

Dynamic material strength measurement at Sandia National Laboratories

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Sandia National Laboratories

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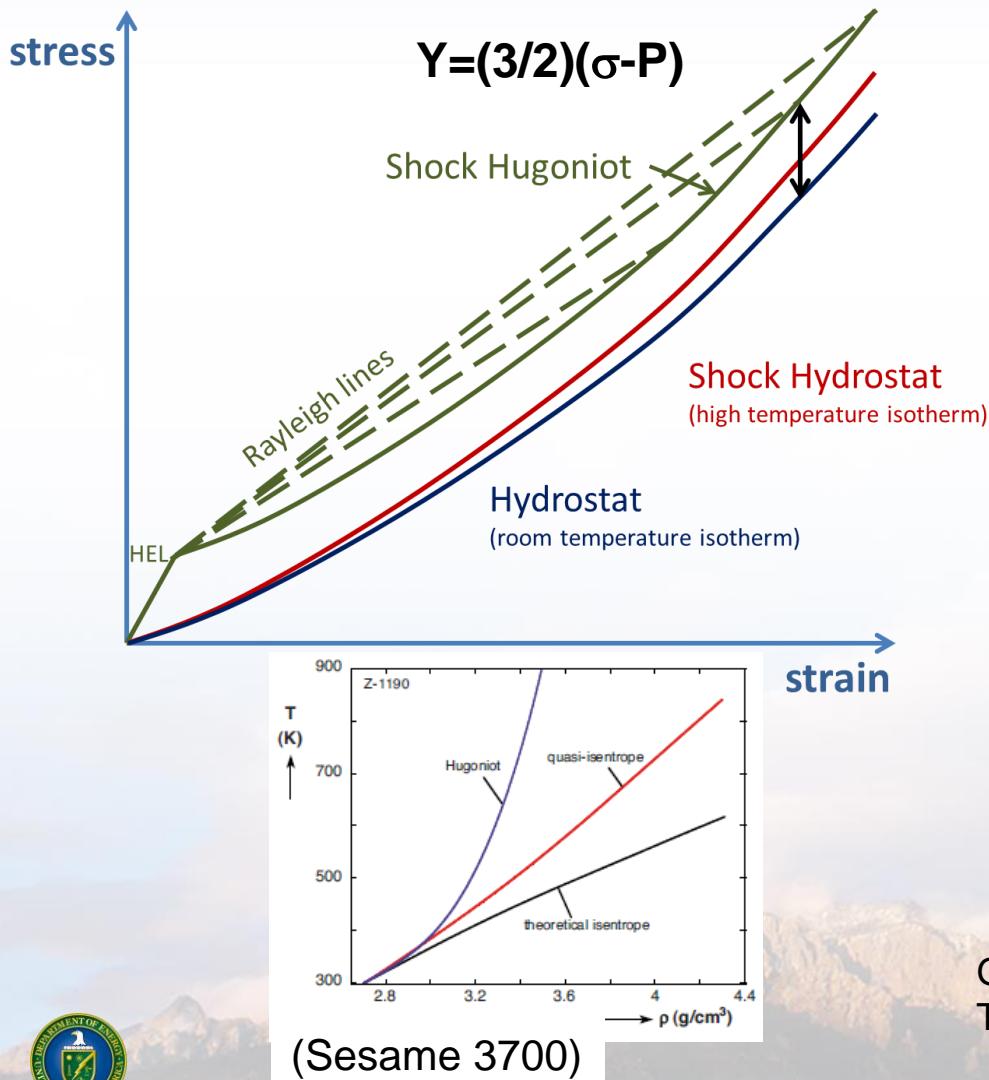
Acknowledgements

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A historical perspective of strength measurement under shock loading



Comparison between Hugoniot and hydrostat

- Prone to large uncertainties
 - 1-2% in measurement of shock state
 - 1-2% in EOS which determines hydrostat
 - Difference of two large numbers
 - Temperature corrections
 - Extrapolation of DAC data to give hydrostat
- Useful when only loading data is available

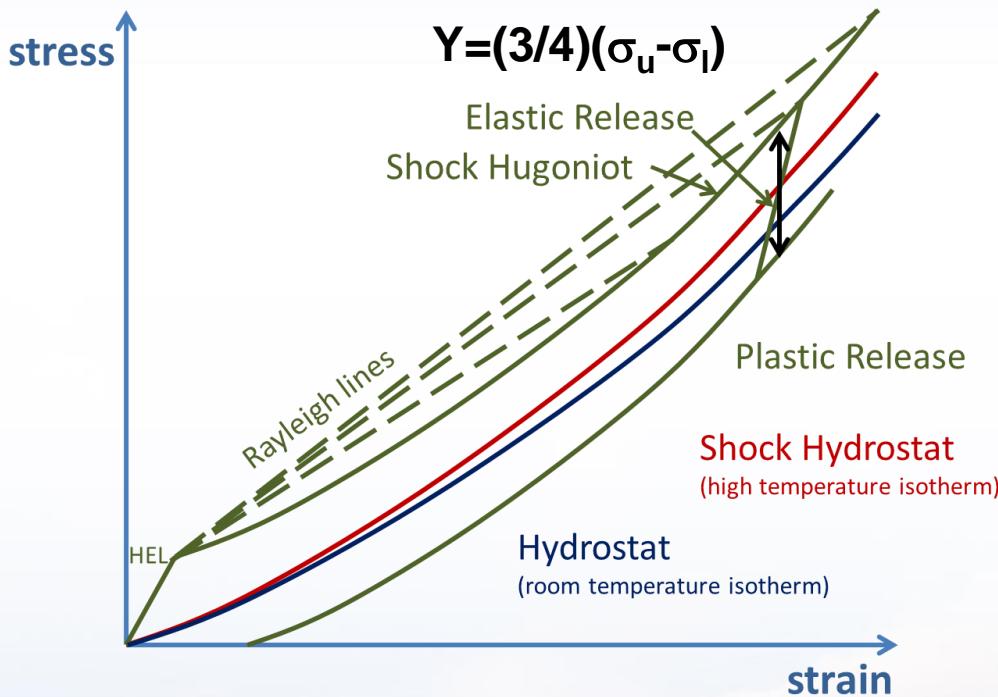
G.R. Fowles, *J Appl Phys* **32** 1475–87 (1961)
T.J. Vogler, *J Appl Phys* **106** 053530 (2009)



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A historical perspective of strength measurement under shock loading

