

# **Summary of Glass Experiments at Sandia National Laboratories**

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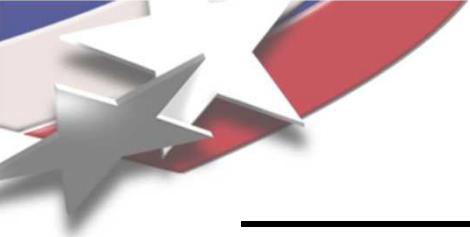
Air Force Research Laboratory, AFRL/MNMW

Glass Review Meeting

SRI

Menlo Park, California

September 6-7, 2007



# Outline

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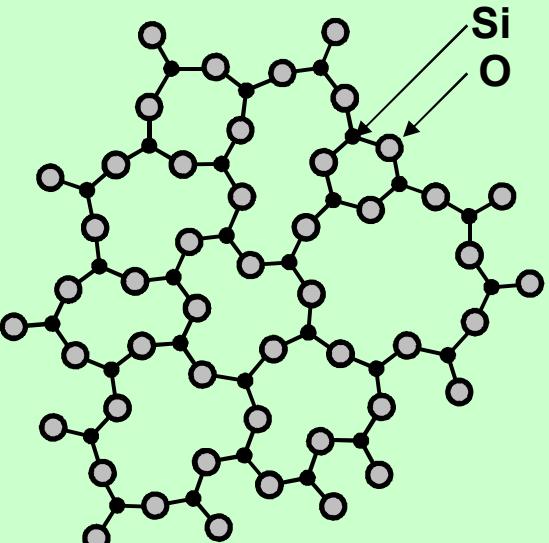
- **Introduction/Experimental Methods**
- **Starphire® Work**
  - Determination of the HEL
  - Loading paths
  - Wave speeds
  - Strength
- **Borofloat® work**
  - EOS, Strength
- **Comparison of silicate glasses**
- **Future Work**
- **Summary**

# Glasses Studied

## GE Type 151 (Fused Silica)

Density = 2.20 g/cm<sup>3</sup>  $\nu$  = 0.16  
 $C_L$  = 5.93 km/s  $C_S$  = 3.77 km/s

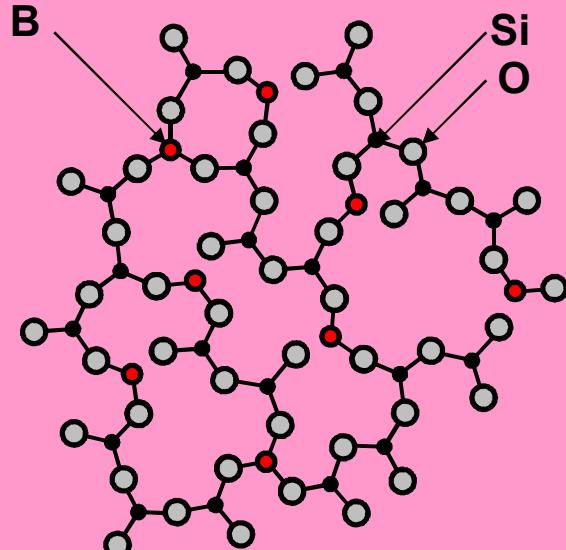
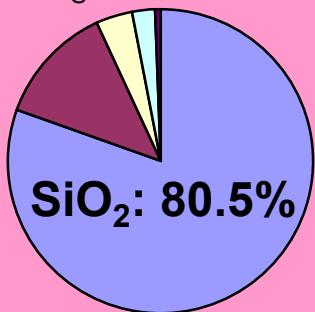
Impurities:  
Up to 50 ppm  
(0.005%)



## Borofloat® (Borosilicate Glass)

Density = 2.21 g/cm<sup>3</sup>  $\nu$  = 0.19  
 $C_L$  = 5.508 km/s  $C_S$  = 3.417 km/s

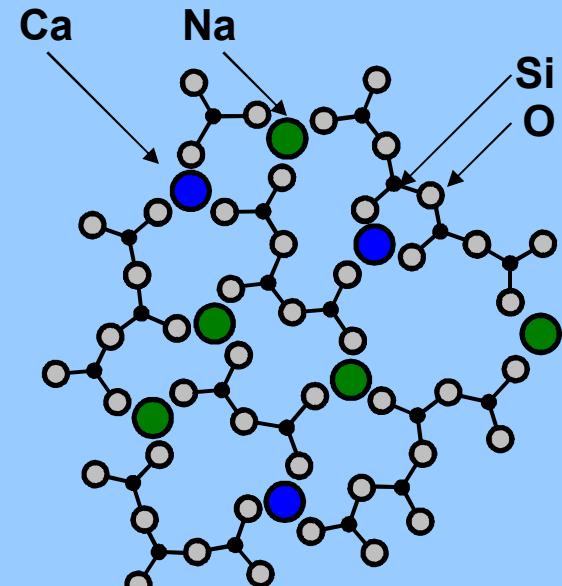
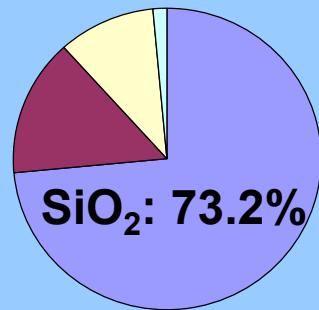
$\text{B}_2\text{O}_3$ : 12.7%  
 $\text{Na}_2\text{O}$ : 3.5%  
 $\text{Al}_2\text{O}_3$ : 2.5%



## Starphire® (Soda-Lime Glass)

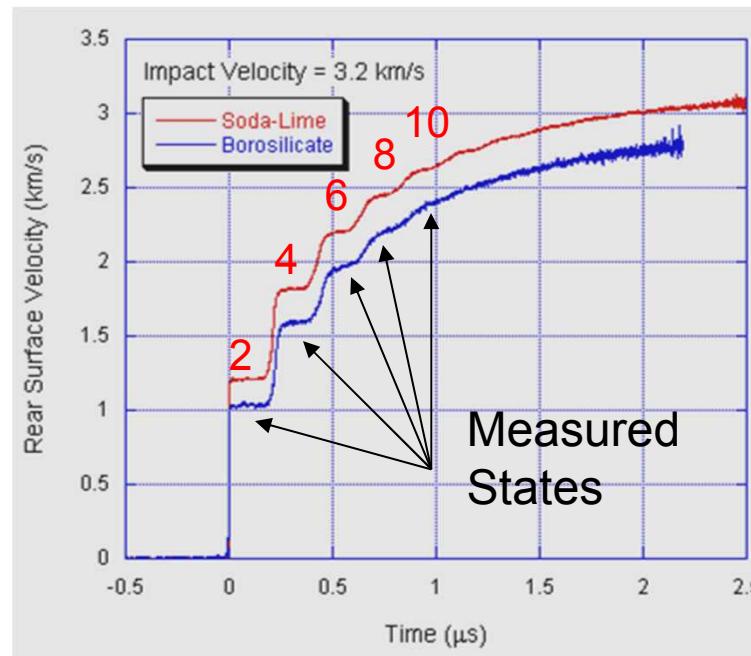
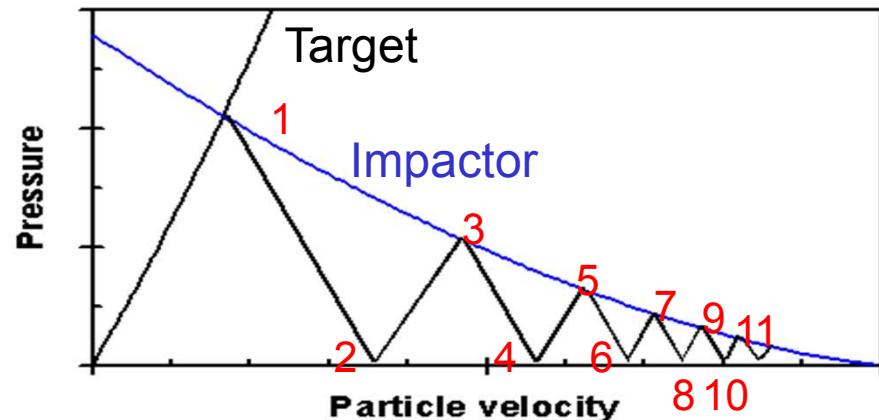
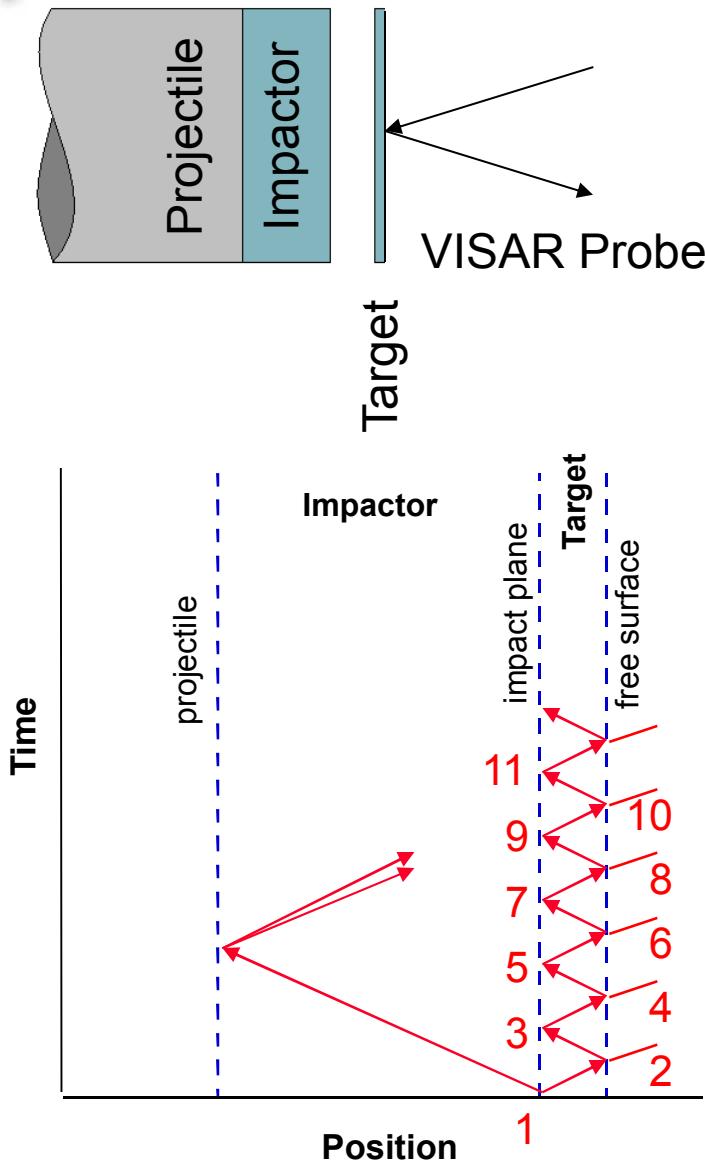
Density = 2.50 g/cm<sup>3</sup>  $\nu$  = 0.22  
 $C_L$  = 5.761 km/s  $C_S$  = 3.437 km/s

