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EXAMINATION OF NON-IDEAL EXPLOSIVES

BY

RYAN CHARLES RETTINGER

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

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UNIVERSITY OF RHODE ISLAND

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DOCTOR OF PHILOSOPHY DISSERTATION
OF
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2019

ABSTRACT

As seen in multiple cases, including the 2013 Boston Marathon bombing, improvised explosives compositions may be as simple as a combination commonly-available fuel/oxidizer (FOX) mixtures initiated by an electrically-heated wire. The predictive knowledge of large scale explosive potential of FOX mixtures is incomplete. Predicting explosive potential from laboratory-scale analytical test data is desirable. Herein the explosive properties of fuel/oxidizer combinations (FOX) were measured at both the small scale (2 g) with bomb calorimetry for heat output and closed-vessel dynamic pressure rise and also on the large scale (5 kg) with high speed photography for detonation velocity and with piezoelectric pressure probes for TNT air blast equivalence. Potassium nitrate (KN), potassium chlorate (KC), potassium permanganate (KMnO_4), potassium iodate (KIO_3), ammonium nitrate (AN), and ammonium perchlorate (AP) were prepared with sucrose (Su) fuel, and KN, AP, and AN were prepared with aluminum (Al) fuel. The results were compared to each other as well as predictions from Cheetah thermochemical code in order to correlate detonation performance, particularly the ideality of detonation performance, with simple laboratory screening tests.

Presented here are the results of around 60 explosive experiments which have become the first series of experiments at the URI explosives test facility to successfully field photon Doppler velocimetry (PDV) and ultra-high speed photography. The experiments outlined herein focus on homogeneous improvised explosives, namely hydrogen peroxide (HP) aqueous solutions fueled with ethanol (EtOH). These

materials have been chosen as a template system for evaluation with time-resolved detonation diagnostics aimed at screening clandestine non-ideal explosive threat materials for detonable character even, and especially, in configurations below their critical diameter. The ‘galloping’ detonation instabilities of these materials have been captured on camera in the stoichiometric mixture of HP:EtOH in diameters from 1 to 2.6 inches; a steady detonation never formed. Reactive particle velocity waveforms for this mixture were measured by PDV through a PMMA pressure-maintaining window. These materials were subjected to both overdriven and underdriven configurations, and non-steady waveforms have been collected to monitor non-ideal explosives under these conditions i.e. inside the infinite diameter region of a range of different shock loading environments. Several mixtures of HP:EtOH have also been artificially doped with glass microballoons to study the ideality of this mixture in a heterogeneous regime. Successful detonations of heterogeneous HP:EtOH mixtures were observed using as low as 40% HP.

ACKNOWLEDGMENTS

I would like to thank our Ordinance Technician Allan Valliere for being so willing to help get these experiments done, rain, snow, or shine often with great inconvenience to him; a great deal of credit goes to him for the impressive frequency with which we've been able to get so many experiments done in such a short amount of time.

I acknowledge the insight and guidance of Dr. James Kennedy and his valuable advice through the many obstacles encountered in this work. I would like to credit Dr. Tao Wei and Dr. Brian Chen with the many hours of instruction helping me get started with PDV. Our success fielding this optical technique is largely due to their generous collaboration in the early years of building the range; before their help, I had zero experience with fiber optics, time/frequency transformations, or the wave interaction mathematics necessary to understand the diagnostics. I would also like to acknowledge the two faithful companions who shared every day out at the Alton Jones test site with me, Ruger and Trig, and the family who waited so patiently and supportively for me to finish my degree. I would also like to thank my research team, both past and present, for the collaborative and friendly environment to which I quickly integrated in spite of being foreign to the area. I'd like to thank my advisors Jimmie Oxley and Jim Smith for the opportunity to build the Alton Jones test site; I could never have expected such an incredible opportunity. My personal relationship with the sovereign, holy, righteous, God Most High has saved my soul from death, my eyes from tears, and my feet from stumbling. He meets me where I am, and fulfills His promise. He made me like a potter shapes a clay vessel, and His banner over me is Love. Please see: Proverbs 3:5, Isaiah 49:9-10, I John 3:11, and Psalms 73:21-28.

PREFACE

This dissertation has been prepared in manuscript format in accordance with the guidelines of the Graduate School of the University of Rhode Island. The research contained herein is separated into two manuscripts. The first manuscript, “Correlation of Thermal Properties and Explosive Performance of Fuel/Oxidizer Mixtures” is being submitted to the journal *Propellants, Explosives, Pyrotechnics*. The second manuscript, “Characterization of Detonation Waveforms in Homogeneous Non-Ideal Explosives” will also be submitted for publication in the journal *Propellants, Explosives, Pyrotechnics*. These experiments are the first two bodies of work to be published which directly relate to work from the new URI Outdoor Explosive Test Facility (OTF) which was being built with this very work in mind. Through the support of his advisors, the OTF was outfitted with a suite of ultra-high-speed diagnostics not previously known to the author or his research group. In establishing the application of these technologies the author experienced an uncanny amount of failure; this work represents over 4 years of work maturing the use of these technologies at URI.

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LIST OF ABBREVIATIONS

ACN - Acetonitrile

C4 – Military Explosive Composition 4

Dcr – critical diameter, below which sustained detonation does not occur

ESD – Electrostatic Discharge

DFT - Density Functional Theory

DSC - Differential Scanning Calorimetry

EA - Ethyl Acetate

EDFA - Erbium-Doped Fiber Amplifier

FOX – Fuel/Oxidizer Mixture

GC/MS - Gas Chromatography / Mass Spectrometry

HMTD - Hexamethylene Triperoxide Diamine

i.d. or o.d. – inner or outer diameter

IR – Infrared Spectroscopy

LC/MS - Liquid Chromatography / Mass Spectrometry

NM - Nitromethane

NMR - Nuclear Magnetic Resonance Spectroscopy

PETN – Pentaerythritol Tetranitrate

PVC – Polyvinyl Chloride

RDX - 2,4,6-cyclotrimethylene-1,3,5-trinitramine

SDT - Simultaneous Differential Scanning Calorimetry

SOP – Standard Operating Procedure

SPME - Solid Phase Microextraction

TGA – Thermal Gravimetric Analysis

TIL – Threshold Initiation Level

TMA - Trimethylamine

MANUSCRIPT 1

FUEL-OXIDIZER MIXTURES: A LAB AND FILED STUDY

BY

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**This manuscript will be submitted to the journal Propellants, Explosives &
Pyrotechnics for publication**

Fuel-Oxidizer Mixtures: A Lab and Field Study

Abstract

As seen in multiple cases, including the 2013 Boston Marathon bombing, improvised explosive threats may be as primitive as a simple mixture of commonly-available fuels and oxidizers (FOX) initiated by an electrically-heated wire. The predictive expectation of large scale explosive threat potential of FOX mixtures is incomplete. Predicting explosive potential from laboratory-scale analytical test data is desirable to screen a large matrix of potential threats in varying concentrations without having to prepare and perform large-scale field tests, which can, themselves, often be inconclusive. Herein the explosive properties of fuel/oxidizer combinations (FOX) were measured at both the small scale (2 g) with bomb calorimetry for heat output and closed-vessel dynamic pressure rise and also on the large scale (5 kg) with high speed photography for detonation velocity and with piezoelectric pressure probes for TNT air blast equivalence. Potassium nitrate (KN), potassium chlorate (KC), potassium permanganate (KMnO₄), potassium iodate (KIO₃), ammonium nitrate (AN), and ammonium perchlorate (AP) were prepared with sucrose (Su) fuel, and KN, AP, and AN were prepared with aluminum (Al) fuel. The results were compared to each other as well as predictions from Cheetah thermochemical code in order to correlate detonation performance, particularly the ideality of detonation performance, with simple laboratory screening tests.

1 Introduction

Hundreds of years ago, the field of energetic materials began with the invention of a fuel-oxidizer mixture of charcoal, sulfur, and potassium nitrate, which became known as black powder [1]. Within the last century, the fuel-oxidizer mixture of ammonium nitrate and fuel oil (ANFO) became popular as a commercial blasting agent [2] and later as a terrorist tool [2, 3]. In the intervening period, the discovery of nitration resulted in a number of well-performing, high-density organic molecules—nitrate esters, nitroarenes, and nitramines. Because these molecules have become the basis of military weaponry, much effort has been expended in modeling their detonation performance. Fuel/oxidizer (FOX) mixtures, when examined by the same protocols, have been termed “non-ideal” explosives because complex, diffusion-limited reaction zone chemistry rarely converts all the available energy in sufficient time to support detonation front propagation, leading to the tendency of models to over-predict the actual detonation performance. Nevertheless, it has become imperative that we understand FOX mixtures since their ease of clandestine creation—simply mixing a fuel and oxidizer together—has made them a common choice in illicit bombings.

We have previously reported a series of 11 oxidizers and 13 fuels examined by differential scanning calorimetry (DSC), simultaneous DSC/TGA (SDT), and by open burn. DSC is usually the first step in evaluating the energy content of an energetic formulation because the technique can use less than a milligram of material. In preparing the fuel/oxidizer DSC samples, great care was taken to make the samples homogeneous. Nevertheless, the DSC traces were difficult to interpret due to the small

size of the prepared batches and the presence of multiple thermal events [4]. Herein we report a re-investigation of some selected FOX mixtures using isoperibol calorimetry—a Parr bomb calorimeter recording the heat release and dynamic pressure rise of 2 gram samples burning under argon. Detonation of select formulations was attempted on the 10 pound-scale. (On average 5 kg of FOX mixtures filled the 4” id x 24” long schedule 40 PVC charge casing, and were boosted with a 546 g donor charge containing PETN-based sheet explosive and C4). The event was recorded by high-speed photography and a single blast pressure transducer.

2 Experimental Methods

2.1 Sample Preparation for Calorimetry, DSC, and SDT

The fuels chosen were sucrose from Fisher Scientific and 23 μm steric acid-coated aluminum powder from Obron. Oxidizers were ground and sieved 100-200 mesh (150-75 μm). Sucrose was also ground with a commercial coffee grinder and sieved 100-200 mesh as well. Fuel/oxidizer (FOX) mixtures were prepared as dry loose powders placed in 50mL plastic pop-top containers; for differential scanning calorimetry (DSC) samples in 500 mg batches and for bomb calorimetry, as individual 2 g samples. Mixing was then conducted with a 500g capacity Resodyn Lab Ram acoustic mixer at 35 - 40 G acceleration for 2 min. Individual DSC samples ~0.25 mg were taken from the 500 mg batch. Sample preparation for SDT was similar, but with sample sizes of 4 to 6 mg.

2.2 Differential Scanning Calorimetry (DSC)

Samples were flame sealed (~0.25 mg) in glass capillaries (borosilicate, 0.06 in. ID, 0.11 in OD) on a metal post cooled by liquid nitrogen to prevent decomposition during sample preparation. Scans were conducted at a ramp rate of 20 °C/min on a TA Q100 DSC. The temperature range was usually 30 °C to 450 °C, and the nitrogen flow rate was set to 50 mL/min. The temperature was calibrated by running indium with a melting point of 156.6 °C. This technique was chosen for oxidizer-sucrose mixtures because exotherms of these mixtures typically fall within the temperature limits of the instrument, as opposed to aluminized mixtures which don't typically react until higher temperatures than the DSC capillaries can be safely tested.

2.3 Simultaneous DSC/TGA (SDT)

A TA Q600 simultaneous DSC/TGA was used to run samples of 4-6 mg in open aluminum oxide pans, and scanned at 20 °C/min under 100 mL/min nitrogen flow. The temperature was calibrated by running Zinc with melting point of 419.5 °C. The temperature range was usually 50 °C to 1000 °C. Oxidizer - aluminum mixtures were analyzed with this technique due to exotherms appearing at higher temperatures.

2.4 Bomb Calorimetry with Pressure Transducer

Heat output and closed-vessel dynamic pressure records were determined using a Parr 6200 calorimeter and Parr 1108 bomb (Alloy 20), fitted with a pressure transducer (Parr 6976 pressure recording system, including a 5108A Kistler IEPE coupler, and a

211B2 Kistler piezoelectric pressure transducer with a calibrated sensitivity of 1.096 mV/psi). The Parr bomb was calibrated (i.e. 10 trials) with benzoic acid ignited with fuse wire (9.6232 J/cm) and cotton string (167.36 J) in 2515 kPa oxygen ($\Delta H_{\text{comb}} = 26,434 \text{ J/g}$) in an oxygen atmosphere. The string was in contact with both the fuse wire and sample. When electrical current was passed through the fuse wire, it sufficiently heated to cause ignition of the cotton string which reliably ignited samples under oxygen. The FOX samples (three to six 2 g samples of the loose pyrotechnic powder under each set of conditions, with the exception of potassium nitrate-sucrose doped mixtures of which only 2 samples each were performed) were ignited with a fuse wire under argon pressure (2859 kPa, 400 psig). This vessel pressure represented the maximum initial pressure which the regulator could handle. It appeared to be a good balance, allowing rapid initiation of burn, and minimizing heat losses with the walls of the Parr bomb [5]. With some energetic materials, it has been observed that there is a critical pressure of ignition associated with a specified input energy [6,7]. Igniting samples at a higher initial pressure is more likely to overcome the critical pressure of the sample. A National Instruments USB-6210 data acquisition card and LabView software were used to collect the pressure/time data at a rate of 10 kSa/s. This sample collection rate of 100 μs sample intervals was resolved sufficiently so that the pressure/time records, including the rapid rise time, appear continuous on the millisecond time-scale of the burn events for these experiments. The heat of reaction displayed on screen of the instrument was manually entered into the pressure record *.csv export file as new line, and a python algorithm extracted meaningful information and displayed the graph.

2.5 Sample Preparation for Detonation Diagnostics

Sucrose and oxidizers were prepared separately by grinding with a Vita-Mix 5000 blender and sieving each to 100-200 mesh (150-75 μm). The aluminum powder (23 μm) from Obron was used as received. Fuel/oxidizer samples of approximately 5 kg were manually mixed in a 37.9 L (10 gal) plastic bag for about 2 minutes. For the detonation studies, schedule 40 clear, polyvinyl chloride (PVC) tubes of 4 inch nominal diameter (10.16 cm) were purchased from McMaster Carr in 8 foot lengths and cut to 24 inches (60.96 cm) long. PVC booster cups were assembled by gluing a 4 inch PVC sewer and drain endcap to a 4 inch PVC coupler. Into the booster cup were placed two sheets (30 g) of #2 PETN sheet explosive which had been cut into circle shape to fit tightly into the booster cup. On top of the sheet explosive, C4 (546 g) was packed and then three more circles of the PETN sheet explosive. Booster cups were taped with duct tape directly to the clear PVC tube so that there was direct contact with the sample mixture. The FOX mixture was added by pouring from the plastic mixing bag, using a craft paper funnel and hand-tamped to settle the loose powder. The test device was placed in a vertical position (booster end down, Figure 1) on a wooden test stand; the bottom of the test device was 91.4 cm (36 in) from the ground. The detonator was inserted last and was initiated by an Ideal® 30-cap electric blasting machine.

Figure 1. Schematic and photo of booster setup

2.6 Detonation Diagnostics

Detonation velocity was determined visually via high-speed camera record using a Phantom V7.11 with a frame rate of 66,019 fps, interframe time of 15.15 μ s, resolution of 160 X 304 pixels, exposure of 0.4 μ s (0.29 μ s exposure for aluminum mixtures), 1 s of pre-trigger, and 1 s of post-trigger. A twisted pair of duplex wire affixed to the detonator, was used as a falling-edge camera trigger (i.e. “make” trigger). Phantom PCC 2.8 software was used to process the camera data, tracking the detonation front and using a distance scaling calibration for each record to obtain a detonation velocity. The detonation front was assumed to be the forward most position of the emitted band of light, following the contribution of the booster (Figure 2). The initiation of the booster produces a significant visual event and fireball,

present even in samples that do not detonate, and is defined herein as the “booster cloud” (Figure 2).

Figure 2. Detonation front in 70:30 $KClO_3$:sucrose with correction for angle

After using the Phantom PCC 2.8 software to track the scaled detonation front position x-y points through time, a correction was made to the geometric coordinates for the angle of incidence (to align the shot to a vertical position). The following equations for rotating the image were used where (X', Y') are the new coordinates:

$$X' = X\cos(\alpha) - Y\sin(\alpha) \quad (1)$$

$$Y' = X\sin(\alpha) + Y\cos(\alpha) \quad (2)$$

Where α is the incident angle from vertical, measured by taking the inverse tangent of two points on the side of the pipe (X_1, Y_1) and (X_2, Y_2) :

$$\alpha = -\tan^{-1}\left(\frac{X_2 - X_1}{Y_2 - Y_1}\right) \quad (3)$$

If two points are taken from the calibrated coordinate system (i.e. for 70:30 KClO₃:Sucrose) in mm (X_1, Y_1) = (89,30) and (X_2, Y_2) = (68,210), then $\alpha = 0.116$ rad, and $Y'(t)$ can be plotted for each time point (using equation 2), then the detonation velocity is the slope found by a linear least-squares fit to the $Y'(t)$ dataset (Figure 3). The detonation velocity was measured by performing a linear regression of all angle-corrected front positions at known camera frame time intervals. The distance vs. time curves were linear ($R^2 > 0.99$) for all of the samples that steadily detonated. Deviations from linearity were attributed to variations in packing density.

Figure 3. Detonation front tracking of tilt- corrected Y' points representing the shock front position through time. Linear slope is detonation velocity ($\text{mm}/\mu\text{s}$).

A pencil gauge pressure transducer (Kistler 6233A, 25 psi limit, calibrated sensitivity of 200 mV/psi) with coupler (Kistler 5134B, 0.05 Hz high pass filter) measured blast overpressure. Fifty foot coaxial cables connected the pencil gauge to the coupler, and coupler to a Tektronix oscilloscope. The pencil gauge was mounted 1.29 m high, positioned 6.096 m (20 ft) from the test device on a wooden stand weighted with sand bags. The Tektronix oscilloscope (model MSO4014B, max bandwidth of 100 MHz)

was set with a typical sampling rate between 5-500 MSa/s; it was automatically triggered on the rising edge of the pressure signal. Figure 4 shows the overall test arena setup.

Figure 4. Original setup of camera & pressure transducer. Later tests were filmed direct line-of-sight ~60m away.

2.7 Predictive Tools

Cheetah 7.0 from Lawrence Livermore National Laboratory (product library: jczs revision 1923 or bkws) was used to predict detonation velocity, detonation pressure, and total energy of reaction. Each mixture was evaluated with Cheetah using the density that was measured for its large scale test [8]. It should also be noted that the product library chosen in the Cheetah software had a significant effect on the detonation energy calculation, as will be discussed later.

The blast effects calculator (BEC V5.1) was used to obtain air blast TNT equivalence from the measured peak air blast pressures [9,10, 11]. For each experiment, a numerical root solver Python algorithm was used to minimize a solution for the TNT equivalent charge mass, i.e. the amount of TNT that would be needed to achieve the same blast pressure at the same distance. This equivalent charge mass is divided by

the actual charge mass of the FOX mixture to yield the normalized TNT equivalence. The equivalence value represents the number of kilograms of TNT that would be needed to observe the same pressure response from 1kg of the sample mixture at the same distance the pressure was measured; thus, TNT equivalence higher than 1 indicate a mixture more powerful than TNT, and those less than 1 are weaker. However, because the booster charge also contributed to the air blast pressure, that exact systematic contribution of the booster must be subtracted in terms of TNT equivalent weight (not in terms of pressure). An experiment with an identical booster and sand as the sample (acting as an inert), allowed the precise TNT equivalent weight of only the booster to be calculated in the same method as combined booster/FOX charges to be subtracted later. This charge configuration also gave a reference visual example of what a ‘failure’ reaction should look like on camera record. The determined booster TNT equivalent weight from this experiment (1.419 kg) was subtracted from the total TNT equivalent weight of each test to find the TNT equivalence of the sample.

$$TNT_{eq} = \left[\frac{(Experimental\ TNT\ eq.Charge\ mass - Booster\ eq\ charge\ mass)}{FOX\ Charge\ Mass} \right] \quad (4)$$

3 Results

3.1 Parr Bomb Results

A Parr bomb calorimeter was used primarily to estimate the maximum available chemical potential energy from each FOX mixture. Combustion was accomplished

under argon gas instead of oxygen gas to determine heat of reaction without any atmospheric oxygen (Table 1). As a result, the heats of reaction (dH_{rxn}) should be necessarily lower than heats of combustion, especially because many of these mixtures are fuel-heavy. *The heat of reaction is intended to provide an upper-estimate of the amount of exothermic energy contribution to wave propagation in the chemical reaction zone of the detonation wave*; in actuality, not all the chemical energy available in the mixture is capable of supporting to the detonation wave. Non-ideal explosives like these FOX mixtures particularly demonstrate this deficiency. The calorimeter is fitted with a pressure transducer to observe the pressure response as a function of time due to rapid gas production, sometimes called internal blast. Similar closed-volume pressure measurements are a common tool for propellant applications. Thus, it was possible to compare the response of a number of common gun propellants (Red Dot, Pyrodex, black powder) to FOX mixtures of interest; some of these materials have demonstrated the ability to detonate and others have failed to detonate even in the most favorable of circumstances. In general, the propellants exhibit a larger amplitude (ΔP) and shorter burn time to peak (Δt), but the FOX mixtures usually release more heat (q_{rxn}). Pressure responses of ammonium nitrate (AN) and potassium nitrate (KN) with sucrose were significantly delayed compared to other FOX (Figure 5). It is interesting to note that KN:sucrose burned only slightly slower and with slightly less energy than a similar mix which was spiked with 3% potassium chlorate (KC), but on the large scale straight KN:Sucrose mixes did not achieve steady detonation, while those with 3% KC did.

Table 1 shows that the available chemical energy from the formulations differ if judged by the sub-milligram-scale by DSC samples (far right column, Table 1) or by the heat of reaction observed in 2 g Parr bomb samples (column, labeled “ΔU” Table 1). Heat of reaction (i.e. Parr data) is greater than DSC heat of decomposition, particularly when fuel was aluminum. However, aluminized formulations were tested in open pans by SDT where there were ample opportunities for sample evaporation or sublimation. A

Figure 5 Pressure vs. time plots for burn of 2g fuel:oxidizer mixes under argon. In parentheses result of 5kg test (D=Detonation; NO=No Detonation). NH_4NO_3 :sugar mix was so slow that it has its own time axis.

comparison of the same oxidizers with different fuels shows the best choice of fuel in terms of energy input is aluminum over sucrose (Table 1). Figure 6 compares heat of

reaction to the rate of the reaction. Interestingly, the ammonium nitrate-sucrose mixture (AN:Su) displayed such a long rise time (~7.6s) that it caused its dP/dt value to be nearly zero. Other fuel/oxidizer mixtures were also examined in the Parr bomb (Appendix 1.1). Neither thermites nor gun propellants released more energy than FOX mixes.

Table 1. Calorimetric Results of FOX Mixtures (2g, 2859 kPa Argon)

Mixture, wt %	Δ Time (ms)	RSD	Δ Pressure (psi)	RSD	Δ P/Time (psi/ms)	RSD	Δ U (kJ/g)	RSD	DSC/SDT 8:2 Ox:fuel (kJ/g)
Oxidizer: Al, 70:30									
K ₂ Cr ₂ O ₇	474	7%	473	6%	1.00	13%	4.18	1%	0
KNO ₂	696	21%	634	14%	0.95	31%	5.20	8%	2.4
KMnO ₄	254	8%	738	9%	2.91	10%	5.31	2%	0.73
KIO ₃	241	38%	824	8%	3.86	46%	4.94	0%	0.49
KNO ₃	403	13%	915	1%	2.30	12%	5.98	3%	1.3
KIO ₄	153	30%	1204	5%	8.50	38%	6.32	1%	0.17
KBrO ₃	105	21%	1482	5%	14.5	23%	6.53	1%	0.45
KClO ₄	78	18%	1780	3%	23.4	20%	7.52	1%	0.8
KClO ₃	96	11%	1730	5%	18.3	15%	7.18	5%	1.5
NH ₄ NO ₃	195	19%	1504	4%	7.85	14%	7.85	0%	0.64
NH ₄ ClO ₄	81	15%	2293	4%	29.0	20%	9.36	1%	1.6
Oxidizer:Sucrose 70:30									
K ₂ Cr ₂ O ₇	2084	29%	113	2%	0.06	29%	1.14	2%	0.1
KMnO ₄	641	5%	288	2%	0.45	3%	2.07	0%	1.8
KIO ₃	334	13%	365	3%	1.11	15%	1.47	1%	0.84
KNO ₂	509	19%	392	3%	0.79	20%	2.61	3%	1.69
KNO ₃	509	3%	534	1%	1.05	3%	2.81	1%	0.68
KIO ₄	183	10%	570	3%	3.13	9%	2.11	0%	1.81
KBrO ₃	78	8%	852	6%	11.02	13%	2.77	2%	1.72
KClO ₄	187	15%	1024	10%	5.59	21%	4.65	0%	0.87
KClO ₃	104	21%	1037	7%	10.53	29%	4.05	0%	2.09
NH ₄ NO ₃	7687	10%	222	9%	0.03	20%	2.70	1%	1.79
NH ₄ ClO ₄	97	7%	1347	4%	13.94	10%	4.88	0%	1.36
KNO ₃ :Sucrose (70-KClO ₃ :30)									
KNO ₃	509	3%	534	1%	1.05	3%	2.81	1%	
KClO ₃ 7%	332	2%	3928	2%	11.80	3%	2.89	2%	
KClO ₃ 17%	248	13%	4369	3%	17.90	17%	3.04	1%	
KClO ₃ 35%	148	12%	5580	3%	38.10	10%	3.41	1%	
KNO ₃ :Sucrose 70:30 + RDX									
RDX 5%	479	4%	4186	1%	8.80	5%	2.93	2%	
RDX 10%	401	7%	4509	3%	11.30	6%	3.11	1%	
RDX 50%	212	18%	7852	4%	37.80	15%	4.24	1%

Figure 6: Comparison of two values obtained via bomb calorimetry-heat of reaction and average slope of pressure rise in closed-vessel bomb.

3.2 Detonation Testing

3.2.1 High Speed Photography and detonation velocity

Potassium nitrate (KN), potassium chlorate (KC), potassium permanganate (KMnO₄), potassium iodate (KIO₃), ammonium nitrate (AN), and ammonium perchlorate (AP) were prepared with sucrose (Su) fuel; in addition, KN, AP, and AN were prepared with aluminum (Al) fuel. All two-component FOX mixtures were prepared at a 70:30 wt:wt ratio with fuel. Later, KN-Su mixtures were adulterated with both KC and high explosive 1,3,5-trinitro-1,3,5-triazacyclohexane (RDX). Table 2 shows FOX mixtures for which detonation testing was attempted. Five of the mixtures failed to propagate

detonation; of these, all exhibited at least a slightly higher than zero TNT air blast equivalency, but only three of the mixtures propagated long enough before failing to record a detonation velocity. Figure 7 provides screen captures of the detonation records. The detonation front position was assumed to be the leading edge of the bright line running ahead of the booster product expansion cloud. Figure 8 shows an enlarged picture of three example FOX mixtures known to be improvised explosive threats which detonated (AN:Sucrose, AN:Al, and KC:Sucrose) and one more example of one which did not detonate (KMnO₄:Sucrose). Detonation was distinguished from a burn by the rapid PVC wall expansion angle immediately behind the front, e.g. AN:Al in Figure 8. The early stages of the KN:Al record suggest a steady detonation, but after some time the wall expansion angle separated from the bright front, indicating a transition to low-pressure burn (Figure 9). It could be said that this mixture was more flammable than detonable, a phenomena known as a ‘pathological detonation’ [12, 13] for which no detonation solution is more stable or faster-moving than the burn front.

Figure 7: A frame from video of each FOX, when reaction was ~75% along 2 ft pipe. FOX 5 to 16 show front separated from booster cloud. (D=Detonation, NO=NO Det).

Figure

8: Detonation tests: 3 steady detonations (left); and one failed (right)

Figure 9a: KN:Sr started with a linear detonation velocity (note dim orange line emerging from booster cloud), but quickly failed. Later this formulation successfully detonated after being spiked with <5% KC or RDX.

Figure 9b: KN:Al Pathological detonation in KN:Al started as an overdriven detonation (note PVC wall expansion angle in early frames), later transitioned to burn.

3.2.2 Blast Pressure

The blast records from 6m (20ft) away are recorded in Table 2 below and represent the peak air blast pressure from a pressure-time trace. An example is shown in Figure 10. The peak amplitude was the only measurement later used from the blast record although some information may be drawn from the later-time section of each record. In particular, it may be possible to determine some late-time combustion reactions which may help characterize the non-ideality of the FOX mixtures, but this section of the blast record is often obscured by reflections from the test environment which are difficult to subtract out from a complex combustion event. For analysis, the blast pressure was first converted to TNT equivalent mass, and the booster contribution was subtracted; the remaining amount of TNT equivalent mass was divided by the actual FOX mixture mass to yield the TNT equivalence of the FOX mixture (Table 2). Later this TNT equivalence was used to infer the amount of energy released by normalizing to the heat of reaction of TNT. Figure 11 shows a rough correlation exists between TNT equivalency and heat of reaction as measured by bomb calorimetry.

Figure 10: Typical blast pressure trace. Pressure presents as sharp rise to a maximum; perturbations later may indicate combustion dynamics are obscured by ground reflections and other complications. A python algorithm reduces sampling frequency to a user-defined 5MHz, locates the maximum value and calculates TNT equivalent mass without a booster correction using the blast effects calculator formula. A booster correction is made later.

Figure 11: Air blast TNT equivalence estimates with calorimetry heat of reaction.

Table 2. Detonation Testing Summary: Strikethrough values are mixtures whose detonation wave eventually failed. Some air blast records which did not collect or were over-saturated are marked “-“. For TNT a literature value [14] was used.

Composition						Charge Params		Bomb Calorimetry				Detonation Measurement		
Ox 1 ID	Ox1 w	Ox2 ID	Ox2 w	fuel ID	fuel w	Charge Mass (kg)	Charge Density (g/mL)	Calorimetry Heat (kJ/g)	dt (ms)	Calorimeter dP (psi)	dP/dt (psi/ms)	Phantom Det Velocity (km/s)	Air Blast TNT Eq booster corrected	Air Blast Energy (kJ/g)
KNO ₃	70	-	-	Al	30	3.64	0.751	5.98	398	915	2.30	0.55	1.20	5.51
NH ₄ ClO ₄	70	-	-	Al	30	3.13	0.691	9.36	79	2293	28.97	2.24	2.10	9.60
NH ₄ NO ₃	70	-	-	Al	30	3.14	0.681	7.85	192	1504	7.85	2.70	2.59	11.86
KMnO ₄	70	-	-	Sucrose	30	5.22	1.101	2.07	507	228	0.45	0.00	0.10	0.46
KIO ₃	70	-	-	Sucrose	30	6.83	1.491	1.47	329	365	1.11	0.00	0.18	0.84
KNO ₃	70	-	-	Sucrose	30	4.71	0.973	2.81	508	534	1.05	0.67	0.28	1.30
KClO ₃	70	-	-	Sucrose	30	4.79	0.989	4.05	99	1037	10.53	2.58	1.42	6.48
KClO ₃	70	-	-	Sucrose	30	5.25	1.102	4.05	99	1037	10.53	3.05	1.08	4.95
KClO ₃	70	-	-	Sucrose	30	5.05	1.287	4.05	99	1037	10.53	2.86	-	-
NH ₄ NO ₃	70	-	-	Sucrose	30	4.12	0.868	2.70	7655	222	0.03	3.49	0.85	3.91
NH ₄ ClO ₄	70	-	-	Sucrose	30	4.66	0.979	4.88	97	1347	13.94	3.89	1.87	8.53
KNO ₃	67.9	KClO ₃	3.0	Sucrose	29.1	5.00	1.143	3.06	470	571	1.21	1.46	0.33	1.53
KNO ₃	67.2	KClO ₃	4.0	Sucrose	28.8	5.00	1.012	3.16	400	537	1.34	1.68	-	-
KNO ₃	63.0	KClO ₃	7.0	Sucrose	30.0	4.71	0.968	2.89	520	587	1.13	1.71	1.12	5.14
KNO ₃	35.0	KClO ₃	35.0	Sucrose	30.0	4.77	1.007	3.41	146	809	5.53	2.24	1.17	5.36
KNO ₃	69.4	RDX	1.0	Sucrose	29.6	5.00	0.910	2.93	390	581	1.49	1.58	0.28	1.30
KNO ₃	67.9	RDX	3.0	Sucrose	29.1	5.00	0.896	3.18	470	571	1.21	1.73	0.39	1.78
KNO ₃	66.5	RDX	5.0	Sucrose	28.5	4.25	0.884	2.93	420	609	1.45	1.76	0.88	4.01
KNO ₃	35.0	RDX	50.0	Sucrose	15.0	4.99	1.053	4.24	208	1139	5.48	4.80	0.96	4.41
TNT	100	-	-	-	-	3.66	0.769	4.57	-	-	-	3.84	-	-
TNT	100	-	-	-	-	4.00	0.814	4.57	-	-	-	4.24	1.00	4.59
Booster	100	-	-	-	-	0.55	-	-	-	-	-	-	0.00	0.00

3.3 Cheetah Thermochemical Predictions

The Cheetah code was used to simulate the detonation parameters of each FOX mixture tested. It uses thermochemical equilibrium to calculate the Chapman-Jouguet (CJ) state, i.e. the composition and thermodynamic states of the detonation products at a point representing a theoretical condition of stability for a 1-D detonation wave. This produces an estimate of detonation velocity and other CJ-state variables; further, the code calculates the process of an adiabatic expansion from the CJ state to the reference state (i.e. ambient pressure and temperature). After the expansion has stabilized through several iterations of chemical equilibrium, the integration of the CJ adiabat reports the total detonation energy. Results are displayed in Table 3.

Table 3: Cheetah Results Summary Displaying Dv and TED. Each mixture was calculated with a density commensurate with measured experimental density.

