SAND2018-6235C

Uncertainties in Low-Pressure Shock Experiments on Heterogeneous Materials

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SEM Annual Conference
Greenville, South Carolina
June 7, 2018

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Motivation

- model development/calibration based on experimental data
- uncertainties in experimental data affect their usefulness for this purpose
- increased need for propagating uncertainties through large-scale calculations (QMU)
- low-pressure shock regime presents additional difficulties in terms of uncertainties
- incorporate material heterogeneity in analysis

Conventional Error Analysis

- Mitchell & Nellis (JAP, 1981) laid out an approach for quantifying experimental uncertainties in high-pressure shock experiments

$$P = \rho_o U_s u_p$$

$$\frac{\delta P}{P} = \left[\left(\frac{\delta \rho_o}{\rho_o}\right) + \left(\frac{\delta U_s}{U_s}\right) + \left(\frac{\delta u_p}{u_p}\right)\right]^{1/2}$$

for symmetric impact

$$\frac{\delta P}{P} = \left[\left(\frac{\delta \rho_o}{\rho_o}\right) + \left(\frac{\delta U_s}{U_s}\right) + \left(\frac{\delta u_p}{u_p}\right)\right]^{1/2} + \left[\frac{\delta P}{P}\right]_{sys}$$

for impact by a standard

- more complicated to when analytic derivatives are not possible (can still use numerical differentiation)
- correlated uncertainties require care

Monte Carlo Impedance Matching

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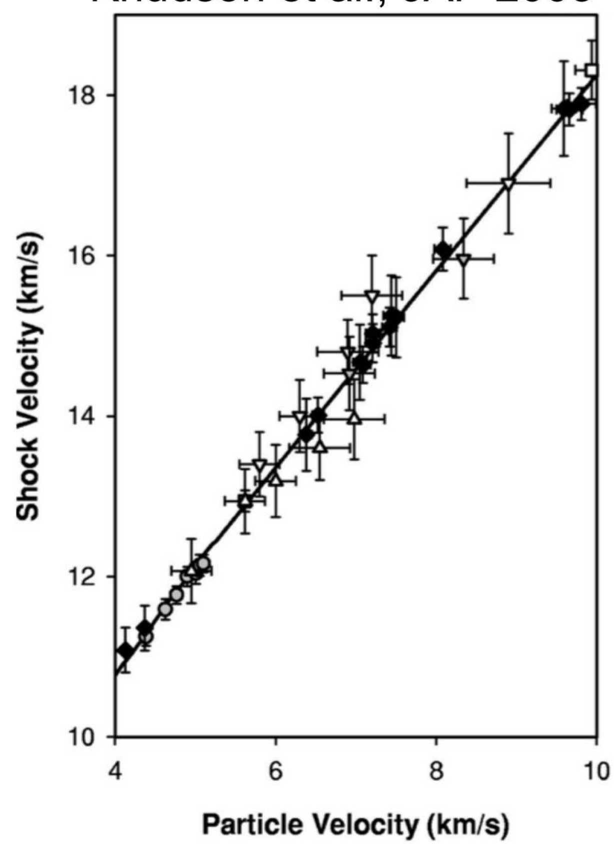
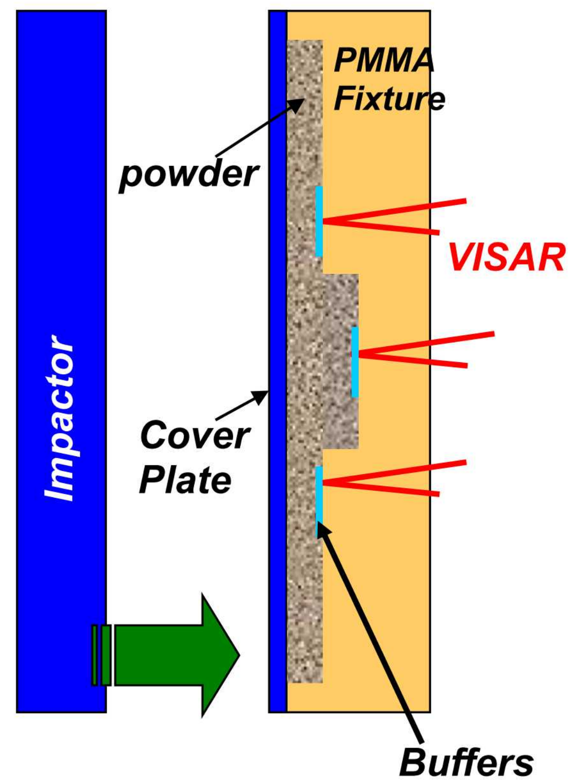
- Knudson, Root, Dolan and others have developed the MCIM approach for high-pressure Z experiments
- analysis performed many times with each experimental measurement (e.g. sample thickness) chosen from a distribution
- behavior of the standard (Al, quartz) $U_s = c_o + s u_p$ parameterized using sampling of original experimental data (variance and covariance)
- adds flexibility to account for all measurements of the experiment and their uncertainties

