SAND2010-4271P

Strength of Materials at High Pressures and Strain Rates

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June 30, 2010

National Nuclear Security Administration

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Sandia National Laboratories

Acknowledgements

- Staff - C.S. Alexander, T. Ao, J.-P. Davis, D. Dolan, M. Furnish, M. Knudson, W.D. Reinhart, S. Root, J. Wise
- Students - J. Brown, D.A. Fredenburg
- STAR - T. Thornhill, J. Martinez, R. Palomino, H. Anderson
- Z - the large crew for design, assembly and operations
- retired colleagues: Lalit Chhabildas, Dennis Grady, Jim Asay

numerous technicians and support staff are essential to facility operations

Outline of Talk

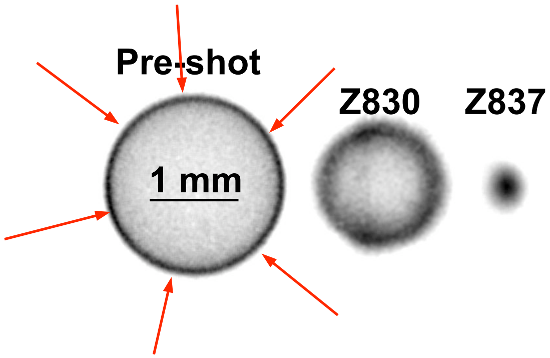
- Introduction to shock and high-pressure physics
- Gas gun technology and examples
- The Z machine and examples
- Background on high pressure strength and techniques to measure it
- Strength of ceramics under shock loading
- Strength of metals under isentropic loading
- Conclusions

Why Do We Need To Know the Behavior of Materials Under Extreme Conditions?

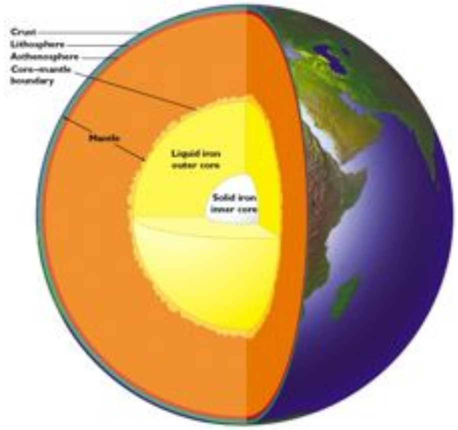
- weapons applications (warheads, armor, etc.)

- explosives behavior and applications

- inertial confinement fusion



- missile intercept; impact of asteroids or orbital debris (V=8-15 km/s)

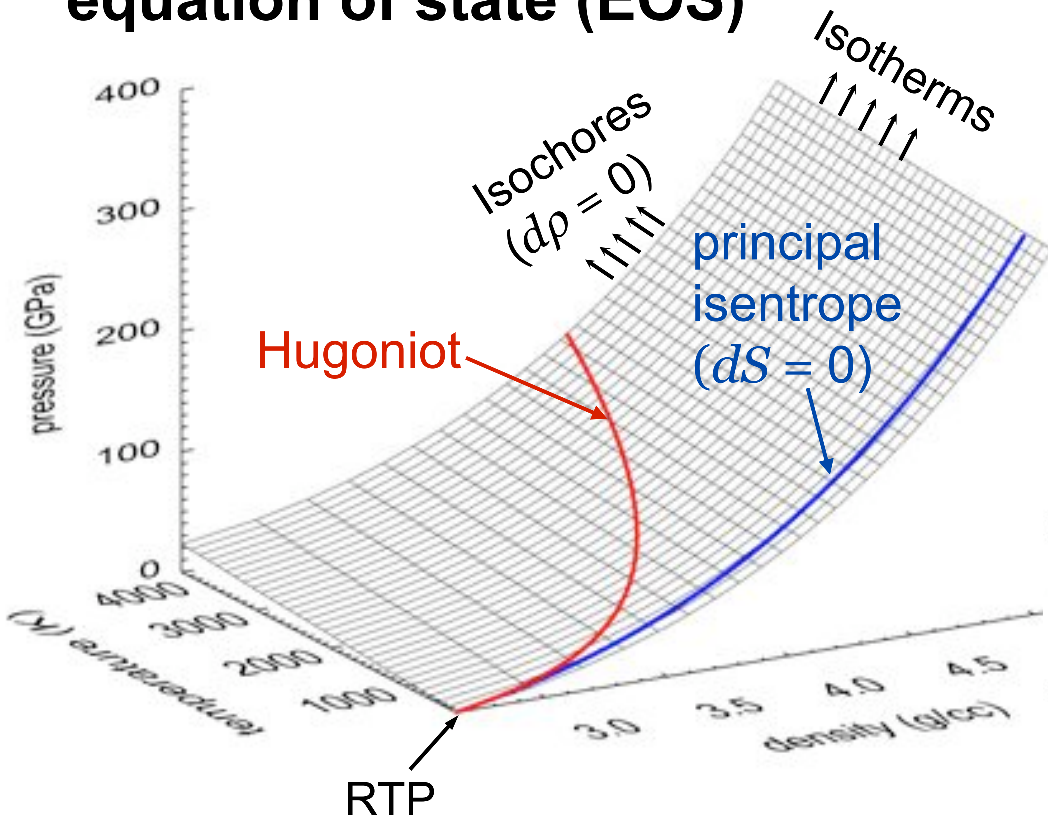


- planetary science (P~360 GPa, T~7000 K)

Material Behavior: EOS & Constitutive Aspects

M. Knudson,
M. Desjarlais

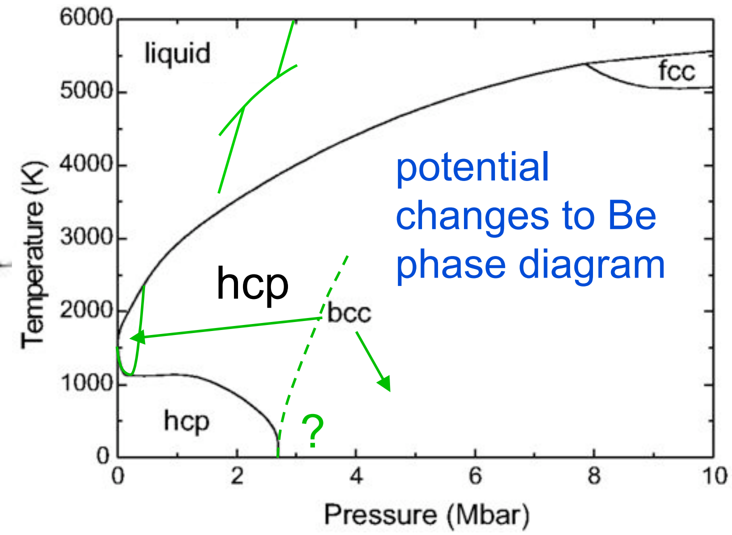
equation of state (EOS)



one thermodynamic state variable as a function of two others:

pressure $P = P(r,T)$

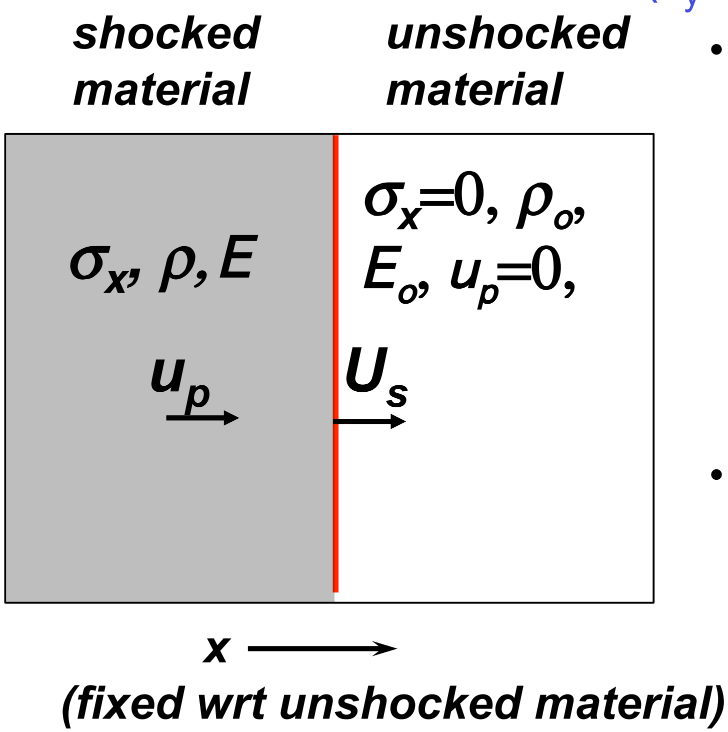
Helmholtz energy $f = f(v,T)$



Also: strength, damage, spall (tensile failure), compaction

What is a Shock Wave?

- A "discontinuous" wave that moves at a fixed velocity (if steady)
  - wave front moves at speed U_s *(shock velocity)*
  - shocked material moves at speed u_p *(particle or mass velocity)*
  - uniaxial strain condition ($\varepsilon_y = \varepsilon_z = \varepsilon_{xy} = \varepsilon_{yz} = \varepsilon_{xz} = 0$)



- States ahead and behind shock <u>*assumed*</u> to be in thermodynamic equilibrium
  - well defined temperature in each state
  - described by equilibrium thermodynamics
- Shock compression is adiabatic
  - very fast process (< 1 ns)
  - irreversible (i.e. NOT isentropic)
  - temperature *typically* increases

Conservation Equations and the Shock Hugoniot

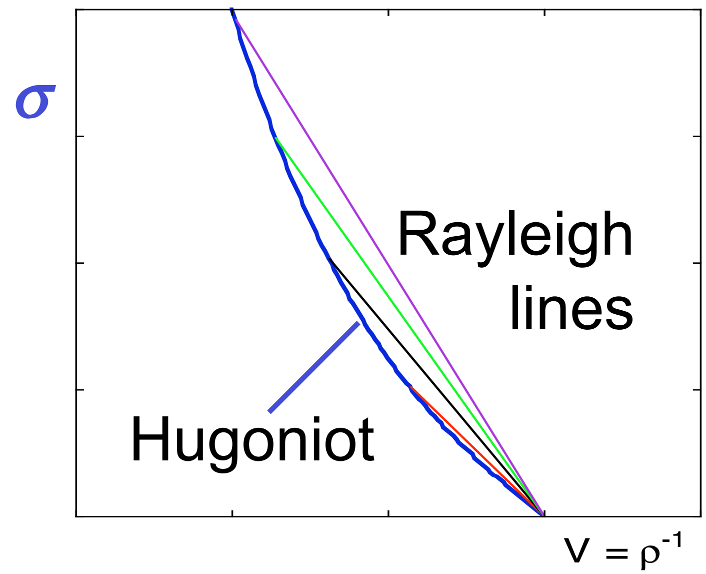
- Five variables: $\boldsymbol{\sigma}_x$, $\boldsymbol{u_p}$, $\boldsymbol{U_s}$, $\boldsymbol{\rho}$, and $\boldsymbol{E}$
- Three conservation relationships (Rankine-Hugoniot jump conditions)
  - By measuring two variables (typically $\boldsymbol{\sigma}_x$, $\boldsymbol{u_p}$, or $\boldsymbol{U_s}$), the other three can be determined

<u>**conservation of**</u>

mass: $\rho_o U_s = \rho (U_s - u_p)$

momentum: $\boldsymbol{\sigma}_x = \rho_o U_s u_p$

energy: $E - E_o = 0.5\boldsymbol{\sigma}_x (V_o - V)$



material loads along the Rayleigh line, so the Hugoniot is a <u>collection of end states</u>, not a material response curve

the Hugoniot is not a complete equation of state (EOS)!

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Gas Guns to Generate Shock Waves

Single Stage Gun 100mm

Propellant Gun 89mm

Two-Stage Gun 29mm

gas guns

- launch thin plates (mm's) at high velocities
- well-posed, repeatable initial conditions
- sample is in uniaxial ***strain***
- used to study material behavior at high pressures and strain rates
- usable in laboratory setting

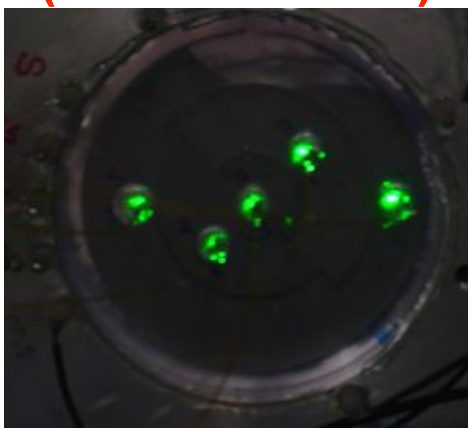
Three-Stage Gun 17mm

Chhabildas, L. C., Dunn, J. E., Reinhart, W. D., and Miller, J. M. (1993). "An impact technique to accelerate flier plates to velocities over 12 km/s," *Int. J. Impact Eng*. **14**, 121-132.

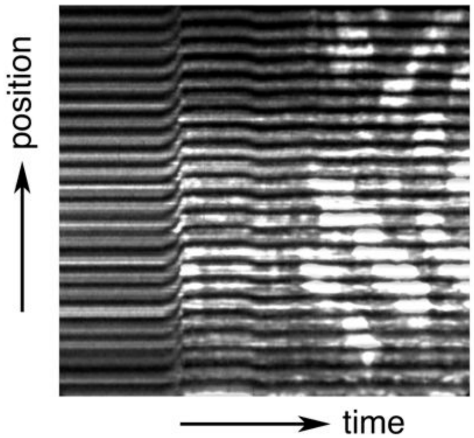
also: explosives, lasers, magnetic loading (Z)

Diagnostics for Dynamic Experiments

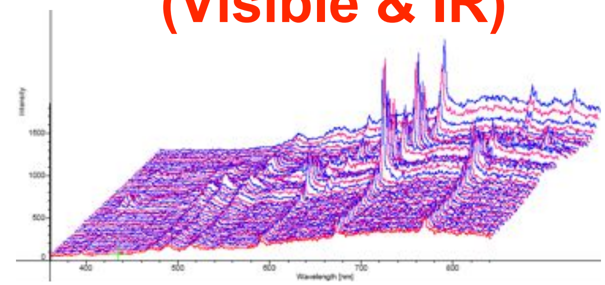
Velocity Interferometry (VISAR & PDV)



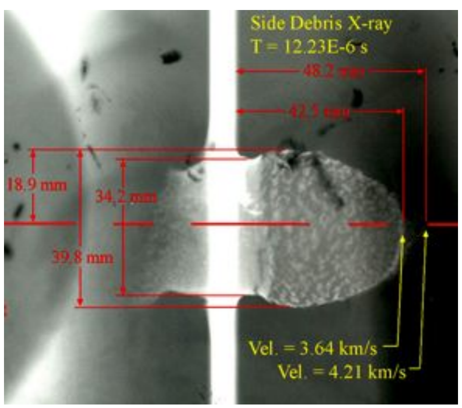
Line-VISAR



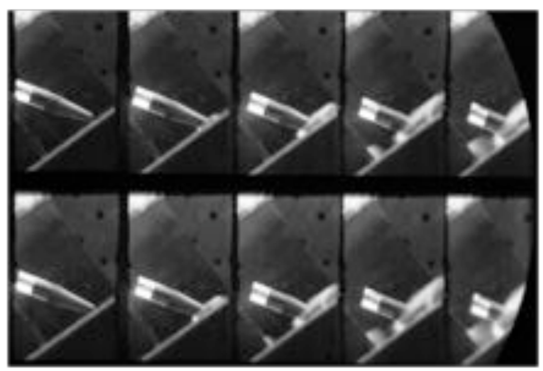
Time-Resolved Spectroscopy (Visible & IR)



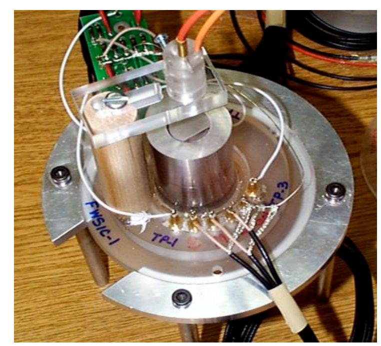
Flash X-rays



High-Speed Photography



Pressure Gauges

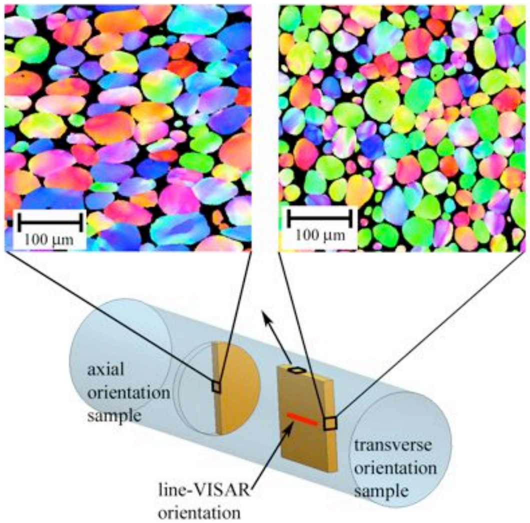


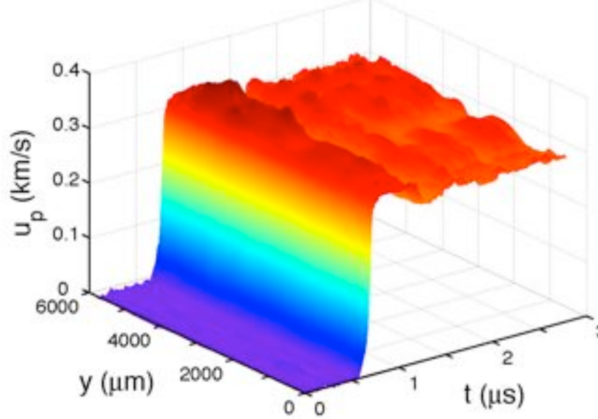
Advanced Diagnostics: pRad, synchrotron, etc.