Composition						Cheetah Prediction	
Ox 1 ID	Ox1 w	Ox2 ID	Ox2 w	fuel ID	fuel w	Cheetah Det Vel (km/s)	Energy of Detonation (kJ/g)
KNO ₃	70	-	-	Al	30	1.23	7.24
NH ₄ ClO ₄	70	-	-	Al	30	2.75	10.21
NH ₄ NO ₃	70	-	-	Al	30	3.57	9.11
KMnO ₄	70	-	-	Sucrose	30	2.12	2.83
KIO ₃	70	-	-	Sucrose	30	3.60	1.39
KNO ₃	70	-	-	Sucrose	30	3.14	2.69
KClO ₃	70	-	-	Sucrose	30	3.78	3.59
KClO ₃	70	-	-	Sucrose	30	4.22	3.61
KClO ₃	70	-	-	Sucrose	30	4.22	3.61
KClO ₄	70			Sucrose	30	3.84	3.25
NH ₄ NO ₃	70	-	-	Sucrose	30	4.60	2.66
NH ₄ ClO ₄	70	-	-	Sucrose	30	4.89	3.93
KNO ₃	67.9	KClO ₃	3.0	Sucrose	29.1	3.039	2.80
KNO ₃	67.2	KClO ₃	4.0	Sucrose	28.8	3.04	2.84
KNO ₃	63.0	KClO ₃	7.0	Sucrose	30.0	3.05	2.96
KNO ₃	35.0	KClO ₃	35.0	Sucrose	30.0	3.44	3.14
KNO ₃	69.4	RDX	1.0	Sucrose	29.6	3.07	2.72
KNO ₃	67.9	RDX	3.0	Sucrose	29.1	3.14	2.77
KNO ₃	66.5	RDX	5.0	Sucrose	28.5	3.21	2.82
KNO ₃	35.0	RDX	50.0	Sucrose	15.0	4.83	4.02
TNT	100	-	-	-	-	4.34	3.42
TNT	100	-	-	-	-	4.50	3.47

Discussion

4.1 General Discussion

The individual results from both the small scale tests and the detonation tests were successful in discriminating and ranking the mixtures. The order from each test may be slightly different, but within the dynamic range of the diagnostics, there was sufficient resolution in measurements to accurately describe the dynamic phenomena and differentiate every mixture, even when only small changes were made. Testing the reproducibility of the detonation experiments was limited by time and cost of duplicate tests, but good agreement was seen from the rare duplicate measurements. Discrepancy between duplicate measurements can possibly be explained by the different experimental density from the replicates, which was not controlled. FOX mixtures were chosen to examine three issues: relative detonability of the oxidizers; effect of the fuel choice on detonation performance; and sensitivity of detonation performance to small changes in composition. The booster charge was chosen to uniformly overdrive detonation across the entire cross-section of the FOX mixture so that no initiation threshold criteria need be considered. A summary of the data is given in Table 2. Among the FOX mixtures studied, AN and AP with sucrose fuel had the highest D_v , though density variations make it difficult to quantify the extent to which they are superior, but without question, the AN and AP mixtures with aluminum performed the best in terms of TNT air blast equivalence.

Table 4: Summary of Measurements and Cheetah Predictions. Strikethrough Dvs are velocities measured prior to failure. Zero input means no observable reaction front; FOX scattered on ground.

Composition						Charge Params		Bomb Calorimetry				Detonation Measurement			Cheetah Prediction	
Ox 1 ID	Ox1 w	Ox2 ID	Ox2 w	fuel ID	fuel w	Charge Mass (kg)	Charge Density (g/mL)	Calorimetry Heat (kJ/g)	dt (ms)	Calorimeter dP (psi)	dP/dt (psi/ms)	Phantom Det Velocity (km/s)	Air Blast TNT Eq booster corrected	Air Blast Energy (kJ/g)	Cheetah Det Vel (km/s)	Energy of Detonation (kJ/g)
KNO ₃	70	-	-	Al	30	3.64	0.751	5.98	398	915	2.30	0.55	1.20	5.51	1.23	7.24
NH ₄ ClO ₄	70	-	-	Al	30	3.13	0.691	9.36	79	2293	28.97	2.24	2.10	9.60	2.75	10.21
NH ₄ NO ₃	70	-	-	Al	30	3.14	0.681	7.85	192	1504	7.85	2.70	2.59	11.86	3.57	9.11
KMnO ₃	70	-	-	Sucrose	30	5.22	1.101	2.07	507	228	0.45	0.00	0.10	0.46	2.12	2.83
KIO ₃	70	-	-	Sucrose	30	6.83	1.491	1.47	329	365	1.11	0.00	0.18	0.84	3.60	1.39
KNO ₃	70	-	-	Sucrose	30	4.71	0.973	2.81	508	534	1.05	0.67	0.28	1.30	3.14	2.69
KClO ₃	70	-	-	Sucrose	30	4.79	0.989	4.05	99	1037	10.53	2.58	1.42	6.48	3.78	3.59
KClO ₃	70	-	-	Sucrose	30	5.25	1.102	4.05	99	1037	10.53	3.05	1.08	4.95	4.22	3.61
KClO ₃	30	-	-	Sucrose	30	5.05	1.287	4.05	99	1037	10.53	2.86	-	-	4.22	3.61
NH ₄ NO ₃	70	-	-	Sucrose	30	4.12	0.868	2.70	7655	222	0.03	3.49	0.85	3.91	4.60	2.66
NH ₄ ClO ₄	70	-	-	Sucrose	30	4.66	0.979	4.88	97	1347	13.94	3.89	1.87	8.53	4.89	3.93
KNO ₃	67.9	KClO ₃	3.0	Sucrose	29.1	5.00	1.143	3.06	470	571	1.21	1.46	0.33	1.53	3.039	2.80
KNO ₃	67.2	KClO ₃	4.0	Sucrose	28.8	5.00	1.012	3.16	400	537	1.34	1.68	-	-	3.04	2.84
KNO ₃	63.0	KClO ₃	7.0	Sucrose	30.0	4.71	0.968	2.89	520	587	1.13	1.71	1.12	5.14	3.05	2.96
KNO ₃	35.0	KClO ₃	35.0	Sucrose	30.0	4.77	1.007	3.41	146	809	5.53	2.24	1.17	5.36	3.44	3.14
KNO ₃	69.4	RDX	1.0	Sucrose	29.6	5.00	0.910	2.93	390	581	1.49	1.58	0.28	1.30	3.07	2.72
KNO ₃	67.9	RDX	3.0	Sucrose	29.1	5.00	0.896	3.18	470	571	1.21	1.73	0.39	1.78	3.14	2.77
KNO ₃	66.5	RDX	5.0	Sucrose	28.5	4.25	0.884	2.93	420	609	1.45	1.76	0.88	4.01	3.21	2.82
KNO ₃	35.0	RDX	50.0	Sucrose	15.0	4.99	1.053	4.24	208	1139	5.48	4.80	0.96	4.41	4.83	4.02
TNT	100	-	-	-	-	3.66	0.769	4.57	-	-	-	3.84	-	-	4.34	3.42
TNT	100	-	-	-	-	4.00	0.814	4.57	-	-	-	4.24	1.00	4.59	4.50	3.47
Booster	100	-	-	-	-	0.55	-	-	-	-	-	-	0.00	0.00	-	-

4.2 Experimental Agreement with Cheetah Predictions

4.2.1 Cheetah Total Energy Detonation (TED)

The first comparison of our experimental data to Cheetah calculations is the comparison of isoperibol (bomb) calorimeter heat output (ΔH_{rxn}) to the Cheetah predicted energy of detonation. The total heat of detonation calculated from Cheetah agrees with the measured heat released in the calorimeter (Figure 12) indicating the chemical reactions in the bomb calorimeter and those simulated in the Cheetah detonation environment are similar. Bomb calorimetry results match predicted detonation energies better than other bench-scale laboratory thermal tests (e.g. DSC or TGA) probably because the temperature in the calorimeter is allowed to climb much higher than in the others tests, and the higher temperatures more closely resemble the

detonation environment; i.e. DSC and TGA may not have access to complete reaction pathways at their temperatures.

Cheetah results on FOX formulations with aluminum fuel were calculated assuming all aluminum reacted, which was not the case, *vide infra*. The calculated energies of combustion were only slightly higher than those of detonation. For the FOX mixtures with sucrose, the Cheetah calculated combustion energy was about 30% higher than detonation; and for TNT, combustion energy was approximately 400% higher than the detonation energy. This is in line with the degree to which these formulations are oxygen deficient in detonation; but when exposed to excess oxygen at longer time-scales, excess fuel burns completely in air. If the FOX mixture compositions were adjusted to stoichiometric, then heat of detonation and combustion would have closely matched, but for this set of experiments, weight percent of fuel was held constant.

Figure 12: Correlation between ΔH_{rxn} and Cheetah predicted total heat of detonation.

4.2.2 Cheetah Detonation Velocity (Dv)

Observed detonation velocities correlate with Cheetah predicted detonation velocities, although all the FOX mixtures fall below the line of agreement (Figure 13). Use of aluminum fuel did not increase the detonation velocity (neither calculated nor observed); in fact, detonation velocities of aluminum-fueled formulations were consistently lower than the sugar-fueled analogs, mostly due to decreased gas production with aluminum. The two TNT shots were performed at slightly different densities, which explains the reason their measured detonation velocities differ. These values agree reasonably well with previously published density vs Dv curves for TNT [15], although agreement is inferred since the density is outside the published range. A line of 75% agreement seems to work well for the majority of steady detonations of FOX mixtures. Since almost none of the FOX mixtures achieved greater than 75-80% of their calculated heat of detonation, it suggests that they are affected by phenomena for which the 1-dimensional Cheetah code cannot account but which are insignificant in the more “ideal” explosives. These non-ideal mixtures are so slow to react and so near their critical diameters that 1-dimensional estimates are particularly unreliable indicators of actual performance on the 5 kg scale. Choice of product library in Cheetah had a profound effect on detonation energy calculation. Figure 14 exhibits the range of results calculated for one formulation (potassium nitrate-sucrose). Based on the match to our calorimetric data, “jczs” was the library used for the data in Table 4. The “bkws” library, whose TED measurement also closely matched the KN:Su calorimetric heat of reaction, was used for determining of percentage active aluminum

discussed later; the jczs reactant library did not contain the needed entry for ‘inert aluminum.’

Figure 13: Detonation velocities (km/s) observed vs Cheetah calculated.

Figure 14: Cheetah library comparisons for potassium nitrate-sucrose. None of the predictions for detonation velocity (blue) matched observed values; thus, the library was chosen by closest match to energy release (red) experimentally observed (URI exp).

4.3 Comparisons of Detonation Velocity to Lab Scale Analytical Tests

4.3.1 Bomb Calorimetry Heat of Reaction (ΔH_{rxn}): The bomb calorimeter measures both the overall heat of reaction (ΔH_{rxn}) and the time-resolved pressure response. Figure 15 shows the relationship between measured heat of reaction and measured detonation velocity. There appears to be a correlation between the heat of reaction of the sucrose-fueled mixtures and their measured detonation velocity but not for the aluminized-materials. For the sucrose formulations the plot suggests a minimum energy (~ 2.8 kJ/g) is needed for detonation in this configuration. Assuming that is true, it was speculated that adding a species which would contribute energy might push low-energy formulations to detonation; this was investigated. However, complete substitution of aluminum (a high-energy fuel) for sucrose, significantly increased the heat release, but detonation velocity decreased. This effect was both predicted by Cheetah and observed in our measurements.

Figure 15: Measured detonation velocities vs calorimetric heat of reaction. There appears to be a trend for sucrose-fueled mixtures but not followed for aluminized.

4.3.2 Bomb Calorimeter Pressure Rise Rate: The pressure rise observed in bomb calorimetry was not a good indication of detonation performance. This was particularly true for the ammonium nitrate-sucrose mixtures since this detonable mixture took longer to react in the calorimeter than any other FOX mixtures, even those which were non-detonable under our conditions. Apparently, rapid chemical kinetics for this mixture appear exclusively at high pressures. This discrepancy is illustrated in Figure 5 and Figure 16. On the opposite end of the spectrum, AP:Su performed well in the calorimeter but produced only modestly higher detonation velocity in the field than the ammonium nitrate mixture.

Figure 16: Correlation average closed-vessel pressure rise rate with measured detonation velocity. Note AN-Su displaying a near-zero dP/dt , but showing a very strong detonation velocity.

4.4 Air Blast Correlation with Laboratory Analytical Measurements

4.4.1 Bomb Calorimeter Heat of Reaction: When air blast pressure measurements were converted to TNT equivalent values and plotted against bomb calorimetry data (Figure 17), a correlation was observed which exhibited the same trend to an energy threshold as seen in the plot of detonation velocities versus bomb calorimetry energy (Figure 15). As expected, the air blast TNT equivalence increased significantly with the aluminum-fueled FOX mixtures. It is well known that aluminum does not react rapidly enough to contribute much of its energy to the detonation front; hence, the provision in Cheetah to make some of the aluminum content “inert”. However, the significant increase in energy of aluminum fueled mixtures does react in time to substantially enhance blast response, as our data attests.

Even though the records appear similar, the pressure rise event in the bomb calorimeter is a relatively slow burn compared to detonation and is, therefore, not directly related to detonation blast pressure in the field. However, bomb calorimeter pressure rise should be better correlated with air blast than with detonation velocity because air blast response allows a larger fraction of the FOX available energy to contribute to the measurement. Combustion rates are quite sensitive to external pressure, and a full range of external pressures would have had to be tested to get an accurate picture of the behavior of each FOX mixture. For some mixtures, namely ammonium nitrate, the 400 psi atmosphere was simply not enough to prompt a violent, rapid burn in the calorimeter, but it detonated relatively well (3.49km/s) despite poor performance in the calorimeter--a modest energy output (2.7 kJ/g) and extremely slow

time to peak pressure (15 times longer than the next slowest, KN:sucrose and KMnO_4 :sucrose, neither of which detonated steadily at the 5 kg scale). This anomaly testifies to the complication of correlating laboratory-scale tests directly with large-scale. Notably, our experimental TNT air blast measurements are in good agreement with a TNT equivalent value of 1.004, even though our experimental densities were lower than those usually tested to establish TNT equivalent fit equations. This emphasizes the fact that air blast measurements do not require an ideal reaction zone to represent the entirety of the energy output of a material. While detonation velocity is strongly dependent on density, blast pressure is less so; as long as the same chemical reactions are taking place, the same overall energy is released in the blast wave, and the air blast response would be similar even if the experiments propagated at wildly different detonation velocities.

Figure 17: TNT Blast equivalence vs heat of reaction. Steadily-detonating aluminized mixtures perform markedly better than most sucrose-fueled mixes, despite lower detonation velocities. TNT air blast eq. from 3rd KC-Su lost due to saturation of signal.

4.4.2: TNT Air Blast versus Pressure Rise Rate (dP/dt): The most promising correlation between lab-scale measurements and detonation performance should arguably be the internal blast-like pressure rise in the bomb calorimeter and the air blast measured in the field. The measurements are similar, and neither requires the mixture to be particularly ideal to perform well. The correlation below (Figure 18) indicates that, indeed, it seems that a more intense pressure event in the closed vessel calorimeter loosely correlates with a higher TNT equivalence, but it provides no stronger correlation than heat of reaction.

Figure 18: Average Pressure rise rate vs. TNT air blast eq. The plot shows a similar trend for predicting TNT eq. as Figure 17, particularly illustrating the AN:Su outlier, which under-performed and AP:Al which over-performed in the closed-vessel

4.4.3 TNT Air Blast Energy vs Bomb Calorimetry Heat of Reaction: In order to compare the heat of reaction with an air blast response, the TNT equivalence value must be transformed into a number which is in the same dimensional units. If we assume the amount of energy that the standard TNT experiments release is its literature value for heat of detonation, then the TNT equivalencies of the FOX mixtures can simply be multiplied by this value and the response recorded by the blast pressure probe can infer the amount of energy in the air blast. Figure 19 compares this air blast energy to the amount of energy released in the bomb calorimeter. This computation is a little tricky because TNT, although the standard to which other explosives are often compared, is, itself, not clearly defined in terms of the chemical energy released. The heat of combustion for TNT (i.e. the amount of heat released when it burns in pressurized oxygen completely to gas) is more than four times higher than the amount of heat released in an oxygen-free environment (i.e. the heat of detonation). The heat of reaction (no oxygen) is likely an upper limit for the amount of energy that can be released in the detonation reaction zone contributing to wave stability and propagation velocities, but it is not clear how much of the 400% extra energy is incorporated into the blast wave over distance. It can likely change over time as more TNT is burned in air. Therefore, the correct number by which all TNT equivalences should be multiplied is surely higher than the heat of detonation but lower than the heat of combustion. Heat of detonation was chosen for comparison; if TNT heat of combustion had been used, the inferred air blast energy would have been significantly higher than those recorded in Table 4 or Figure 19.

Figure 19: Air blast energy vs. bomb calorimetry heat of combustion. This plot should look identical to that in Figure 17, but because values on both axes are kJ/g, the line of agreement can be drawn. It illustrates which mixtures infer more or less energy in air blast than in calorimetry and highlights differences in detonation performance--mixtures that did not steadily detonate virtually all appear below the line. Blast energy inferred for these mixtures was much lower than heat of reaction in the calorimeter. It is not believed that the mixtures indicated above released more energy in air blast than in the calorimeter; normalizing TNT equivalence by the TNT heat of detonation (no oxygen) simply infers a minimum estimate of the energy released.

4.5 Doping of Potassium Nitrate-Sugar to achieve steady detonation: Potassium nitrate with sucrose fuel (KN:Su) was a particularly interesting mixture in that a non-steady detonation wave emerged for a couple of charge diameters but eventually failed. The failing velocity profile indicated a detonation velocity of 0.67 km/s, which was well below the Cheetah-predicted value of 3.14 km/s. This means that the mixture was likely very close to its critical diameter, and the detonation wave was

highly curved. The failure occurred because the energy losses in the form of pressure relief waves at the charge edges eventually coalesced and disrupted the over-driven detonation condition from the booster charge. At this point, the shock wave decoupled from the chemical reaction, and the detonation wave was quenched. It is possible that increasing the charge diameter would transition this material into a detonable regime, but it seemed more interesting to alter the available energy content by doping the KN:Su with a more energetic, more explosive compound to investigate how close this borderline formulation was to forming a steady detonation. Two strategies were employed to increase the available energy to the KN:Su mix: first, maintaining the 70:30 wt:wt KN:sucrose ratio while substituting RDX, a highly-ideal monomolecular explosive; and second, substituting potassium chlorate (KC) for portions of the potassium nitrate. When substituting RDX, as much as 50:50 RDX:FOX was used, and the detonation velocity was in excellent agreement with Cheetah predictions at this high concentration of ideal explosive dopant. It was found that both 5% and 3% RDX in complementary concentrations of 70:30 KN:Su were detonable, but 1% RDX failed similar to the unadulterated KN:Su; the threshold was therefore between 1-3%. The second strategy of doping KN:sucrose was to exchange a small fraction of the KN with KC, an oxidizer which successfully detonated in a FOX mix with sucrose fuel. Following this idea introduced mixtures which were still 70% oxidizer, but of that, mixtures with 50%, 10%, and 5.6%, and 4.2% KC were made. In these mixtures, KC constituted 35%, 7%, 4%, and 3% of total FOX mixture, and all but 3% KC detonated steadily in field tests. In bomb calorimetry tests corresponding to field tests, samples were spiked in a similar fashion to the RDX, maintaining the 70:30 ratio of KN:Su. It

is notable that such small amounts of added energy pushed the KN:sucrose into a detonable configuration. The bomb calorimetry energy at threshold percentage of RDX and KC is trivially larger than the unadulterated KN:Su mix; both the data and detonation theory indicate that energy output alone does not guarantee detonation. Gas production, diameter, confinement, and most importantly, the *rate* of energy release by the formulation under shock loading must be fast enough to sustain detonation. If we make the rather speculative assumption that the rates of all the oxidizer/sucrose reactions are similar because the rate of reaction in these low density powders is diffusion controlled, only then might we expect a smooth correlation between energy of reaction and detonation performance.

Using Cheetah to calculate for several mixtures of doped KN:Su using both RDX and KC, the predicted total detonation energy (TED) and the detonation velocity (Dv) of the lightly doped mixtures are considered in Figure 20 to investigate the narrow threshold region of the experimental space.

Figure 20: Cheetah comparisons for KN:Su doped mixtures. Left, Cheetah Dv is compared to experimentally-measured Dv. All mixtures under-performed compared to calculations but followed trend of small increase in energy with add energetic. Right, Cheetah-calculated total detonation energy compared to calorimetric results (BC for bomb calorimeter) for doped KN:Su mixes. Trend is reversed- experimental

points are slightly above predicted. Adding dopant at these levels has a trivial effect on predicted or experimental values for energy release or detonation velocity. [Experimental value for D_v of neat KN:Su mixture is off-scale (0.67kJ/g).]

The doping experiments illustrate that a very small amount of a more explosive component can easily enhance a marginal formulation, in this case KN:Su, into a steady detonation. To better illustrate this effect, the plot in Figure 21 was created by normalizing the inferred air blast energy (Figure 19) to the heat of reaction of each FOX mixture. This plot infers what fraction of the heat in the bomb calorimeter was released in air blast. Remember that the air blast energy numbers are minimum estimates inferred from normalizing TNT equivalence with TNT's heat of detonation. Almost without exception, mixtures that failed to detonate appear below the TNT line, and those which detonated appear above it.

Figure 21: Fractional energy inferred from air blast (normalized to TNT heat of rxn) compared to calorimetric heat of reaction.

4.6 Partial aluminum reaction

Because it is believed only a small fraction of the aluminum powder added reacts in the reaction zone of these FOX mixtures, a Cheetah study was undertaken to infer the extent of reaction in the three aluminum-fueled fox mixtures. For the AN-Al mix, the experimental detonation velocity was only 2.7 km/s, but Cheetah predicted a 3.57 km/s wave speed. For this investigation, the decrease from predicted velocity will be exclusively attributed to partially-reacting aluminum in the reaction zone, although the kinetics of the oxidizer may also be contributing. By letting Cheetah simulate a series of virtual mixtures using its ‘inert’ aluminum (iAl) reactant and gradually varying its ratio to ‘active’ aluminum (aAl), the trend in Cheetah-calculated detonation velocity was fit to a multi-order polynomial. With the fit calculated, the experimental detonation velocity was numerically solved to indicate the inferred fraction of aAl to iAl. Figure 22 illustrates the Cheetah-calculated trends of Dv vs. percent aAl for the three aluminum-fueled mixtures using two distinct Cheetah product libraries. Plots in Figures 22a, 22b, and 22c start (at the right) with 30% aAl, which would be the 0%iAl point; note all the Cheetah-calculated values in Table 4 refer to this “all-aluminum-active” point. As each line travels leftward, the concentration of aAl decreases and is replaced with iAl, keeping the ratio of oxidizer to total fuel (aAl and iAl combined) constant, as well as maintaining the experimental density for each simulation. This monotonically decreases the detonation velocity until the intersection of the predicted Dv decreases to the value measured in the field (horizontal dotted line in Figures 22a, b,c). This point is numerically solved for each mixture and reported in Figure 22d. These numbers indicate that even though the bomb calorimeter and the air blast response accommodate the slow Al reactions, the dynamic shock-loaded chemical

environment was only able to extract a very small percentage of the exothermic energy available from oxidizing the aluminum inside the reaction zone. Increasing amount of inferred %aAl ($AP < AN < KN$) inversely trends with the qualitative understanding of reaction rates among these oxidizers ($KN < AN < AP$). Since AP is expected to exhibit a particularly fast reaction, less of the slow, diffusion-limited aluminum chemistry will be able to contribute to the reaction zone, and therefore support the detonation front. Conversely, the slowest-reacting oxidizer in this list, KN, infers the largest amount of Al reacting in the reaction zone, since the slow-burning reaction zone in KN likely provides the most time for Al to react. It should be noted that KN alone is not “energetic”; KN decomposition is endothermic [4]. Unfueled KN should never detonate. If the inferred aluminum content is correct, the cusp of stable detonation solutions seen in Figure 22c around 4% aAl is particularly delicate for KN compared to AN or AP. The latter both contain enough energy, themselves, to, at least theoretically, propagate detonation without fuel. KN must be fueled in order to detonate even under the best circumstances; but when the fuel is very slow-acting, KN is particularly susceptible to a terminal drop in energy output. While the exact numbers for inferred aluminum reacted (aAl) are very sensitive to the Cheetah product library used (Figure 22d), this trend of increased fuel consumption in the reaction zone by slower-reacting oxidizers may extend to fuels beyond aluminum. It is an interesting opportunity for further investigations.

Figure 22a, 22b, 22c: Cheetah-calculated D_v trend with decreasing fractions of active aluminum and the inferred fraction of aluminum active in AP:Al, AN:Al, and KN:Al, respectively, based on experimental D_v measured herein. Results for two different product libraries (see Figure 14) are shown in 22d. Library comparisons for inferred active aluminum different in magnitude, but relative order is preserved.

4.7 Ideality

To globally evaluate the degree of non-ideality of the FOX mixtures tested herein, we propose a quantity of ideality η , where $\eta = D_{v \text{ exp}}^2 / D_{v \text{ Cheetah}}^2$ and $D_{v \text{ exp}}$ is the experimentally-measured detonation velocity, and $D_{v \text{ Cheetah}}$ is the Cheetah-predicted detonation velocity. For simplistic chemistries, the term η is expected to be linear with energy output such that if the quantity η is 0.5, only half of the energy output was achieved inside the reaction zone where the detonation wave could be supported; thus, the closer η is to unity (100%), the closer the formulation performed to the ideal, 1-

dimensional Cheetah prediction. From the plot in Figure 23 it can be seen that a cutoff value around that of the bomb calorimetric heat of reaction for potassium nitrate-sucrose (2.8kJ/g) is at the threshold between mixtures which are highly non-ideal and those closer to ideal. An interesting observation about this plot is that oxidizers tested with different fuels seem to remain similar in quantity of η . KN:Su and KN:Al differ in η by 15%; but AP:Al/AP:Su differ by only 1%; and AN:Al/AN:Su, by only 3%. Also noted was that the experimental detonation velocity of the KN:Su doped mixture containing 50% RDX was in near perfect agreement with the Cheetah predicted detonation velocity and sits near unity in Figure 23. Bomb calorimetry indicated that the added RDX did not appreciably increase the available energy content of the mixture; however, the added RDX apparently gave the mixture access to 100% of its available energy inside the chemical reaction zone, whereas Figure 23 indicates that, for most FOX mixtures, only 50-60% of their energy was able to contribute to detonation velocity. When this RDX doped KN-Su mixture is examined in air blast efficiency, no significant increase in energy was observed relative to the other steadily-detonating FOX mixtures (Table 4). This illustrates that ideal and non-ideal explosives alike will respond similarly in terms of blast pressure. Even mixtures which failed to detonate, namely KN:Su, KMnO_4 :Su, and KIO_3 :Su, each released significantly higher fractions of their bomb energy in the conservative air blast results (46%, 22%, and 57%, respectively, Figure 21) compared to their ideality inside the reaction zone (4.55%, 0%, and 0%, respectively) inferred from Figure 23. A more comprehensive study completing the matrix of possible oxidizer-fuel combinations will reveal whether this is a global truth or just coincidence with these few samples.

Figure 23: Ideality of FOX mixtures inferred from Cheetah calculations and detonation measurements. Most FOX mixtures release between 50-60% of predicted detonation energy (Cheetah). Threshold mixtures which eventually failed or barely remained stable released between <25% of predicted energy.

4.8 Pathological Detonation

The KN:Al data point is odd because the mixture exhibited a detonation to burn transition. The mixture could be said to be more flammable than detonable. The video record is quite clear about this transition. Initially, the shock-driven reaction propagated as the other FOX mixtures, but eventually a strangely turbulent, slightly dimmer flame front began to sharply separate from shock front position where the PVC casing walls were flared. This burn front was much cooler than the detonation

front, as seen by the color temperature and light intensity in the frames captured by the Phantom camera (Figure 9b). After some induction time, the PVC casing finally burst, but all at once rather than progressively, as in the wave propagation scenarios observed in traditional detonation and with the other detonable FOX mixtures. Although it has been sparsely observed, certain complicated reaction kinetics and wave dynamics lead to very interesting and non-intuitive detonation instabilities, of which this low-density configuration of KN:Al is a prime example. These instabilities, or rather competing eigenvalues of wave stability conditions, have been named pathological detonations and represent only marginal cases of explosive science [12, 13]. We believe the most contributing factors to the pathological condition in the case of 70:30 KN:Al are the extremely low experimental density (which encourages very fast convective burn rates and discourages high detonation velocities), the low gas production of aluminized FOX compositions, and the light confinement. All these factors retard the speed of the detonation in the traditional sense, giving opportunity for the very high-energy, low-pressure combustion kinetics to overtake the otherwise slow but steady detonation. Further experiments at different diameters and with slightly different component ratios, as well as good charge density control and embedded pressure gauges, would be a good start to understand the complex combustion/detonation environment in this improvised, non-ideal material.

5 Conclusions

Measurement or calculation (Cheetah) of heat of reaction (oxygen-free) is a useful first step in determining whether a formulation is potentially detonable. It appears

there is a minimum energy density which a formulation must possess to be detonable. However, examination of Table 4 clearly shows that some materials with relatively high reaction energy (i.e. KNO_3/Al) do not support steady detonations, while others with relatively low reaction energy (i.e. $\text{AN}/\text{sucrose}$) do. Clearly any small-scale test or model must take into account the rate of reaction as well as total gas and energy release, but there is evidence to indicate that higher heats of reaction indicate a higher degree of ideality compared to prediction.

The potassium nitrate-sucrose mixture exhibited low heat release in the bomb calorimeter, as well as slow pressure rise times, and it did not steadily detonate on the 5 kg scale. This mixture did show a temporary and failing detonation wave before failing completely (Figure 9a), unlike the potassium permanganate and potassium iodate mixtures, which failed to produce any reaction light throughout the high-speed record of attempted detonation. In spite of this, they released some fraction of their energy to air blast, contributing 22% ($\text{KMnO}_4:\text{Su}$) and 57% (KIO_3) of their respective heats of reaction to air blast energy (Figure 21).

The substitution of aluminum for sucrose dramatically increased the energy released (as measured in the calorimeter), but as predicted by Cheetah, the detonation velocity actually decreased significantly. Due to the slowness of the reaction of the oxidizer with aluminum, only a fraction of the energy released by the aluminum oxidation supported the detonation front [16]. The residual energy was released later in the air blast as the hot, unreacted aluminum particles reacted with atmospheric oxygen. It

appears that the slow kinetics of potassium nitrate allowed time for more aluminum to contribute energy in the reaction zone than the faster ammonium nitrate or perchlorate. The mixture ($\text{KNO}_3\text{:Al}$) did not formally detonate in the traditional sense (a pathological detonation); it transitioned to a fast burn. The rate recorded in Table 4 is prior to the burn, but the burn velocity was marginally faster (0.70 km/s), as judged by video record and discussed above (Figure 9b).

The potassium nitrate-sucrose mixture was prodded into detonation by spiking it with 3 wt% RDX or 4 wt% potassium chlorate. Both these chemicals were capable of adding rapidly-available energy to the mixture. However, the total energy released by these potassium nitrate-sucrose mixtures with additives was only a little over half that of KN:Al , which failed to detonate in the traditional sense. This observation points to the importance of the rate at which the energy is provided. Figure 5 colors the bomb calorimetry trace to reflect the large-scale detonation result- red for full detonation, blue for failure to detonate. In general, FOX mixtures which exhibited a rapid rise to peak pressure detonated on the large scale. Those FOX mixtures which reached peak pressure more slowly did not detonate at the large scale, with the exception of AN:Su which burned so slowly that it required its own axis (see top of Figure 5). AN-sucrose apparently has an extremely pressure-dependent decomposition rate law, making low-pressure burn-time tests a poor indicator of reaction rate in the detonation time scale for this mixture. AP:Su burned extremely fast in the bomb calorimeter, yet marginally outperformed other FOX mixtures with similar energy output. Regardless of fuel choice (sucrose or aluminum) the oxidizers tended to perform to a similar degree of

ideality, e.g. AN:Al and AN:Su were of similar ideality ‘ η ’, as well as AP:Su and AP:Al.

Density was not controlled in this study; therefore, discrepancies between repeated detonation velocity measurements (TNT, KC:Su) can be attributed to the difference between the experimentally-measured densities at the 5kg scale (Table 4). Cheetah predictions account for decreased explosive performance with lower density mixtures. As seen in Figure 24, the detonation energy, reported from Cheetah in kJ/g, is not constant, but decreases quadratically with density (air blast response would likely remain constant). This means that lower density mixtures appear to release their energy content less efficiently, contributing to further decrease of the detonation velocity beyond that of the ratio ρ/ρ_0 , i.e. the density penalty to detonation performance is greater than the decrease in available energy density in kJ/cm³. At all densities, the total energy of detonation (TED) calculated by Cheetah was less than the literature value for heat of detonation (-4.5 kJ/cm³) [14].

Detonation velocity is strongly dependent on density [17]. The FOX mixtures were far from full density since they were used at tap-density; thus, a significant amount of reaction time was spent in diffusion and compaction of the fuel and oxidizer. High explosives, such as pentaerithritol tetranitrate (PETN) or trinitrotriazacyclohexane (RDX), have reaction zone lengths less than 100 μ m, reacting rapidly enough that much of their energy supports the detonation front [18]. This is in contrast to a non-ideal explosive where the reaction zone length is long, for example in ANFO the estimated reaction zone is 8 to 12 mm [18]. With these FOX mixtures, the fraction of

energy released to the front must be significantly less than even TNT. How much less and the role of compaction in these composite materials will be the subject of future studies.

Figure 24: Cheetah predictions for detonation velocity and heat of reaction for TNT as a function of density.

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Appendix 1.1

Parr Bomb Calorimetry Output for Thermites vs. Gun Propellants

Mixture wt,wt	Δ Time (ms)	RSD	Δ Pressure (kPa)	RSD	Δ P/Time (kPa/ms)	RSD	Δ U (kJ/g)	RSD
Thermites								
Fe ₃ O ₄ , Mg 80,20	1501	9%	424	10%	0.3	19%	2.12	0%
Fe ₃ O ₄ , Mg 70,30	1322	3%	970	7%	0.7	9%	3.22	1%
Fe ₃ O ₄ , Mg 60,40	1043	17%	1539	3%	1.5	16%	3.73	0%
Bi ₂ O ₃ , Al 70,30	288	13%	1810	8%	6.3	4%	1.75	1%
Bi ₂ O ₃ , Al 90,10	210	50%	2277	12%	12.8	46%	1.61	1%
Bi ₂ O ₃ , Al 80,20	113	6%	2704	8%	23.9	13%	1.90	2%
Gun Propellants								
BP Meal	183	6%	4812	9%	26.4	13%	2.83	1%
BP 07 Mesh	139	9%	5000	3%	36.1	6%	2.78	1%
BP 20 Mesh	127	16%	5033	3%	40.4	13%	2.79	2%
Pyrodex	116	8%	5143	1%	44.6	9%	2.87	1%
Red Dot	86	13%	9761	3%	115.1	15%	4.40	0%

MANUSCRIPT 2

**CHARACTERIZATION OF DETONATION WAVEFORMS IN
HOMOGENEOUS NON-IDEAL EXPLOSIVES**

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Characterization of Detonation Waveforms in Homogeneous Non-Ideal Explosives

Abstract

Presented here are the results of around 60 explosive experiments which have become the first series of experiments at the URI explosives test facility to successfully field photon Doppler velocimetry (PDV) and ultra-high speed photography. The experiments outlined herein focus on homogeneous improvised explosives, namely hydrogen peroxide (HP) aqueous solutions fueled with ethanol (EtOH). These materials have been chosen as a template system for evaluation with time-resolved detonation diagnostics aimed at screening clandestine non-ideal explosive threat materials for detonable character even, and especially, in configurations below their critical diameter. The ‘galloping’ detonation instabilities of these materials have been captured on camera in the stoichiometric mixture of HP:EtOH in diameters from 1 to 2.6 inches; a steady detonation never formed. Reactive particle velocity waveforms for this mixture were measured by PDV through a PMMA pressure-maintaining window. These materials were subjected to both overdriven and underdriven configurations, and non-steady waveforms have been collected to monitor non-ideal explosives under these conditions i.e. inside the infinite diameter region of a range of different shock loading environments. Several mixtures of HP:EtOH have also been artificially doped with glass microballoons to study the ideality of this mixture in a heterogeneous regime. Successful detonations of heterogeneous HP:EtOH mixtures were observed using as low as 40% HP.