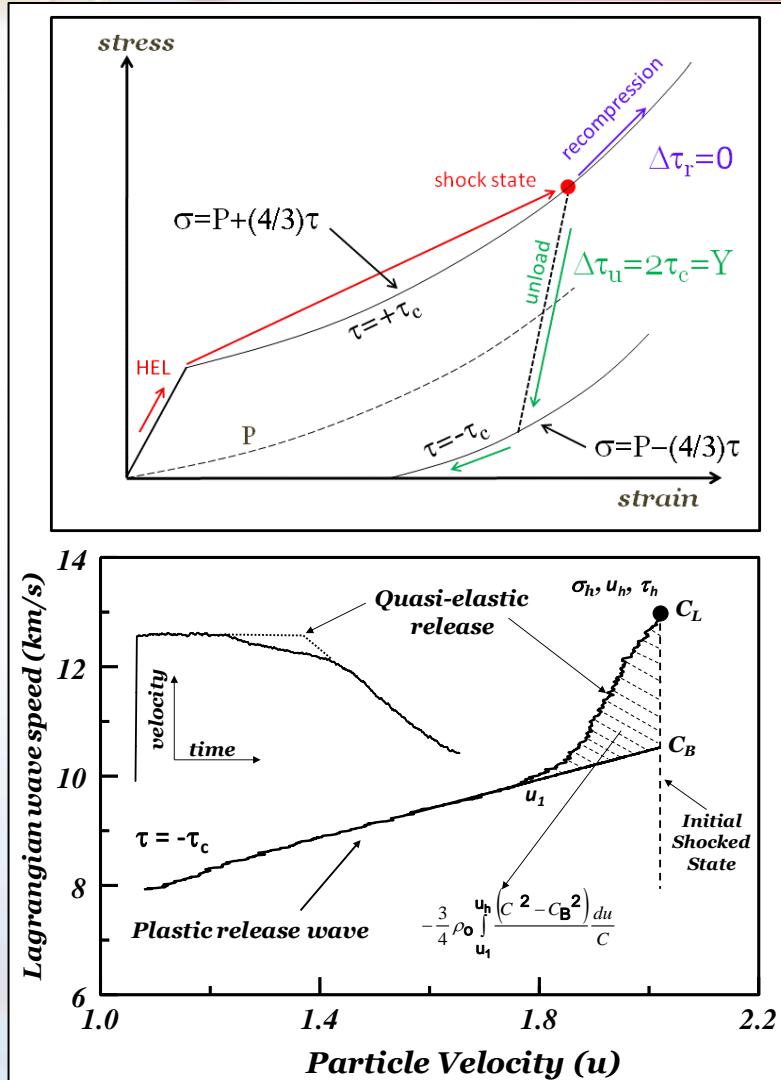


Measurement of release response for improved uncertainties

- Measurement of Δu during release provides improved resolution compared to stress difference
 - 1-2% in Δu
- During release material states go from upper to lower yield surfaces
- Assumes von Mises yield criterion
- Assumes isotropic hardening
- Assumes mean stress is at hydrostat
- Assumes that the shock state lies on the upper yield surface



A historical perspective of strength measurement under shock loading



The self-consistent technique

Measured wave profiles are used to determine wave speed as a function of strain or particle velocity

- Integrate differential form of the conservation equations:

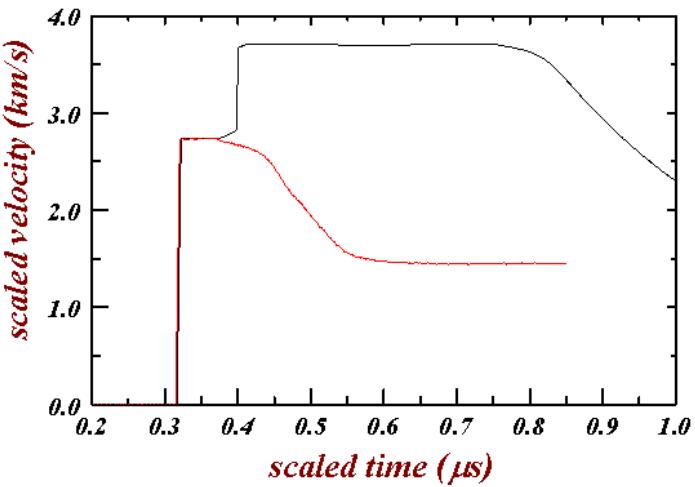
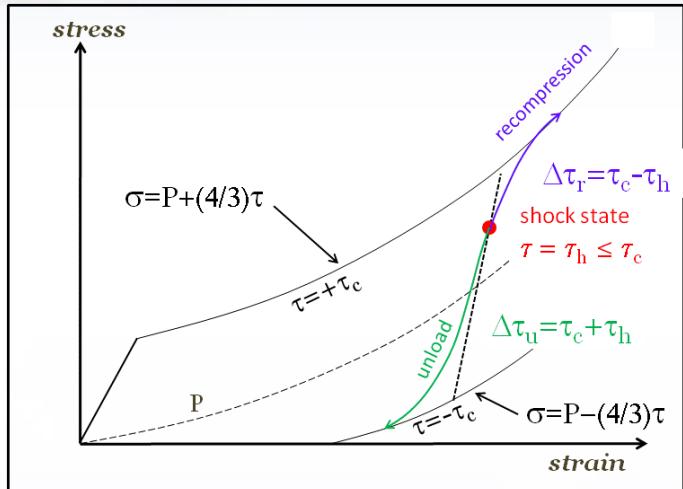
$$d\sigma_x = \rho_0 c du_p, \quad d\varepsilon_x = \frac{du_p}{c},$$

To get $\tau_c + \tau_h = -\frac{3}{4} \rho_0 \int_{a_h}^{e_1} (c^2 - c_B^2) d\varepsilon$

- With release data only, maintain all assumptions
- Elastic release from upper ($+\tau_c$) to lower ($-\tau_c$) yield surface
 - Implies $\tau_h = \tau_c$
- $Y = 2 \tau_c = \tau_c + \tau_h = \Delta \tau_u$



A historical perspective of strength measurement under shock loading



The self-consistent technique

- Addition of reloading data allows removal of assumptions about shock state
- Reloading experiments are more technically challenging due to high impedance backing
- Integrating conservation equations gives:

$$\tau_c + \tau_h = -\frac{3}{4}\rho_0 \int_{\epsilon_h}^{\epsilon_1} (c^2 - c_B^2) d\epsilon, \quad (\text{unloading})$$

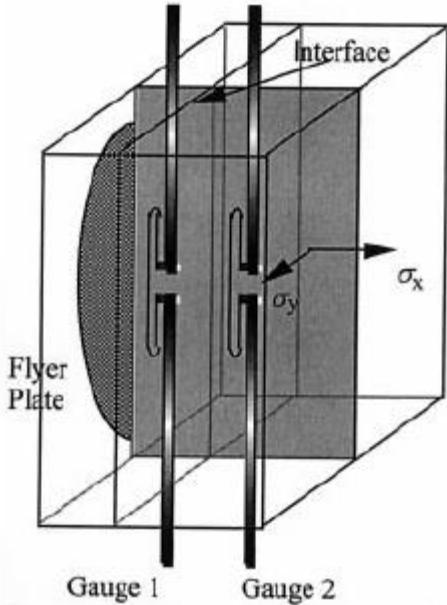
$$\tau_c - \tau_h = \frac{3}{4}\rho_0 \int_{\epsilon_h}^{\epsilon_2} (c^2 - c_B^2) d\epsilon, \quad (\text{reloading})$$

- Solve for τ_c and τ_h
- Explicitly determine yield surfaces and location of shock state





A historical perspective of strength measurement under shock loading



$$Y = (\sigma_x - \sigma_y)$$

Direct measurement of σ_x and σ_y

- Using lateral stress gauges allows for a direct measure of σ_y
- Longitudinal stress is determined with additional gauges or other techniques
- Generally limited to lower stress (<25 GPa)
- Calibration and interpretation of gauge data can be difficult
- Samples must be sectioned to allow gauge placement
- Electrical insulation can be problematic in metals



