SAND2016-5092C

Exceptional service in the national interest

Sandia National Laboratories

Quasi-Isentropic Compression of Free-Machining (C36000) Brass

Paul E. Specht and Seth Root

Sandia National Laboratories, NM USA

PETER 2016 New Models in Hydrocodes
Le Grand Large, St. Malo, France
Session 1B: Experimental Methods and Results
Wednesday, June 1st, 2016 12:00

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Approved for Unlimited Release, SAND2015-XXXXP.

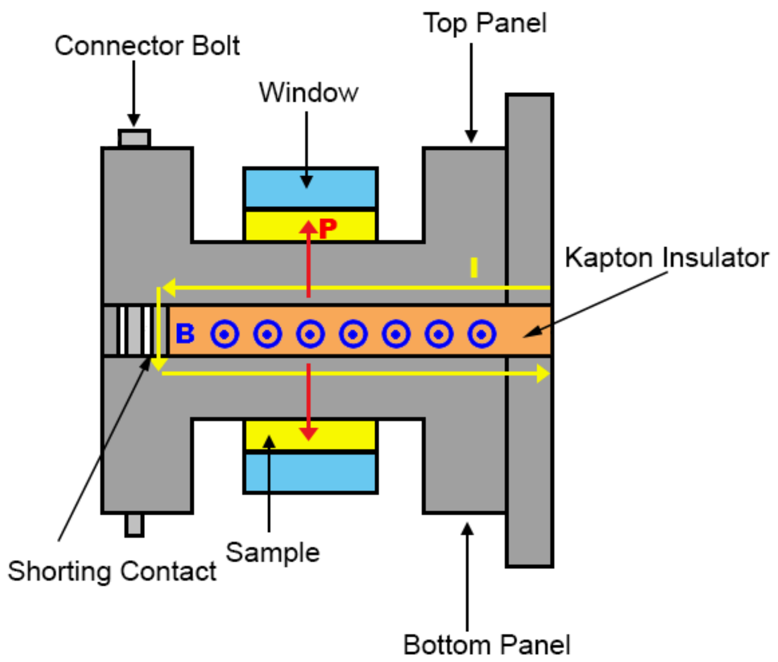
Quasi-Isentropic Compression

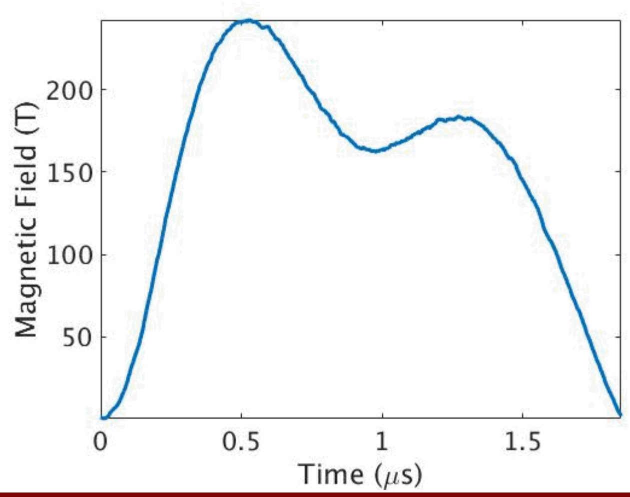
- Quasi-isentropic compression provides access to a different portion of the equation of state (EOS) than the Hugoniot
  - Reach high pressure states with lower temperature increase
  - Quasi-isentropic because not completely reversible
    - Effects from plastic work exist, but are small
  - Achieved through ramp loading
    - Pulsed power, Laser drives, graded density impactors
- Ramp loading provides a continuous measurement of the quasi-isentrope
  - Multiple experiments are not necessary like determining a Hugoniot
- Sample unloading also provides a measurement of the shear strength of the material

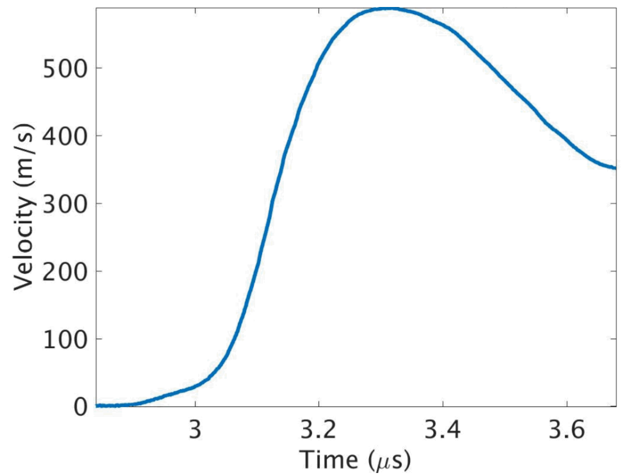
Magnetic Compression

- Current flow generates a magnetic field between the top and bottom panels
- The resulting Lorenz force, **F = J x B**, compresses the sample [1]