1 Introduction and Background

Materials characterized as “explosives” release sufficient energy to “support” or “propagate” a detonation. Military explosives have been classified as such using detonation tests of prescribed size and initiating charge [1]. Homemade explosives (HMEs) often fail these tests because they release too little energy to support detonation in the prescribed tests; therefore, they are not recognized as real explosive threats. However, these HMEs will perform as explosive materials if the charge size is increased beyond a configuration-specific size, the critical diameter (D_{cr}). At sizes less than D_{cr} , an explosive will not propagate detonation; any conventional explosivity or detonability test performed under the critical diameter of the material will indicate that the material is not an explosive. The critical charge size of many potential threat materials is so large that they are frequently not perceived as threats, when in reality they were simply tested below D_{cr} . For example, as dictated by shipping regulations, ammonium nitrate (AN) is not classed as an explosive, rather as DOT 5.1, because it does not propagate detonation at a diameter of 3.65 cm [1]. However, with sufficient AN (e.g. when the diameter exceeds 100 cm) it becomes detonable, as was accidentally demonstrated by the explosion in West Texas in April, 2013 [2]. Field testing at large scales is hazardous, expensive and slow. Thus, the **goal of these studies was to determine whether a material is detonable at any scale by performing experiments with less than a few pounds**. A further complication exists in screening a material for explosivity. To confirm that a material is an explosive, traditional testing must be done well above critical diameter and with a sufficient initiating charge. Thus,

detonation failure can occur for several reasons including: (1) The material is too small in size; (2) It is insufficiently initiated; or (3) It is not an explosive. Traditional detonability tests do not differentiate. For non-ideal explosives, a term which describes most homemade explosives (HME), the constraint of performing small-scale testing necessarily means studying these materials in configurations well below their critical diameters (D_{cr}). When steady detonation is not possible, conventional metrics, such as detonation velocity, yield little information. New diagnostics must be devised. We have made several approaches to this problem. [3]

When a shock travels into an inert material, the peak pressure and wave velocity attenuate in time. This is a familiar phenomenon since we know that sound intensity wanes with distance from the noise source. However, if a shock of sufficient strength transits through an energetic material, the bonds in that material break and reform into new product molecules; this conversion releases energy. If the energy release occurs fast enough, the energy released contributes to the propagation of the shock front, and that shock reaches a stable flow which does not attenuate as long as energetic material remains. Following energy release, the hot product molecules expand and the elevated pressure in the region behind the shock front drops; this region is termed “the Taylor wave”. A one-dimensional depiction of this behavior is shown in Figure 1. In three-dimensions, reflections from the charge boundary relieve pressure from the chemical reaction zone at the charge edge, causing detonation front curvature and transferring some energy into accelerating the charge confinement. These effects are most severe at the charge boundary. At and below some critical diameter (D_{cr}), losses at the edges

overpower energy production, and detonation wave fails. For diameters larger than D_{cr} , the energy feeding detonation outweighs losses at the edge, and thus detonation propagates at a steady state.

Figure 1: Simulated PDV interfacial velocity of detonation wave structure illustrating the reaction zone and Taylor wave regions.

Characterizing detonation behavior for sub-critical diameters of non-ideal explosives is extremely challenging. **Unless supported by special device design, detonations fail for lack of sufficient and timely energy release from the reaction.** Detonation velocity is used as a measure of explosive performance; high detonation velocities reflect the high rate of energy release of conventional explosives. However, if the energy release lags in time (i.e., the reaction cannot keep up with the shock), the shock wave will decouple from the chemical conversion process, and the detonation will “fail.” Thus, an accurate velocity profile gives critical insight into the presence or absence of chemical reaction fast enough to support the detonation front.

To examine detonation of materials below their critical diameters, we chose to use transparent liquid explosives—liquid because the material can be easily shaped; transparent because high-

speed photography can be used as a diagnostic. A versatile array of techniques can enable in-situ monitoring of ignition and failure of detonation in real time. Visualizing the reaction wave should be straightforward with clear liquid explosives, such as nitromethane or hydrogen peroxide because they should be radiating brilliantly while detonating. Our initial successful test of a hydrogen peroxide/ethanol mixture shows this to be the case (Figure 2).

Figure 2. Development of detonation in hydrogen peroxide/ethanol mix (13.4%EtOH-balance 70%HP in water). Time between each frame was 3.3 us and each frame exposure = 30 ns. Shock-to-detonation transition is visible at about 26us from trigger.

Hydrogen peroxide (HP), discovered in 1818, is a clear liquid sold in aqueous solution. To consumers, it is available from pharmacies at 3 to 6 wt% concentrations; to industry, it is commonly available from 30 to 70wt%. Its uses are many: bleaching agent, detergent, disinfectant, propellants and chemical reagents. The pulp and paper and fabric industries are major users of its bleaching power; the corn industry is one of the many chemical industries exploiting its chemical reactivity. In 2015, world

capacity for H₂O₂ production was about 1.7 million tons annually. Because it can be used to make explosives it is on the Chemical Facilities Anti-Terrorism Standards (CFATS) list which controls solutions over 30 wt%. Nitromethane (NM), like hydrogen peroxide, is a clear liquid, but one with a strong organic odor and only slightly soluble in water. NM is a powerful solvent and a simple organic molecule (CH₃NO₂), from which other organic species can be prepared. NM has been examined as an explosive for decades since its simple atomic structure provides an experimental platform for studying basic detonation chemistry.

We intended to use a compilation of previous strategies to approach a small scale test suite that can probe potentially explosives materials below what would be their critical diameter. Our present experimental configuration is a cylindrical sample material or “acceptor” into which a shock wave is introduced by a cylindrical high explosive booster charge or “donor”. The time-resolved response of the acceptor to the imparted shockwave characterizes the acceptor as a potential threat by identifying if any detonation-like behavior was observed even if the acceptor is tested below its critical diameter.

The following three strategies outline our proposed approach:

1. Over-driven detonation failure: A material may fail to detonate because it is below its critical diameter or because it has no explosive character at all. By measuring detonation wave structure profiles through time, detonable character and failure rates will identify detonable materials whose failure to detonate in conventional

tests is simply a problem of charge size rather than those whose chemical contribution is too slow to grow to a detonation.

2. Under-driven shock to detonation transition: Characterizing the ignition and growth to detonation of a sample already identified to have detonable character (strategy 1) will indicate how easily a particular threat material may be initiated.

3. Steady detonation reaction zone structure: Making direct measurements of reaction zone length and assessing its sensitivity to chemical energy content or diluent added will indicate the maximum reaction zone thickness which propagates at a particular diameter and can be expanded to include a range of charge sizes.

In the *first experimental design, over-driven detonation*: examination of failure profiles), potentially-explosive samples will be subjected to booster conditions which should shock it to higher pressures and velocities than the theoretical detonation conditions of that sample material. This ensures that if detonation of that material were possible, it would exhibit detonation-like behavior in the initial (e.g. <5mm) stages of being shocked, i.e. before any sidewall effects could be felt. If detonation of that material is not possible, this test should show it as such and would still yield useful information. In other words, this design distinguishes between detonation failures caused by smallness of charge versus failures due to no explosive chemistry. A shock wave traveling through inert, non-explosive samples would quickly attenuate (decay) at a predictable (using hydrocodes) rate based on its thermodynamic properties; but if the sample exhibits detonable character, even if it is below its D_{cr} , the contribution of the chemical reaction could be measured by both PDV and ultra-

high speed photography. The PDV record would follow the particle velocity versus time profile by measuring the interfacial velocity of a sputter-coated, coaxial window in contact with the end of the cylindrical sample. The emitted light from chemical reaction behind the shock front (indicative of detonation) will be observed with ultra-high speed cameras. If the sample material exhibits detonable character in the initial stages but is below its critical diameter, the velocity profile (PDV) and the emitted light (cameras) will show the decay and eventual failure of the detonation wave into an inert shockwave. This decay process should indicate how far below D_{cr} the sample being tested is [4]. The effect of any shock-induced chemical contributions from a sample, especially one slowly releasing energy, would not be observed by techniques recording only the shock velocity decay, e.g. velocity pins or microwave interferometer, because the chemical contribution of the sample would not release rapidly enough to support the shock front. Late-time reactions would be invisible to these techniques, but the PDV approach would visualize the entire wave profile, including decay, which would indicate the presence of late-time reactions and chemical contributions which did not contribute to the wave velocity attenuation.

In order to track the attenuation of shock into a potential threat sample, end-on interfacial velocities for various lengths of sample could be collected. Comparison of signal attenuation among samples and a baseline inert material would indicate whether the sample material is contributing energy to the shockwave or whether it is attenuating the shock as in an inert. Only by measuring the entire wave profile (not just the wave velocity) can the nature of chemical energy contribution be determined. The rate and nature of quenching would indicate how far below critical diameter the

tested configuration is. The wave profiles of materials for which the critical diameters are known would be correlated to inert materials. The relationship, thus established, would serve as the benchmark for materials for which denotation or D_{cr} is unknown.

The experimental setup requires the use of a polymethylmethacrylate (PMMA) window which is acoustically impedance-matched to the sample so as to avoid reflections from that surface thus preserving the accurate particle velocity time history behind the shock front. Accompanying PDV will be high-speed photography. It is expected to show reaction light (directly related to temperature of the sample) in the first stage after the initial shock input, but this will be quenched if the sample is non-detonable or too far below its D_{cr} . The material chosen for design 1 are mixtures of HP and fuel. These homemade explosives (HME) can be clear liquids, which facilitate photo visualization; and being fuel-oxidizer mixtures, their chemical energy release can easily be tuned by adjustment of the fuel-oxidizer ratio.

The *second experimental design, under-driven shock to detonation transition* or SDT, attempts to observe an energetic sample transition a weak shock (imparted from the booster) into a pseudo-steady detonation. This test requires that the sample tested has detonable character and is above its critical diameter; otherwise, the detonation will grow into a pseudo-stable state then decay as in design 1. In this experimental design, the shock input by the booster is below the theoretical conditions calculated for a stable detonation in the sample material.

This transition begins as the booster-imparted shockwave traverses the sample without causing any chemical change. The sample behaves as an inert material during this

period. As the shocked sample remains under pressure loading, the chemical chain reaction begins to grow in the elevated pressures and temperatures behind the initial shock front. After the reaction has been allowed sufficient time to develop, a visibly-bright reaction wave accelerates through the shocked material much faster than the initial shock. This stage is labeled ‘superdetonation’ because it is traveling faster than the steady state shock would. When the superdetonation wave overtakes the initial shockwave, it will decay to its equilibrium value, if the sample is above D_{cr} ; or if the sample is below D_{cr} it will be quenched at the point where they intersect with the shock rarefactions from the sample. Until this happens, the center of the charge material proceeds as if the configuration were in an ‘infinite diameter’. In other words, the diameter of the charge takes effect only after the rarefaction waves have equilibrated, which takes longer for larger diameters. This window of time for which the charge behaves in an infinite diameter can be simulated with hydrodynamic modeling tools, namely ALE3D from Lawrence Livermore National Laboratory (LLNL) and CTH from Sandia National Laboratory. As long as this process can be completed while the experiment is kept in an infinite diameter state, the steady detonation conditions for that non-ideal material can be directly observed. LANL researchers have reported several SDT observations using magnetic embedded gauges including diluted nitromethane [5] (Figure 3) and concentrated HP solutions (no fuel added) [6].

Figure 3: LANL magnetic gauge SDT measurements of nitromethane/MeOH mixtures (left) [5], and hydrogen peroxide/water solutions (right) [6].

This transition to steady-state detonation has not been previously observed with ultra-high speed imaging directly. Our initial tests using this configuration seemingly captured this phenomenon (Figure 2). Figure 2 was taken using a Specialized Imaging SIMD16 camera, 304,000 frames/second ($3.3\mu\text{s}$ inter-frame). The charge (13.4%EtOH- balance 70%HP in water solution) was contained in a 1" diameter by 4" long clear PMMA (polymethylmethacrylate) pipe equipped with a 1.1" diameter x 1.1" long cylindrical PETN-based booster. The charge was oriented vertically and initiated at bottom by the booster. In frames at $9.9\mu\text{s}$ and $19\mu\text{s}$ the under-driven wave propagates into the explosive. Initially, the shock wave enters the material with flat curvature (not pictured). In the following few microseconds (seen at $9.9\mu\text{s}$), the wavefront in the sample assumed extreme curvature, channeling light from the booster to the camera. Frame at $19\mu\text{s}$ illustrates the inert shockwave travelling through the sample. The last frame ($26\mu\text{s}$) illustrates the chemical reaction wave, which had been developing within the compressed region behind the shock, accelerating and overtaking the initial shock front in textbook SDT fashion. While Figure 2 illustrates our ability to observe some detonation events and is a necessary milestone, this study

of the reaction zones will be deferred until after experiments of type 1 and 3 are performed. Future tests will use PDV to confirm the photographic record interpreted as SDT. Use of PDV will effectively simulate the magnetic gauge experiment of Los Alamos [5, 6] by testing subsequently longer charges to act as ‘gauges’ embedded in a larger charge [7].

The *third experimental design, steady detonation*: reaction zone measurements will make direct measurements of the reaction zone length of steadily-detonating, non-ideal explosives. Specifically, it will observe the lengthening and weakening of the reaction zone as a result of dilution of an explosive material with an inert solvent. By measuring the structure of flow in the reaction zone as the material approaches critical diameter, relationships between diluent concentration and the fraction of energy available to support detonation can be drawn. By comparing these measured values to the theoretical calculations for the maximum energy contribution, the fractional energetic contribution to the detonation will be obtained. This reported value will greatly facilitate the understanding and prediction of the behavior of these materials. Once measured, the dynamic reactivity of these materials can be modeled and simulated in hydrodynamic reactive flow codes.

Los Alamos researchers have shown that the steady reaction zone of detonating nitromethane (NM) can be measured using photon Doppler velocimetry (PDV) [8] (Figure 4). They interpreted the length of reaction zone by mapping the literature value for the particle velocity at which total reaction should have taken place. In the

experimental record, the time/special distance to this point was reported as the reaction zone.

Figure 4: LANL approaches at studying steady detonation reaction zones with adulterated (sensitized [9] and diluted [8]) nitromethane.

A Russian research team uses the steady-state reaction zone assumption to measure the convergence of Taylor wave immediately following the reaction zone, to determine reaction zone length [10] (Figure 5). If the steady assumption holds, the length of the reaction zone should be the same in the PDV record regardless of the charge configuration (e.g. charge diameter, length, or booster size), but the Taylor wave (not steady-state) should diverge. By obtaining two or more PDV records of similar charges which differ only by one of these parameters, the Taylor wave divergence should begin at the end of the steady reaction zone.

Figure 5: Steady detonation wave profiles obtained by Russian scientists [10] for nitromethane illustrating steady, 1-dimensional reaction zone (0-50ns) and divergent Taylor wave (50-600ns) as evidence that flow within the reaction zone remains steady as the charge configuration changes, but the release wave (Taylor wave) diverges.

Initial tests will confirm methodologies by testing nitromethane, which has been tested by the Los Alamos researchers [8,9], the Russian scientists [10] as well as others. This requires two independent tests at different lengths to confirm the steady reaction zone assumption. Successive tests will focus on diluted NM/acetone mixtures. As the adulterant concentration is increased, the reaction zone will begin to lengthen and weaken. At some critical amount, detonation will fail to propagate; this is the critical diameter (Dcr). The study will examine the failure point of the NM/acetone mixture as well as points of dilution beyond detonation failure.

The diagnostic technologies used to characterize a growing (design 2) and failing (design 1 and 2) detonation fronts could be used to measure the length of the chemical reaction zone. Design 3 does not directly screen questionable materials for detonable

character but rather characterizes the nature of reaction zone lengthening as a function of available energy density. For this test, a detonable material must be tested above its critical diameter, and the chemical energy available will be diminished in subsequent tests by dilution until its failure. This approach will specifically measure what fraction of its energy the non-ideal explosive is using to support the detonation wave.

2. Experimental Details

Before the experiments the facility and instrumentation had to be acquired, set up, and proven fully functional. The development of an empty field at the URI Alton Jones campus included the planning and construction of a 2200 ft² building to house office space, lab space, and machine shop. The office was equipped with electricity, air conditioning, heat, and firing lines were buried for the convenience of initiating experiments without having to run cable for each shot. A firing pad, a 20 ft. diameter circle was excavated and back-filled with sand to prevent rock-throw; and adjacent to it a 10 ft diameter x 20 ft long buried instrumentation bunker was constructed. Although a number of standard operating procedures (SOPs) were in effect, with added facilities, it was deemed necessary to create one that outlined the responsibilities and duties of each present at the site, especially in regards to safety (Appendix 2.1). Diagnostics instrumentation, discussed below had to be specified and purchased.

2.1 Materials

All materials were obtained through commercial vendors. High explosive materials, including Primasheet sheet explosive and composition C4 were purchased through American Energetic Systems. Hydrogen Peroxide (HP) was purchased through Wilkem Scientific at 50wt% in water, then boiled in house to obtain 70%. Batches from 500 mL to 2 L were individually poured into a large boiling dish and allowed to come to a rolling boil on a large hot plate inside a fume hood. The temperature was often monitored to qualitatively assess the concentration. Since the boiling point of the stock HP 50% mixture was around 110°C and the boiling point of 70%, around 125°C, progress of the concentration was relatively easy to monitor. Usually concentration was allowed to proceed until the solution was boiling about 130°C. By creating a slightly more concentrated solution, it was easy to add water to obtain a precise concentration. Several batches were distilled in this manner and combined. The precise concentration of the combined batches was determined via refractive index (Atago RX-5000CX). The standard curve was used from Schumb [12]. The large batch was diluted to reach exactly 70.00wt% HP: 30wt% H₂O. Diethylamine Triamine (DETA) and ethanol (EtOH) were purchased through Sigma Aldrich. Glass microballoons were provided by 3M in the size range of 70 to 15 microns. Red Mills xanthan gum was purchased from Ocean State Job Lot, and 200proof EtOH was purchased from Fisher Scientific. All explosive detonators, unless otherwise noted, were RP-501 exploding bridgewire detonators (EBWs) manufactured by and purchased from Teledyne-RISI. All polymeric fixture stock, including polypropylene (PP), low and high density polyethylene (HDPE and LDPE), acrylonitrile butadiene styrene copolymer (ABS), polymethyl methacrylate (Plexiglass, acrylic, PMMA),

polyvinyl chloride (PVC), and nylon 6,6 (nylon), as well as all hardware were all purchased from McMaster-Carr, with the exception of schedule 40 PVC pipes which were purchased from Home Depot. Thin (0.0003in) thick polyimide films were purchased from CS Hyde.

2.2 Fixture Design

Fixture Design and Components: All fixtures were designed and built in-house at the URI explosive test facility. Fixtures used in this work contain (4) main features designed to reliably align and rigidly affix the major components of the experimental design. These features are the detonator, the booster, the sample explosive, and the PDV probe. These components and their fixture requirements are discussed later.

Several different fixture adaptations have been used through the course of this project; and with each design the governing principles of change were a) safety, b) reliability in alignment, c) rigidity, d) ease of machining and assembly, and e) cost. The safety concerns address the potential damage to personnel, instrumentation, and infrastructure from either blast pressure or fragmentation. The best practice to prevent damage from fragmentation was to design the device entirely from low density materials, namely plastics. By ensuring that the device was made entirely of plastic materials, it was reasonable to assume that the explosive event would break the fixture materials into small, low kinetic energy fragments. These fragments, because of their low density would slow quickly in air because of high drag forces, upon the incident of striking a piece of equipment (personnel would be in a sheltered location) they

would have little to no damaging power to penetrate. Potential danger from blast pressure is difficult to measure, particularly for delicate instrumentation. If of sufficient magnitude, the blast wave can damage equipment by pressure loading in the first 10 μ s, but it can also damage through reverberations in the instrument casing and benchtop that last 1000s of microseconds (μ s). Instrument manufacturers rarely, if ever, specify the damage thresholds for these types of stimuli; therefore, extreme caution was taken to prevent such damage. Blast pressure can be easily calculated, but how that translates to damage in complex internal working of high-speed cameras is unknown. By keeping the entire device and explosive loading as small as possible, several safety concerns were addressed, while simultaneously allowing instrumentation to gain closer optical access to the experiment. Only when absolutely necessary did the experiment size grow to a large enough that excessive distance was required to safely capture the event record without putting the equipment at significant risk.

Because safety considerations require that the fixture be made entirely of plastic, the second and third consideration for device design, reliability of alignment and rigidity, become more complicated. Plastic materials have notoriously high thermal expansion coefficients and often deflect under machine tooling which make dimensional stability and reproducibility much lower than their metal analogs. Aluminum or steel fixtures would serve the priority for repeatability and rigidity much better but would also be a severe fragmentation hazard. Since plastic was the low-frag option, it was imperative that the plastic components be rigorously validated for dimensional stability and

remade if the temperature significantly changed between the time it was machined and the time it was to be used. Particularly thick and well-supported features were used and only very light stresses could be applied to prevent bulging and deflection which degrade the alignment reproducibility. One benefit of liquid explosives is that they will always fill the container in perfect contact, avoiding the necessity of putting the material under pressure in the fixture as is often done with solids to ensure consistent contact pressure.

Many fixture designs were changed simply to make them easier to machine so that there was less down-time between experiments. Creation of the fixtures is described in more detail in Appendix 2.2. The best practice for making a fixture easy to machine is to reduce the number of components and number of tool changes during the process. Also a much quicker assembly can be achieved by eliminating the need for an alignment step of freely moving components by building features which indicate the detonator, booster, sample pipe, and PDV probe in alignment with each other upon assembly. A drawing of the most comprehensively accommodating fixture is pictured below in Figure 6. This design accommodates the most aggressive chemical incompatibilities via the inclusion of thin (0.0003in) Kapton (polyimide) film. The design operates by providing a rigid framework inside which pressure can be applied to clamp the explosive train (booster/donor, sample explosive/acceptor) in place. This fixture is specifically designed to allow assembly and installation of all components without the detonator, which, for safety, is inserted last. The device applies screw pressure to a block of polypropylene (PP) which slides freely along the guide rails.

When screw pressure is applied, the gap between the det block and the probe block closes down on the explosive stack and fixes the components location with the clamping force of friction. This design has proven most rigid and reliably alignable but has many components; when possible a simpler fixture was used. The liquid seal and chemical compatibility of this design rely on a thin Kapton film to protect fixture components from chemical incompatibilities with the acceptor. In the case of both HP/EtOH and nitromethane/DETA acceptor mixtures, the Kapton provided excellent protection from incompatible encounters.

Figure 6: Scheme for vise-style fixture used in some tests. Top view illustrates each component, each of which was machined in house except the EBW which was purchased. Bottom Assembled view shows the operating principle for alignment. Guide rails are chemically affixed to top and probe block; det block is retracted to place booster/sample/window stack in place. Screw applied pressure forms liquid-tight seal. Not pictured is Kapton film which serves as gasket and chemical barrier

The design constraints change based on the explosive materials being used, namely whether they are liquid or solid, chemical compatibility with other components, and optical clarity. When working with nitromethane (NM), for example, many polymeric

materials are incompatible because NM is a powerful solvent. The best materials for working with NM are polytetrafluoroethylene (Teflon or PTFE), polypropylene (PP), and polyethylene (PE). Because of the high cost of PTFE, the latter two were chosen. PP is usually cheaper in sheets and was therefore chosen for the det block. Because PP is chemically-resistant, it also resists the solvents in common adhesives and, therefore, would have been challenging to glue. Because adhesives were used to seat the top block, guide rails, and probe block, for these components either PVC or ABS plastic was used. PE was chosen for the sample pipe after a few tests with 'clear' PVC showed that its strong blue tint and rather thick walls (schedule 40) were a problem. The PE pipe was purchased as very thin (0.022in), clear tubes which gave excellent optical access to the interior of the pipe and could be purchased in a large variety of diameters (0.5" id to 2.5" id). The PE pipe was also compatible with both NM and HP:EtOH mixtures, although the PE demonstrated structural degradation with prolonged exposure to NM.

In nearly all cases, the experimental fixture was designed such that the fixture could be assembled without the detonator or the sample explosive. When the fixture was mounted and secured, the last step before firing the experiment was to fill the liquid sample explosive through an included hole in the acceptor pipe. Special precautions were taken to ensure that the filling hole did not retain an air bubble capable of disrupting the shock wave in the acceptor material, namely by placing it at the probe (downstream) end of the acceptor pipe and propping the entire fixture up to make the fill hole the highest point on the acceptor pipe. Figure 6 shows the final configuration.

Figure 7: Vise-style design on wooden support being filled with NM:DETA. Incline props fixture towards probe end (left), making air bubble millimeters from where shock impacts PMMA window. To minimize leaking, shot is fired immediately after fill.

For clear explosives, like nitromethane and HP:EtOH mixtures, optical access to the interior of the pipe is highly beneficial; backlighting the acceptor pipe aids visualization of wave propagation. Often the judgment on whether a material detonates or not is based on visual clues. When opaque materials are used or when the visibility into the experiment is no longer necessary, then thicker, more rigid and necessarily, less clear, pipes can be used. This was the case when very short acceptor lengths were used to work inside the infinite diameter; no camera record was necessary because a visual diagnostic would not have been helpful.

2.2.1 Detonator/Initiation Train

Early tests employed electric #8 blasting caps to initiate the explosive event. These devices work by accepting electrical current from a fireset, then passing that current through a thin nichrome bridgewire that rapidly heats. This wire is in direct contact with a heat-sensitive primary explosive which explodes upon heating of the bridgewire. This small explosive output from the primary explosive is enough to

ignite a low-density pentaerythritol tetranitrate (PETN) pellet in direct contact with the primary explosive. As the shock wave travels into the low-density PETN, it grows in intensity, then contacts another two or three pellets of PETN which are successively higher in density. This stack progressively grows the detonation to a sufficient size that the detonator can initiate many high explosive materials simply by placing it in direct contact with them. In this case, the detonator was placed, end-on, in contact with a small disc (0.75in od x 0.085in thick) of Primasheet. This begins the explosive train, which started with an electrical signal and became a steady detonation wave at the booster interface. Electric blasting caps have 100s of microseconds (μ s) in electronic jitter; thus, synchronizing diagnostics with the fireset would be impossible. For early tests in the series, blasting caps were used with 'make-wire' triggers which triggered directly from the explosive output. This triggering strategy was totally independent of the electronic delay and allowed use of cheaper #8 blasting caps during the prototyping stage of these experiments. Blasting caps are not precision devices, either in timing or in explosive output, but they were used in early experiments to keep costs down while different device designs were prototyped; once the test strategy and diagnostic capabilities were sufficiently developed, only EBW detonators were used.

Exploding bridgewire (EBW) detonators were chosen for this work for their safety and reliability. EBW detonators are intrinsically safe since they possess very high threshold voltage and current (4000V and 100s of amps). The detonator functions by passing very high currents through a thin bridgewire, similar to the electric blasting cap; but in the EBW the wire does not simply heat slowly on the 10s of microsecond

scale as in the blasting cap but rather explodes violently in under 50 ns. The exploded wire expands violently against the PETN ignition pellet with extreme force. If an electrical input to the detonator below the threshold is applied, then the wire simply does not heat fast enough to shock the PETN to detonation. EBW detonators are extremely reliable, since the industry which manufactures them requires them to be so. Dimensionally, the detonators are very precise, and the dimensions from the specifications can be used successfully to machine devices that will fit every detonator without taking custom measurements for each (Figure 8). The reliability in timing of EBWs used in these experiments has been qualitatively shown to be 25-50 ns, with a few exceptions. The company offers EBWs with tighter timing, but this timing is more than adequate for the experiments.

Figure 8: EBW sketch from company

The EBW detonators require a special fireset, a machine designed to reliably provide threshold currents above the manufacturer's recommendation; for all EBW-initiated experiments a Teledyne-RISI model FS-10 fireset was used. This unit consists of a control module which operates on a 40V rechargeable battery and connects to the

firing module via three conductor wire, which should be shielded if possible. The experimenter operates the control module by hand, and thus it must be in a protected bunker with the personnel. The firing module components include high-voltage converter, capacitor, and spark gap discharge; the outputs of the firing module are the high voltage posts to which the detonator leads are attached. Only high-voltage rated firing wire from Teledyne was used. This firing module is charged when the control module 'Arm' momentary lever is pulled; after a 15 second wait, it is ready to fire. The third wire carries the trigger signal from the controller which, when pulled to ground, initiates the spark gap discharge to fire the detonator connected to the high voltage. This particular fireset allows for external triggering but requires a signal at greater than 30V. The Stanford Research Systems DG535 signal delay generator was purchased with a special feature that provided special, high-voltage outputs linked to the standard low-voltage outputs. Triggering is discussed in a later section.

2.2.2 Booster/Donor Charge

The booster charge or donor charge (synonymous) for this work was always at least as large in diameter as the sample and was constructed from an ideal high explosive material, typically C4, which contains 91wt% 1,3,5 trinitro-1,3,5 triazacyclohexane (RDX), and the balance plasticizers and binders. This explosive is chosen because it can be easily hand-packed into a useful configuration at a reproducible density. The added 9% plasticizers and binders decrease sensitivity of C4 compared to neat RDX and transform texture of crystalline, powdered RDX into a moldable putty (Figure 9).

Figure 9: (Left) C4 being weighed into PE donor pipe. (Right) packed booster in sealed tube ready to shoot. C4 easily conforms to shape of the pipe under pressure

The principles that governed booster material choice and dimensional design were as follows: a) safety; b) reproducibility; c) high output; and d) chemical compatibility with the sample explosives. Safety is a primary concern because each booster must be pressed into the booster pipe (Figure 9). This places the experimenter at risk if the explosive material is particularly sensitive to impact, friction, or electrostatic discharge. C4 presents a small risk; therefore, it is a good choice for this component. In fact, C4 is so insensitive that the EBW detonator cannot be guaranteed to initiate it. For this reason the small disc (0.75" o.d. x 0.08" thick) of Primasheet (61% PETN-based sheet explosive), which is more sensitive to initiation, was used to ensure the reliable detonation of the C4 donor. Early tests utilized a stack of Primasheet discs as the entire booster; but as the device design became more mature, the hand-packed C4 booster became standard. Reliability constraint dictated that the donor charge be packed to a reproducible density to produce a standard output waveform. This is difficult to verify, but C4 is commercial manufactured using RDX, which is an ideal

explosive. This means a C4 donor charge will perform similarly in many different configurations, and it is not particularly sensitive to diameter or confinement. C4 is a high-output, high acoustic impedance explosive which will overdrive the liquid explosives being tested. By choosing a donor charge configuration which always overdrives the acceptor material, the acceptor material does not have to grow to detonation, a phenomena which may lead a detonable configuration to fail at initiation. This strong booster guarantees ignition in the early stages (i.e. inside the infinite diameter) and gives the best chance for a long-lasting steady detonation after that. The booster charge was characterized using the same diagnostics subsequently used in the actual experiments. Results from these experiments are presented later.

2.2.3 Sample Explosive/Acceptor Charge

The explosives used for the main charge were largely chosen for their applicability to improvised clandestine threats. Although many threat materials are solid mixtures of fuels and oxidizers, the utility of windowed-PDV is largely dependent of the uniformity of the waveform on the timescale of the waveform features to be measured. In this case, a timescale of <10 nanoseconds was of interest, and the explosives used detonated around 6 μ m/ns. This required a geometrically-smooth detonation wave to at least 60 μ m, which most solid fuel-oxidizers or other non-ideal improvised explosives cannot provide. Homogeneous liquid materials, however, provide smooth detonation fronts because they contain no density interruptions. The homogeneous explosive mixtures of hydrogen peroxide (HP) and ethanol (EtOH) are threat materials but also provide a homogeneous platform for windowed-PDV. As it turned out, the

HP:EtOH waveforms, although smooth, were particularly turbulent and difficult to interpret. Nitromethane (NM) acceptors were used to verify our diagnostics by comparing our results to the abundance of data published regarding NM in the existing literature.

Three different internal diameters (ids) have been used throughout this work, nominally 25mm, 40mm, and 65mm. These diameters were increased by necessity, since the diameter effect strongly influenced these non-ideal explosives. Working with smaller acceptor ids is preferred, but when steady detonations were not achieved at a particular diameter, increasing the id was a simple way to encourage the HP:EtOH mixtures to detonate. Unfortunately, even up to 65mm id was insufficient to produce detonation in the stoichiometric HP:EtOH mix. Diameters above 65mm would likely provide a steady platform for detonation in the non-ideal mixtures, but going any larger would have contradicted the nature of the project the mission of which was to eventually evaluate explosive behavior on the small scale. Early tests used a schedule 40 'clear' PVC acceptor pipe to contain the sample explosive. In these tests, the nominal id was 25mm, and the wall thickness was ~4mm. This wall thickness gave the pipe body sufficient strength such that features could be machined into the pipe wall to grip and clamp the det block and probe block to the pipe, but the thinner (.022") PE pipe required external framework- leading to the vise design.

2.2.4 Photon Doppler Velocimetry (PDV) Components

Photon Doppler Velocimetry (PDV) data is a Fourier transformation of the Doppler-shifted beat frequency through a heterodyne interferometer. The URI PDV setup was constructed of individual components as will be discussed below. This basic components of PDV are a laser, a circulator, a probe, a reflector, and a data logger. An overall schematic is shown in Figure 10. Figure 11 shows bare-probe configuration of a test characterizing particle velocity of a RP-501 exploding bridge-wire detonator. This test confirmed the velocimetry record by allowing the reflective surface of an RP-501 detonator to expand into air. A bare fiber probe was used to emit and transmit the incident and reflected light.