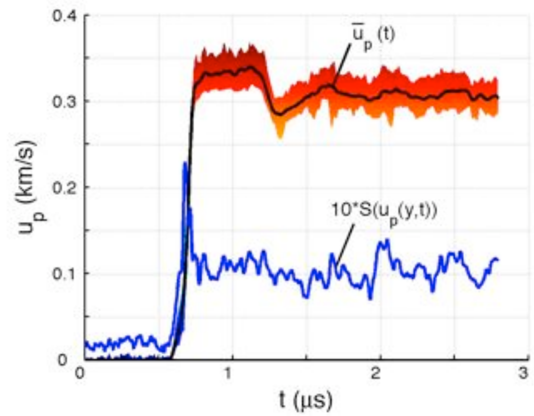
Heterogeneous and Statistical Aspects of Spall

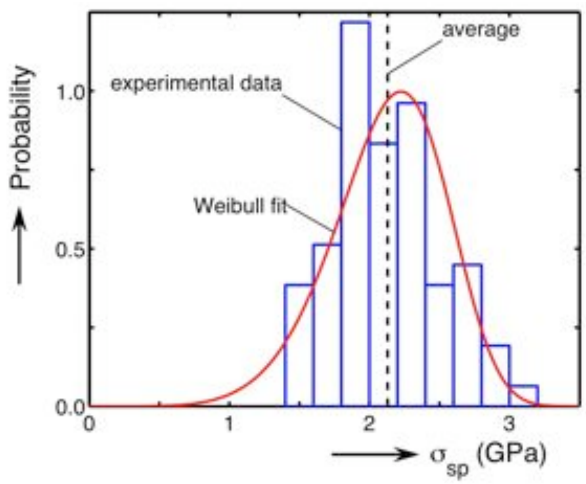
J. Clayton,
T. Vogler

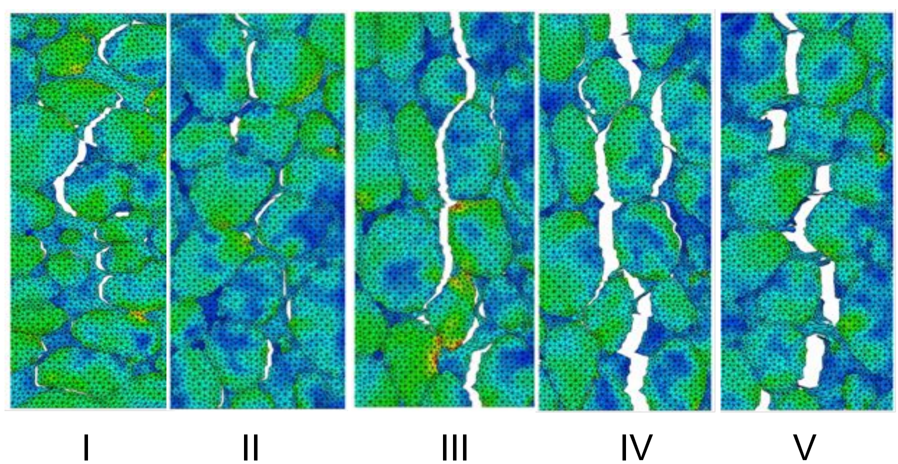
WHA - tungsten heavy alloy







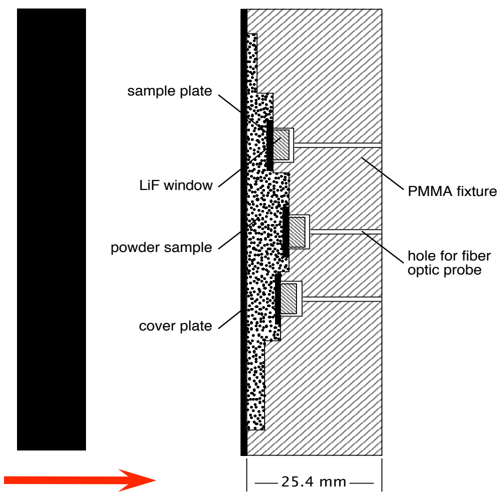


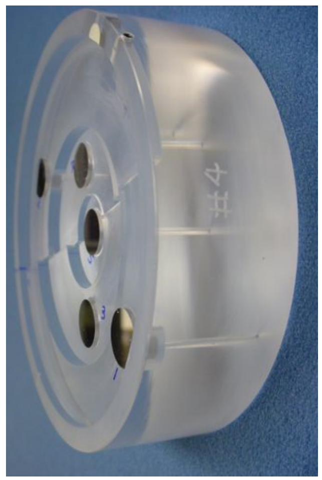


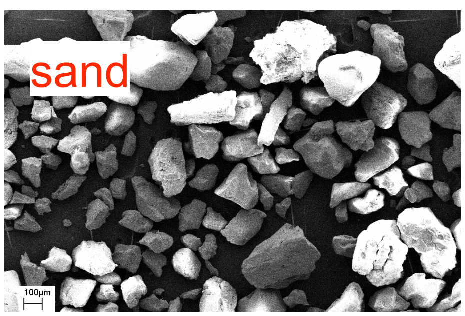
Vogler, T. J., and Clayton, J. D. (2008). "Heterogeneous deformation and spall of an extruded tungsten alloy: plate impact experiments and crystal plasticity modeling," *J. Mech. Phys. Solids* 56, 297-335.

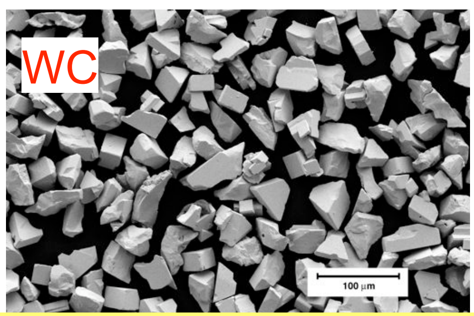
Compaction of Granular Ceramics

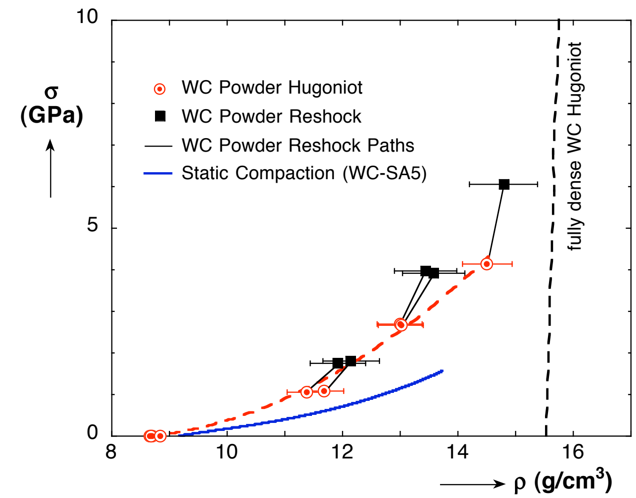
D. Grady,
T. Vogler

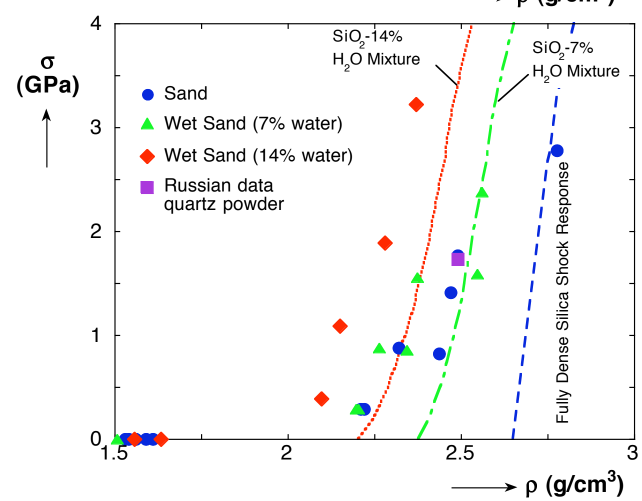










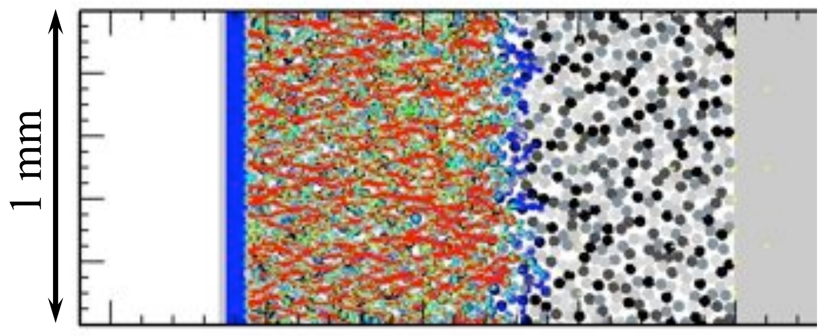


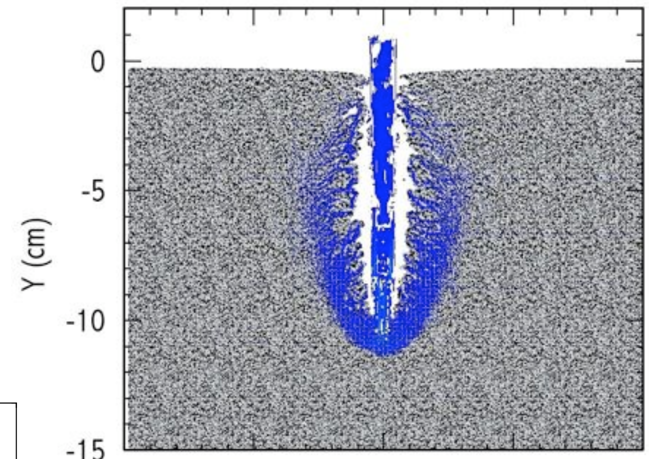
Vogler, T.J., Lee, M.Y., Grady, D.E., 2007. "Static and dynamic compaction of ceramic powders." *International Journal of Solids and Structures* **44**, 636-658.

Brown, J.L., Thornhill, T.F., Reinhart, W.D., Chhabildas,L.C., Vogler, T.J., 2007. "Shock response of dry sand." in Shock Compression of Condensed Matter – 2007, American Institue of Physics, 1363-1366.

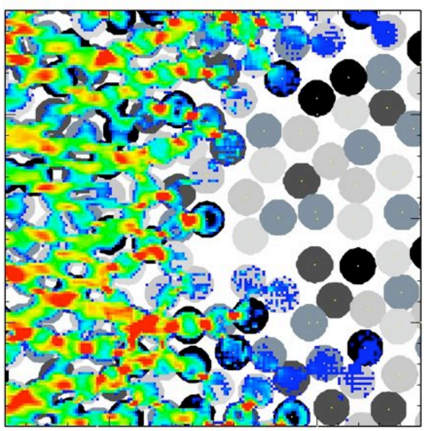
Mesoscale Modeling of Granular Materials

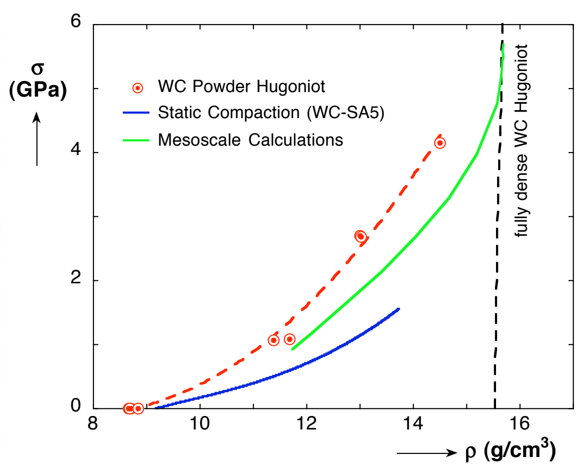
J. Borg,
T. Vogler

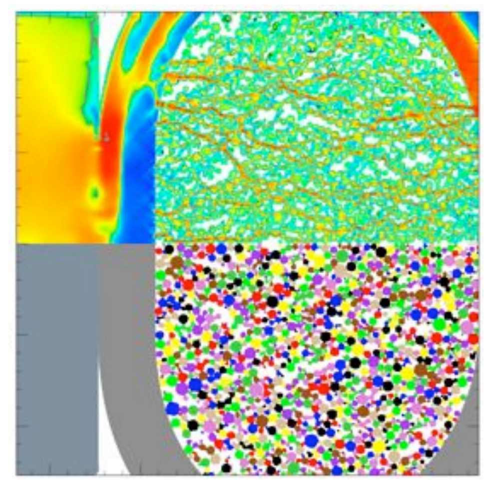




Borg, J. P., and Vogler, T. J. (2008). "Mesoscale simulations of a dart penetrating sand," *Int. J. Impact Eng.* ***35, 1435-1440.***







Borg, J. P., and Vogler, T. J. (2008). "Mesoscale calculations of the dynamic behavior of a granular ceramic," *Int. J. Solids Structures* ***45, 1676-1696.***

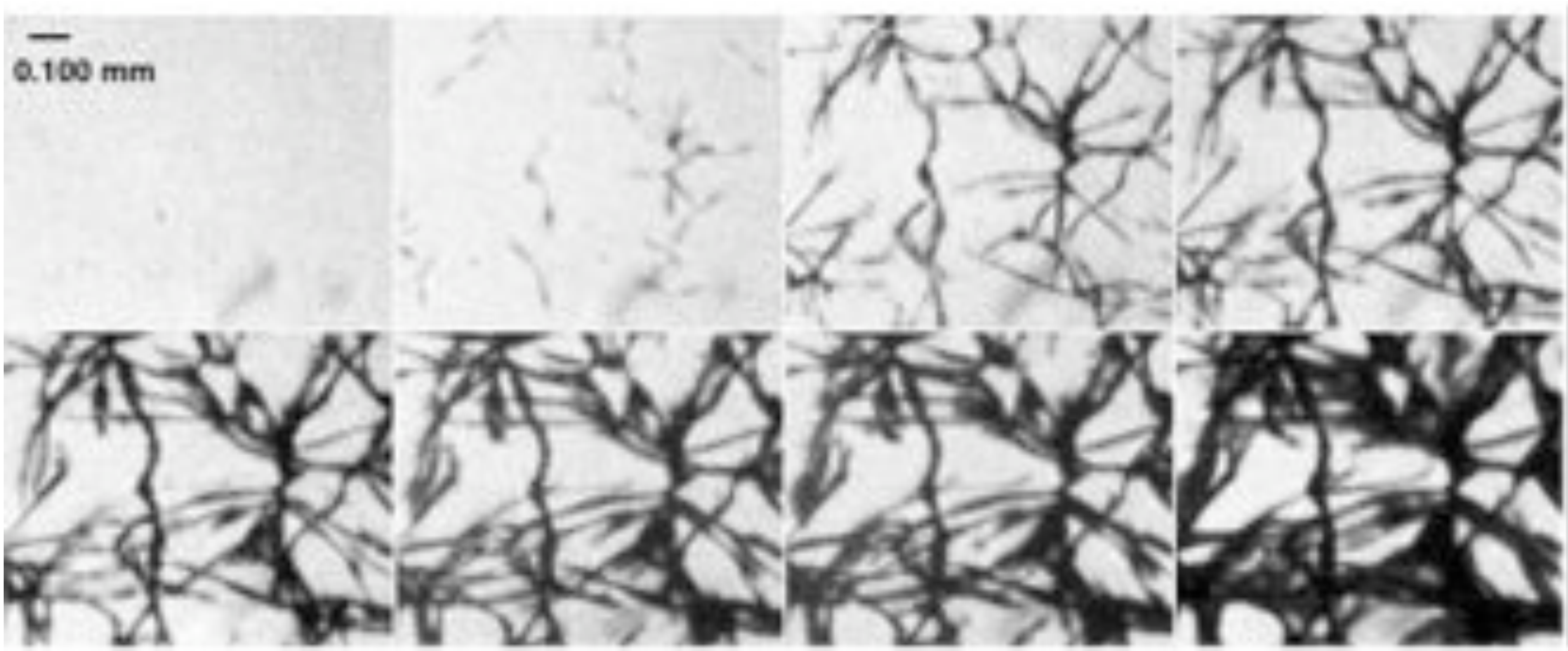
Borg, J. P., and Vogler, T. J. (2009). "Aspects of simulating the dynamic compaction of a granular ceramic," *Modelling Simul. Mater. Sci. Eng.* ***17, 045003.***

Nanosecond Freezing of Water

- 2.7 GPa (ice VII)
- 25 ns exposure

t(ns) from shock arrival=

230	330	530	630
730	830	930	1530



D.H. Dolan and Y.M. Gupta, J. Chem. Phys. **121**, 9050 (2004).

