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Removing Full-Scale Testing Barriers: A Fundamental Detonation Characterization Technique for Novel Energetic Formulations at the Laboratory Scale

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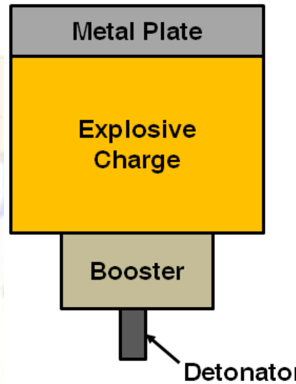
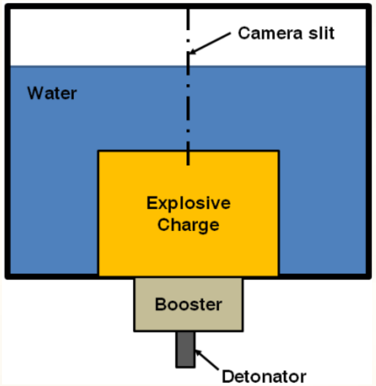
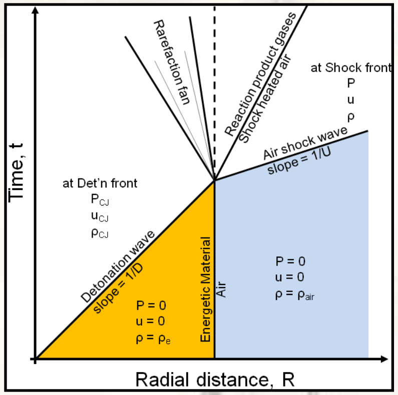
Overview

Background





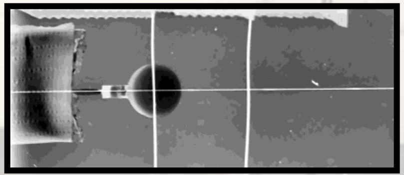


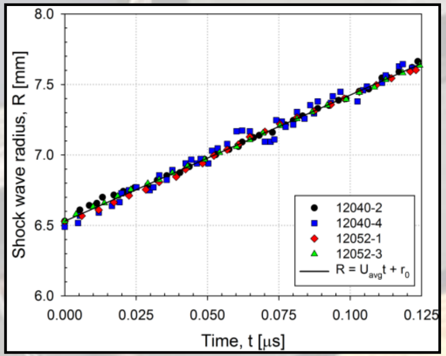
Objective

1. $U = C_0 + su$
2. $\rho = \dfrac{U\rho_{air}}{U - u}$
3. $P = \rho_{air} C_0 u + \rho_{air} s u^2$
4. $\rho_{CJ} = 1.386\,\rho_e^{0.96}$
5. $\dfrac{P}{P_{CJ}} 235 \left(\dfrac{u}{u_{CJ}}\right)^{-8.71}$
6. $\dfrac{\rho_{CJ}}{\rho_0} = \dfrac{D}{D - u_{CJ}}$
7. $P_{CJ} = \rho_e u_{CJ} D$

Theory/Methodology

Experimental Methods



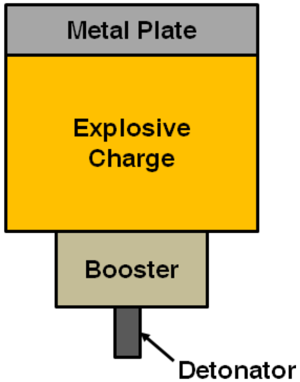


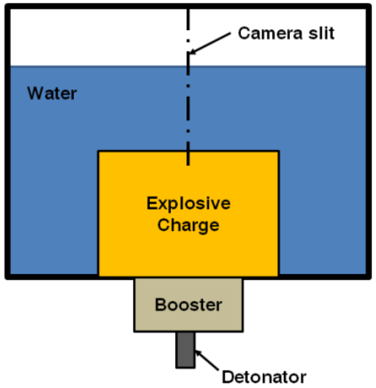
Results and Discussion

Conclusions

Background

- **Early detonation characterization research performed by Goranson[1]**
  - Free-surface velocity measurements of 'flyer plates' positioned adjacent to an energetic charge
  - Determined reaction-zone length and CJ pressure
- **Holton extended experiment by replacing the flyer plate with an optically transparent material (most commonly water)[2]**
  - Streak image taken parallel to charge axis of sympathetically detonated cylindrical charge submerged in distilled water
  - Water shock wave velocity measured
  - Empirical water shock wave parameters implemented
  - Detonation velocity as a function of density relationship known *a priori*
  - Detonation pressure calculated using above and hydrodynamic theory





1. Duff, R.; Houston, E. Measurement of the Chapman-Jouguet pressure and reaction zone length in a detonating high explosive. *The Journal of Chemical Physics* **1955**, 23 (7), 1268.
2. Holton, W. *The detonation pressures in explosives as measured by transmitted shocks in water*; NAVORD Report 3968; Naval Ordnance Laboratory: White Oak, MD, December 1954.

