LA-UR- 12-01718

Approved for public release; distribution is unlimited.

Title: Ultra-high-speed imaging for explosive-driven shocks in transparent media

Author(s): Michael Murphy
Steven Clarke

Intended for: Presentation at SEM XII International Congress & Exposition on Experimental and Applied Mechanics, June 11-14, 2012, Costa Mesa, CA

Los Alamos NATIONAL LABORATORY
EST. 1943

SEM XII International Congress & Exposition on Experimental & Applied Mechanics, June 11-June 14, 2012, Costa Mesa, CA
Session 069 Shock/Blast Loading of Materials III

Ultra-high-speed imaging for explosive-driven shocks in transparent media

Michael Murphy
Steven Clarke

W-6 Detonator Technology
Los Alamos National Laboratory

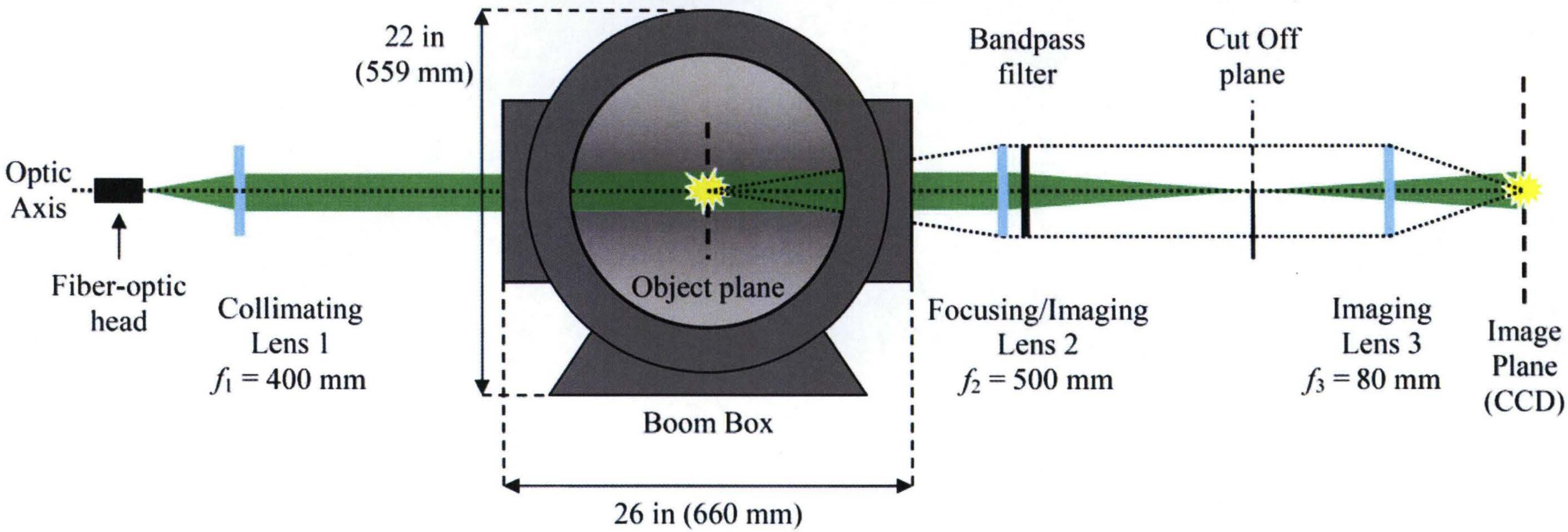
Abstract

Development of the shock wave image framing technique (SWIFT) is presented. Novel applications, data-reduction procedures, and pseudo-aquarium applications are discussed.

Outline

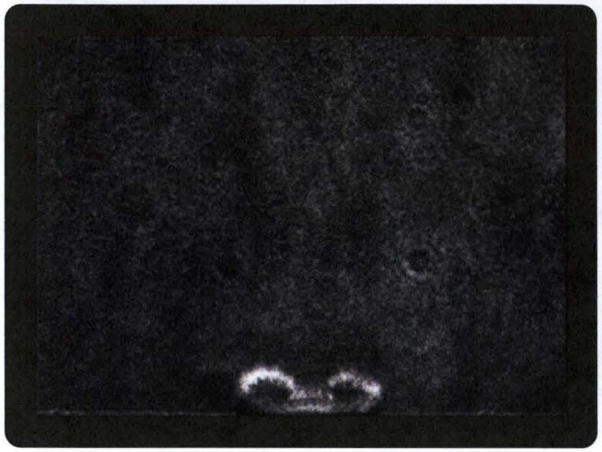
- Shock wave image framing technique (SWIFT) – Experimental setup
- Novel applications – Why do we care?
- Reduction procedures for quantitative results – Comparisons to other data
- Pseudo-aquarium experiments
- Summary and ongoing efforts

Shock Wave Image Framing Technique (SWIFT)



- Inline lens-based imaging system for schlieren, shadowgraph, or backlight recording of explosive events
- SIMD (Specialised Imaging) ultra-high-speed framing camera for high-quality image recording
- Reveal 5 (Spectra-Physics) 5-Watt CW laser with spoiled coherence @ 532 nm for backlighting
- Precise optical band-pass filter (1.0 +/- 0.2 nm) centered on 532 nm for explosive luminance attenuation
- Infinity-corrected imaging train for rapid magnification changes in a robust configuration employing high-quality Nikon lenses and corresponding F-mount architecture