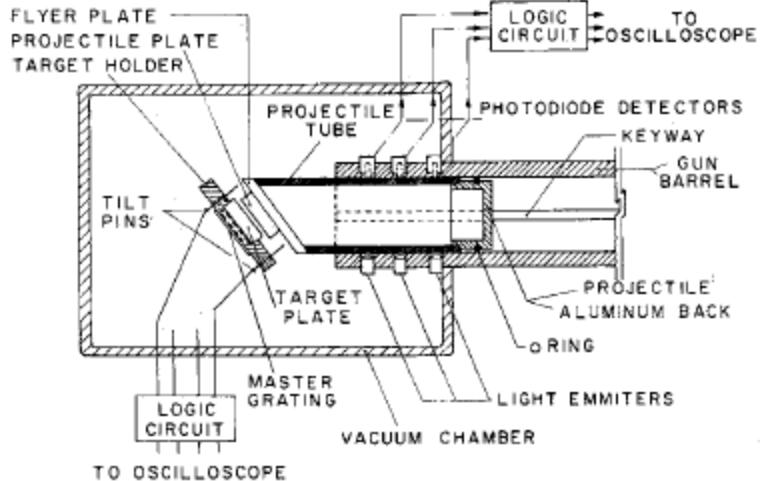
J. Millett and N. Bourne, *Scripta mater.* **42** 681-5 (2000)
Z. Rosenberg, *SCCM* 1999, 1033-7 (2000)



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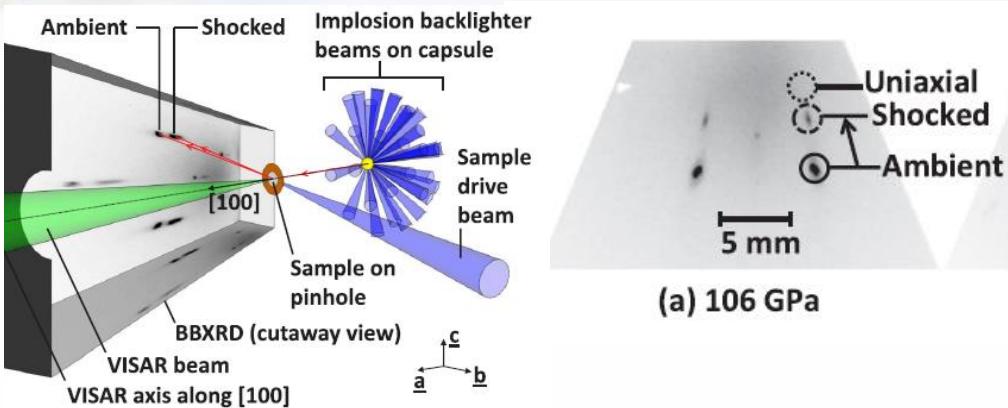


Direct measurement of σ_x and σ_y

- Oblique impact experiments generate both compression and shear waves
- Longitudinal and shear wave speeds are measured directly
- Bulk response is determined
- Difference between longitudinal and bulk response is attributed to strength
- Ability of glue bonds and friction to transmit shear stress limits experiments to lower shear stress levels



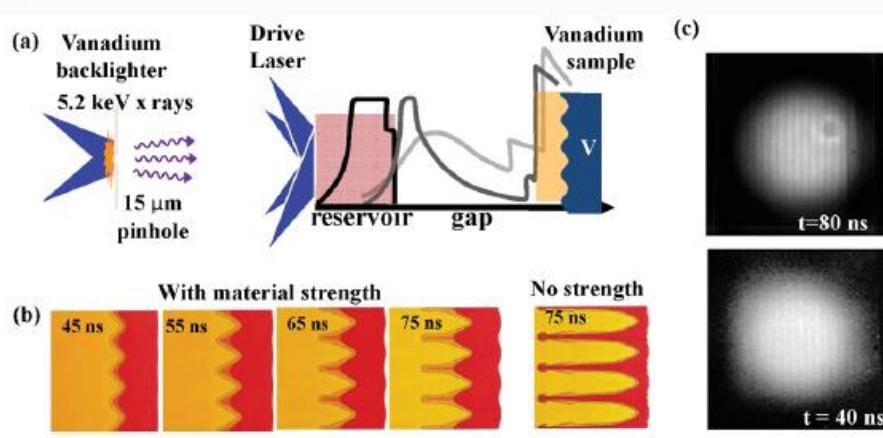
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X-ray diffraction

- Shift of Laue spots determine lattice aspect ratio
- Combine with σ_x and DFT simulations to get strength

P.A. Rigg and Y.M. Gupta, *Phys. Rev B* **63** 094112 (2001)
Comley et. al, *Phys. Rev. Lett.* **110** 115501 (2013)



Rayleigh-Taylor instability growth

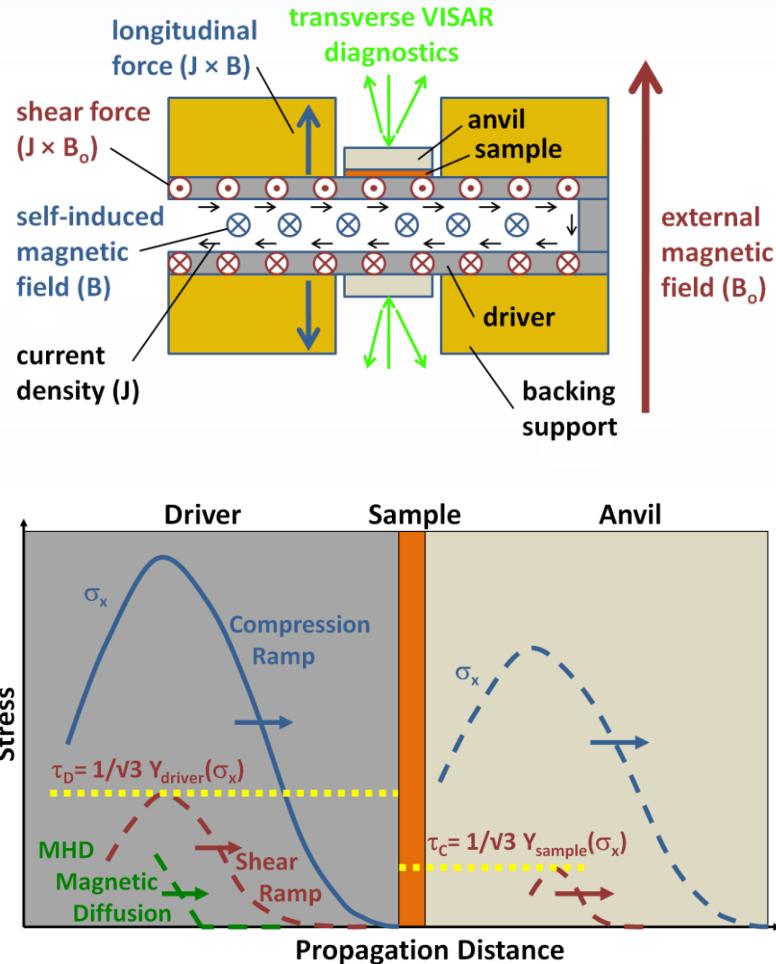
- Growth of perturbation is measured
- Simulations are used to infer strength by matching growth rate to experiment

J.F. Barnes et. al, *J Appl Phys* **45** 727–32 (1974)
Park et. al, *Phys. Rev. Lett.* **104** 135504 (2010)