Figure 10: Schematic of PDV setup shows components inside the fiber optic enclosure which include two fiber optic splitters and one fiber optic circulator.

Figure 11: Sketch and Data obtained from initial PDV tests. Surface velocity was predicted (CTH) and measured via PDV. Predicted CTH calculations employ basic assumptions which can be fine-tuned for more accurate results, but agreeable velocities were obtained.

2.2.4.1 PDV Window

For windowed-PDV to properly measure waveforms of detonating explosives, the end face of the explosive charge must be fitted with an acoustically-matched, optically transparent window. The most common materials for this are lithium fluoride, quartz and sapphire, but appropriate windows are very expensive. It happens that these materials are a poor choice for PDV windows in this application because they are not very well matched to the acoustic impedance of the HP-EtOH explosive. Wave mechanics dictate that waves transiting from low to high acoustic impedance would cause high-pressure reflections back into the delicate reaction zone of the explosive. This would have been the case with detonation waves traveling from low impedance HP-EtOH into lithium fluoride. The measured waveform, in such a case, would not be

a reliable measurement of the internal state of the reaction zone. There would be no way to know if the impedance mismatch would have significantly perturbed the reactive flow. By choosing an acoustically-matched, optically-transparent material for the window, no significant reflection would return towards the reacting media; and the entire reaction zone waveform could be collected by the PDV system as unperturbed as possible.

Various methods were used to produce the windows from PMMA stock. Sometimes the windows were cut to length from cylindrical stock, and sometimes PMMA was purchased as sheet stock with the desired thickness, and discs were cut to diameter. When stock of the correct thickness was chosen, the factory surface finish was quite smooth, so much so that visually no distortion was visible when looking through it. The factory surface could easily be used as-is for the experiments, but if cylindrical stock was cut to length, it took considerable effort to polish the front and back surfaces. The polishing procedure was first done with a series of sandpaper with increasing grit number-600grit, 1000 grit, 2000 grit. Once the sandpaper steps cleared the surface of machine marks, the last steps were to use Nova plastic polishing compounds, number 2 and 3. These polishing compounds never produced a surface as optically smooth as the factory finish on the cast sheets. It was preferable to cut and turn discs from the right nominal thickness, but the drawback to using the factory surfaces was that the casting process did not produce perfectly parallel surfaces. This discrepancy was often negligible, but it was never properly characterized.

In addition to surface finish and optical clarity, a major consideration in preparing the experimental windows was the shock transit time. The shock transit time dictates how long the PDV experiment can take place. The PDV experiment requires a reflection from the explosive/window interface, which it observes through the shocked window material. As long as the shock front moves through the window material, the PDV record continues uninterrupted, but once the shock in the window reaches the back surface, a relief wave reflects back toward the interface and will disrupt the interfacial velocity record when they meet. The longer (thicker) the window, the more time before this happens. Assuming a trivial change in shock velocity as the detonation wave transits into the acoustically matched window, a $6\text{mm}/\mu\text{s}$ shock speed requires a little more than 3mm of window length to record a $1\mu\text{s}$ waveform. This is a typical length when measuring non-ideal waveforms, although reaction zone lengths are only in the 10s of nanoseconds; therefore, technically, a much thinner window may be used. However, for growth to detonation studies, much longer times may be required. Depending on the shock-to-detonation conditions, the required time of experiment in these cases may be a few microseconds, requiring much thicker windows. The window is often made a smaller diameter than the acceptor pipe for simplicity of construction; but if long experiment times are required, the diameter of the window must accommodate an uninterrupted experiment time before relief waves coalesce in the center. Just like the infinite diameter principle, the window shock wave experiences relief waves which will disturb the experimental record if the aspect ratio of the experiment is too long. Larger diameter windows are required for longer duration experiments. (A more thorough description of the wave transit through the

window and the manner in which PDV measurements are effected by the window is found later.)

Reflective coatings were used at the explosive/window interface to better reflect the laser light back into the PDV system. This reflective layer is very important to the PDV measurement and several attempts have been made to provide the best coating. The principle guiding the choice of reflective coating is getting the diffusiveness correct. The factory surface of the PMMA is a specular reflector with an index of refraction of about 1.4925 at 1550nm. This makes a reflection coefficient of 3.75% or -14.3dB. This, alone, may be enough reflection for PDV; but the explosive liquids, both NM and HP:EtOH, have similar indices of refraction to PMMA such that the reflection is virtually quenched when the liquid is in direct contact with the window. This necessitates a reflective coating. The most reproducible reflective coating is sputter-coated metal, applied in the materials characterization laboratory in the URI engineering department. In these studies, the sputter target has always been gold, but could have been any other common mirror-like metal, e.g. aluminum and silver. Copper would have been a poor choice because it is incompatible with HP. More discussion of window/reflector interface and surface preparation will be discussed later. Thin aluminum foil has been used successfully for the reflective coating, but it is often difficult to lay on smoothly while gluing to the window. It may be possible to use only the Kapton film as the reflective coating, but it was never tried.

2.2.4.2 PDV Probe

The windowed-PDV technique requires laser light, emerging from the sample leg of the PDV interferometer, to pass axially through the window and reflect off the acceptor/window interface. This reflected light must then return and be collected by the same probe which emitted the incident beam. The fiber-optic component which mounts directly to the PMMA window and is responsible for directing the light onto the acceptor/window interface is called the fiber optic probe. There are three types of probes employed during the experiments at URI: a) bare fiber probes, b) collimated probes, c) focusing probes. The simplest type of probe is the bare fiber probe. The bare fiber probe is made directly from the fiber optic cable which carries the incident and reflected laser light to and from the interferometer. Because the several inches of the fiber optic cable attached to the fixture were always damaged during the experiment, a long section (10m) of bare fiber (core, cladding, and a tight, 200um buffer only) was spliced on as a leader to protect the bulk transmission cable from damage. The preparation of the fiber probe was done simply by first stripping and cleaning the end of the bare fiber which would be mounted in the fixture. A Fujikura CT-30 single-mode fiber cleaver was used to cut the fiber end to an accurate 90° angle. This fiber could now be directly incorporated into the fixture. The numerical aperture of the SM-28 bare fiber used in all bare fiber probes was 0.14, which corresponds to a light spreading angle coming out of the fiber of 16°. Figure 11 is a schematic of the bare fiber probe illustrating the laser light incident to the gold reflector and the reflected, Doppler-shifted light returning to the fiber. The light

which is imaged back onto the fiber core is often a very small percentage of the light sent in the first place.

Figure 12: Sketch of bare fiber laser probe in windowed-PDV application. Sketch is not to scale but illustrates the orientation of the probe to the window and the spreading angle. The higher index of refraction in PMMA (1.4925) deflects the spreading angle to a narrower cone. More detailed discussion on geometry of a bare fiber reflector and dynamic response is in Appendix 2.3

Bare fiber probes struggle to collect much return light for two reasons: a) the emission and collection optical cross-section is the mode field diameter of the single mode fiber, approximately $10.4\mu\text{m}$; and b) the spreading angle quickly disperses the light across a large area. Together this means that by the time the reflected light images back onto the bare fiber, the projected cone may be many orders of magnitude larger in cross-sectional area than the collection cross-section. To minimize this loss, thinner windows should be used, and the fiber should be placed as close as possible to the

back surface of the window. The amount of returned light is often many orders of magnitude less than the incident light, even when reasonable precautions are taken. In these cases, external amplification of the light may be necessary to record enough return light to record the experimental record. Bare fiber probes offer the ability to utilize the reflection of the laser at the fiber/air interface as the reference leg of the interferometer. A more thorough discussion of the interferometer is discussed later, but the other PDV probes typically come from the manufacturer with an anti-reflective coating which prevents using this reflection.

The second type of probe, which is more common in conventional PDV applications, is the pigtailed collimated probe. This probe was purchased from AC Photonics, in 4mm o.d. stainless steel package. Collimated probes operate by receiving laser light from a single mode fiber optic cable which is pigtailed into a graded-index (GRIN) lens. The GRIN lens receives the fiber-couple light and curves the typical numerical aperture dispersion of light, such that once the beam exits the probe, it remains focused at a constant diameter (Figure 13a). This is equivalent to handheld laser pointers used in presentations, which project a single dot of constant size even at a great distance. The typical beam diameter for the AC Photonics probes is $450\mu\text{m}$, or about 1800 times larger than the $10.4\mu\text{m}$ of the collection diameter of the bare fiber probe. The increased collection lens cross-section significantly increases the collection efficiency and decreases the necessity for external amplification. The problem with these probes is that the acceptance angle is quite low, and the margin for error in alignment is particularly narrow; this is particularly true of specular reflective coatings. The PMMA surface should be roughed with a fine-grit sandpaper or course

eraser prior to sputtering. If aluminum foil is used as the reflector, the diffuse side should be faced towards the PDV probe when using collimated or focusing probes.

Focusing probes are constructed similarly to the collimated probes, but the GRIN lens is cut very precisely to continue bending the cone of projected light coming from the fiber until it folds over onto itself and starts to converge. The manufacturer cuts the GRIN lens to a precise length such that the light converges at a particular point, the focal point or working distance of the probe (Figure 13b). The working distance can be specified, but for working distances above 50mm, different optics are used by the manufacturer. Most probes used in this work were between 5-10mm. It should be noted that the actual focal distance is difficult to predict in these experiments because the PMMA causes the angle of convergence to change. This precise new angle would be calculable if the lens stack was published by the manufacturer; but without knowing the optical component properties, it is impossible to predict exactly where the probe will focus inside the PMMA window. When using these probes, the probe-holding fixture component should provide sufficient adjustability to move the probe closer and further from the window to locate the place where the maximum light is returned, i.e. where the focal point falls directly on the reflective surface at the window-explosive interface. However, this optimized probe distance is not the ideal location for the probe, but rather the focal point should ideally be placed slightly back into the window (Figure 12b). The most efficient light collection is at the focal point, but throughout the experiment, the interface is moving towards the probe. The best light collection will occur when the reflector is passing through the focal point, but if the probe were placed so that the focal point was at the reflective surface at the onset

of shock approach, then as the experiment commenced, the light return would get worse as the interface traveled away from the focal point. If, however, the focal point were placed a short distance away from the reflective surface, in the path of the interface, then as the interface moved, the amount of light throughout the entire experiment would be maximized because the reflector moves ‘through’ the focal point and back out again on the other side. However, if the probe were pulled too far back from the reflector, the initial shock jump of the interface would not be recorded. A careful balancing of these competing principles should be considered when mounting the probe.

Figure 13a (left): Diagram of collimated probe used for windowed-PDV. Figure 13b (right): Focused probe used in same application. Note focal point is not placed directly at the reflective surface; thus, return light is maximized through the dynamic event as the explosive/window interface travels in sync with the detonation waveform.

2.3 Alignment and Mounting of Assembly

Regardless of the fixture design it is imperative that the detonator, donor charge, acceptor charge, and PDV probe be aligned coaxially and with excellent surface contact between mating components. Parts were cleaned with both a water/soap solution and rubbing alcohol to remove any dirt, debris, or chemical contamination. This step is particularly important for HP-EtOH mixtures because many common contaminants, namely biological and ferrous or copper-containing metals can be particularly incompatible with high concentrations of HP. The different pieces of the fixture are usually designed to come into alignment on a flat surface. For the vise configuration, an alignment jig was used to place the donor charge, acceptor charge and window in coaxial alignment while the vise screw was turned to apply pressure to the stack; the PDV probe and detonator were installed later. The accuracy of aligning features in slab components (det block, probe block, etc.) was often controlled by the computer numeric controlled (CNC) milling machine, and cylindrical components were turned on a manual milling machine.

2.3.1 Aligning Cylindrical Shafts: A preferred strategy has been used to align rigid cylindrical shafts, namely detonators, guide rails, and PDV probe casings, referred to as a 'v-block' seat to the block components. This design uses exactly three points of contact to align a cylinder geometry orthogonal to a slab geometry, which was a common feature in the non-ideal explosive fixtures. The design used a machined 120° pocket, the sides of cut perpendicular to the contact of a cylinder of the perfect

diameter, firmly seated in the pocket. A set nylon set screw is used to apply pressure and to become the third point of contact 120° from either of the other points of contact. If metal fixtures had been used, then drilled and reamed holes would have provided an excellent fit, but because plastic materials were exclusively used, the dimensional stability prevented tight-fitting components from being used. Using the v-block seat to align components may have resulted in slight dimensional variation; it secured them coaxially without accounting for high tolerance on the hole in the slab. The Figure 13 is a sketch of the detonator block for a simplified geometry (not the vise configuration). This block accepted 1.6"nom diameter PE tubing which could be glued into one end, and the detonator laid into a v-block seat on the other.

Sometimes components were aligned with an external fixture. For example, when the vise configuration was used, external alignment jigs were employed. Whenever possible, the alignment of the explosive stack, (i.e. the stack of 0.022" wall thickness PE tubing that was the donor and acceptor charges and the PMMA window), was done by machining a pocket in the component slab (e.g. the top block or probe block) into which the cylindrical component (e.g. the donor pipe or acceptor pipe) perfectly sat. The PE tubing was too weak to utilize the v-block feature (pressing a set screw onto these pipes would crush and distort the shape); thus a circular pocket, usually no more than 0.125" deep was cut, for example into the det block, so that the alignment between the det block and the booster could be achieved. In the vise configuration, this method was later used in the det block to align the donor charge and in the probe block to align the PMMA window.

2.3.2 Alignment of PDV Probe: Alignment of the PDV laser probe caused the most fixture adaptations; still, an extremely reliable process has not been found. The difficulty is designing a fixture component in plastic is the balance between ease of machining, rigidity, and smooth adjustment in at least (1) degree of freedom in tilt away from the charge axis and (1) in axial travel which adjusts where the focal length of the probe was relative to the reflective surface of the window. Using bare fibers, the adjustment was the least sensitive; a flat table or shelf feature was made for the fiber to lay on. Usually this was the factory surface of a PVC sheet which had been set to lay across the diameter of the window. The centerline was scribed by hand with the carbide tip of a height gauge to leave a small trench feature (about 0.025" deep) for the fiber to lay in. This feature was scribed in such a way to align the fiber with the axis of the charge, usually by indicating with an outside edge of the probe block. The bare fiber, once in the trench, was lightly secured by spring clamp padded with expanded PE foam to allow the fiber to slide in and out. The challenge in these configurations was in getting the fiber as close as possible to the window without touching.

When using the stainless steel barrel of either collimated or focusing probes, the alignment was particularly difficult. Both probe types were particularly sensitive to alignment; being off a tiny degree in tilt or focal distance would result in 10-15dB of loss. Further study would require the standardization of this reflector-alignment relationship to prevent what would sometimes take an hour or more of alignment. In general, the more degrees of freedom the fixture provided in terms of adjustment, the less rigid the fixture was; if a desired alignment was achieved, it was very sensitive to

small environmental changes, e.g. thermal expansion or vibration. In many early cases, the experimental PDV signal was never recorded, attributed mostly to fixtures where reliable light return from the reflective surface of the window was not achieved.

2.4 Diagnostics

More details on cameras and PDV setup can be found in Appendix 2.3.

2.4.1 High Speed Photography

2.4.1.1 SIMD Ultra-High Speed Framing Camera: A Specialized Imaging SIMD 16 digital framing camera was used for virtually every experiment. This camera works by individually controlling 8 intensified charge-coupled device (iCCD) camera channels that simultaneously view the same image via 8-way beam splitter. The master timing module programs each camera channel for a particular time delay from the trigger signal. Each camera channel captures two images at different times, a minimum of 550 ns apart, which gives most non-ideal experiments 16 distinct frames to record the dynamic event. Long-exposure images, called bright field (bf) images, are routinely taken prior to the experiment. These are for the explicit purpose of distance scaling the dynamic image for which many features of the fixture are often difficult to resolve. The basic requirements to collect dynamic images are a rigidly-timed trigger event (for which the delay to breakout of explosive light is well-known), the expected event duration in microseconds (found by: $\sum_{i=0}^n D_{vi} * len_i$; where D_{vi} is detonation velocity in mm/us of the 'ith' explosive feature in a linear stack, and len_i is the length in millimeters of that component along the detonation trajectory), and a

rough idea of how bright the explosion will be. For example, a 1.6in id nominal experiment would use a 1.6in long C4 donor charge, which detonates about 8mm/us. This donor component, therefore, requires around 5 μ s of event time. Most acceptor charges detonate around 5.5-6.5mm/us and are usually between 4 and 6 charge diameters long. Therefore most acceptor charges require between 25-45 μ s. Adding these components together sets the experiment time. Exposure times are typically 35ns, and the arbitrarily number gain is set to 3/10 for each channel. These settings have been largely successful in recording non-ideal detonation in dozens of experiments, and we have even been able to capture several detonation instabilities whose erratic and turbulent wave propagations were well-resolved using this camera.

2.4.1.2 Optronis SC-25 Digital Streak Camera: This digital streak camera is used to capture a single spatial dimension (a line) smeared through time. It is a seemingly continuous record (compared to discrete frames) of the light passing through a thin (50-80 μ m) adjustable slit, usually focused either axially or orthogonal to a cylindrical charge. Oriented axially, the streak camera record will capture the light propagation of the detonation wave travelling down the donor and acceptor charges. While typically experimenters who orient the slit orthogonal to the charge axis are attempting to measure the charge casing expansion, we have exclusively used the former strategy since the latter usually requires high-intensity backlighting. The camera passes light focused through a traditional camera lens through an adjustable-width slit (horizontal slit in this case), which falls on a photocathode. The photocathode accepts photons from the slit and ejects electrons downstream. These electrons are guided up or down by the electronic field applied over a distance called the streak tube. Inside the tube,

the slit of photoelectrons are directed by a sweeping electronic field that begins at the top, but once triggered, sweeps the line downward, linear in time, according to a sweep speed specified by the experimenter. This smears the recorded light across the end of the streak tube, where an electron multiplier and phosphor screen await the oncoming electrons. This photoelectrons are amplified (sometimes as much as 40dB) in the electron multiplier based on a user-specified gain. This gain is reported in voltage, the minimum being 330V. For most experiments, the gain was between 370-415V. The amplified photoelectrons strike a phosphor screen which glows where impacted for a long-duration relative to most exposure times; this light is observed by a modified charged-coupled detector (CCD) array. This array is capable of storing the electrons glowing from the phosphor in an on-chip storage well so that interframe time is not wasted on analog to digital conversion. The CCD is exposed for a very long duration to capture as much light as possible from the phosphor. The exposure time is gated by the photocathode which can turn on and off much faster than the CCD. The finished record is a 2-D array of pixels with different intensities, an image of sorts, but only one axis (horizontal, in our case) represents an array of columns corresponding to the same special dimensions, and the vertical represents rows of time for those special points. The intensity values are light intensities, but appear to be smeared through the record for a continuous, time-resolved history of the light event.

2.4.1.3 Photon Doppler Velocimetry (PDV): PDV is a heterodyne interferometric technique that sends incident laser light, often fiber optically coupled, to a moving reflector (explosively-driven in this case). The reflected light is Doppler-shifted by the moving reflector (blue-shifted for objects moving towards the interferometer), and

optically mixed with a reference amount of un-Doppler-shifted light. This mixing yields two beat frequencies of constructive and deconstructive interference, one of which represents the difference between the Doppler-shifted signal and the reference. This beat frequency in experiments of explosively-driven reflectors is on the GHz scale and can usually be interpreted by a high-bandwidth oscilloscope. The URI PDV system consists of the following components:

1. Laser source: RIO Grande 1W maximum power 1547nm diode laser with built-in erbium-doped fiber amplifier (EDFA) amplification
2. Fiber optic-based interferometer: Individual components purchased from various manufacturers including fiber optic (fo) couplers, circulator, and FC/APC connections. A Fujikura 50-s automatic fusion splicer was used to construct the interferometer and all components were mounted inside a metal box and bulkhead fittings were installed to prevent agitation of the fiber optic components during experiments.
3. Photoreceiver: A Miteq 20GHz receiver was purchased and mounted with a heat sink into a small steel project box.
4. Digitizer: a Tekronix 70,000 series oscilloscope with a 12.5M record length, 100GSa/s sample rate and 25GHz maximum bandwidth was used to collect all PDV records.

The assembled PDV system sits collectively inside a protected personnel bunker. The experiment sits approximately 30m away behind a concrete barricade. The use of fiber optic cables carries the incident light and return signal back and forth from the equipment. (Figures 12 and 13).

The PDV probe was spliced onto a long (50m) leader of fiber which was strung between the fixture and the bunker before each shot.

2.4.1.4 Triggering: Two particular instruments have demanding triggering constraints- the FS-10 fireset and the PDV digitizer. The streak camera and SIMD both accepted TTL levels for trigger in parameters. The oscilloscope requires a trigger signal no greater than 5V, but preferably lower than 1.2V so that the trigger signal can be fully-resolved; the oscilloscope has a full scale of only 1.2V. The fireset requires no less than a 30V trigger to initiate the EBW. Two preferred methods of triggering were used; the choice of which was determined by which diagnostics were being used. The most complex timing sequence was used when the FS-10 fireset, SIMD 16, streak camera, and PDV scope were all used at once. This strategy used the signal delay generator to manually trigger the firing sequence, and all other devices responded downstream. The signal delay generator 'T0' line, fired at the onset of the timing sequence with no delay, served as the streak camera trigger; and both the fireset and the SIMD were triggered by the high and low voltage outputs, respectively, of the same channel after a pre-determined delay from T0. The delay time was specifically chosen to represent the delay needed by the streak camera to reach the linear section of the sweep time. This time is different for each sweep speed, and the precise factory-calibrated sweep speeds were used to calculate the correct delay time. The SIMD 16 was triggered at the exact same time as the fireset, and the PDV scope was triggered directly off the FS-10 trigger via a homemade 16dB attenuator. The ignition delay for the FS-10 (the delay between a 'go' signal for the FS-10 and the breakout of reaction light from the detonator) was measured to be about 9.5 μ s for the EBW 501s, and was

factored into the streak and SIMD delay times. The oscilloscope record length is 12.5MSa, and with the minimum sample interval of 10ps/Sa, the total record length was 125 μ s. This time was long enough that the trigger position could be placed at 25% of the total record, and every experiment would be easily captured with the remaining record length.

If the streak camera is not being used for a particular experiment, the signal delay generator DG535 is not necessary. Rather, the FS-10 trigger cable, which carries the ~40V ‘Go’ signal from the control module to the high voltage module is split via BNC splitter to trigger both the SIMD16 and the oscilloscope. In this case the experiment is initiated by manually triggering the FS-10 box, and the firing module trigger line (~40V) is attenuated and received by both the scope and framing camera.

2.5 Data Analysis

2.5.1 Camera Records: Immediately after the experiment, results were saved and viewed to interpret qualitatively what happened. The camera record often is the first place to look for the answer to whether or not the acceptor material showed signs of reaction. When detonation velocity was measured one of two methods were used: a) a combination of MS Excel and the included SIM control software, or b) a Python image processing algorithm (Appendix 2.4). The best results came from the Python algorithm. Both methods require the distance calibration from the image. In order to accurately determine the scale of the image, each record must be converted from pixels to millimeters. This is best achieved by placing a scale in the field of view during

the bright field image exposures. The larger fraction of the field of view the reference image takes up, the better reference it is. Often, an 8.5" x 11" piece of paper was used, taped to the back of the mounting stand, directly behind the fixture. This accomplished three things: a) it provides a distance calibration; b) it reflects donor explosive light back through the clear acceptor pipe to visualize the progression of the shock front; and c) its provides a uniform background for the bright field image, preventing natural features (e.g. trees, grass) from obscuring the features of the fixture.

Using the first method of analysis, MS Excel and the Sim software, is done by constructing a spreadsheet like the one in Figure 14.

Distance Calibration						
x0	y0	x1	y1	ds (px)	ds (mm)	f (mm/px)
991	342	1009	590	248.65	42.85	0.1723
Angle Calibration						
x0	y0	x1	y1	theta (rad)	theta (deg)	
613	338	1039	312	-0.061	-3.493	
Shock front traking						
frame	Time (μs)	xpos	ypos	x' (mm)	y' (mm)	
9	23.068	863	473	890.2	832.6	
10	25.264	904	471	931.0	873.6	
11	27.46	940	445	965.4	911.1	
12	29.656	972	466	998.6	941.8	

Figure 14: Example spreadsheet for measuring shock velocity of SIMD16 records. Distance calibration parameters, representing two discrete points some known real distance apart ($\langle x_0, y_0 \rangle$ and $\langle x_1, y_1 \rangle$). The quantity 'ds' represents absolute distance between two

point or the magnitude of the vector between calibration points. The parameter 'f' represents the conversion factor between pixels in the record and millimeters on the fixture. Angle calibrations are necessary in certain records for which the charge axis is tilted from the Cartesian pixel array. The columns labeled "x'" and "y'" represent the tilt-corrected shock front pixel coordinates converted to millimeters. The frame and time columns are manually entered from the Sim record.

The second method of analysis is through the use of a Python algorithm which incorporates all the steps of choosing the shock front at each point into an interactive

applet. The details of this analysis are explained in Appendix 2.4. This algorithm displays individual frames and has the optional ability to display a line plot of the light intensities along a user-selected vector of pixels, say the charge axis of symmetry in most cases.

2.5.2 PDV Records: Because PDV is a frequency-domain result, it is not clear whether the record contains meaningful data simply by looking at the time domain signal. A Python applet was written in-house to perform a short-time Fourier transform (sFFT) on the digitizer data and display meaningful section of the spectrogram. The program also uses a peak-fitting technique to fit the often sparse frequency domain time slice to a Gaussian curve. The parameters of the Gaussian equation are useful to determine the middle frequency or the frequency with which the dynamic signal demonstrates the most overlapping character. This strategy is used to gain better frequency resolution since the tradeoff between time and frequency resolutions is inversely linked; by selecting a good time resolution, as long as the peak velocity has 3-4 frequency terms, the Gaussian fit works quite well. More about this algorithm and its development is discussed in Appendix 2.4. Figure 15 is one of the Python outputs, which shows the time and frequency domain results.

Figure 15: Typical spectrogram of detonation waveform using windowed-PDV. Top shows time-domain signal directly from oscilloscope to illustrate intensity of signal. Bottom shows frequency domain heat map- a frequency spectrum at interval time slices. Color scale is in dB. Note the reverberations and multiple reflections visible in this record. The presence of these features is common but unpredictable.

The user selects the meaningful region of the frequency-domain spectrogram, and the intensity threshold for the noise floor is adjusted until the background variations disappear. Then, the program iterates through the time slices, looking for the peak velocity and trying to fit a Gaussian curve to the data.

Figure 16: Gaussian fit velocity profile obtained by the Python algorithm which fits the entire time slice frequency spectrum to a Gaussian curve to obtain an accurate peak frequency from poorly-resolved frequency intensities. (Inset) a zoomed in plot of the first 100ns, of which the first 50ns or so is considered the chemical reaction zone.

Figure 17: Velocity profile output from the Python image analysis. The shock velocity inferred from the framing record is displayed as the slope of the linear fit to the position vs time data (5.715 mm/ μ s) for this non-ideal explosive mixture.

2.6 Final Considerations

This type of testing is fraught with hazards and ways to “mess up.” It is recommended that a timeline of events be constructed, with careful thought to all triggering aspects.

A checklist is also imperative. An example of one used in these tests can be found in Appendix 2.5.

3. Typical Results

Throughout this work different experimental strategies were used, and each is discussed in detail later, but typical results from the diagnostics are presented here to provide a basic understanding of how the data was interpreted. Although the majority of this work focused on the HP:EtOH improvised, non-ideal explosive, several experiments were performed with a well-documented mixture of the homogeneous explosive nitromethane (NM) sensitized with diethylamine triamine (DETA). In all these NM experiments, the amount of sensitizer was either 1% or 2%. These experiments were conducted to compare the URI windowed-PDV results to the literature windowed-PDV experiments [10,12] which were done on either neat or sensitized NM.

3.1 PDV Results

The earliest results were obtained to calibrate the PDV equipment and components; the experiment captured the PDV record of the end-on aluminum surface of a 501 EBW detonator being propelled in air. This experiment is much simpler than the non-ideal configurations, and even better represents the traditional usage of PDV. Figure 18 displays the experimental configuration.

Figure 18. Sketch of first PDV fixture. Axial view (Top Left), side view (Top Right), & isometric (Bottom Left). (Bottom Right): Photograph of detonator & fiber optic taped in place. Distance between probe & detonator was adjusted ~ 5mm

The principle measurement in this experiment is the explosively-driven disc, which used to be the end-on face of the RP-501 detonator. When the detonator is fired, the explosion forces the aluminum casing outward in all directions. The PDV probe is measuring two phenomena happening simultaneously. First, the sharp shock wave mechanics reverberating in the aluminum disc, and the relatively slow acceleration of the detonator towards the probe. The detonation wave couples directly with the aluminum casing. When the transmitted shock reaches the free surface, a relief wave is sent backwards into the aluminum and the free surface jumps off with twice the particle velocity of the incident shock. The release wave travels back to the rear surface, originally in contact with the explosive, and reflects again at the density discontinuity, sending a pressure pulse back towards the free surface. These reverberations go on for several iterations, causing the aluminum surface to jerk forward and back relative to the shockwave. Simultaneously, the explosive product gasses adiabatically expand along their isentrope, cooling in temperature and increasing in volume as time progresses. This volume expansion is felt as kinetic

energy by the aluminum casing, which accelerates quickly at first, then levels off as gasses sufficiently expended their p-v work. This acceleration continues, provided the disc stays intact; product gasses escape around fractures in the aluminum casing rather than driving it. The PDV system records the net sum of these two effects. The record displays ‘ring-up’ of the Al flier as it accelerates. The shock ring amplitude is lower than the acceleration from gas expansion, making the final velocity history look like stair-steps. This was simulated by CTH hydrodynamic modelling code. This code is a finite element solver which has built-in libraries for standard fixture materials (plastics, metals, adhesives) as well as reactive models for explosives. The CTH framework serves as a loose comparison to the PDV. Figure 19 displays the results of the PDV experiment and the CTH simulation.

Figure 19: PDV of RP-501 EBW detonator. (Top Left): Time-domain trace from oscilloscope. (Bottom Left): Power density plot, i.e. spectrogram, of frequency domain using sFFT analysis. (Right): Compiled Gaussian fits for each time slice. (Inset Right): CTH histories plotted for tracer particles plotted through time; y-coordinates from CTH results are inverted because velocities are relative to CTH mesh coordinates.

It should be noted that the CTH material models used in the simulation, both for the explosives and the inert materials, were not validated to the ones used at URI, and as such are not expected to match up exactly.

In this case, the experiment trigger was the increased light values the reflected light once the shock wave breaks out onto the free surface. The amount of absolute amount of light reflected from the aluminum surface is no higher after the shock breakout, but rather at that point, begins to beat against the reference light reflecting from the clean-cut end of the bare fiber probe to produce a dynamic beat frequency within the bandwidth of the AC-coupled Miteq photoreceiver. The preferred method of triggering is by a parallel voltage reduction ($\sim 15\text{-}20\text{dB}$) of the 40V FS-10 fireset trigger line to the firing module of the FS-10. Using the scope signal to trigger itself may fail to trigger if the signal is less than one division above the noise.

The results of the detonator surface velocity validation were in excellent agreement with the predicted shape and magnitude of the CTH results. The experiment record ended at around 900ns because the aluminum disc struck the fiber traveling at $3.236\text{mm}/\mu\text{s}$, and the CTH results corresponding to this time indicate the aluminum was travelling around $3.4\text{ mm}/\mu\text{s}$. This agreement within 5% was sufficient for proof of concept that the URI PDV system was performing as expected.

Following the validation of PDV system capability, was the ability to capture detonation waveforms through optically-clear windows. For early tests, the donor charge was chosen to be punched-out discs of PETN based sheet explosive. The discs

are known to be easy to initiate with a detonator, and can be easily stacked for a consistent density donor charge. Many early experimental fixtures were constructed using poly-lactic acid (PLA) or ABS 3D printed plastic filament. A diagram of the original windowed-PDV fixture is shown in Figure 20.

Figure 20: Partial cut-away sketch of original windowed-PDV fixture showing relevant components. This experiment was intended to collect a waveform from the PETN donor stack alone (no acceptor material) through the PDV window.

This initial attempt at collecting a detonation waveform from windowed-PDV was successful. The reflector used on the explosive-contact side of the window was 0.003in thick aluminum tape, diffuse side towards the probe. This reflector is excessively thick and would serve poorly for experiments where high time resolution is necessary within the first 50ns of the detonation waveform (i.e. anytime the reaction zone is under investigation). This thick aluminum tape will attenuate the true peak pressure sufficiently to disrupt the ability of the PDV system to interpret the early

reaction velocity profile, but for validation, it served the proof of concept that an detonation waveform can be collected with the URI PDV system, see Figure 21.

Figure 21: Initial waveform results collected from PETN sheet explosive stack through a PMMA window to which a 3mil aluminum foil reflector was adhered. (Top Left) Time-domain oscilloscope trace. (Bottom Left): Frequency-domain spectrogram. (Right): Velocity profile from Gaussian fit peak centers at each time slice. (Inset): First 250ns of velocity record; note the perturbed region within the first 50ns because of the thick (0.003in) aluminum foil which serves as the reflector. The measured velocity (~ 2.1 mm/ μ s) is lower than expected, but is consistent with a slight attenuation of the peak pressure in the aluminum reflector.

Further non-ideal waveforms were collected from many different configurations and fixtures, but will all be discussed in detail later, presented in a similar manner. It should also be noted that the donor charges constructed with C4 explosive cannot be characterized directly with the same method. PMMA windows are only clear under a certain threshold pressure, which happens to be between the peak pressure of the PETN sheet explosive donor charge and C4; i.e. if detonating C4 is placed directly in contact with PMMA windows, the resulting transmitted shock will denature the optical properties of the PMMA such that it is no longer transparent, and the laser light

can no longer pass through the opaque section to be Doppler shifted and returned to the interferometer- the resulting record will simply be blank. However, this test is not for naught, but because the shock strength transmitted into the PMMA is so strong, the shock front itself will serve as the reflective surface, as is sometimes the case in windowed-PDV experiments. This shock velocity must be corrected for the refractive index of the PMMA, unlike the particle velocity fringes that observed through the shocked region of PMMA. Figure 22 displays a typical donor characterization experiment where C4 is in direct contact with the PMMA window.