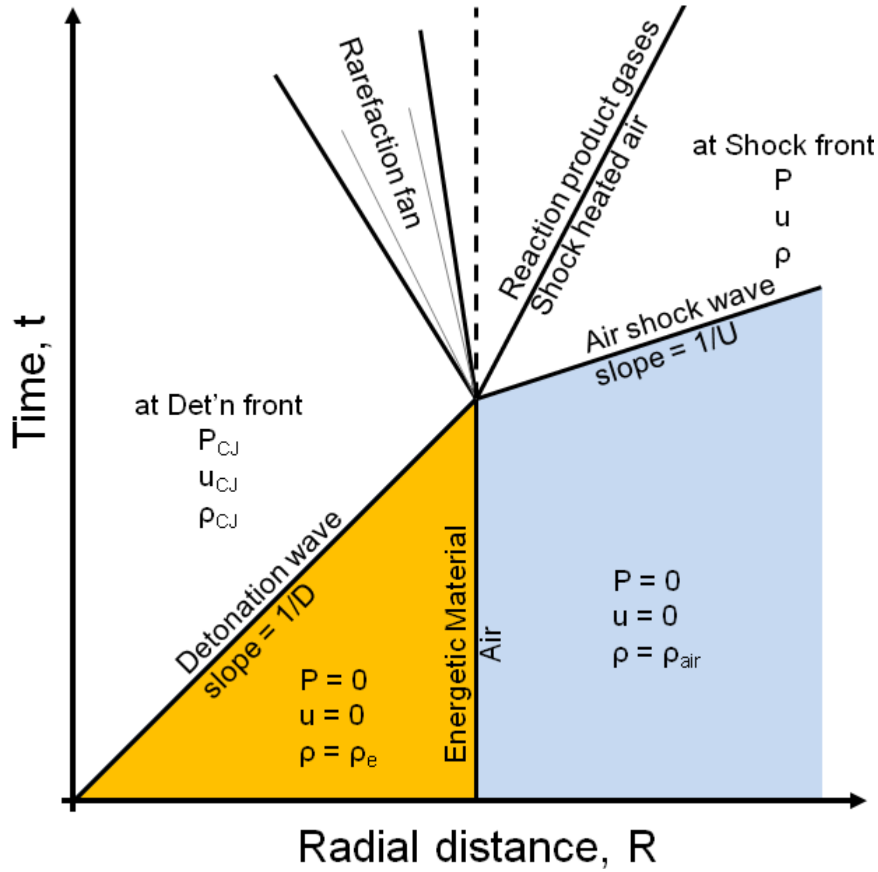
Research objective

Proposed to measure air shock wave velocity *U* at the energetic material—air interface and infer all other state properties using theoretical/empirical foundation

Energetic material detonating in atmospheric air

- Detonation wave transferred into air as shock wave possessing different state property values
- 8 variables needed to define interaction
  - Detonation wave: D, P_{CJ}, u_{CJ}, ρ_{CJ}
  - Air shock wave: U, P, u, ρ

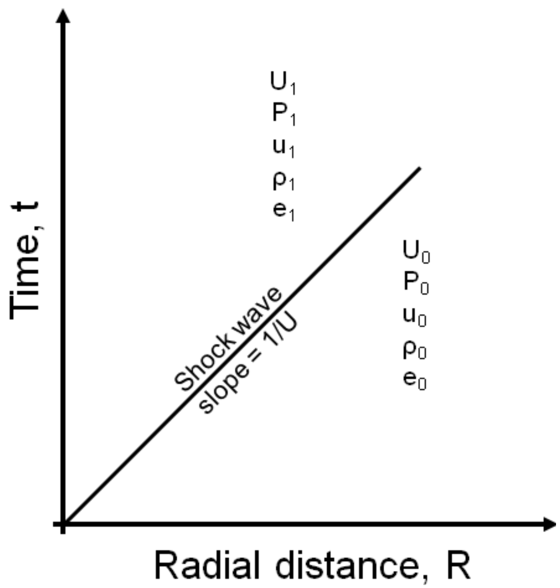
Detonation Interaction



Shock wave

Shock wave fully defined by five state variables:

- Velocity *U*, pressure *P*, particle velocity *u*, specific volume, *v* (or density *ρ*), and specific internal energy, *e*
- Specific internal energy eliminated by combining equation of state, *i.e.*, *e = f(P, ρ)*, and conservation of energy



Mass

$$\frac{\rho_1}{\rho_0} = \frac{U - u_0}{U - u_1} = \frac{v_0}{v_1}$$

Momentum

$$P_1 - P_0 = \rho_0 (u_1 - u_0)(U - u_0)$$

Energy

$$e_1 - e_0 = \frac{P_1 u_1 - P_0 u_0}{\rho_0 (U - u_0)} - \frac{1}{2}\left(u_1^2 - u_0^2\right)$$

