R1-B.1: Fundamental Explosivity & How to Deter It

Abstract—This project aims to recognize when a material is detonable and to do so with only one to two pounds of the material. The goal is investigating non-ideal explosives reacting well below their critical diameter (Dcr). Since stable detonation is not possible below Dcr, the materials in question, usually fuel-oxidizer mixtures, will be monitored with time-resolved propagation diagnostics. By using both conventional and experimental techniques, pressure and detonation velocity profiles will be measured. This will infer whether the chemistry in the sample is capable of reacting on detonation time scales. Because these tests are non-ideal in nature, explosive radial loading will over-compensate for any losses at the edges of the charge. This configuration will give the materials their best chance to perform explosively. Results from this test will be compared and integrated with hydrodynamic chemical modelling codes, in particular LLNL’s ALE3D and Sandia’s CTH. This year, new diagnostic techniques have been theorized and preliminary testing has confirmed proof of concept. These diagnostics will be adaptations of existing technologies, which have never been used to witness propagation in explosives, until now.

I. PARTICIPANTS

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<th>Students</th>
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II. PROJECT OVERVIEW AND SIGNIFICANCE

This project will reduce the necessity of performing very large scale detonability tests on suspect improvised explosives, diluted explosives and demilitarized explosives. This has a huge safety benefit, not just for those who would have done the large-scale tests, but for those who would have had to synthesize the materials for those tests. If the capability for detonation exists on any scale, this approach will target the markers for the ability to detonate, but on the small-scale (~1lb), using only conventional diagnostics to make the assumptions. The goal is to develop chemical kinetic models which will allow prediction of what materials and concentrations of materials may be a detonation threat.
III. RESEARCH ACTIVITY

A. State-of-the-art and technical approach

The approach to non-ideal detonation is difficult to study, and to date, no elegant, inexpensive approach to measuring detonation velocity exists for researchers in the field. PDV has proved very useful for surface velocity measurements, but has only sparingly been used for detonation measurements. This project has been forced to stretch the functionality of this diagnostic to develop embedded fiber optic probes, in collaboration with URI’s Electrical Engineering Department. By adjusting the approach slightly, these probes can be embedded into explosive charges and act as time-resolved interferometers-similar to microwave interferometers, but without the size constraints of microwave waveguides; fiber optics are non-intrusive. This project has also proven an elegant approach to the most costly part of the PDV system; by traditional telecom modulation techniques, we have shown promise of interpreting the signals of interest with a digitizer of significantly lower cost. Preliminary surface velocity tests have already been proven successful.

A.1 Objective

The goal is to create a test which indicates that a material is potentially explosive at some scale but to do so at a scale well below its critical diameter. A positive response to this test would imply the capacity to detonate at a larger scale.

A.2 Executive summary

The goal of this approach is to convincingly demonstrate, by performing only a small number of experiments, which suspect formulations of explosives are incapable of detonating even at very large diameters. The approach we take may also provide a sliding scale of “explosivity” that characterizes the performance of non-ideal or weakly-detonating explosives.

A.3 Background

Decompositions, which release energy, can self-propagate. If a material decomposes with the release of energy and gas sufficiently fast, it can potentially detonate. Detonations propagate by rapid wave mechanics; the rapid exothermic chemical reaction supports the detonation wave. However, energy is lost at the surfaces/edges of the material. As a result, detonation velocity decreases with a decrease in diameter of the material (see Fig. 1). At some critical diameter (Dcr), expansive cooling release waves are so significant that detonation can no longer propagate. Dcr is characteristic of the explosive and dependent on confinement, density, particle size, temperature and impurities. In general, the less energy a material has to release and the slower the reaction rate, the less energy it can afford to lose to the edges. Therefore, a larger diameter of material is required to support detonation. This means weakly explosive materials may not support detonation unless very large charges are constructed.