$\text{Na}_2\text{O}$ : 14.7%  
 $\text{CaO}$ : 10.3%  
 $\text{Al}_2\text{O}_3$ : 1.4%



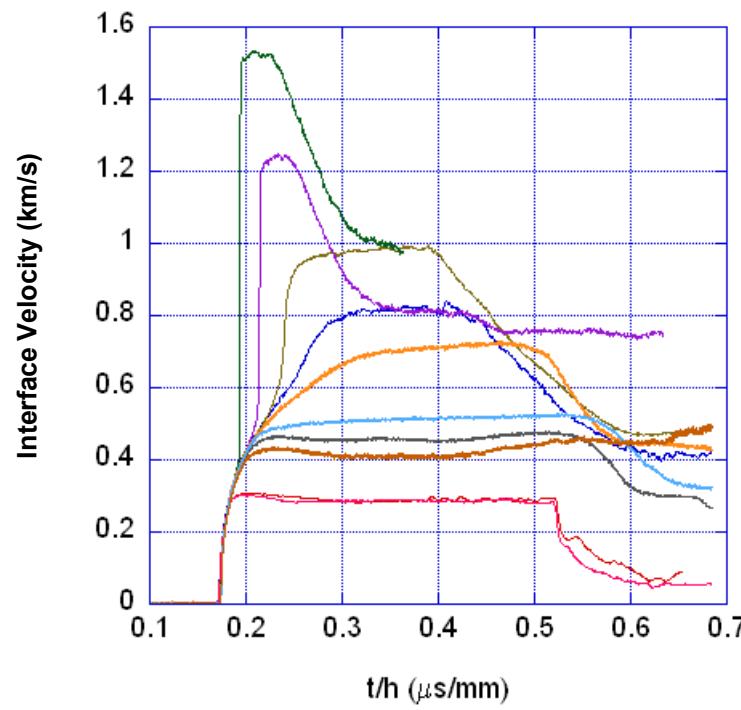
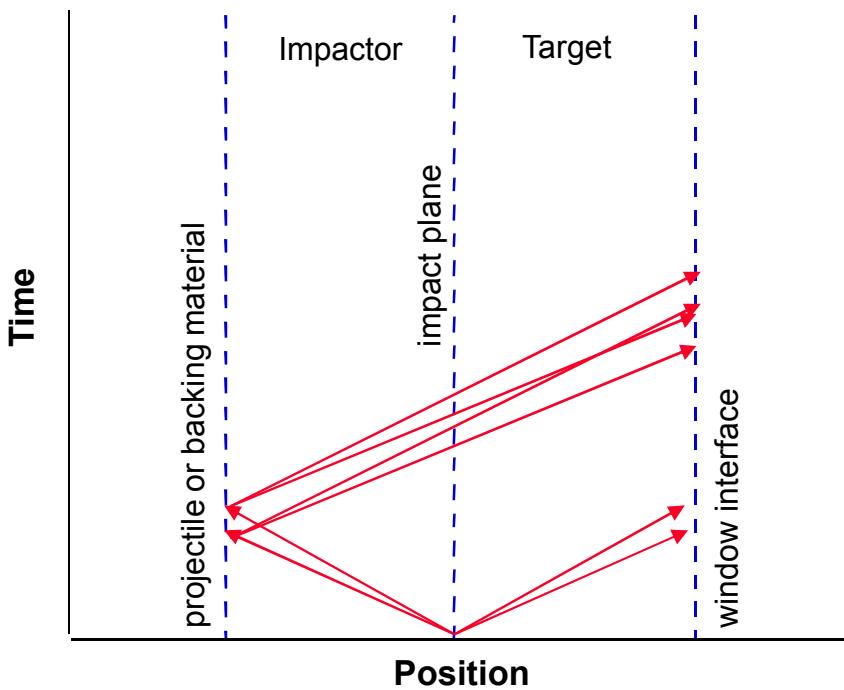
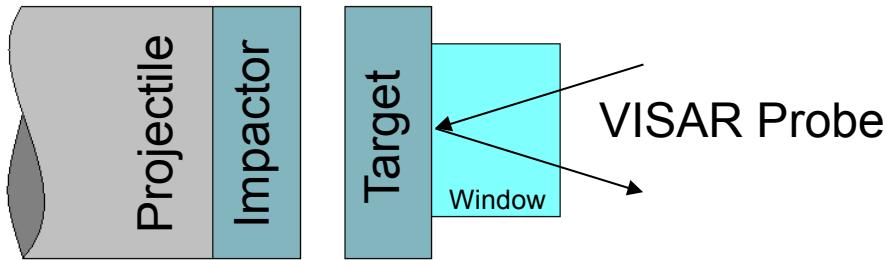
# Experimental Methods