$$P = k_e \frac{B^2}{2\mu} = k_e \frac{\mu}{2}\left(\frac{I}{w}\right)^2$$



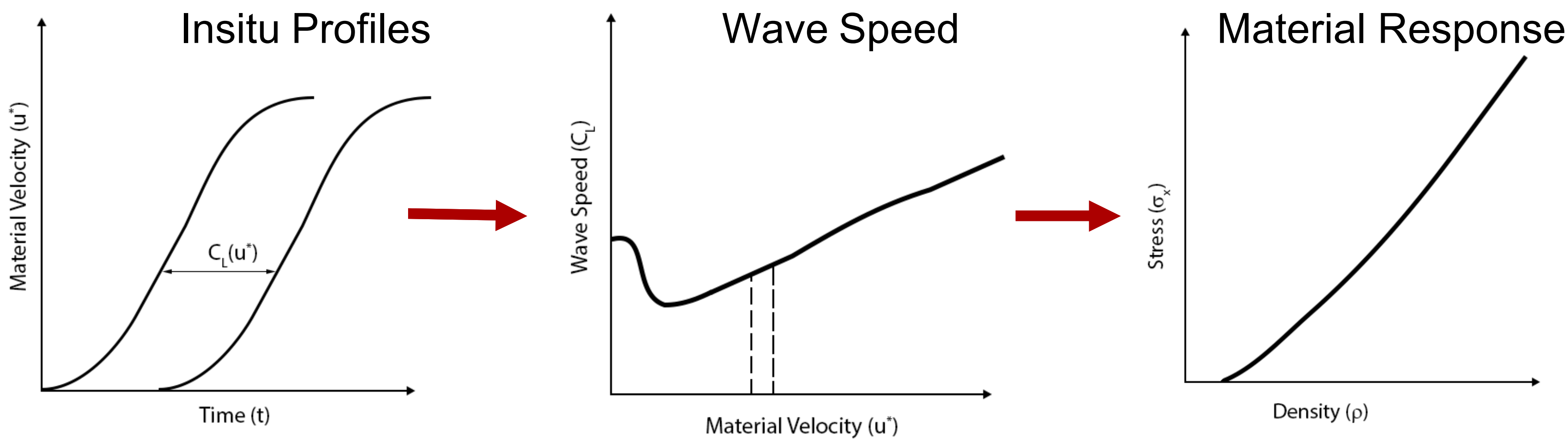




[1] T. Ao et al., Rev. Sci. Instrum. 79, 013903 (2008).

Quasi-Isentrope Determination

- Quasi-isentrope is easily determined with Lagrangian, or insitu, material velocities at two locations in the sample [2]
  - Direct Lagrangian analysis
    - $dv = -\frac{-du^*}{\rho_0 C_L(u^*)}$ $d\sigma_x = \rho_0 C_L(u^*) du^*$
  - Assumes simple, steady waves



[2] J.P. Davis et al. J. Appl. Phys. **116**, 204903 (2014).

Quasi-Isentrope Determination

- Quasi-isentrope is easily determined with Lagrangian, or insitu, material velocities at two locations in the sample [2]
  - Direct Lagrangian Analysis
    - $dv = -\frac{-du^*}{\rho_0 C_L(u^*)} \qquad d\sigma_x = \rho_0 C_L(u^*) du^*$
  - Assumes simple, steady waves
- Usually velocimetry measurements are at window interfaces
  - Need to be mapped to insitu profiles
- There are two mapping methods
  - Inverse Lagrangian analysis (ILA) [2]
    - Iterative method of characteristics approach
  - Transfer function method [3]
    - Iterative approach using MHD simulations and Fourier tranforms

[2] J.P. Davis et al. J. Appl. Phys. **116**, 204903 (2014). [3] Brown et al., J. Appl. Phys. **114**, 223518 (2013)

