blood	1.05			

Understanding Water "Stretch"[a]

- *Stable* pressure state in fluids is positive
- If the local pressure drops below vapor pressure, fluid *cavitates*
- Experimental research demonstrates that water can "stretch" in a *metastable* state and sustain negative pressures *before* cavitation
- New EOS permits fluid to stretch to metastable states (negative pressures) P < Pcav; then fluid returns to stable (positive) vapor pressure
- Modeling approach consistent with experimental evidence of vapor bubbles appearing once P<Pcav



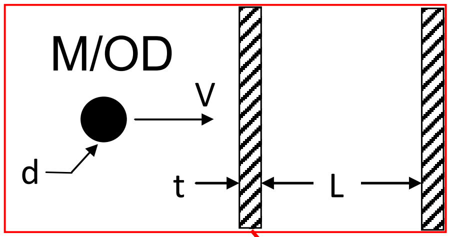


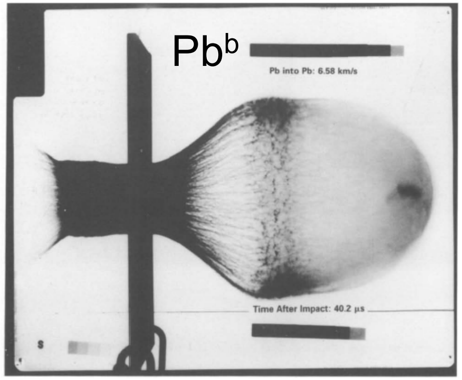
[a]*Davitt et al.* , J. Chem. Phys. 133, 174507 (2010)

Tillotson-Brundage EOS Development[a,b,c,d,e]

[a] *Tillotson , General Atomic Report GA-3216, (1962)*
[b] *Anderson et al., Int. J. Imp. Engrg. 9, (1990)*
[c] *Ahrens & O'Keefe, Int. J. Imp. Engng. 5, (1987)*
[d] *Ahrens & O'Keefe, Imp. and Explosion Cratering (1977)*
[e] *Brundage, Procedia Engng (2012)*

Whipple Shield



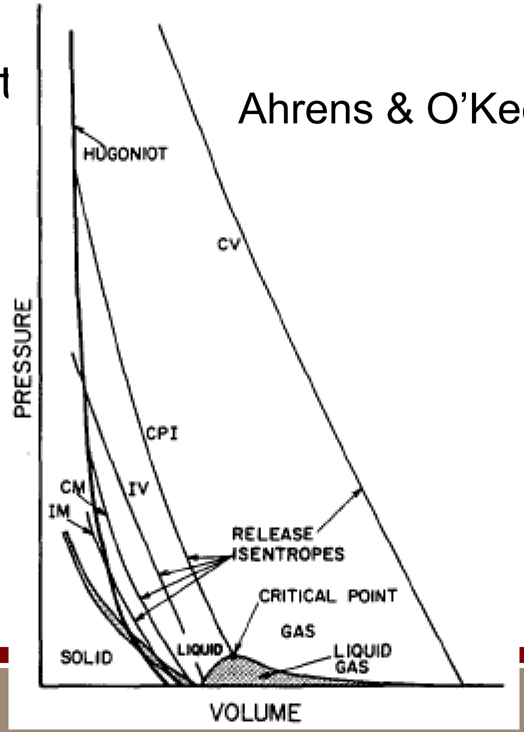


- Two-phase,Tillotson EOS meant to capture vaporization upon release for hypervelocity impacts[a] of metals
- Single equation for compression ($\rho \geq \rho_0$) and different one for expansion ($\rho < \rho_0$)
- No polymorphic phase transformations

<u>Key Model Revisions by Brundage</u>

- Filled gaps in ρ - E space
  - Added new *tensile* regions
  - Significant updates to expansion region[e]
- Cavitation model added for liquids[e]