Figure 22: C4-containing donor charge. (Top Left) Time domain and (Bottom Left): spectrogram first illustrates the weak reflective properties of an incoming shock wave. The particle velocity reflected from the gold surface is not visible because the PMMA has been chemically denatured and can no longer transmit the IR radiation. The density discontinuity at the strong shock front is a good enough reflector such that when the shock approaches the rear surface of the window (i.e. closing the distance to the probe), the shock velocity beat frequency becomes gradually visible in the spectrogram.

The index-corrected velocity profile (Figure 22, right) indicates a shock velocity that has been somewhat attenuated from the detonation condition of C4. This attenuated

shock velocity is in part because the shock-matching condition of C4 into PMMA is a reduction in pressure, and also because the shock strength has been attenuated during the time the reflection from the front was too far away from the probe to return enough light. This can be seen by the negative slope of the shock velocity on approach to the window's rear surface. Other tests indicate the attenuation is very non-linear at the early stages of shock transmission; rapid attenuation has been recorded in experiments with thinner windows where the shock velocity is visible immediately after contact with the PMMA. It appears the initial shock jump happened at 0.0us in the spectrogram of Figure 22, where the spike in DC response indicates a change in DC light, but the shock reflection is still indiscernible from the broadband noise until about 75ns.

3.1 High Speed Camera Results

3.1.1 SIMD Records

Images from the SIMD camera were first inspected visually. Different explosive materials and fixture configurations determined exactly what was able to be inferred just by looking, but the first question having a high-speed record of the event can answer is whether or not the material demonstrated a steady detonation wave. For a steady detonation, the wave speed is perfectly constant after a short equilibration time (<1 diameter for these cases). To judge perfect linearity isn't possible from visual inspection of the frames, but these mixtures tend to either detonate steadily or highly erratic- rarely anything in between. Any experiment whose video appeared steady resulted in a constant detonation velocity upon further computational analysis. The

erratic cases, of which there are several, were not often evaluated in terms of their exact velocity profiles, but rather on the grounds that they were, in fact, erratic.

The only experiments for which there are no SIMD records are those for which no acceptor or only a few millimeters of acceptor material is chosen. In these cases, it was deemed that no meaningful data would be observed by filming these fixtures; still some of these experiments were filmed for the purpose of observing the velocity and consistency of the donor charge, a characterization which would be impossible with the longer interframe times of a typical experiment. A typical SIMD record of these ‘booster-only’ experiments is shown below in Figure 23.

Figure 23: C4 Donor Characterization Experiment. (Top Left): Photograph of fixture for donor characterization experiment. (Bottom Right): Brightfield image of fixture in SIMD camera prior to explosive event. (Middle): Photo sequence of detonation progress in the donor charge. (Right): Python processing algorithm output from dynamic record at middle. Shock velocity is represented by the slope of a linear, least-squares fit to the horizontal shock position vs. time data. Distance calibration was done using the apparent o.d. of the donor charge, 1.689in.

The numbers calculated for detonation velocity in these donor charges were necessarily higher than expected for C4, the booster explosive in this experiment. Proposing that C4 experiences a real, 1-dimensional detonation velocity of $\sim 10\text{mm}/\mu\text{s}$ (see the slope in Figure 23) is quite preposterous. This illusion is an artifact of the corner-turning phenomena of the highly curved detonation wave that was expected for these configurations. The initial diameter of the detonation surface is approximately the diameter of the EBW detonator- 0.295in in this case. Immediately spreading into a 1.6in diameter donor explosive causes sharp curvature through in the early stages of the donor detonation wave. The longer detonation runs in the donor charge, the detonation front's radius of curvature grows flatter. This necessarily means that the point of contact between the detonation surface and the donor pipe wall (i.e. the bright line all around the circumference of the donor charge in the camera record) is traveling faster than the leading, axial point by a non-linear ratio related to the distance traveled; i.e. the longer the travel, the more closely matched these two velocities will be. This misleading line of progress is the only indicator of reaction visible to the camera because C4 is opaque which obscures the leading point of the detonation surface.

To evaluate this result, and to collect a measurement for the detonation velocity of the C4 used in our experiments, a long cylindrical section 0.5in id was packed with C4 similarly to the previously-used donor charges. The velocity of the C4 was measured in the 0.5" diameter clear PE pipe, the result was $7.845\text{ mm}/\mu\text{s}$. This result is in excellent agreement with published values for C4 at the experimental density of 1.66 g/mL [14]. Figure 24 shows the experimental records for this configuration.

Figure 24: C4 detonation velocity characterization experiment. (Left): Brightfield image at top, followed by the dynamic progression of a linear detonation event captured on SIMD record. (Right): Points picked from camera record imply a highly-linear detonation velocity for the 0.5in x 4in long section of the fixture. The calculated detonation velocity (7.845 mm/ μ s) is in good agreement for C4 at the experimental density.

The reason this experiment illustrated a lower, realistic velocity is because the aspect ratio length:diameter was much larger; detonation fronts running through these long aspect ratios quickly equilibrate the differential velocity between the central charge axis and the bright, observable line seen by the camera on the radial boundary of the charge.

4. Discussion

4.1 Steady Detonations/ Reaction Zone Measurements:

One of the most valuable measurements of chemistry in non-ideal explosives is the reaction zone length. The end of the reaction zone is the sonic plane, behind which no exothermic release can possibly support the detonation. For most ideal explosives, the length of the reaction zone such that >75-85% of the available chemical energy contained in the explosive (determined by either closed bomb or detonation calorimetry) is released. The best measurement of energy release inside the reaction zone (i.e. between the shock front and the sonic plane) is the detonation velocity. To determine exactly how much energy is released in the reaction zone, a detailed description of that material's ideal detonation Hugoniot must be known, as well as a reasonable estimation of its chemical kinetics so that equations of state (EOSs) may be calculated for partially-reacted states. It was thought that the reaction zone measurements of the HP-EtOH mixtures could be measured in a similar manner to strategies outlined by others [8, 10-13] primarily by collecting two steady waveforms which should have similar pseudo-1-dimensional behavior but vary by initial condition, primarily charge length. If two steady waveforms are collected for charges which differ only by initial conditions, the reaction zone should be steady and constant in the pair; i.e. constant relationship between the shock front and the sonic plane should develop. Behind the sonic plane, though, the initial conditions govern the flow of the expanding product gasses, which will be different in the two experiments by design. If the two experiment's waveforms are overlaid, the region for which they lie atop one another will be considered the reaction zone, and the point from whence the

diverge will be called the sonic plane. The length of the reaction zone, measured either by distance or by time was the target measurement.

If steady detonations in the non-ideal material were able to be measured, a correlation could be made between the chemical reaction zone thickness and the amount of available energy by changing the component ratios; poorer oxygen balanced explosives (either fuel rich or lean) will contribute less energy overall to the reaction zone energy economy, but will have similar reaction kinetic rates and pathways. Presumably, the less energy the acceptor material has to offer, the longer its reaction zone will likely be. Total available chemical energy can be calculated by thermochemical codes like Cheetah (Lawrence Livermore National Laboratory or LLNL), as seen in Figure 25.

Figure 25: Predictions of Cheetah thermochemical code; Note sensitivity of detonation velocity and energy to mixture composition. Reaction zone thickness is shortest at the optimum concentrations.

Knowing mixtures of 70% HP with ethanol fuel to be detonable [15] in glass tubes at 15-17mm i.d., 1in charges (well above published detonable diameter) were constructed to achieve steady detonations in HP/EtOH. Concentrations consistent with our previous work [3] were used which correspond to the oxygen-balanced mixture of 70% HP with ethanol. This ratio is 13.6 wt%EtOH- balance 70:30 wt:wt HP:water, or total percentages of 60.48:25.92:13.6 HP:water:EtOH. This ratio was expected to be the most ideal, that is to say it was expected to be steadily detonable over the greatest range of initial conditions (e.g. charge diameter, donor charge incident shock strengths, confinement materials, etc.). By benchmarking this mixture's reaction zone thickness, then slowly changing the concentration of the ingredients to starve the reaction zone for energy, the efficiency of reaction should non-linearly decrease; i.e. the fraction of available chemical energy reacted in the reaction zone should decrease for less ideal mixtures because of 3-dimensional effects like shock spreading and front curvature.

The stoichiometric mixture will be called "Test Mix A" or TMA. Nominal 1in inner diameter, clear PVC pipes were chosen as charge confinement to observe detonation light propagation with high-speed camera. These mixtures were overdriven across the entire cross-section by the included PETN-based sheet explosive donor charge stack in a 3D-printed fixture to give them a best chance of initiating uniformly; discs of PETN sheet were stacked to at least as long as the diameter of the pipe; i.e. the length:diameter ratio was set to 1, to within one disc thickness (0.082in). The initial tests using this configuration were unfortunately a series of unstable and poorly-visible

detonations illustrated in Figure 26. These initial tests were only filmed in high speed to observe whether a detonation had taken place or not.

Figure 26: Initial high-speed imaging of HP-EtOH detonations in 1in nom PVC pipes. (Top) Shot 20160426-001 and identically prepared 20160426-002 (bottom). Both contain TMA in 1in diameter x 4in long acrylic tubes. The detonation front is unstable in both records. The shape goes from flat to curved to flat and the brightness changes significantly. This reaction environment is very unpredictable and is exhibiting behavior consistent with being close to critical diameter.

A steady waveform in the HP:EtOH mixture is required for the reaction zone measurement to succeed, since the assumption behind overlapping reaction zones and diverging Taylor waves is the theory of the 1-dimensional steady state flow in the reaction zone. For two reasons we changed the acceptor pipe to a ‘clear’ PVC material: a) The PVC was compatible with more acceptor materials, namely nitromethane (NM) which we intended to shoot as well, and b) the PVC pipe served as slightly better confinement for the near-critical TMA mixture, which should have

encouraged it to detonate. The results of this experiment also failed to form a steady detonation, but the clear PVC's thick walls (1" schedule 40) and heavy blue tint made the detonation front much more difficult to see, especially in the case of the unsteady detonation, where the front goes through sections of the event without giving off any light at all. In the clear PVC, the shock wave was totally invisible during these dark waves. We chose to switch to a radically different fixture configuration, based around 1.1in nom id polyethylene pipes. These pipes were marketed as shipping tubes, but were very clear, very thin (0.022" wall) and chemically compatible with both HP and NM. A larger fixture was designed to clamp the detonator block and the PDV probe block onto the pipe using three threaded 1/4" x 20 UNC nylon threaded rod. This fixture was largely successful in overcoming the difficulties of working with thin pipe, but was difficult to align. The booster stack of PETN sheet explosive discs was also suffering because the discs were being put under threaded clamping pressure. Up until this point, the stack had been made slightly larger than the acceptor pipe and when clamping pressure was applied, the viscoelastic properties of the PETN sheet explosive allowed it to slowly flow away from an otherwise secure liquid seal between the last disc in the stack and the on the acceptor pipe. From this time on, C4 explosive was hand-packed into donor pipes of the same diameter as the acceptor. This is so the donor pipe and acceptor pipe can mate and clamping pressure does not directly strain the explosive donor charge.

At this point, we decided to calibrate our steady detonation/reaction zone model on an explosive we know is capable of detonating: NM. Sensitized nitromethane was

formulated by adding 1 or 2% DETA and shot in identical configurations as the HP:EtOH mixtures. These efforts proved to agree with the literature for shape and reaction zone thickness. The first shot in 1.1in PE pipe boosted with C4 shows a steady detonation and recorded a smooth waveform in the PDV record as seen in Figure 27.

Figure 27: (Left): SIMD records of shots 20170818-001 and 20170818-002, which are 4 and 6in long 1.1in PE, respectively, both with 98:2 wt:wt NM:DETA. (Right): The PDV record for 20170818. (Inset, Right): Zoomed in to the closest 250ns, the reaction zone of the NM is very smooth within the first 25ns, then decreases with minimal perturbation out to 550ns.

The CJ (sonic) condition in NM is estimated to be around 1.8 mm/ μ s when matched on PMMA. It can be shown that from this record, the NM detonation waveform reaches this value between 70-100us, which is near the value obtained in reference 8. In another work, the reaction zone of neat [10] and sensitized [12] NM was found by shooting multiple experiments with slightly different initial conditions to observe where the waveforms overlap. We chose to change the acceptor charge length to

verify the PDV technique against the published values. The results are displayed in Figure 28.

Figure 28: Overlays of wave 1.1in id PE acceptor pipe PDV wave profiles with varying initial conditions. (Left): 98:2 wt:wt NM:DETA plotting results from experiments whose acceptor pipe section was 3,4,5, and 6 times the diameter; (Right) 99:1 wt:wt NM:DETA in 1.1in id PE acceptor pipes that were 4 and 6 times the diameter in length.

There is not much of a trend to observe in Figure 27 except that particle velocity histories from shorter acceptor pipes do, as expected, stay lower throughout the record, but globally, excellent agreement between experiments can be seen. Any spots that appear sharply erratic are likely due to poor reflections and low light levels which make it difficult for the Gaussian fitting engine to find accurate midpoints of the spectra. Upon closer investigation within 200ns, seen in Figure 29, the location of the reaction zone is difficult to identify.

Figure 29: Reaction zone timescales of Figure 28. Excellent agreement between shots and early times almost perfectly overlap. For 1% DETA (right) traces decisively diverge around 40-45ns. Inferred reaction zone length agrees with published values.

The first attempt to prompt stable detonation in HP:EtOH mixtures was to increase the diameter from 1.1" to 1.6". This test also demonstrated a galloping detonation, unstable and behaving as if very near critical. Steady detonations were attempted with TMA mixtures as large as 2.6in, with nearly identical results: galloping failure. This behavior is not understood to be typical over such a large range of diameters. Increasing the fixture to any larger diameters would deviate from the mission of the project, to assess non-ideal explosives on the small scale, so HP:EtOH was not pursued to find steady detonation and reaction zone length further. In order to do so, heavier confinement (i.e. aluminum) casings may encourage the HP:EtOH to detonate, but with impedance mismatches such as that, the stability of complex cellular detonation structures which are difficult to measure with windowed-PDV would likely arise. Future work will switch to include higher concentrations of HP (90%) which are more ideal and not likely to fail at the diameter of these tests.

4.4 Infinite diameter studies

Because the HP-based non-ideal materials refused to detonate even under the best stoichiometric conditions, more involved studies were attempted. Namely, immediately after being struck by the detonation wave of the donor, for some short distance (approx. the length of 1 diameter along the charge axis), the detonation in the non-ideal explosive will continue as if in the infinite diameter. The detonation waves in this region are by definition non-steady, so the idea of steady-state reaction zone overlapping no longer holds, but valuable information about the dynamic response or either growth to detonation or decay to a pseudo-stable detonation state were attempted for the HP:EtOH mixture.

4.4.1 Overdriven Failure

The standard C4 booster/donor charge used up to this point is more than sufficient to over-drive these materials to a detonation condition above their theoretical infinite diameter steady state condition. At early times when the shockwave in the acceptor is nearer the donor charge, the condition should be particularly overdriven, and as the overdriven condition proceeds deeper into the acceptor, the attenuation of the rarefaction wave should decrease the peak pressure until a pseudo-stable state of the acceptor material's detonation condition is met. As long as the attenuation to some steady state was reached before the rarefactions from the charge side walls coalesce at the center of the charge, the central axis of the acceptor should continue as if in the infinite diameter, decaying to a steady detonation velocity before exiting the infinite diameter region and failing.

PVC pipes (1 ½ in nom schedule 40) were bored to precision diameter and packed with C4 donor charge, which formed the liquid seal inside the pipe. PMMA windows were glued into a seat bored at the opposite end of donor charge, leaving a known-distance cavity between the reflective surface of the window and the pressed surface of the donor charge. In this cavity TMA would later be poured, such that the donor charge was in direct contact with the acceptor for reliable shock transmission. The acceptor cavities were nominally 5mm, 7.5mm, and 15mm in length, expecting that the 15mm acceptor would have decayed down to a new pseudo-stable detonation condition, and by probing multiple different acceptor cavity lengths, the dynamic overdrive-to-steady process may be studied in full. The results are displayed in Figure 30.

Figure 30: Overlaid traces from 5, 7, and 15mm acceptor thicknesses. (Inlaid): The first 100 ns of the larger record is enlarged for comparison.

Conclusions

In attempts to assess non-ideal explosives below their critical diameter, the most ideal mixture of hydrogen peroxide and ethanol, in stoichiometric proportions, was subjected to several shock loading experiments cased in low-impedance cylindrical 1in, 1.6in, and 2.6in diameter sizes. In each case, the full cross-section of the non-ideal material was boosted with a hand-packed C4 donor charge, for which direct-coupling is necessarily an overdriven condition in the HP:EtOH mixture made by fueling 70% HP a solution. At each diameter, a galloping detonation was observed on the high speed camera record. These detonation instabilities seem to be an intrinsic detonation performance feature of these materials in low-impedance charge casings, since far less ideal ratios of these components have proven to detonate in small glass test tubes.

The HP:EtOH mixture was placed in a variety of configurations to study its ability to, for example, grow to detonation in an underdriven shock loading experiment or decay to a pseudo-steady detonation wave in an overdriven scenario all before the shockwave in the sample explosive material has left the infinite-diameter regime; i.e. the early time after being stimulated by the incident donor shock pulse before the diameter effects have not yet overtaken the 1-D like behavior instigated by the initial conditions.

Mixtures of HP:EtOH were doped with xanthan gum and glass microballoons to artificially introduce hot spots into an otherwise homogeneous mixture. Near-ideal

behavior was seen from these mixtures. Primitive limits of detonability at the 1.6in scale were performed, and when failures occurred, slight amounts of dopants were added to incite a detonation response. These studies indicate a minimum energy content required to detonate, and if we assume the threshold values of dopants completely react, it infers the amount of energy loss from curvature and side losses at the charge edge. Integrating a more complete list of these studies to detonation curvature measurements, detonation shock dynamics (DSD) modeling frameworks, and more comprehensive implementations of windowed-PDV are of interest. The complex chemical environment of these materials and what contributes to their unstable detonation behavior across a wide range of diameters will be the subject of further study.

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Appendix 2.1 Responsibilities and Safety

FL-012: SOP –Velocimetry and High-Speed Photography Safety

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Dr. Jimmie Oxley (Principle)

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I Objective:

To describe project-specific procedures for conducting velocimetry measurements using photon Doppler Velocimetry (PDV) and high-speed photography to study explosive detonation. This document will cover responsibilities and safety. Other applicable SOPs include FL007, FL010 and FL011.

II Location:

All explosive testing conducted at the Alton Jones (AJ) Outdoor Test Facility (OTF) will be conducted in accord with FL007, the overarching SOP for all range activities at Alton Jones.

III Personnel and Responsibilities:

A The Range Manager, Jimmie Oxley, is responsible for approving any activities or experiments conducted at the AJ OTF facility.

B The Ordinance Technician (OT), Alan Valliere, is responsible for:

- i. Maintaining custody of all explosive materials. The OT is responsible for logging bulk explosives and detonators in and out of the magazines and maintaining safe storage and handling practices during their use. He is also responsible for returning the unused ATF regulated materials to the magazine and recording how much of each explosive was used.
- ii. Maintaining personnel restrictions on site. Before each test, the OT must calculate a safe radius, both barricaded and unbarricaded. He will decide at what time certain personnel are restricted to remain outside the safe radius. He is responsible for knowing that no one has entered the safe radius before every test is performed. If the safe radius is larger than his line of sight, either he, or someone delegated to do so, must patrol the area prior to each experiment.

- iii. Notifying the local police and/or fire department, if necessary, that explosive testing will occur.
- iv. Inserting and arming the initiator into the explosive bulk charge, including the installation of lead wires, shock tube or det-cord, and to initiating the charge only when it is safe to do so.

After the explosive has been fired, the OT will be the first and ONLY person allowed out of the protected area to observe the test pad. No personnel may enter within the safe radius until the OT has inspected the pad and given an 'All Clear' signal

C Experimenter: This test requires at least one experimenter in charge of the following duties:

- i. Planning the diagnostic strategy (i.e. which equipment is needed and where it is to be located).
- ii Ensuring that all the equipment required is present and in working order. He must ensure equipment protection measures are in place; and to do so, he must be able to predict the severity of the explosive event and the relative scale of the data so that the data is recorded in the dynamic range of the diagnostics (e.g. framing rates, light levels, reflection coefficients, oscilloscope bandwidth, etc).

Planning the device fixture/configuration. This requires an understanding of the sample explosive sensitivity and detonability so that the device is optimized for booster material and size, overall charge size (i.e. diameter, length), and diagnostic access. Planning should also include wiring layouts and timing trains, and their integration to the fixture itself.

- iii. Manufacturing the device fixture/configuration. This involves ordering raw materials and fabrication. Fabrication involves using the on-site machine shop at the AJ OTF or the laser cutters or 3D printers in Beaupre.
- iv. Providing the test explosive charge which may include synthesis and formulation of explosive and/or non-explosive ingredients. This includes maintaining an inventory of the chemicals and explosives needed to ensure enough is on-hand for the proposed test. During winter months or in the event of a prolonged power outage, the experimenter needs to consider whether chemicals need to be stored in Beaupre.
- v. Characterizing and calibrating the diagnostic equipment. This includes the characterization of the timing for all the diagnostic equipment in use for the experiment--laser power and behavior, camera timing, lensing and resolution, oscilloscope timing and expected voltage levels. Most calculations can be done prior to the day of testing, but some needs to be done the day of testing, especially that

which pertains to the reflector and trigger of the device, which should be characterized immediately prior to discharge.

vi. Set-up and takedown of the diagnostic equipment. This includes setting up the camera(s), PDV optics, data acquisition, and triggering and overseeing the takedown and safe storage of all equipment.

vii. Preparing the booster. The current design dictates that a high explosive (HE) booster be packed by hand. The experimenter is responsible for seeing that this process is done safely. If a press die is required, the experimenter is responsible for designing, machining, polishing and cleaning to prevent grit creating a safety hazard. A second person must be present during the packing process.

viii. Assembling the device fixture/configuration. The experimenter is responsible for final assembly (gluing, lubricating, polishing, and final cleaning), leak-checking, measuring precise dimensions, documenting by photography. He should ensure that the device is free of dirt and ready to use. This includes characterization of the reflector when necessary for PDV measurements. If the device is assembled with explosive materials and storage is required, the device must be stored in the explosive magazine located in the lab wing of the AJ OTF shop.

ix. When the experimenter hands the assembled device to the OT, the responsibility for the active device transfers to the OT. If the test of the active device is cancelled prior to detonation and it is deemed the device may be safely collected and stored for later use, the OT must either store the device or transfer custody of the device back to the experimenter.

x. The experimenter is responsible for all diagnostics. Once he has given the approval for testing to commence, he will verbally (possibly by radio transmission) inform the OT that diagnostics are armed and ready.

xi. Data Collection. The experimenter is responsible for collecting and saving all data relevant to the experiment. Once the test has been completed, the experimenter must save all data before any other duties are carried out. The experimenter is responsible for backing up all data onto the group's shared network data drive (\\10.30.199.15\\backup\\instrument backups\\projects\\non-ideal detonation/ saved under a new folder for each day of testing.)

xii. Data analysis. The experimenter is responsible for interpreting and processing data collected during the experiment, including any time-frequency transformation strategies and image processing needed to produce the intended measurements.

D Collaborating Experimenters: Other experimenters may be present at any stage of the testing process but must coordinate with the experimenter and, during any

explosive test, the OT. In the event that the collaborating experimenters are using their own equipment and diagnostics, a detailed description of their function and safety hazards must be communicated to both the experimenter and the OT so that appropriate setup and safety measures can be made.

E Driver: In the even that chemicals or explosives need to be transported to or from the AJ OTF, a URI employee, grad student or faculty member, may transport them securely stored in the group's Ford E350 Box Truck, RI State license plate #1096, in compliance with the URI fleet vehicle policies. The driver (or accompaniment) must maintain a valid ATF Employee Possessor Permit. Any explosives transported must be either detonated or stored after use in an ATF approved magazine.

F Guests: Guests are permitted at any stage of the testing process but must be coordinated by the experimenter and during any explosive test, the OT. Guests are required to abide by all PPE and personnel restrictions.

IV Safety

A PPE: For any operations conducted at the AJ OTF, all personnel must wear closed-toed shoes and safety glasses. During specific operations, extra PPE may be required, such as hearing protection or hard hats. The OT may specify PPE required.

B Mechanical Hazards: Fabrication of the test fixture or stand exposes the operator to many mechanical hazards. Even during safe usage, metal and/or plastic parts may be ejected from a milling machine. Any personnel operating the equipment must be trained in its safe use. In addition to safety glasses and closed-toed shoes, personnel operating machining equipment must not have loose clothing; long hair must be tied back, and jackets or sweaters, zipped or buttoned so that no object becomes entangled. If cutting fluid is used, nitrile gloves may be used, but not required. Ear protection is recommended for long term use of any loud tools but not required. During an explosive event, blast waves and fragments are produced. It is the responsibility of the OT to see that personnel are at a safe location/distance, but it is the responsibility of the experimenter to protect equipment and cabling from the explosive event.

C Chemical Hazards: Many tests require the synthesis or formulation of explosive and non-explosive materials. Typical chemical hazards exist--toxicity, acidic, etc. It is the responsibility of the experimenter and OT to review the safety data sheet (SDS) of

all materials used. Prudent and safe storage of all chemicals is the responsibility of the experimenter. Special considerations may be needed for chemicals at AJ OTF since the building is not climate controlled; volatile solvents may evaporate or aqueous formulations or adhesives, freeze. Even if not particularly hazardous, many materials are ineffective if allowed to freeze. Flammable liquids must be stored in the flammable safety cabinet located at the south end of the laboratory wing. Oxidizers are stored in the safety cabinet at the north end of the laboratory wing. All other chemicals may be stored in the cabinets of the laboratory, as long as the cabinet is clearly labeled on the outside, and care is taken to segregate acids from bases.

i. Hydrogen peroxide (HP) above 10% concentration can damage human tissue. Detonable HP formulations are often above 60% concentration and carry extreme risk of skin or eye damage. HP reacts catalytically with some metals and metal oxides, particularly iron-containing metals. Such contamination over time may destroy an entire bottle of HP and build hazardous pressure inside the bottle. HP should be stored in thoroughly cleaned dark glass or plastic bottles, dated, and checked periodically for pressure buildup. HP can also be incompatible with epoxies which use amine-based curing agents; therefore, no epoxied syringe needles should be used without compatibility testing. HP is subject to degradation from ultraviolet light and should not be stored in direct sunlight or in transparent containers.

ii. Nitromethane (NM) is toxic and a good solvent for most plastics. Some of its incompatibilities are only noticed over time; therefore, it should always be stored in glass bottles. Nitrile gloves are recommended for handling mixtures of HP and/or NM. However, it should be noted that nitrile is not compatible with NM for extended periods; therefore, gloves must be changed if they are contaminated with NM. NM is often sensitized with diethylamine triamine (DETA), but may also be sensitized with other amines or strong acids (i.e. 90% nitric acid). These sensitizing materials carry their own hazards; in the case of DETA and other amines are considered carcinogenic. DETA and NM/DETA mixtures readily absorb water from the atmosphere, which turns the solution from transparent yellow to milky, turbid in appearance. Since the effect on explosive sensitivity and performance is unknown, best practice is to prepare NM and HP mixtures fresh daily and store them in sealable containers to prevent environmental contamination. Further details on material compatibility with focus on HP, NM and their mixtures should be sought in their individual Safety Data Sheet (SDS).

D Laser Hazards: Photon Doppler Velocimetry (PDV) requires use of high power lasers, usually in the near infrared (NIR) region of the spectrum which is invisible to

the human eye. Eye damage is possible, especially if the laser energy is being focused to a point, as it often is during PDV experiments. Laser safety goggles must be worn if the laser is turned above 500mW regardless of the focusing environment. If collimated light is being used anywhere in the area, laser safety glasses must be worn above 150mW. Typically, a very small, eye-safe amount of light is used to make characterizations and measurements while the experimenter is exposed to the laser beam (i.e. while attaching the probe in the personnel bunker). Only after the device and probe have been moved to the final experimental location and all personnel have retreated to their safe radii, may the laser power be turned to higher, non-eye-safe power for data collection.

E Explosive Hazards: These arise at several stages throughout the execution of an explosive test series. No explosive handling, for any reason, may be performed without at least two persons present, and explosive handling may only be done by persons approved by the Range Manager. Only persons maintaining valid ATF employee possessor permits may access the magazines. Any unlicensed personnel handling explosive material must be directly supervised by licensed personnel, and it is the responsibility of the licensed person to maintain custody of the explosive until it is safely stored (and logged if any was used) back into the magazine. During the packing of the booster, hydraulic pressure is applied, using the press die, to pack composition C-4 (C4) into the booster pipe. Often the booster is packed into a separate pipe, but sometimes the booster and sample explosive occupy the same pipe. If the latter is the case, it is critical to take special measures to ensure compatibility and to leak-proof the interface between the booster if the sample is a liquid. Pressing requires caution and an attention to details that no explosive particles (RDX particles) fall at the pinch points in the die. The die for packing the booster is constructed of cast Nylon 6, 6, rather than metal, to reduce friction and impact forces. The flat and mating surfaces of the die should be thoroughly cleaned prior to each booster packing. During pressing, if RDX particles are present between the flat, mating surface of the booster pipe and the bottom of the die, this not only presents a pinch point but the gritty explosive particles may deform the machined plastic surface finish which may lead to later leaking of a liquid explosive. If the explosive is a liquid, e.g. HP or NM, which are relatively insensitive (compared to nitroglycerin), filling the sample pipe should be done using a glass or polypropylene syringe. Epoxied needle connections should be avoided without prior chemical testing to prevent rapid HP decomposition and bubbling. If a disc of PETN-based sheet explosive will be used as a booster, the cutting operation should always take place atop a rubber or foam pad to prevent PETN particles from being impinged by the cutter.

If electric blasting caps (EBCs) are used, they should only be handled by the OT. Exploding bridgewire detonators (EBWs) should only be used when precise timing is critical, due to their cost. EBCs carry an inherent risk associated with the primary explosive contained within, and should be treated with extreme caution. Specific safety measures pertaining to initiators are the responsibility of the OT, including but not limited to shunting firing lines when not in use (to prevent stray currents across the bridgewire), continuity checks (to ensure the bridgewire is intact), and connection of the detonator to the appropriate firing system. EBWs are inherently safer to mechanical and electrical insult, due to the extreme power flux required to function; conditions nearly impossible to meet in an accident scenario. Safe distances from the explosive charge will be determined by the OT in order to protect personnel, but it is the responsibility of the experimenter to protect the equipment from blast and ejecta. It is imperative that all personnel are accounted for and the security to the site is maintained on shot day. In accordance with FL007, the gate(s) leading to the test area must be closed and the “Do not enter-Explosive Test In Progress” sign must be displayed for incoming traffic to see.

F Hazards to equipment:

i. High-Speed Cameras are expensive and are easily damaged! Camera setup should involve minimum movement of the camera since internal electronics and optics can become damaged or misaligned if the camera is not handled with extreme care. When setting up, be sure the pathway from case to bench/tripod is clear and free of tripping hazards. It is also possible to damage the cameras by exposing them to excessive light during a test (i.e. while shutter is open). The excessive level of light is different based on the exposure time of a particular test. It is possible to over-expose the cameras even during normal lighting conditions in the ambient outdoor environment while focusing or collecting images prior to the explosive test (i.e. ‘bright-field’ images). It is imperative that any new lighting environment (new to the experimenter) be approached conservatively; slowly approach the amount of light exposed to the cameras until the appropriate settings have been reached. It is recommended to design a mock-up experiment for the sole purpose of determining light levels prior to data being collected; by doing this the experimenter can ensure that no data will be lost. The best method for determining the appropriate light level is to film an event with a constant light output (i.e. a rate stick) and shoot bracketed exposure times in the test shot (i.e. short to long exposures on each frame). By reviewing the results of this test, the proper light values can be approximated by only a single test. Most of the light emitted from a detonating explosive comes from the superheated carbon particles not fully oxidized in the detonation reaction zone. These particles are blackbody radiation emitters. Therefore, the brightest reaction light will be from fuel (carbon)-heavy, hot-burning explosives. If aluminum or other metal fuels are involved, it is imperative that a conservative strategy is adhered to so that the cameras are not damaged; these explosives are extremely bright! Cameras can also be

damaged by the explosive event itself, both by fragment impact and blast pressure. Predicting damage by these stimuli is nearly impossible, and the experimenter must carefully gauge whether each particular event is safe for the equipment. If any signs of equipment damage are observed, a new strategy must be developed immediately.

ii. PDV Equipment may easily be damaged since it contains extremely sensitive electronics and delicate fiber optics which become damaged if they receive excessive power signals. Laser input voltage must be between 12-14V. The laser is controlled through software, which means that a potential scenario arises such that the accidental push of a button may activate the laser emission. Take extreme caution when the RIO laser software is open, especially using the HiTechniques Synergy computer, or any other touch screen computer which increases the risk of inadvertent soft keys being pressed. The laser is equipped with a manual shut-off switch which must be in the 'off' position while the laser is not actively being used. Although the laser itself is not likely to be damaged by accidentally switching it on, it is typical practice to have fiber optic components connected in line with the laser which will become damaged and rendered useless if exposed to the full output power the laser is capable of emitting. Therefore, take extreme caution in turning on the laser, as it may be connected in a configuration which it is only appropriate to turn the laser to a low power setting.

Appendix 2.2 Test Fixtures

The current test device is named 'Vise-007' and functions to clamp the detonator, sheet explosive, booster charge, sealing gaskets, sample charge, polymethylmethacrylate (PMMA) window, and PDV laser probe in concentric alignment with each other using sufficient force that the liquid sample explosive does not leak out. The design is specifically engineered so that the booster charge and sheet explosive disc are inserted during assembly, but the liquid explosive and detonator can be excluded until immediately prior to testing. This allows many devices to be safely fabricated and stored in the magazine in days leading up to testing. The device functions much like a bench vise, depending on alignment rails along which a sliding block travels axially. The booster, sample and PMMA window are stacked and aligned using a jig (and then a hollow threaded screw is turned which compresses the sliding block against the stack. A diagram of the device is shown below in Figures 1

and 2.

Figure 1: The configuration named 'Vise-007' exploded view.

Figure 2: Vise-007 shown fully assembled.