Equation of state

$$e = f(P, v \text{ or } \rho)$$

Hugoniot

$$P = f(\rho)$$

Detonation Interaction

Detonation wave

Unknown: D, P_{CJ}, u_{CJ}, ρ_{CJ}

Mass

$$\frac{\rho_{CJ}}{\rho_e} = \frac{D}{D - u_{CJ}}$$

Momentum

$$P_{CJ} = \rho_e u_{CJ} D$$

Air shock wave

Unknown: P, u, ρ

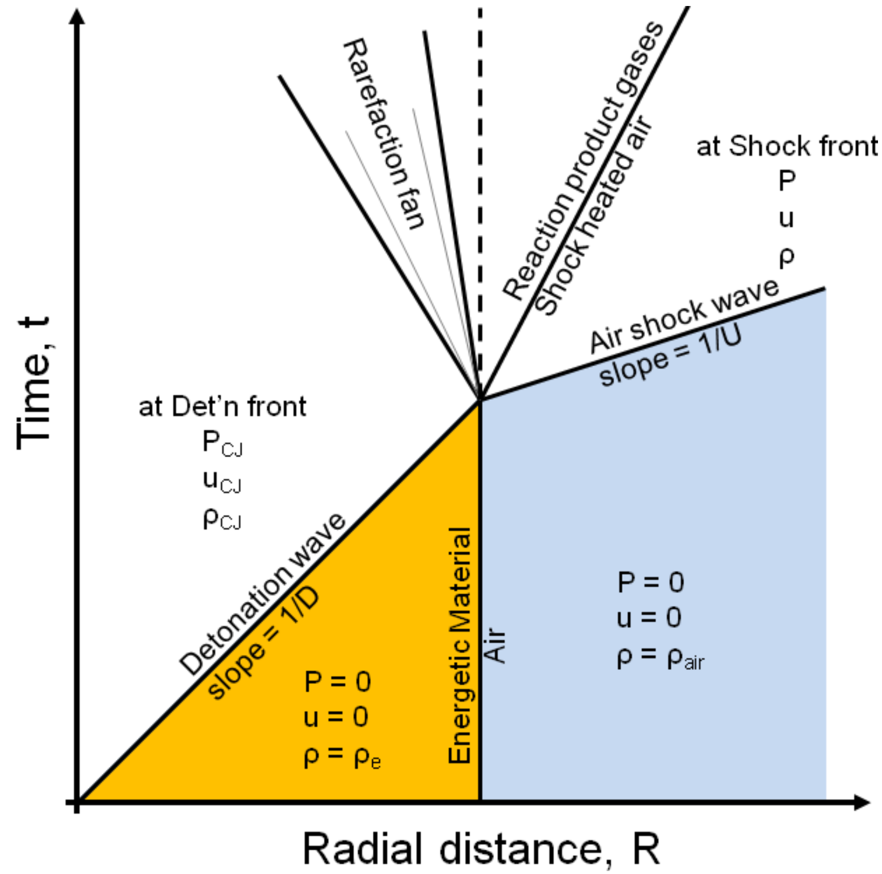
Known: U

Mass

$$\frac{\rho}{\rho_{air}} = \frac{U}{U - u}$$

Momentum

$$P = \rho_{air} U u$$



Energetic *P-u* Hugoniot

Detonation wave equations

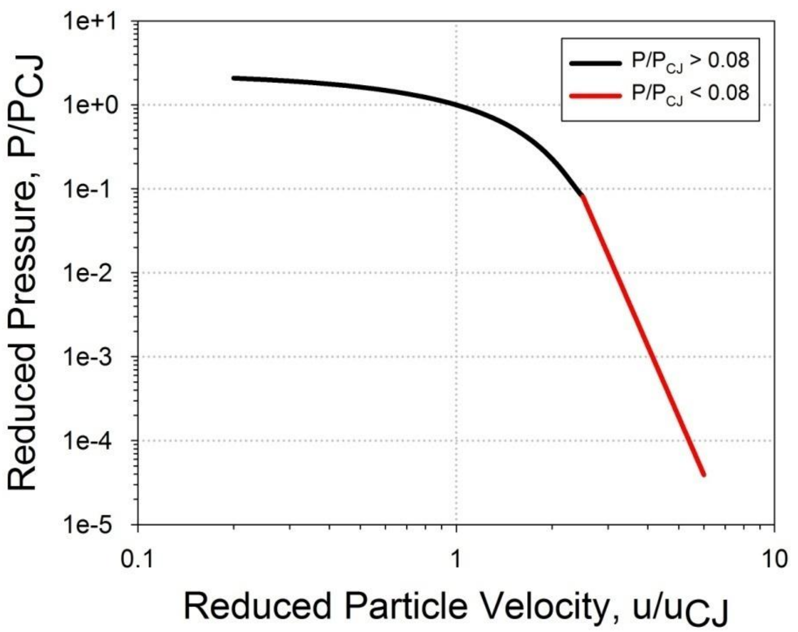
- Cooper developed reduced form of *P-u* Hugoniot for compilation of energetic materials[3]
- Data collapsed into a narrow band able to be approximated by two correlations based upon reduced pressure:

For reduced pressures above 0.08:

$$\frac{P}{P_{CJ}} = 2.412 - 1.7315\left(\frac{u}{u_{CJ}}\right) + 0.3195\left(\frac{u}{u_{CJ}}\right)^2$$

and for reduced pressures below 0.08:

$$\frac{P}{P_{CJ}} = 235\left(\frac{u}{u_{CJ}}\right)^{-8.71}$$



3. Cooper, P. *Explosives Engineering*; Wiley-VCH, Inc: New York, 1996.

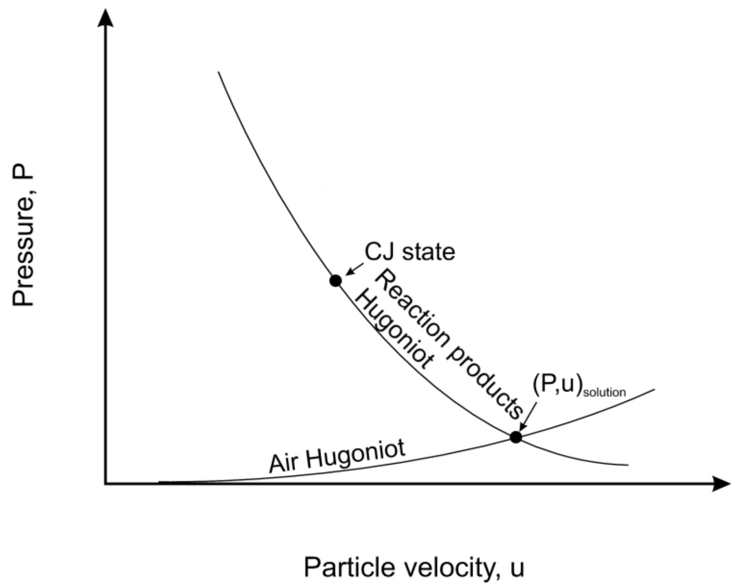
Energetic *P-u* Hugoniot

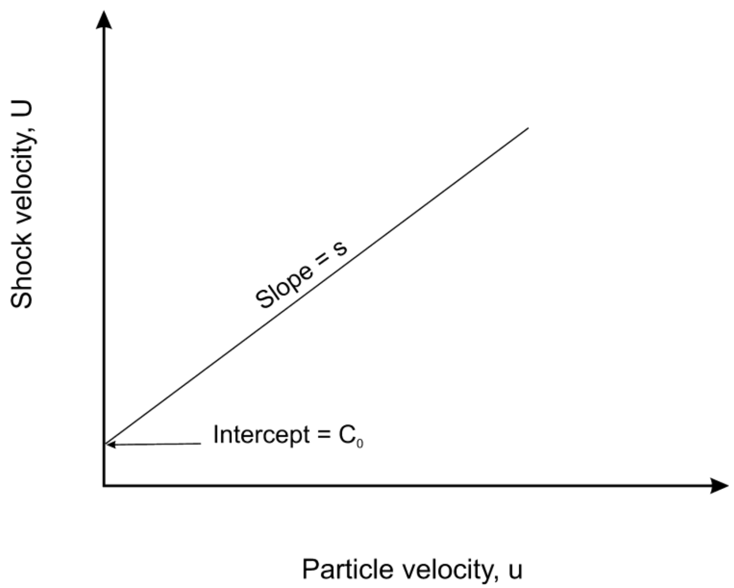
Detonation wave equations

- Reduced pressure P/P_{CJ} is anticipated to be extremely low due to large shock impedance discrepancy ($\rho_e \approx 1500^*\rho_{air}$)

$$\textbf{Energetic material: } Z_e = \rho_e D \qquad \textbf{Air: } Z_{air} = \rho_{air} U$$

- Assume detonation velocity D and air shock wave velocity U are on the same order of magnitude
  - Air shock wave pressure $P < P_{CJ}$, air particle velocity $u > u_{CJ}$
  - P/P_{CJ} anticipated to fall below 0.08 threshold





Detonation Interaction

Detonation wave

Unknown: D, P_{CJ}, u_{CJ}, ρ_{CJ}

Mass

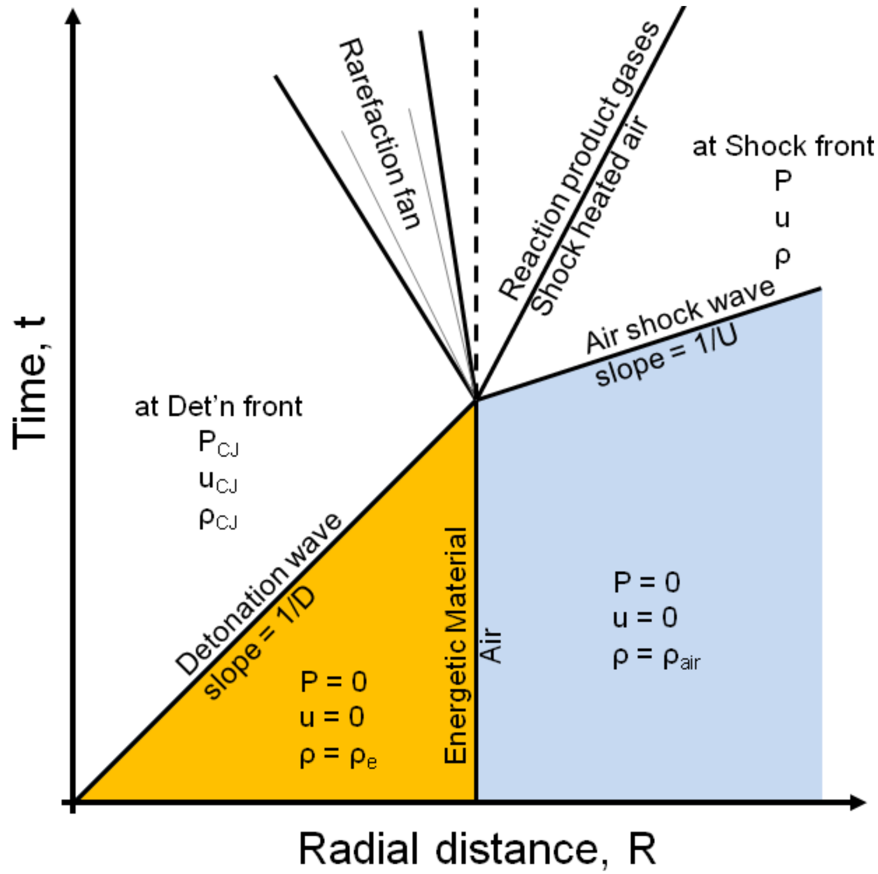
$$\frac{\rho_{CJ}}{\rho_e} = \frac{D}{D - u_{CJ}}$$