Novel SWIFT applications – Initiators

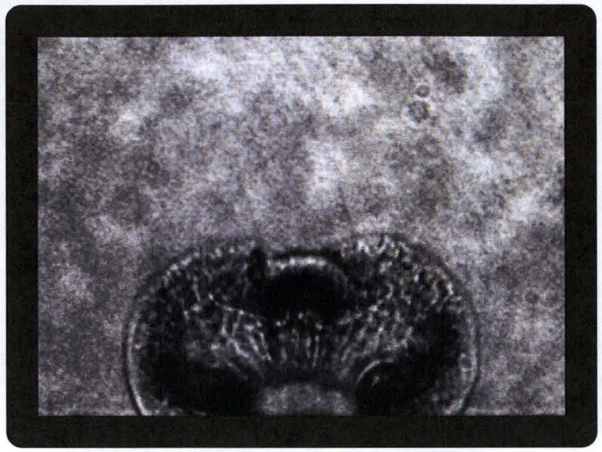


20 ns inter-framing

Chip slapper initiator

Schlieren imaging

Supersonic expansion visualized

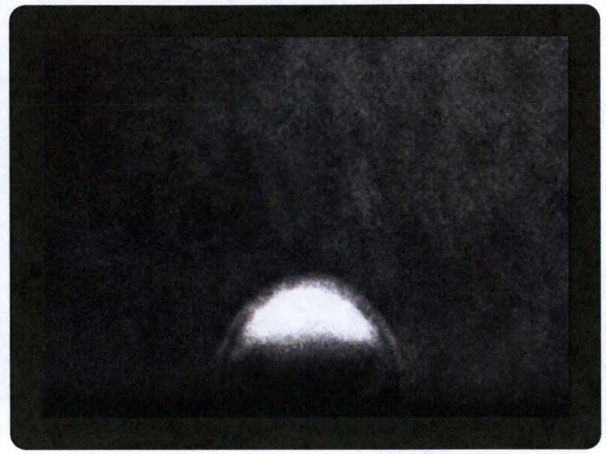


20 ns inter-framing

Chip slapper initiator

Backlight imaging

Impact flyer visualized



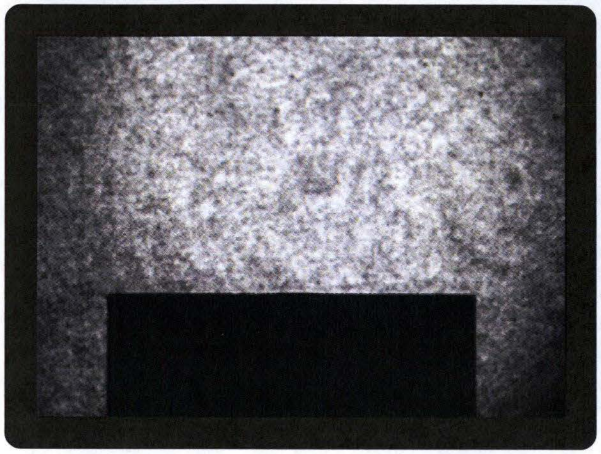
50 ns inter-framing

Direct optical initiator

Schlieren imaging

Leading shock wave visualized

Novel SWIFT applications – Detonators and high explosives

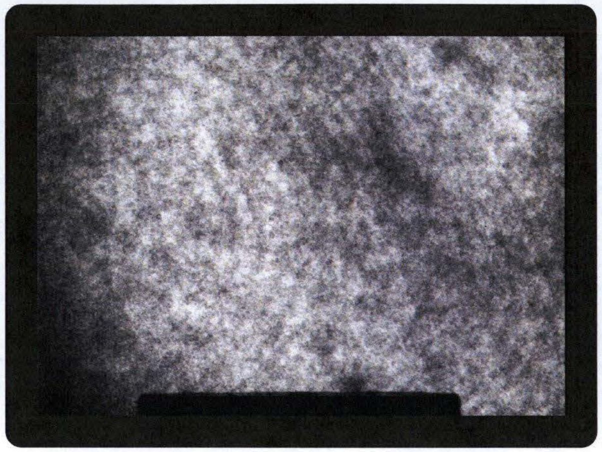


105 ns inter-framing

Detonator (into PMMA)

Backlight imaging

Leading shock wave visualized

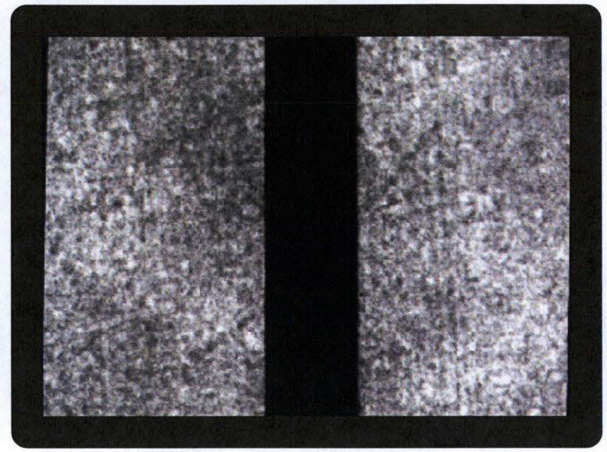


135 ns inter-framing

Detonator (into air)

Backlight imaging

Explosively-driven metal layer and onset of detached shock wave visualized



280 ns inter-framing

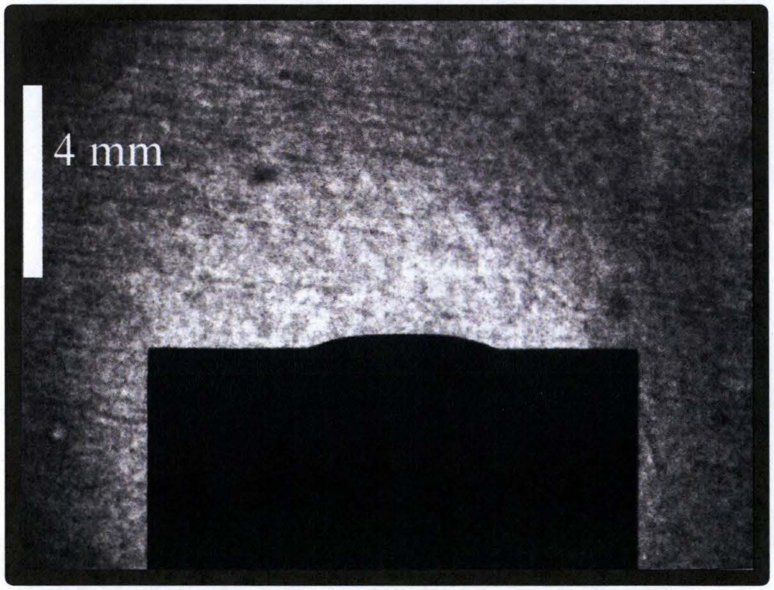
HE column (in PMMA)

Backlight imaging

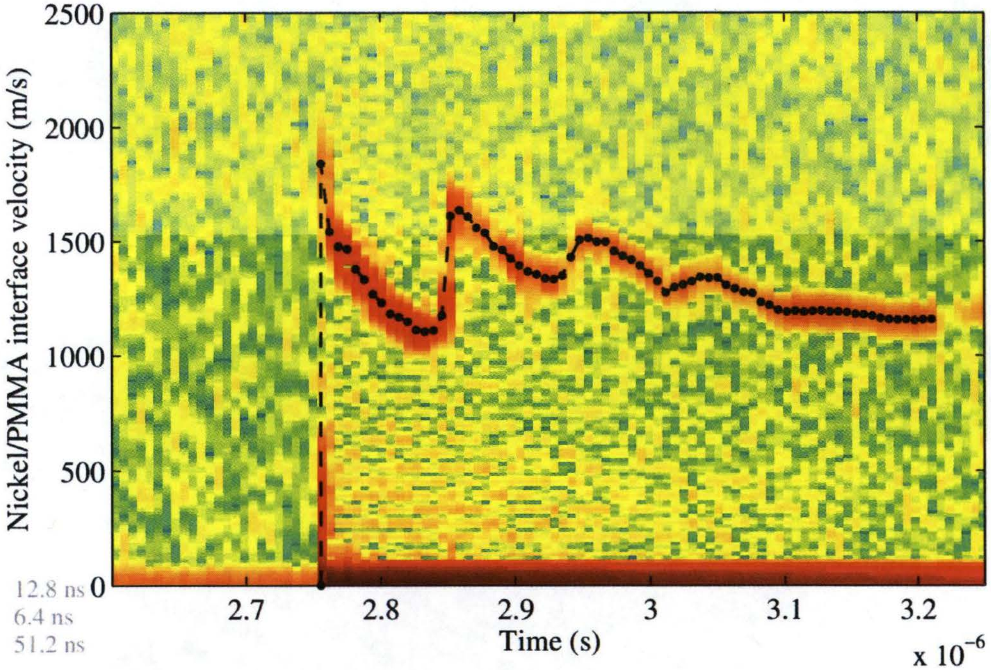
Detonation-interaction shock waves visualized

Quantitative data reduction – Detonator output into PMMA

A PDV probe (collimating) is axially aligned with the detonator center, and is viewing the nickel cup through a PMMA window placed in intimate contact with the cup. The velocity of the nickel/PMMA interface is obtained at the detonator center, which allows the interface pressure to be determined.