Knudson et al., JAP 2003



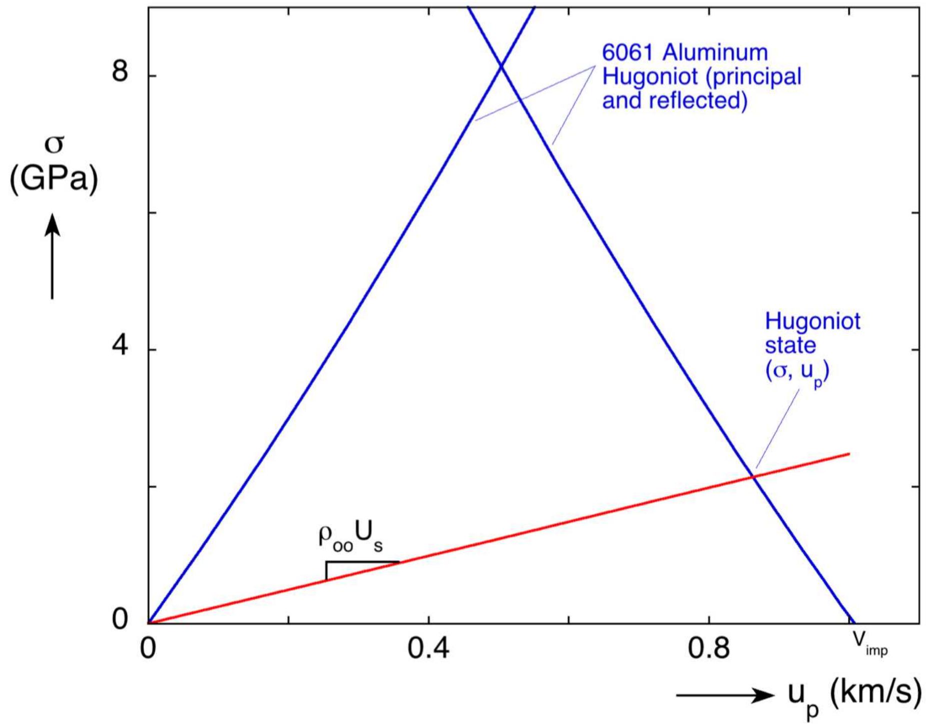
Error Analysis for Compaction Experiments for Heterogeneous Materials

- quantify random uncertainties; reduce if possible
- identify and reduce/eliminate systematic uncertainties
- utilize Monte Carlo Approach → forward propagation of uncertainties for many realizations:



- brute force approach: large number of experiments for a few cases. Is scatter consistent with estimated error bars?

Shock Analysis of Experiments



Measured quantities:

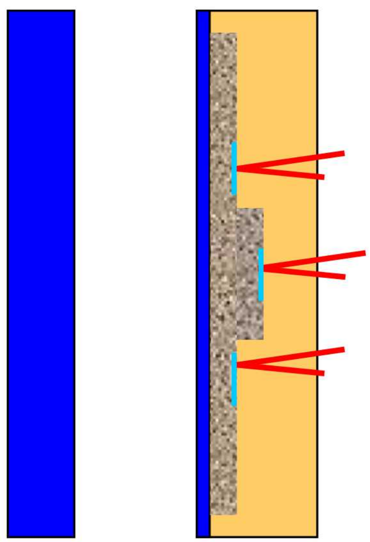
- flyer velocity (V_{imp})
- sample volume } ρ_{oo}
- sample mass } ρ_{oo}
- sample thicknesses (x_i)
- shock arrival times (t_i)

Known Quantities

- shock response of Al

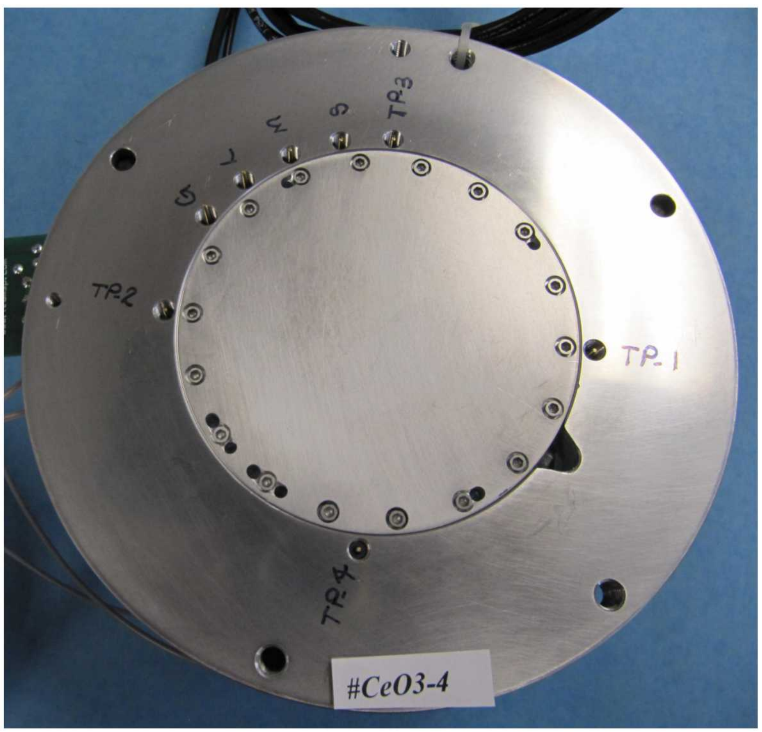
Other Uncertainties

- ~~flyer bowing~~
- tilt corrections
- non-step velocity history
- release response of Al (strength)
- sample heterogeneity



Tilt Corrections

- tilt is measured through four pins around target
- each arrival time is shifted by Δt_i , assumed due to rigid rotation of impactor (ignore bowing since thick)