## Plate Reverberation Technique

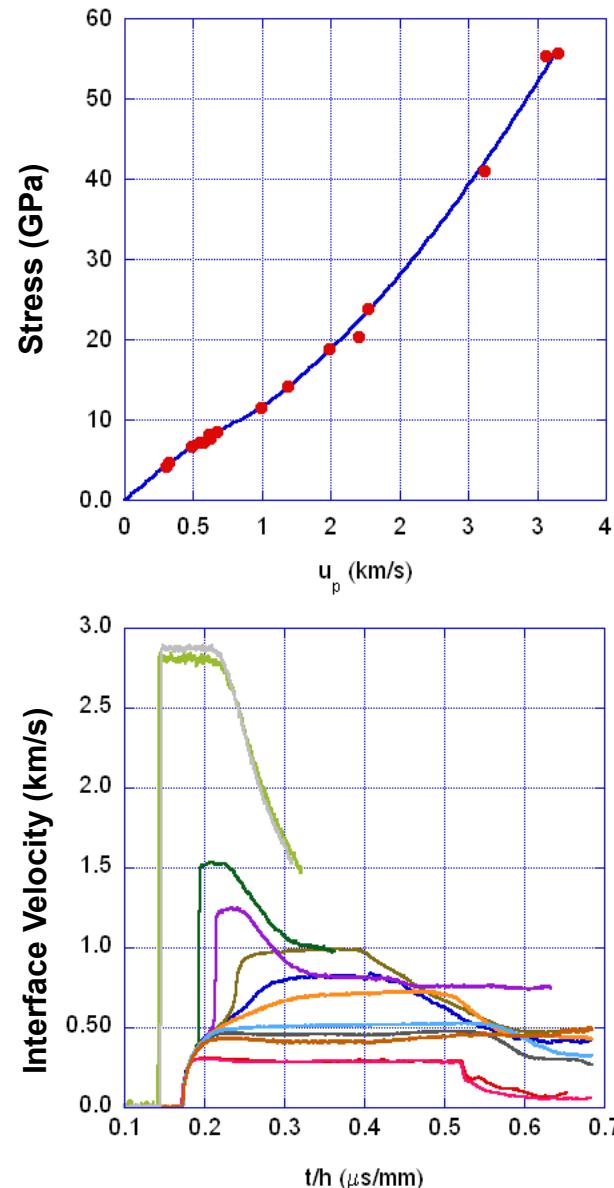


# Experimental Methods

## Transmitted Wave Technique

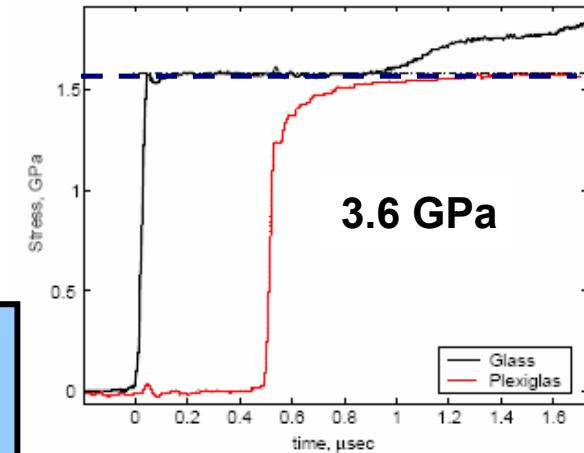
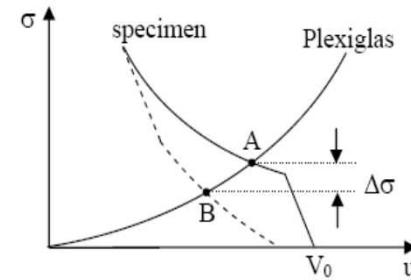
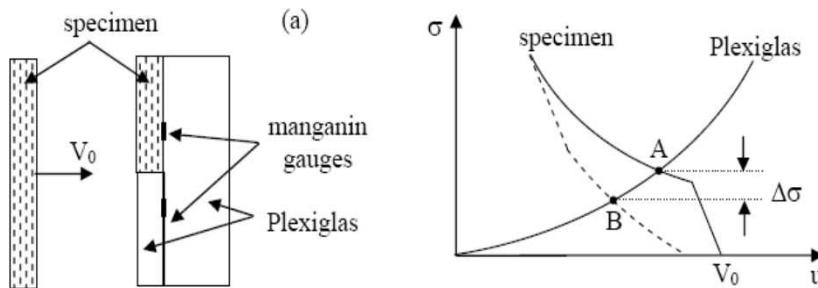
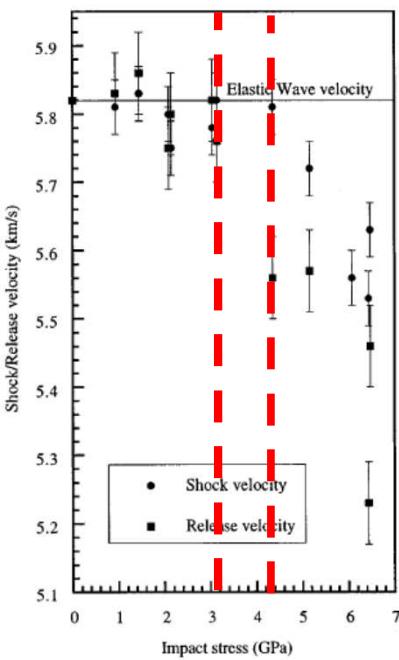


# Soda-Lime Glass Hugoniot Response



- Now have experimental data to 55 GPa!!
  - Hugoniot response is distinct from fused silica and borosilicate glass (more on this later)
- 3 response regions
  - Elastic (0 to ~3.5 GPa)
    - Based on published work
  - Intermediate (~3.5 to 7.5 GPa)
    - Onset determined by loss of shear strength
    - Longitudinal response mimics elastic behavior
      - Self-similar and reversible loading paths
    - Any shear stress initiates failure
    - Pullback response observed
  - “Normal” plastic (> 7.5 GPa)
    - Shock formation
    - Plastic deformation
    - Mixed phase appears as regrowth of strength (in unfailed material)

# Soda-Lime Glass Elastic Response



**Split target technique shows onset of inelastic response (E-P or failure?) between 3.6 – 4.3 GPa**

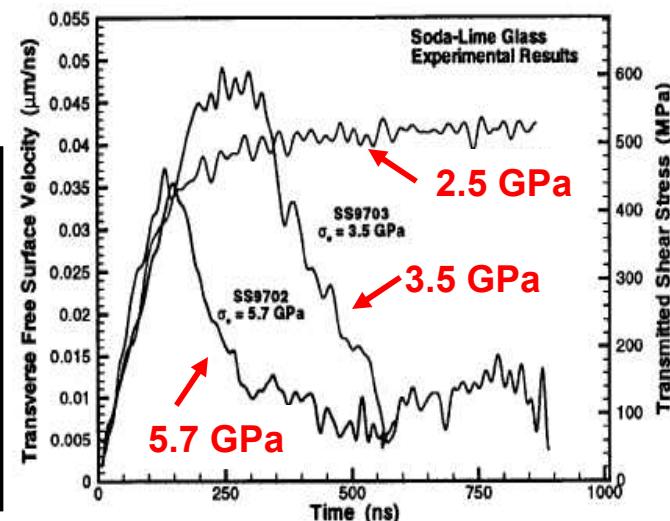
• Rosenberg, Z., Ashuach, Y., Dekel, E.  
"On The Use Of Manganin Stress Gauges To Determine Yielding And Fracture In Shock Loaded Solids"  
Proc. 12<sup>th</sup> Int. Symp. On Plasticity (2006)

**Shock / release velocity split (& index of refraction cusp)**

• Dandekar, D.P.  
"Index of Refraction and Mechanical Behavior of Soda Lime Glass Under Shock and Release Wave Propagations", J. App. Physics **84** 6614 (1998)

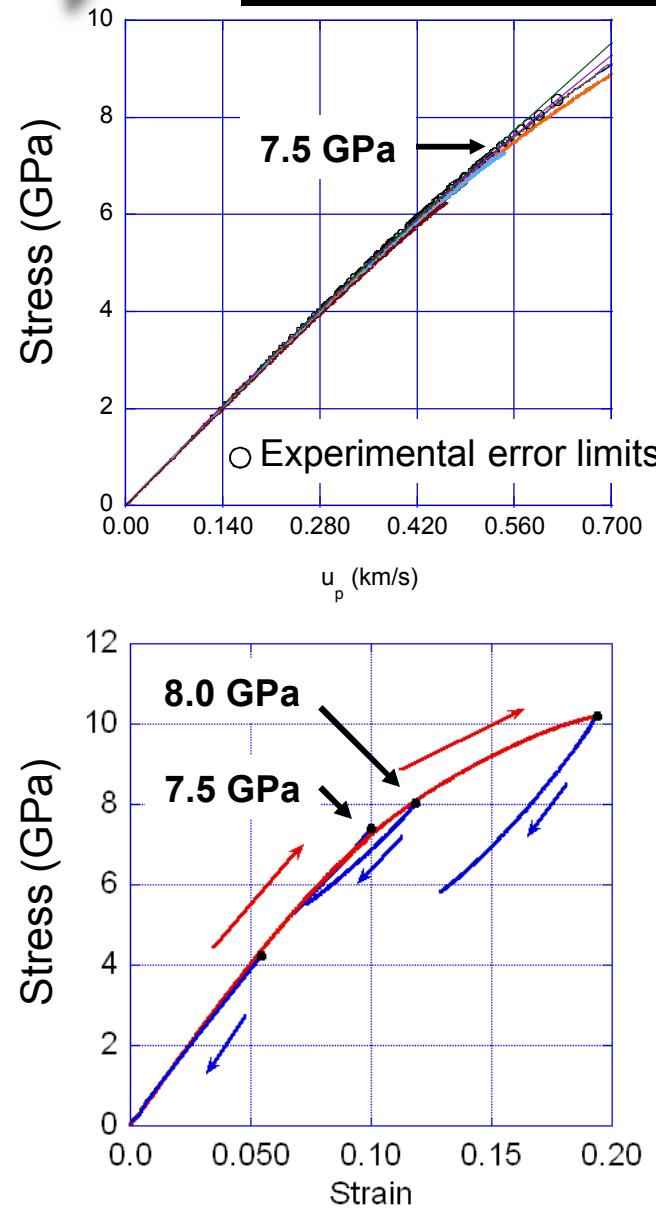
**Shear resistance drops for longitudinal compression above 3.5 GPa.**

• Clifton, R.J.  
"Response of Materials Under Dynamic Loading"  
Int. J. Sol. Struct. **37**, 521 (2000)