5 ns exposure, 75 ns inter-framing

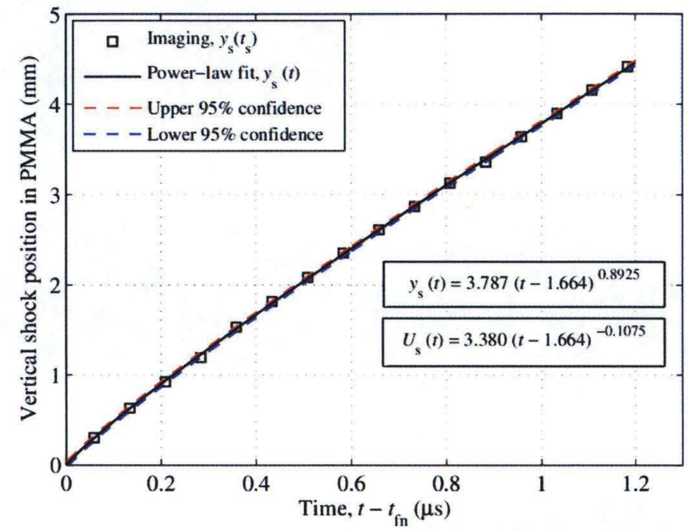


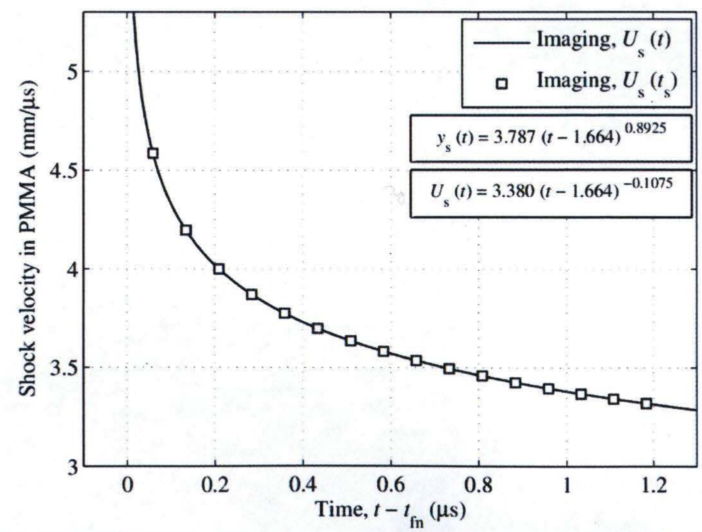
Quantitative data reduction – Centerline detonator output

Ex: Detonator output into PMMA

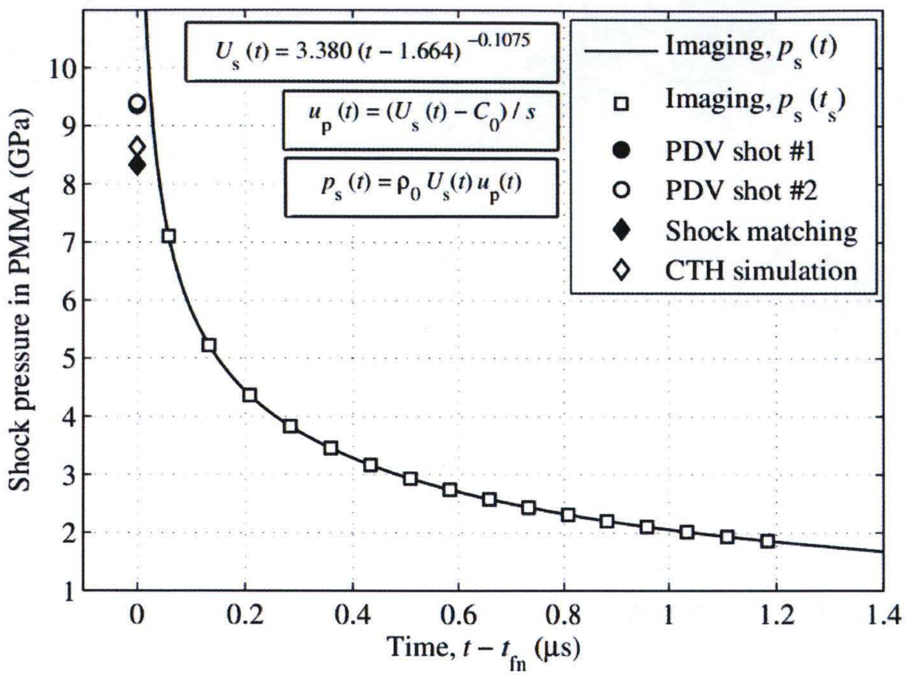
Non-linear least squares fitting is employed to determine the best-fit parameters for the model $y(t) = a\,(t-b)^c$, where y denotes vertical shock position, and b denotes detonator function time. The best-fit curve is plotted over experimental data along with 95% confidence bounds (top right).

Shock velocity $U(t) \equiv \mathrm{d}y/\mathrm{d}t$ is calculated from the empirical fit equation describing vertical shock position by taking the first derivative in time (bottom right). Fitting methods are used to obtain instantaneous velocities for Hugoniot analyses.





Quantitative data reduction – Detonator output into PMMA

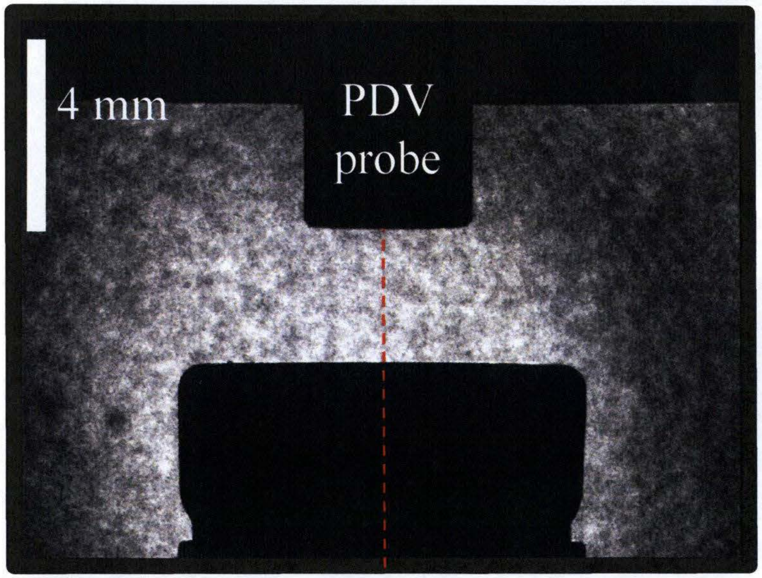


Interface variables	*Shock matching (calculation)	Numerical Simulation (CTH)	Experiment (PDV)
u_{int} (mm/us)	1.458	1.38	1.577 1.583
P_{int} (GPA)	8.33	8.64	9.35 9.40
*CTH results suggest the shock strength in Ni decays by 8% over the 241 um cup thickness			