Outline of Talk

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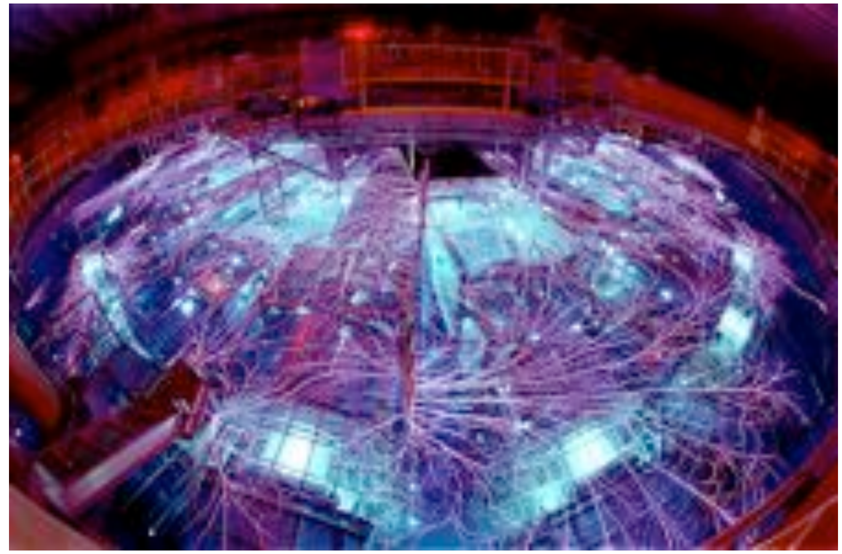
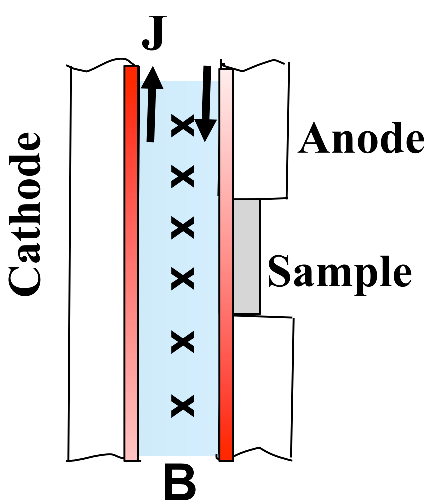
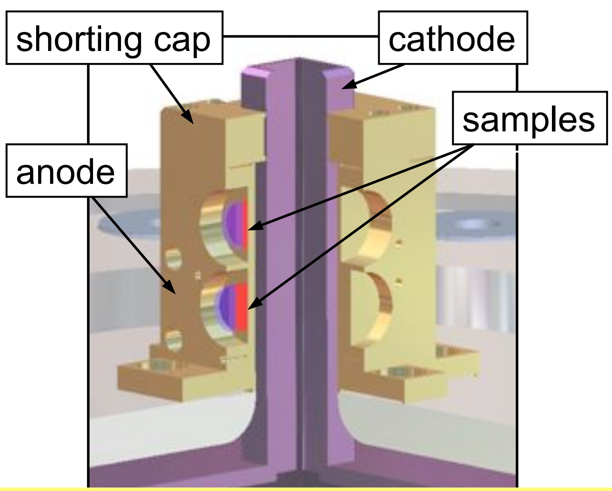
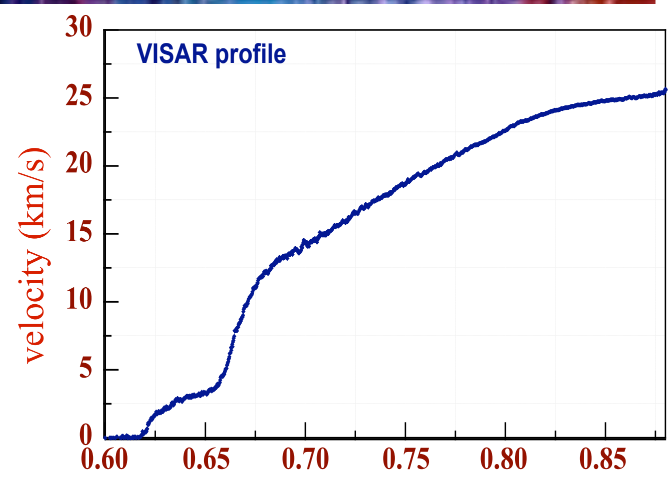
Z Pulsed Power Machine

- Designed for ICF applications
- Generates ~26 MA over 100's of ns
- Utilize current to generate magnetic forces
- Magnetic forces create smooth waves in materials
- Waves used for isentropic loading (to ~400 GPa) and to launch high-velocity flyer plates (to ~40 km/s)



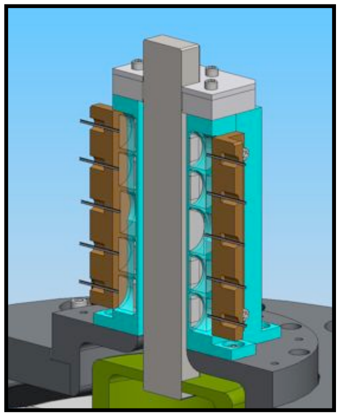


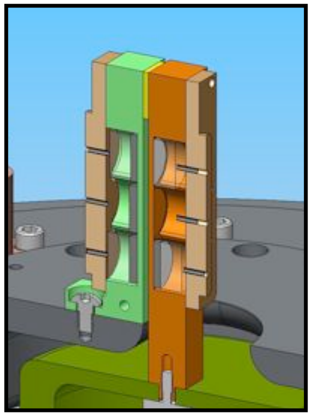




Davis, J.-P., Deeney, C., Knudson, M. D., Lemke, R. L., Pointon, T. D., and Bliss, D. E. (2005). "Magnetically driven isentropic compression to multimegabar pressures using shaped current pulses on the Z accelerator," *Physics of Plasmas* 12, 056310.

Two Approaches Developed for Accurate EOS Studies – Both Major Advances

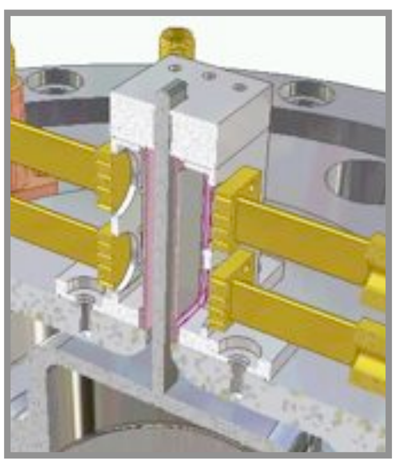


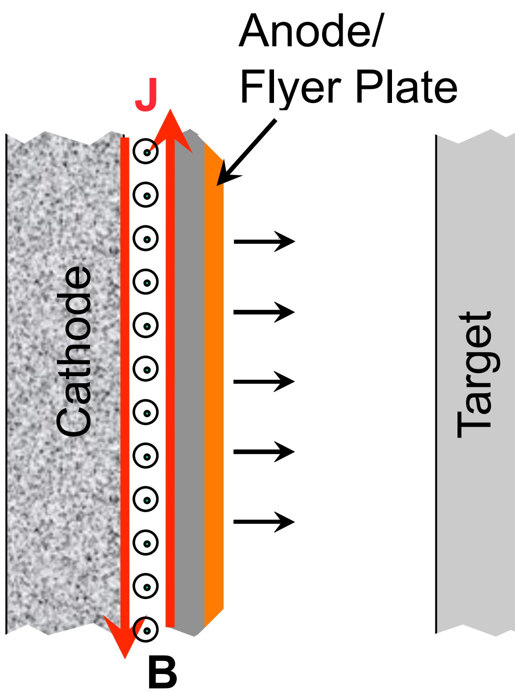


Isentropic Compression Experiments (ICE)*

Magnetically driven Isentropic Compression Experiments (ICE) to provide measurement of continuous compression curves to ~4 Mbar - previously unavailable at Mbar pressures

* Developed with LLNL





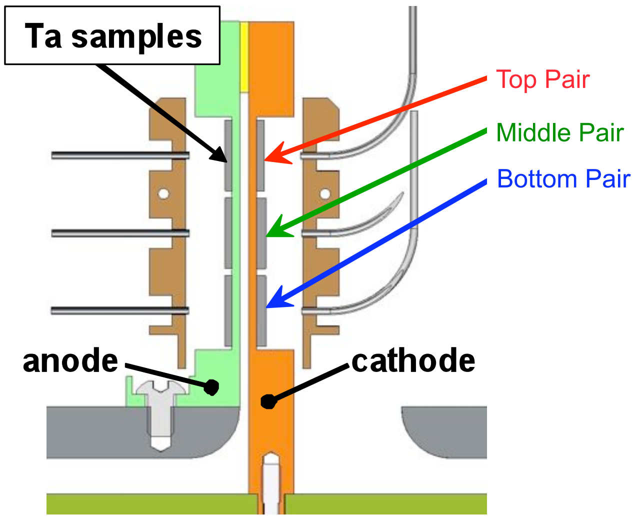
Magnetically launched flyer plates

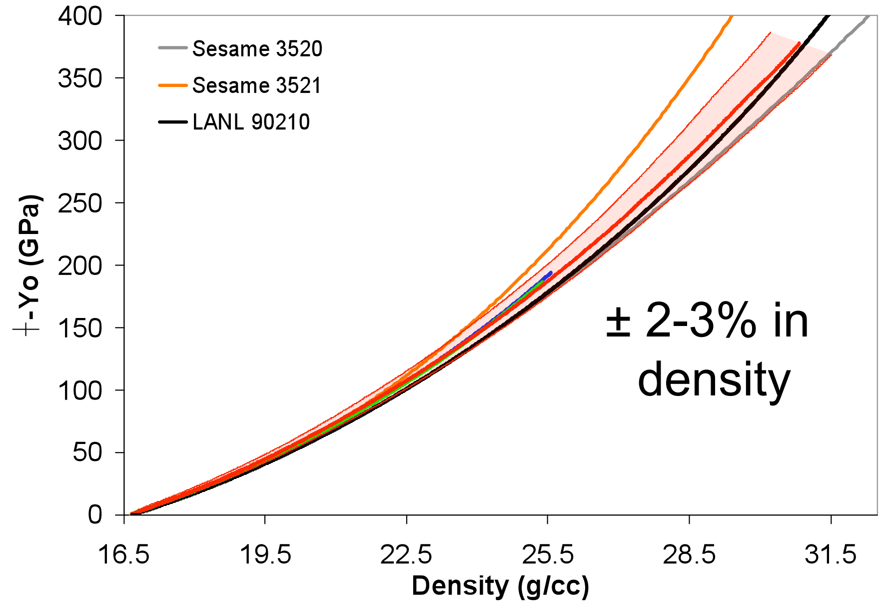
Magnetically driven flyer plates for shock experiments at velocities to > 40 km/s
exceeds gas gun velocities by > 5X and pressures by > 10X with comparable accuracy

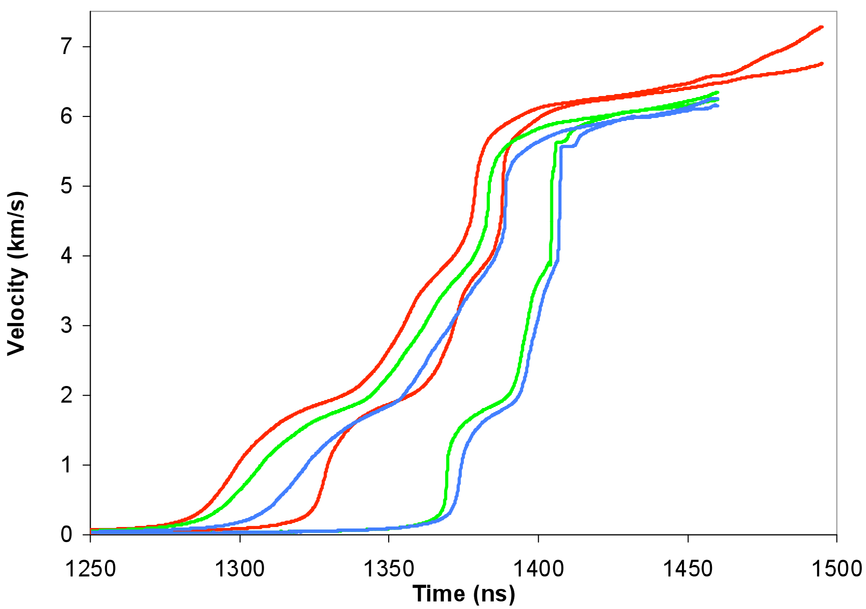
Lemke, et al., J. Appl. Phys. 98, 073530 (2005)

Quasi-Isentrope of Ta to nearly 400 GPa

J.-P. Davis



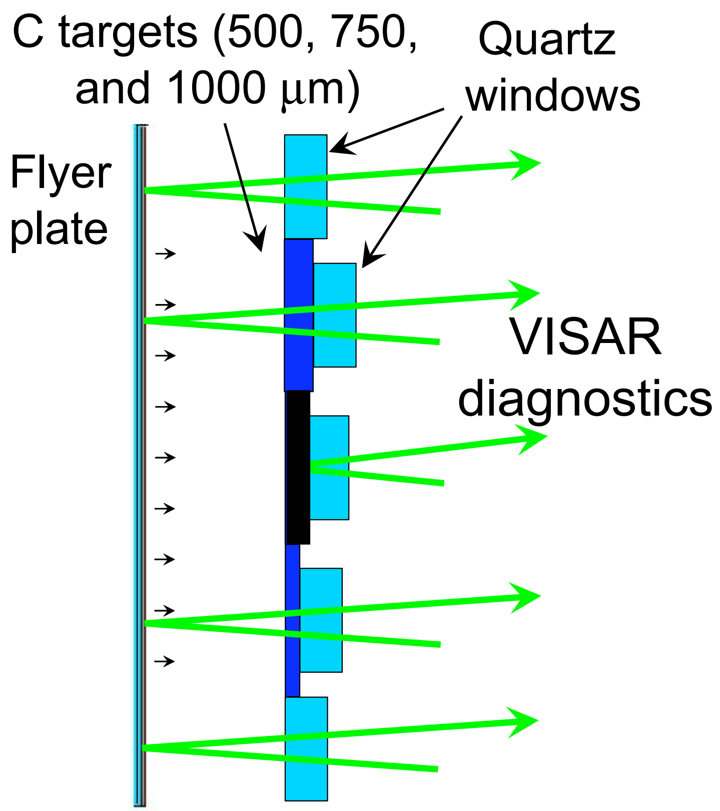


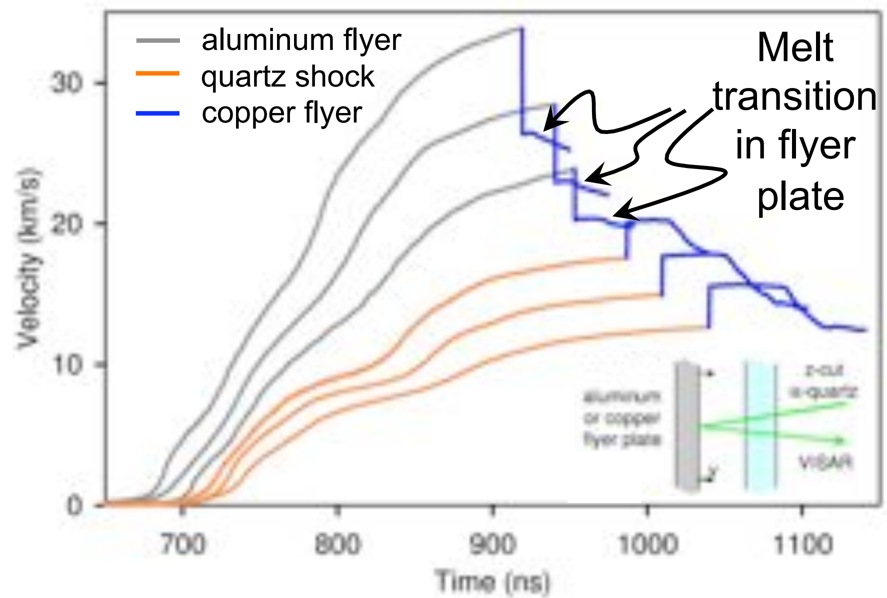


The extracted isentrope discriminates between various tabular equations of state for Ta

Quartz of Interest as Standard - Window in Z Shots

M. Knudson
M. Desjarlais



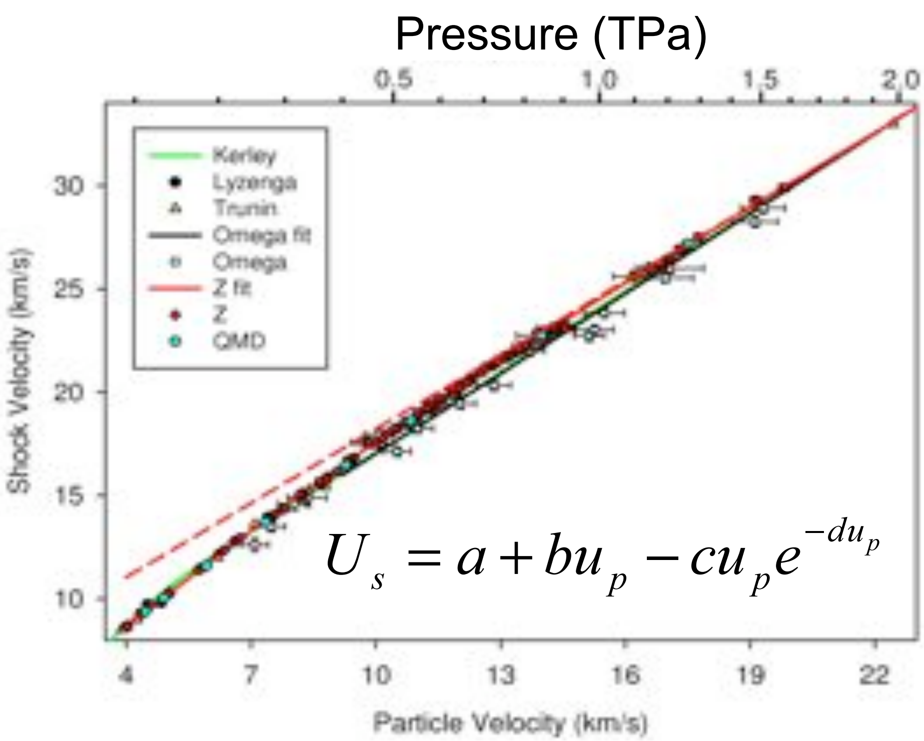


Knudson, M. D., M. P. Desjarlais and D. H. Dolan (2008). "Shock-wave exploration of the high-pressure phases of carbon." *Science* ***322: 1822-1825.***

quartz data has large uncertainty and scatter, and U_s-u_p exhibits significant curvature in the several 100 GPa regime; attributed to dissociation