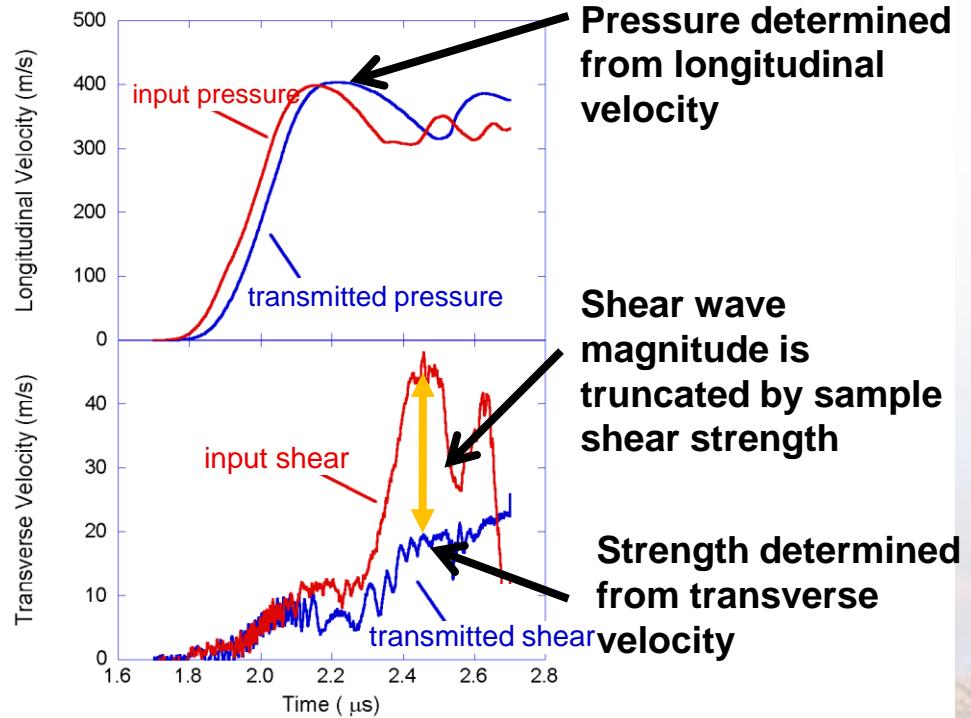
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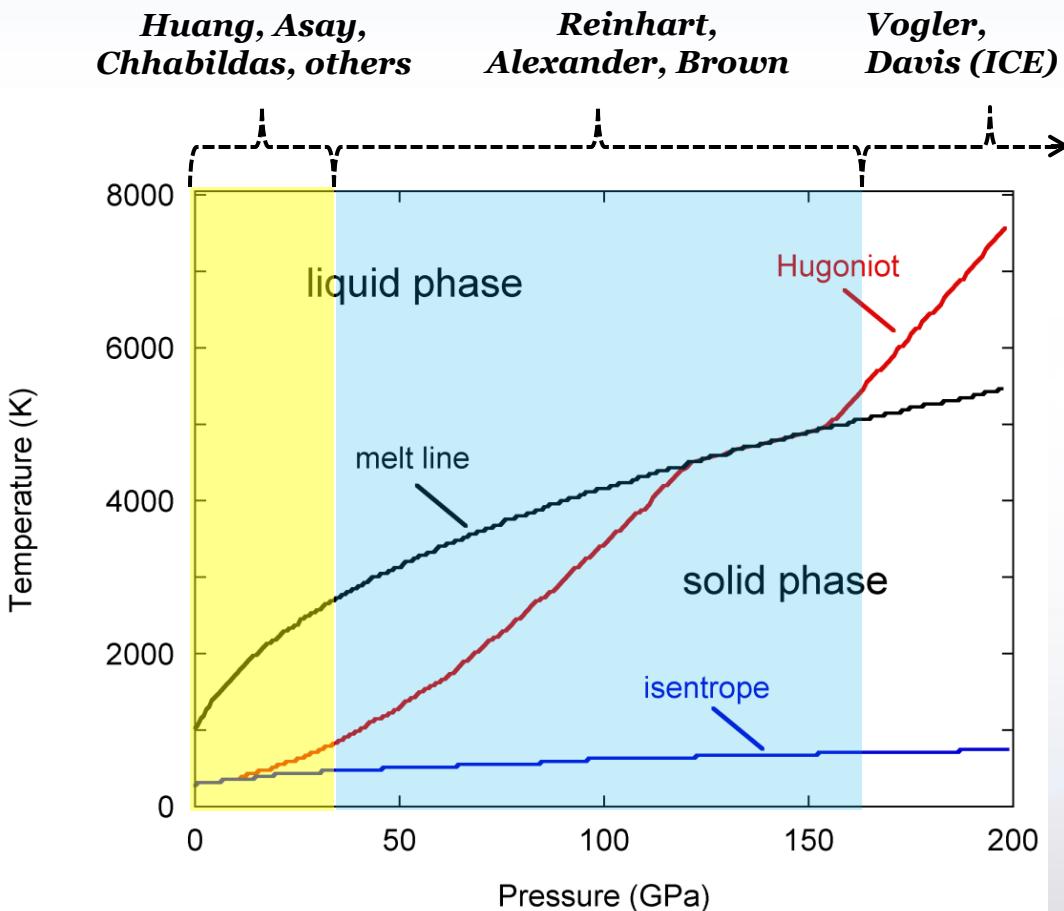
Magnetically Applied Pressure-Shear (MAPS)

- Secondary applied magnetic field results in shear wave generation during pulsed power driven compression experiments
- Shear wave provides direct probe of strength



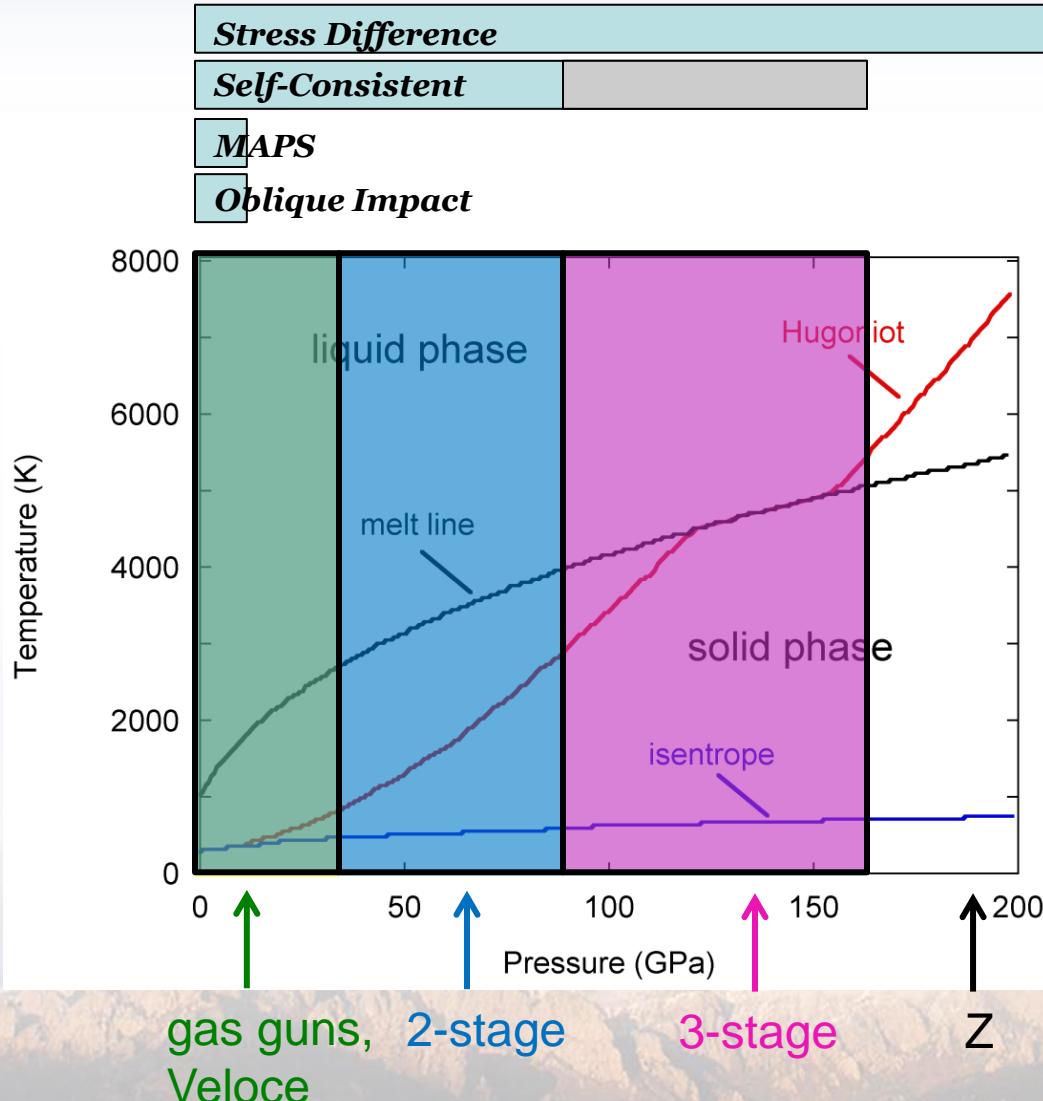
Aluminum (6061-T6): A case study in strength measurement