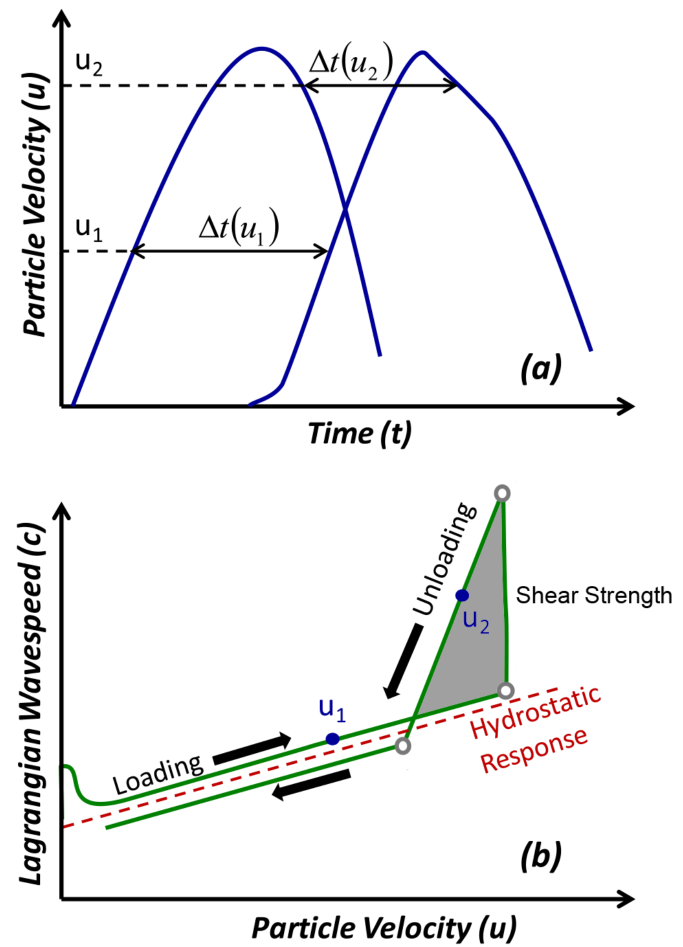
Insitu Velocity Determination

- Inverse Lagrangian analysis (ILA) [2]
  - Iterative method of characteristics approach
  - Requires two samples of differing thicknesses
  - Only applicable over the difference in thickness between samples
  - Only applicable over sample loading
    - Non-uniqueness of the mapping and significant elastic-plastic effects
- Transfer function method [3]
  - Iterative approach using MHD simulations and Fourier analysis
  - Requires on sample
    - Dependent on EOS standards
  - Assumes hydrocodes accurately represent the physics
  - Enables mapping through release
    - Shear strength measurement

[2] J.P. Davis et al. J. Appl. Phys. **116**, 204903 (2014).   [3] Brown et al., J. Appl. Phys. **114**, 223518 (2013)

Shear Strength Measurement

- Upon unloading the material experiences an initial elastic then plastic release
- In Lagrangian coordinates [3]
  - $d\sigma_x = \rho_0 C_L(u^*) du^* \qquad d\varepsilon = \frac{du^*}{C_L(u^*)}$
- The longitudinal plastic stress relates to the shear stress [3]
  - $\sigma_x(\varepsilon) = P(\varepsilon) + \frac{4}{3}\tau(\varepsilon)$
- A correction is applied to account for attenuation

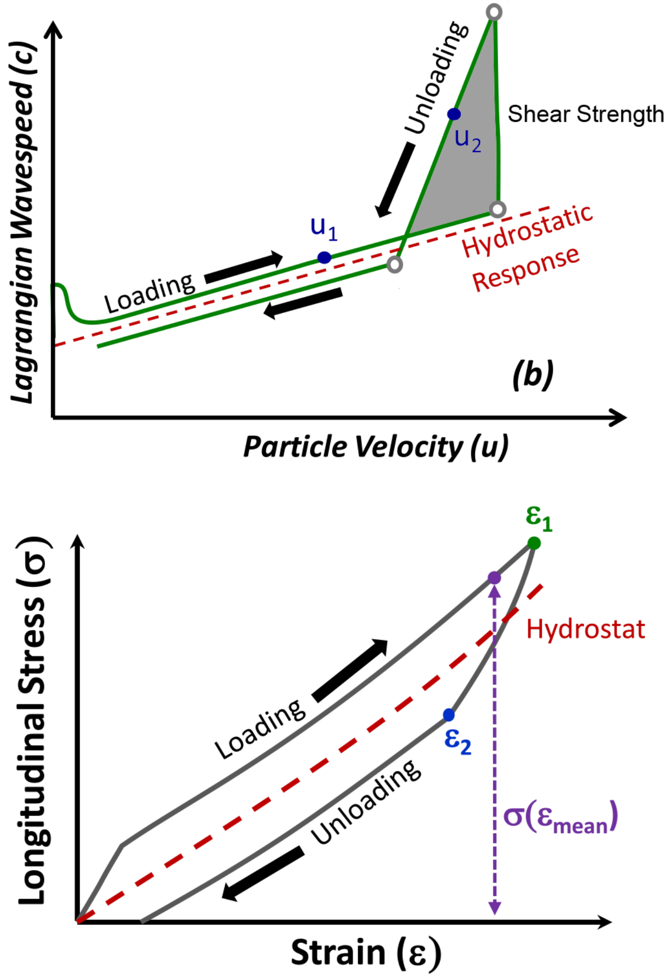


From Brown et al., J. Appl. Phys. **114**, 223518 (2013).