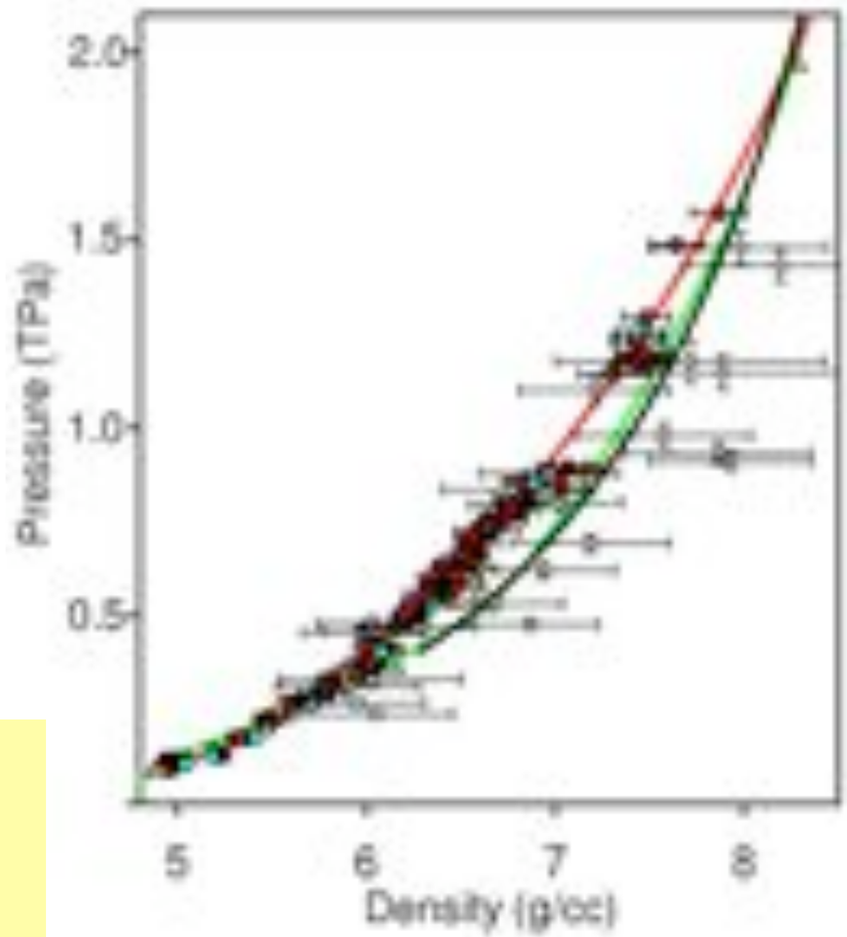
New Hugoniot Data for α-Quartz to 1.5 TPa

M. Knudson
M. Desjarlais



$$U_s = a + bu_p - cu_p e^{-du_p}$$

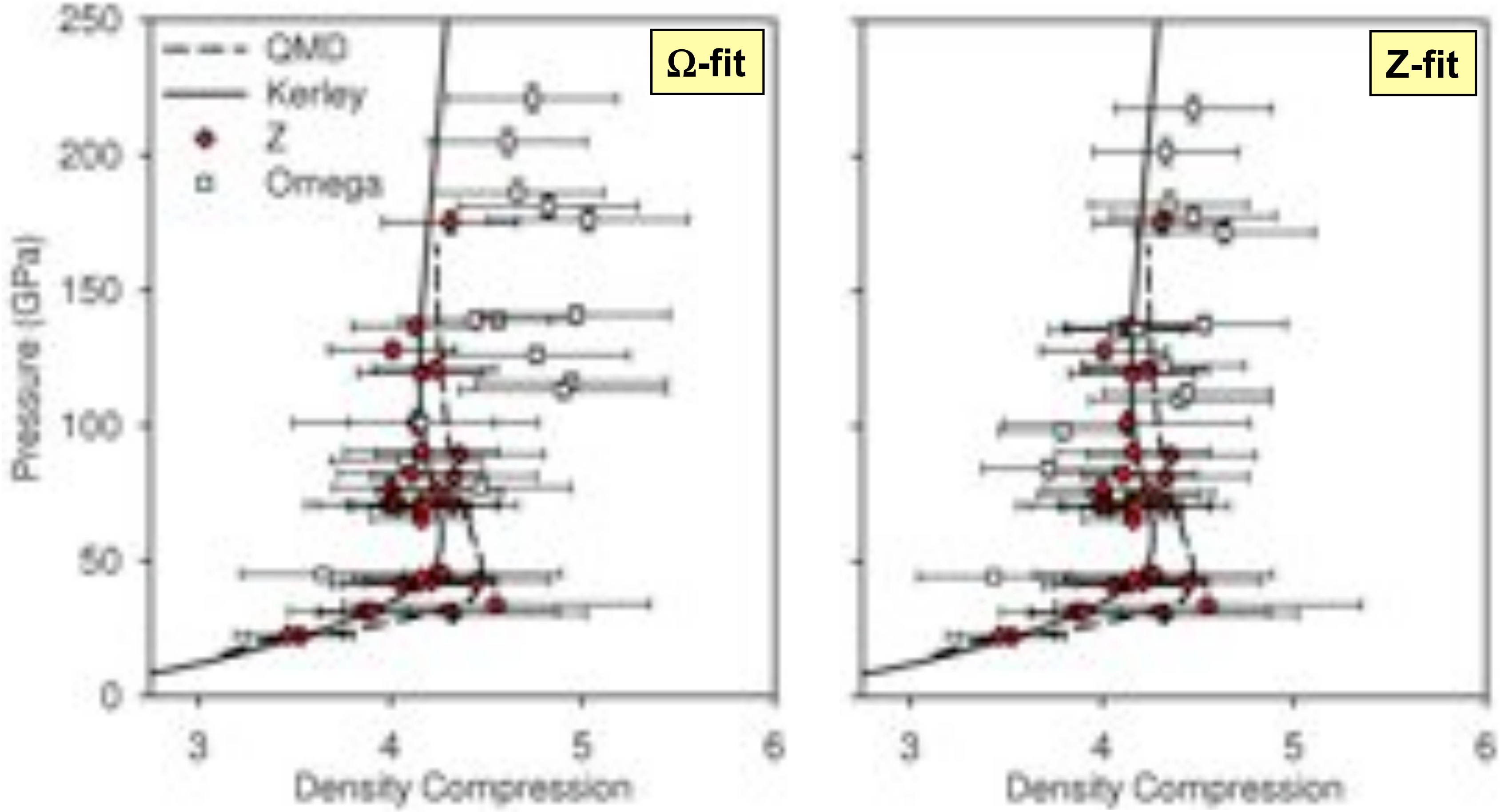
Data set includes ~150 points



Knudson, M. D. and M. P. Desjarlais (2009). "Shock compression of quartz to 1.6 TPa: redefining a pressure standard." *Physical Review Letters* ***103: 225501.***

Deuterium Results Affected by New Quartz Fit

M. Knudson
M. Desjarlais



M.D. Knudson, et al., Phys. Rev. Lett. **87**, 225501 (2001); Phys. Rev. Lett. **90**, 035505 (2003); Hicks, et al., PRB 79, 014112 (2009)

Knudson & Desjarlais, PRL 103, 225501 (2009)

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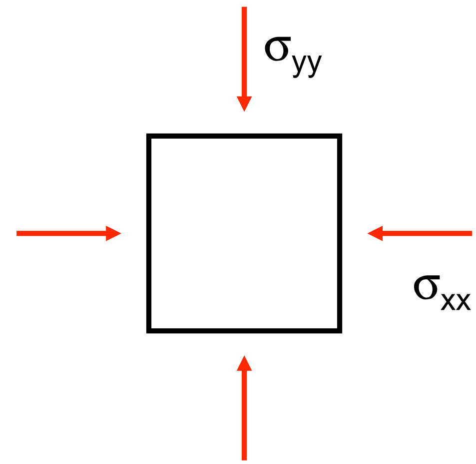
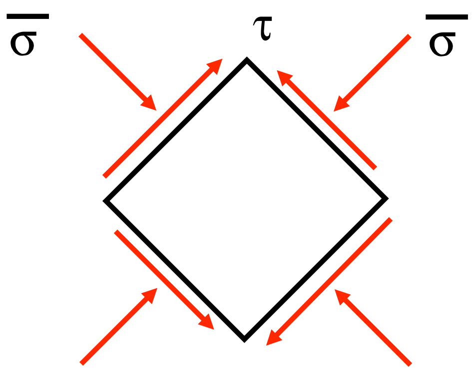
What is Strength?

- strength is the ability of a material to sustain $\tau_{ij} \neq 0$ or $\sigma_{xx} \neq \sigma_{yy}$
- for a 1-D shock or isentropic experiment, $\sigma_{yy} = \sigma_{zz} \neq \sigma_{xx}$
- conservation equations provide no information about σ_{yy}



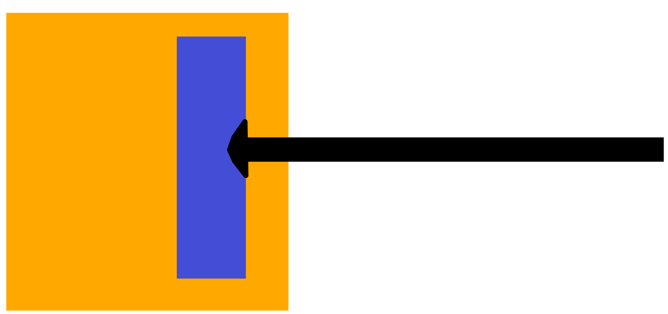


By a simple tensor transformation (45° rotation), the stress state can be expressed as a mean stress (mechanical pressure) and a shear stress

By analogy with uniaxial tension, $Y=2\tau_c$

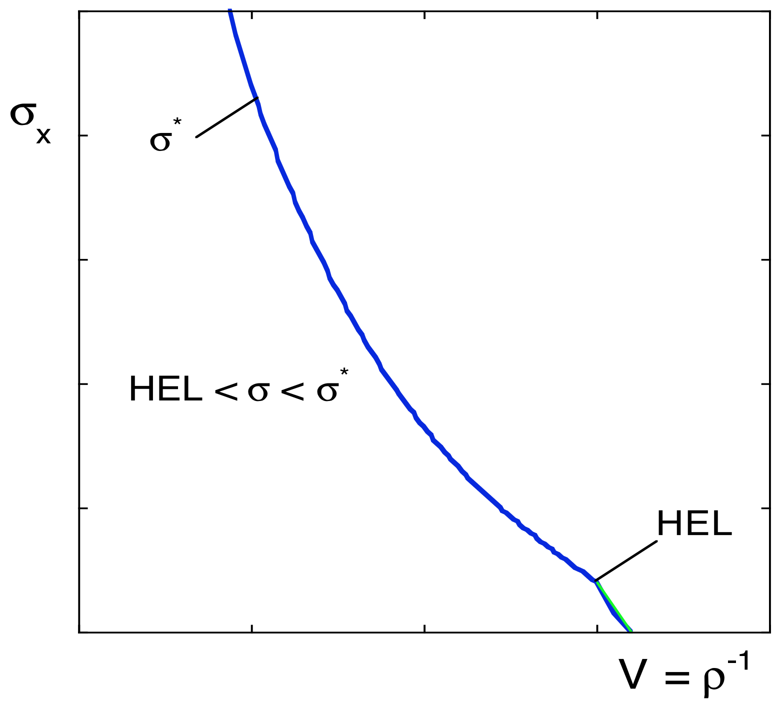
Why Do We Care About Strength?

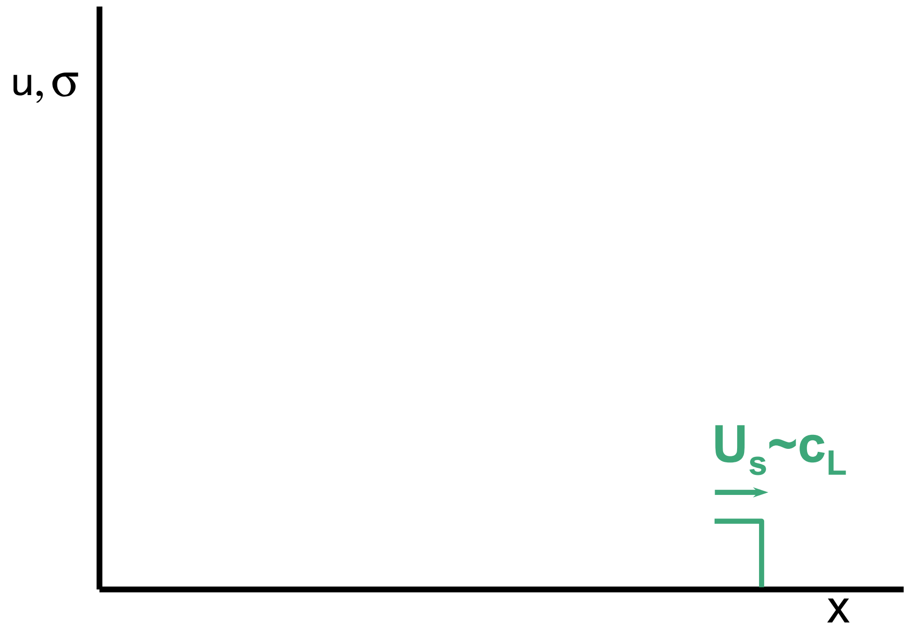
- increases uncertainties in EOS models
- strength affects stress state in diamond anvil cell
- understanding of strength needed for accurate computational results
- Rayleigh-Taylor instabilities inhibited by strength
- weapons and armor applications (ceramic armor, penetrators, etc.) influenced by strength