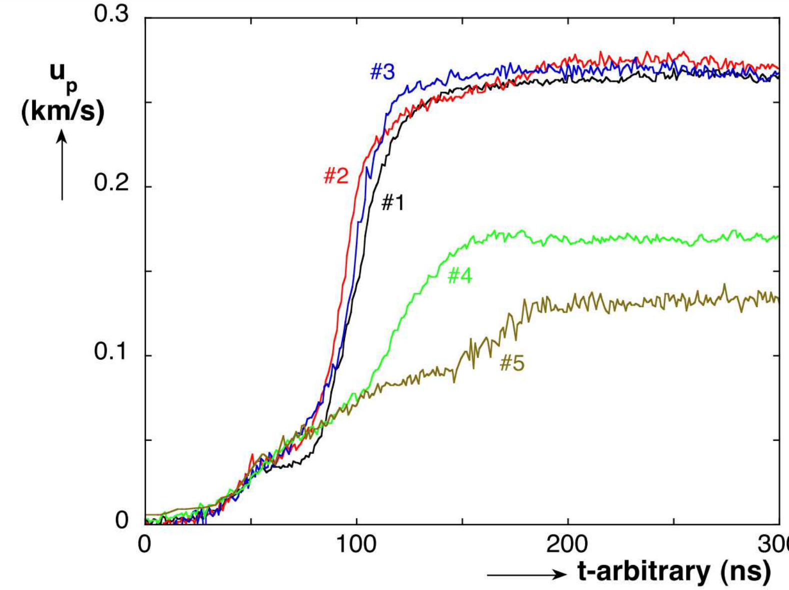


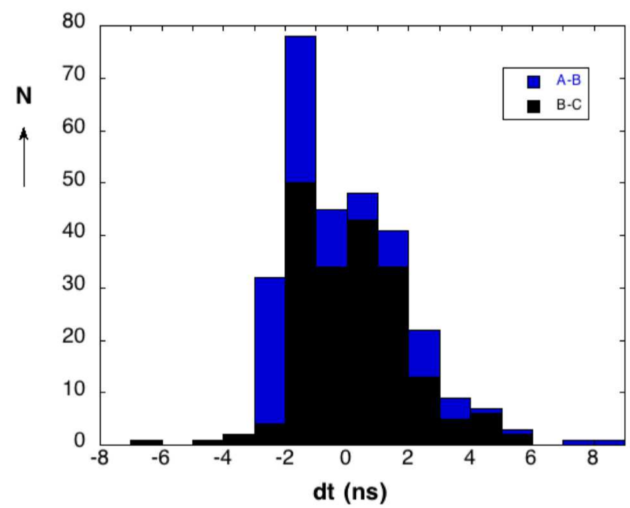
- fit plane to four pin times in (x,y,t) space
- residuals are estimate of uncertainty in tilt correction (δt_{tilt})
- δt_{tilt} typically a few ns but problematic if one pin is lost

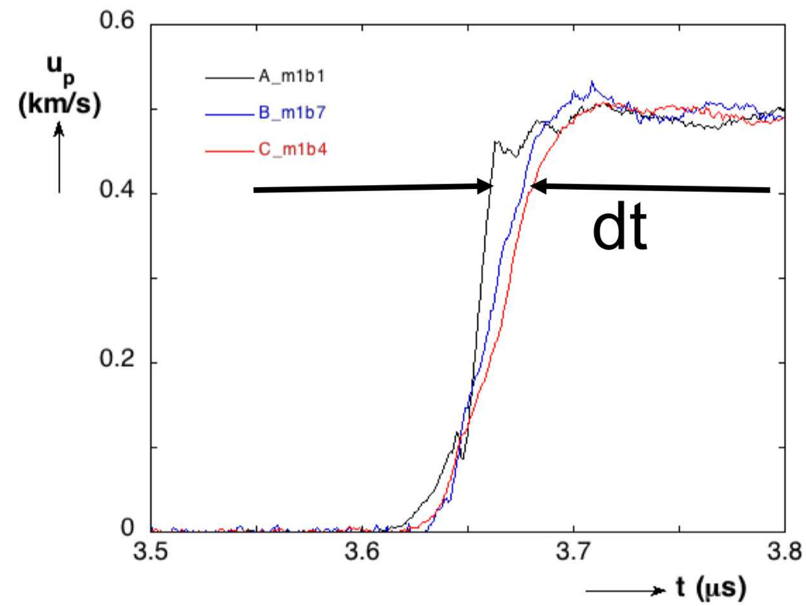
Uncertainties Caused by Non-Step Velocity Jump

Velocity histories for different positions can agree very well or poorly. How to incorporate that into the uncertainties?

- compare velocity histories from 10-90% of peak
- take uncertainty due to shape (δt_{shape}) as standard deviation of dt values