Materials:

The test device is constructed mostly of plastic materials in order to minimize the amount of energy contained in the fragments when the device explodes. By maintaining low impedance materials, potential damage sustained to equipment and infrastructure is minimized. The det block and probe block are constructed from acrylonitrile butadiene styrene (ABS) plastic (McMaster.com, 2" wide x 4' long x 3/8" thick bars); the rails are constructed from polyvinyl chloride (PVC, Home Depot, 1/2 sch. 40 PVC pipe); and the slider block is constructed from polypropylene (PP, mcmaster.com, 2" wide, x 4' long x 3/8" thick bars) with the use of a Viton® o-ring (mcmaster.com, O-ring #211). The choice of plastic materials is made considering a balance of cost, chemical compatibility, rigidity, and machinability. The det block and probe block must be glued to the PVC rails; thus, ABS was chosen since it and PVC

are both easily glued with PVC glue (Home Depot, all-purpose PVC glue). Polypropylene is preferred because it is chemical resistance; unfortunately, that resistance extends to the solvents in the glue so that it cannot be easily glued to the PVC; ABS was chosen instead. The slider block is made from polypropylene because the slider block requires no glued surfaces, and PP is the best balance of cost and machinability; PP is also quite 'slippery' and will bind less as it slides on the rails. [PP is the least expensive material available from McMaster in the shapes required, and, with the exception of the fluorinated polymers like polytetrafluoroethylene (PTFE), is the most chemical resistant.] PP is also the easiest to machine of the group, which means faster cutting speeds can be used. The booster pipe and sample pipe are both made from polyethylene pipe (McMaster.com polyethylene shipping tube). This tubing is extremely thin (0.022" wall thickness, either 1.09" or 1.64" diameter), and is easy to crush inadvertently. This tubing is used because it is low confinement, and it is extremely clear so that reaction light can be easily observed. The window material chosen is PMMA (mcmaster.com 2" wide x 4' long x 3/8" thick) because of its optical clarity and its shock impedance match with the liquid explosives. By choosing something that matches acoustic impedance with the explosive and its detonation products, a minimal shock reflection is observed when the detonation profile reaches the window. The booster/explosive and window/explosive interfaces are protected by a layer of 0.0003" Kapton® film. The film also acts as a sealing gasket. The film must be thin to prevent attenuation of the detonation wave profile into the window or the attenuation of the booster detonation wave into the sample. The window is

sputter-coated with a sub-micron gold (Au) layer at the PMMA/Kapton® interface to act as a reflective surface for the interferometer..

Dimensions:

The dimensions of the device are based on available pipe diameters of either 1.09” ID or 1.64” ID. If larger diameters are used, a redesign of the fixture would be required. The diameters are chosen with the goal of the project to collect detonation measurements on a reasonably small scale. Many of the materials intended to be tested are below their critical diameter, but the diameter of the test charge is chosen such that ‘infinite diameter’ regions may be studied within reasonable time scales. In other words, for an arbitrary diameter charge, the central axis of the detonation does not experience acoustic coupling with the charge diameter until the relief wave experienced at the charge edges transmitted radially towards the center reaches the axis. This means that larger diameters will provide longer experimental windows in time and space to probe the ‘infinite’ diameter regime. This region can be estimated to be about one charge radius in length. This means that once the detonation has passed this length inside the sample pipe, a region of equilibration with the charge axis and charge edges begins which may not become steady for as long as six charge diameters in length. If a sample explosive is below its critical diameter, the detonation will likely quench (i.e. fail) as soon as the release wave reaches the charge axis. If a longer ‘infinite’ diameter experiment is required, a larger diameter test device must be fabricated.

Machining the components: Tolerances are $\pm 0.001''$ unless otherwise noted.

Det Block: The det block is made from 2'' wide x $\frac{3}{8}''$ thick x 4' long bars purchased from McMaster Carr. These bars are cut to 4.125'' long using a horizontal band saw. Because all dimensions are nominal, the slightly oversized bars are machined to size using a vertical knee milling machine to 2.000'' wide x 4.000'' long x .375'' thick. The thickness is not machined, the bar thickness is used as-is and can vary as much as $\pm 0.040''$. Also, it should be noted that a hand-cut notch should be cut in the upper-left corner of each 2.000'' x 4.000'' block to signify which end is being placed against the stop in the milling vise. This way, each block is placed back in the exact orientation in the vise as it was during a previous step (this includes the slider block and probe block components). The det block has 3 features machined into the one face, two tight-fitting 0.800'' holes inset all but .050'' through the thickness of the bar; later these holes will seat the guide rails and will become a glue joint. The last feature is a $\frac{1}{2}''$ x 13 thread per inch (tpi) threaded hole through which a 2'' long nylon screw will be inserted to provide pressure that seals the stack together. The tap drilling step and tapping step are both done on the vertical milling machine.

Slider Block: The slider block is made from polypropylene bars, purchased 2'' wide x $\frac{3}{8}''$ thick by 4' long. The bars are cut to 4.125'' $\pm 0.05''$ long and then machined to specifications (2.000'' wide by 4.000'' long). The native $\frac{3}{8}''$ thickness is not machined, but used as-is. The slider has five main features as follows. The first three

are machined onto the booster-facing face of the bar; the latter three are drilled on the top 3/8" thick edge and tapped.

V-notch slider pockets: The slider pockets are machined to center the 0.800" o.d. rails on 2 sides of a v-block like feature. The vblock feature of this pocket is cut with a 0.500" diameter cutter, so radii are all 0.250". The feature geometry should be calculated so that the v-block edges are tangent to a 0.800" pipe at 120 deg from each other, and 30 deg from either horizontal centerline. Later, a #8x32 nylon screw will descend onto the third 120 deg point, securing the rail and adjusting the friction of the slider as needed to remove tolerance slop. Note: enough room should be removed from the top of the v-block feature to ensure easy tapping for the rail tension screw holes.

PETN sheet pocket. This pocket allows (1) 0.75" x 0.080" (2mm or one layer) of PETN sheet explosive to serve as a priming charge to the c4 booster. This pocket is inset such that one layer of PETN sheet explosive may be flush with the mating surface between the slider and the booster.

Detonator seating hole: The RP-501 detonators are specified not to exceed 0.295" OD, and are therefore drilled with a 0.295" (letter M) drill. This may also be done using a v-block feature as described for the rail pockets.

Set screws along face: (3) Set screw holes are drilled along the 3/8" thick top face to secure the rails and detonator to the slider. The rail tension screws can be easily

drilled (#29 wire gauge drill) and tapped (#8x32), but the detonator set screw threads require extra steps. Also, it should be noted that the y-location of the set screw hole for the detonator is offset to accommodate the depth of the sheet explosive pocket, 0.080", and should be at 0.1475" from the back edge rather than 0.1875" which is true center of the thickness. If not, the detonator set screw hole will blow through the PETN sheet explosive pocket walls, deforming the bottom of the pocket. Because standard taps are strongly tapered to gradually cut threads and remain easy to adjust for concentricity in the first several threads, and most cutting sections are no more than 1" long, steps must be taken to ensure full threads are cut to the depth of the .295" detonator hole. One of three options may be taken to ensure thread depth.

V-block feature: if a v-block feature is used for the detonator hole, then sufficient material along the tapped set screw path may be milled out to make sure the #8 tap may cut full threads from the top edge to the beginning of the v-block pocket. It must be noted that as much material as possible should be left so as not to perturb the PETN sheet explosive pocket.

Drill-through: The #29 drill can be plunged to a depth of 1.75" from the top edge, through and out the other side of the detonator hole. This way the taper of the tap can be plunged through, and full threads can be cut all the way down to where the set screw meets the detonator. It should be noted, that if this method is used, a .25" drill bit should be used to clear way for the un-threaded section of the tap, should it be a larger diameter than the threaded section.

Flat bottom taps: If flat-bottomed taps are available and the .25” clearance hole made where appropriate, the #29 drill can be used to drill a hole that breaks through the detonator bore, but does not disturb the other side of the bore. The tapered tap can be used in the milling machine, but only plunged to the depth of the detonator hole. Then, subsequent taps included in a tap set may be used to tap the full depth of the hole, being careful not to damage the opposite side of the detonator bore. The flattest-bottom tap will cut full threads to the full depth of hole without damaging the opposite wall of the detonator bore.

Probe Block: The probe block is constructed in a similar fashion to the det block, with (2) 0.800” holes aligned for rail alignment and gluing. The feature in the center is to seat the fiber optic probe (4.0mm x 10.0mm brass lens housing). The probe bore hole is a #21 wire gauge drill (0.159” Diam). A #29 wire gauge drill is used to drill an orthogonal hole which will be tapped to a #8x32 machine screw thread in order to set the probe in place.

Rails: The alignment rails start as ½” nom. PVC pipe. One end of the rail is bored to a constant diameter and tapered slightly to seat a 60deg live center on the tailstock. The pipe, now suspended between the chuck and live center is turned to 0.800” OD. Two rails are needed for each device. It is imperative that the rails are of equal length.

Window:

Machining: The PMMA windows are machined from 3/8" nom. thick cast PMMA bars. The window dimensions are typically 1.75" in diameter, but may vary depending on the sample pipe diameter. Windows 1.75" in diameter accommodate both 1" and 1.5" nominal sample and booster pipes. The bars are purchased as 2" wide x 3/8" thick x 4' long, and individual 2" lengths are cut. A stack of 2" x 2" x 3/8" squares are pressure turned on the lathe to a constant diameter of 1.75"; it is also possible to cut circular discs from the bar by using hole saws on the drill press, but extracting the discs without damaging the window surface is difficult, and requires the use of a buffer (i.e. plywood) by cutting a disc of the buffer material and not extracting the slug. When the PMMA disc is cut, the saw may be unscrewed from the drill arbor and (using the buffer material as a protection) punched out from the saw. The discs must be thoroughly deburred (via a file or belt sander) and cleaned before turning to prevent misalignment of the stack. The use of both a drive plate and center adapter must be used to accommodate the stack. Alternatively, the windows may be machined from bar stock using the lathe. This method is far more difficult because each face must be machined and polished to accept the reflective coating to a high degree of smoothness. *

Polishing: If for any reason either front, optical surface of the PMMA is no longer smooth, it must be polished. The polishing can usually start by manually sanding the window, face-down on 600 grit sandpaper placed atop a granite surface plate. The paper should be generously lubricated with oil or WD-40. The next step should be 1000 grit then 2000 grit sandpaper, followed by Nova polish compound #3 then #2.

The nova polish may be applied via Kimwipe or other delicate task wipe. Using a red laser beam, the optical quality of the finish can be observed by passing the beam through the window and observing the laser dot several inches away from the back surface of the window. Speckling and asymmetric distortion of the laser dot indicates a bad polish, which may require that the experimenter start over at 600 grit sandpaper and go again through the previous steps until a good optical finish is obtained.

Sputtering: The windows are sputtered under the guidance of Mike Platek at the URI SEM lab, using the gold sputter-coater.

Figure 3: Gold sputter coater with controls & chamber. Power switch (right) not visible.

Any 1.75” diameter windows must be sputtered individually, but windows 1.1” in diameter (cut to match 1” nominal sample pipes) may be done two at-a-time. Operating the sputter coater is done as follows:

Open valve on Argon gas tank, setting regulator between 5-10 psi to the sputter coater

Clean samples to be sputtered, removing the protective film and carefully cleaning the residual adhesive on the optical surface. It is recommended to leave the protective film on the opposite (non-sputtered side) until the window is installed in the final device.

Using double-sided sticky glue dots (Dollar Tree), adhere the bottom surface of the window to the center of the sample post in the sputter coater chamber.

Close and firmly seat the sputter chamber lid, cleaning the seals if necessary.

Toggle the sputter coater on, using the switch on the right side of the machine.

The machine will automatically begin to pump down the pressure in the chamber, indicated by the noise of the vacuum pump and a gas flow setting of 'off' indicated by the light labeled as such lit up.

When the pressure in the chamber reaches <25mTorr, the 'sputter' button under of gas flow options may be selected to introduce argon gas into the chamber. Initially, the flow will increase the pressure in the chamber significantly. The user must wait until the pressure decreases to 50mTorr. The argon flow may be adjusted using the argon flow knob until 50mTorr is reached and becomes stable.

Using the manual timer on the front of the machine, the user will dial in 300-500s of sputter time and start the sputter process in timed mode.

While the window sputters, the next window should be cleaned as previously described.

Once the sputter coater has finished its timed cycle, the 'off' switch should be toggled, and after 10s, the chamber will self-vent and the lid may be removed.

The sample may be carefully removed taking care not to touch the gold surface, as the adherence to PMMA is very poor.

Ensure the glue dot is successfully transferred to the next sample, and the next sample may be sputtered in the same way.

Once all sputtering is complete, the power switch should be toggled 'off', and the argon tank valve should be securely closed.

Sputtered samples should be stored in a hard case which does not allow movement. The gold coating is extremely fragile and must be intact for the optical techniques to succeed. The gold layer is located at sealing interface between of the liquid sample in the vise configuration; damaged areas to the gold reflector near the seal may result in leaking.

Booster Pipe/sample pipe: The booster pipe and sample pipe are constructed from the same type and size of pipe. For this test series, a thin-walled (0.022") polyethylene pipe is chosen for its optical clarity and chemical compatibilities. This thin wall makes machining and alignment difficult, especially because the sample chamber must be sealed liquid-tight to the booster pipe on one end and to the window on the other. The pipes can be purchased at several diameter options, but for this series, 1" nominal (1.099" ID, 1.149" OD) and 1.5" nominal (1.645" ID 1.689 OD) pipes are chosen based on the critical diameter of the materials of interest and the desired 'infinite diameter' experiment window. The pipes are machined using a nylon ID support. The support is a cylindrical segment of nylon machined to fill the inner diameter of a sample/booster pipe. The support bar is used to prevent deflection of the thin-walled

tubing during both while clamping in the lathe chuck and at the cutter/pipe interface while machining. It must fit tightly to be effective; an expansion arbor may also be used for the same purpose. Using the support bar inserted into the booster/sample pipe stock, the pipe is faced and parted to length. Boosters for this series should be 1.250" long when 1" nominal pipe is used, and 1.645" long when 1.645" id pipe is used. Both booster and sample pipes should be thoroughly cleaned first with soapy water then with either acetone or rubbing alcohol to remove chemical contaminants. It is very important to preserve the end-faces of these parts, especially where liquid-seals will be made.

Kapton® seals: 0.0003" (7.62um) are cut by hand with scissors. The seals should be rectangular, oversized compared to the sample pipe outer diameter in width by approximately 1/8" and in length by approximately 1". The seals should not be laser cut, since the process generates flaky, black, burned Kapton® at the edges which may have unknown chemical effects on the sample explosives.

Screws:

Set screws: (4) #8x32 2" long screws are used to secure the detonator, the alignment rails, and the fiber-optic probe in place. These screws should be plastic (usually nylon) and should be sanded flat at the point of contact; otherwise, when the screw is setting a shaft, the rotational motion will misalign the shaft.

Vise pressure screw: (1) ½”-13 x 1.5” long nylon screw is used to provide clamping pressure to secure the booster, sample pipe, and window together. This screw must be faced on the lathe and drilled to slightly oversize the detonator. For RP-501 Detonators, this bore size should be 0.3160” (letter ‘O’ drill). In order to preserve the threads, a threaded chuck adapter should be used.

Assembly

First, all components must be cleaned thoroughly with water/detergent-based cleaner and then acetone. Certain plastics are incompatible with acetone, in which case either rubbing alcohol or ethanol should be used. All dirt and chemical residue must be cleaned from the parts prior to assemble.

Alignment jig: alignment v-blocks or half-profiles (Appendix E) are be used to align the booster, sample, and window coaxially. Sometimes the det block and probe block may have insets to accept the booster pipe and window, respectively, which alleviates the necessity of a jig spacer at those interfaces. Note that if such an inset is desired, 0.5” thick material ought be used for these blocks to allow for the necessary features.

Appendix 2.3 Diagnostics

High Speed Cameras

Specialised Imaging SIMD-16: the SIMD16 camera is used to capture ultra-fast images from the detonation event.

Figure 1. SIMD-16. Not shown the supplemental camera port

Figure 2. Potential camera setup using SIMD-16.

Basic operating principles and layout: The camera is equipped with (8) individually-controlled intensified CCD cameras, which can each store, on the CCD

chip, (2) light intensity records at different times. The time between the first and second image on any one channel must exceed 550 ns to prevent ghosting. Incoming light is focused using a standard Nikon F-mount bayonet lug lens mount. Once inside the camera, the light first travels first through a half-mirror, directing half of the photons onto an alternative camera via the side port on the left-hand side of the camera. The rest of the light is passed deeper inside the SIMD, and then interacts with an 8-way beam splitter (BS) which directs the light to (8) different intensified CCD cameras (iCCDs). The iCCDs are described in stages; the first is a photocathode (PC) which, because of the photoelectric effect, emits electrons into free space opposite the side facing the lighted image. The electrons are amplified by passing through a micro-channel plate (MCP) electron amplifier. These channels amplify the electron signal by cascading electrons with the walls of each micro-channel, charged to very high voltage. A single electron liberates many electrons after each impact with the walls of the charged MCP. These cascaded electrons travel further downstream, until they make contact with a phosphor screen. The phosphor grains are chosen such that a minimum clear down time of 550 ns is necessary before another image can be captured without ghosting of the previous image. This time may vary depending on the amount of light visible in the previous image. The camera does not have any software or firmware protection from this effect; therefore, it is up to the experimenter to be aware of timing and frame rates which prevent undesired ghosting. The phosphor screen is imaged onto a conventional CCD camera. The exposure of the image is controlled by the duration of current to the PC. This fast electronic gating (rather than manual shutter) allows for exposures as low as 3ns. Because each of the

cameras is controlled individually, the triggering of each camera is programmed directly onto the cameras individual iCCD cameras. This hard-programmed delay can be in increments of 1ns, but a required 55ns initial delay is required between the trigger time and the first image. Typically, the camera timing is controlled by setting an initial delay (usually 9.5us representing the delay time of the FS-10 EBW fireset), then calculating the expected event window. The software has a special mode designed for this type of setup, using *custom*, *continuous* recording. By setting the initial delay, event window and exposure time, all timing parameters are constrained for recording, and framing rate is automatically calculated to evenly space the frames inside the window.

Basic operating instructions: To hook up the camera, plug in the power source and switch on the camera. Connect an Ethernet cable to the network port and open the SIM control software on a computer connected to the same network as the camera. The default IP address of the camera is **192.168.0.100**. For network connectivity troubleshooting, refer to the SIMD manual. The SIMD should now be communicating with the computer, and the software should confirm a stable connection to the camera through the software. Install the appropriate lens on the SIMD and focus as best as possible through the passive eyepiece viewer. Confirm focus to the SIM by activating ‘focus’ mode in the software. The aperture should be open as much as possible (2.8 stop) and select a modest exposure time (500us on a sunny day, 5ms in poor lighting). The gain should not be raised above a modest setting, about 3, unless extremely poor lighting necessitates. If imaging conditions are cloudy or indoors, as much as 5ms

exposure may be necessary in order to see a bright-field image (i.e. the real-time, ambient light-visible image of the setup which confirms focus, field of view, etc); if more than 5ms is needed to visualize an image easily seen by the naked eye, another problem is suspected (check the lens cap).

When focus mode is activated, the camera chooses a random channel to display the field of view in a separate applet window. The camera will automatically choose a random channel to display the focus mode image so each channel wears uniformly over time. When the bright-field image is visible during focus mode, lens focus should be adjusted if necessary. To capture a successful bright field record, the camera should be configured to capture an event with the same settings (iris, gain) as used in focus mode, but the exposure should be set to 0.5 – 0.75 times the exposure used in focus mode; if not, then the bright field record will likely be overexposed. The ‘Test’ soft key will capture an event record with the current settings, and the resultant image record should be stored for later reference using the suffix “BF” for “bright field.”. The recommended time for collecting a bright field image, however, is during a trigger test. The trigger test is outlined in detail in a later section, but in principle, the camera settings are optimized to collect a bright field image and the camera is armed (selecting the ‘Arm’ soft key rather than ‘Test’); this technique simultaneously verifies the trigger mechanism is capable of triggering the camera and collects the bright field record. It should be noted that the bright field image should be collected at least once immediately prior to testing, which means after the detonator has been installed and after the sample explosive has been filled. Later, the bright field image

and the dynamic image may simply be overlaid to make for a better-looking record as well as verifying internal alignment of each channel. Once the bright-field image has been recorded, the camera settings optimized for the upcoming shot event should be sent to the camera (i.e. typically 10-75 ns exposures and event times calculated between 1.1-1.25 times the expected event window).

Appropriate exposure time depends on three factors: a) the brightness of the event (temperature and black body emissivity of the hot particles); b) the speed of the event (i.e. shock speed); and c) the lens/distance combination (i.e. the light-gathering ability of the current configuration). Obviously, brighter explosions and better light-gathering configurations should be captured with shorter exposures. Booster-only shots (very bright) captured with the Tamron 150-600mm lens (currently our best light gatherer) from a distance of about 20m is best captured with 35ns exposures, but the same event captured from the 500-1500mm lens (our worst light gatherer) requires about 55ns to attain the same light values. Typically, no longer than 65ns is necessary to collect adequate light values from typical experiments.

Detonation velocity may dictate the exposure time to minimize shock blur, a phenomenon caused by the motion the shock travels during the exposure time. This can be easily calculated if a good estimate of the detonation velocity is known prior to the experiment. For example, if an 8" (203mm) long HP-EtOH sample with detonation velocity of 6.0mm/us is viewed over a total field of 800 pixels (~63% of the horizontal field of view), the shock will travel 23.6px/us, or 42.3ns/px. This

means that the shock will travel the distance of one pixel every 42.3ns. The maximum exposure time must be below this duration to prevent shock blur altogether, but is generally acceptable if under 2-3 times this value. Alternatively, for a booster-only event captured at the same field of view (800px), but with a length of 1.645” (41.8mm) and a detonation velocity of 9mm/us, the relevant values become 172px/us or 5.8ns/px. This brings the recommended exposure time down to a maximum of about 25ns to prevent shock blur, which is far below the recommended exposure time for this event using certain lenses; this represents a case where higher gains are needed to attain good images with no blur.

Triggering: The SIMD camera comes with 4 default trigger modes which are software-selected to apply to one of two trigger ports on the back of the camera (‘Trig 1’ & ‘Trig 2’). Selecting ‘Trig 1’, for example, will totally deactivate ‘Trig 2’, i.e. no redundancy can be established using the other port. The 4 modes are as follows:

Rising Edge: an externally-controlled voltage signal increasing in voltage once the event is to be triggered.

Falling Edge: A decreasing voltage signal from an external source.

Make: Using no external voltage control, internal electronics detect when the two conductors of the selected trigger lines are mated/shorted; this triggers the event.

Break: Using no external voltage control, internal electronics detect when the two conductors of the selected trigger lines break contact; this triggers the event.

These methods should be used in conjunction with a global timing strategy chosen by the experimenter to optimize synchronicity and timing validation between all diagnostics. The trigger should be tested prior to capturing the event by arming the camera ('Arm' soft key) and attempting to simulate the trigger mechanism (e.g. touching 'make' wires together, firing a 'short-circuit' test on the FS-10, executing a single-shot pulse from the DG535). If triggering from the event itself (i.e. make or break wires), often the minimum (55ns) delay time is used, but if triggering from the FS-10, a built-in delay time is used to accommodate the fireset and detonator delay (grouped as the 'ignition delay') of about 7-10us.

The output trigger of the SIM must be connected to any supplementary camera, e.g. the SI Kirana in order for the other camera to trigger. Optionally, the output trigger pulse ('Trig out' port on the back of the SIMD) can be coupled back to a free channel on a TTL-capable oscilloscope so that the first frame of the camera image may be synced to the oscilloscope record. This is most important when the camera image is being compared to an orthogonal diagnostic technique like shorting pins or a failure cone witness plate.

Handling and care: Damage to the SIM may occur by keeping the camera in focus mode with a high (100s of us) exposure for too long, or otherwise exposing the photocathode to excessive amounts of light. This damage is noticed by the number of dead pixels in the record of each channel. The best practice to preserve the camera is to creep up on the amount of light permitted into the camera in order that the sensitive

parts are not exposed any more than necessary. Also, the alignment of the SIMD's 8 individual cameras is extremely delicate. Vibration or jostling of the camera, or otherwise careless behavior, may cause misalignment or even breakage of internal optical components. Many of these adjustments or repairs would have to be done by SI personnel, possibly requiring the camera to be shipped out for repair.

To turn the camera off, as long as there is no active file transfer in process, the power switch may be simply turned off, and the camera unplugged. Note: the captured image is temporarily saved locally on the individual graphics cards of each iCCD after a recorded event. As long as the power is not turned off or the cameras are otherwise overwritten, the previous image can always be recalled using the 'Resend' soft key. A special note about using the supplementary camera port: The mechanical aperture is located upstream of the half-mirror, such that if the SIMD aperture is closed, the supplementary camera will not receive any light. In order for the supplementary camera to view the image, the SIM must be in focus mode, and the iris (aperture) must be open or the 'open shutter' soft key must be used. DO NOT LEAVE THE SIM IN FOCUS MODE ANY LONGER THAN ABSOLUTELY NECESSARY-ACCELERATED AGING OR DAMAGE WILL OCCUR.

Data analysis: Analyzing data from a SIM record requires three steps

- Distance calibration (i.e. converting pixels to mm)

- Point tracking (Locating a series of x-y positional points at specific frame intervals that represent the motion of interest)

Mathematical manipulation: This step may include rotational modifications, least-squares fitting to model functions, and possibly treating the data in intervals.

The data analysis can be done one of three ways, starting with the software itself. By manually picking calibration points from the SIM images in the software and then recording the frame delay time and the x-y points of interest (e.g. the detonation front) in a spreadsheet for each individual frame, a framework for calculating velocities, for example, can be standardized. Using this method can be difficult because the technique of picking points is very user-specific. The second option is using the algorithm written in Python 3.x. The algorithm is made specifically to import *.TIFF files generated by the SIMD camera. The algorithm allows the calibration step to be conducted on a bright-field image, from which the known-distances in the experimental fixture can be easily seen. Assuming the field of view in the bright field image and dynamic record are the same, the distance calibration is applied to the dynamic image. The applet accommodates a feature in which the user selects two points between which a series of pixels is chosen to represent, for example, the pixels along the charge axis. The next step is to display individual frames from the dynamic record. Showing these frames one at a time will give the user the ability to select individual points. If the two-point line was chosen, a 2-D plot of the individual light intensity values for the pixels chosen along that line. This allows the user to quickly identify the most intense pixel along the shock front, and select it for that particular frame. Once the pixel of interest is chosen, the software records it in an array to be used later. The next step is to insert the frame interval, which currently is only a

constant value, although the SIMD allows the experimenter to insert individual delay times for each frame. With the points of interest individually chosen, and the frame interval entered, the software will generate a distance vs. time plot from the data and displays a linear least-squares fit line automatically. It is recommended to choose points from all frames initially, even frames that represent transient behavior, if only to see the event as a whole. Once the linear region is displayed, the user can repeat the process, only selecting points of interest in frames which represent linear behavior. In this way, a linear detonation front can be reliably measured from a dynamic SIMD record, displaying the detonation velocity as a statistical fit to the distance vs. time data chosen by the user.

Specialised Imaging Kirana:

Basic operating principles and layout: This camera is not intensified like the SIM but utilizes a similar on-chip storage strategy. The Kirana has a maximum framing rate of 5,000,000 frames per second (fps) and a minimum exposure of 20ns (1/max fps). The on-chip storage mechanism stores light from 180 separate time events in charge-storage wells immediately adjacent to the photo-active area on the pixel. Unfortunately, at the time of writing, the on-chip storage wells leak light both forward and backward in time. This makes the record difficult to interpret, and the problem is worse if the wells are saturated. To minimize this problem, keep exposure times as low as possible, or stop the camera down manually (Note: neither the Kirana nor the SIMD have automatic focus or motorized aperture features- as a result, slivers of PTFE are inserted in to the Nikon lens' aperture armature to keep

the iris wide open all the time). When using the Kirana in the SIMD side-port configuration, it is not necessary to provide a second lens; the one used on the SIMD is optically aligned to provide the same image and focus on each camera. External optics between the SIMD side port and Kirana are optional, notably since the sensor size difference between the two cameras makes for a different sized field of view in each record. The Kirana must have physical support underneath itself when mounted to the SIMD to prevent excessive strain at the lens mount. A foam block cut to size is often sufficient. The Kirana is composed of two components, the camera and the power supply unit. The network, power, and trigger connections are located on the power supply unit. To get a live view from the Kirana, pressing the 'live' button will enter a mode similar to the 'focus' mode with the SIMD camera software. Remember that no live image can be captured by the Kirana on the side port of the SIMD if the SIMD shutter is not opened either by being in focus mode or by using the 'Open Shutter' soft key. The Kirana cannot individually-control when frames are captured like the SIMD; rather it is programmed with constraints on initial delay, frame rate, and exposure time. The control of the Kirana is, in general, simpler than the SIMD, the image records look, in general, better quality than the SIMD images (because they are not imaged over phosphor grains), and the Kirana can capture 180 images rather than the SIMD's 16 images. The Kirana has an intrinsic decrease in sensitivity to either a conventional CCD camera or the SIMD since only a small fraction of each pixel area is photosensitive and there is no electronic gain setting like the SIMD. The rest of the pixel area is taken up by charge well storage and is not light sensitive. The SIMD also has on-chip storage,

but because of the image intensifiers, it is orders of magnitude more sensitive. This means a longer exposure time will be needed on the Kirana than on the SIM to capture similar levels of signal to noise from the same event. Typical exposure times on the Kirana are 70ns for an event that would be a 35ns exposure and gain of 3 using the SIMD.

Basic operating instructions: In general, the Kirana is a simpler camera to operate and can be used stand alone or as a side camera to the SIMD connected via the side port on the SIMD. When using the cameras connected, they must be independently controlled using the individual camera software, individually armed and triggered.

Setup and assembly: The Kirana power supply unit should be plugged in and capture cables should be plugged in between the camera body and power supply. Once the Ethernet cables are connected to the same network as the control computer, the Kirana control software can be opened. The software should already be configured to recognize the IP address of the camera, but the manual should be consulted for any network connection problems. Once the software has successfully connected to the camera, the user can enter the 'live' mode by pressing the soft key. Note: before entering live mode, ensure that the camera settings are appropriate for the amount of light the camera will see- no more than 500us to start. If an image is not visible, the exposure can be incrementally increased, but even on a cloudy day or indoors, an image should appear with a 10ms exposure if everything is working properly. Once the experiment is sufficiently aligned inside the field of view of the camera, similar settings used

in live mode should be used to collect the ‘Bright-field (BF) Image’; now the camera should be armed for the trigger test which will simultaneously confirm the trigger method and collect the BF image. Once the BF image has been collected and the trigger has been verified, the dynamic settings should be calculated and set in the software. After this, the camera should be armed and is ready to capture the dynamic event. Note: if the fixture or camera were accidentally bumped or otherwise moved between the time of the BF image and the time when the event is ready to be fired, another BF image should be manually triggered to accommodate the new position of the fixture in the field of view. It can be helpful later during data analysis, if the BF and dynamic images are in perfect alignment.

- a. **Lens:** Like all other URI high-speed cameras, the lens mount is a Nikon F-mount bayonet style.
- b. **Optical alignment:** The Kirana can only be aligned and aimed by entering ‘live’ mode in the software. If connected to the side port of the SIMD camera, the manual port on the SIMD camera can be used to get the image size and alignment ‘close’, before entering live mode. Live mode should be limited to the time needed for alignment purposes only, especially with the SIMD camera, and light levels should be as modest as possible.
- c. **Triggering:** The Kirana can be triggered similarly to the SIMD, but the software does not have a designated place for the experimenter to select ‘Make’ or ‘Break’ modes explicitly. The user simply selects “Rising Edge” or ‘Falling Edge’ mode. With no external triggering circuitry, the Kirana

uses internal triggering circuits to bring a 4-5V potential between the center and ground conductors on the “Trigger 1” port. By keeping the trigger wires normally open, the voltage will remain high until the trigger port conductors are shorted (i.e. a ‘make’ wire), and if the software is set to accept a ‘Falling Edge’ trigger, then the camera is configured for a ‘make wire’. Likewise, if the trigger conductors are normally closed, the potential across conductors is shorted to 0 V, and the separation of the conductors causes the potential to rise (i.e. ‘break’ wire), and the software can be configured to look for a ‘Rising Edge’. If external circuitry is used, e.g. the output signal from the SIMD (or other camera, oscilloscope, etc), the signal delay generator, etc, then the external source should be connected without concern, and the Kirana will allow the external source to drive a pulse, for example. In this case, the trigger should be looking for a ‘Rising Edge’. No more than 15V should be presented to the camera trigger (this is not verified with the manufacturer).

- d. **Handling and Care:** The Kirana camera is separated into two separate parts, which makes setting it on a tripod easier, but because the capture cables that connect the two parts (camera body and power supply) are relatively short and inflexible, the power supply must reside in close proximity to the camera body, but need not be mounted to a tripod. Often a small table near the camera tripod will suffice. Extremely heavy lenses need to be supported by external fixture (e.g. second tripod, wood brace, etc) to prevent excessive strain on the lens mount hardware.

- e. **Data Analysis:** Currently, the only analysis method for Kirana camera records involves the Kirana control software, similar to the first method described for the SIMD. A spreadsheet should be used to collect the calibration points and to pick the x-y points of interest to track a dynamic event. Using the calibration data, the x-y points can be converted to distances, and rotated if appropriate. The linear Excel function 'linest' can be used to calculate the linear fit parameters, namely the distance-time slope (i.e. velocity).

Optronis SC-25 Streak Camera:

Basic operating principle: All streak cameras record the 1-d linear spatial field of a slit smeared through time across a second axis. The resulting record is a single 'frame' which represents the light values along the slit through time. This camera is digital, in contrast to older operating mechanisms. The camera operates by focusing (via Nikon lens) the light passing through a variable-thickness slit onto a photocathode (PT). The PT transforms the photons into photoelectrons, which are ejected from the back surface of the PT towards the streak tube. The streak tube directs the slit of photoelectrons to the extent of the electron multiplier plate perpendicular to the slit direction. For example, our camera is made such that the slit is oriented horizontally, therefore, the streak tube directs the line of photoelectrons to the top edge of the multiplier. When the streak unit is triggered, the sweep sequence begins; this is an electromagnetic field which is applied to the photoelectron stream. This field directs the flow from top to bottom, such that the line of photons at early times strikes the top

of the electron multiplier, and as time progresses, the line is swept towards the bottom. When an object moves or a wave traverses the slit, the smear record leaves behind a record of the changing event light through time. With this camera, it is possible to resolve sub-nanosecond events. It should also be noted that the sweep unit has discrete setting of sweep speed. A spreadsheet should be kept to distinguish the different sweep speeds according to the factory-determined list. Although the software allows the user to select generic sweep speeds (e.g. 10ns/mm) these software settings are only nominal, and the streak camera manual shipped from the factory allows the exact sweep speed to be included in the calculation. The table in the included manual also outlines the delay times for each sweep speed. These delay times correspond to the time between the sweep unit being triggered and the *center* of the exposure time. The event time is calculated by multiplying the streak speed (e.g. 10ns/mm) by the 20mm streak tube height across which the photoelectrons are swept during the dynamic event window. This yields, for example, 200ns, which would be this particular experiment's window of data collection. The inside cover of the Optronis instrument manual lists the specific values for each nominal sweep speed, with the corresponding center-delay time for the URI camera. When choosing the sweep speed in the camera software, understand that the user is only choosing nominal values. The actual values are the ones listed in the manual.