Figure 1: From left to right, the chemical reaction of more and more material (orange) supports the detonation front (red); at the edges, loss of energy results in lower pressure, slower moving detonation (yellow).
Large charges are self-confining. This effect can be simulated with heavy-walled containment. Rather than create large charges in an attempt to support detonation, we propose to develop a test where the weakly energetic material of unknown detonability is surrounded by high explosive confinement at the outer boundary. The idea is to drive a slightly convergent strong shock into a modest-sized sample by surrounding the sample with a detonating explosive. Figure 2 is a notional sketch of the test fixture. The detonation in the donor is expected to outrun the shock (or detonation) in the test sample. Therefore, the shock front in the sample would be concave, as in Figure 2, an extremely favorable condition for driving detonation. If detonation still does not develop under these conditions, it suggests that the test material will not support detonation at any size; the chemical kinetics are too slow. Firing this device is analogous to testing a very large sample, but without the hazard and expense of building and firing it.

Figure 2: Proposed device with high explosive (yellow) creating shock wave into test material (blue); long reaction zone in non-ideal sample in purple & detonation products shown in red.

A.4 Previous tests

In initial tests, samples were contained in a short, (1inch diameter x 3-12 inch tall) thin-walled plastic tube. Concentrically surrounding the tube was another cylinder filled with the high-explosive donor, e.g. sensitized nitromethane or hydrogen peroxide/fuel mixtures. It was expected that the detonation running downwards in the donor would drive a shock into the test samples along the axis of the configuration. Preliminary tests showed promising but inconclusive quantitative results. The largest challenge was the metric used to measure the effect—only a witness plate. The witness records were somewhat counterintuitive from traditional witness records (e.g. gap tests), for which cratering indicates a detonation and no cratering indicates a failure. In our test, if an inert material was tested, it ejected a high-velocity jet of incompressible, unreacted, condensed-phase sample material into the witness plate. This created measurable craters in each plate. If a known explosive was tested, all the material converted to a highly compressible gas which left no cratering on the witness plate. For the materials most of interest, modestly energetic materials, craters were formed which could not be easily interpreted. Further experiments need to be done to establish limits of detonability for materials which exhibited partial reaction.

Although the witness record will no longer be the sole metric, future tests will use witness records so that inferences about previous tests can be made by comparing them to those with more extensive diagnostic measurements. Because equations of state for the metal materials used as witness plates are well-known, craters may be modeled with some degree of accuracy, at least for comparison sake. Even if the exact crater cannot be reproduced in the model, the relative strength of each penetrating jet should be reproducible with hydrodynamic modeling simulations.

Chemistry presents itself in an explosive below its critical diameter as the conversion of explosive reactants to products, but not fast enough to support the delicate feedback that propagates the steady shockwave. Materials which are completely inert will exhibit no appreciable deviation from predicted equation of state attenuation in a boosted configuration, but materials with the capacity for detonation chemistry will have
some unknown effect on the shock propagation. It is unclear what effect failing detonation will have on the shock profile. Son et al. at Purdue University have attempted to evaluate the failure of non-ideal explosives to support detonation using microwave interferometry. Experiments were boosted by conventional high explosives in heavy-walled steel confinement vessel, and the shock front was tracked through the ideal explosive booster and into the non-ideal material as the detonation failed [1]. The technique is promising but not applicable to systems that absorb microwave radiation; most liquids have rotational absorptions in the region used for interferometric measurements. The microwave technique relies on the sample material being a pseudo-lossless extension of the waveguide; reflections from the shock discontinuity (index mismatch) are Doppler shifted corresponding to the velocity of the discontinuity.

A.5 Diagnostic approach

As a replacement for microwave interferometer in our test configuration, we have adapted conventional photon Doppler velocimetry (PDV) to become a time-resolved, embedded shock tracking technique which will work with liquids or solids (see Fig. 3). We wished to embed a velocimetry probe (fiber optic) along the symmetry axis of the cavity holding the sample. Upon finding no successful attempts published for doing this with non-invasive sized probes appropriate for our device, we pursued collaboration with the URI Department of Electrical Engineering to develop our own. The proposed device configuration takes advantage of the new technique vide infra and the old witness record metric. Other diagnostics are suggested in future experiments, (e.g. streak photography), looking for emissive evidence of chemical reaction. The PDV system is completely fiber-based and, therefore, requires minimal experimental preparation; the only sacrificial component is an arbitrary length of polymer fiber.

