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# Investigation of Cavitation as a Brain Injury Mechanism in Blast Exposure

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# 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 [1,2]
  - Latest statistics show 267,000 US warfighters sustained TBI
  - 69% as a result of IED blast exposure in Iraq & Afghanistan
- Sandia Focus: Primary Blast Injury (caused by direct blast exposure)
  - Investigate early-time wave mechanics leading to localized brain injury
  - Previous work suggests shear stress & deviatoric shear energy correlate with localized brain injury identified in clinical TBI study
  - Separate work suggests intracranial cavitation may also cause brain injury
- Research Approach:
  - Develop Equation-of-State (EOS) model to capture cavitation phenomena in water & water-bearing soft tissue
  - Conduct macroscale simulations of blast exposure using Cavitation EOS
    - Identify local hydrodynamic conditions that give rise to intracranial cavitation
    - Identify specific brain regions experiencing cavitation phenomenon
  - Create micromechanical models to investigate details of cavitation-induced damage

[1] Defense & Veterans Brain Injury Center TBI numbers: DoD numbers for traumatic brain injury, 2010.
[2] Fischer, H., 2007, United States Military Casualty Statistics: Operation Iraqi Freedom and Operation Enduring Freedom, Congressional Research Service Report RS22452.

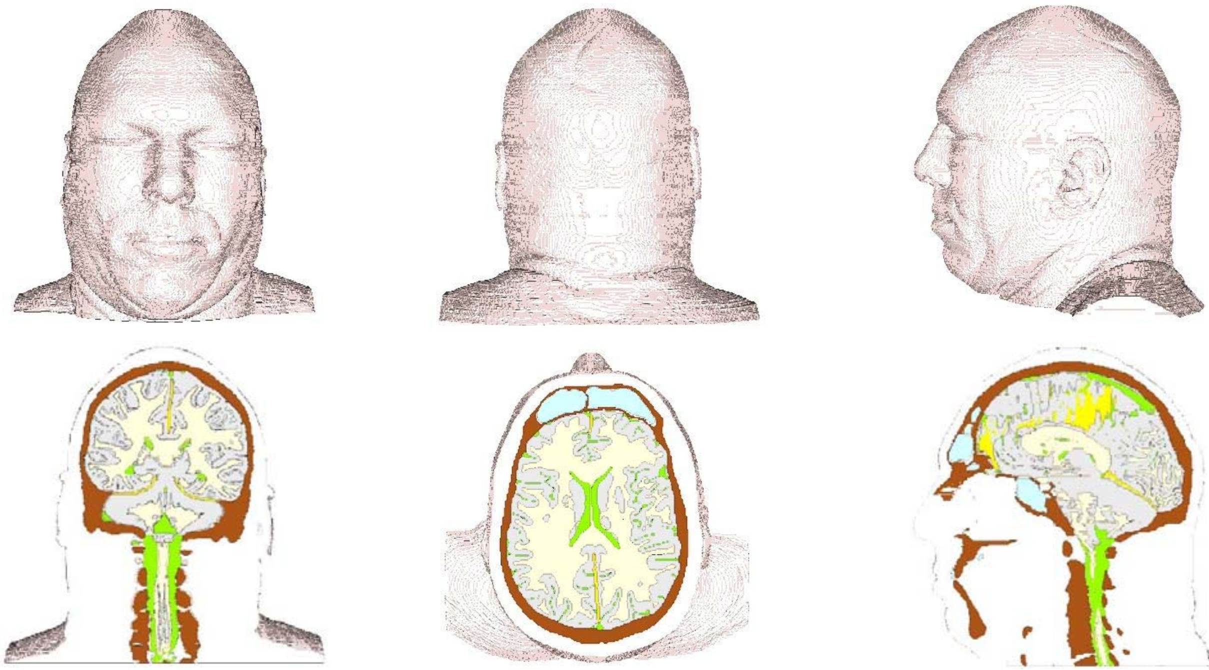
# TBI Macroscale Modeling & Simulation

## Head-Neck Model

- Finite volume model developed from Visible Human Project [3] data
  - Constructed from 256 1mm-thick, axial anatomical slices of human male from the VHP
  - Anatomically correct distributions of white & gray brain matter, cerebral spinal fluid, bone, falx & tentorium membranes, muscle/scalp

Full Model Images:

Coronal, Axial, & Sagittal Cuts:



Model Size: 5.9M Cells

[3] National Institutes of Health, 2007, "The Visible Human Project," National Library of Medicine http://www.nlm.nih.gov/research/visible/visible_human.html

# TBI Macroscale Modeling & Simulation
## Constitutive Models

- Biological Materials:
  - White & Gray Matter – Mie-Gruneisen EOS, Viscoelastic models [4]
    - M-G EOS being replaced by Tillotson-Brundage Cavitation EOS [5]
  - Bone - Linear Elastic model w/ Fracture [4,6]
  - Falx & Tentorium (membranes) –Elastic models [4]
  - Muscle & Scalp - Elastic models [4,7]
  - Cerebral Spinal Fluid (CSF) – Mie-Gruneisen EOS
    - Being replaced by Tillotson-Brundage Cavitation EOS
  - Sinus Air (and surrounding air) - Non-linear Compressible EOS

[4] Zhang, L., Yang, K.H., & King, A.I., 2001, "Comparison of Brain Responses between Frontal and Lateral Impacts by Finite Element Modeling," J. Neurotrauma **18**(1), pp. 21-30.
[5] Brundage, A. L., 2013, "Prediction of Shock-Induced Cavitation in Water," Proc. 2013 APS Shock Compression of Condensed Matter, Seattle, WA.
[6] Carter, D.R., 1985, "Biomechanics of Bone," Biomechanics of Trauma, Appleton-Century-Crofts, Norwalk, CT, pp. 135-165.
[7] Mak, A.F.T. & Zhang, M., 1998, "Skin and Muscle," in Handbook of Biomaterial Properties, ed. J. Black & G. Hastings, Chapman & Hall, London, pp. 66-69.

# Modeling & Simulation

## Methodology & Validation

- Simulation Methods
  - Eulerian methods using CTH (w/ finite volume model)
    - Blast, Projectile Penetration
  - Lagrangian methods using Presto (w/ finite element model)
    - Blunt Impact, Imposed kinematic conditions (e.g. acceleration)
  - Lagrangian-Eulerian coupled methods using Presto/CTH (w/ finite element model)
    - Blast (greater accuracy than Eulerian description)
- Head/Neck Model Validation
  - Compared Simulation predictions with laboratory data
    - Magnetic Resonance Tagging & Elastography data on the human head (in vivo) courtesy of Prof. Philip Bayly research team, Washington University at St. Louis, MO USA [8,9]

[8] Sabet A.A., Christoforou E., Zatlin B., Genin, G.M., Bayly, P.V., 2008, "Deformation of the Human Brain by Mild Angular Head Acceleration," J. Biomech., **41**, pp. 307-315.
[9] Feng Y., Abney T.M., Okamoto R.J., Pless R.B., Genin G.M., Bayly P.V., 2010, "Relative Brain Displacement and Deformation during Constrained Mild Frontal Head Impact," J. Roy. Soc. Interface, **7**(53), pp. 1677-1688.