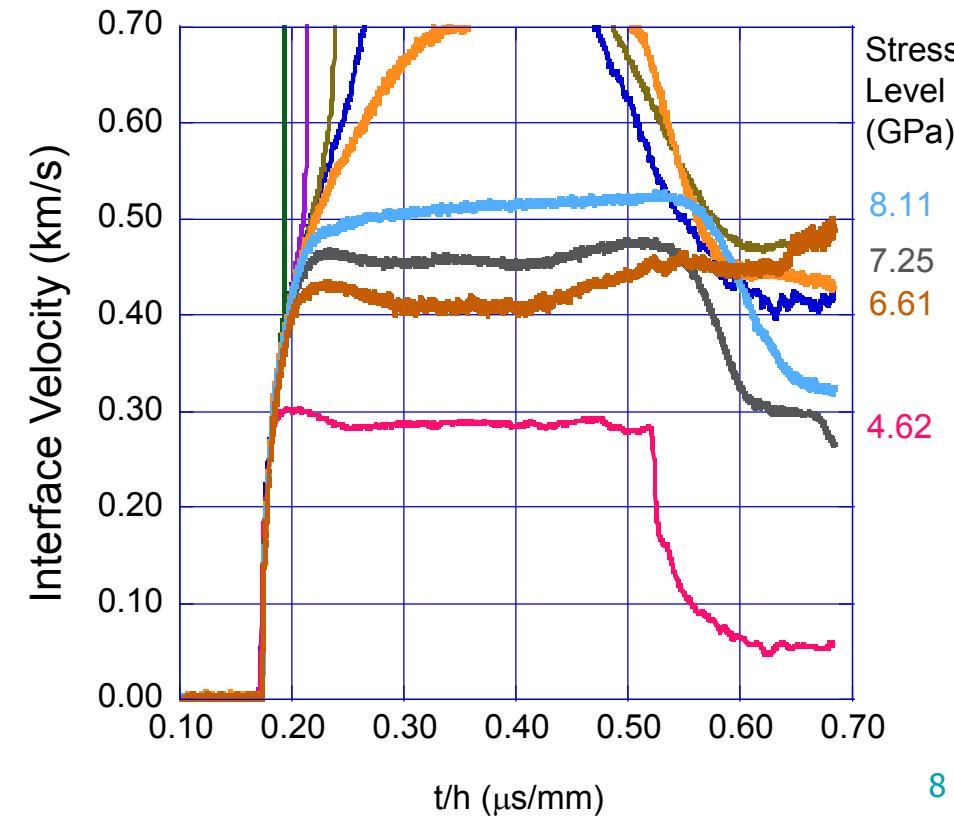


# Soda-Lime Glass

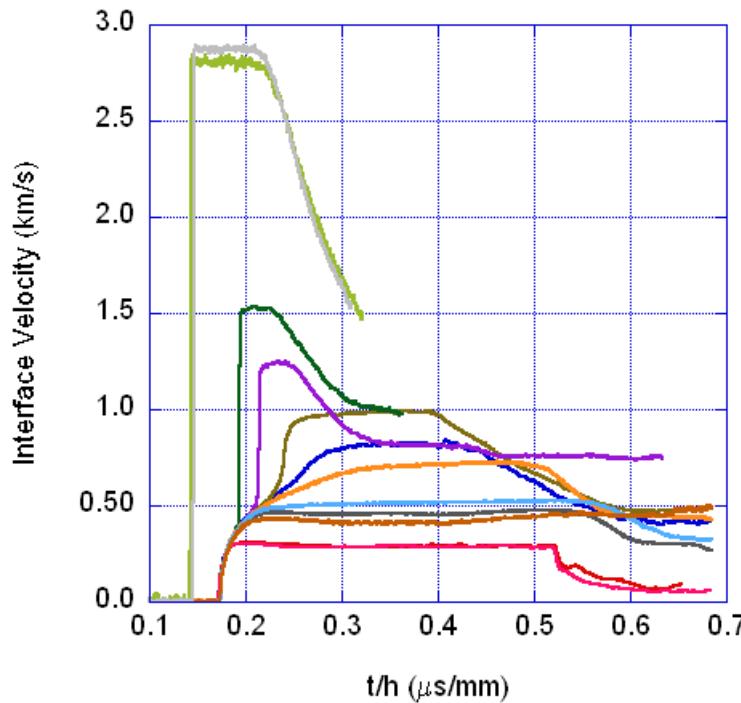
## Intermediate Response



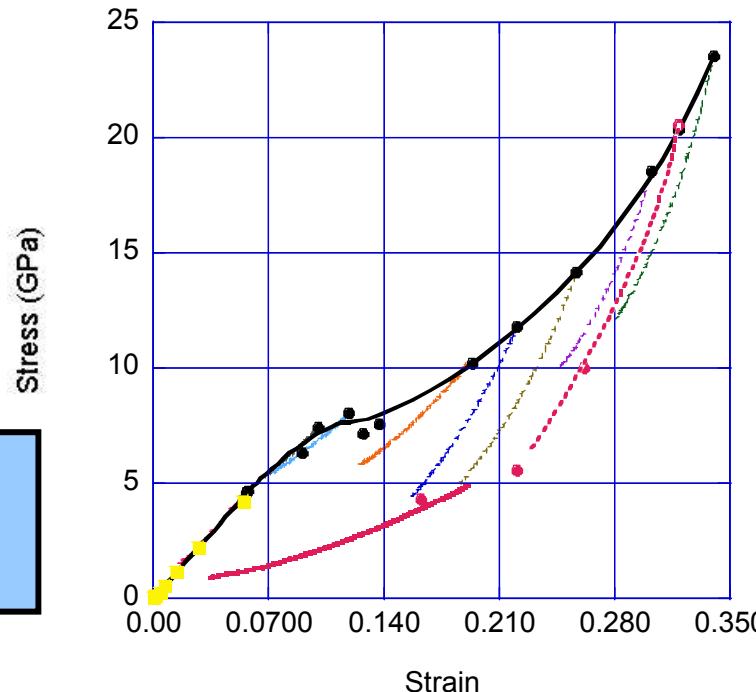
- Intermediate (3.5 – 7.5 GPa)
  - Onset determined by loss of shear strength
    - Any shear stress initiates failure
  - Longitudinal response mimics elastic behavior
    - Self-similar and reversible loading paths
  - Pullback response observed



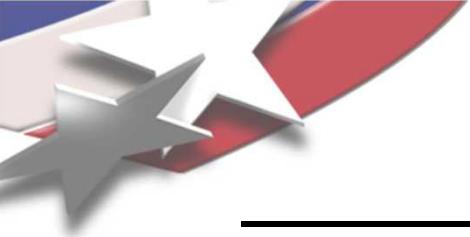
# Soda-Lime Glass Plastic Response



- “Normal” plastic (> 7.5 GPa)
  - Shock formation
  - Ramp portion overdriven ~ 30 GPa
  - Plastic deformation
  - Mixed phase appears as regrowth of strength (in unfailed material) (more on this later)



Steepening of release paths suggests onset of mixed phase region



# Let's Review...

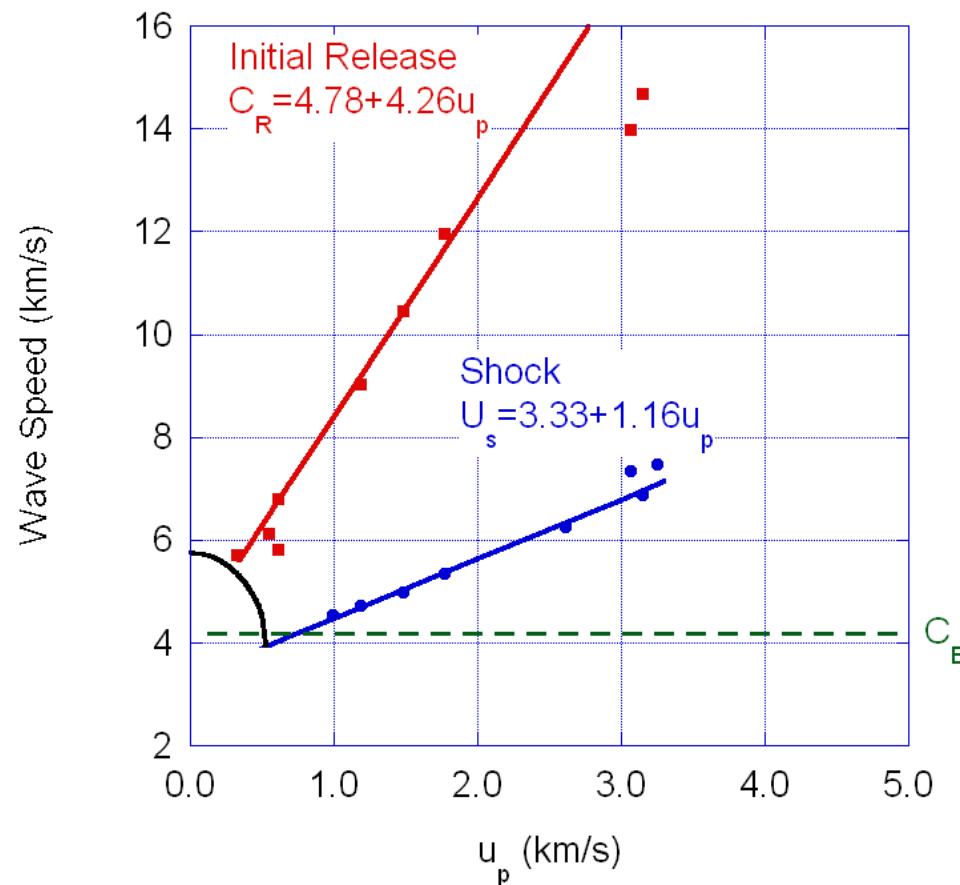
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- Self-similar loading paths
  - 7.5 GPa
- Onset of loading/release path hysteresis
  - 7.4 – 8.0 GPa
- Reports of inelastic response as low as 3.5 GPa

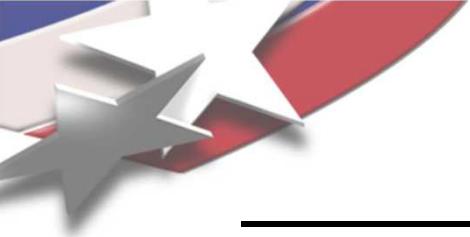
At first, these observations appear to conflict

What is occurring in the intermediate response region that leads to these observations?