Photon Doppler velocimetry (PDV) is a simplistic Doppler interferometer composed of a coherent source (a 1550 nm communications-grade laser) and very high frequency photodetector and digitizer. The elegance of PDV has almost completely replaced the older VISAR (visual interferometer system for any reflector) systems but neither has been successfully used with embedded, single-fiber probes. PDV is almost exclusively used to measure surface velocities of metallic objects, such as fragment velocities, gas gun projectile velocities or cylinder wall expansions for performance testing. We have designed a modified PDV measurement system. Modifications include modulating the laser light such that the Doppler beat frequency beats against the new modulation frequency, resulting in two beat patterns--Doppler plus modulation and Doppler minus modulation. The latter can be detected by a low bandwidth oscilloscope, i.e. a $5000 scope vs those typically used for PDV, $200,000.

We have successfully proved this approach, examining the surface velocity of the aluminum casing from exploding bridgewire detonators (EBW, Teledyne, RP-501). Modeling simulations (as seen in Fig. 4) agreed well with the measured surface velocity.

![Figure 3: Diagram of modified PDV experiment.](image)

![Figure 4: Pressure profile of EBW in detonation (left) & material velocity along central axis (right).](image)
The second modification to PVD is the use of a multi-mode polymer optical fiber (POF) in the terminal segment of the interferometer sample arm. This low-impedance fiber probe will be embedded in the center axis of the device. Embedded high-impedance glass fibers may transmit shock information ahead of the detonation front; modeling by CTH has confirmed this (see Fig. 5).

Finding a way to connect single mode glass fibers (9 micron diameter) and multimode polymer fibers (63 micron) without significant back reflection has been an ongoing activity during this year. As the detonation wave propagates, the shock compression will sharply change the fiber density, and, thus, the index of refraction in the fiber probe, causing a reflection. This reflection will be constantly moving and should cause a Doppler shift proportional with the shock velocity as described for PDV surface velocity measurements. The modified PDV can measure Doppler shifts in 1550 nm light for surfaces moving in air as fast as 20 km/s and in embedded polymer fibers as fast as 14.8 km/s--faster than any detonation velocity observed in ideal explosives.

These diagnostics will feed directly into validation and development of the small-scale detonation device. In addition to developing a method of measuring velocities in fast reacting materials, modeling and simulation are underway to determine the most favorable configuration for driving a smooth concave shock to the central sample material. In parallel with setting up the new diagnostics, we have further developed our skills using the hydrodynamic codes to optimize the explosive test geometry, as well as predicting scale-up results.

B. Major contributions

The project is still in the setup phase. However, its discussion has stimulated work at both Purdue and Los Alamos National Laboratory. As more laboratories become involved, this extremely challenging problem has a chance of being solved.

C. Future plans

Once experimental design, diagnostic configuration and signal processing are optimized; any number of threat materials can be tested. The project plans, first, to investigate the utility of the test device. Tests are planned with both hydrogen peroxide-fuel mixtures and solid oxidizer-fuel mixtures (see Project Report R1-A.1). Characterizing the detonability of these mixtures will aid the correlation with other small-scale tests and may allow certain materials to be deleted from the threat list. This test will also allow us to assess the effectiveness of a given diluent or adulterant in an explosive mixture. True safe limits for materials can be established.

C.1 Future work

Most of the required instrumentation has been purchased. The initial test of the developed diagnostic tools will use known explosives well below their critical diameters, i.e. where they always fail to detonate. When these metrics are well-developed, suspect materials (explosive or not) can be investigated with small scale experiments and modeling simulations to infer the likelihood of a threat. Other experiments will investigate alternative methods of observing chemistry in the non-ideal samples via streak photography; over-compensating for edge losses and looking for reaction light in the sample over time.