Momentum

$$P_{CJ} = \rho_e u_{CJ} D$$

***P-u* Hugoniot**

$$\frac{P}{P_{CJ}} = 235\left(\frac{u}{u_{CJ}}\right)^{-8.71}$$



Air shock wave

Unknown: P, u, ρ

Known: U

Mass

$$\frac{\rho}{\rho_{air}} = \frac{U}{U - u}$$

Momentum

$$P = \rho_{air} U u$$

***U-u* Hugoniot**

$$U = C_0 + su$$

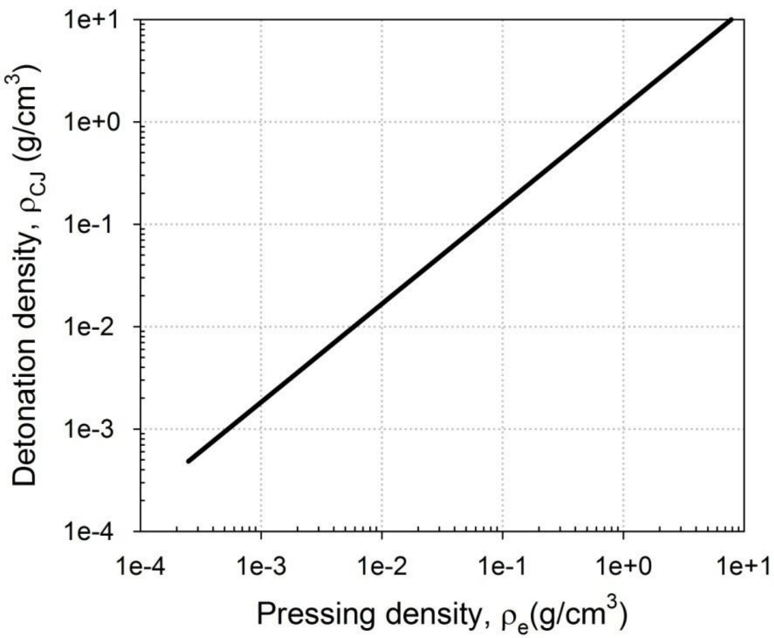
Final equations

Detonation density relationship

- Second universal energetic reaction products Hugoniot unavailable
- Cooper developed relationship to relate detonation density to energetic pressing density