- Aluminum is a common engineering material
- Material strength in shock induced solid-liquid coexistence regions has not been studied
- Solid-liquid coexistence is expected to influence strength
- Phase boundaries have some uncertainty (~ 5 GPa) depending on theoretical approach used



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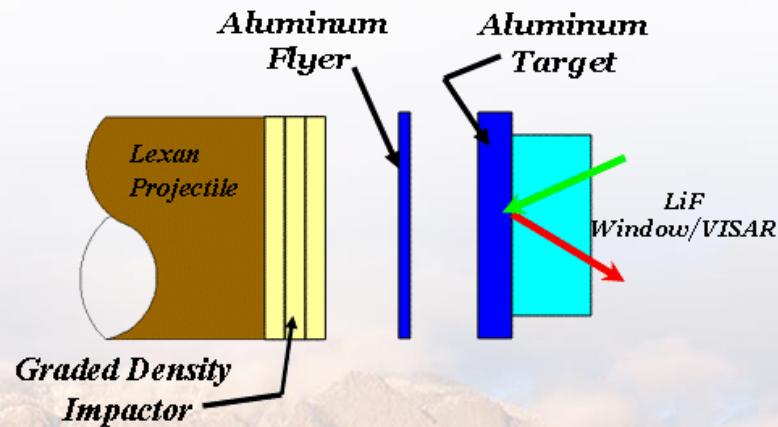
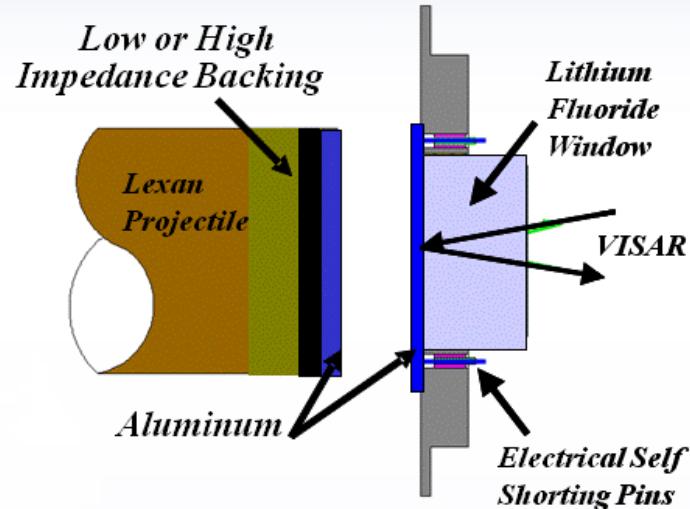
Aluminum (6061-T6): Many excellent examples of strength measurement techniques



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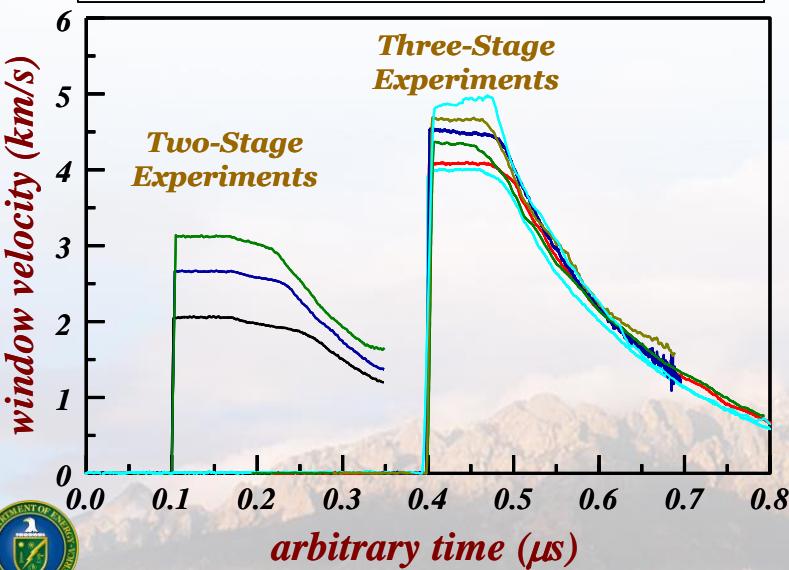
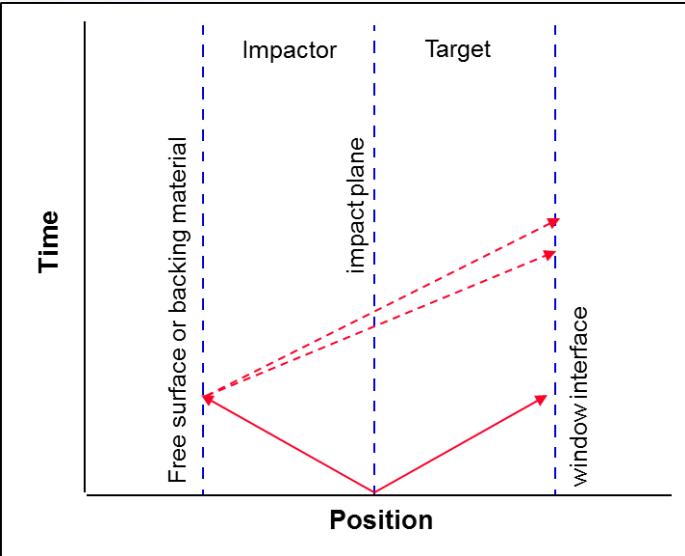
Experimental design: gun tests

- **Symmetric impact**
 - 0-10 km/s impact velocity
 - Single-Stage pressures: to ~20 GPa
 - Two-Stage pressures: to ~90 GPa
 - Three-Stage Pressures: to ~ 160 GPa
- **Diagnostics**
 - High sensitivity, ultra-clean VISAR interferometer
 - CTH simulations used to determine 3rd stage flyer velocity
- **Previous difficulties**
 - Separation of impactor and backing during projectile launch
 - Window materials
 - Impact velocity limitations (~7km/s)



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Wave speeds are determined by Lagrangian analysis of wave profile data



- Symmetric impact experiments allow shock and release wave speeds to be determined knowing only time of impact (and recorded wave profiles)
- Impact time must be determined with high accuracy

1,2-stage shots:

- Measure time of impact with electrical and optical probes

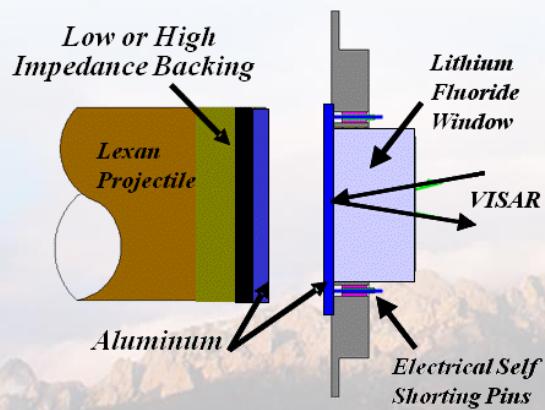
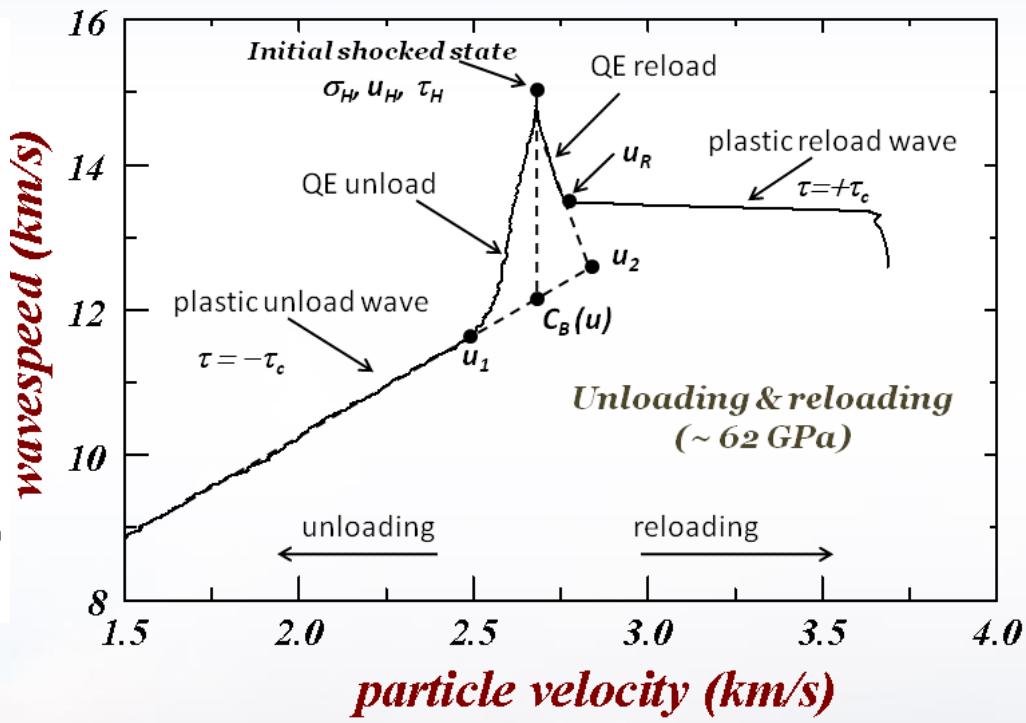
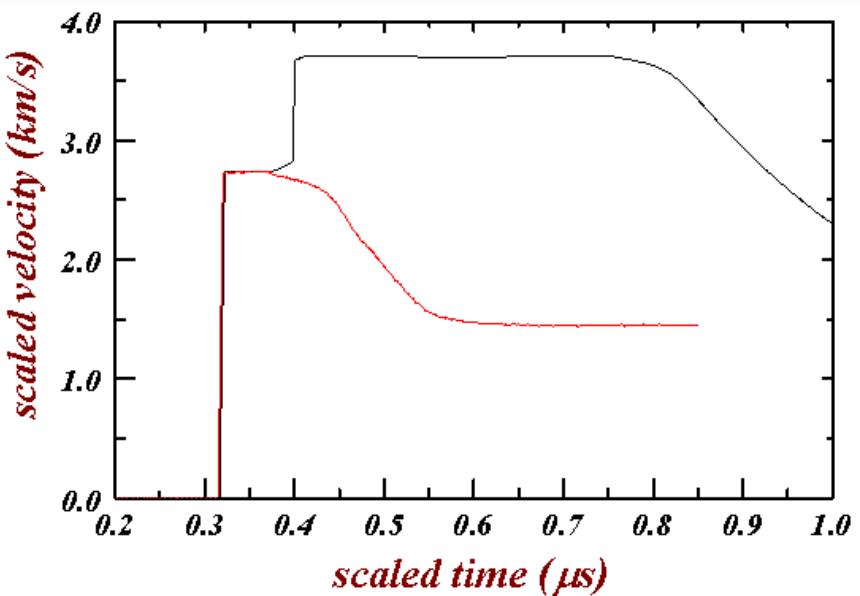
3-stage shots:

- Measure u_p
 - VISAR data with window impedance correction
 - $\frac{1}{2}$ impact velocity (symmetric impact)
- Use AI EOS to determine shock velocity
- Shock breakout is used as fiducial



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Representative wave profile data and wave speed information at 62 GPa



$$\tau_c + \tau_h = -\frac{3}{4}\rho_0 \int_{\epsilon_h}^{\epsilon_1} (c^2 - c_B^2) d\epsilon, \quad (\text{unloading})$$

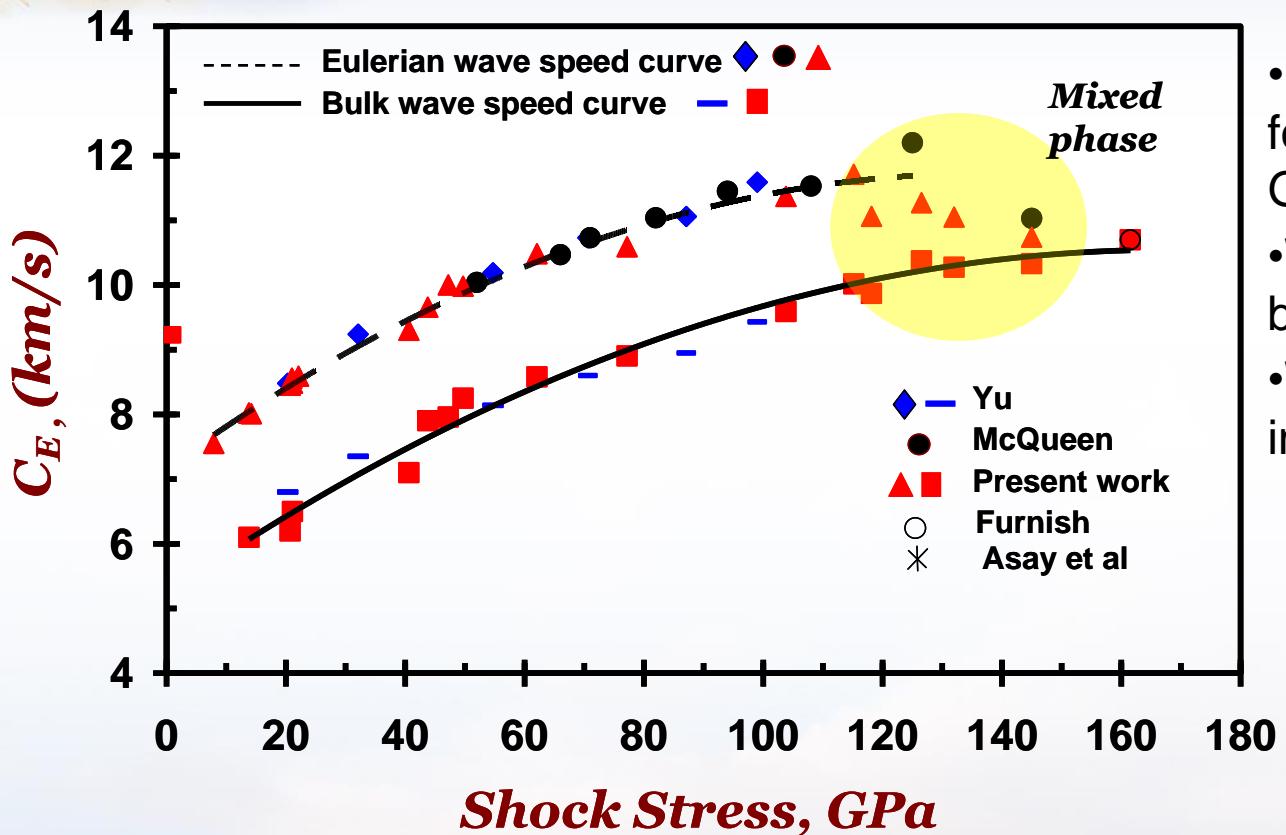
$$\tau_c - \tau_h = \frac{3}{4}\rho_0 \int_{\epsilon_h}^{\epsilon_2} (c^2 - c_B^2) d\epsilon, \quad (\text{reloading})$$