Figure 5: Shock front in the polymer fiber core slightly trails shock in annular cladding (left); periodic perturbations cause irregular discontinuities ahead of shock in sample when core is higher acoustic impedance than cladding (right).
IV. EDUCATION & WORKFORCE DEVELOPMENT ACTIVITY

Each URI project supports one or more graduate students. (See listing with projects.) This is their best learning experience. Undergraduates are also supported on the projects as their class schedules permit.

This will be our 4th summer to host a Minority Serving Institute (MSI) professor. However, this is not an appropriate topic for a visiting professor to work on. He/she cannot take this type of work (on explosives) back to his/her home institution. Furthermore, 10 weeks is not sufficient training time to work safely with these materials.

Every summer our Center funds are used to support high school teachers. They conduct research in URI labs under the mentorship of a graduate student. The teachers worked fulltime for 8-10 weeks. In addition, this summer (2014) we have 2 forensic scientists from Qatar and 2 professors and their students from West Point.

Eight professional classes were offered so far in 2014, providing training for well over 160 professionals. For over a decade we have offered classes to DHS and its components. Since 2014, we have offered three week-long courses with lecture and labs to TSA.

K-12 outreach continues to be hosting high school teachers in the summer and providing chemical magic shows at schools K-12.

V. RELEVANCE AND TRANSITION

A. Anticipated end-user technology transfer

We anticipate that this test will transfer into National Lab use. We also expect it to be adopted by industrial safety and risk management.

VI. LEVERAGING OF RESOURCES

While this may become a wide-spread technique, it is not expected to yield a “product.”

VII. PROJECT DOCUMENTATION AND DELIVERABLES

A. Peer reviewed journal articles


B. Other Presentations

1. Seminars
a. Sensitivity and Stability of Fuel Oxidizer Mixtures J.C. Oxley; J.L. Smith; M. Donnelly ISICP; Poitiers; June 2014
b. Peroxide Explosive-J.C. Oxley; J.L Smith; P. Bowen; J Brady; L. Steinkamp; J Canino ISICP; Poitiers; June 2014
c. URI Explosive Research” Ludwig-Maximilian University of Munich: June 2014
d. TED Conference “Explosive-Polymer Interactions”-J Oxley, J Smith, J Canino, D. Swanson, G. Zhang, Charlottesville, NC; April 8-11, 2014
e. TED Conference New Approaches to Swabbing-J. Canino, J. Smith, J Oxley Charlottesville, NC; April 8-11, 2014
f. ISADA: “Taming the Peroxides and Other HME” J. Oxley Oct, 2013 Den Haag
g. NATAS “Thermal Impact vs Sensitivity?” Aug. 4, 2013; Bowling Green, KY

2. Short Courses
a. Fundamentals of Explosives Jan, May  2014
b. Explosive Safety for Technicians  Feb 2014
c. Fundamentals of Explosives for TSA-Explosive Specialists Feb, April, May 2014
d. Combustion March 2014
e. Fundamentals of Explosives for EOD Mar 2014
f. IABTI Regional Meeting; “Explosive Short Course” Colorado Spring; CO Sept 17, 2013

3. Briefings

4. Invited Lectures
b. Plenary Lecture: “Explosive Detection: How We Got Here and Where are We Going?” International Symposium on Chemical Propulsion & Energetic Materials June 2-6 2014; Poitiers, FR
h. FACSS/SciX “Taming the Peroxide Explosives and Other HME;” Milwaukee; Oct 2 2013

C. Student theses or dissertations produced from this project
D. Transferred Technology/Patents

1. Patent Applications Filed
   a. Non-Detonable Explosive or Explosive-Simulant Source J Oxley, J Smith, J Canino
   d. Melt Castable Explosive Formulations Containing Erythritoltetranitrate J Oxley, J Smith; A Broun, R Rettinger

E. Software Developed

1. Databases

F. Requests for assistance/advice

1. From DHS
   a. Several requests about threat compounds—confidential

VIII. REFERENCES