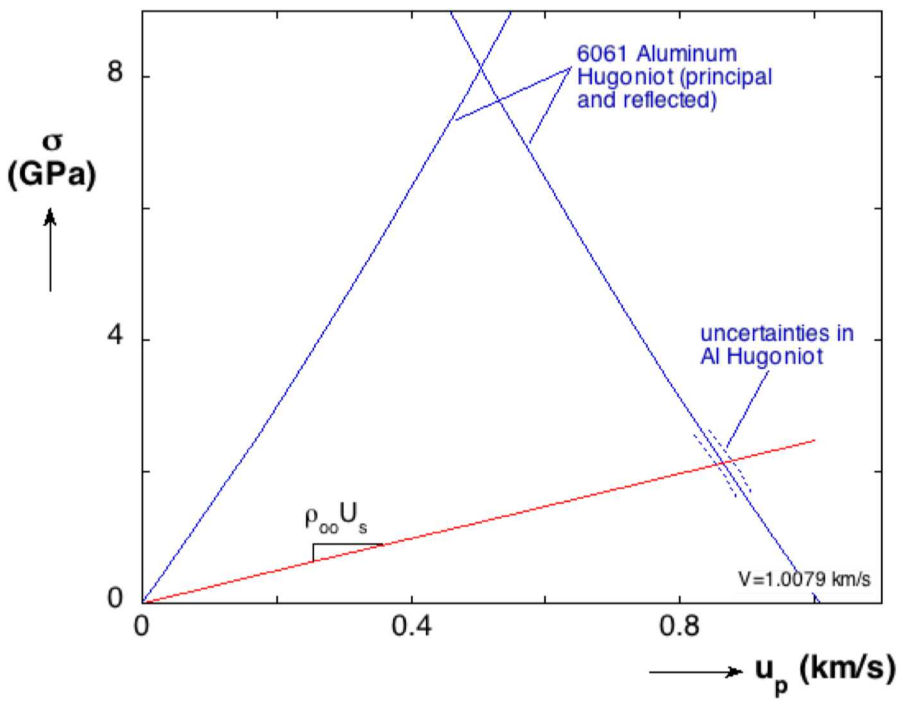


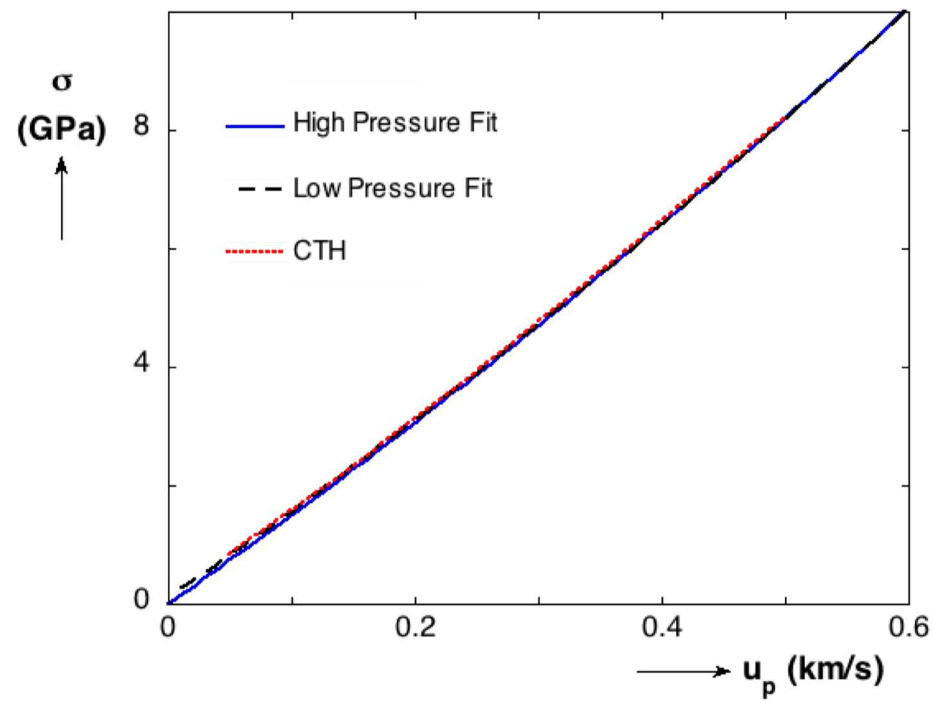




Shock Hugoniot of Al

Response of Al for impedance matching incorporates uncertainties in c_o and s values (variance and co-variance) from high-pressure experiments. High and low pressure fits agree well.