# Wave Speed Data



- Wave speed can be calculated knowing transit times and sample thickness
  - Ramp gives continuous curve
  - Discrete points from each shock
- Wave speed data suggests fluid like response between 6.6 - 8.0 GPa



# Let's Review...

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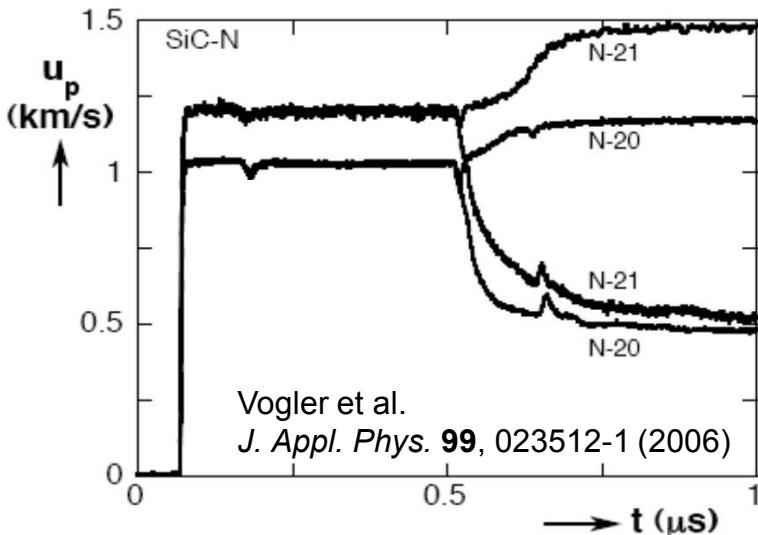
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At first, these observations appear to conflict

- Fluid response 6.6-8.0 GPa

# Strength Determination

## - A quick primer



Hugoniot state stress is a combination of mean and shear stress

$$\sigma_h = \sigma_m + \frac{3}{4}\tau_h$$

Upper and lower yield surfaces, determined via reshock and release experiments, are defined by

$$\sigma_{\max} = \sigma_m + \frac{4}{3}\tau_c \quad \sigma_{\min} = \sigma_m - \frac{4}{3}\tau_c$$

Results in a shear strength in the shocked state of

$$\tau_c = \frac{3}{8}(\sigma_{\max} - \sigma_{\min})$$

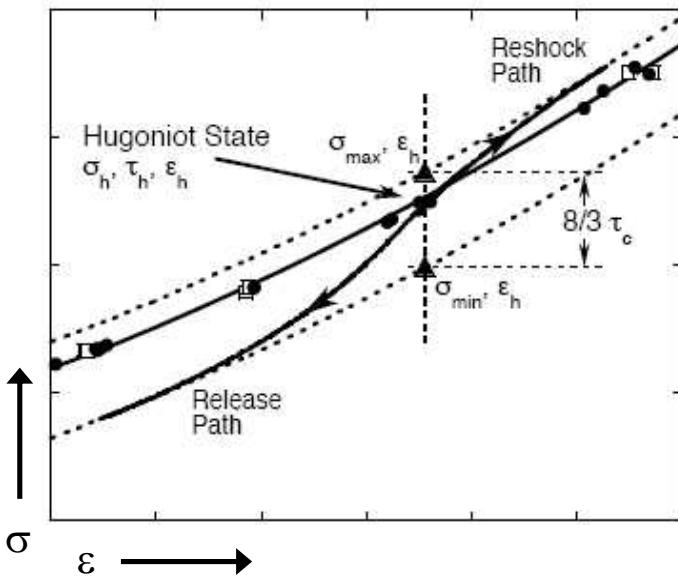
Strength is determined from shear stress as

$$Y_h = 2\tau_c = \frac{3}{4}(\sigma_{\max} - \sigma_{\min})$$

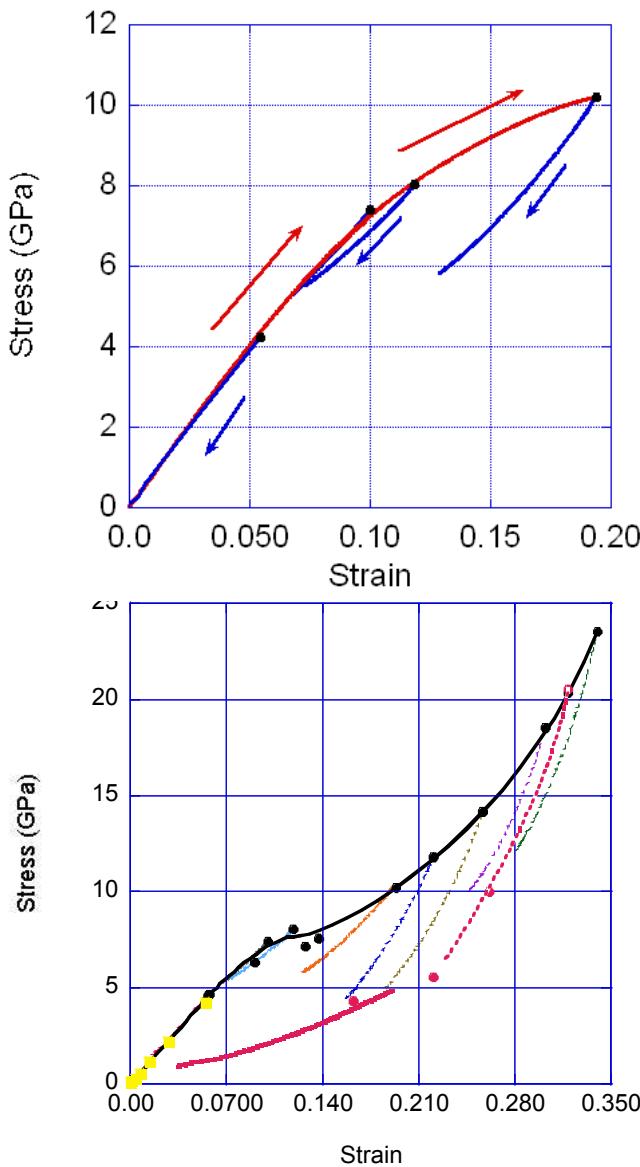
Since only release data is available to date, symmetry is assumed so that

$$Y_h = 2\tau_c = \frac{3}{2}(\sigma_h - \sigma_{\min})$$

Note that if  $Y=0$ , loading and release will occur along the Hugoniot

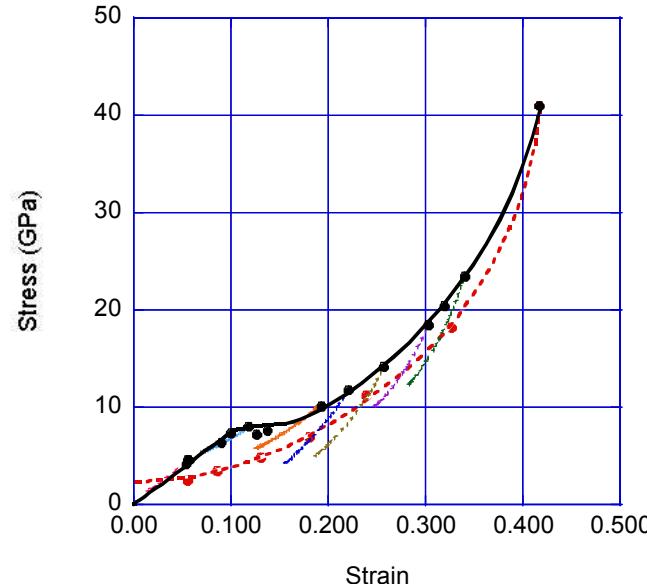


# Release Response



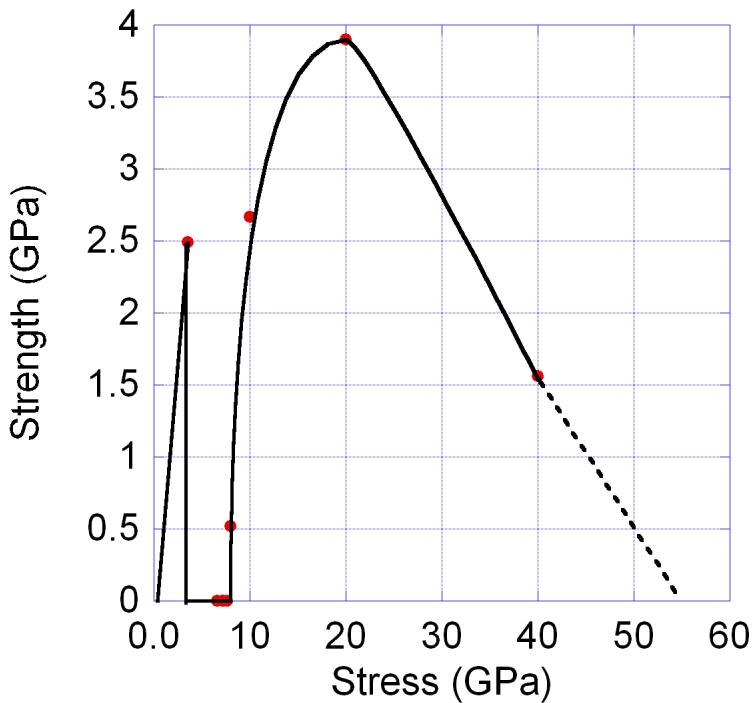
$$Y_h = 2\tau_c = \frac{3}{2}(\sigma_h - \sigma_{\min}) = \frac{3}{2}(\text{hysteresis})$$

- No hysteresis below 8 GPa
  - Elastic -or- No Strength
- Hysteresis builds 8-20 GPa
  - Increasing strength
  - Stishovite-like mixed phase is likely
- Decreases above 20 GPa
  - Decreasing strength?
  - Precursor to phase transition?