[3] Brown et al., J. Appl. Phys. **114**, 223518 (2013).

Shear Strength Measurement

- Upon unloading the material experiences an initial elastic then plastic release
- In Lagrangian coordinates [3]
  - $d\sigma_x = \rho_0 C_L(u^*) du^* \qquad d\varepsilon = \frac{du^*}{C_L(u^*)}$
- The longitudinal plastic stress relates to the shear stress [3]
  - $\sigma_x(\varepsilon) = P(\varepsilon) + \frac{4}{3}\tau(\varepsilon)$
- A correction is applied to account for attenuation
- Compare results at mean stress or strain



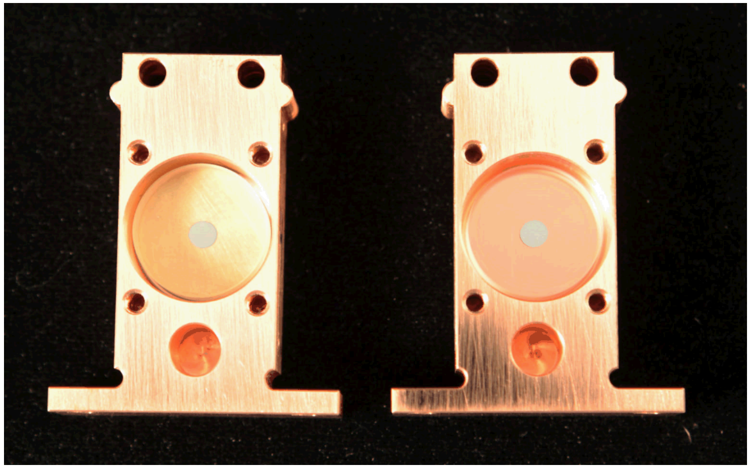
From Brown et al., J. Appl. Phys. **114**, 223518 (2013).

[3] Brown et al., J. Appl. Phys. **114**, 223518 (2013).

Experimental Parameters

Sandia National Laboratories

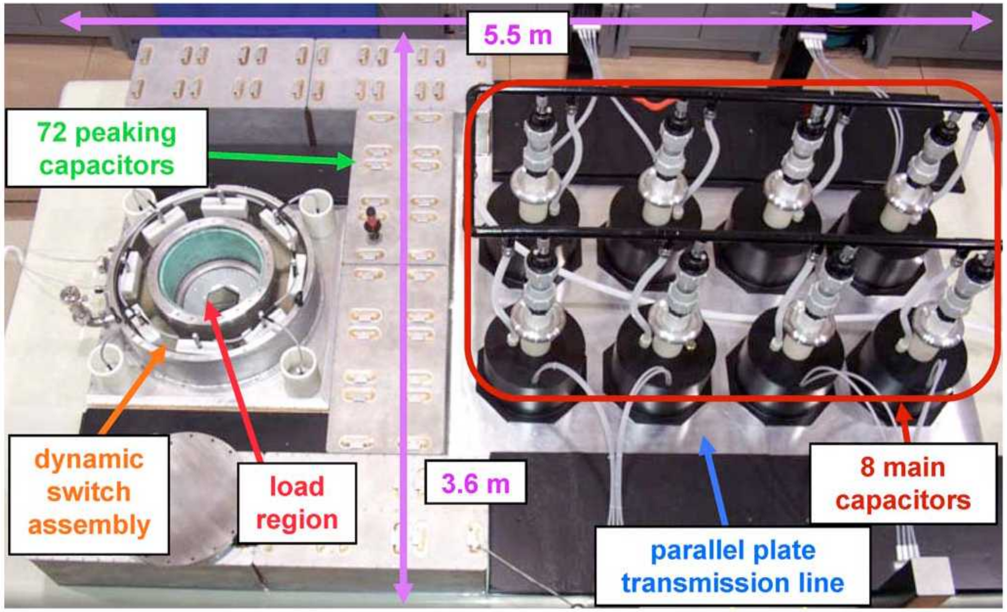
- Experiments were preformed on free machining brass (C36000)
  - 61.5% Cu, 35.5% Zn, 3% Pb
  - Density 8.45 g/cm^3
- Six experiments
  - 2 dual sample and 4 single sample
  - Pressures ranged from 5 to 14 GPa
  - Used copper panels, LiF windows
    - Both have well know EOS
  - Window interface velocities were obtained using a dual VPF VISAR
- Performed on VELOCE pulsed power machine