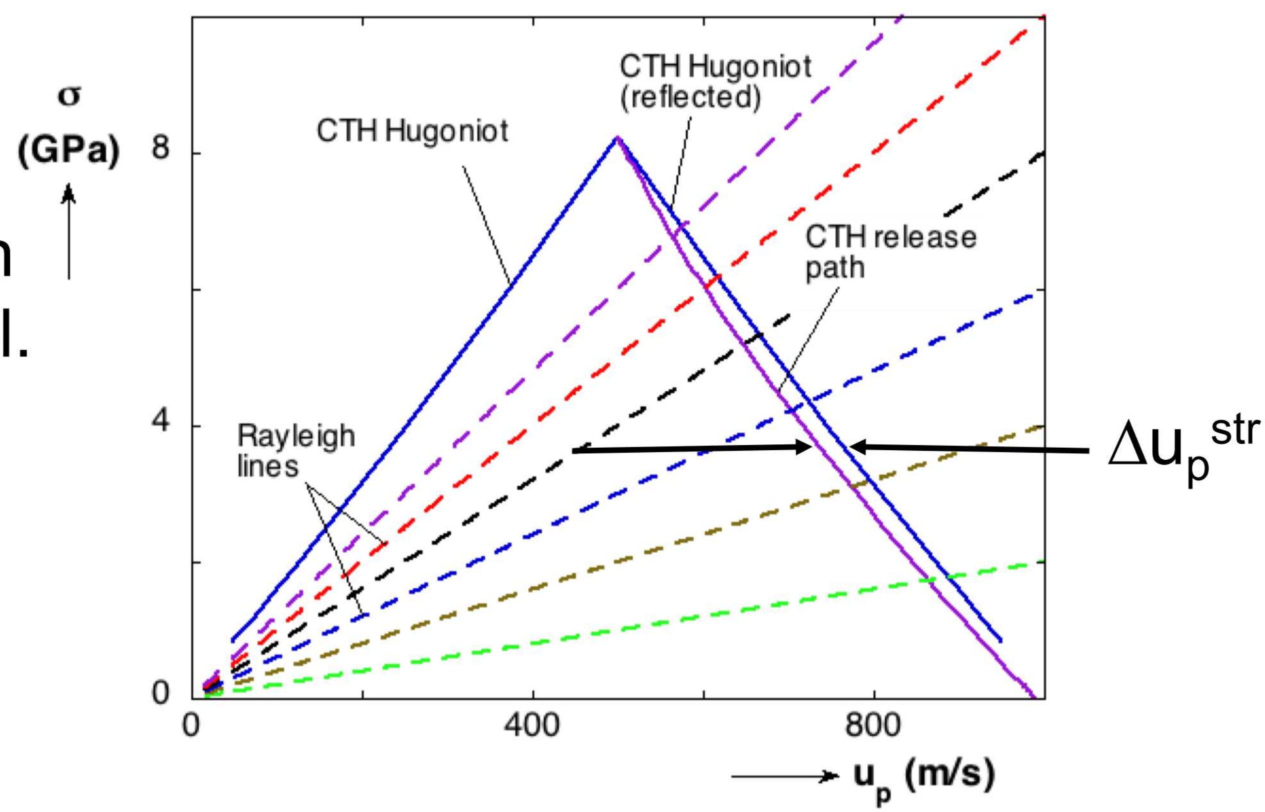




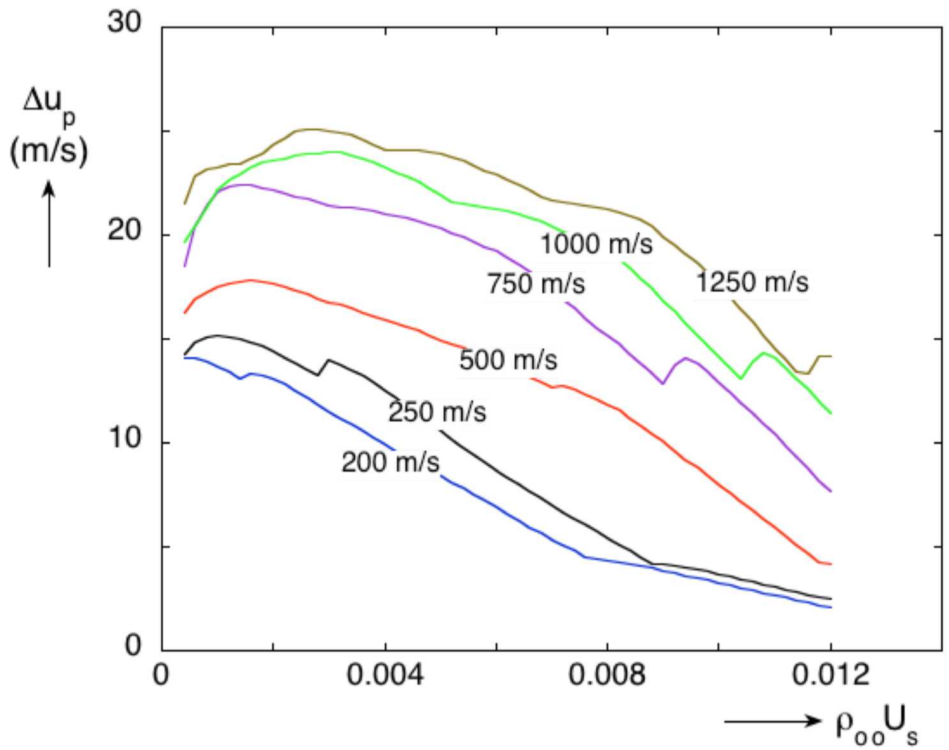
Al Release with Strength (1)

- use CTH simulations to determine difference in Al release path with and without strength
- tabulate correction to particle velocity (Δu_p^{str}) as a function of the Rayleigh line slope and impact velocity.
- subtract from u_p with an uncertainty $\Delta u_p^{str}(1+\delta)$

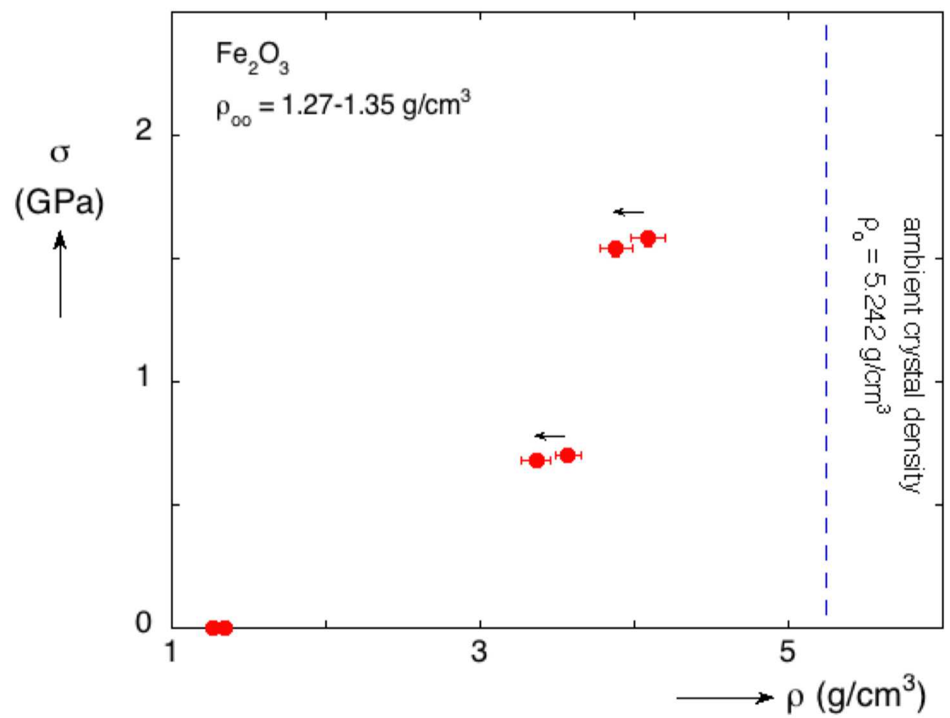
Calculation has been done with S-G model. Need to repeat it for other strength models.