Density Relationship

$$\rho_{CJ} = 1.386\,\rho_e^{0.96}$$



P-u Hugoniot for air

Momentum

$$P = \rho_{air} U u$$

$$+$$

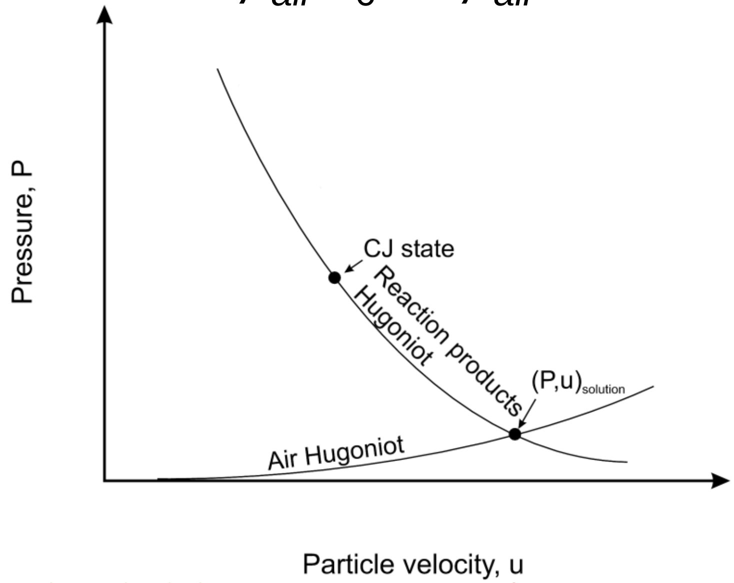
***U-u* Hugoniot**

$$U = C_0 + s u$$

$$=$$

***P-u* Hugoniot**

$$P = \rho_{air} C_0 u + \rho_{air} s u^2$$



Detonation Interaction

Detonation wave

Unknown: D, P_{CJ}, u_{CJ}, ρ_{CJ}

Mass

$$\frac{\rho_{CJ}}{\rho_e} = \frac{D}{D - u_{CJ}}$$

Momentum

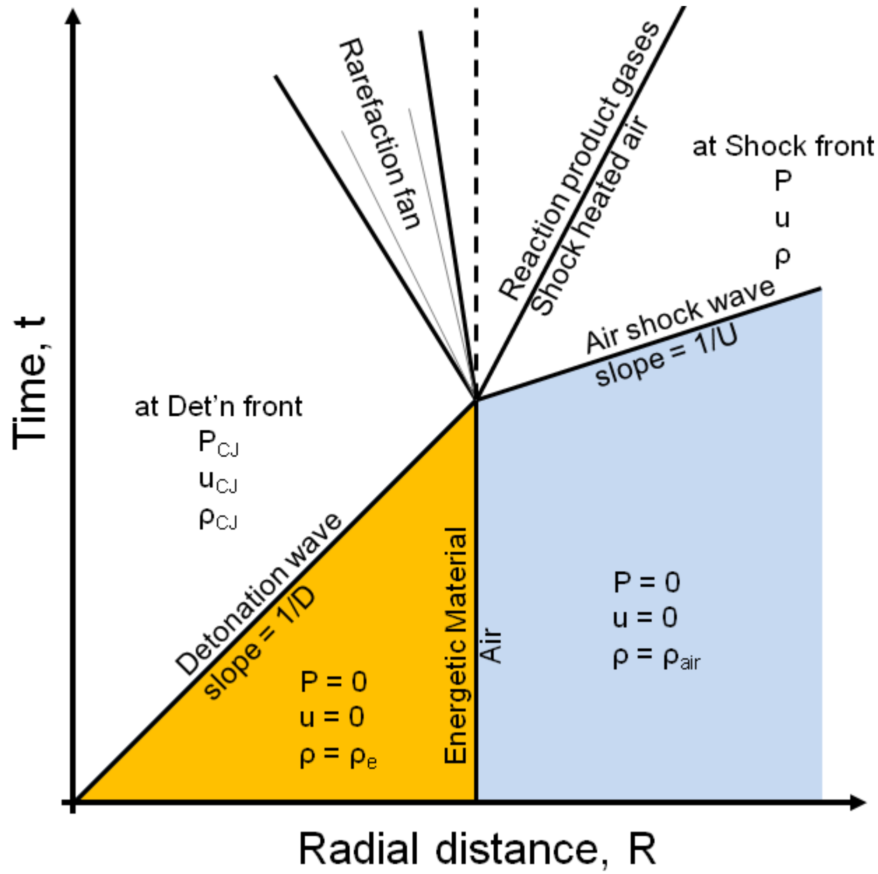
$$P_{CJ} = \rho_e u_{CJ} D$$

***P-u* Hugoniot**

$$\frac{P}{P_{CJ}} = 235\left(\frac{u}{u_{CJ}}\right)^{-8.71}$$

Density Relationship

$$\rho_{CJ} = 1.386\,\rho_e^{0.96}$$



Air shock wave

Unknown: P, u, ρ

Known: U

Mass

$$\frac{\rho}{\rho_{air}} = \frac{U}{U - u}$$

***U-u* Hugoniot**

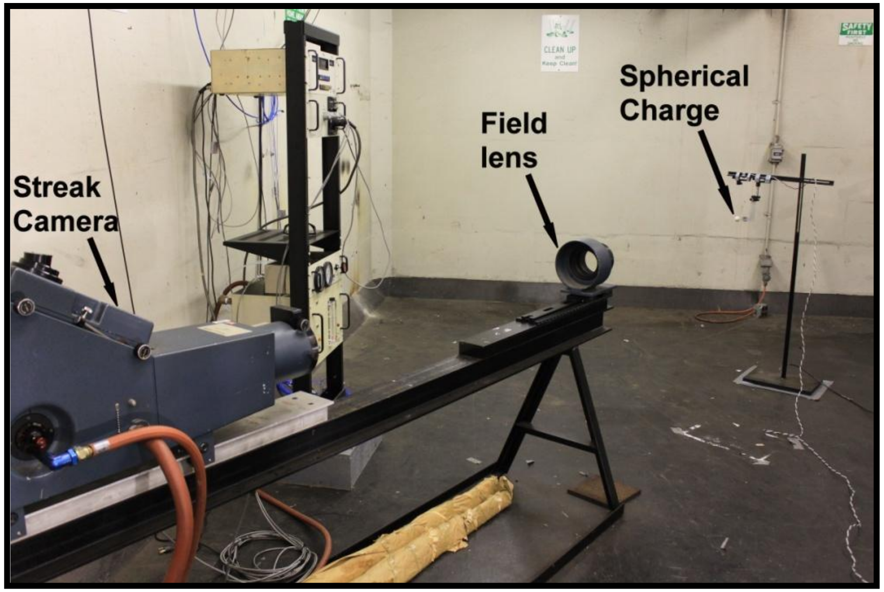
$$U = C_0 + su$$

***P-u* Hugoniot**

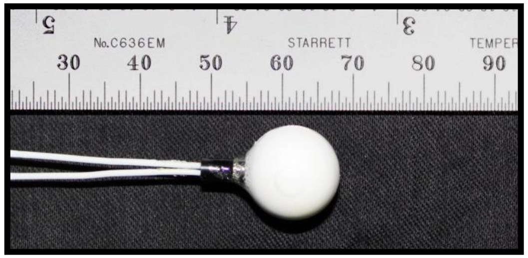
$$P = \rho_{air} C_0 u + \rho_{air} s u^2$$

Experimental methods

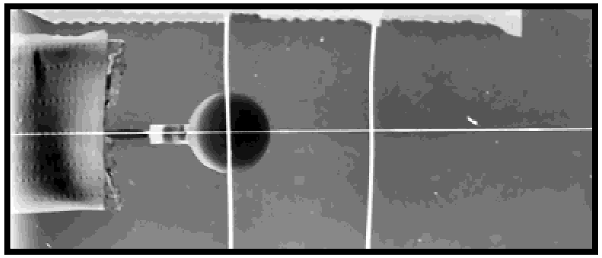
- **Film-based streak camera captures radial shock wave expansion rate at the energetic material–air interface**
  - Beckman & Whitley Model 770
  - 8 mm/µs writing speed
  - 90 cm *f*/6.3 field lens
  - Spherical 2 g RDX charges
  - RP-3 EBW detonator [29 mg PETN]



- **Spherical RDX charges**



a) Fully assembled 2 g spherical RDX charge



b) Static streak-camera image of the spherical charge in the test plane

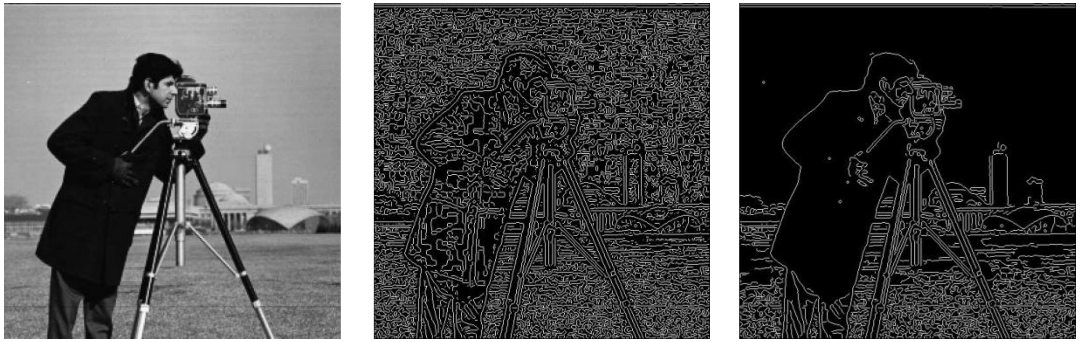
c) Dynamic spherical charge detonation streak record

Experimental methods

- **Streak records digitized using high-resolution scanner**
  - HP 8200 flatbed scanner
  - 8-bit grayscale @ 4800 dpi

- **Digitized records analyzed in MATLAB to track radial shock wave expansion rate**
  - Standardized test-bed image used for calibration
  - ‘Canny’ edge-detection filter with threshold
  - First 1.2 mm of radial shock wave expansion[4]