Representative sample panels
Single - 1

VELOCE Pulsed Power Machine

- VELOCE [1] is a compact pulsed power machine located at the Dynamic Integrated Compression Experimental (DICE) facility at Sandia National Laboratories
  - 3 MA of current
  - Rise times from 440 to 550 ns
  - Pressures from 5 -20 GPa

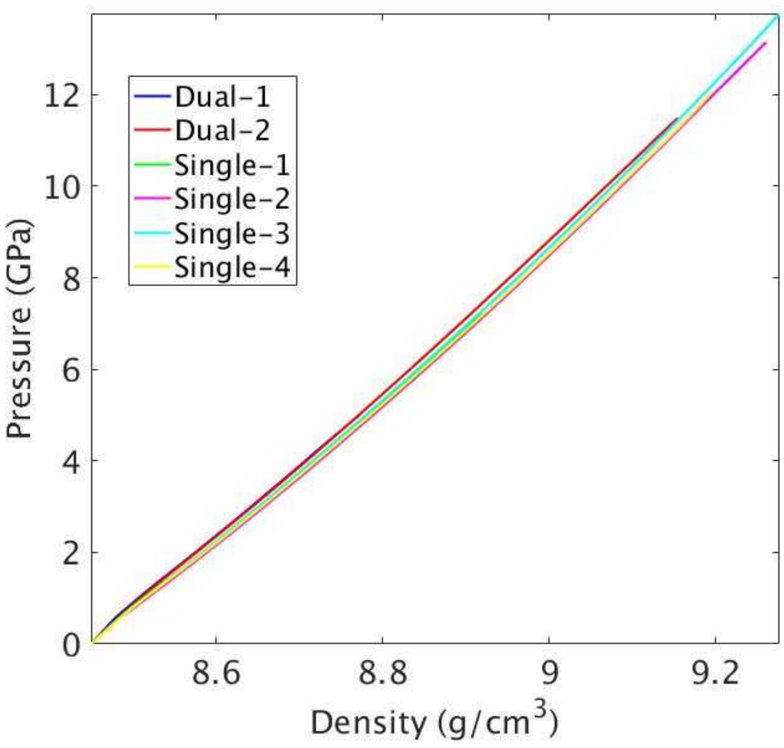


From T. Ao et al., Rev. Sci. Instrum. 79, 013903 (2008).

[1]T. Ao et al., Rev. Sci. Instrum. 79, 013903 (2008).

Experimental Quasi-Isentrope

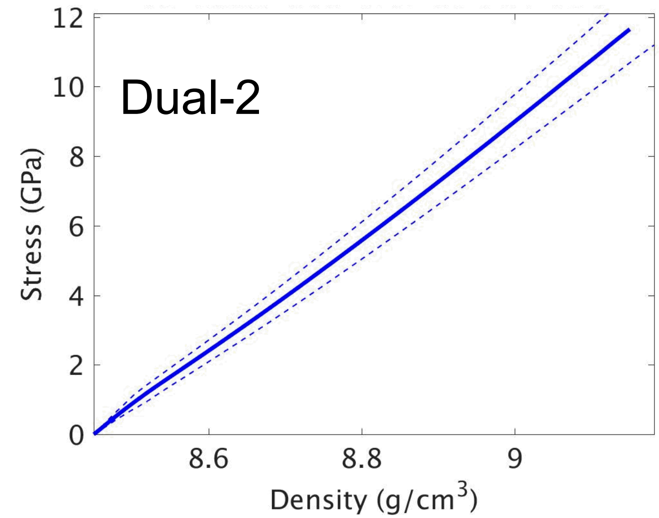
- Dual sample experiments were analyzed with CHARICE [4]
- Single sample experiments were analyzed with an in-house MATLAB code
- The experimental quasi-isentropes are consistent across configurations
- Contain an initial elastic region
  - Generates entropy, but not enough to invalidate the analysis method [4]