Al Release with Strength (2)

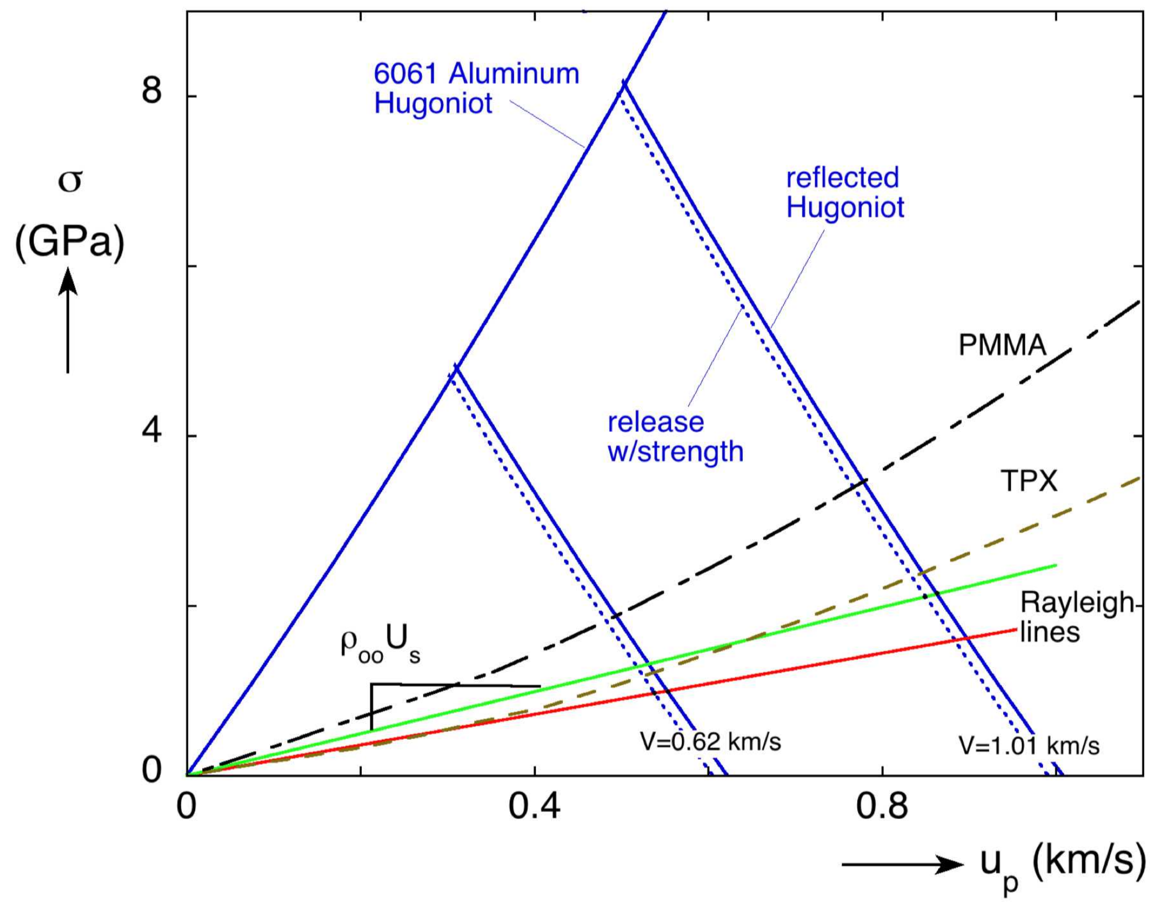


- interpolate on surface for correction
- Al strength correction increases with V



- modest systematic error corrected
- can verify by using other driver (LANL uses Cu), especially if elastic (ZrO2)

Plan to Characterize Al Release Path

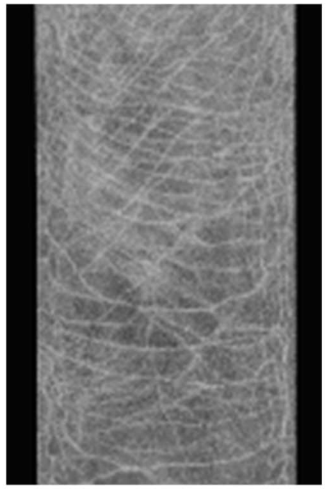


- measure release into PMMA, TPX, free surface for comparison with calculated values
- integrate release path by impacting Al directly

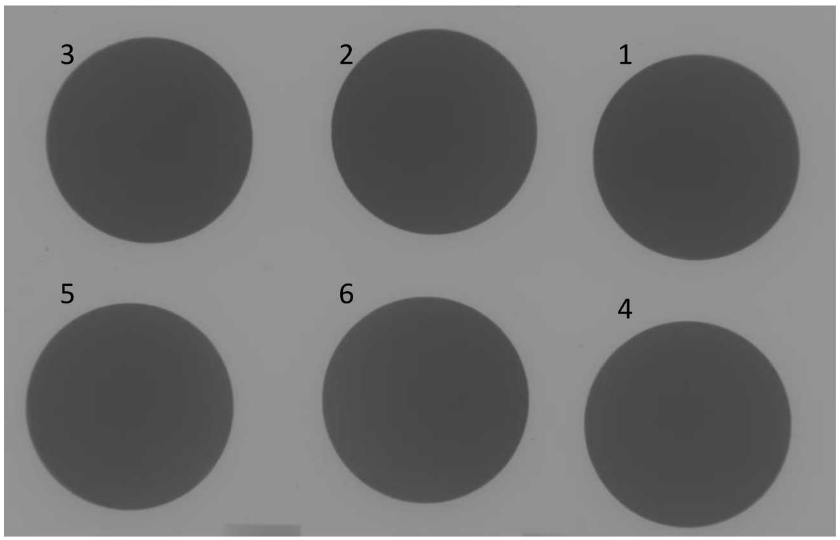
- ring-down by impact onto thin sapphire target
- will these be sufficient to constrain release path?