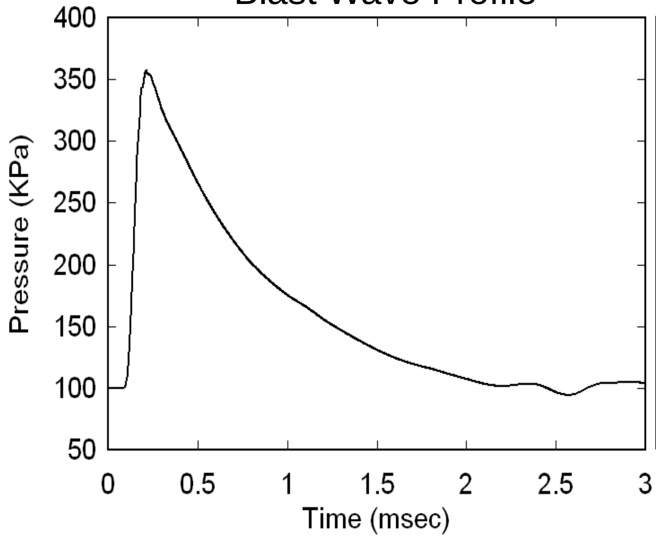
# TBI Modeling & Simulation

## Example: 3.6 bar (360 KPa) Blast

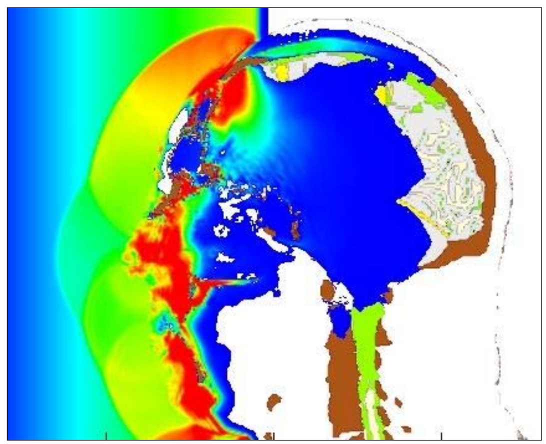
Snap-Shot Images of Blast-Induced Pressure Wave Propagating through Head

Time ~ 130 μs after blast wave encounters head

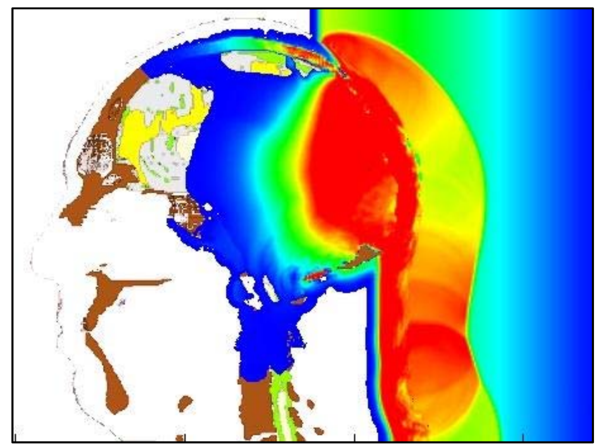
Blast Wave Profile



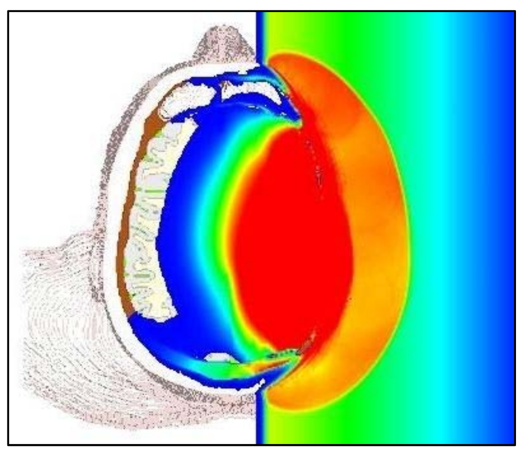

Frontal Blast

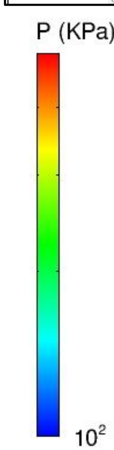


Rear Blast



Side Blast





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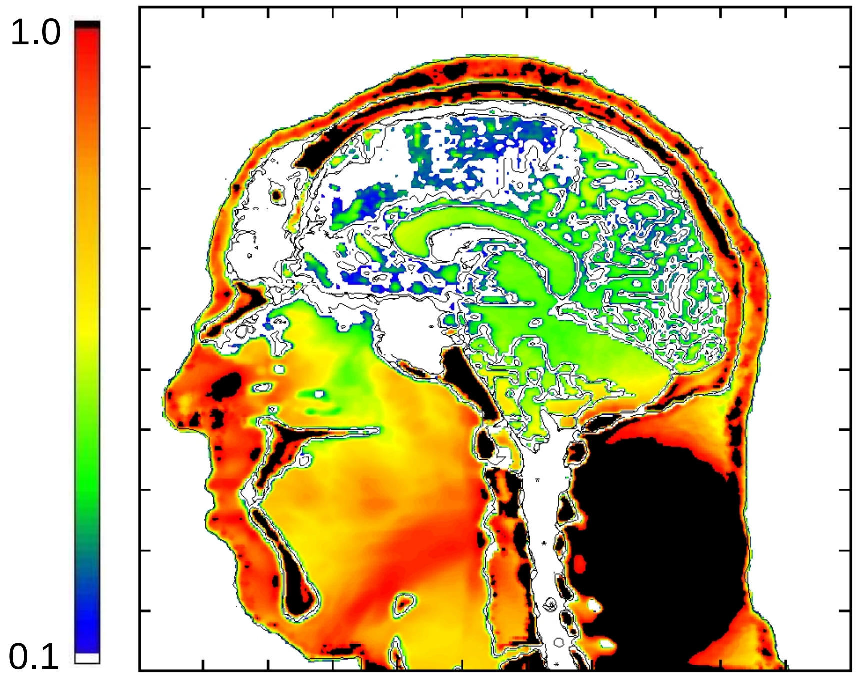
# TBI Modeling & Simulation