$$Y = 2 \tau_c = (\tau_c + \tau_h) + (\tau_c - \tau_h) = 1.3 \text{ GPa}$$

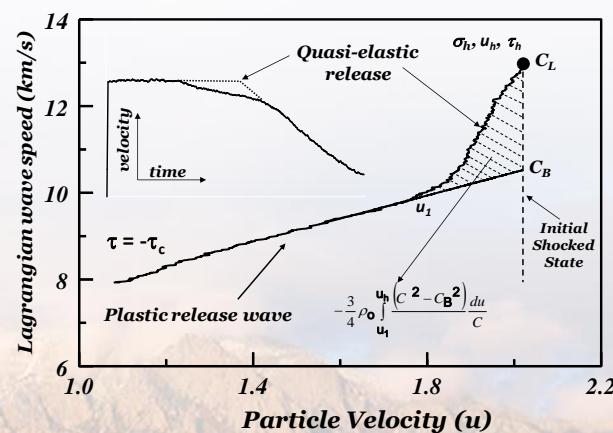


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Comparison of shock and bulk wave speeds provides clear evidence of mixed phase region

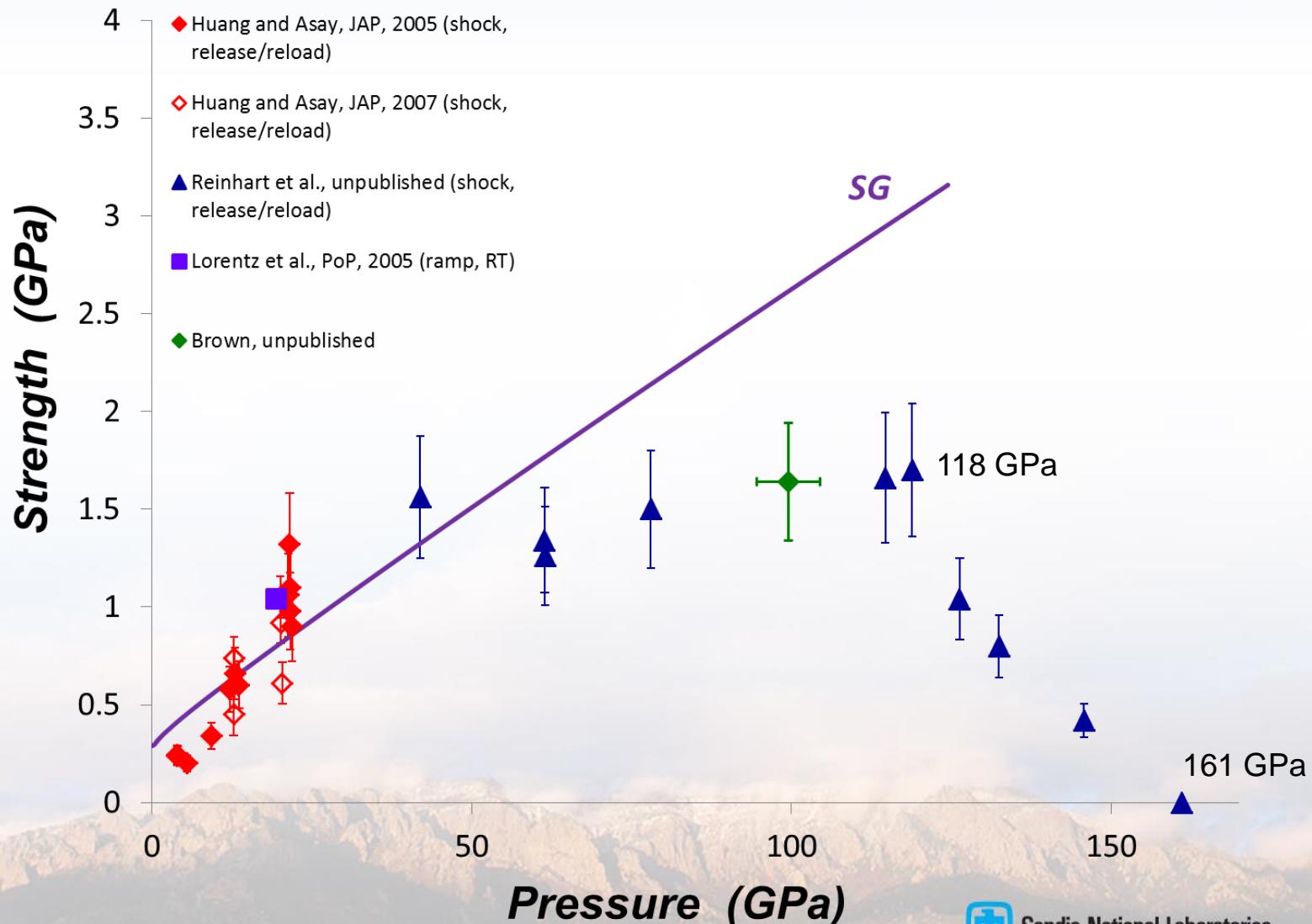


- Finite flow strength persists for shock states up to ~ 145 GPa
- Wave speed transitions to bulk over mixed phase region
- Wave speeds equal to bulk indicative of full melt