dwell of penetrator on confined ceramic

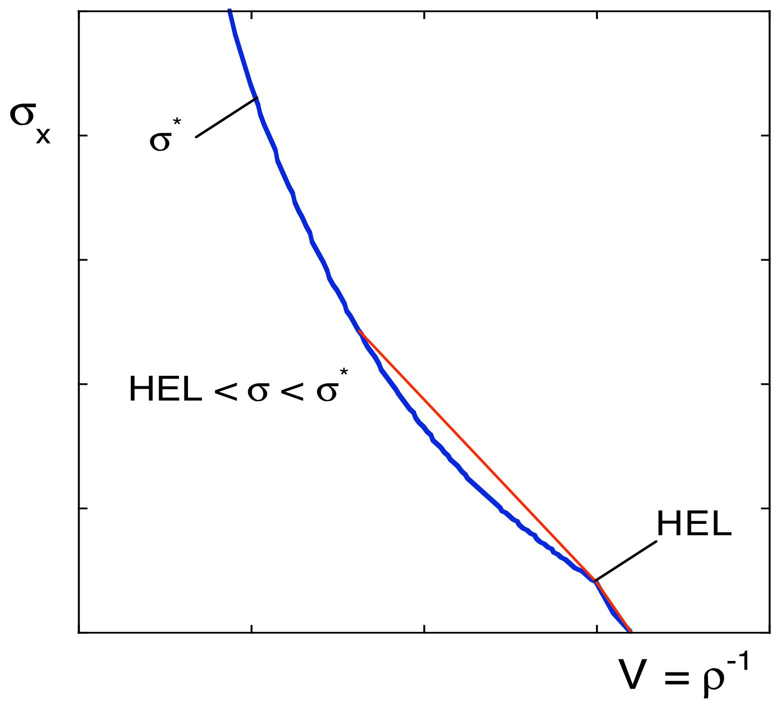
Effect of Strength on Shock Waves

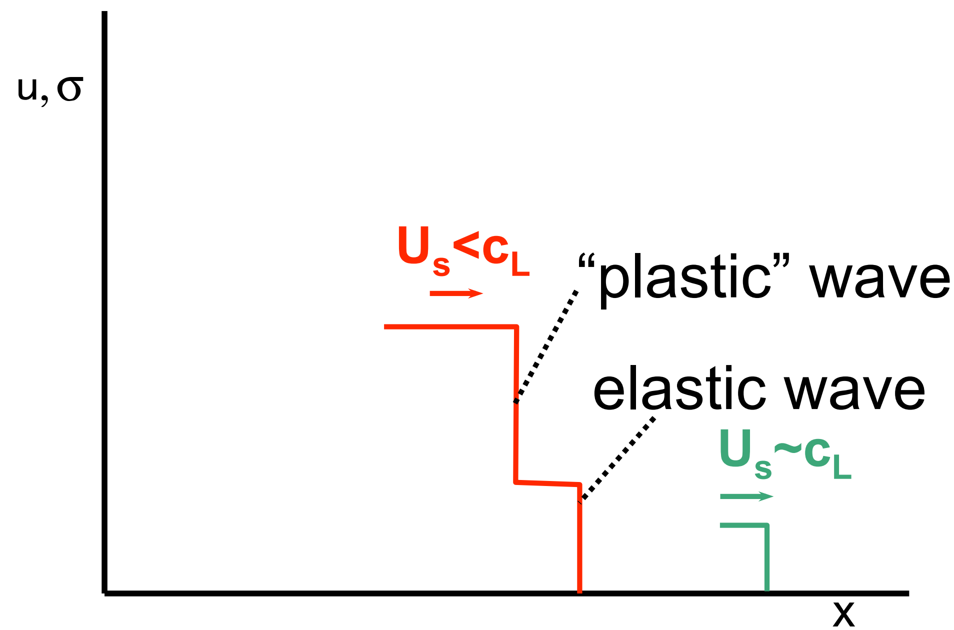




- most solids display elastic behavior for low shock stresses

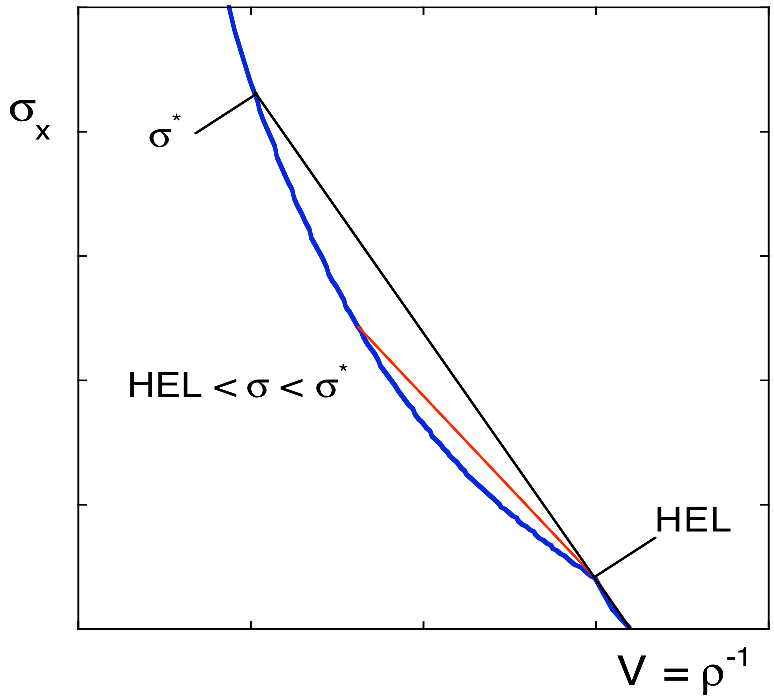
Effect of Strength on Shock Waves

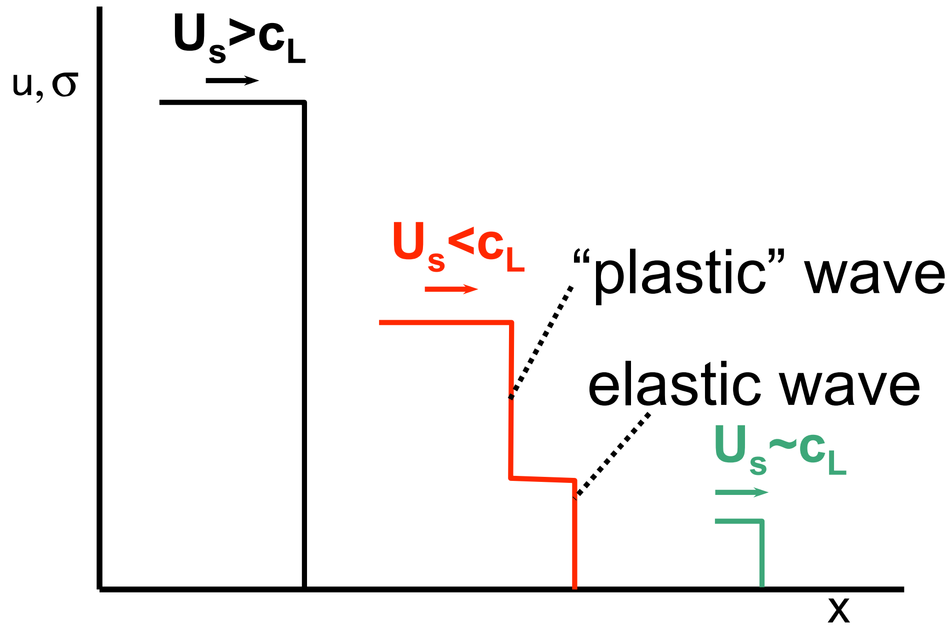




- most solids display elastic behavior for low shock stresses
- for stresses somewhat above HEL (Hugoniot elastic limit), a two-wave structure develops

Effect of Strength on Shock Waves





- most solids display elastic behavior for low shock stresses
- for stresses somewhat above HEL (Hugoniot elastic limit), a two-wave structure develops
- for high stresses, plastic wave travels faster than elastic precursor

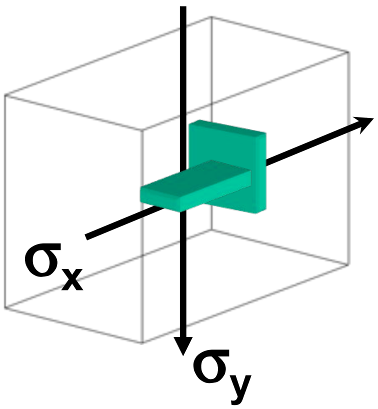
above HEL, σ_y is unknown regardless of stress level!

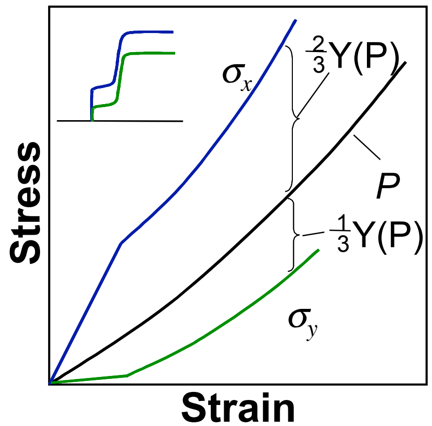
Typical Values of HEL

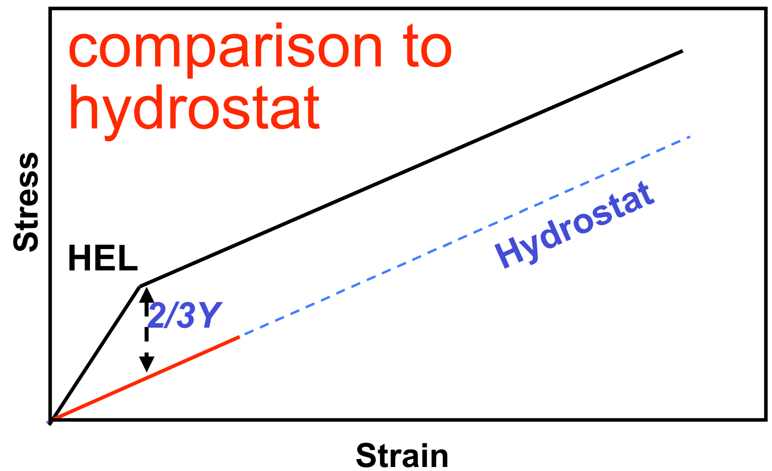
Material	HEL (GPa)
6061-T6 Al	0.5
tungsten	3 - 4.5
silicon carbide (SiC)	12 - 14
boron carbide (B_4C)	15 - 18
diamond	60 - 100

Techniques to Determine Strength at High Pressures

lateral gauges







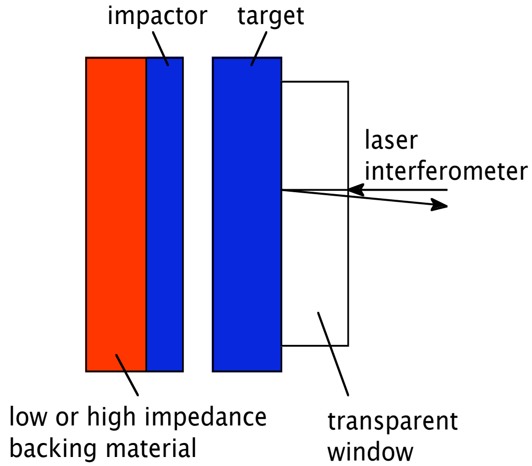
- *stress gauges can provide independent measures of σ_x and σ_y to determine dynamic strength*
- *calibration of gauges difficult*
- *only function to ~20 GPa due to shorting of insulation*

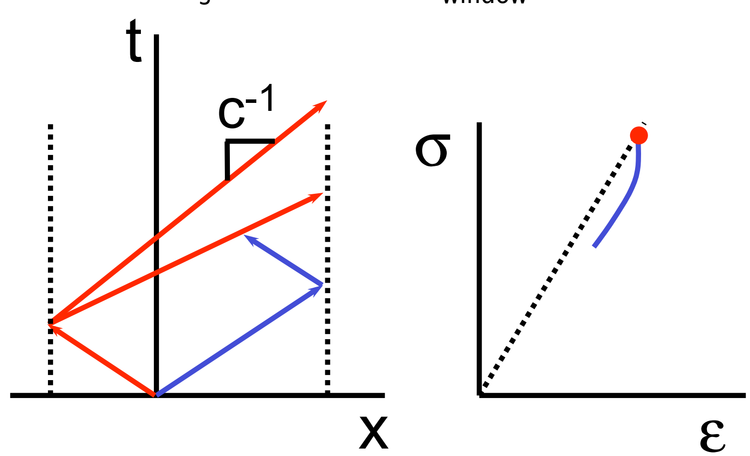
- *most common method: compare with hydrostatic data*
- *hydrostat from ultrasonic sound speed data (C vs. P) or diamond anvil cell (P - V)*
- *uncertainties can be very large*

also: X-ray diffraction, pressure-shear loading, growth of Rayleigh-Taylor instabilities, within diamond anvil cells

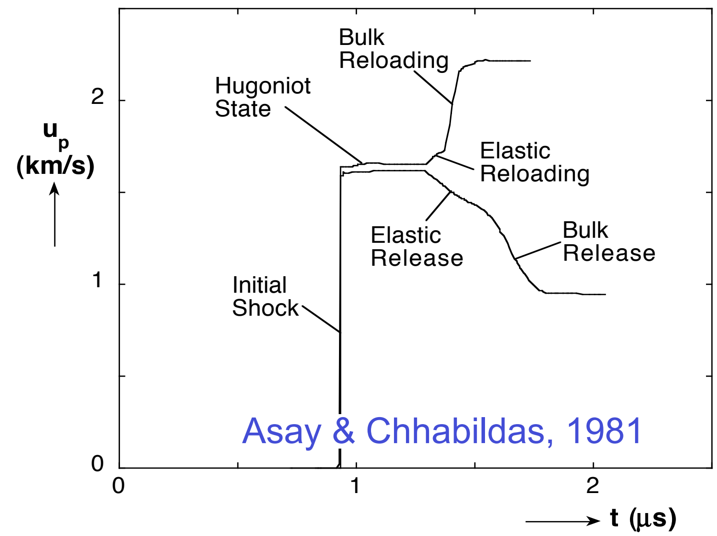
Self Consistent Method (Asay, Lipkin, Chhabildas, *et al.*)

reshock & release configuration





results for 6061-T6 Al



- wave speed determined from VISAR release or reloading profiles
- unloading path calculated from incremental relations

strength based on relative difference from Hugoniot state

Past Work: the Self Consistent Method

Sandia - reshock/release of Al, Be, Cu, Mo, Ta, V, W (Asay, Chhabildas, *et al.*)

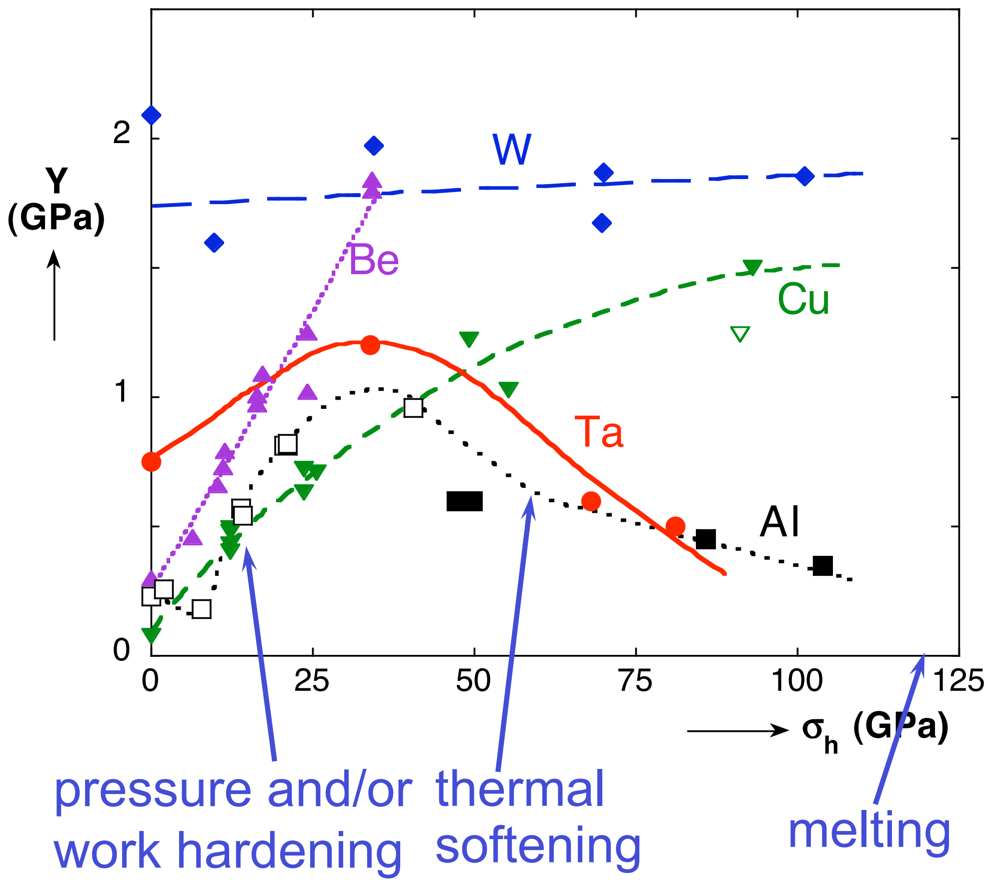
WSU - reshock/release of Al

LANL - release of 2024 Al

Russia - results of an experiment by Al'tshuler *et al.*, 1999, using longitudinal gauges agree with results of Asay & Chhabildas [1981] and with lateral gauge measurements

Strength of Metals Under Shock Loading

metals studied to high pressure using self-consistent method



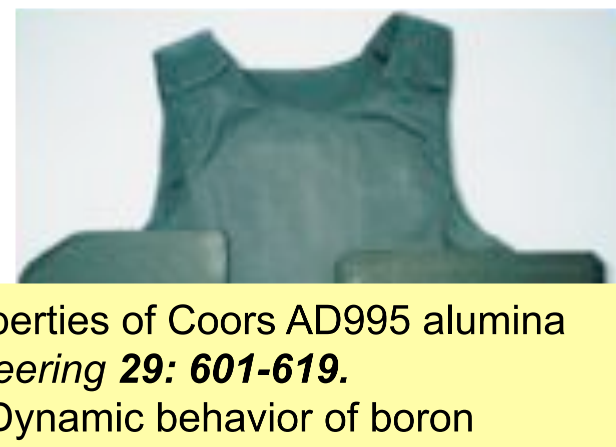
- strength increases due to work and pressure hardening
- ultimately decreases due to thermal softening

Outline of Talk

- Introduction to shock and high-pressure physics
- Gas gun technology and examples
- The Z machine and examples
- Background on high pressure strength and techniques to measure it
- Strength of ceramics under shock loading
- Strength of metals under isentropic loading
- Conclusions

Strength of Armor Ceramics

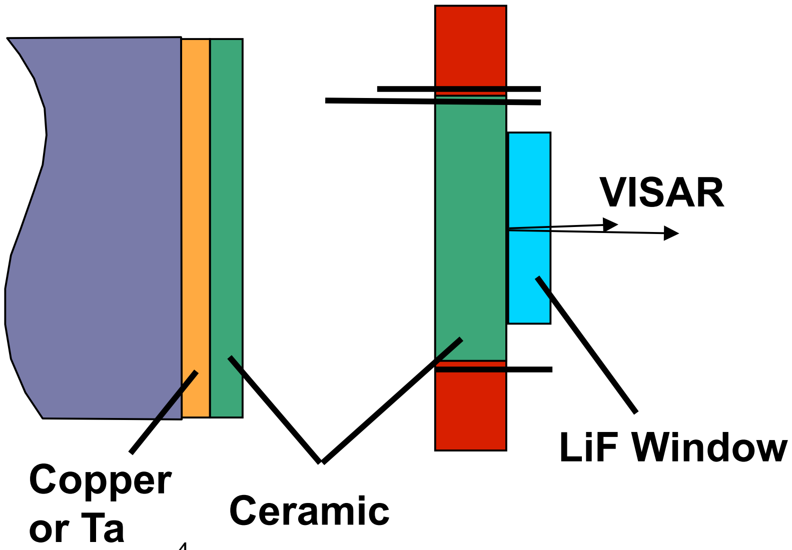
- Al_2O_3, B_4C, and SiC considered or fielded for personnel or vehicle protection
- ceramic armor performance closely linked to specific configuration --> need for accurate models for use in armor design
- “conventional wisdom” says (most) ceramics lose strength when shocked