This camera is particularly sensitive to shock and vibration. The assembly of the camera is comprised of four components: a) main body b) streak unit c) readout unit d) lens. For many reasons, this camera should be considered as two separate instruments:

1) the streak camera and 2) the readout unit. Because these cameras are made from modular components, the main body and streak unit communicate directly with each other, but the readout unit communicates directly with the computer software but NOT the streak camera. In fact, the streak camera and readout unit are more or less completely independent of each other. The only interaction between them is the generic TTL output trigger of the streak camera which is ported externally (via BNC to SMA coax jumper) to the input trigger of the readout unit. It is recommended that the streak camera assembly be left assembled as much as possible, mostly to prevent damage during assembly of the components. If possible, leave the streak camera assembled in a stable, temperature-controlled environment which is as close to the location the camera will be used as possible.

To assemble the camera, clear a large footprint of space to set the camera up with plenty of space all the way around for leveling the feet later. The main body unit has feet which orient the camera position. Start by placing the main body securely down onto the table, making sure that the leveling feet provide a steady (not rocking) framework to mount the other components. Connect the streak unit to the left-hand side of the main body by unscrewing the captive thumb screws for the side panel of the main body. Both the right and left side of the streak camera have these panels and thumb screws, but only the left-hand side has the appropriate terminals to accept the streak unit. Be sure the correct panel is removed to prevent an awkward moment of replacing the streak unit into the storage box while replacing the wrong panel and removing the correct one. Remove the side panel and carefully remove the streak unit

from the padded storage box. This operation should be done with extreme caution; the streak body in the high-voltage, high-precision component which is most sensitive to static discharge and vibration. The streak unit contains a current-limiting resistor array across the terminals to safely discharge and static buildup. To remove the resistor array, pull directly away from the terminals, the array will dislodge; quickly but carefully install the streak unit to the side of the streak camera. Next the readout unit may be installed. First remove the rear panel on the main body, then indicate and install the readout assembly onto the rear end of the main body. The next step is to install a Nikon f-mount lens (no power focus or aperture) to the front of the main body. Notice the lens mount is immediately upstream of the slit assembly. It should be noted that this camera is often mounted to the side port of the SIMD camera.

The last step in the assembly is to connect the appropriate cables. The BNC to SMA jumper between 'Trigger out' on the main body unit to the readout 'Trigger in' port should be installed using the cable provided by SI. The recommended trigger method for this camera is the signal delay generator DG535 or other signal delay generator, because the camera needs such significant amounts of pre-trigger to function properly. The appropriate trigger channel from the signal delay generator should be connected to the 'Trigger in' port on the streak unit- not on the main body. The Ethernet cable should be connected to the same LAN network as the computer with streak camera software, and the IP addresses should be compatible. This constitutes the communication lines between the streak camera and the computer, but unfortunately, the readout unit requires a separate camera link cable pair running from readout

directly to the camera link ports on the computer DVI card. Note- no computer that lacks camera link cables can be used to run the streak camera- currently only the High-Techniques Synergy computer is outfitted for such connections. The remote module may be connected, if desired, but because the camera link cables prevent the computer from being any significant distance from the streak camera, it is often not useful and certainly not necessary.

To power up the unit, both the main body power key must be inserted and turned on, as well as the power switch on the readout unit. In order to collect a bright-field image, the user must open the micrometer head controlling slit width all the way (clockwise). This micrometer head can be set to a precision width, but often the only two values used are all the way open (~2mm) during alignment and all the way closed (50-80um) during the dynamic event; knowing how to choose the slit width will be discussed later. Once the slit is all the way open, the software may be opened to visualize a 2-D spatial image. The camera is placed into 'Live' mode and the streak tube chooses an arbitrary area to divert the electrons onto the multiplier/phosphor. The camera automatically changes where the active area is each time the live mode is activated, so that the wear is evenly distributed across the whole multiplier. Many of the frequently-used operations can be done through the remote control for the streak camera. However, because camera link cables are limited to a few meters, the computer is always close by, so that the remote box is rarely used and often contributes more to the already cluttered cable landscape on the workbench. When the streak and readout units are both communicating with the computer, an image can be

obtained on the screen; toggle the streak camera from ‘Streak Mode’ to ‘Focus Mode’ in the software, and the display mode to ‘Live’. This should produce an image on the screen if the object is in view. If the object is not in view, then the gain may be gradually increased, but no more than 450V. If this number has been achieved, then the problem is likely elsewhere. The minimum gain voltage (330V) is often sufficient for bright-field imaging and alignment on sunny days. It is recommended that the experimenter take (2) focus-mode bright field images before the experiment: one with the slit all the way open, so that the experimenter can see the location on the test fixture that the slit is imaging across, and one with the slit closed to the width used in the experiment, especially if there are visible features in this view for distance calibration. At this stage, the camera is aimed and focused. Once that is done, and both bright field images are collected, the timing train must be calculated and streak speeds determined for the dynamic experiment.

The timing train is calculated as follows. First, calculate the estimated event window of interest; generically, for 1-dimensional experiments, the event window is calculated as such: $Event\ Time = \sum_i^n \frac{len_i}{D_i}$, where len_i is the length of the i th component, the booster, for example; and D_i is the detonation velocity for that component; this is summed for all explosive components. For a typical experiment, two explosive components contributing to the event window are often present: the donor and acceptor charges. In this case, the donor (booster) charge may be 1.645” long (typical for 1.645” ID HDPE pipe) packed with C4 explosive which has a detonation velocity

of about 8mm/us. This particular component will have an estimated event time of 5.22 us ($1.645'' * 25.4\text{mm/in} / 8\text{mm/us} = 5.22\text{us}$).

This represents the total time the detonation wave will transit the donor charge. If the acceptor charge, for example is 6in long filled with NM/DETA which detonates at about 6.2mm/us, the event window for the second component is 24.6us. Thus, the total estimated event window is 29.8us. By calculating the event window for the experiment, the experimenter can begin to determine the ideal streak speed setting. If the explosive event were to be captured perfectly-fitting to the streak window, the streak speed must be $24.6\text{us} / 20\text{mm (streak path)} = 1.23\text{us/mm}$. Because the streak camera contains only discrete options for streak speed choices, the experimenter must choose a streak speed that completely encompasses the event window of interest. This means that the chosen streak speed would have to be slower than the 1.23us/mm calculated in the example. The two largest sources of uncertainty when it comes to determining streak speed are estimation of explosive event time and estimation of delay from triggering the detonator to breakout of detonation. To determine the best streak speed, add in the uncertainties in detonation velocity and triggering time to estimate a 'worst case' scenario for the event time and choose the next slowest sweep speed to accommodate. The event is captured by placing the camera in 'Streak' mode (not focus mode), and 'Single Acquisition' is chosen from the acquisition menu.

There are very subtle indicators that the streak camera is armed and ready to collect an image, and the best practice is to arm the camera and intentionally trigger the

acquisition with the intended triggering method, whatever that may be. To be sure that the camera is armed and ready to receive a trigger, both the streak camera and the readout unit should be assessed individually. To verify that the streak camera is ready for a trigger, the streak camera control dialog box should first be set with the correct configuration parameters, particularly the camera must be in 'ON' mode, rather than standby, the shutter must be open, the gain must be appropriately set, and the sweep speed must be appropriate. To calculate the exposure time for a given experiment, realize that the slit width will be swept vertically across at the sweep speed. If the slit width is set to 80um and the sweep speed is 1us/mm, the exposure time is 1us/mm or $1\text{ns}/\text{um} * 80\text{um} = 80\text{ns}$. This exposure time is quite large for a bright explosive material from a reasonable distance and would likely saturate; 50um slit width (i.e. 50ns exposure) would be a better choice. Determining the right exposure for a particular shot may require a test shot which demonstrates the correct lighting. Always place features in the field of view which represent a difference of a known distance in the focal plane of the experiment. Using this technique will make the distance calibration later much easier and more reliable. A simple 8 1/2" x 11" piece of paper will suffice, as long as both ends can be clearly seen. Note that the distance-scaled features, the edges of a piece of paper in this example, need not be visible during the dynamic event, but must be visible in the bright field images. That the streak camera is armed and waiting for trigger is verified by both the 'Accumulate 1 image' message at the bottom right of the software window and also the blinking green-yellow-green-yellow LED light on the back of the readout. Verify that the streak camera is on, the shutter is open, the gain is set appropriately, and the readout

unit is communicating, and then fire the experiment. If successful, the 'Accumulate 1 Image' message will go away, and the dynamic record will automatically display on the screen. The image must be saved before continuing. When breaking down the streak camera for long-term storage, the individual components should be removed in the reverse order in which they were installed, carefully as always. Remember to replace the discharge resistor array on the streak unit, and to prevent any debris from rattling around inside the padded cases.

Triggering: Because the streak camera electronics need to be 'spun up' to the linear streak region used during the experiment, the required delay time is written in the manual for each sweep speed. These delay times are given specifically for the delay time from trigger to the *center* of the event window. To obtain the appropriate delay time to the beginning of the event, e.g. to coincide with the detonation breakout, half of the event window must be subtracted from the listed delay time. For example, a 1mm/us sweep speed would yield a 20us event window and has a delay time (to center) of 48.6us listed in the table. This represents the delay-to-center; half the event window (10us) subtracted from the delay-to-center time yields a 38.6us delay-to-start time, i.e. the time from the streak camera trigger to the beginning of the 20us dynamic exposure time. The typical triggering configuration uses the DG535 signal delay generator to send trigger signals to the streak camera and FS-10 fireset.

For accurate timing, EBW detonators should always be used to narrow the uncertainty in ignition delay. In many cases, a standard electric blasting cap cannot

be used in conjunction with the streak camera simply because it is not possible to accurately trigger the exposure to capture the explosive event. The timing uncertainty in electric blasting caps can be as large as 100s of microseconds, often an order of magnitude larger than the event window; thus, trigger by picking up the current rise to the detonator is not feasible. Even if a shorting pin were used to pick up the initial bulging of the detonator and trigger the streak camera, the delay-to-start time (38us in the above example) would be too long to capture anything, i.e. the 15-35us typical for small scale experiments would be over before the streak camera exposure even started. Because the fireset can be triggered by the delay generator directly, this delay is simply programmed in and executed. It should also be noted that the experimenter may require a 'dark time' where the record starts a specified time before the event.

PDV Optical Interferometer

RIO Grande 1W Laser System: **CAUTION- THIS LASER IS CAPABLE OF CAUSING EYE DAMAGE IF USED INCORRECTLY.** Be sure no high-power settings are active while any personnel are present without 1550nm-optimized radiation safety glasses. The Rio laser system powers a low-power (-30dBm at output) seed laser which is pumped through an Erbium-doped fiber amplifier (EDFA). This EDFA functions by surging power to its own pump lasers, which are bifurcated into the erbium-doped fiber section. This laser uses is controlled via USB-to-serial link; included software will control the laser power in two modes- automatic power control (APC) and automatic current control (ACC). Using the first, APC method, the

output power is the most stable, but very low power outputs are not possible. For fiber optic characterization, ACC mode set to 0.70-0.75A is sufficient to map the reflection profile of the finished device. Only once the device has been placed outdoors and in an environment free of personnel can the laser power be turned up. Note: during an explosive test, the power should not be turned above 24.7dBm because of the CW damage threshold for the components used in the PDV system at the current time. The laser is equipped with two safety interlocks, one hard switch protruding from the multi-channel connector on the front of the laser module, and the other is a soft switch in the software control interface. The laser should be turn 'on' for as short a time as possible and with as little power as necessary to perform a task. The laser should not be left on when not needed. It is up to the experimenter to disclose the laser safety environment to other personnel on site and to possibly restrict other personnel from the immediate area if they are not equipped with appropriate laser safety goggles. For diagnostic purposes, the only meaningful parameters for using the laser are whether it is on or off, what power value is active (through either ACC or APC mode), and to which port the FC/APC fiber output is installed.

Fiber Optic Components and enclosure: Many different fiber optic components are used in the PDV system; some are of unknown origin and should be used with cautiously when high laser powers are used. To date, 24.7dBm has proven to be below the damage threshold for all components, and no more power should be used unless backup components are purchased in case of failure.

Figure 3: Diagram of PDV technique illustrated above shows the components inside the fiber optic enclosure which include (2) fiber optic (fo) splitters and one fiber optic circulator.

The box itself is folded sheet steel, roughly 12" x 18" x 4" in size, and has a smoke gray acrylic cover. Each day the enclosure is used, the light characteristics should be carefully characterized at certain points. A full characterization should be done biannually to ensure none of the components are experiencing degradation or aging. The fiber optic enclosure should be handled with care because jostling may cause bending in some of the fiber coils which present as losses in the returned light. Measures have been taken to reduce the sensitivity of the device to vibration and motion, but it is still possible to incur losses by mishandling.

- ii. **Fiber Optic Cable and splicing techniques:** In addition to the radiation hazard of powerful laser emission, fiber optic cable carries intrinsic hazard

due to the small size of glass fiber trimmings involved in splicing and cleaving the bare fibers together. The splicing operations are done using the Fujikura 70S splicing machine, and cleaving operations are conducted using the fiber cleaver included with the splicing machine. The greatest fiber handling hazard lies in the cleaving operation, since the cleaved end is a small sliver of glass. Care should be taken to ensure the cleaved fiber end remnant is safely collected by the rotating rubber wheels designed to take the remnant away from the cleaving blade and deposit it in the fiber receptacle. To prevent overflow, the receptacle should be emptied before it reaches half-capacity.

- iii. **Fiber Optic Connectors:** All connections in the current PDV system are physical contact (FC) angle-polished (APC) or FC/APC. APC connections are used to prevent back reflections at the connectors, something that could be particularly problematic with a coaxial interferometer such as this. The FC connection has advantages, namely lower insertion loss than other connectors. Most vendors will provide components outfitted with FC/APC connectors, but typically, they are bought with bare fiber ends, and FC/APC connectors are spliced on when needed. Each component in the enclosure has been outfitted with FC/APC connectors on both ends so that losses within the system can be traced directly to their source, even though each of these connections introduces at least a 1-2 dB loss. At the bulkhead ports connecting the components inside the box with those outside, bulkhead-style connectors for FC/APC connectors were used. Typically, each component would be fusion-

spliced to each other, but then troubleshooting a single component is impossible. Each connection provides a loss of 1-2dB at best, but can be much more if the connection is dirty or the mating sleeve is machined improperly.

Appendix 2.4 Python

Python PDV Processing Algorithm

Rettinger implementation of PDV Processing

```
import numpy as np
```

```
import matplotlib.pyplot as plt
```

```
plt.ion()
```

```
import pandas as pd
```

```
import scipy.optimize as spo
```

```
from tkinter import *
```

```
import tkinter.filedialog as tkfd
```

```
def pdsfind(array, target):
```

```
    i = (array-target).abs().idxmin()
```

```
    return (i, array[i])
```

```
def findall(string, target):
```

```
    i = 0
```

```
    ans = []
```

```
    while i <= len(string)-len(target):
```

```
        if string[i:i+len(target)] == target:
```

```
            ans.append(i)
```

```
            i+=len(target)
```

```
        else:
```

```
            i+=1
```

```
    return ans
```

```
class App:
```

```
    def __init__(self, master):
```

```

h = self.h = Frame(master)
h.grid(column=0, row=0)
b = self.b = Frame(master)
b.grid(column=0, row=1)
f = self.f = Frame(master)
f.grid(column=0, row=2)

labs = self.labs = { }
buts = self.buts = { }
ents = self.ents = { }
slids = self.slids = { }
frames = self.frames = { }
rbs = self.rbs = { }

# Title
labs['title'] = Label(h, text = 'PDV Process')
labs['title'].grid(column=0, row=0, columnspan=2)
buts['load'] = Button(h, text = 'load file', command = self.load)
buts['load'].grid(column=0, row=1)
buts['overlay'] = Button(h, text = 'Overlay File', command = self.overlay)
buts['overlay'].grid(column=1, row=1)

# Files loaded
frames['fns'] = Frame(h)
frames['fns'].grid(column=0, row=2, columnspan=2)
fnlab = self.fnlab = Text(frames['fns'], width = 45, height = 3, font='Times')
fnlab.insert(END, 'No Files Loaded')
fnlab.config(state=DISABLED)
fnlab.grid(column=0, row=0)

```

```

# Time Domain and cropping
ptdframe = frames['ptd'] = LabelFrame(b, text = 'Time Domain and cropping')
frames['ptd'].grid(column=0, row=0)

# Number of samples to plot
e=ents['nsamps'] = Entry(ptdframe, width = 8)
e.insert(END, 1500)
ents['nsamps'].grid(column=0, row=0)
labs['nsamps'] = Label(ptdframe, text='n samps to plot')
labs['nsamps'].grid(column=1, row=0)


# Plotting
b = self.buts['ptd'] = Button(ptdframe, text = 'Plot time domain', command =
self.ptd)
b.grid(column=0, row=3, columnspan=2)
b = self.buts['pickt0'] = Button(ptdframe, text = 'Pick t0', command = self.bindt0)
b.grid(column=0, row=4)
b = self.buts['pickt1'] = Button(ptdframe, text = 'Pick t1', command = self.bindt1)
b.grid(column=1, row=4)
b = self.b

# FFT
fftframe = frames['fft'] = LabelFrame(b, text= 'Frequency Transform')
fftframe.grid(column=0, row=1)

# FFT Params
# nFFT
e = ents['nfft'] = Entry(fftframe, width=8)
e.insert(END, 10)

```

```

e.grid(column=0, row=0)
l = labs['nfft'] = Label(fftfame, text = '2** x nfft')
l.grid(column=1, row=0)
#      noverlap
e = ents['noverlap'] = Entry(fftfame, width=8)
e.insert(END, 9)
e.grid(column=0, row=1)
l = labs['noverlap'] = Label(fftfame, text = '2** x noverlap')
l.grid(column=1, row=1)
#      plot fft
b = buts['pfd'] = Button(fftfame, text = 'Plot FFT', command = self.pfd)
b.grid(column=0, row=2, columnspan=2)
#      pcolormesh vmin vmax sliders
s1 = slids['vmax'] = Scale(fftfame, orient= HORIZONTAL, from_=0, to=100)
s1.grid(column=0, row=3, columnspan=3)
# Picking parameters
pf = self.frames['params'] = LabelFrame(self.b, text = 'Experiment Params')
pf.grid(column=0, row=2)
#      Shock arrival time
satb = self.buts['sat'] = Button(pf, text = 'Shock arrival', command = self.bindsat)
satb.grid(column=0, row=0)
#      FD Limits
fdl = self.buts['fdl'] = Button(pf, text = 'Freq. Dom. Limits', command =
self.bindfdl)
fdl.grid(column=1, row=0)
# Velocity Conversion
vcf = self.frames['vc'] = LabelFrame(self.b, text = 'Velocity Conversion')
vcf.grid(column=0, row=3)

```

```

#    laser wavelength
e = self.ents['lw'] = Entry(vcf, width=8)
e.insert(END, 1547.718)
e.grid(column=0, row=0)
l = self.labs['lw'] = Label(vcf, text = 'Laser Wavelenth (nm)')
l.grid(column=1, row=0)

#    Index Correction
e = self.ents['ic'] = Entry(vcf, width=8)
e.insert(END, 1)
e.grid(column=0, row=1)
l = self.labs['ic'] = Label(vcf, text = 'Index correction')
l.grid(column=1, row=1)

#    Slice peaks
b = self.buts['vc'] = Button(vcf, text = 'Convert to Velocity', command = self.vc)
b.grid(column=0, row=2, columnspan=2)

def vc(self):
    lw = float(self.ents['lw'].get())*1e-9
    ic = float(self.ents['ic'].get())
    #  $f = 2 * v/c * f_0$   $ic = 2 * ic * v / lam_0$ 
    #  $v = f * lw / (2 * ic)$ 
    f2v = self.f2v = lambda f, lw=lw, ic=ic: f*1.e9 * lw / (2.*ic)
    fig, ax = self.velfig, self.velax = plt.subplots(1,1)
    colors = plt.cm.viridis(np.linspace(0,1,len(self.fns)))
    for i, fn in enumerate(self.fns):
        print('Processing: ', self.fn_s[self.fns.index(fn)])
        data = self.data[fn]
        ss = data['ss']

```

```

freqs = pd.Series(ss.index)
fbar = freqs.median()
ts = pd.Series(ss.columns)
vels = data['vels'] = pd.Series([])
sigs = data['sigs'] = pd.Series([])
f0s = data['f0s'] = pd.Series([])
imaxs = data['imaxs'] = pd.Series([])
ipeaks = data['ipeaks'] = pd.Series([])
icount = 0; failures = []; successes = []
for t in ts:
    Is = 10*np.log10(ss.ix[:,t])
    plt.draw()
    fbar = freqs.median
    g_1 = self.g_1
    try:
        ipeaki, ipeak = (Is.idxmax(), Is[Is.idxmax()])
        ipeaks[t] = ipeak
        pguess = [Is.max(), Is.idxmax(), .05, 0]
        popt, pcov = spo.curve_fit(g_1, Is.index, Is, p0 = pguess)
        a,f0,c,d = self.a, self.f0, self.c, self.d = popt
        imax = g_1(f0, *[a,f0,c,d])
        #print(imaxs[t], self.slids['vmax'].get())
        if ipeak < float(self.slids['vmax'].get()):
            #print('%0.3fus Below threshold'%t)
            killthisline
        imaxs[t] = imax
        f0s[t] = f0

```



```

        vels[t] = f2v(f0)

        successes.append(t)
    except:

        #print('no convergence at time: %.2f us'%t)

        sig = 0

        f0 = 0

        failures.append(t)

    if icount % 100 == 0:

        print('t (us): ', t, ' ', len(failures), ' failures; ', len(successes), ' successes')

        icount+=1

    self.fftax[1][i].scatter(f0s.index, f0s, c='r')

    self.velax.plot(vels.index, vels, color=colors[i], label = self.fn_s[i])

    self.velax.scatter(vels.index, vels, c=imaxs)

    self.velax.vlines(0, 0, vels.max(), linestyle='dashed')

    self.velax.legend(loc='best')

    self.velax.set_xlabel('Time (us)')

    self.velax.set_ylabel('Velocity (m/s)')

def g_1(self, x, *p):

    a,b,c,d = p

    y = a*np.exp(-np.power((x-b),2.)/(2.*np.power(c,2)))+d

    return y

def bindfdl(self):

    self.pickfdl0 = self.fftfig.canvas.mpl_connect('button_press_event', self.setfdl0)

def setfdl0(self, event):

    self.fftfig.canvas.mpl_disconnect(self.pickfdl0)

    self.pickfdl1 = self.fftfig.canvas.mpl_connect('button_press_event', self.setfdl1)

    ax = event.inaxes

```

```

flag = False
for row in [0,1]:
    for col in range(len(self.fns)):
        if ax == self.fftax[row,col]:
            flag == True
            break
    if flag:
        break
print('row: ', row, ' col: ', col)
data = self.data[self.fns[col]]
data['fdl0'] = [event.xdata, event.ydata]

def setfdl1(self, event):
    self.fftfig.canvas.mpl_disconnect(self.pickfdl1)
    print(event.xdata, event.ydata)
    ax = event.inaxes
    flag = False
    for row in [0,1]:
        for col in range(len(self.fns)):
            if ax == self.fftax[row][col]:
                break
        if flag: break
    print('row: ', row, 'col: ', col)
    data = self.data[self.fns[col]]
    t1, f1 = data['fdl1'] = [event.xdata, event.ydata]
    t0, f0 = data['fdl0']
    tmin = min([t1,t0]); tmax = max([t1,t0])

```

```

fmini = min([f1,f0]); fmax = max([f1,f0])

s = data['s']

tmini, tmin = pdsfind(pd.Series(s.columns), tmin)
tmaxi, tmax = pdsfind(pd.Series(s.columns), tmax)
fmini, fmin = pdsfind(pd.Series(s.index), fmin)
fmaxi, fmax = pdsfind(pd.Series(s.index), fmax)
self.fftax[1][col].set_xlim(tmin, tmax)
self.fftax[1][col].set_ylim(fmin, fmax)

print(tmini, tmin)
print(tmaxi, tmax)
print(fmini, fmin)
print(fmaxi, fmax)

ss = data['ss'] = s.iloc[fmini:fmaxi, tmini:tmaxi]
ss.columns=ss.columns-data['sat']

print('ss.shape: ', ss.shape)

def bindsat(self):
    self.picksat = self.fftfi.canvas.mpl_connect('button_press_event', self.setsat)

def setsat(self, event):
    self.fftfi.canvas.mpl_disconnect(self.picksat)
    print('sat: ', event.xdata)
    ax = event.inaxes
    print('inaxes: ', ax)
    flag = False
    for row in range(2):
        print('row: ', row)
        for col in range(len(self.fns)):
            print('col: ', col)

```

```

        if ax == self.fftax[row][col]:
            print('Found it')
            flag = True
            break
    print('row: ', row, 'flag: ', flag)
    if flag:
        break
    print('row: ', row, 'col: ', col)

fn = self.fns[col]
print('clicked in file: ', fn)
data = self.data[fn]
data['sat'] = sat = event.xdata
try:

self.fftax[0][col].collections.pop(self.fftax[0][col].collections.index(data['tdsat']))

self.fftax[1][col].collections.pop(self.fftax[1][col].collections.index(data['fdsat']))
    print('Removed sat line')
    plt.draw()
except:
    print('No SAT lines to remove')
ymin, ymax = self.fftax[0][col].get_ylim()
data['tdsat'] = self.fftax[0][col].vlines(sat,ymin, ymax, 'k', linestyle='dashed')
ymin, ymax = self.fftax[1][col].get_ylim()
data['fdsat'] = self.fftax[1][col].vlines(sat,ymin, ymax, 'k', linestyle = 'dashed')
    print('drew SAT Line')

```

```

# setting secondary x axis with offset for shock arrival
rawticks = self.fftax[1][0].get_xticks()
newticks = [t-sat for t in rawticks]
print('rawticks: ', rawticks)
print('newtics: ', newticks)
#self.tdtx = self.fftax[0][col].twinx()
#self.tdfx = self.fftax[1][col].twinx()
#self.tdtx.set_xticks(newticks)
#self.tdfx.set_xticks(newticks)
plt.draw()

def pfd(self):
    print('plotting frequency domain')
    fig, ax = self.fftf, self.fftax = plt.subplots(nrows=2,
                                                    ncols = len(self.fns),
                                                    squeeze= False,
                                                    sharex = 'col')
    for i, fn in enumerate(self.fns):
        data = self.data[fn]
        t0 = data['t0pick']*1.e-6
        dt0 = t0 - data['rawt0']
        ds0 = int(dt0 * data['sf'])
        t1 = data['t1pick']*1.e-6
        dt = t1-t0
        ds = int(dt * data['sf'])
        print('Rows to read: ', ds)

```

```

print('Importing Data')

data['raw'] = pd.read_csv(fn, usecols = [3,4], names = ['ts', 'vs'], skiprows=ds0,
nrows = ds)

print('Imported data')

data['raw'].index = data['raw']['ts']*1e6


nfft = 2**int(self.ents['nfft'].get())

print('NFFT: ', nfft)

noverlap = 2**int(self.ents['noverlap'].get())

print('noverlap: ', noverlap)

data['specs'], data['freqs'], data['midts'], data['im'] =
ax[1][i].specgram(data['raw']['vs'], Fs = data['sf'],

                                NFFT = 2**10,

                                noverlap = 2**9)


data['dfreq'] = data['freqs'][1]-data['freqs'][0]

fmax = 10

#ax[1][i].images.pop(ax[1][0].images.index(data['im']))

s = data['s'] = pd.DataFrame(data['specs'], columns =
data['midts']*1.e6+data['t0pick'], index=data['freqs']*1e-9)

fmaxi = (pd.Series(s.index)-fmax).abs().idxmin()

print('fmaxi: ', fmaxi)

print('s.shape: ', s.shape)

s = data['s'] = s.iloc[:fmaxi, :]

print('s.shape: ', s.shape)

# Populating the vmax slider with values

s1 = self.slids['vmax']

imin = 10*np.log10(s.min().min())

```

```

imax = 10*np.log10(s.max().max())
print('imin: ', imin, ' imax: ', imax)
s1.config(from_= imin, to= imax)
s1.set((imin+imax)/2.)
s1.config(command = self.vmax)
print('s1.get(): ', s1.get())

data['pcm'] = ax[1][i].pcolormesh(s.columns, s.index, 10*np.log10(s),
cmap='viridis')

ax[0][i].plot(data['raw']['vs'].index, data['raw']['vs'], 'b-')
print('ylim: ', ax[1][i].get_ylim())
ax[1][i].set_ylim(top=fmax)
print('ylim: ', ax[1][i].get_ylim())
ax[0][i].set_xlim(data['t0pick'], data['t1pick'])
ax[0][i].set_ylabel('Voltage (V)')
ax[1][i].set_xlabel('Time (us)')
self.fftfreq.colorbar(data['pcm'], ax = ax[0][i], orientation='horizontal')

plt.draw()

def vmax(self, strval):
    print('vmax reset to '+strval)
    vmin = int(strval)
    for i, fn in enumerate(self.fns):
        data = self.data[fn]
        data['pcm'].set_clim(vmin = vmin)
    plt.draw()

def bindt0(self):

```

```

        self.pickt0 = self.ptdfg.canvas.mpl_connect('button_press_event', self.sett0)
def sett0(self, event):
    self.ptdfg.canvas.mpl_disconnect(self.pickt0)
    print('setting t0')
    ax = event.inaxes
    i = np.where(self.ptdax==ax)
    i = i[1][0]
    print('Picking file: ', i)
    fn = self.fns[i]
    data = self.data[fn]
    t0 = data['t0pick'] = event.xdata
    try:
        t0curi = ax.collections.index(data['t0cur'])
        #print('t0curi: ', t0curi)
        ax.collections.pop(t0curi)
        plt.draw()
        #print('Popped a line')
    except:
        print('No Cursor to remove')
        data['t0cur'] = ax.vlines(t0, 0, data['raw']['vs'].max(), color='g')
    print()
def bindt1(self):
    self.pickt1 = self.ptdfg.canvas.mpl_connect('button_press_event', self.sett1)
def sett1(self, event):
    self.ptdfg.canvas.mpl_disconnect(self.pickt1)
    print('setting t1')
    ax = event.inaxes

```



```

i = np.where(self.ptdax==ax)
i = i[1][0]
print('Picking file: ', i)
fn = self.fns[i]
data = self.data[fn]
t1 = data['t1pick'] = event.xdata
try:
    t1curi = ax.collections.index(data['t1cur'])
    ax.collections.pop(t1curi)
    plt.draw()
except:
    print('No Cursor to remove')
    data['t1cur'] = ax.vlines(t1, 0, data['raw']['vs'].max(), color='r')
def ptd(self):
    fig, ax = self.ptdfig, self.ptdax = plt.subplots(ncols = len(self.fns), squeeze =
False)
    for i,fn in enumerate(self.fns):
        data = self.data[fn]
        row0 = 0; row1 = data['nrows']
        ptdis = np.array([int(x) for x in np.linspace(row0, row1,
int(self.ents['nsamps'].get()))])
        print('Finding non-indicies')
        self.notindicies = ptd_not_is = np.array(list(set(range(row0, row1))-set(ptdis)))
        #fo = open(fn, buffering=1)
        print('Importing data')
        td_data = data['raw'] = data['raw_'] = pd.read_csv(fn, skiprows=ptd_not_is,
                                usecols=(3,4),
                                names=['ts', 'vs'])

```

```

data['raw'].index = data['raw']['ts']*1.e6
print('Data imported with shape: ', data['raw'].shape)
print('ptdis: ', np.shape(ptdis))
print('ptd_not_is: ', np.shape(ptd_not_is))
#    Plotting Time domain data
ax[0][i].scatter(data['raw'].index, data['raw']['vs'], marker = '.', color='b')
ax[0][i].set_xlim(data['raw'].index.min(), data['raw'].index.max())
ax[0][i].set_xlabel('Time (us)')
ax[0][i].set_title(self.fn_s[i])
ax[0][0].set_ylabel('Voltage (V)')

#print('nrows - ptd_not_is: ', row1-ptd_not_is)
def findnrows(self, fn):
    data = self.data[fn]
    self.headeris = 6
    fo = open(fn, buffering = 1)
    nrows = 0
    for line in fo:
        nrows+=1
    fo.close()
    data['nrows'] = nrows
    print('nrows: ', nrows)
def load(self):
    self.nrows = []
    fn = tkfd.askopenfilename()

```

```

fn_ = fn[fn.rfind('/')+1:-4]
fns = self.fns = [fn]
self.data = {fn: {}}
data = self.data[fn]
fn_s = self.fn_s = [fn_]
print('Processing File: ', fn_, ' *****')
self.header(fn)
self.findnrows(fn)
self.fnlab.config(state=NORMAL)
self.fnlab.delete(1.0, END)
self.fnlab.insert(1.0, fn_)
self.fnlab.config(state=DISABLED)
def header(self, fn):
    data = self.data[fn]
    a = open(fn)
    row = 0
    for line in a:
        coms = findall(line, ',')
        if row > 10:
            break
        if line[:15] == "Record Length":
            data['rl'] = int(line[coms[0]+1:coms[1]])
            print('Record Length: ', data['rl'])
            data['rawt0'] = float(line[coms[2]+1:coms[3]])
            print('Raw t0 (s): ', data['rawt0'])
        if line[:17] == "Sample Interval":
            data['si'] = float(line[coms[0]+1:coms[1]])

```

```

data['sf'] = np.power(data['si'],-1)
print('Sample Interval (s): ', data['si'])
print('Sample Frequency (hz): ', data['sf'])
if line[:14] == ""Trigger Point"":
    data['trigtime'] = float(line[coms[0]+1:coms[1]])
    print('trigger time (s): ', data['trigger time'])

```

```

row+=1
a.close()

```

```

def overlay(self):
    fn = tkfd.askopenfilename()
    self.fns.append(fn)
    self.fn_s.append(fn[fn.rfind('/')+1:-4])
    self.data[fn] = { }
    self.header(fn)
    self.findnrows(fn)
    self.fnlab.config(state=NORMAL)
    self.fnlab.insert('%d.%d'%(2, 0), '\n'+fn[fn.rfind('/')+1:-4])
    self.fnlab.config(state=DISABLED)