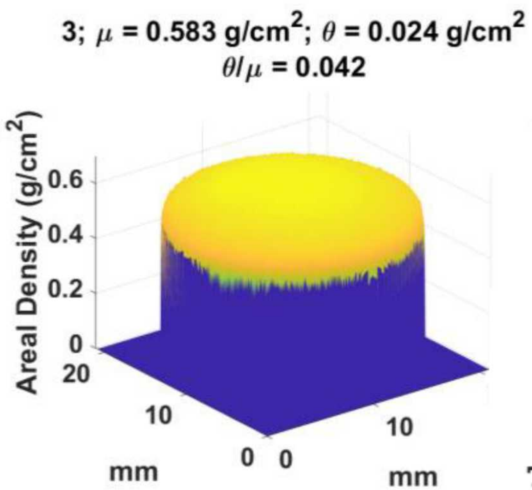
Sample Heterogeneity

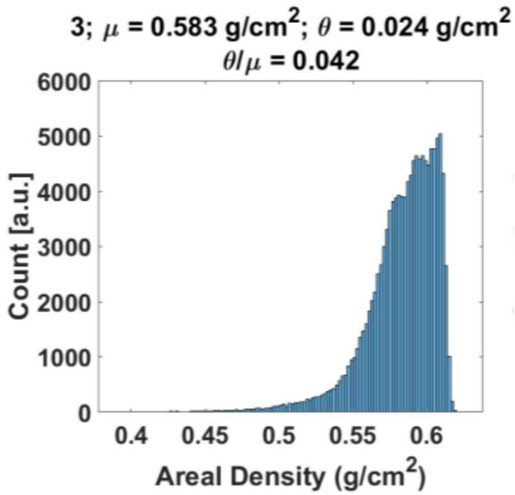
SiC, 800 grit



- tomography provides full picture of sample but is difficult, time-consuming, and not quantitative
- radiography more practical



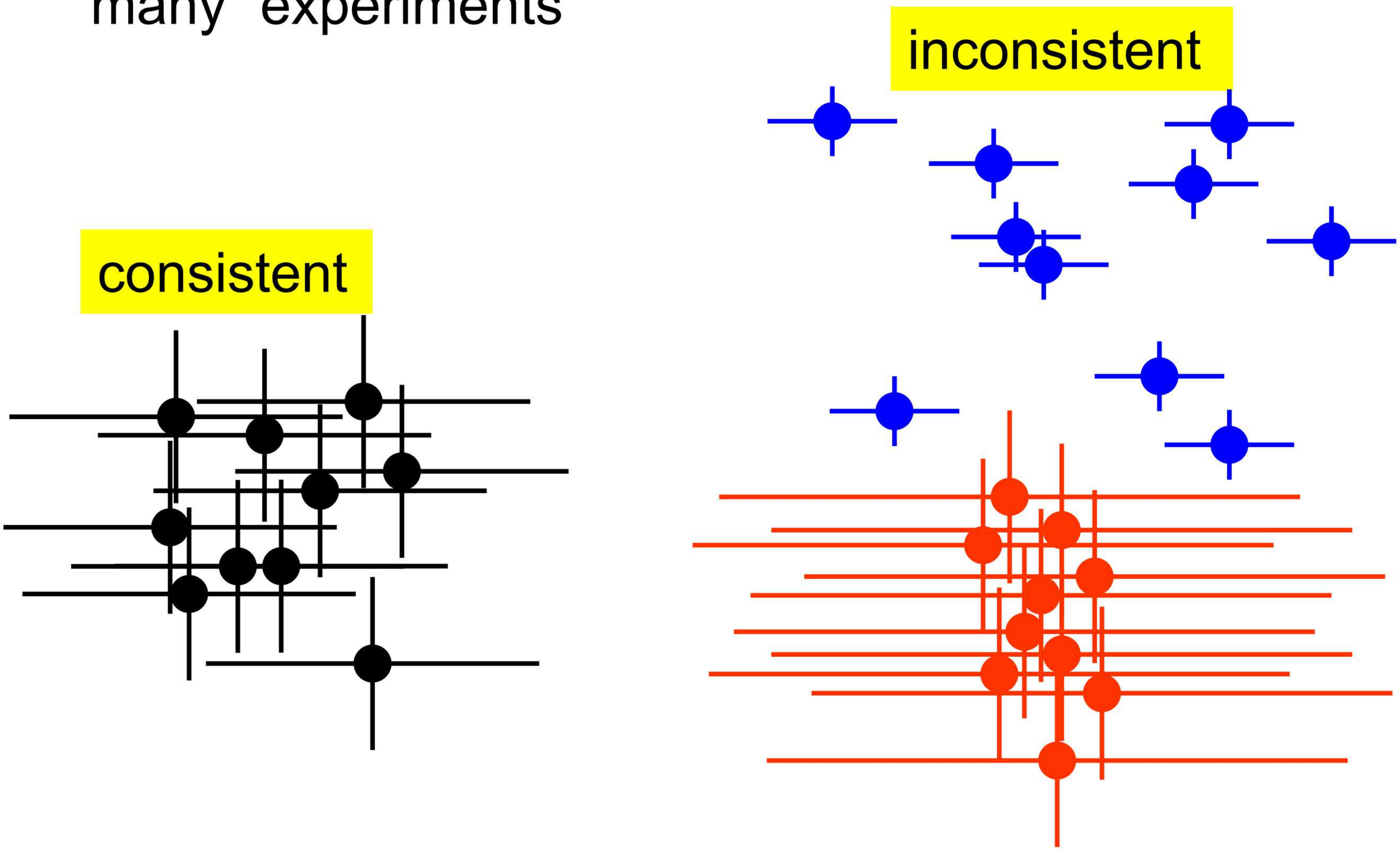




- need to remove low order variation and correct for it in experiments
- extend to loose powder capsules