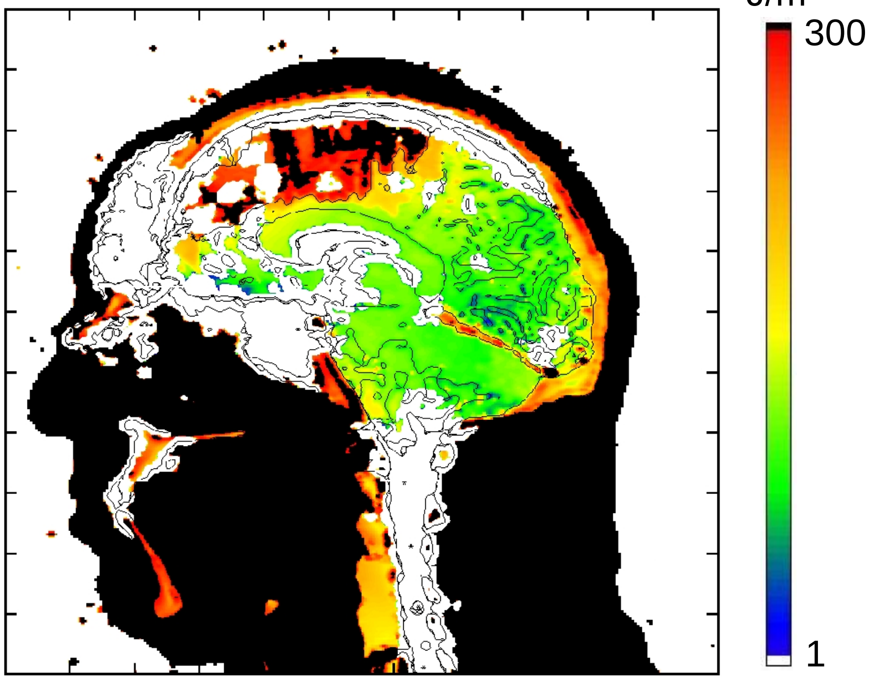
## 3.6 bar Frontal Blast Exposure: Compressive Pressure & Energy

Max Pressure & Isotropic Compressive Energy (ICE) associated with Crush

- No known correlation with local tissue injury

$$ICE = Pos[\int P \frac{d\rho}{\rho}]$$



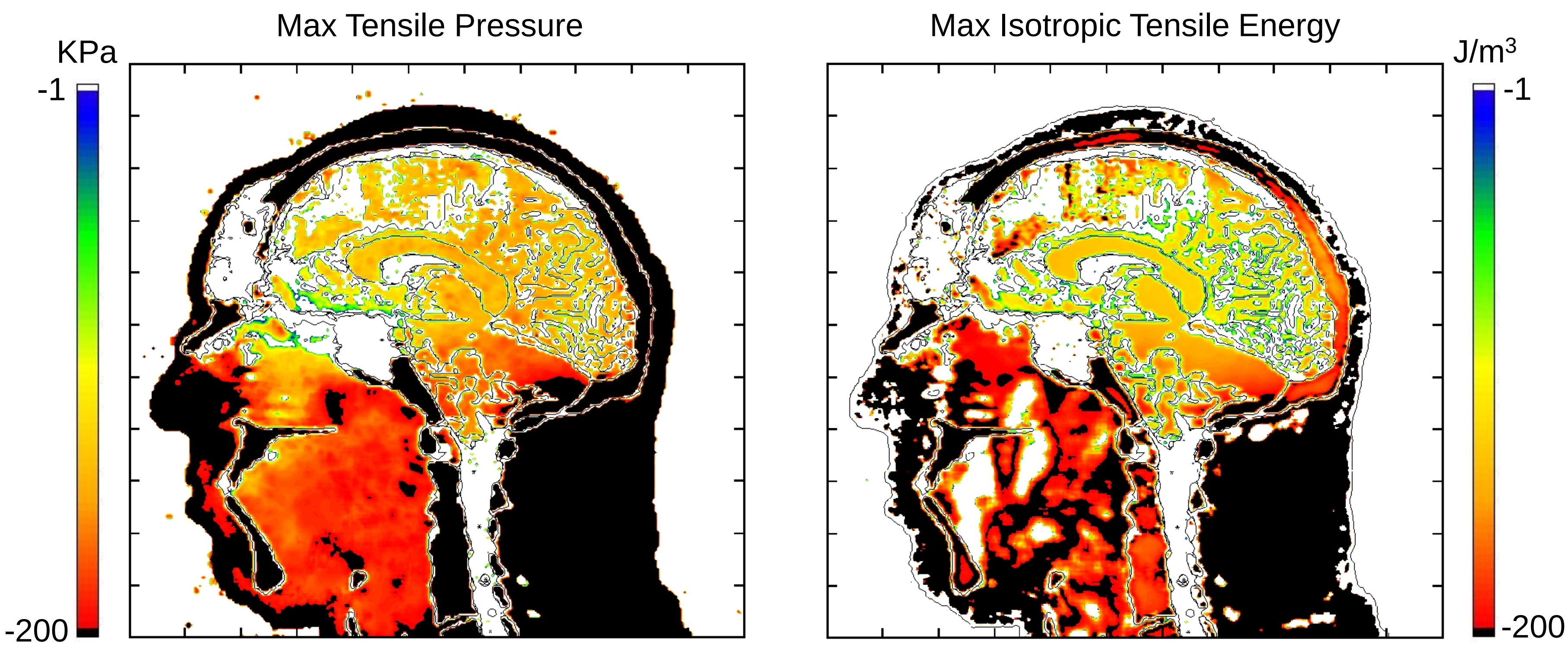
TBI Modeling & Simulation

## 3.6 bar Frontal Blast Exposure: Tensile Pressure & Energy

Max Tensile Pressure & Isotropic Tensile Energy (ITE) associated with volumetric Dilatation & possibly Cavitation