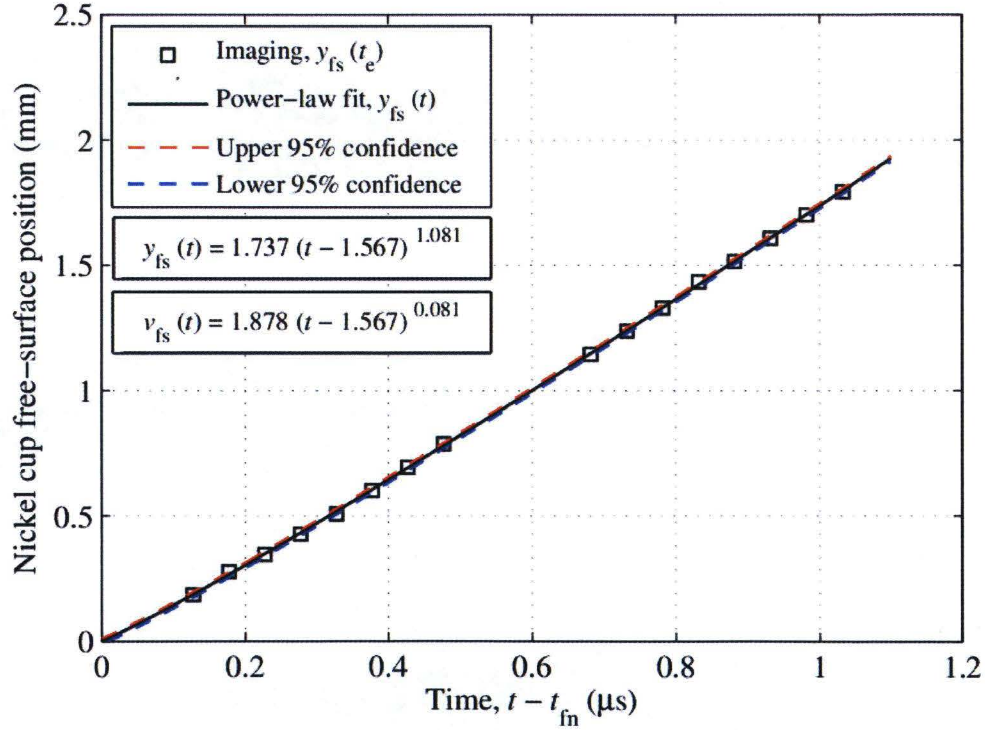
Using the known shock Hugoniot for PMMA, the calculated equation for shock velocity is mapped to shock pressure (top left). Overall agreement between imaging experiments, PDV experiments, and calculations is good; however, the asymptotic behavior of the power-law fit limits the accuracy of the reduced imaging data at very short times. Work is progressing to determine a more appropriate fit model based on shock physics.

Quantitative data reduction – Detonator output into air

A PDV probe (collimating) is axially aligned with the detonator center, and is viewing the nickel cup as it accelerates through ambient laboratory air. Measurements of the jump in free-surface velocity can be converted to the shocked state of the nickel, as well as the C-J pressure of the HE.

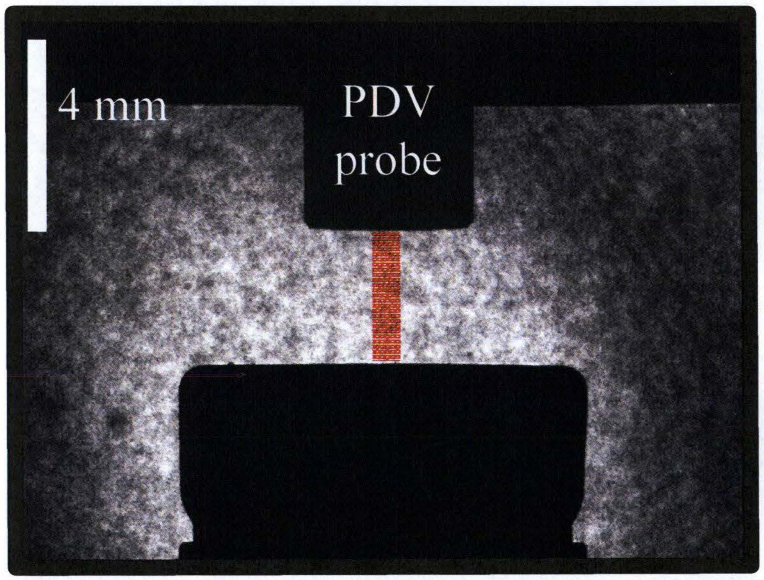


5 ns exposure, 50 ns inter-framing



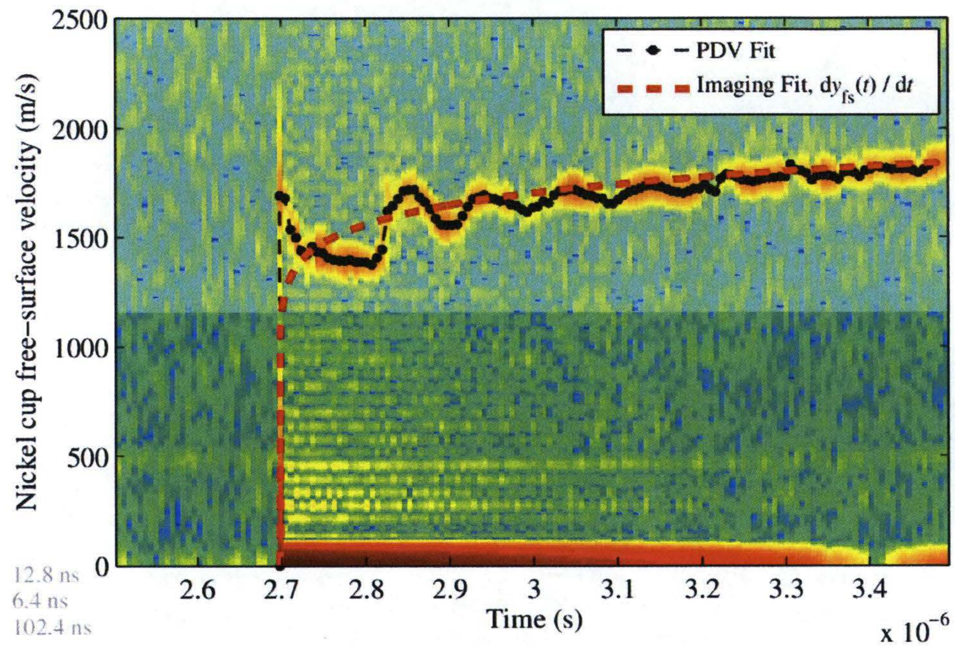
Quantitative data reduction – Detonator output into air