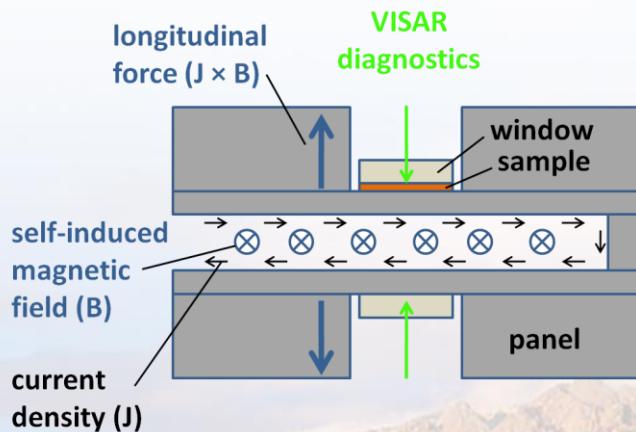
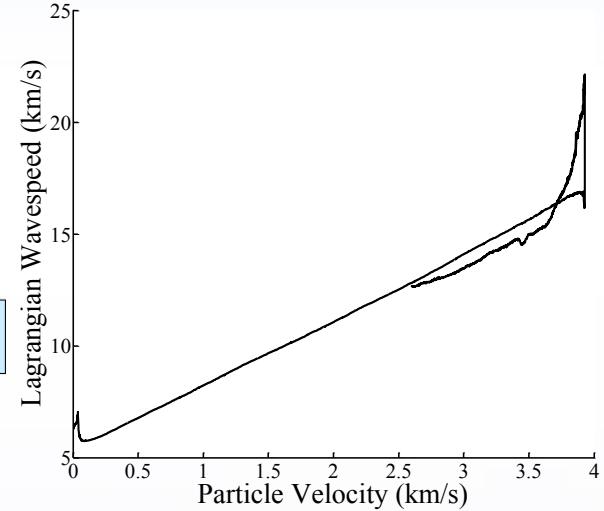
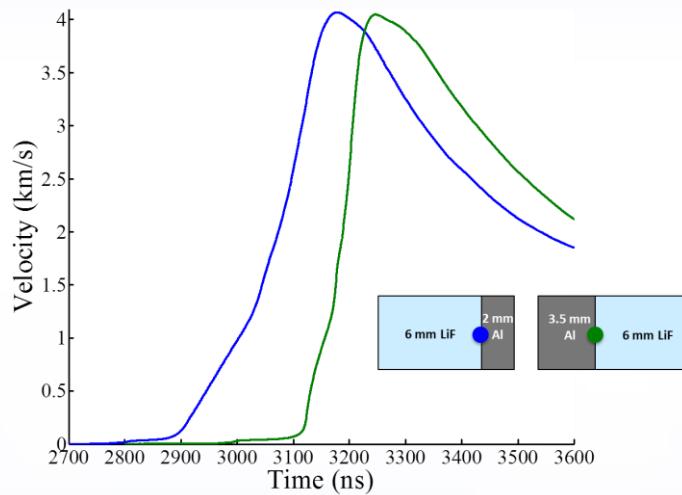
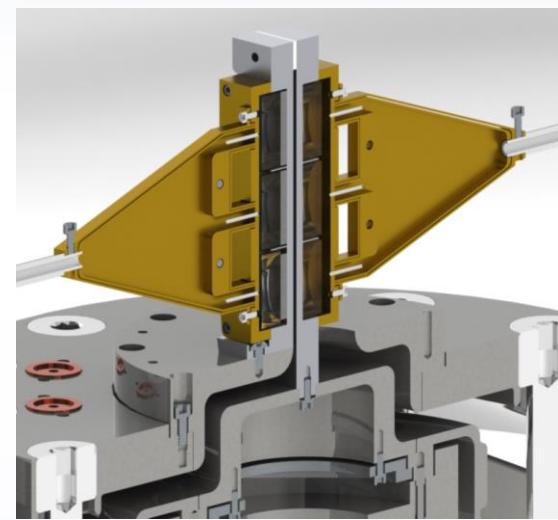
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Loss of strength observed through mixed phase region under shock loading



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Pulsed power drive allows for isentropic (ramp) compression

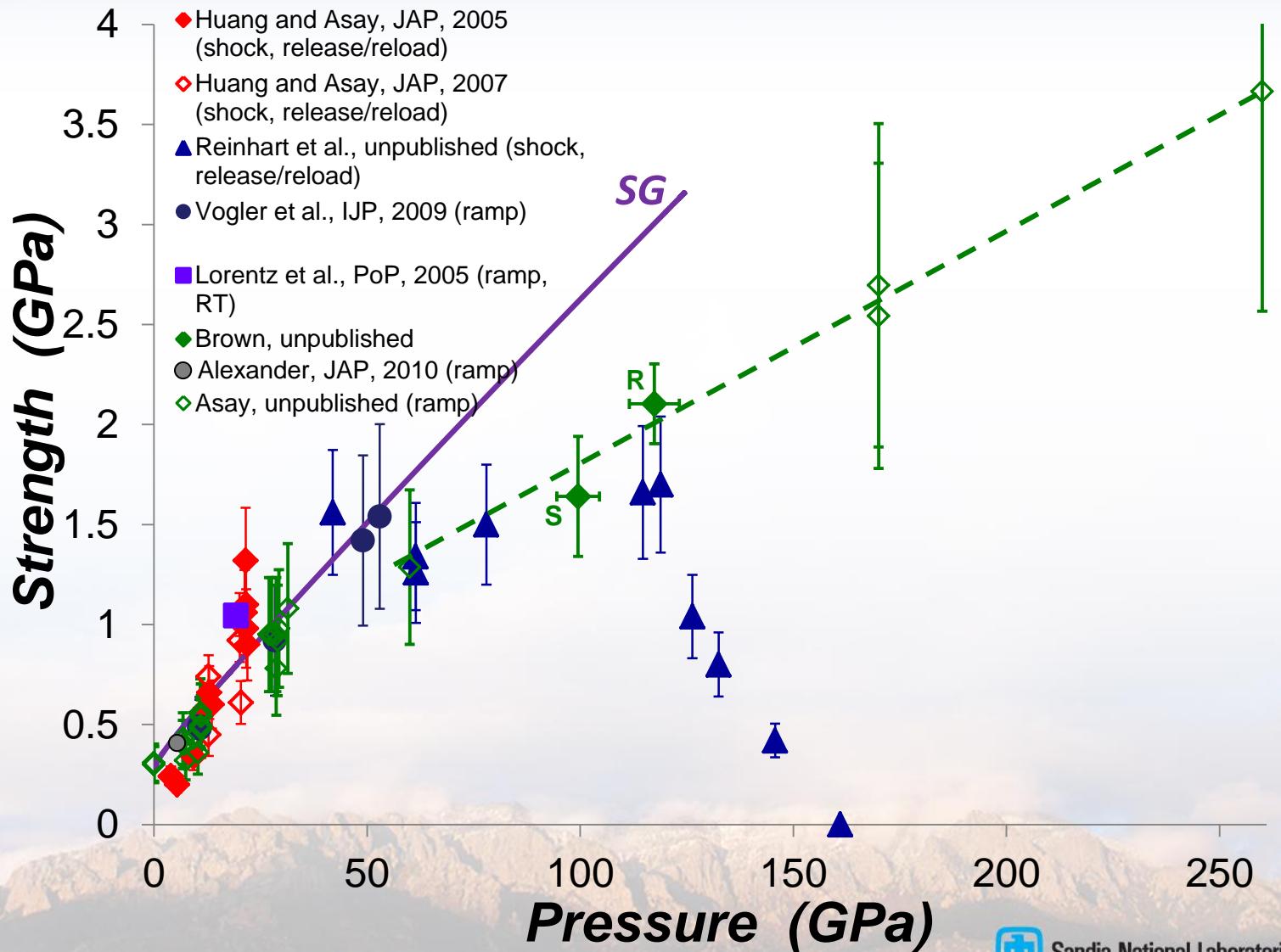


- 117 GPa peak compression
- Design ensured steepening ramp wave did not result in shock formation
- Similar Lagrangian analysis to find wave speeds



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Comparison with isentropic loading data illustrates effect of shock heating





Summary

- Strength can be measured using a variety of techniques
- No one technique is superior. Each has advantages and disadvantages
- In shock compressed aluminum, strength and wave speed data clearly indicate a mixed phase region between ~115-160 GPa
- Strength continues to increase above 115 GPa under ramp compression



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