- Suspected tissue injury mechanism

$$ITE = Neg[\int P \frac{d\rho}{\rho}]$$



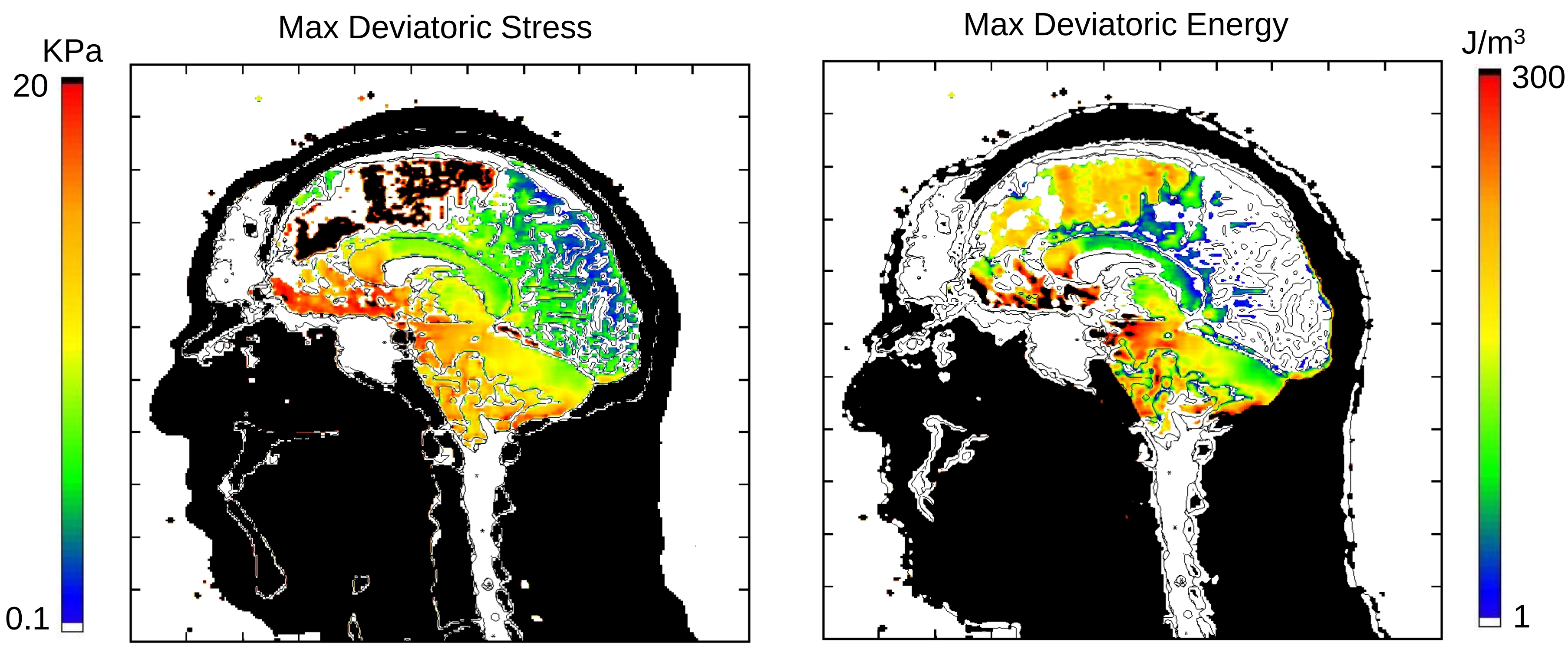
# TBI Modeling & Simulation

## 3.6 bar Frontal Blast Exposure: Deviatoric (Shear) Stress & Energy

Max Deviatoric Stress & Energy (DSE) associated with Shear & Tearing

- Suspected tissue injury mechanism
  - Cytoskeleton disruption & membrane rupture

$$DSE = \int tr(\mathbf{Sd})dt$$



# Blast-Induced TBI Research Summary

- Completed Work:
- Combined simulation & clinical study of TBI blast subjects suggest possible correlation [10]
  - Between maximum deviatoric (shear) stress & energy with local regions of brain hypoactivity in TBI subjects
  - Simulation predictions also show localized regions in brain experiencing elevated levels of tensile pressure and energy
    - Possible Cavitation
  - Cavitation hypothesized to cause local injury leading to TBI [11-13]
    - Collapse of bubbles formed in fluid cause local shock wavelets that could damage surrounding tissue
  - Need exists to model intracranial cavitation in simulations

[10] Taylor P.A., Ludwigsen J.S., Vakhtin A.A., Ford C.C., 2013, "Simulation and Clinical Assessment of Blast-Induced Traumatic Brain Injury," Neurotrauma Letter, submitted.

[11] Lubock P., Goldsmith W., 1980, "Experimental Cavitation Studies in a Model Head-Neck System, J. Biomech. **13**, pp. 1041-1052.

[12] Brennen C.E., 2003, "Cavitation in Biological and Bioengineering Contexts," Proc. 5th Int. Symp. Cavitation, Osaka, Japan.

[13] Nakagawa A., Fujimura M., Kato K., Okuyama H., Hashimoto T., Takayama K., Tominaga T., 2008, "Shock Wave-Induced Brain Injury in Rat: Novel Traumatic Brain Injury Animal Model, Acta Neurochir. Supp. **102**, pp.421-424.



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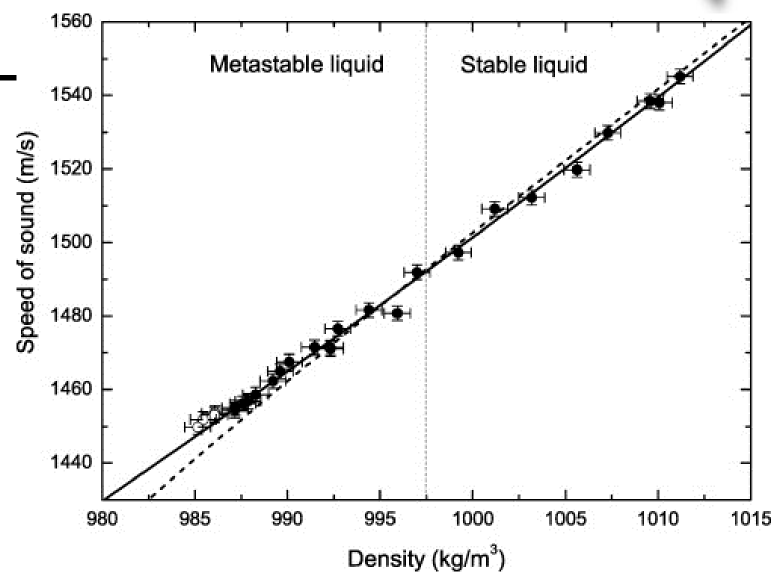
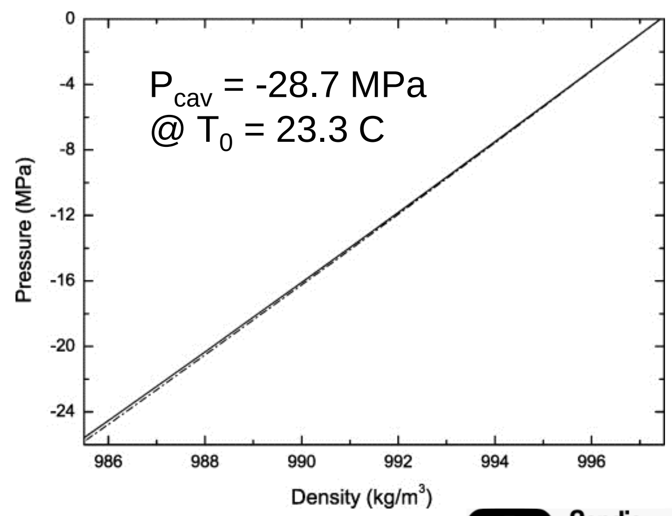
# Tillotson-Brundage Cavitation EOS Model Cavitation Description

- Manifests as individual vapor bubbles or large (steady or unsteady) cavities that contain air or water vapor; both can quickly cause damage (and noise) upon collapse
- Occurs locally from release to pressures near vapor pressure of liquid (boiling at ambient T)
- Represents a two-phase flow comprising of the liquid and its vapor (or other dissolved gasses)

# 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



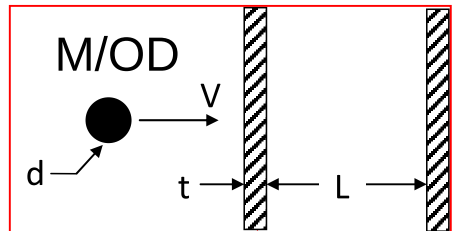



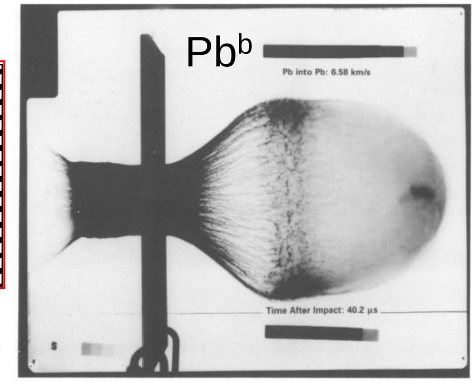

[a]*Davitt et al.* , J. Chem. Phys. 133, 174507 (2010)