SWIFT



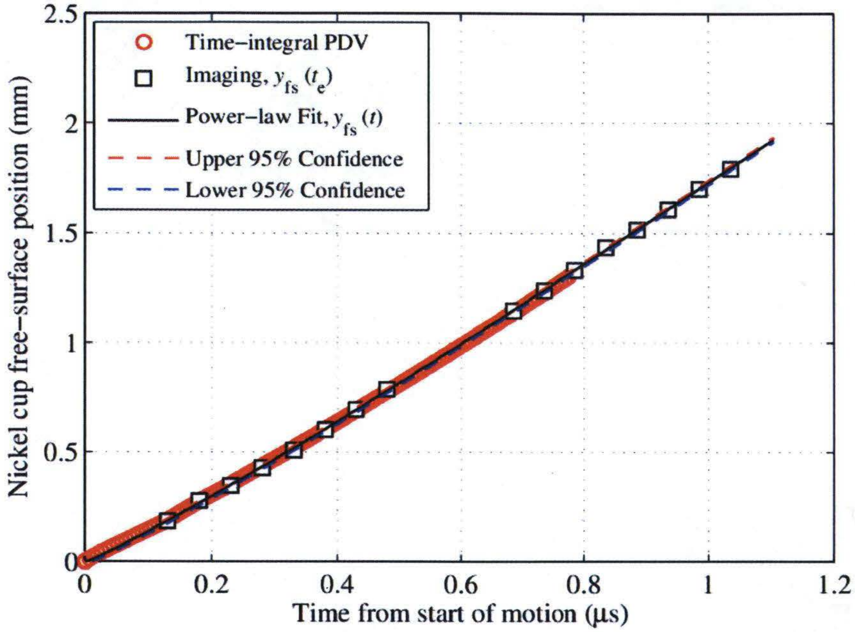
5 ns exposure, 50 ns inter-framing

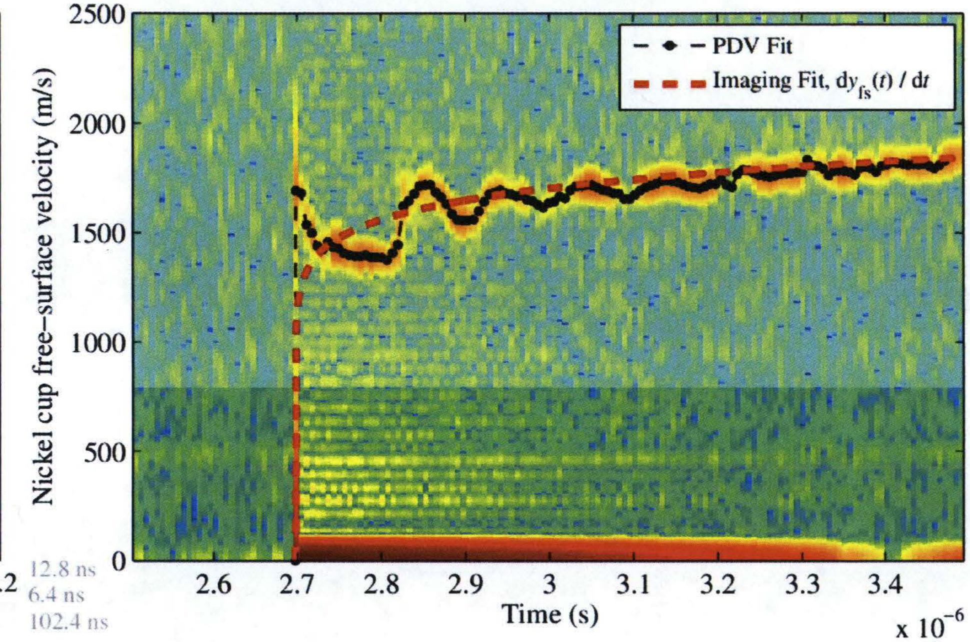
Centerline PDV



A Gaussian fitting method is employed to find the peaks of the measured velocity data for each FFT window

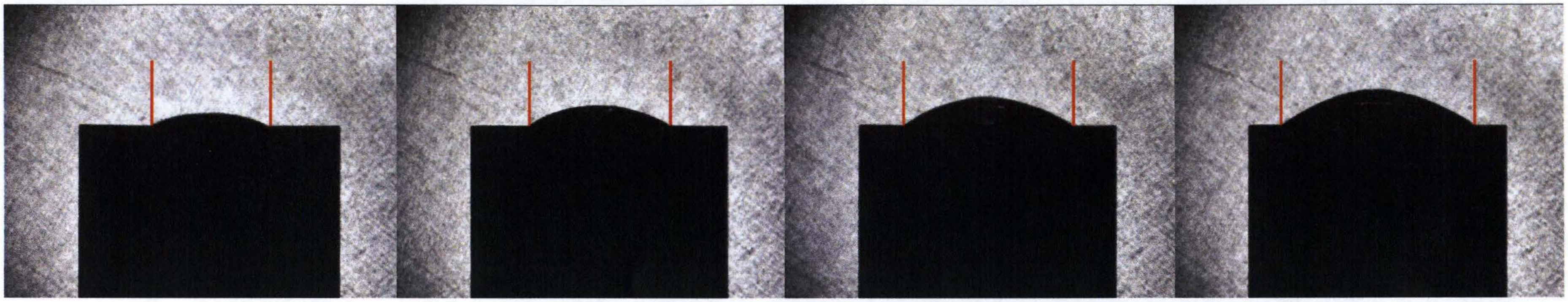
Quantitative data reduction – Detonator output into air

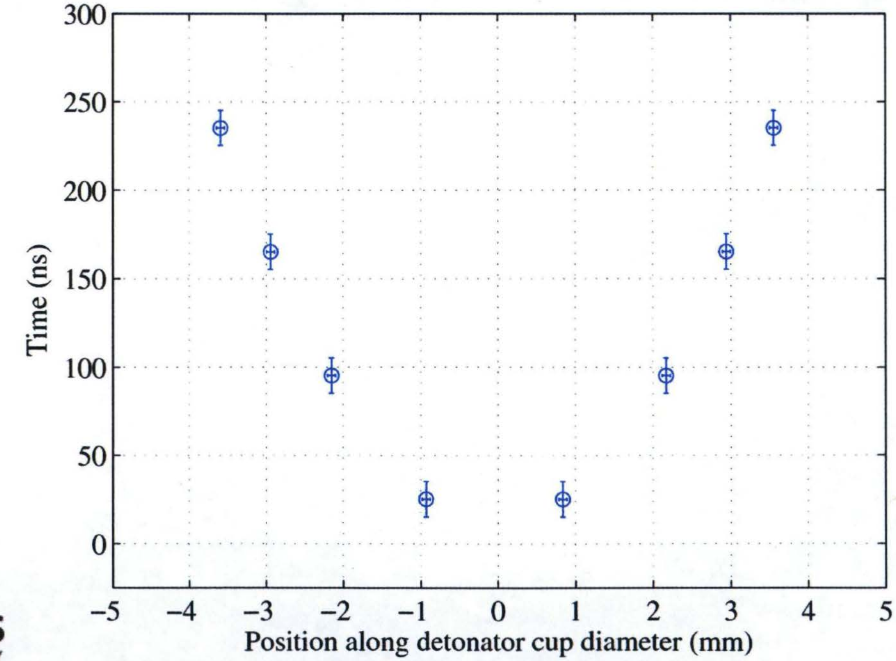




Excellent agreement is observed that supports the use of simultaneous SWIFT recording and PDV techniques to validate the reduced data resulting from each method.

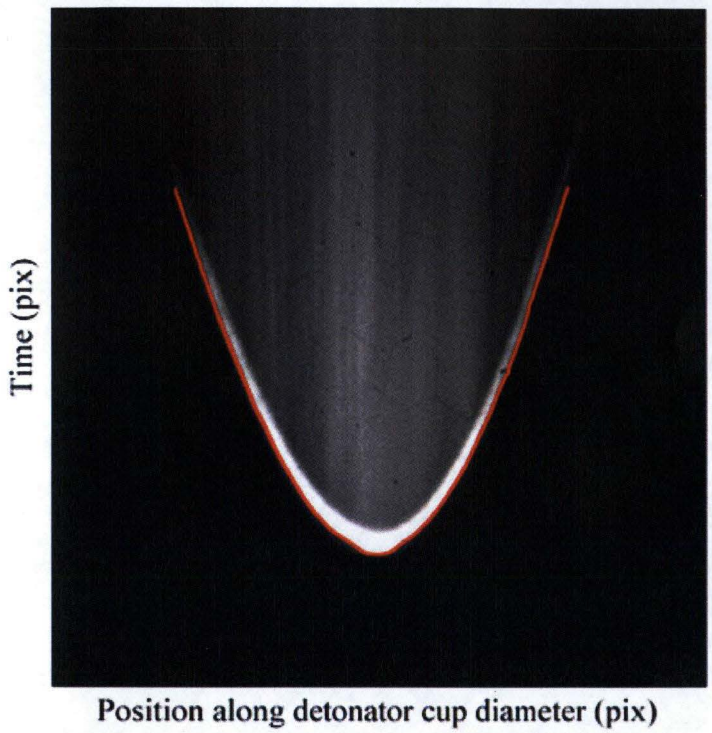
Quantitative data reduction – Detonator pseudo-streak data