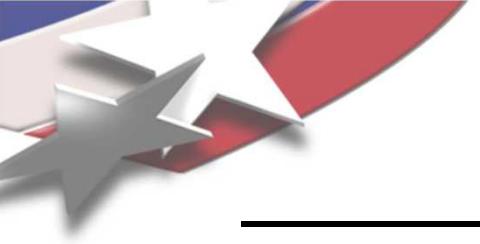


# Strength of Soda-Lime Glass

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- Linear elastic response up to 3.5 GPa
- Rapid loss of strength 3.5 - 6.6 GPa
  - Assumed immediate due to other reports (Rosenberg et al., Dandekar)
- Strength rebuilds above 8 GPa
- Strength projected to return to zero near 55 GPa



# Let's Review...

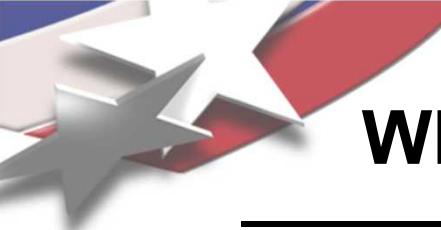
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- Self-similar loading paths
  - 7.5 GPa
- Onset of loading/release path hysteresis
  - 7.4 – 8.0 GPa
- Reports of inelastic response as low as 3.5 GPa

At first, these observations appear to conflict

- Fluid response 6.6-8.0 GPa
- Complete loss of strength at 3.5 GPa

Now we see that all observations are consistent if all strength is lost at 3.5 GPa



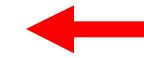
# What makes soda-lime glass unique...

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- Complex shock response within the intermediate region
  - Rapid strength loss
    - Fluid – like response:
      - Self-similar loading/release paths
      - Response termed pseudo-elastic due to mimicking of some elastic properties
      - Computational models may be sufficient extending elastic ramp to 7.5 GPa
    - Smallest shear stress will initiate failure (important in experiment design as failure will initiate at glass-glass interfaces)
- At high pressure, shock response clearly differs from other silicates
  - Altered phase transition kinetics?
  - Stiffer response (not consistent with changes to 'structure')

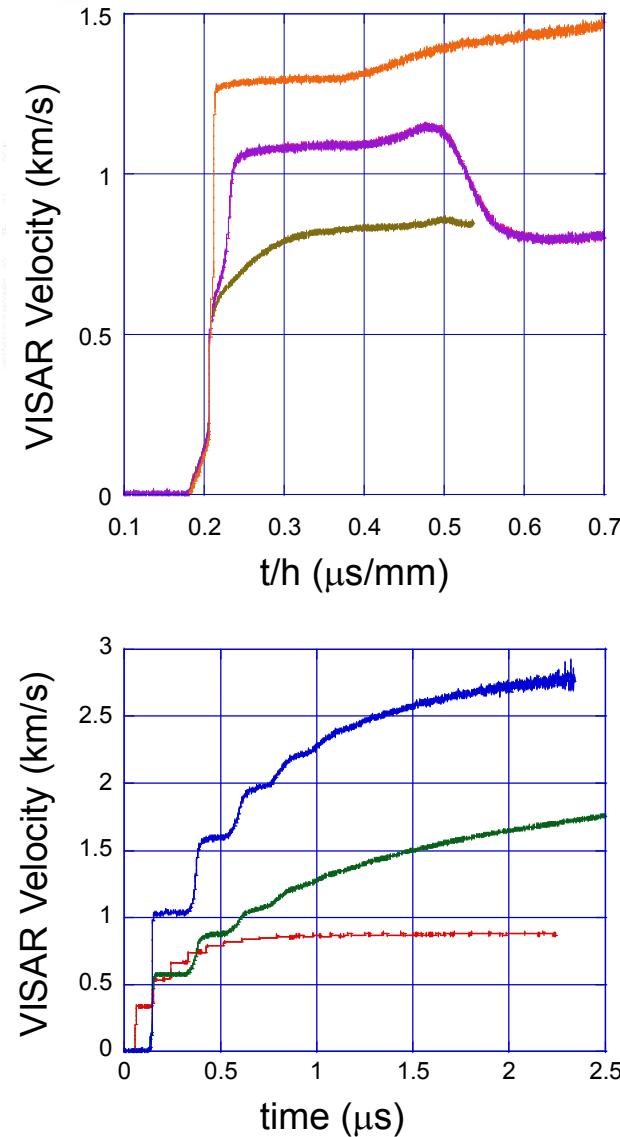
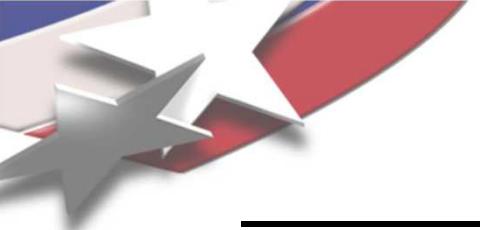


These items require further experimentation to clarify or confirm.

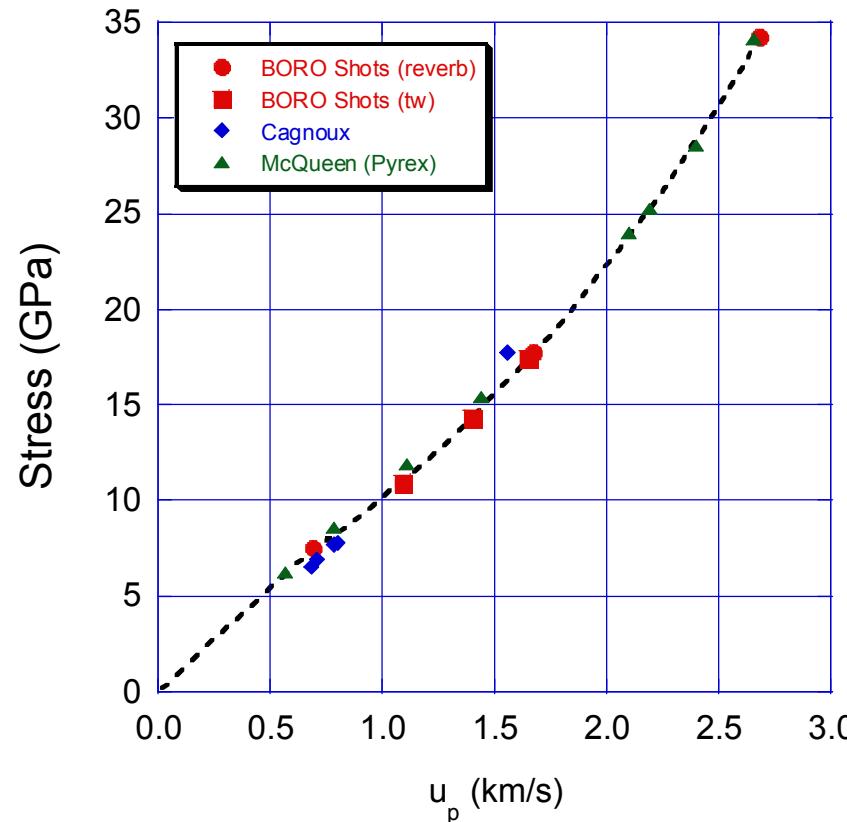


# Borofloat® Results

## Equation of State

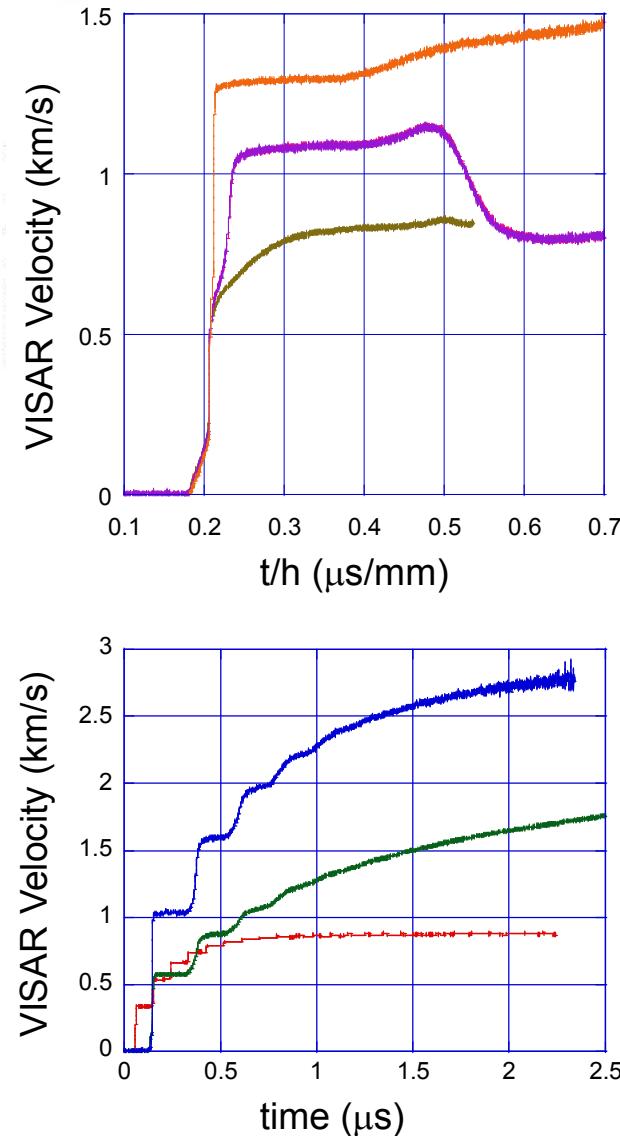
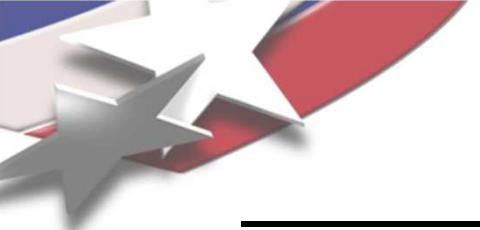