# 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



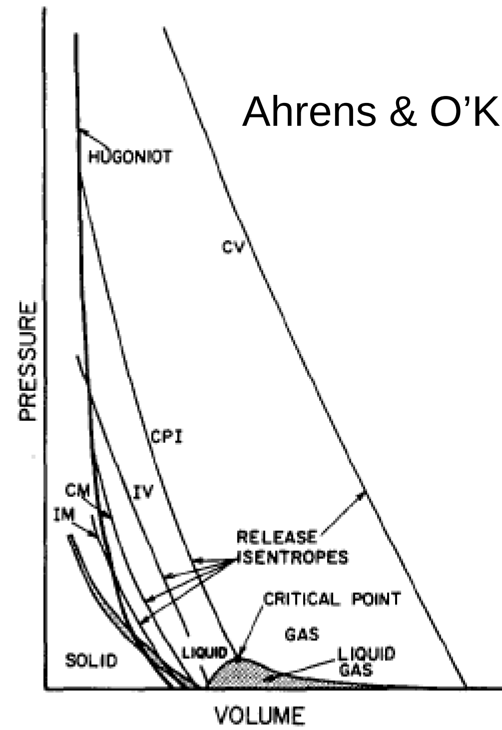




- Two-phase,Tillotson EOS meant to capture vaporization upon release for hypervelocity impacts[a] of metals
- Single equation for compression ($\rho \geq \rho_0$) and different one for expansion ($\rho < \rho_0$)
- No polymorphic phase transformations

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

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

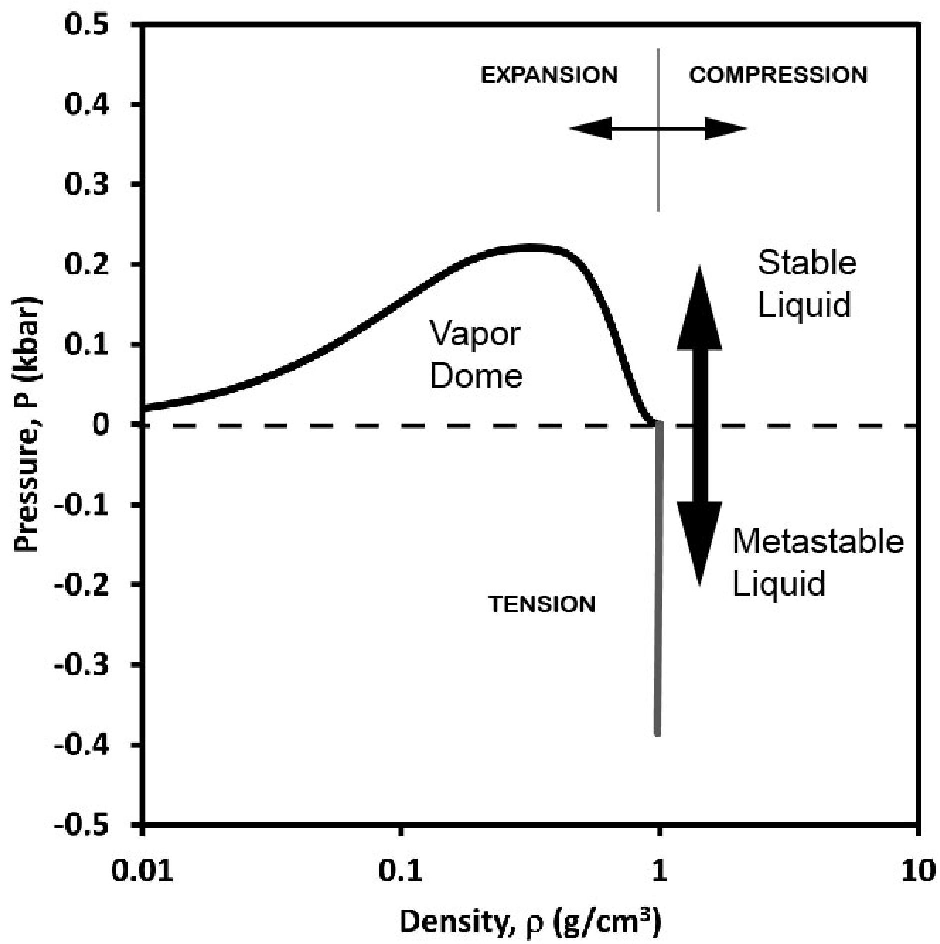
Ahrens & O'Keefe[c]



## 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
- Modified Tillotson, MGR, and SESAME EOS

EOS surface in compression

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

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

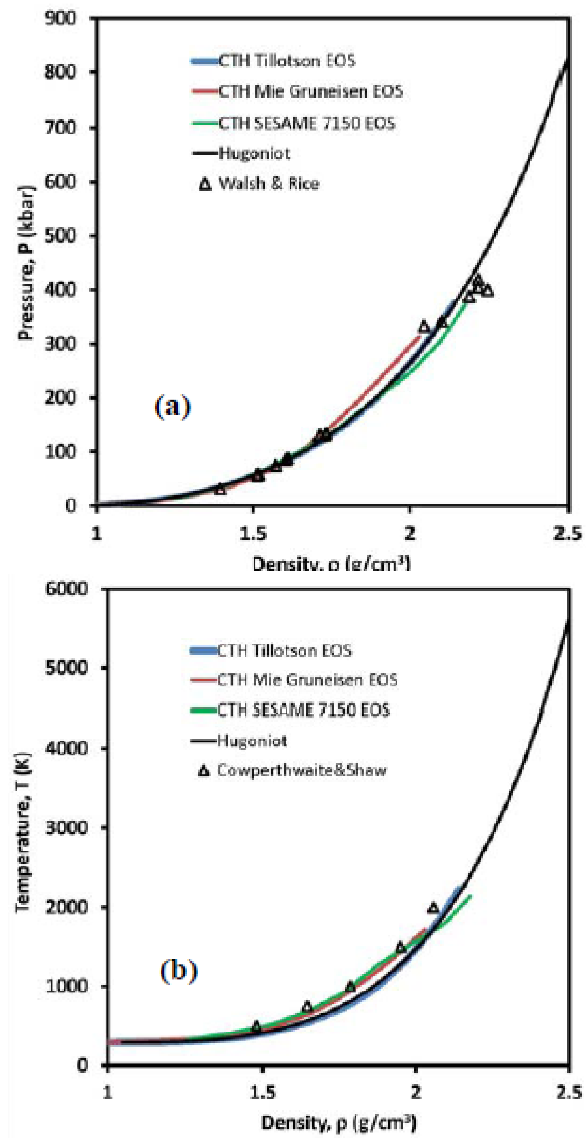
$$E_H(\rho)=\frac{1}{2}P_H(\rho)\left[\frac{1}{\rho_0}-\frac{1}{\rho}\right]$$