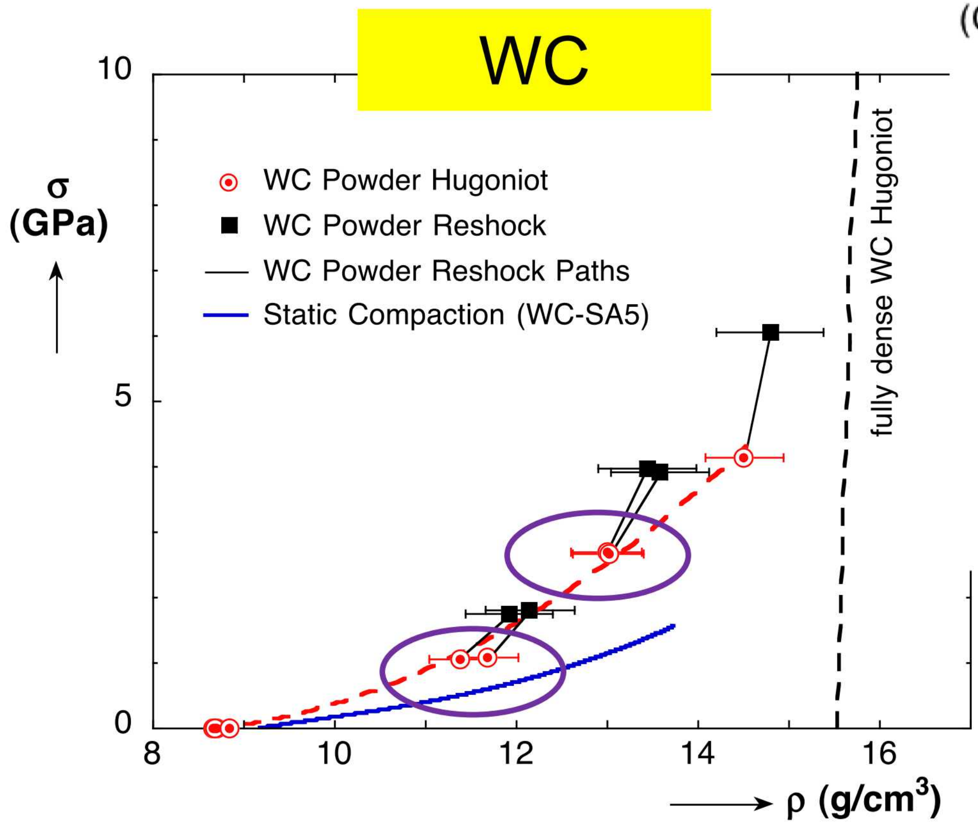
The Brute Force Approach

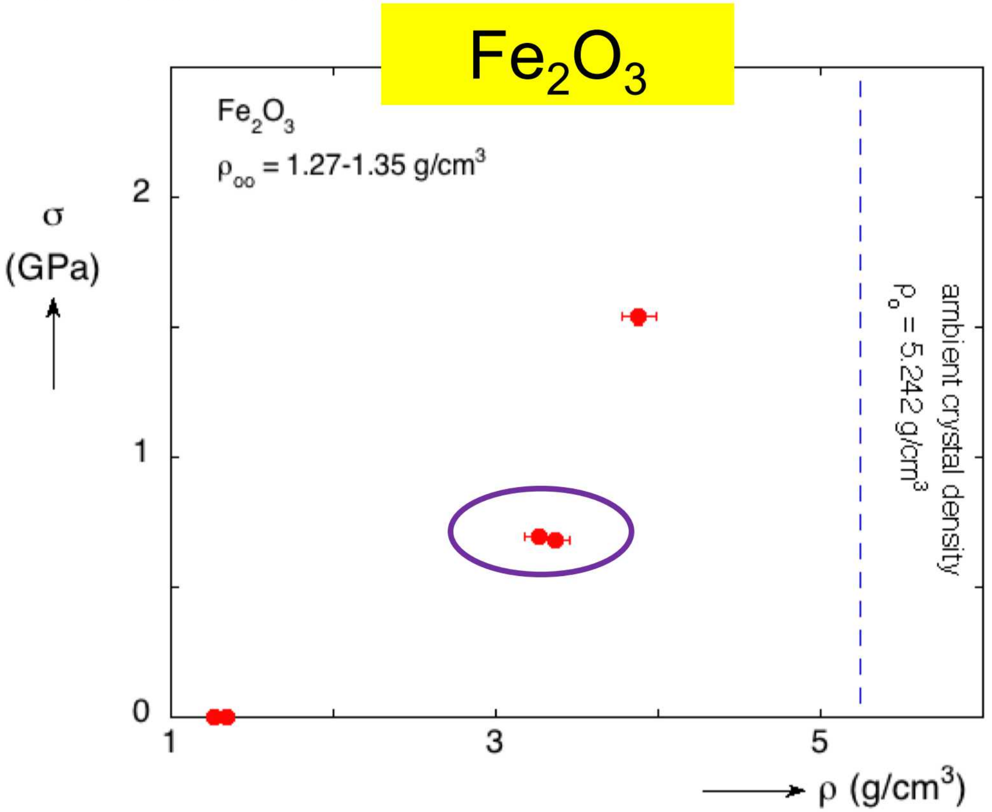
- estimates of uncertainties from an individual experiment should be consistent with scatter from ”many” experiments



The Brute Force Approach (2)

- no such large data set in this regime for this class of materials, but what data we have is consistent





- consistency of large data set will not preclude systematic error

Conclusions

- low-pressure experiments present additional difficulties for estimating uncertainties (strength of standard, finite rise time of wave)
- sample heterogeneity can play important role – external characterization crucial; may need to X-ray every sample or at least representative ones
- Monte Carlo approach extended to low-pressure regime to evaluate uncertainties
- brute force approach can allow random uncertainties to be evaluated