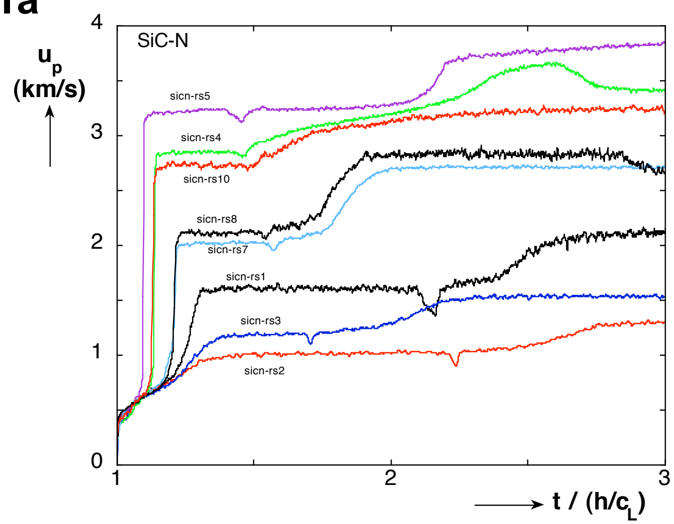


Reinhart, W. D. and L. C. Chhabildas (2003). "Strength properties of Coors AD995 alumina in the shocked state." *International Journal of Impact Engineering* ***29: 601-619.***
Vogler, T. J., W. D. Reinhart and L. C. Chhabildas (2004). "Dynamic behavior of boron carbide." *Journal of Applied Physics* ***95: 4173-4183.***
Vogler, T. J., W. D. Reinhart, L. C. Chhabildas and D. P. Dandekar (2006). "Hugoniot and strength behavior of silicon carbide." *Journal of Applied Physics* ***99: 023512.***

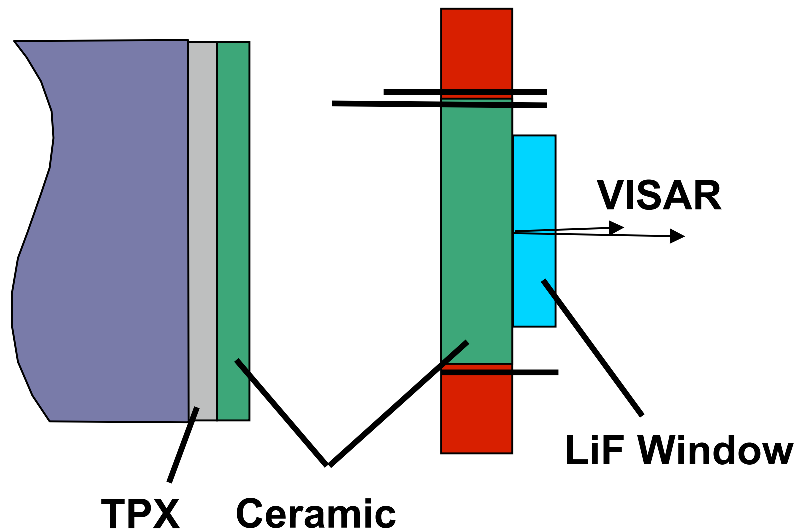
Reshock & Release Experiments for B_4C and SiC

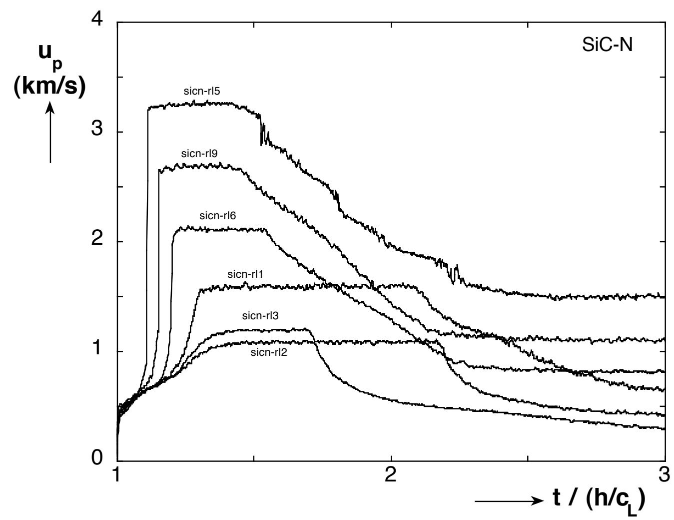
Reshock Configuration



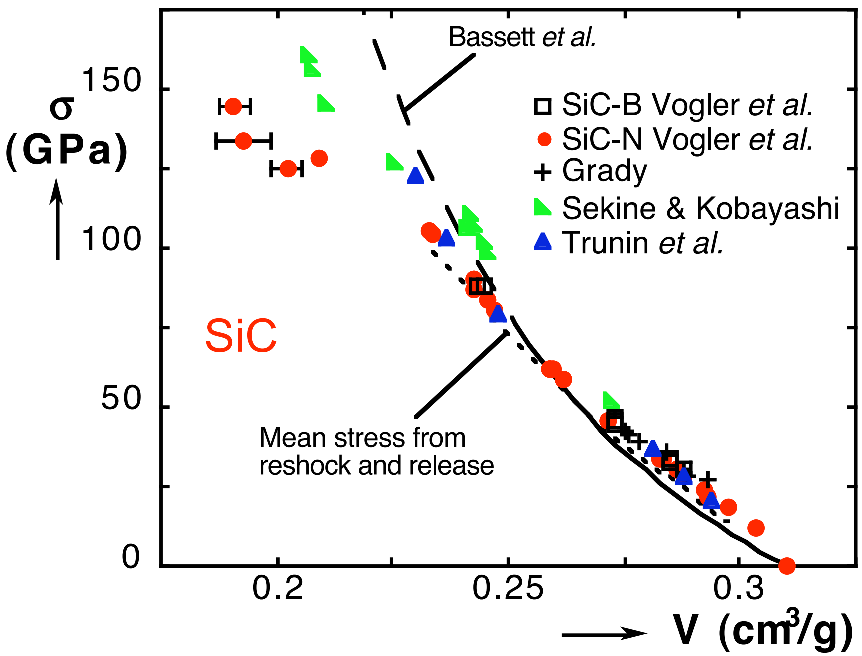


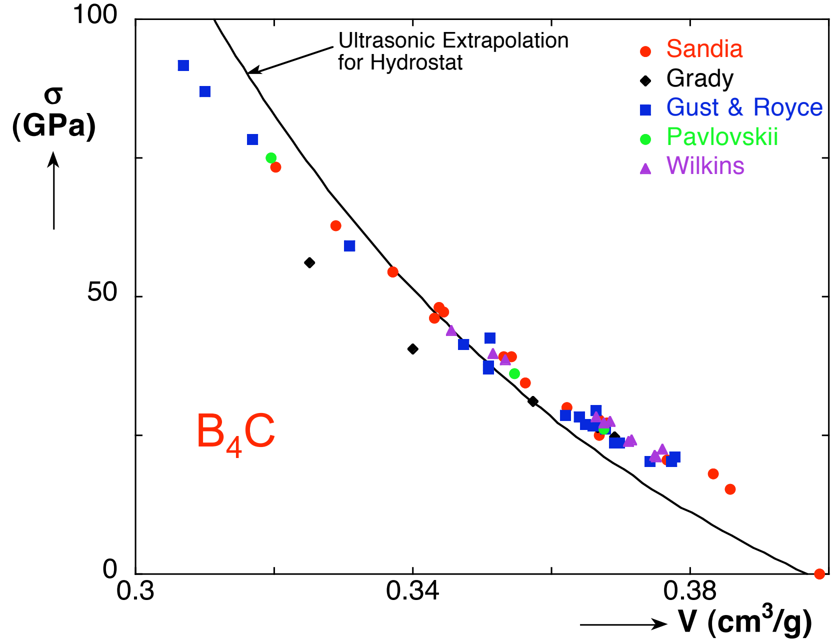
Release Configuration





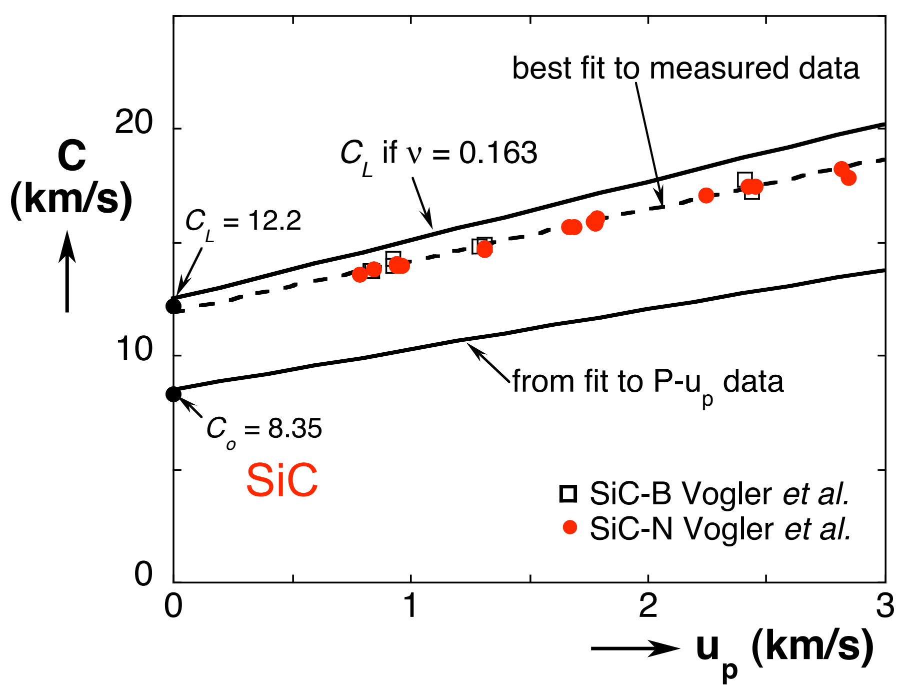
Hugoniots for SiC and B_4C

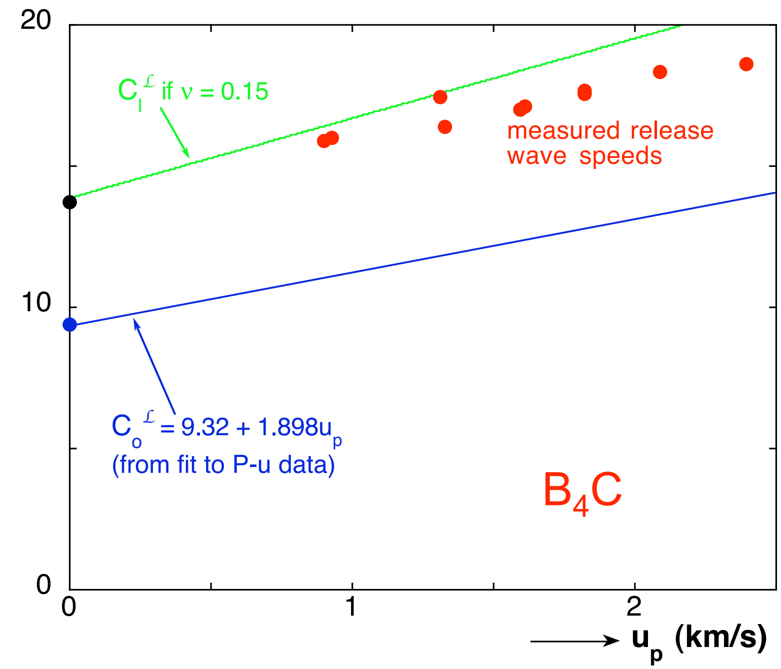




- Sandia studies have completed data sets, agreement with other studies generally good
- phase transition observed in SiC at ~105 GPa
- possible phase transition in B_4C at ~40 GPa, but evidence inconclusive (behavior may be due to shock amorphization)

High Release Wave Speeds Are Indicative of Elastic Behavior





- **release waves arrive much faster than expected bulk wave speeds (based on Hugoniot)**
- ***ν* appears to be increasing in B_4C**

$$C_{bulk} \approx \frac{1}{\rho_o} \frac{d\sigma}{du}\bigg|_{Hugoniot}$$

material displays elastic behavior in shocked state

Analysis of Reshock & Release Experiments

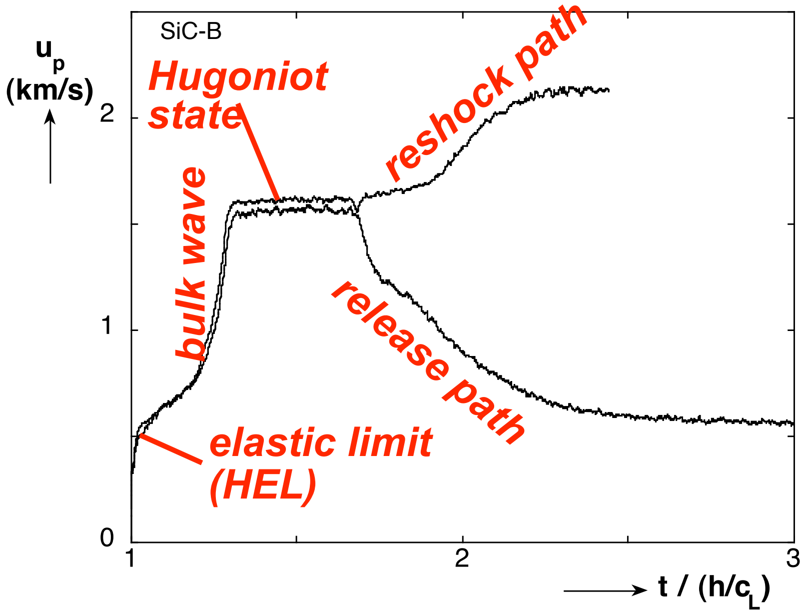
- *Incremental form of conservation equations used to calculate σ-ε paths*

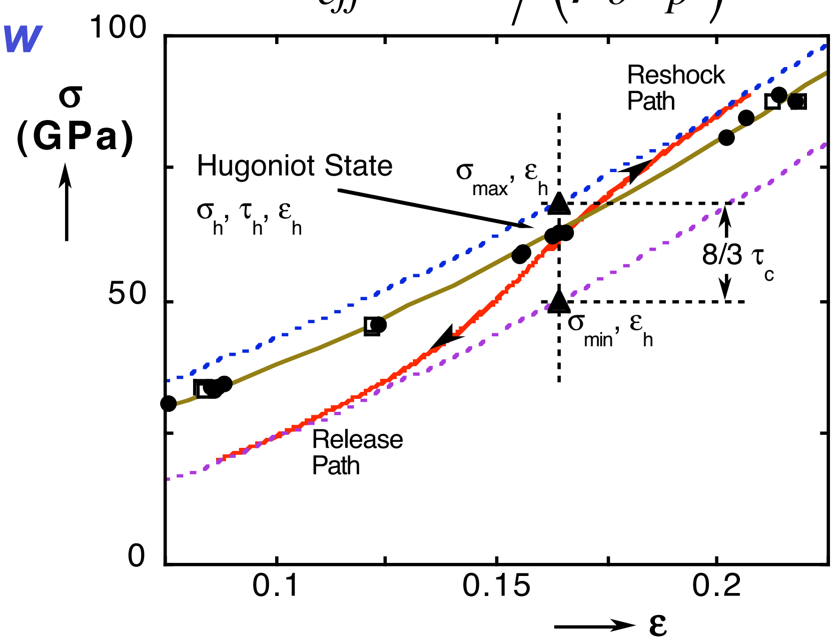
$$\Delta\sigma = \rho_o c\,\Delta u$$
$$\Delta\varepsilon = \Delta u / c$$

c based on effective shock:

$$U_{eff} = \sigma^H / \left(\rho_o u_p^H\right)$$

- *Account for presence of window*

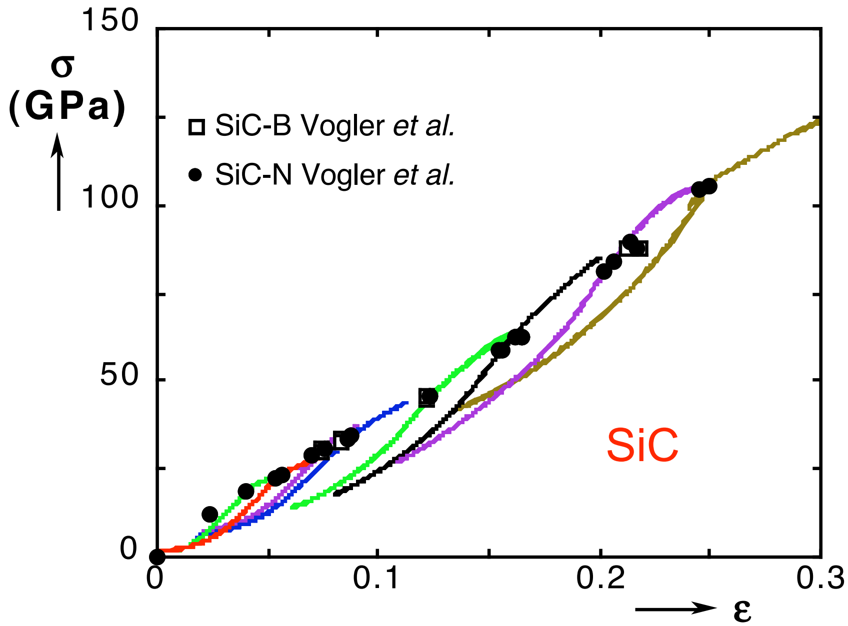


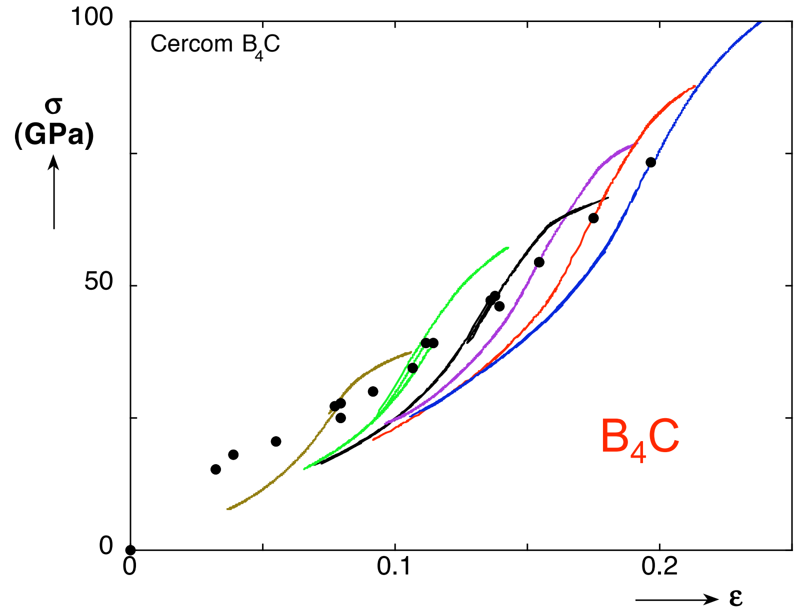


- *most of reshock path arrives later than release*
- *both arrive at elastic wave speed*