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

Solve for $P_H$, $T_H$

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

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



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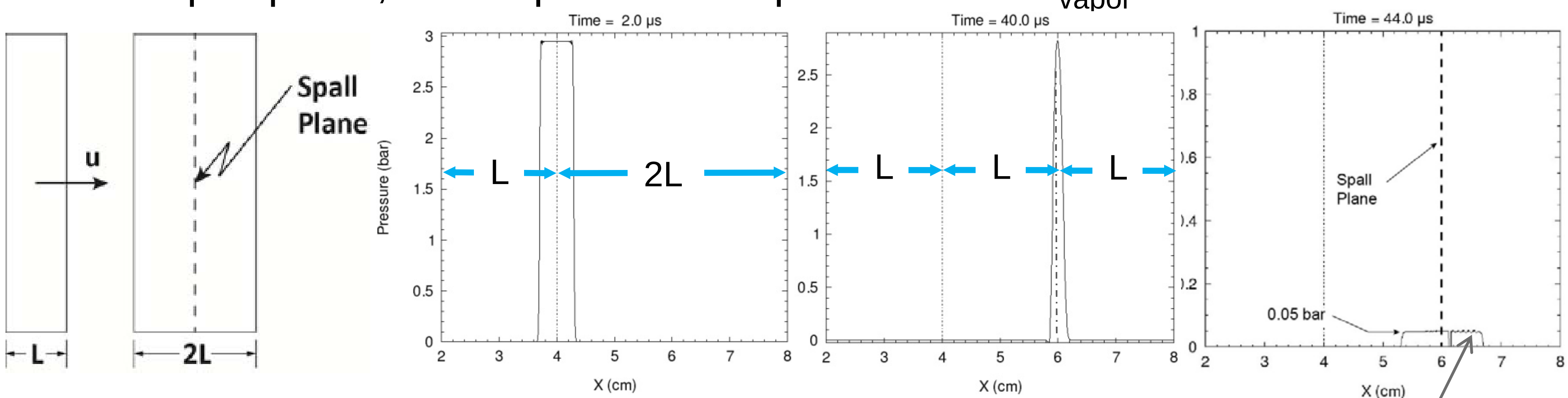
# Cavitation Model Testing

- Cavitation process is ‘liquid spall’ where water in metastable tensile state ruptures
- Evaluate w/1D computational spall experiment
- At spall plane, model produces vapor at stable $P_{vapor}$




## Key Parameters

u = 40 cm/s

L = 2 cm

P = 2.95 bar (calc)

$P_{vap}$ = 0.05 bar

Tillotson-Brundage EOS Results

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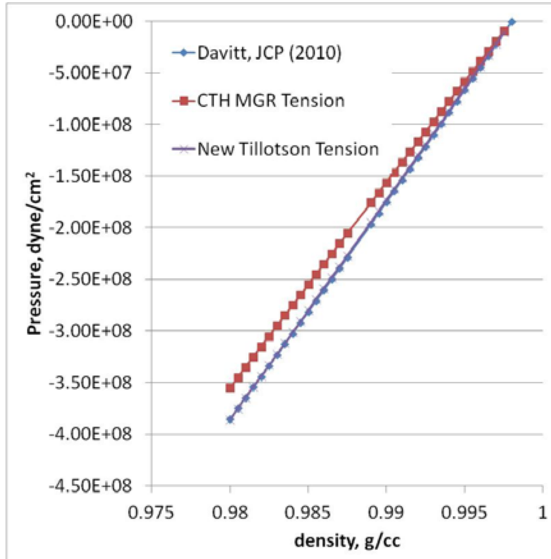
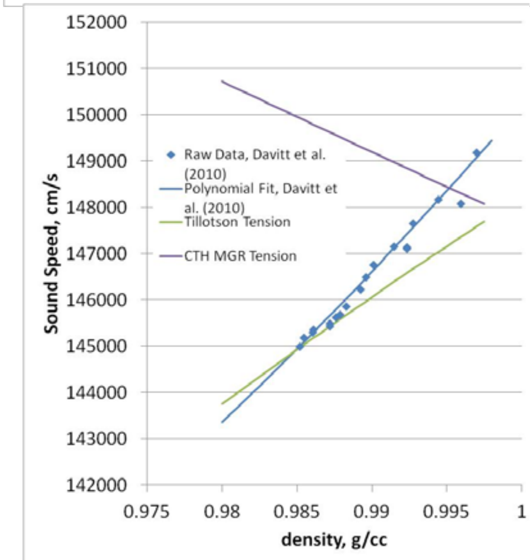
# Evaluate new EOS surface for tension with water data

- *Mie-Gruneisen (MGR)* EOS in CTH, previously used to model biological materials
- In tension, MGR EOS underpredicts tensile stress state in water and has wrong trend in sound speed
- New model for all materials fits pressure data for water but underpredicts sound speed, although gets correct trend



# Tillotson-Brundage Cavitation EOS Development Summary

- New EOS for water captures realistic physics of metastable stretching before cavitating at stable vapor state
- Revised EOS development required adding tensile region for water (or water-like material)
- Generalize EOS in tension for fluidized soft tissue in human body
- Improvement in prediction of tensile states
- Models are being implemented in Sandia Shockwave Physics codes
  - CTH (Eulerian description)
  - Coupled CTH-PRESTO (Eulerian-Lagrangian description)

# Blast-Induced TBI Research Summary

- Current Work:
  - Conduct macroscale simulations of blast scenarios leading to TBI
    - Employ Brundage-Tillotson EOS to model cavitation in brain & CSF
  - Identify intracranial regions experiencing cavitation
    - Parameterize local hydrodynamic conditions associated with cavitation
- Future Work:
  - Develop micromechanical models of those regions in brain that experience cavitation
  - Investigate details of brain tissue damage on microscale using hydrodynamic conditions defined from macroscale simulations

Questions?