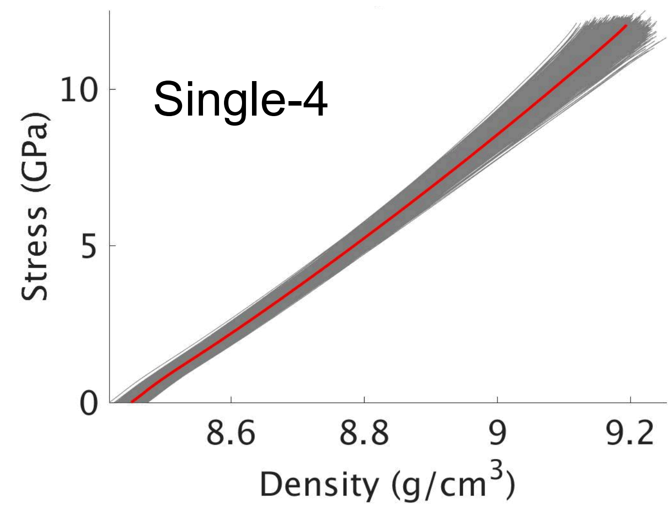


[4] J.P. Davis, Tech. Rep. SAND2007-4984, SNL, 2007.

Quasi-Isentrope Error Estimations

- Dual sample experiments
  - Experimental uncertainties are propagated through the inverse Lagrangian analysis
- Single sample experiments
  - A Monte Carlo approach was used
    - All experimental errors are assumed uncorrelated and normally distributed
    - 2000 variations of the results are run and the material response from each extracted
- Results presented are typical of all experiments



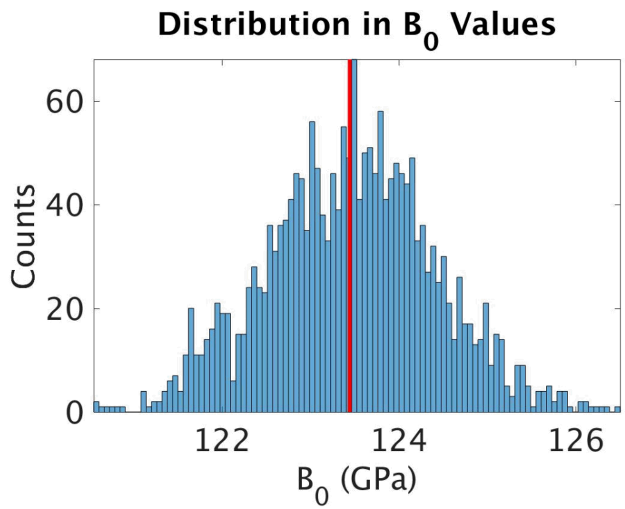


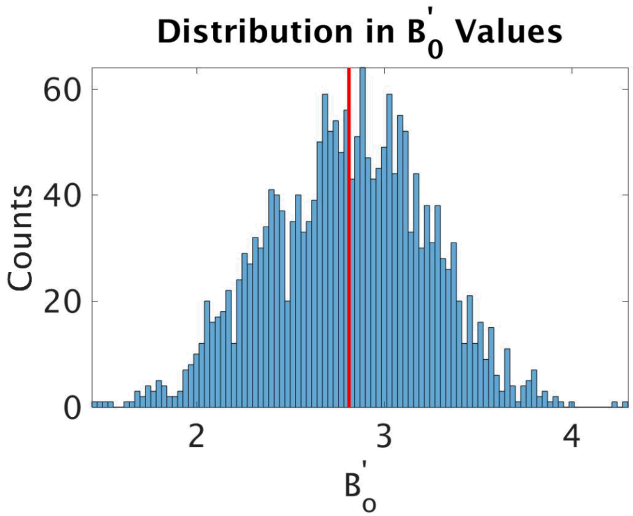
Quasi-Isentrope Fit

- The quasi-isentrope can be fit to a Vinet EOS [5]
  - $P = \left[3B_0 \frac{(1-x)}{x^2}\right] exp[\eta(1-x)]$
  - $x = \left(\frac{V}{V_0}\right)^{1/3} \qquad \eta = \frac{3}{2}(B_0' - 1)$
- Error determinations
  - Single sample: fit the bounds
  - Dual sample: distribution from iterations

Experiment	B_0 (GPa)	B_0'
Dual - 1	139.4 ± 11.6	2.62 ± 0.62
Dual - 2	130.2 ± 16.0	2.91 ± 1.16
Single - 1	123.5 ± 1.8	2.81 ± 0.35
Single - 2	116.8 ± 2.8	4.62 ± 0.40
Single - 3	120.1 ± 1.2	4.38 ± 0.21
Single - 4	118.6 ± 5.9	4.29 ± 1.00