- Wide range of results (4 – 34 GPa)
- Results consistent with previously published Hugoniot response of Pyrex®

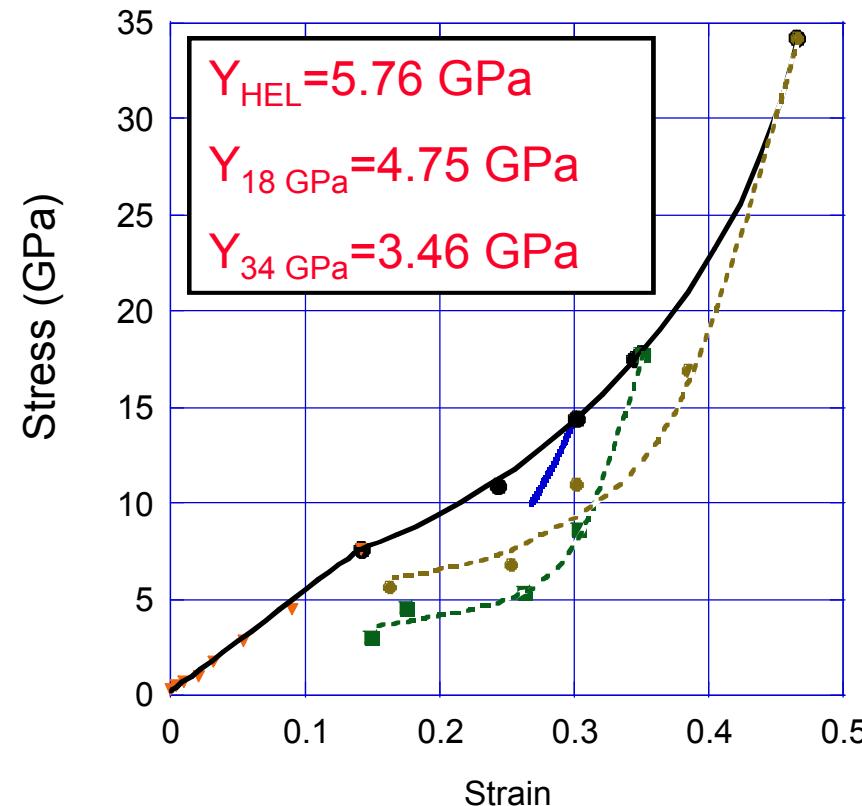


# Borofloat® Results

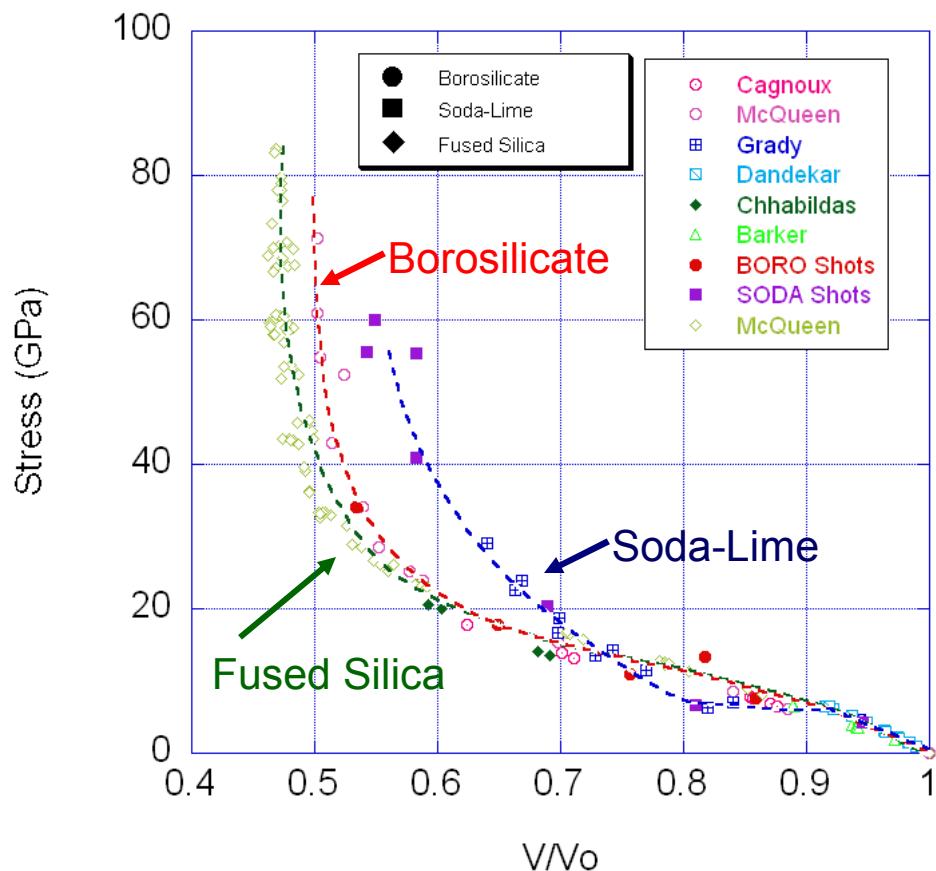
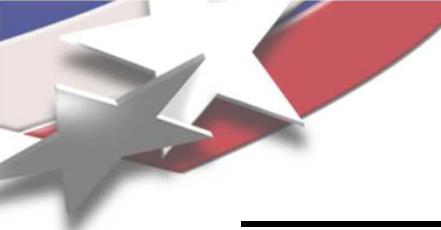
## Strength



- Strength estimated from release data
  - Complicated by phase transition
  - Appears to be mixed phase (15-18 GPa)
  - Appears complete by 34 GPa
- Reshock experiments will help answer questions



# Comparison of Silica Glasses

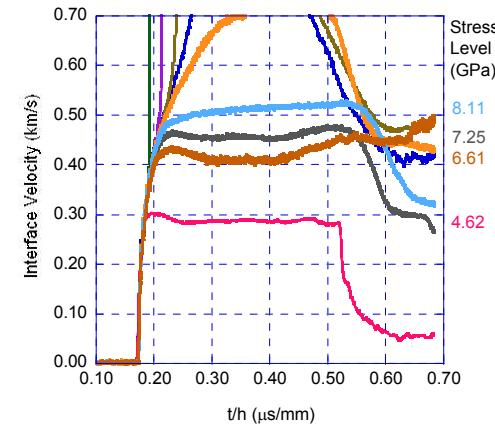
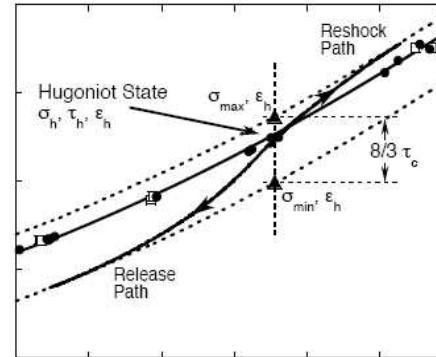


- Shock response of soda-lime glass distinct from fused silica and borosilicate glass
  - Loss of strength
  - Altered phase transition kinetics

- Shock response of borosilicate glass is similar to fused silica
  - Similar network structure
  - Si-O and B-O bond similarity