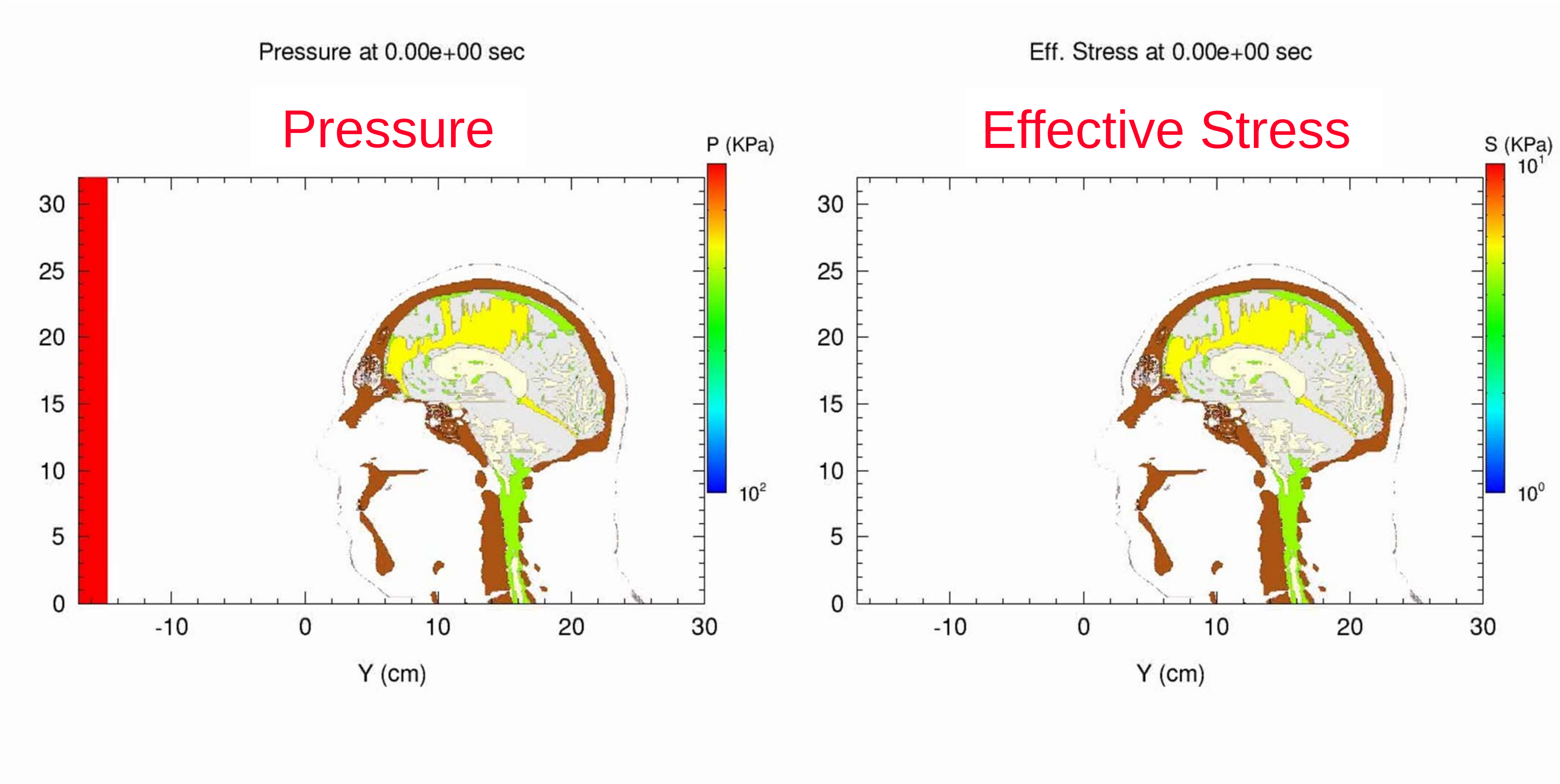
Supplemental Slides

Terminal Ballistics Technology

TBT Target Protect Target Defeat

# TBI Modeling & Simulation

## 3.6 bar Frontal Blast Exposure: mid-Sagittal Plane




Note: Run Videos Simultaneously



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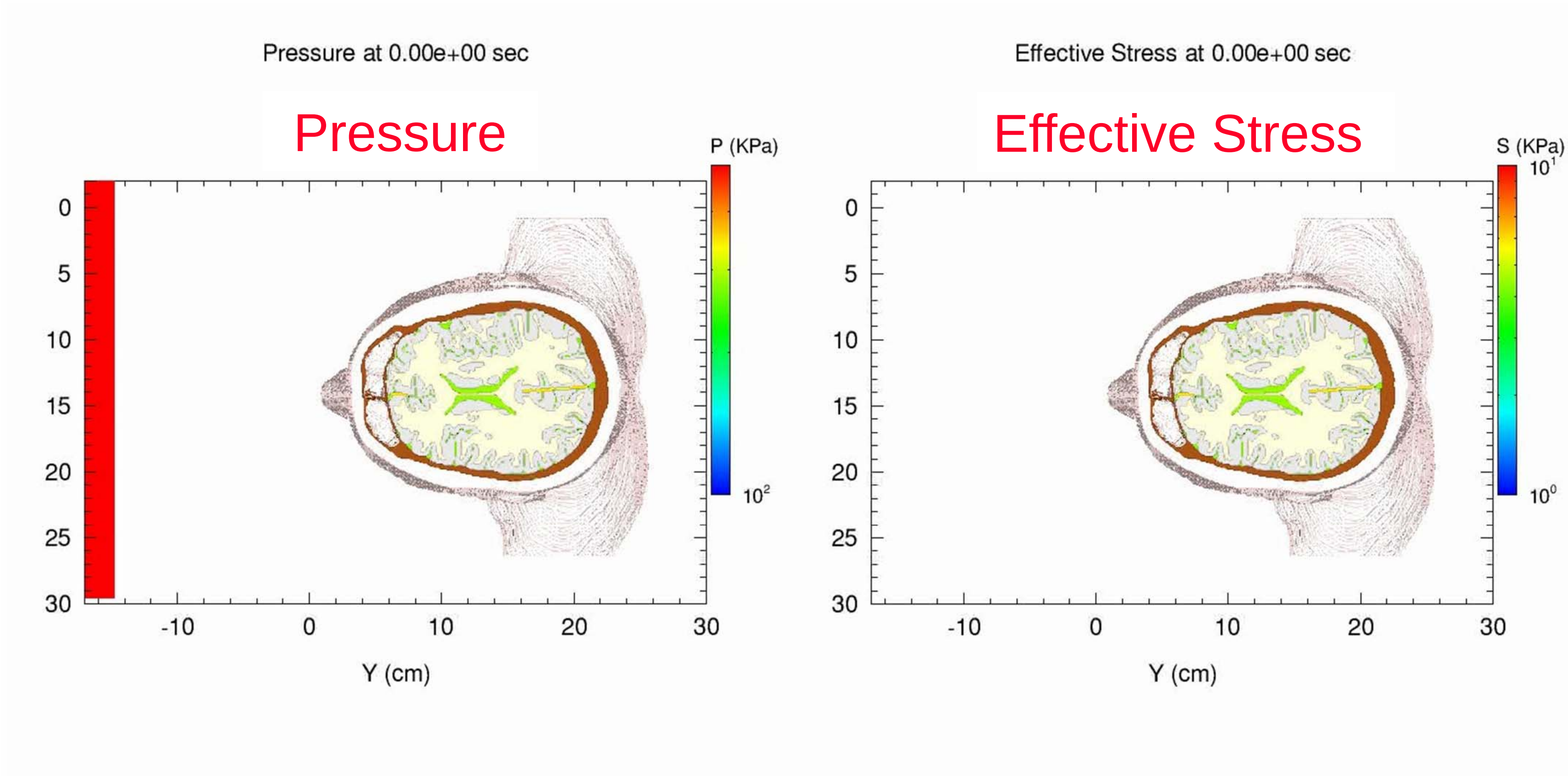
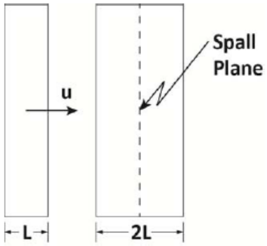
TBI Modeling & Simulation