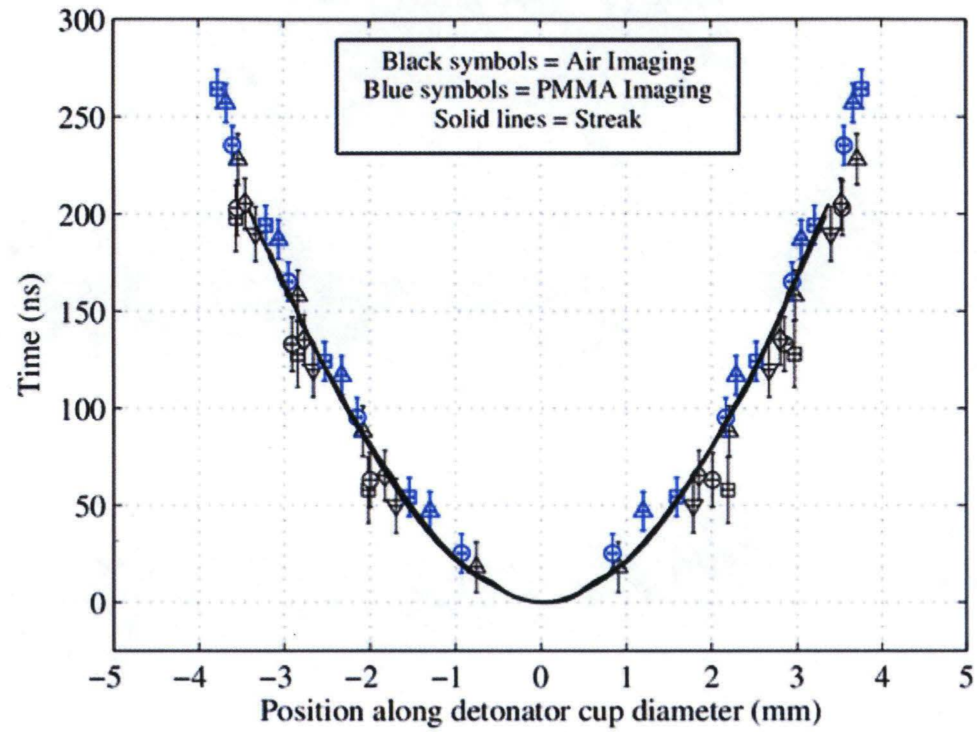




Pseudo-streak data is obtained from the image sequences by tracking the explosive breakout across the detonator surface (top). The breakout locations from each image are paired with the corresponding frame times to yield position-time data (bottom).

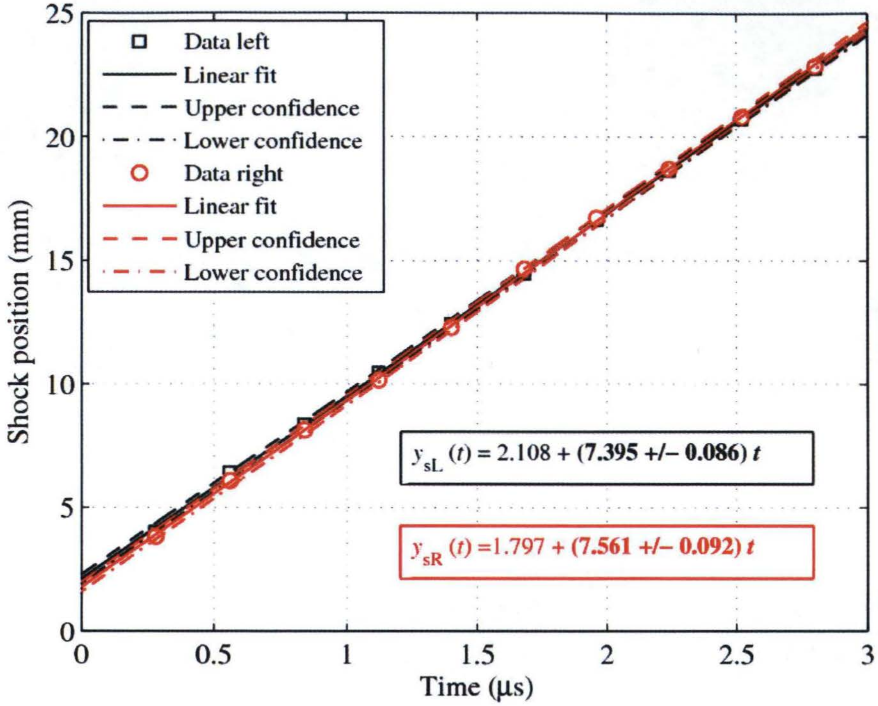
Quantitative data reduction – Detonator pseudo-streak data

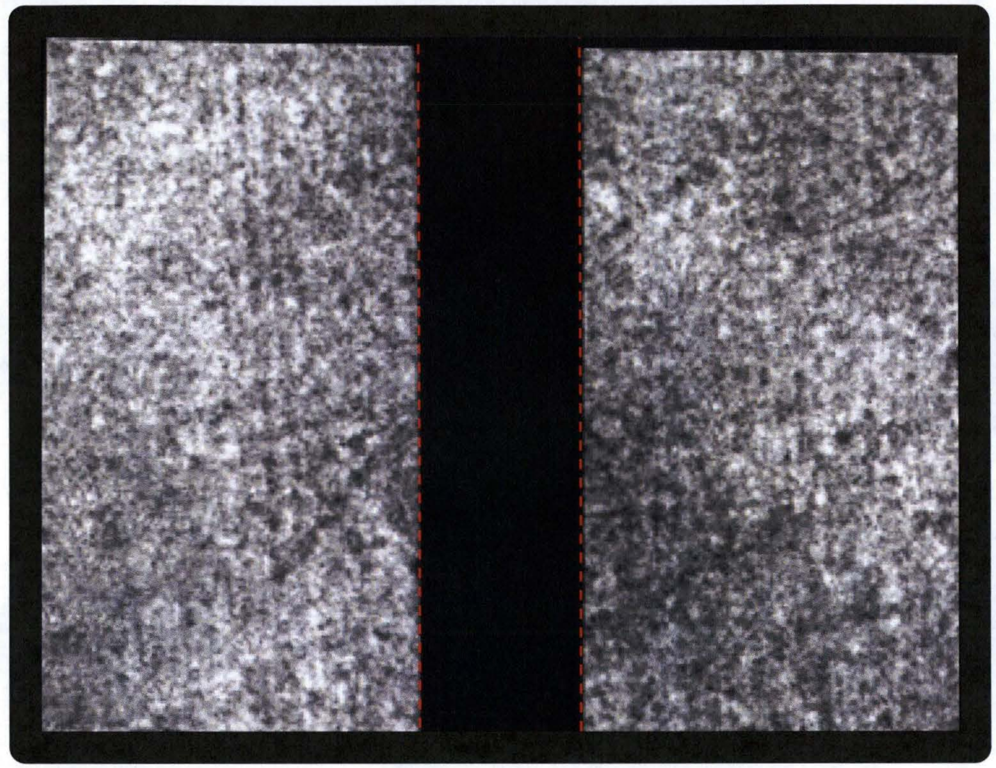




Good agreement with real streak images suggests the pseudo-streak data can be used to quickly describe detonator breakout, as well as to validate experimental streak records.