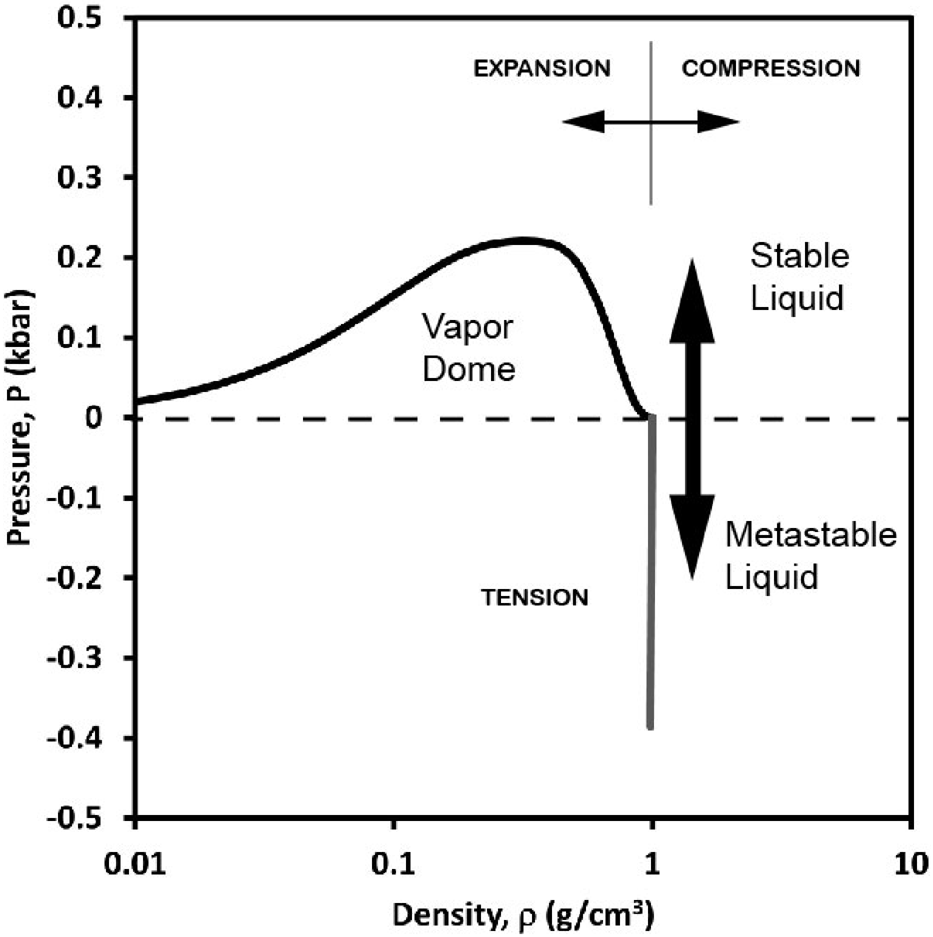
Ahrens & O'Keefe[c]



New EOS for Shock-loaded Metastable Fluids

- *Extend* Tillotson EOS to capture tension and cavitation in fluids
- EOS fit to general form in compression, expansion, and tension

$$P(\rho,E)=\left[a+\frac{b}{\frac{E/E_0}{(\rho/\rho_0)^2}+1}\right]\rho E+f(\rho)$$



Shock Hugoniot Results

- Compare shock end states to available data
- Tillotson-Brundage, MGR, and SESAME EOS

Tillotson-Brundage EOS surface in compression

$$P(\rho,E)=\left[a+\frac{b}{\left(E/\left(E_0\eta^2\right)+1\right)}\right]\rho E+A\mu+B\mu^2 \quad (\rho\geq\rho_0,\,E\geq 0)$$

Assume end states in thermodynamic equilibrium: $E=E_H$, $P=P_H$

$$E_H(\rho)=\frac{1}{2}P_H(\rho)\left[\frac{1}{\rho_0}-\frac{1}{\rho}\right]$$

a,b,E_0,A,B adjusted for best fit to data

Solve for P_H, T_H

$$P_H(\rho)=\frac{-b_H+\sqrt{\left(b_H^2+4a_Hc_H\right)}}{2a_H} \quad T_H(\rho)=T_0+\frac{E_H(\rho)-E_C(\rho)}{C_V} \quad (\rho\geq\rho_0)$$

$$\frac{dE_C}{d\rho}=\frac{P(\rho,E_C)}{\rho^2} \quad (at\ \rho=\rho_0,\,E_C=0)$$