- *Technique to estimate:*
  - *Strength of the material in the shocked (damaged) state*
  - *Dynamic mean stress curve*
  - *Shear stress in Hugoniot state*

Reshock & Release Paths



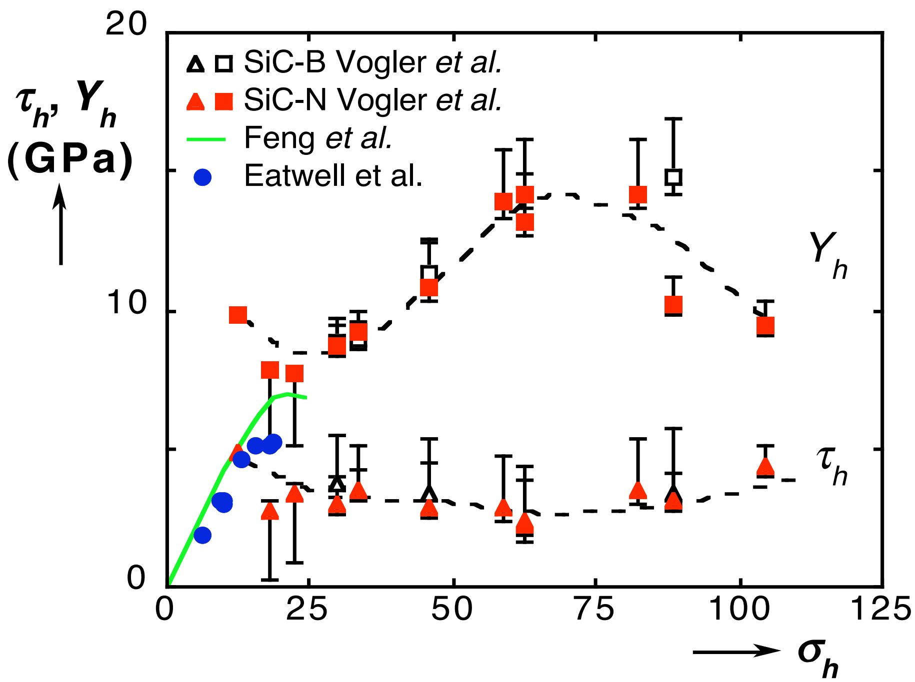


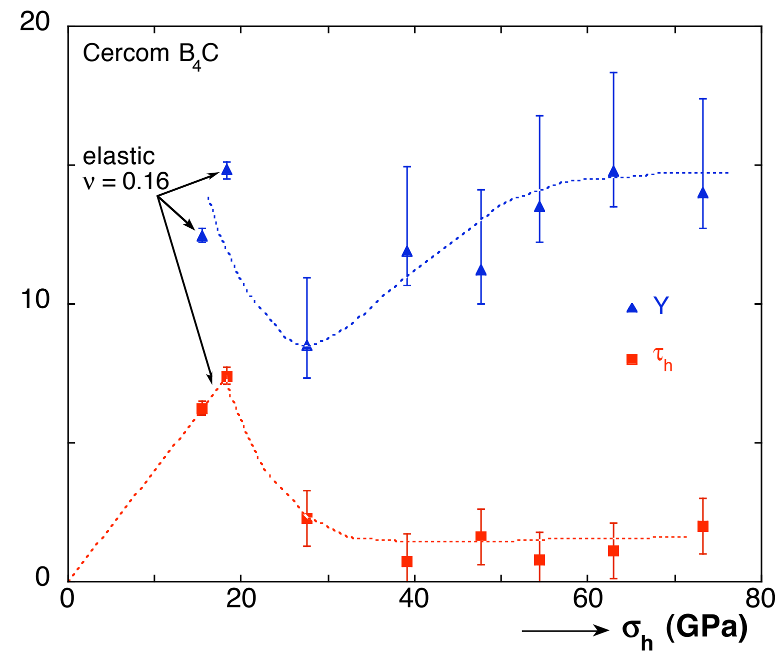
- release paths below Hugoniot
- reshock paths only slightly above Hugoniot
- shallow reshock >100 GPa due to phase transformation

- release paths below Hugoniot
- reshock paths significantly above Hugoniot

comparable behavior on release; SiC behaves in "metal-like" manner while B_4C behaves unexpectedly

Strength in Shocked State





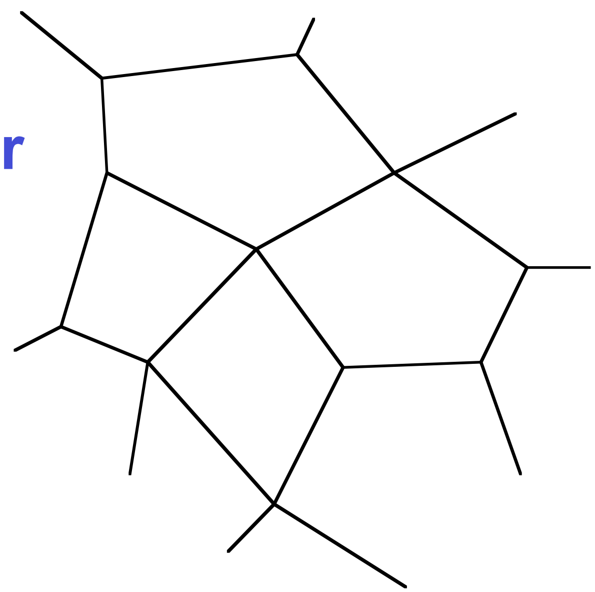
- **significant strength retained**
- **apparent loss of strength approaching phase transition**
- **t_h remains approximately constant**

- **material retains only small shear stress in Hugoniot state but large apparent strength during reshock/release**
- **strongly suggestive of damage**
- **kinetics and physical mechanisms unclear**

how important is this behavior in an armor application?

Behavior of B_4C (and Al_2O_3): A Possible Physical Explanation

- initial shock creates damaged (micro-cracked) material and possible local melting but relatively small relative motion
- material equilibrates after shock passage; melted material solidifies; interfaces at rest or "healed" by solidification (similar to concept of Swegle & Grady, 1986)
- when perturbed by release or reshock, material responds elastically



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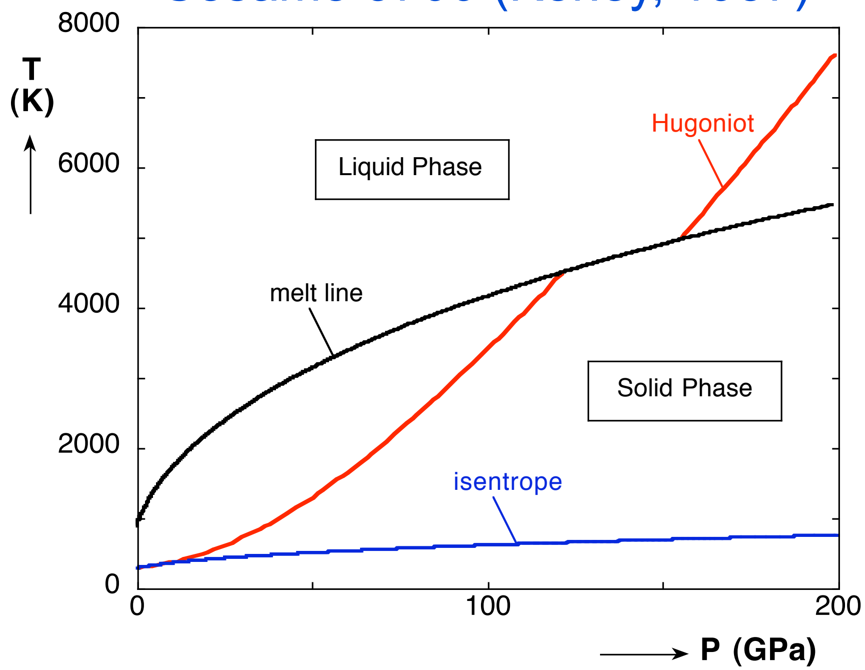
Isentropic Loading Accesses Cool Regimes Where Strength Is More Important

Sesame 3700 (Kerley, 1987)



- Hugoniot passes into liquid phase at ~120 GPa
- Isentrope remains in solid phase, rise of T minimal

Steinberg-Guinan Strength Model (rate-independent version):

$$\frac{Y}{Y_o} = \left(1+\beta(\varepsilon_p+\varepsilon_i)\right)^n \frac{G(P,T)}{G_o} \qquad G(P,T) = G_o + \frac{\partial G}{\partial P}\frac{P}{\eta^{1/3}} + \frac{\partial G}{\partial T}(T-T_o)$$

strength larger under isentropic loading due to smaller ΔT

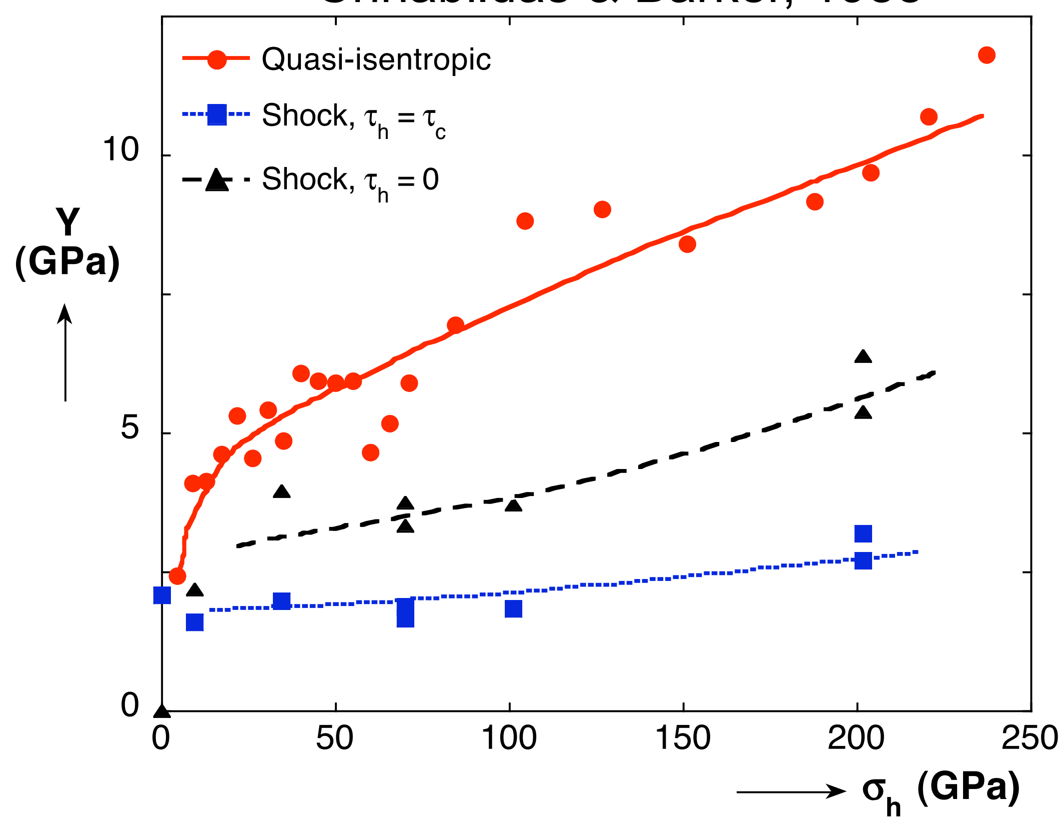
Strength Under Quasi-Isentropic Loading: Previous Work

aluminum - isentrope stiffer than Hugoniot to 9 GPa (Barker-SNL)

tungsten - isentrope from graded-density impactor lies above Hugoniot up to 140 GPa due to strength

molybdenum - isentrope from Z compared with hydrostat to estimate strength (Reisman-LLNL/SNL)

Chhabildas & Barker, 1988

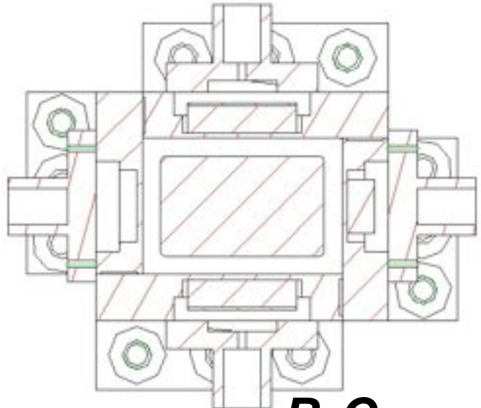


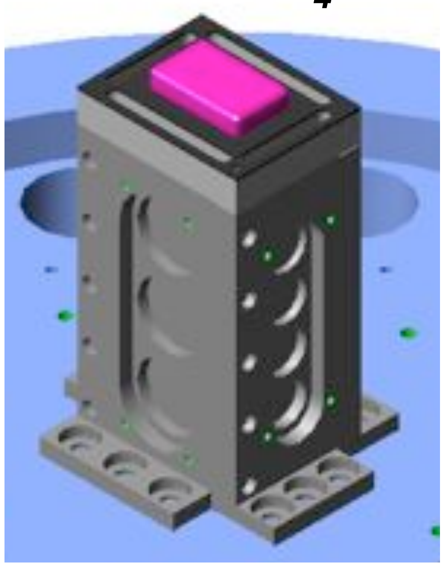
lateral gauges

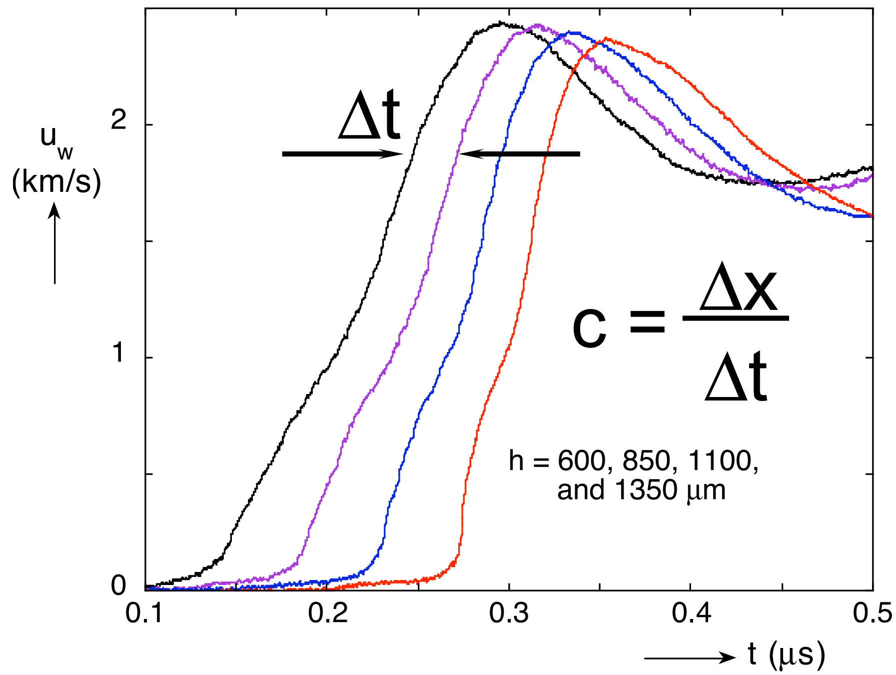
- AD-1 aluminum and copper (Bat'kov *et al.*)
- copper, iron, steel (Rosenberg *et al.*)

growth of Rayleigh-Taylor instabilities - aluminum and vanadium (LLNL)