Image.jpg | Canny filter | w/ Threshold



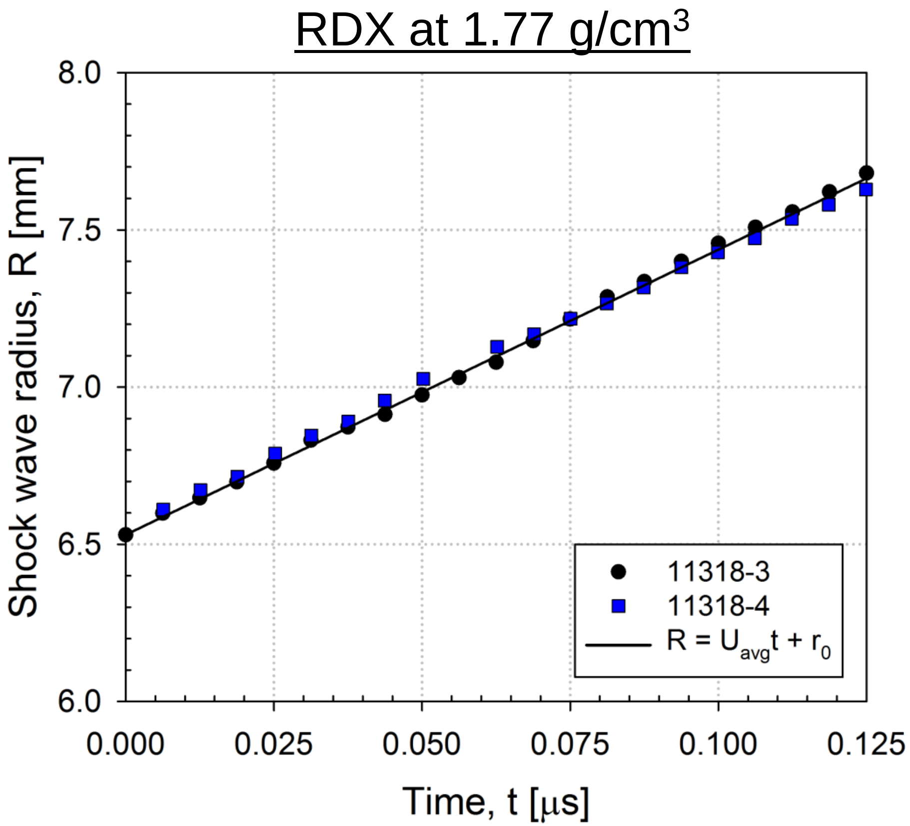
- **Best-fit linear correlation determined for each data set[4]**

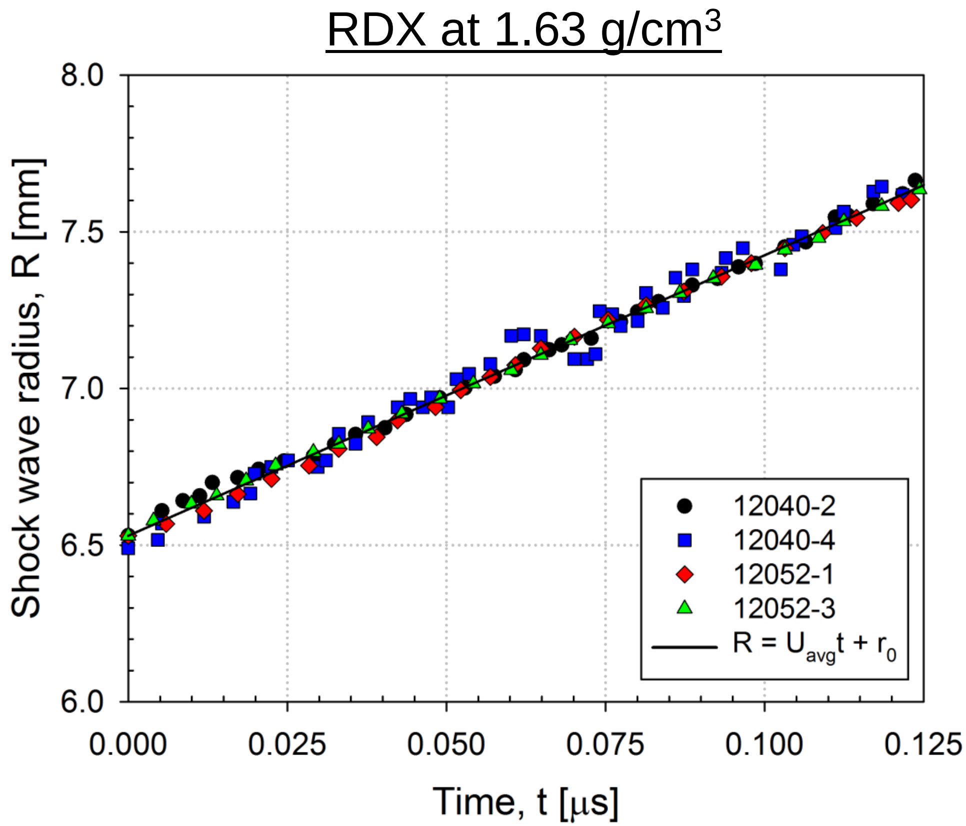
$R = Ut + r_0$ — *R*: shock wave radius, *t:* time, r_0: charge radius, *U:* shock wave velocity

- **Detonation wave and air shock wave data calculated from measured shock wave velocity and theory**

4. Rigdon, J. K.; Akst, I. B. An analysis of the “Aquarium technique” as a precision detonation pressure measurement gage. In *Proceedings of the Fifth Symposium (International) on Detonation*; U.S. Naval Ordnance Laboratory and the Office of Naval Research: Pasadena, CA, 1970.