Pseudo-aquarium experiments – HE detonated within PMMA





- Feasibility test
- HE tube initiated at an angle (non-ideal test parts)
- RDX-based explosive @ 1.5 g/cm^3 encased within a polysulfone tube that is embedded within PMMA
- Extreme light-refraction at the curved shock fronts masks interior flow features

Pseudo-aquarium data – Traditional aquarium analysis

Under an assumption that the flow is steady, Johnson et al. (1983) employ the following fit equation for the shock-front geometry

$$r(z) = r_0 + \tan(\theta_{\min})\left[z + \frac{1}{a}\left(\frac{\tan(\theta_{\max})}{\tan(\theta_{\min})} - 1\right)\left(1 - e^{-az}\right)\right]$$

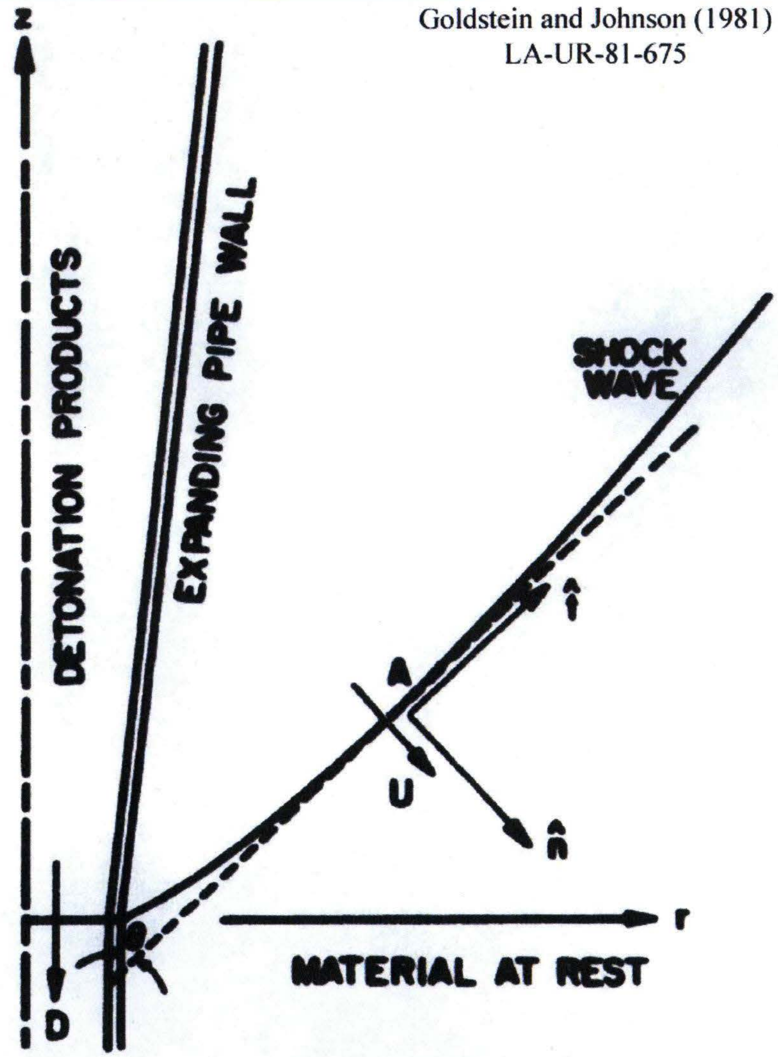
$$\frac{\mathrm{d}r(z)}{\mathrm{d}z} \equiv \tan(\theta) = \tan(\theta_{\min})\left[1 + \left(\frac{\tan(\theta_{\max})}{\tan(\theta_{\min})} - 1\right)e^{-az}\right]$$

$$\theta(z) = -\tan^{-1}\left[-\tan(\theta_{\min}) - \tan(\theta_{\max})e^{-az} + \tan(\theta_{\min})e^{-az}\right]$$

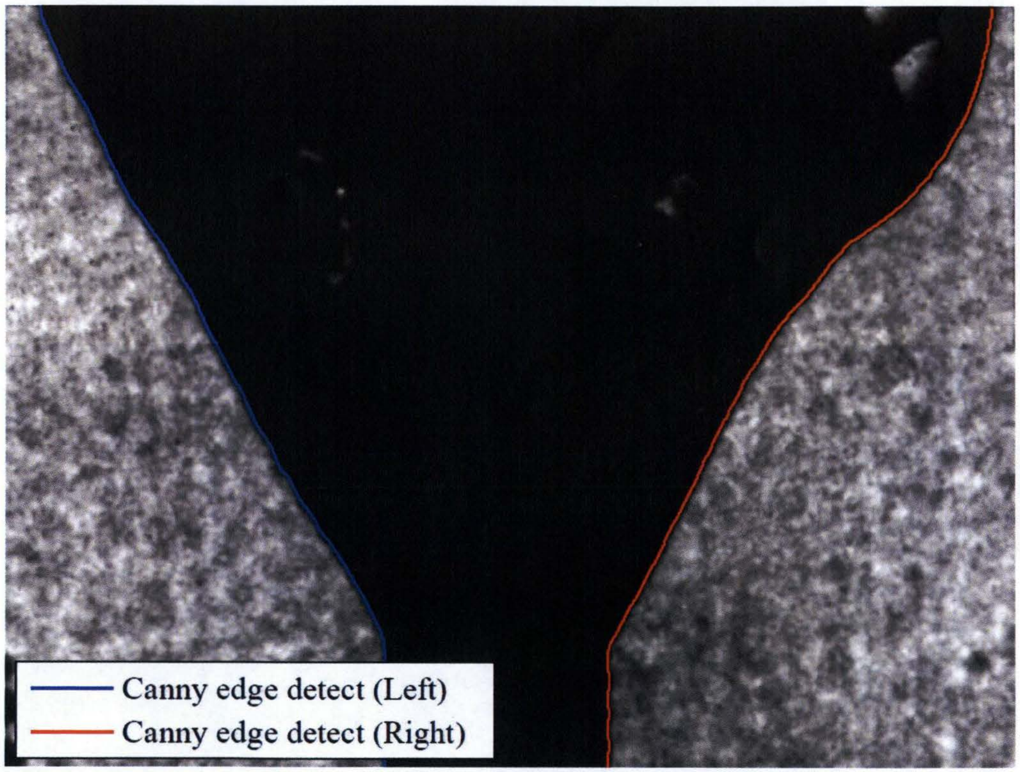
$$p_s(\theta) = \frac{\rho_0}{s}\left[D\sin(\theta) - C_0\right]D\sin(\theta)$$

The interface pressure is calculated as $p_{s,\max} \equiv p_s(\theta_{\max})$

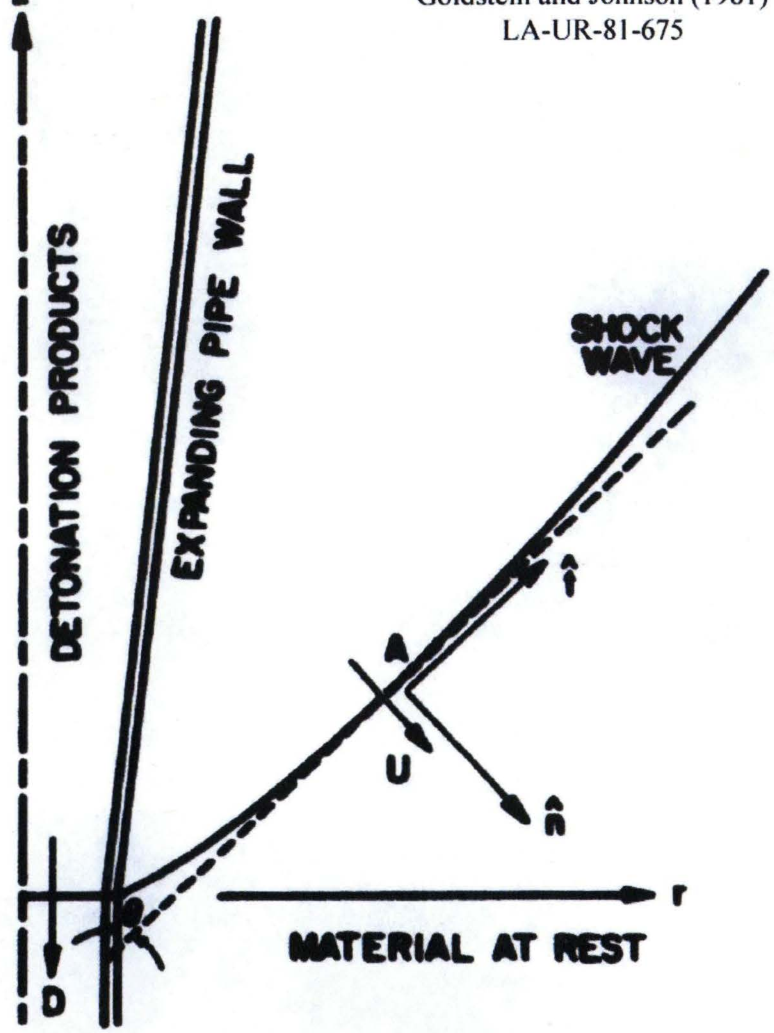
Goldstein and Johnson (1981)
LA-UR-81-675