Results for 6061-T6 Aluminum to 55 GPa





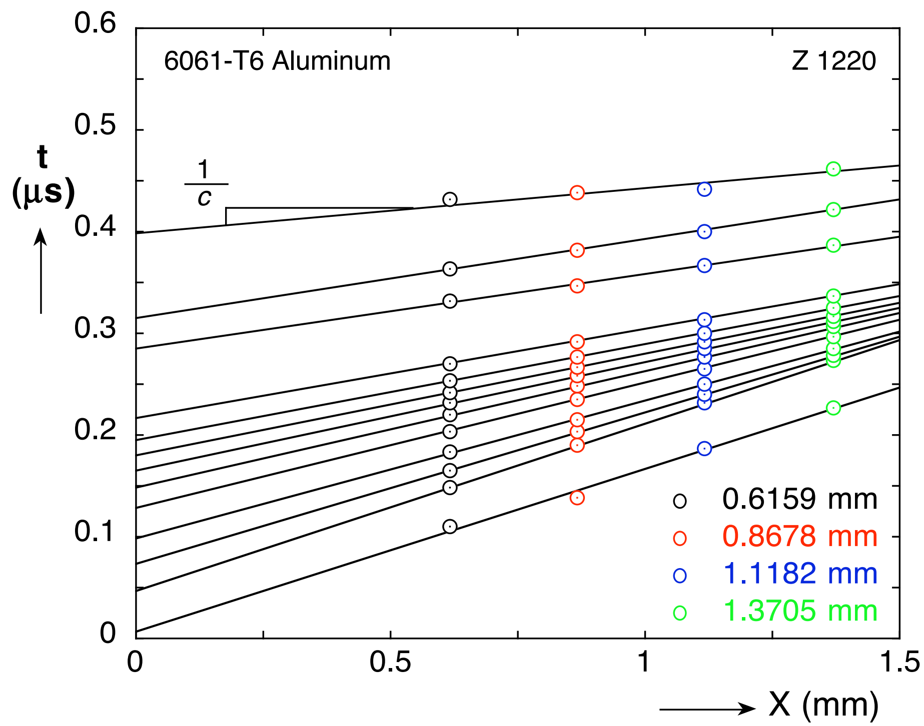


- four profiles, both loading and unloading histories
- peak attenuation evident
- unloading structure develops in thicker samples

Lagrangian Analysis Technique

- *backwards integration technique of Hayes is non-unique for elastic-plastic materials*
- *Lagrangian analysis technique follows previous work by Grady and others*

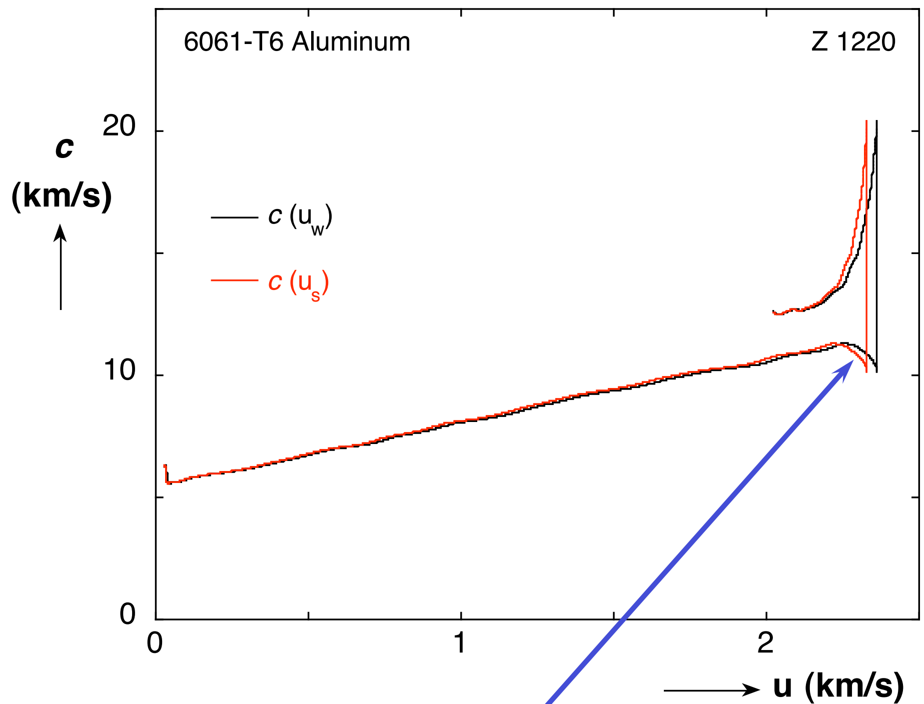
1) determine $c(u_w)$ by least-squares fit to VISAR data



Lagrangian Analysis Technique (2)

2) correct $c(u_w)$ to $c(u_p)$ by impedance matching of window and sample

$$\Delta u_s = \frac{Z_s + Z_w}{2Z_s}\Delta u_w$$



relaxation due to drop in strain rate?

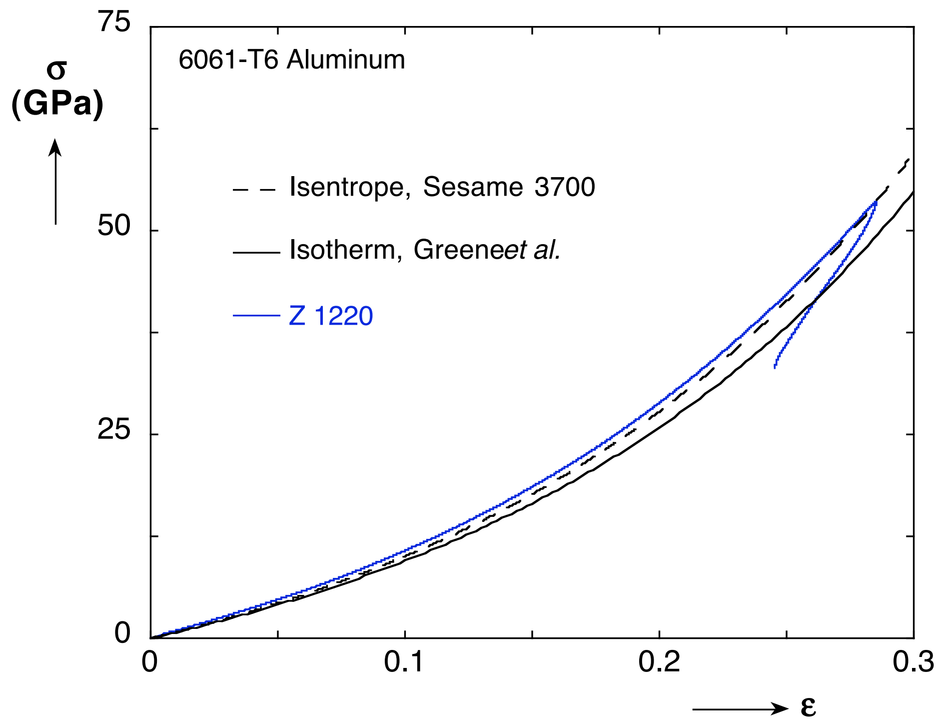
Lagrangian Analysis Technique (3)

3) integrate stress and strain using incremental relations:

$$\Delta\sigma = \rho_o c \, \Delta u_p$$

$$\Delta\varepsilon = \Delta u_p / c$$

for unloading, ignore attenuation by beginning at lowest peak u_p



Assumptions in Lagrangian Analysis Technique

- characteristics not bent by window interactions
- rate-independent material
- all points experience same loading history
- window behavior known
- window loads along its principal isentrope

none of assumptions fully met!

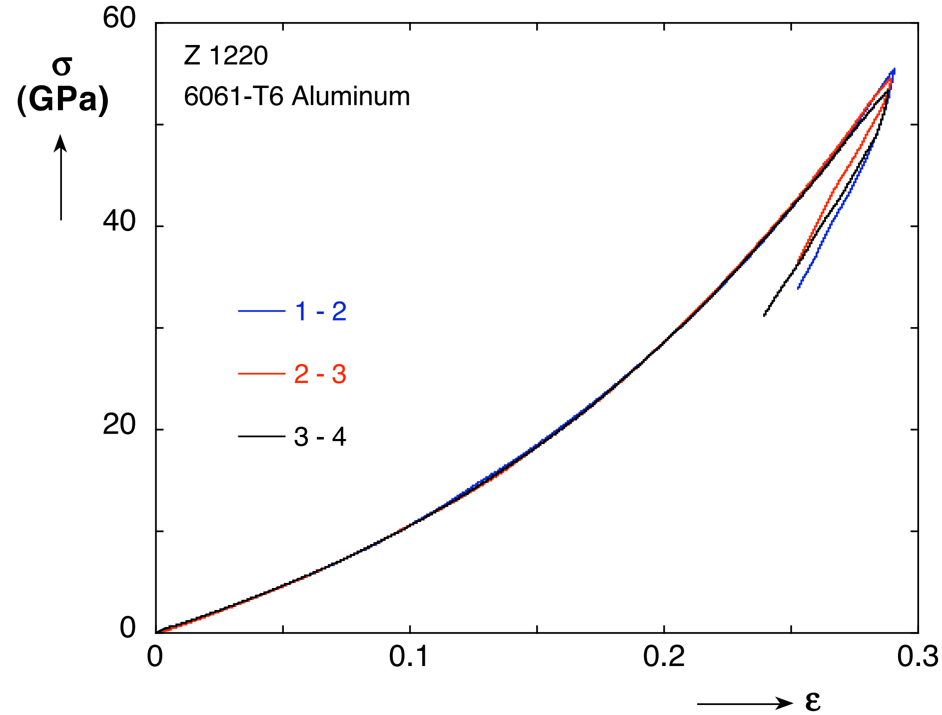
none is too bad, either!

Strength Measurement

Since stress-strain histories are somewhat different for each material point, VISAR results are analyzed in a pairwise fashion.

Loading responses are very similar for the three pairs.

Difference between loading and unloading curves is a measure of the strength.



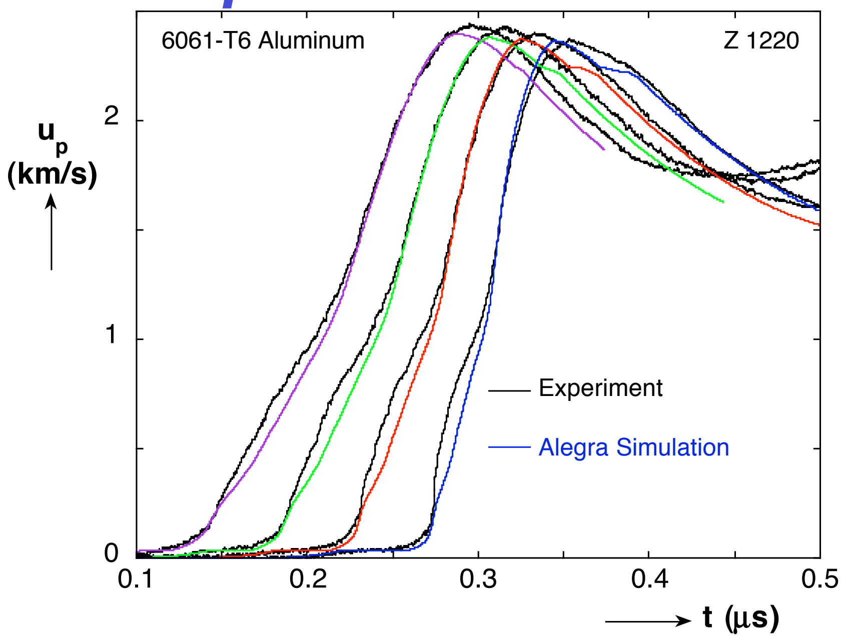
$$Y = \frac{3}{4}(\sigma_L - \sigma_U)$$

= ~~3.1~~, 2.2, 1.5 GPa

results suspect due to wave interactions

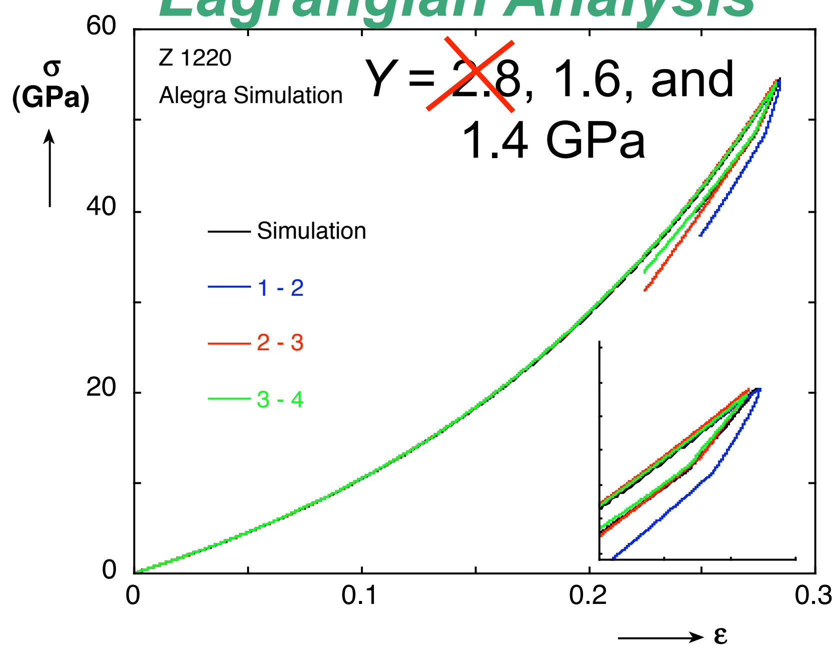
Simulated Data for Z 1220

Experiment & Simulation



- 1-D Alegra simulation - arbitrary Lagrangian-Eulerian magneto-hydrodynamics code, Steinberg-Guinan-Lund strength model
- current input somewhat off on loading, too much structure in unloading wave

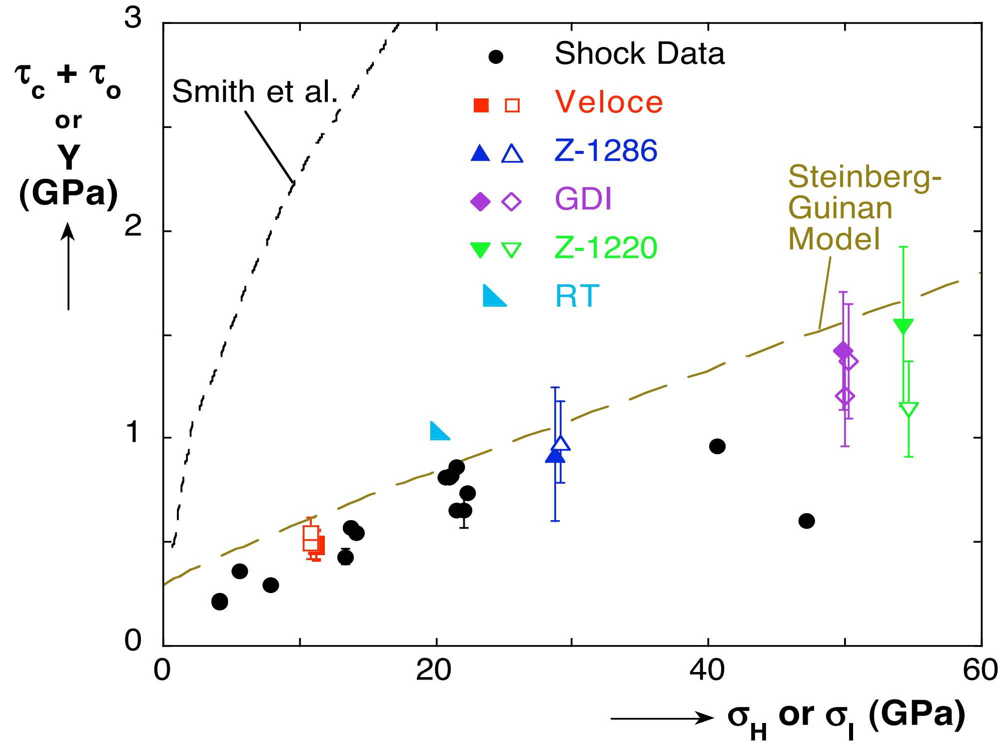
Lagrangian Analysis



- loading captured extremely well
- first pair affected by window perturbations reaching drive surface, but others accurate measurements of *Y (1.48 GPa)*

Strength Under Isentropic and Shock Loading

- strength under isentropic loading continues to increase with increased stress (due to pressure and/or work hardening)
- current experimental results agree with Steinberg model
- results of Smith et al. significantly different



Asay, J. R., Ao, T., Davis, J.-P., Hall, C. A., Vogler, T. J., and Gray, G. T. (2008). "Effect of initial properties on the flow strength of aluminum during quasi-isentropic compression," *J. Appl. Phys.* **103**, 083514.

Vogler, T. J., Ao, T., and Asay, J. R. (2009). "High-pressure strength of aluminum under quasi-isentropic loading," *Int. J. Plast.*, **25**, 671-694.

Conclusions

- self-consistent technique can be applied to shock or ramp loading for metals or ceramics
- SiC retains significant strength and shear stress in shocked state in a “metal-like” manner
- B_4C
  - retains considerable strength in the shocked state
  - shear stress is low or zero
  - current concepts of strength inadequate to describe this behavior
  - physical mechanisms unclear - damage or “thermal trapping”?
- strength measurements under isentropic loading to 60 GPa for aluminum
- strength results are relatively insensitive to timing errors (1 ns shift gives ~8% error in Y at 60 GPa)
- conservative estimate of 20-30% uncertainty on Y at 50 GPa for Al,

Work Needed

- comparison of different techniques (e.g. Rayleigh-Taylor, DAC, and self-consistent) for same materials
- utilize pressure-shear techniques to decouple effects of pressure, strain rate, work hardening, etc.
- grain scale investigations to understand mechanisms associated with strength retention/loss in metals and ceramics
- establish connections between experiments and molecular dynamics simulations
- investigate effect of solid-solid phase transformations on strength and vice-versa