Single - 1

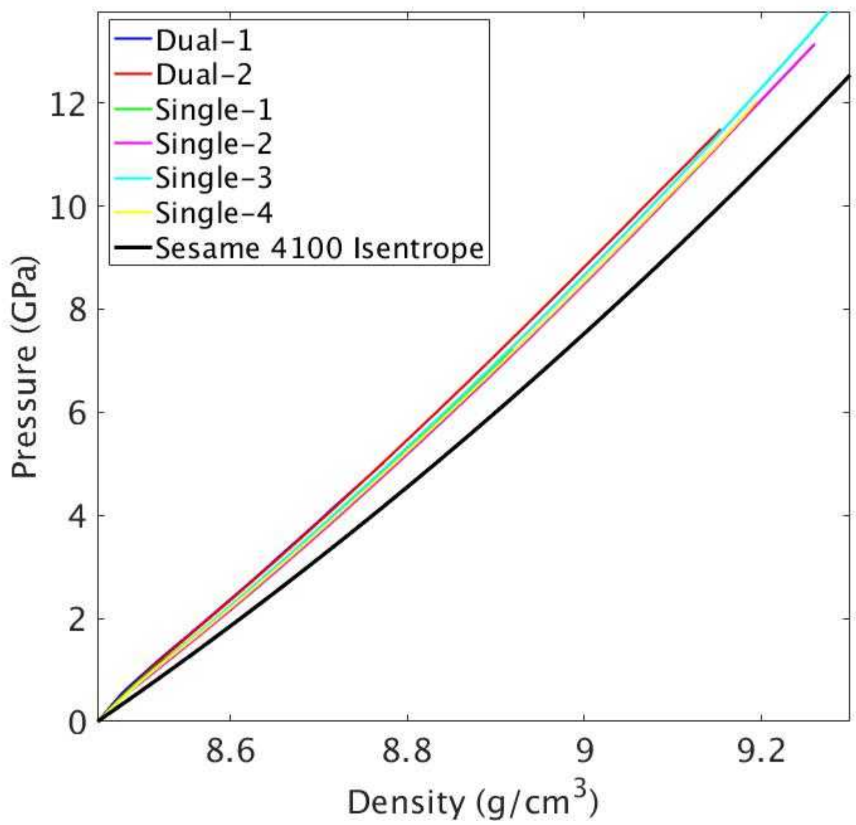




[5] P. Vinet et al. J. Phys.: Condens. Matter **1**, 1941 (1989).

Quasi-Isentropic Comparison

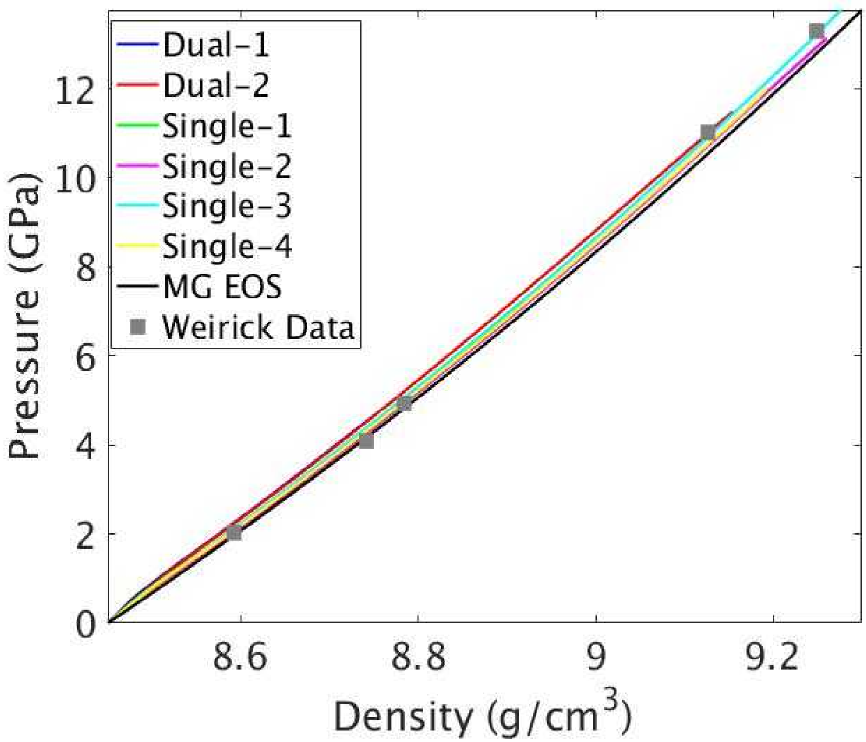
- The experimental quasi-isentropes are stiffer than Sesame 4100 isentrope
  - Sesame 4100 is an old model
  - Experimental data is all at higher pressures than these experiments
  - Relies on mixture routines at high pressures
  - Table does contain entropy or free energy