# Future Work

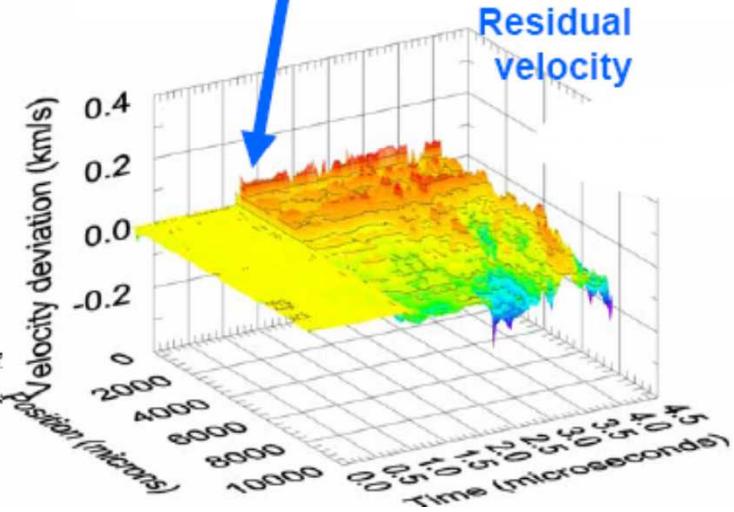
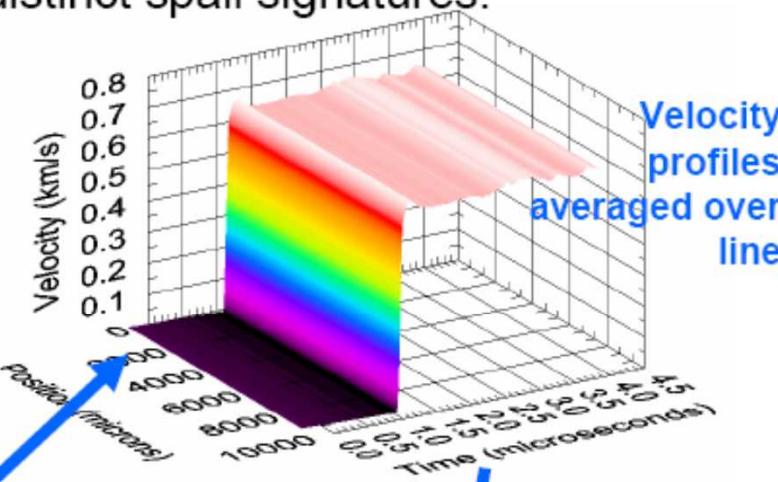
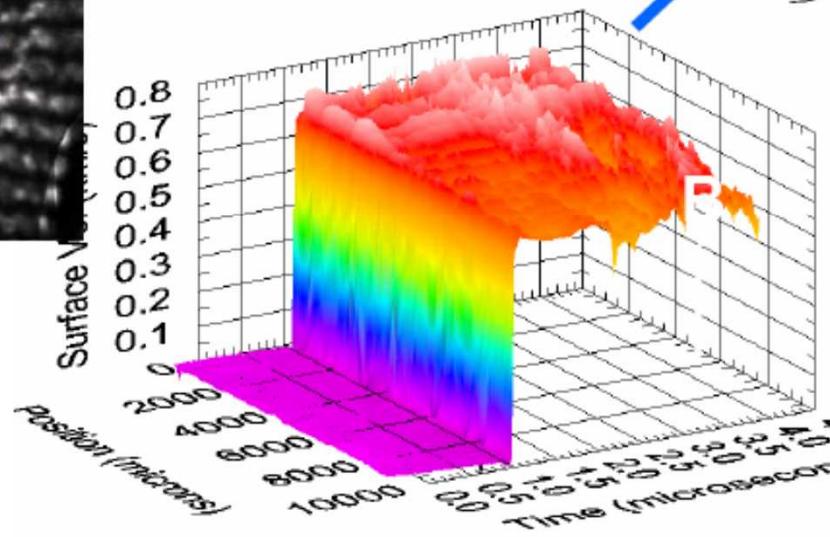
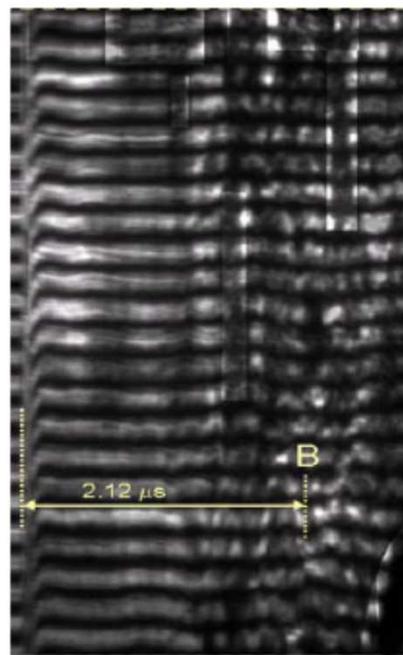
- Strength measurements to 50 GPa (Shock – reshock – release)
- Investigate failure
  - initiation
  - propagation
- Spatial uniformity of response (Line-VISAR experiments)
- Isentropic Compression
  - Determine hydrostat
  - Is strength loss related to thermal softening?
  - Structural stability at lower strain rates ( $10^5$  –  $10^6$  s $^{-1}$ )





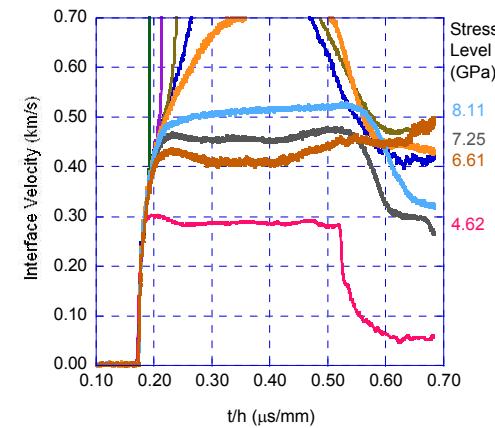
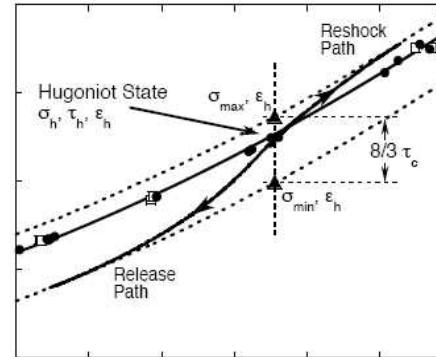
## Intermittent shallow pullback signatures are visible

Particle velocity variation in “compression” comparable to variation in pull back  
This is consistent with failure wave modification of material prior to spallation.  
Not all pullbacks appear to be “classic” or distinct spall signatures.

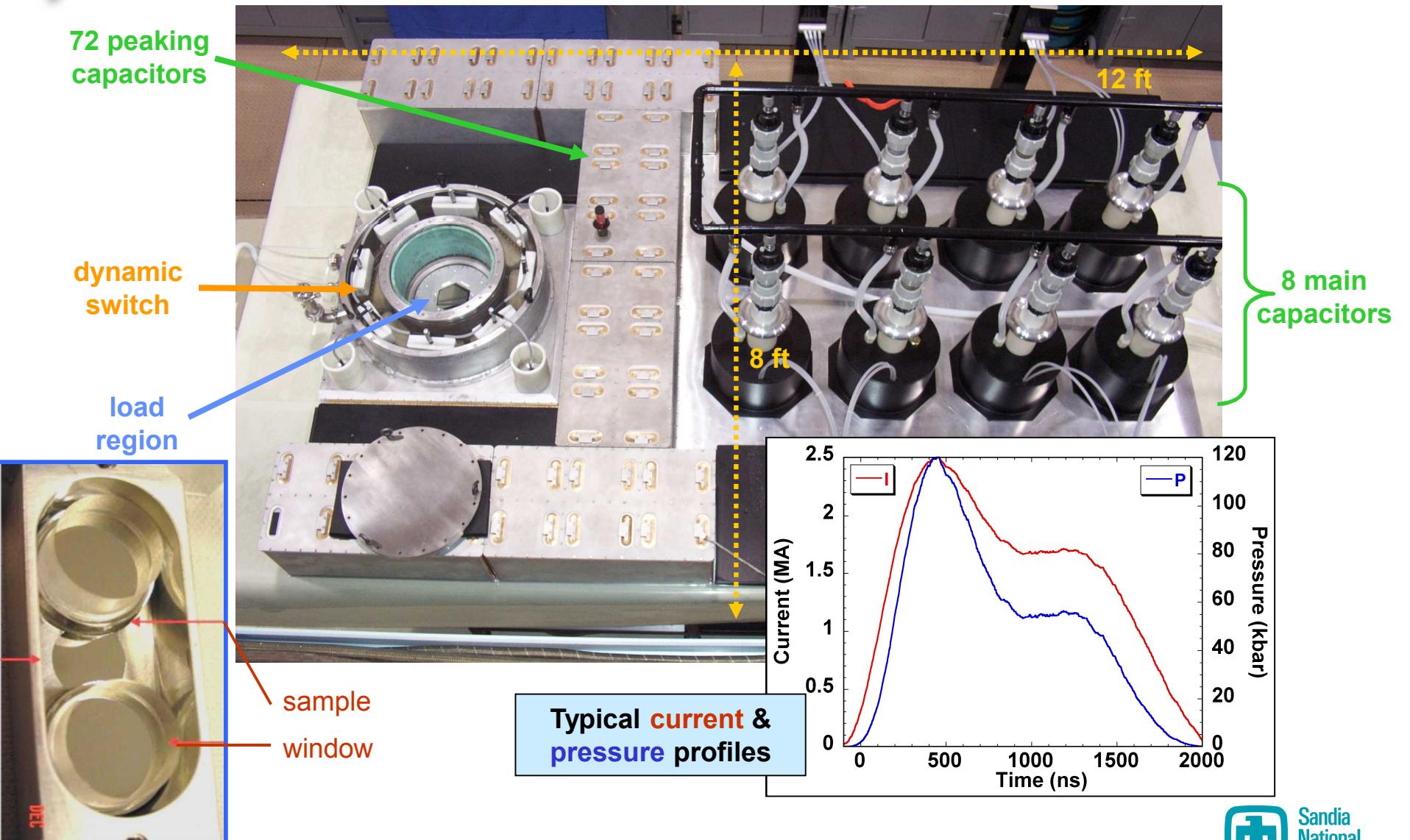


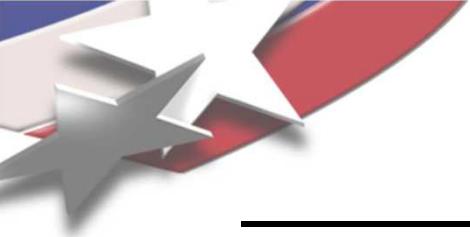
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- Investigate failure
  - initiation
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# Veloce Pulser at SNL





# Summary

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- **Starphire®**
  - Hugoniot defined to 55 GPa (3 response regions)
  - Work continues on strength determination
  - Need to examine failure mechanisms
  - Need to examine thermal effects (ICE)
- **Borofloat®**
  - Hugoniot data agrees well with Pyrex®
  - Work continues on strength determination
  - Expected to be very similar to fused silica (mixed phase)