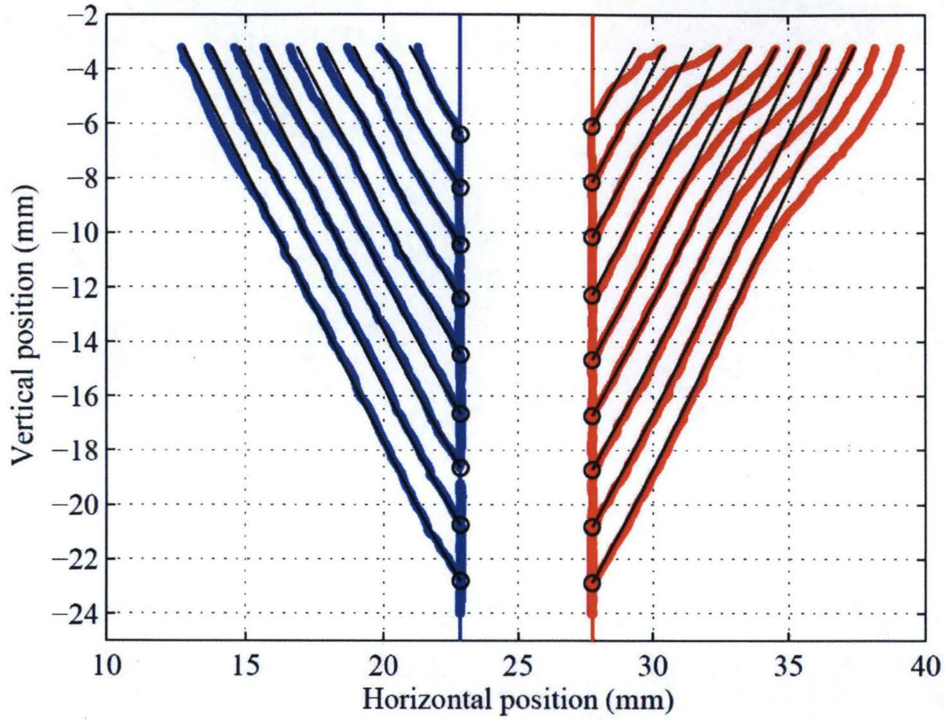
Pseudo-aquarium data – Edge detection

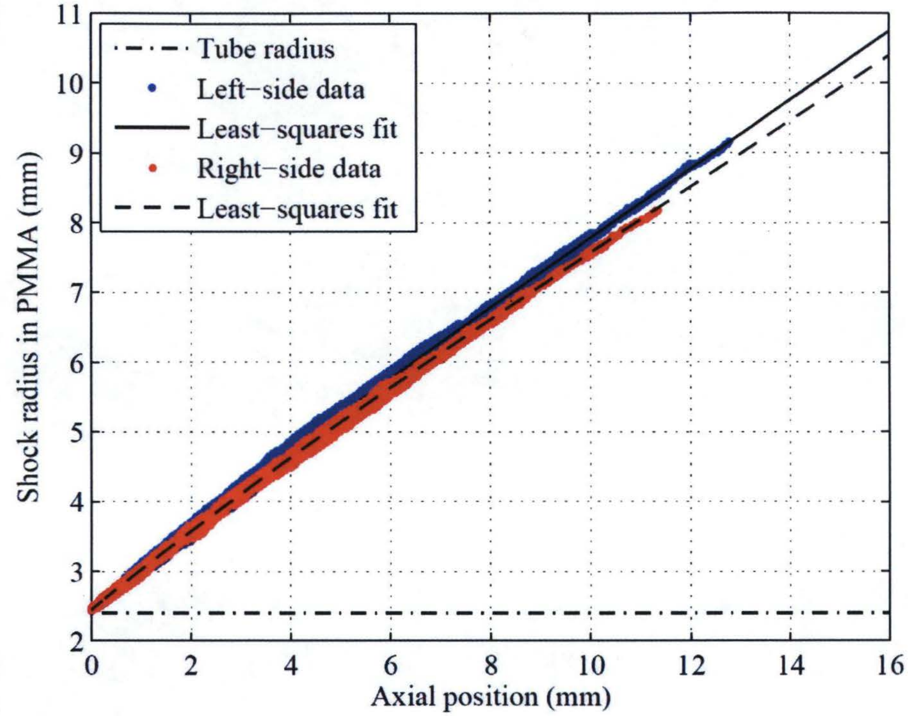


Goldstein and Johnson (1981)
LA-UR-81-675



Pseudo-aquarium data – Ensemble data





The edge-detected curves are plotted together by subtracting their measured intersection points with the polysulfone/PMMA interface in order to verify the steady nature of the flow in the HE charge. Aquarium analysis is applied to the ensemble data to extract the parameters necessary to calculate the shock pressure in PMMA as a function of either axial position along the explosive charge or radial position within PMMA.

Pseudo-aquarium data – Calculated results

Aquarium Analysis Results

Fit Parameters	Left side	Right side	% Diff
r_0 (mm)	2.415	2.444	1.2%
$\tan(\theta_{min})$	0.4922	0.4655	5.6%
1/a (mm)	2.943	4.086	33%
$\tan(\theta_{max})$	0.6469	0.591	9.0%
θ_{max} (deg)	32.9	30.6	3.6%
D (mm/μs)	7.395	7.53	1.8%
$P_{s,max}$ (GPa)	4.437	3.737	17%

The aquarium results suggest the diameter of the PMMA through hole that holds the explosive charge housing is 4.859 +/- 0.024 mm, which agrees well with the machining spec of 4.88 +/- 0.01 mm. Of interest is the observation that the detonation velocity on the right side is greater than the left side, but the calculated shock pressures at the respective interfaces differ in the opposite sense by up to 17%.

Summary and ongoing efforts

- SWIFT provides direct visualization of initiator, detonator, and HE-interaction flows
- Ultra-high-speed image sequences alone provide novel information critical to understanding device output into various media (extremely useful for numerical code validation)
- Numerous quantitative datasets can be extracted from SWIFT recordings, and more are currently being developed
- SWIFT data is currently being used to validate PDV, streak data, and device timing measurements (shock switch, 1st-light breakout, etc.) with good fidelity
- 2-D axi-symmetric small-scale gap testing using SWIFT is underway to characterize HE performance at multi-dimensional length scales relevant to detonator technology
- Extension of the technique to larger scales is currently underway

Summary and ongoing efforts