Quasi-Isentropic Comparison

Sandia National Laboratories

- Past Hugoniot data is compared to the current experiments
  - Isentrope and Hugoniot are second order tangent
- Current Mie-Gruneisen (MG) EOS [6] matches well
  - Experimental data is slightly stiffer
  - MG EOS is based on higher pressure Hugoniot data
- Gas gun experiments at low pressure by Weirick [7] agree with the experimental results



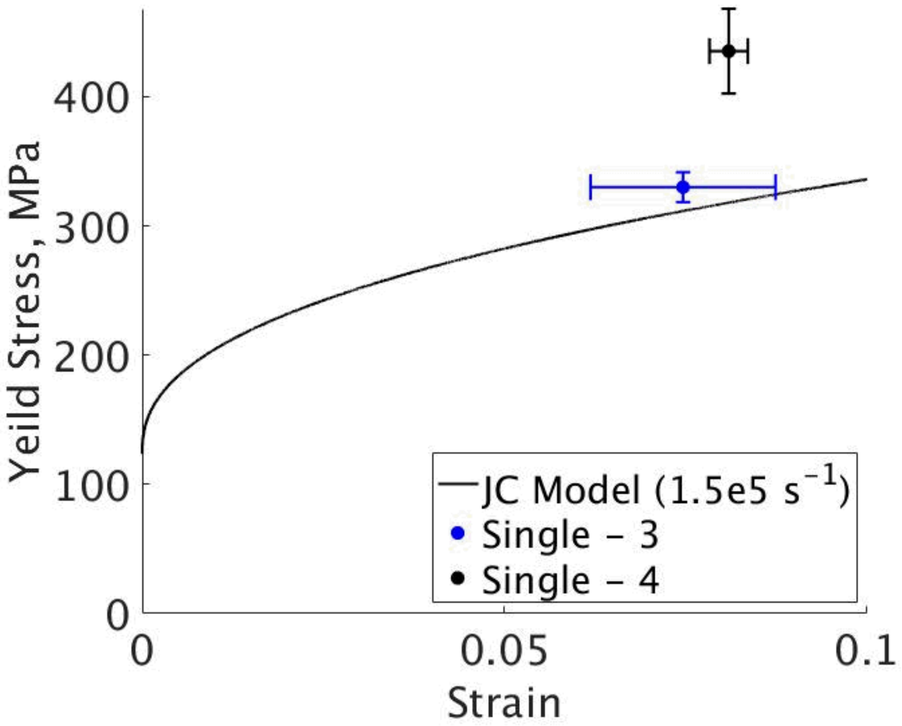
[6] S. Marsh, *LASL Shock Hugoniot Data*, U. of Cal. Press, 1980. [7] L. Weirick, Tech. Rep. SAND93-3919, SNL, 1994.

Shear Strength

- Shear strength is only determined from the single sample experiments
  - Assume symmetry about the hydrostat
    - $Y = 2\tau$
- Shear strength measurements were only obtained for 2 experiments
  - Earlier experiments did not record the release long enough
  - Single - 3 and Single - 4
  - Strain rates range from 1e5 s^{-1} to 2e5 s^{-1}
- In-house MATLAB code was used to determine the shear strength
  - Corrections were incorporated for attenuation of the signals

Shear Strength Comparison

- Coefficients for the empirical Johnson-Cook constitutive model exist for Brass [8] in many hydrocodes
  - Lead free alloy
- The shear strengths measured are slightly higher than predicted by JC model
- Error estimated from the Monte Carlo simulations



[8] G. Johnson and T. Holmquist, Tech. Rep. LA-11463-MA, LANL, 1989.

Conclusions

- The quasi-isentrope of Brass 36000 was obtained using magnetic ramp compression
  - Results obtained with both ILA and the transfer function method were in good agreement
  - The measured quasi-isentrope was in good agreement with past Hugoniot data at low pressures, but stiffer than the Sesame 4100 table
- The shear strength of 36000 Brass was obtained at high pressures for two experiments
  - The experimental yield strengths were larger than predicted by the JC model
    - Model was calibrated for a different alloy
- Future efforts will focus obtaining more shear strength measurements and a comparative study on a lead free brass alloy

Acknowledgements

- Thanks is due to members of the Dynamic Integrated Compression Experimental (DICE) facility at Sandia National Laboratories for constructing the targets and running the experiments
  - Randy Hickman
  - Nicole Cofer
  - Keith Hodge
  - Joshua Usher