## 3.6 bar Frontal Blast Exposure: Axial Plane above Eyes




Note: Run Videos Simultaneously

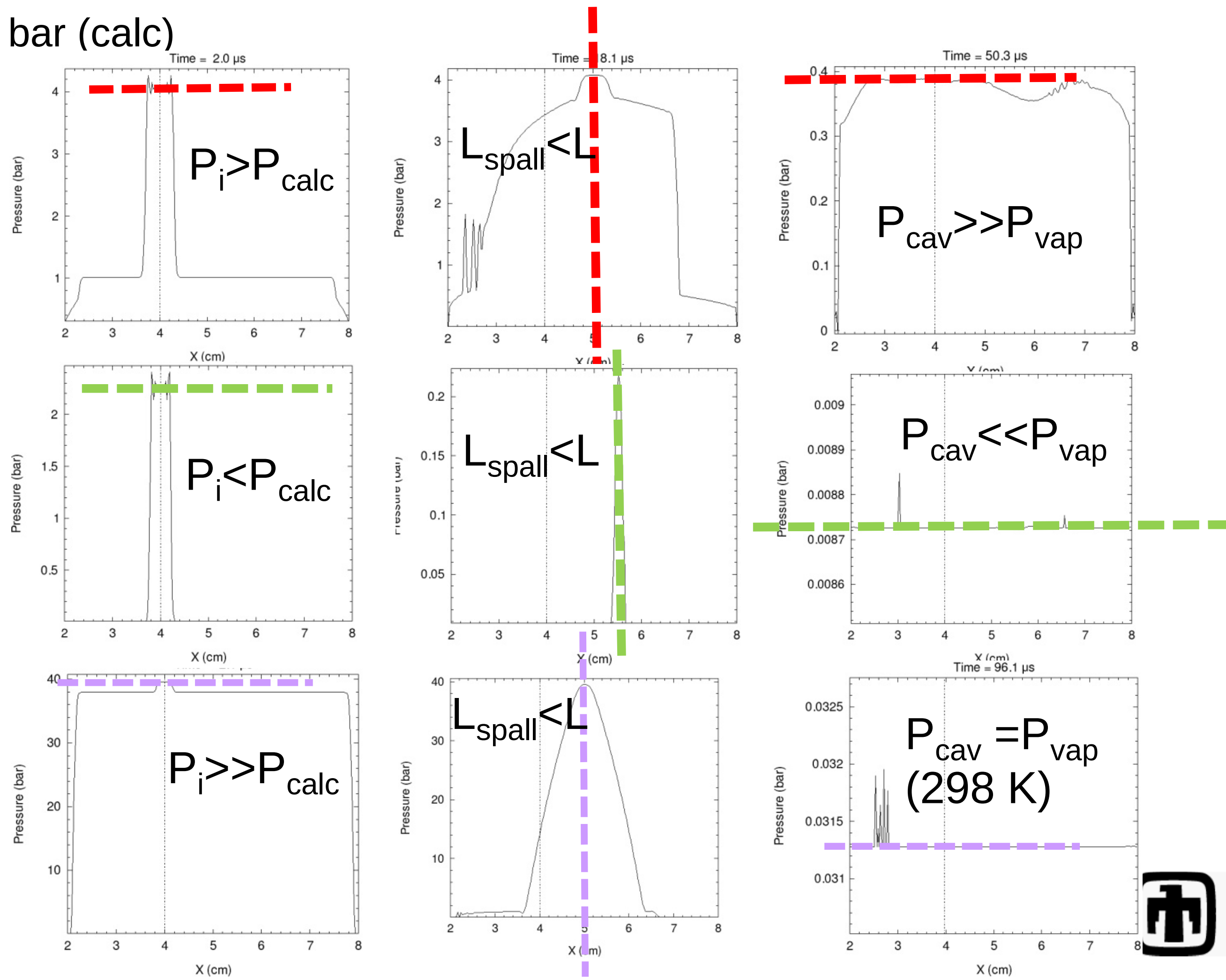
# Current SESAME EOS inadequate




## Impact Conditions

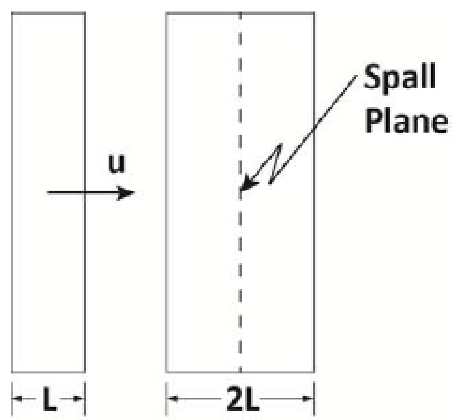
u = 40 cm/s
L = 2 cm
P = 2.95 bar (calc)

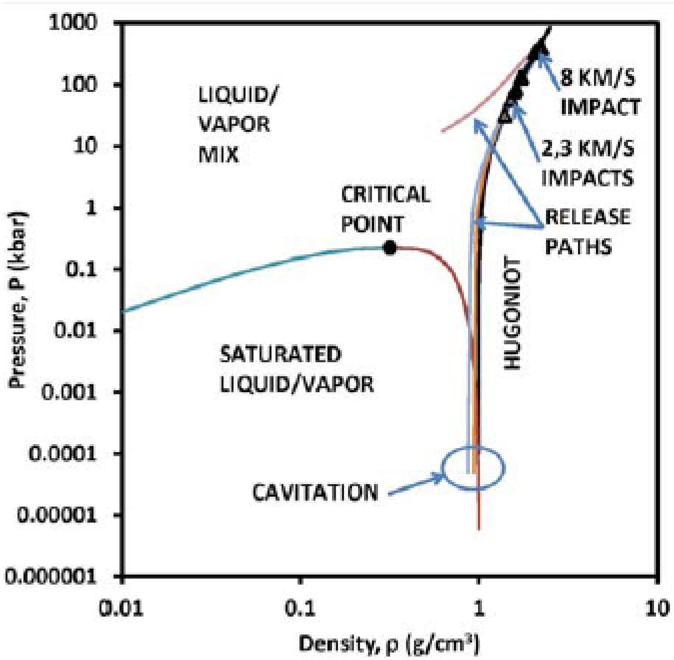
- SESAME 7150 (water)
- SESAME 7153 (water with vapor dome
- Harvard (5 phase EOS)



# Cavitation Processes on Phase Diagram

- At spall plane, release to vapor pressure at lower velocities
- Prompt vaporization at hypervelocity impacts




Water Phase Diagram

<u>Key Parameters</u>

u = 2, 3, 8 km/s

L = 2 cm

$P_{vapor}$ = 0.05 bar