Shock wave radius-versus-time data





Calculated detonation wave and air shock wave properties for RDX at 1.63g/cm^3

Charge	ρ_{air} (g/cm^3)	U (mm/µs)	D (mm/µs)	P_{CJ} (GPa)	ρ_{CJ} (g/cm^3)	u_{CJ} (mm/µs)	P (MPa)	U (mm/µs)
Published	-	-	8.34	28.3	2.16	-	-	-
12040-2	$1.207e^{-3}$	8.85	8.40	30.4	2.22	2.22	87.0	8.14
12040-4	$1.207e^{-3}$	9.06	8.61	31.9	2.22	2.28	91.2	8.34
12052-1	$1.213e^{-3}$	9.16	8.71	32.7	2.22	2.31	93.7	8.44
12052-3	$1.206e^{-3}$	8.74	8.30	29.7	2.22	2.19	84.8	8.04
Average	$1.208e^{-3}$	8.95	8.51	31.2	2.22	2.25	89.2	8.24
St. Dev.	$3.202e^{-6}$	0.19	0.19	1.4	0	0.05	4	0.18
% Dev.	-	-	1.98	10.2	2.78	-	-	-

Results and discussion

Calculated detonation wave and air shock wave properties for RDX at 1.77g/cm^3

Charge	ρ_{air} (g/cm^3)	U (mm/µs)	D (mm/µs)	P_{CJ} (GPa)	ρ_{CJ} (g/cm^3)	u_{CJ} (mm/µs)	P (MPa)	u (mm/µs)
Published	-	-	8.69	33.6	2.34	-	-	-
11318-3	1.202e^{-3}	9.18	8.73	35.3	2.40	2.28	93.3	8.46
11318-4	1.202e^{-3}	8.96	8.51	33.6	2.40	2.23	88.9	8.25
Average	1.202e^{-3}	9.07	8.62	34.4	2.40	2.26	91.1	8.36
% Dev.	-	-	0.81	2.53	2.56	-	-	-

Single laboratory-scale experiment provides same information as multiple full-scale tests that require kilograms of material

Theoretically calculated detonation wave properties predicted to within 3%* of published data for two densities of Class V RDX

*** 5/6 properties, 10% deviation for empirically calculated value**

Results and discussion

Calculated detonation wave and air shock wave properties from previous research

Explosive	ρ_e (g/cm³)	ρ_{air} (g/cm³)	U (mm/µs)	D (mm/µs)	P_{CJ} (GPa)	ρ_{CJ} (g/cm³)	P (MPa)	u (mm/µs)
HMX/Inert	1.781	$1.07e^{-2}$	7.42	8.73	33.5	2.34	53.0	6.53
Calculated	-	-	-	8.60	34.5	2.41	53.8	6.79
% Dev.	-	-	-	1.5	3.0	2.9	1.5	4.0
HMX/TNT/Inert	1.776	$3.79e^{-3}$	7.84	8.21	31.2	2.40	21.2	7.13
Calculated	-	-	-	8.26	31.7	2.41	21.3	7.18
% Dev.	-	-	-	0.6	1.7	0.4	0.5	0.7
TNT	1.636	$0.971e^{-3}$	7.34	6.93	20.7	2.15	47.8	6.71
Calculated	-	-	-	6.80	20.0	2.22	47.8	6.71
% Dev.	-	-	-	1.9	3.4	3.2	0	0
Composition B	1.717	$0.947e^{-3}$	8.67	7.98	29.5	2.34	65.5	7.97
Calculated	-	-	-	8.05	29.2	2.33	65.5	7.98
% Dev.	-	-	-	0.9	1.0	0.4	0	0.1

Results and discussion

Calculated detonation wave and air shock wave properties from previous research

Explosive	ρ_e (g/cm³)	ρ_{air} (g/cm³)	U (mm/µs)	D (mm/µs)	P_{CJ} (GPa)	ρ_{CJ} (g/cm³)	P (MPa)	u (mm/µs)
Cyclotol	1.752	$0.936e^{-3}$	8.64	8.27	31.3	2.38	64.2	7.94
Calculated	-	-	-	8.01	29.5	2.37	64.2	7.95
% Dev.	-	-	-	3.1	5.8	0.4	0	0.1
Octol	1.821	$0.943e^{-3}$	8.86	8.49	34.2	2.46	68.1	8.14
Calculated	-	-	-	8.23	32.2	2.46	68.1	8.15
% Dev.	-	-	-	3.1	5.8	0	0	0.1
HBX-1	1.712	$1.253e^{-3}$	7.61	7.31	22.0	2.18	67.0	6.97
Calculated	-	-	-	7.22	22.4	2.21	66.5	6.97
% Dev.	-	-	-	1.2	1.8	1.4	0.7	0

Theoretically calculated detonation wave and air shock wave properties predicted to within 3.5% of published data for 32/35 properties from seven historical data sets using single shock wave velocity measurement and atmospheric conditions

Conclusions

Laboratory-scale experimental detonation characterization technique established and verified

- Composed from conservation laws, material Hugoniots, and empirical relationships
- Able to determine detonation wave properties: D, P_{CJ}, ρ_{CJ}, and u_{CJ} and shock wave properties: U, P, ρ, and u
  - Verified using two densities of RDX (1.63 and 1.77 g/cm^3)
    - Predicted 5/6 properties to within 3% of published data
  - Reproduced historical data sets for seven energetic materials
    - Predicted 32/35 properties to within 3.5% of published data

Single laboratory-scale experiment provides same information as multiple full-scale tests that require kilograms of material

- Highly-advantageous cost-savings approach for the formulation of novel insensitive energetic materials
- Eliminates initial formulation scale-up requirements necessary for determining detonation performance parameters

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Questions?

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