```

```

root = Tk()
app = App(root)
root.mainloop()

```

Python SIMD Image Processing

```
import numpy as np

import matplotlib.pyplot as plt

plt.ion()

import pandas as pd

import scipy.optimize as spo

from tkinter import *

import PIL.Image as pil

import matplotlib as mpl

import tkinter.filedialog as tkfd


class App:

    def __init__(self, master):

        h = self.h = Frame(master)

        h.pack()

        b = self.b = Frame(master)

        b.pack()

        f = self.f = Frame(master)

        f.pack()


        labs = self.labs = { }

        ents = self.ents = { }
```

```

buts = self.buts = { }

vs = self.vars = { }

self.figs = []; self.axes = []


l = labs['title'] = Label(h, text = 'Python Sim image process')

l.grid(column=0, row=0)

#    Load images

f = Frame(b)

f.grid(column=0, row=0)

b1 = self.buts['load'] = Button(f, text = 'Load Image', command = self.load)

b1.grid(column=0, row=0)

b2 = self.buts['show'] = Button(f, text = 'Show Image', command = self.show)

b2.grid(column=1, row=0)

b3 = self.buts['showbf'] = Button(f, text = 'Show BF', command = self.showbf)

b3.grid(column=2, row=0)

#    Calibration

f = LabelFrame(b, text ='Calibration')

f.grid(column = 0, row=1)

b4 = self.buts['cal0'] = Button(f, text = '(x0,y0)', command = self.cal0)

b4.grid(column=0, row=0)

e1 = self.ents['cal0'] = Entry(f, width = 15)

e1.insert(END, '(554.9601,620.1441)')

e1.grid(column=1, row=0)

```

```

b5 = self.buts['cal1'] = Button(f, text = '(x1, y1)', command = self.call)

b5.grid(column=2, row=0)

e2 = self.ents['cal1'] = Entry(f, width = 15)

e2.insert(END, '(554.9601, 376.3745)')

e2.grid(column=3, row=0)


l = Label(f, text = 'ds (mm)')

l.grid(column=0, row=1)

e3 = self.ents['ds'] = Entry(f, width = 8)

e3.insert(END, 215.9)

e3.grid(column=1, row=1)


b1 = self.buts['calcf'] = Button(f, text = 'mm/px:', command = self.calcf)

b1.grid(column=2, row=1)

e1 = self.ents['calf'] = Entry(f, width = 10)

e1.insert(END, '1.00')

e1.grid(column=3, row=1)

#    selecting line to plot series of intensity plots

f = LabelFrame(b, text = 'Single Line Plots')

f.grid(column = 0, row=2)

b4 = self.buts['line0'] = Button(f, text = '(x0,y0)', command = self.pickline0)

b4.grid(column=0, row=0)

```

```

e1 = self.ents['line0'] = Entry(f, width = 15)

e1.insert(END, '(7.994e+01,9.061e+01)')

e1.grid(column=1, row=0)


b5 = self.buts['line1'] = Button(f, text = '(x1, y1)', command = self.pickline1)

b5.grid(column=2, row=0)

e2 = self.ents['line1'] = Entry(f, width = 15)

e2.insert(END, '(1.499e+02, 9.515e+01)')

e2.grid(column=3, row=0)


# Orientation selection radiobuttons

ff = Frame(f)

ff.grid(column=0, row=1, columnspan=4)

o = self.oflag = StringVar()

o.set('v')

b1 = self.buts['hline'] = Radiobutton(ff, text = 'Horiz. Line', indicator=True,
                                     variable=o, value = 'h')

b1.grid(column=0, row=1)

b2 = self.buts['vline'] = Radiobutton(ff, text = 'Vert. Line', indicator=True,
                                     variable=o, value = 'v')

b2.grid(column=1, row=1)

b1 = self.buts['tline'] = Radiobutton(ff, text = 'True Line', indicator=True,
                                     variable=o, value = 't')

```



```

b1.grid(column=2, row=1)

b3 = self.buts['plotlines'] = Button(ff, text = 'Show Line Plots', height=3,
                                     command = self.lpininit)

b3.grid(column=3, row=1, rowspan=2)


imflag = self.imflag = IntVar()

imflag.set(1)

b1 = self.buts['plotim'] = Radiobutton(ff, text = 'Show Image', variable=imflag,
value=1)

b2 = self.buts['noim'] = Radiobutton(ff, text = 'No Image', variable = imflag,
value=0)

b1.grid(column=0, row=2); b2.grid(column=1, row=2)


b4 = self.buts['prev'] = Button(f, text = 'Previous Frame', command =
self.decrement)

b4.grid(column=0, columnspan=2, row=3)

b5 = self.buts['next'] = Button(f, text = 'Next Frame', command = self.advance)

b5.grid(column=2, columnspan = 2, row=3)


# Data Table and report

f = LabelFrame(b, text = 'Data Table')

f.grid(column=0, row=3)

l = Label(f, text = 'interframe spacing (us):')

```

```

l.grid(column=0, row=0)

e1 = self.ents['ifs'] = Entry(f, width = 8)

e1.insert(END, 2.198)

e1.grid(column=1, row=0)

b1 = self.buts['pickxpt'] = Button(f, text = 'Pick x pt', command = self.bindxpt)

b1.grid(column=0, row=1)

self.xvals = pd.Series([])

self.yvals = pd.Series([])

self.markers = pd.Series([])


b1 = Button(f, text = 'Gen Plot', command = self.genplot)

b1.grid(column=0, row=2)


go = False; go = True

if go:

    self.load(goflag = go)

    self.showbf(goflag = go)

    self.calcf()

    self.plotline()

    #self.lpinit()

def genplot(self):    # Plotting x vs t for selected points

    if self.oflag.get() == 'h':

        xs = self.xvals

```

```

if self.oflag.get() == 'v':

    xs = self.yvals

if self.oflag.get() == 't':

    print('correcting xvals for true line angle')

    x0, y0 = self.line0

    x1, y1 = self.line1

    dx = x1-x0

    dy = y1-y0

    ds = np.sqrt(np.power(dx,2)+np.power(dy,2))

    if dx>dy:

        self.xvals = self.xvals*(ds/dx)

        xs = self.xvals

        print('Mostly horizontal')

    if dy>dx:

        self.yvals = self.yvals*(ds/dx)

        xs = self.yvals

        print('Mostly vertical')

ifs = float(self.ents['ifs'].get())

allts = self.allts = pd.Series([])

for n in range(1,17):

    allts[n] = ifs*(n-1)

ts = self.ts = allts[xs.index]

fig, ax = self.velfig, self.velax = plt.subplots()

```

```

ax.scatter(ts, xs, s=75, marker = 'o', c='b', label = 'Raw')

model = lambda x, m, b: m*x+b

d = self.d = spo.curve_fit(model, ts, xs, p0=(1,0))

m,b = self.mfig, self.bfit = d[0]

print('m: ', m, ' b: ', b)

tfits = np.linspace(ts.iloc[0],ts.iloc[-1])

ys = model(tfits, m, b)

ax.plot(tfits, ys, 'k--', label = 'y = %.3f *x + %.3e'%(m,b))

ax.legend(loc='best')

ax.set_xlabel('Time (us)')

ax.set_ylabel('Distance (mm)')

ax.set_title(self.fn)

plt.draw()

def bindxpt(self):

    fig = self.lpf

    fig.canvas.mpl_connect('button_press_event', self.pickxpt)

    print('Please pick x-value on plot')

def pickxpt(self, event):

    x = event.xdata

    y = event.ydata

    self.xvals[self.an] = x

```

```

self.yvals[self.an] = y

ax = self.lpax

d = self.ds[self.an]

xs = pd.Series(d.columns); ys = pd.Series(d.index)

xi = (xs-x).abs().idxmin(); yi = (ys-y).abs().idxmin()

if self.oflag.get() == 'h':

    xmatch = xs[xi]

    ymatch = self.Is[xmatch]

if self.oflag.get() == 'v':

    ymatch = ys[yi]

    xmatch = self.Is[ymatch]

print()

print('xmatch, ymatch: ', xmatch, ymatch)

print()

try:

    ax.collections.pop(ax.collections.index(self.markers[self.an]))

    plt.draw()

except:

    print('No mark to remove')

self.markers[self.an] = ax.scatter(xmatch,ymatch, s=100, marker = '*', c='g',

zorder=11)

print('should be there...')

plt.draw()

```

```

def decrement(self):

    n = self.an

    if self.an == self.ns[0]:

        print('Cannot decrement')

    else:

        n=self.an = n-1

        self.slp(n)

def advance(self):

    n = self.an

    if self.an == self.ns[-1]:

        print('Cannot advance')

    else:

        n = self.an = n+1

        print('advancing to frame: ', n)

        self.slp(n)

def lpinit(self): # Line plot initialization

    fig = self.lpfig = plt.figure()

    n = self.an = self.ns[0]

    self.slp(n)

def slp(self, n=1): # "show line plot"

    plotim = self.imflag.get()

```

```

orientation = self.oflag.get()

fig = self.lpfirg

for axes in fig.axes:

    fig.delaxes(axes)

ax = self.lpax = fig.add_subplot(111, zorder = 10)

d = self.ds[n]

#((x0i,y0i),(x1i,y1i)) = self.lplims


#local vars

xs = pd.Series(d.columns)

ys = pd.Series(d.index)

xis = pd.Series(xs.index)

yis = pd.Series(ys.index)

s0 = self.ents['line0'].get()

ci = s0.index(',')

x0 = float(s0[1:ci]); y0 = float(s0[ci+1:-1])

print('x0: ', x0, ' y0: ', y0)

s1 = self.ents['line1'].get()

ci = s1.index(',')

x1 = float(s1[1:ci]); y1 = float(s1[ci+1:-1])

print('x1: ', x1, ' y1: ', y1)

x0i = (xs-x0).abs().idxmin(); x1i = (xs-x1).abs().idxmin()

y0i = (ys-y0).abs().idxmin(); y1i = (ys-y1).abs().idxmin()

```

```

xmin, xmax = sorted([x0i,x1i])

ymin, ymax = sorted([y0i, y1i])

self.line0=(x0,y0); self.line1 = (x1,y1)

self.line0i = (x0i,y0i); self.line1i = (x1i, y1i)


# line plots

if orientation == 'h':

    print('plotting horizontal line plot')

    xs = self.axs = pd.Series(d.columns[x0i:x1i])

    ys = self.ays = d.iloc[y0i, x0i:x1i]

    self.lp = ax.plot(xs,ys, color = 'r', marker = 'D', zorder=10)

    self.Is = pd.Series(ys, index = xs)

    if plotim:

        ax2 = self.lpax2 = ax.twinx()

        ax2.pcolormesh(d.columns, d.index, d, zorder = 1)

        self.linecursor = ax2.hlines(d.index[y0i], d.columns[x0i], d.columns[x1i],
color='white', linestyle='dashed')

        self.linecursor2 = ax2.vlines(d.columns[x1i], d.index[y0i], d.columns[y1i],
color='white', linestyle='dashed')

    if orientation == 'v':

        print('Plotting vertical line plot')

        ys = self.ays = pd.Series(d.index[ymin:ymax])

        xs = self.axs = d.iloc[ymin:ymax, x0i]

```



```

self.lp = ax.plot(xs,ys, color = 'r', marker = 'D', zorder = 10)

self.Is = pd.Series(xs, index = ys)

if plotim:

    ax2 = self.lpax2 = ax.twinx()

    ax2.pcolormesh(d.columns, d.index, d, zorder = 1)

    self.linecursor = ax2.vlines(d.columns[x0i], d.index[y0i], d.index[y1i],
color='w', linestyle = 'dashed')

    self.lincursor2 = ax2.hlines(d.index[y1i], d.columns[x0i], d.columns[x1i],
color='w', linestyle='dashed')

if orientation == 't':

    print('Plotting true line- i.e. picking pixels along arbitrary angled line')

    print('indecies, x0,y0, x1,y1: ', x0i, y0i, x1i, y1i)

    if plotim:

        ax2 = self.lpax2 = ax.twinx()

        ax2.pcolormesh(d.columns, d.index, d, zorder=1)

        self.linecursor = ax2.plot([d.columns[x0i], d.columns[x1i]], [d.index[y0i],
d.index[y1i]],

                                color='w', linestyle='dashed')

        plt.draw()

    # Now in pixels

    dxi = x1i-x0i; dyi = y1i-y0i

    if dxi>dyi:

```

```

print('dxi > dyi')

yistep = 1./dxi*dyi

print('yistep: ', yistep)

print()

yi = y0i

pts = self.pts = pd.Series([])

for xi in range(x0i,x1i):

    yim = (yis-yi).abs().idxmin()

    x = xs[xi]; y = ys[yim]

    #print(xi,yi,yim, ' ', x,y)

    pts[xs[xi]] = ys[yim]

    yi += yistep

if plotim:

    self.pixels = ax2.scatter(pts.index, pts, c='yellow', s=25, marker='+')

    Is = self.Is = pd.Series([])

    for r,c in zip(pts,pts.index):

        Is[c] = d.ix[r,c]

    self.lp = ax.plot(Is.index, Is, color='r', marker = 'o', markersize = 7)

if dyi > dxi:

    print('dyi > dxi')

    print('I dont know how to do that...')

ax.set_title('Image #'+str(self.an))

if plotim: ax.set_zorder(ax2.get_zorder()+1)

```

```

ax.patch.set_visible(False)

plt.draw()

def pickline0(self):

    print('picked!')

    self.bindline0 = self.bfig.canvas.mpl_connect('button_press_event', self.setline0)

    print('pick first line point')

def setline0(self, event):

    print('picking...')

    self.bfig.canvas.mpl_disconnect(self.bindline0)

    x = event.xdata; y = event.ydata

    self.line0 = (x,y)

    self.ents['line0'].delete(0,END)

    self.ents['line0'].insert(END, '(% .3e,% .3e)'%(x,y))

    print('Point selected: ', x,y)

    print()

def pickline1(self):

    self.bindline1 = self.bfig.canvas.mpl_connect('button_press_event', self.setline1)

    print('pick second line point')

def setline1(self, event):

    self.bfig.canvas.mpl_disconnect(self.bindline1)

    x = event.xdata; y = event.ydata

    self.line1 = (x,y)

```

```

self.ents['line1'].delete(0,END)

self.ents['line1'].insert(END, '(% .3e, % .3e)'%(x,y))

print('point selected: ', x,y)

self.plotline()

print()

print('finding closest points...')

x0,y0 = self.line0

x1,y1 = x,y


def plotline(self):

    s0 = self.ents['line0'].get()

    ci = s0.index(',')

    x0 = float(s0[1:ci])

    y0 = float(s0[ci+1:-1])

    s1 = self.ents['line1'].get()

    ci = s1.index(',')

    x1 = float(s1[1:ci])

    y1 = float(s1[ci+1:-1])


    ax = self.bax

    im = self.B

    cols = pd.Series(im.columns); rows = pd.Series(im.index)

    c0i = (cols-x0).abs().idxmin()

```

```

c1i = (cols-x1).abs().idxmin()
r0i = (rows-y0).abs().idxmin()
r1i = (rows-y1).abs().idxmin()

c0 = cols[c0i]; c1 = cols[c1i]
r0 = rows[r0i]; r1 = rows[r1i]

ds = np.sqrt(np.power(c0-c1,2)+np.power(r0-r1,2))
dis = np.sqrt(np.power(c0i-c1i,2) + np.power(r0i-r1i,2))  #pixels on line

cis = c1i-c0i  #total pixel change along x
ris = r1i-r0i

b = self.B
bis = pd.Series(b.index)
bcs = pd.Series(b.columns)

x0i = (bcs-x0).abs().idxmin()
x1i = (bcs-x1).abs().idxmin()
y0i = (bis-y0).abs().idxmin()
y1i = (bis-y1).abs().idxmin()
self.lplims = ((x0i,y0i),(x1i,y1i))

```

```

def usecal(self):

    cal0 = self.ents['cal0'].get()

    comi = cal0.index(',')

    x0 = float(cal0[1:comi]); y0 = float(cal0[comi+1: -2])


    cal1 = self.ents['cal1'].get()

    comi = cal1.index(',')

    x1 = float(cal1[1:comi]); y1 = float(cal1[comi+1: -2])


    print('Chosing Calibration points: ')

    print('(% .2f, % .2f), (% .2f, % .2f)'%(x0,y0, x1,y1))

def cal0(self):

    self.bindcal0 = self.bfig.canvas.mpl_connect('button_press_event', self.setcal0)

    print('Pick 1st calibration point')

def setcal0(self, event):

    x = event.xdata

    y = event.ydata

    print('(x0, y0): ', '(% .2f, % .2f)'%(x,y))

    self.bfx0 = x

    self.bfy0 = y

    self.bfig.canvas.mpl_disconnect(self.bindcal0)

    self.cal0hline = self.bax.hlines(y, 0, self.w,

                                     linewidth=1, linestyle='dashed')

```

```

self.cal0vline = self.bax.vlines(x, 0, self.h,
                                linewidth=1, linestyle='dashed')

self.ents['cal0'].delete(0,END)

self.ents['cal0'].insert(END, '(% .4f,% .4f)'%(x,y))

def cal1(self):

    self.bindcal1 = self.bfig.canvas.mpl_connect('button_press_event', self.setcal1)

    print('Pick 2nd calibration point')

def setcal1(self, event):

    x = event.xdata

    y = event.ydata

    print('(x1, y1): ', '(% .2f, % .2f)'%(x,y))

    self.bfx1 = x

    self.bfy1 = y

    self.bfig.canvas.mpl_disconnect(self.bindcal1)

    self.ents['cal1'].delete(0,END)

    self.ents['cal1'].insert(END, '(% .4f, % .4f)'%(x,y))

    self.cal1hline = self.bax.hlines(y, 0, self.w,
                                    linewidth=1, linestyle='dashed')

    self.cal1vline = self.bax.vlines(x, 0, self.h,
                                    linewidth=1, linestyle='dashed')

def calcf(self, flag = 'tilt'):

    cal0 = self.ents['cal0'].get()

    comi = cal0.index(',')

```

```

x0 = float(cal0[1:comi]); y0 = float(cal0[comi+1: -2])

cal1 = self.ents['cal1'].get()

comi = cal1.index(',')

x1 = float(cal1[1:comi]); y1 = float(cal1[comi+1: -2])

if flag == 'tilt':

    dp = np.sqrt(np.power(y1-y0,2)+np.power(x1-x0,2))

    ds = self.ents['ds'].get(); ds = float(ds)

    self.f = ds/dp

    print('f (mm/px): ', self.f)

    self.ents['calf'].delete(0,END)

    self.ents['calf'].insert(END, '%.3e'%self.f)

self.setcalf()

def setcalf(self):

    f = self.ents['calf'].get()

    f = float(f)

    ims = self.ims

    for im in ims:

        im.index = im.index*f

        im.columns = im.columns*f

    for n in self.ds:

```



```

d = self.ds[n]

d.index = d.index*f

d.columns = d.columns*f

'''try:

for im,cols in zip(self.im_s, self.sax):

    for ax in cols:

        ax.collections = []

        ax.pcolormesh(im.columns, im.index, im)

        ax.set_xlim(left=im.columns[0], right=im.columns[-1])

        ax.set_ylim(bottom=im.index[0], top=im.index[-1])

except:

    print('no sfig to replot')

'''

try:

    b = self.B

    b.index = b.index*f

    b.columns=b.columns*f

    self.bax.collections = []

    self.bax.pcolormesh(b.columns, b.index, b)

    self.bax.set_xlim(b.columns[0], b.columns[-1])

    self.bax.set_ylim(b.index[0], b.index[-1])

except:

    print('bf image not rescaled')

```

```

plt.draw()

print('Axes now in milimeters')

def showbf(self, goflag=False):

    if goflag:

        fn = self.bfn = 'C:/Projects/Non-Ideal/20181024 HP EtOH XG and GMB/Shot-
001 BF.TIF'

    else:

        fn = self.bfn = tkfd.askopenfilename()#'c:/Projects/Diagnostics/20181003
Sheet Strip/20181003 shot-001 Detasheet strip BF.TIF'

    im = self.bfim = pil.open(fn)

    B = self.B = pd.DataFrame(np.array(im))

    w = self.w; h = self.h

    B = self.B = B.ix[:h,:w]

    fig, ax = self.bfig, self.bax = plt.subplots()

    self.figs.append(fig)

    self.axes.append(ax)

    self.bfim = ax.pcolormesh(self.B)

    ax.set_title(fn)

    plt.draw()

def load(self, goflag = False):

    if goflag:

```

```

        fn = self.fn = 'C:/Projects/Non-Ideal/20181024 HP EtOH XG and GMB/Shot-
001 HP-EtOH-XG-GMB overlay.TIF'

    else:

        fn = self.fn = tkfd.askopenfilename() #'c:/Projects/Diagnostics/20181003 Sheet
Strip/20181003 shot-001 Detasheet strip dynamic overlay.TIF'

    print('loading image: ', fn)

    im = self.im = pil.open(fn)

    D = self.D = pd.DataFrame(np.array(im))

    print('Image Loaded')

    # breaking up images

    nrows, ncols = D.shape

    self.vmin, self.vmax = (D.min().min(), D.max().max())

    print('max value: ', self.vmax, ' min value: ', self.vmin)

    npy = 4; npx = 4

    w = self.w = int(ncols/npx)

    h = self.h = int(nrows/npy)

    print('Image width (px): ', w)

    print('Image height (px): ', h)

    ims = self.ims = []

    ds = self.ds = {}

    d_s = self.d_s = {}

    im_s = self.im_s = []

    ns = self.ns = []

```

```

m = np.array(range(1,17)).reshape(4,4)

print(pd.DataFrame(m))

self.f0 = 1; self.f1=16

frames = range(self.f0, self.f1+1)

for n in frames:

    ns.append(n)

    row, col = np.where(m==n)

    row = row[0]; col = col[0]

    print('n: ', n, 'row: ', row, ' col: ', col)

    x0 = int(col*w)

    x1 = int((col+1)*w-1)

    y0 = int(row*h)

    y1 = int((row+1)*h-1)

    im = D.ix[y0:y1,x0:x1]

    im.index = range(0,h)

    im.columns = range(0,w)

    ds[n] = im

    print('x0: ', x0, ' x1: ', x1)

    print('y0: ', y0, ' y1: ', y1)

    #print(im.head().ix[:,5])

    #ims.append(im)

    x_ = 300

    y_ = 300

```

```

xs = self.x_s = np.int32(np.linspace(x0,x1,x_))
ys = self.y_s = np.int32(np.linspace(y0,y1,y_))
im_ = D.ix[ys,xs]
im_.index = range(y_); im_.columns= range(x_)
im_s.append(im_)
d_s[n] = im_

print()

def show(self):

    fig, ax = self.sfig, self.sax = plt.subplots(4,4, sharex=True, sharey=True)
    fig.subplots_adjust(hspace=.01,wspace=.01)

    self.figs.append(fig)
    self.axes.append(ax)

    w = app.w; h = app.h

    self.qms = []

    m = np.arange(1,17).reshape(4,4)

    print('plotting:')

    for n in sorted(self.d_s.keys()):

        im = self.d_s[n]

        row, col = np.where(m==n)

        row = row[0]; col = col[0]

        ax = self.sax[row][col]

        ax.axis('off')

        self.qms.append(ax.pcolormesh(im.columns, im.index, im,

```

```

        vmin=self.vmin, vmax = self.vmax))

    textx0 = im.columns[0]

    texty0 = im.index[0]

    ax.annotate('Frame %i'%n, (textx0,texty0), color='w')

    cmap = mpl.cm.viridis

    norm = mpl.colors.Normalize(vmin=self.vmin, vmax = self.vmax)

    print('Frame #%i'%n)

plt.draw()

```

```

root = Tk()

app = App(root)

print('app defined')

root.mainloop()

```

Appendix 2.5 Pre-Shot Checklist

The following section will be written in the form of questions the experimenter must be prepared to answer prior to certain stages of any proposed shots. The checklists/questions are asked in an order that steps from the design and planning stage all the way through the shot itself and the data analysis.

Dimensions

Are the charge size dimensions appropriate for the steady/infinite diameter studies desired? (i.e. steady detonation requires $L/D \geq 5-6$, infinite diameter is 0.5)

Is the booster of sufficient size to cause detonation in the sample material at the required time (i.e. should this be overdriven? Underdriven?)

Fixture

Are the materials in the proposed fixture design compatible with the sample explosive (if not, what measures will be taken to preserve rigidity or optical clarity).

Are the materials chosen to maximize machinability and chemical compatibility while minimizing cost? What compromises are being made in these areas and for what trade-off?

Have tolerances been test-fit? Sliding components require tight tolerances, but if tolerances are too tight, the parts will bind and motion will be choppy.

If the materials being used are different than recommended in this document, what implications may result? e.g. shock impedance mismatching, optical clarity

Has the mounting post been maintained at the proper distance, such that to mount the shot, only the horizontal bracket must be installed? (This may require digging a post hole to install a 4x4 wooden post on which the shot can be placed.

High explosive

Is the booster material (C4) packed to the same density as previously recorded (i.e. 1.57 g/cc)?

Does the sample explosive pose a new hazard that must be mitigated (e.g. carcinogen, volatile, corrosive)?

Do sufficient PPE components exist on site to handle the chemical hazard of the sample explosive (e.g. gloves, safety glasses)?

Equipment

1. Diagnostics: are all cameras and PDV equipment calibrated and functioning properly?
 2. Has the triggering scheme been proven with the exact configuration used during firing? (This may require a bare detonator be shot and filmed to confirm breakout times)
 3. Have all cable/wire schemes been mapped to ensure appropriate cabling exists on-site and all connections can be guaranteed.
 4. Are all extraneous pieces of equipment able to be removed from the site prior to testing? Can you be sure the area will be clear of extra equipment?
-
- iv. **Lensing:** Using the current camera configuration, can the distances and filming strategy be verified for field of view on each shot? Has a mock device been imaged with the proposed strategy to ensure mirror placement and ease of adjustment?
 - v. **Mirrors:** have mirrors been cleaned and dedicated to the purpose of shooting the proposed test series. Mirrors must be free of scratches and a mounting strategy must be in place prior to shoot day that has been proved successful.
 - vi. **Timing:** Has the timing strategy been proven while instruments are in their proposed locations, wired and connected in the same way they will be connected during the proposed tests? This may require extra oscilloscope measurements to ensure timing schemes between triggering electronics and diagnostics. This may also require the experimenter to construct extra circuitry that accommodates the proposed timing scheme.

Triggering

Triggering from the detonator: This strategy is fairly easy to implement due to the built-in ‘make’ wire triggering capabilities of the SIMD, Kirana, and Phantom cameras. Sub-microsecond reproducibility has been shown for this type of trigger and can prove useful when using detonators for which timing contains excessive delay and jitter (i.e. electric blasting caps). The trigger is constructed by one of two strategies, both utilizing the trigger circuit internal to the camera as illustrated below:

Figure 1: Shown are both acceptable triggering schemes for triggering from a detonator. Scheme A uses two insulated wires often twisted together to form the switch. When the detonator is initiated, pressure presses the wires together. This method is not recommended because the delay and jitter times observed (often in 10s of microseconds). Scheme B uses a makewire grounding out the casing of the detonator to the trigger circuit and triggers as soon as the casing flies through air and strikes the positive lead of the makewire. The positive lead is often made from

a pointed sheet metal or wood screw with conductive coating (not black oxide, sinc, brass, or stainless steel is preferred).The connection to the detonator is made by stripping ~2" of insulation from the negative lead of the trigger circuit and twisting it onto the metal body of the detonator. The negative lead should be secured with electrical tape to ensure good electrical contact with the detonator, but the path between detonator casing and positive lead should not be obstructed, if possible, by tape or other insulated material.

Example circuitry behind the ‘make’ trigger built into all high speed cameras on-site. Before the make wire trigger is connected, the positive side of R1 is pulled high, usually to 4-5V. The negative side is pulled to ground. When the make wire trigger is connected by either method, current begins to flow across R1 and the majority of the source voltage is dropped across R1, pulling the positive lead down to ground.

- a. Method A: twin lead wire ‘make’ trigger. To impliment this trigger, typically, one wire is stripped ~2.5" and the one-bare-one-insulated pair is twisted tightly together and taped securly to the detonator. It must be known that the trigger wires may not interfere with the dimensional fit of the detonator in the fixture (i.e. the wires must not cause the detonator to be misaligned or otherwise make inappropriate contact with the booster.
- b. Method B: typically this method is used for more precise timing but requires more forethought to execute. As stated in the figure description

above, the positive terminal is usually a wood or sheet metal screw with a conductive coating (i.e. not black oxide coating). Note: the screw should have a pointed end (not a flat-bottomed machine screw), but the point should be slightly dulled with sandpaper or file so that the aluminum casing of the detonator is not damaged during installation. The test fixture must accommodate this screw to be aligned with the detonator at the desired location. If the fixture material is plastic, a #8 sheet metal screw is typically used by drilling a #29 wire gauge drill hole orthogonal to the detonator bore. Drilling this hole may cause blow-out of block material on the inside of the detonator hole so that the detonator can no longer fit snugly. The positive lead screw hole should be drilled before the detonator bore is machined to minimize the consequences of this blow-out. To install the trigger, first the positive and negative trigger lead wires should be connected to the screw and detonator, respectively, ensuring no wires are connected to the camera (i.e. the trigger leads should be floating). The detonator should be securely mounted into the fixture and secured with the nylon set screw. Once the detonator is securely in place, a multimeter should be connected at the BNC connector (which will eventually be connected to the trigger port of the camera) and made to measure resistivity or continuity. The positive lead trigger screw should be very slowly tightened until continuity is measured with the multimeter. The screw should then be retracted until continuity is lost. Several cycles of approach and retract should be made to ensure the

detonator/screw contact is firm and reproducible. If, for example, the detonator is not firmly seated, the slop may be noticed by the difference in approach vs. retract cycle rotation. Upon the last contact, the screw should be carefully retracted to approximately 1/8 of a turn past where contact is known to be made. Before the trigger is deemed ready, once all wires are laid in the final experimental location and the device fixture is mounted securely, the trigger wire should be checked one last time for continuity (before being plugged in to the camera). Once trigger leads have been plugged into the camera, the trigger leads should be checked to see they are at the typical 4-5VDC, indicating that trigger circuitry of the camera is operating and leads are 'un-made'.

Triggering from the Fireset output: Triggering from the Scorpion HB-10 Solid State Electronic Capacitor Discharge Blasting Unit is not recommended because the delay and jitter associated with the unit are usually insufficient to capture good timing with the SIMD or Kirana cameras or the PDV record. Jitter as much as 150us has been measured using this technique. When using EBW detonators fired by the FS-10 fireset, one of two methods can be used to trigger the diagnostic equipment:

Method A: Direct pickup of manual trigger signal. To use this method, directly monitor the red binding post terminal (trigger signal) vs the white binding post terminal (GND). Note that if this is hooked directly to the oscilloscope or camera, the local ground of the FS-10 battery (white terminal) may be driven to earth ground.

After the FS-10 charged and fired, this signal has two distinct features- namely it raises slowly (0.75us) from 0V to the battery voltage (usually 30-40V). After some dwell time, current begins to flow through the detonator and causes an erratic decaying sinusoid which raises above and below the battery voltage as much as +/- 50V and can last for several microseconds. These raw voltage signals are above the damage threshold for both the camera and oscilloscope. Using the voltage divider, the raw trigger signal from the FS-10 is passed through the voltage divider and the second (~2%) port is passed to the oscilloscope and camera. This causes the ~25V battery voltage to appear as 500mV, acceptable to both instruments. The trigger may simply be constructed by using the raise in trigger signal from 0-500mV when the trigger is pressed, but it should be noted that the **voltage divider is sensitive to radio communication transmission. Care must be taken to ensure that the trigger level will not be accidentally reached by the regular radio communication between the experimenter and OT.** The trigger level can be custom-controlled on both the oscilloscope and the camera, and if higher precision is desired, the trigger threshold values can be set above the battery voltage to encourage the instruments to trigger based on the release of current through the high voltage leads to the detonator.

Method B: Passive sensing of current with looped Hall sensor. By placing only one loop of insulated wire around a high voltage lead, the inductance of the current flowing to the detonator (100s of amps) will generate a small fraction of the high-voltage current in the sensor. It has been observed that as much as 75Vmax, 40V typical can be detected using this method. **Because these voltages are above the**

damage threshold for the diagnostics, using this method requires the use of a voltage divider as well. It is recommended that the inductance sensor be made from as short a segment of wire as possible, to reduce the amount of inductance captured by the sensor. Typically, the sensor is constructed from a screw-terminal BNC connector and a short coil (~1/4" in diameter) is manually twisted around a cylindrical object with 20ga wire. The wire ends are placed in the screw terminal ports and a BNC-coaxial jumper cable is used to carry the trigger signal to the oscilloscope.

a. Calibration Check

- vii. Equipment calibration, function, reflection
- viii. Distances lensing, camera view
- ix. Triggering chain, timing
- x. Detonator function/timing
- xi. Cabling (trig and networking)
- xii. Computer software and handshaking/coms

b. Fixture Approval Check

- i. Dims
- ii. Moving parts
- iii. Liquid seal
- iv. Booster packed (weighed)
- v. Disc cut
- vi. Kapton cut
- vii. Window cut/sputtered

- viii. assembled
- c. Shoot Morning Check
 - i. Equip on/function
 - ii. Flick test
 - iii. Camera set up- coms
 - iv. Shot pole and shelf
- d. Pre-det check
 - i. Return light
 - ii. Trigger tests (including radio interference)
 - iii. Camera focus
 - iv. Cabling/coms
- e. OT Pre-det Check
 - i. Continuity of Det
 - ii. Personnel retreat
- f. <Insert detonator>
- g. Pre-fill check
 - i. Return light
 - ii. Brightfield images
 - iii. Return light to Miteq DC probe
- h. <Fill Sample>
- i. Pre-shot check
 - i. Leak watch
 - ii. Return light to ILX (record)

- iii. Return light to Miteq (record)
- iv. Reference leg insert
- v. Camera and scope arm
- vi. Laser power on high
- vii. Confirm Ready to OT

k OT Pre-Shot Sequence

Fire-in-the-hole' verbal notification

Safety interlock

20-second radio warning

- j. <Fires Shot>
- II. Data Storage
- III. Data analysis
 - a. Imaging
 - i. Calibration of mm/px
 - ii. Point Tracking (all cameras)
 - b. PDV
 - i. Python Algorithm
 - ii. Time-Frequency Conversion Strategies
 - iii. Interpolation of Frequency Domain