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**by Thuvan Piehler, Charles Hummer, Richard Benjamin, Eugene Summers,
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INTRODUCTION

The detonation front of an explosive can be modified by adding an external energy source such as electrical energy to the chemical energy of the explosive. When an electric field E is applied and current flows only in the reaction zone width of ≤ 0.1 millimeter, the electrical power P_{elec} deposited per unit area in the high explosive is expressed as

$$P_{elec} = \sigma E^2 \Delta \quad (1)$$

where σ is the electrical conductivity; Δ is the conduction zone width; and E is the applied electric field [1].

If electrical energy could be coupled into the explosive detonation wave by passing electric current through it, a significant fraction of the chemical energy should be converted to electromagnetic energy. If the converted energy is redirected into the detonation zone towards the latter stages of its travel, an increase in detonation velocity to 10-20% may be expected. Consequently, the pressure in the CJ plane is expected to increase by the order of 20-40% [2].

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OBJECTIVE

The objective is to assess the possibility of using electromagnetic fields to enhance the detonation velocity of explosives. It is anticipated that the introduction of high currents will increase the energy content of the conduction gases in the vicinity of the detonation front through ohmic heating. This increased energy should then lead to an increase in the detonation velocity.

EXPERIMENTAL SETUP

The first step in this effort is to design an experimental setup where the electrical energy can be efficiently delivered to the advancing CJ plane. An electrical pulsed power supply was designed and built at ARL that can deliver sufficient energy to the CJ plane in a very short time. This new experimental arrangement required a design of the rails that maintains current conductivity during the detonation, and a power supply design that delivers the current to the rails in the very short time of the experiment. A series of tests using a well characterized plastic bonded explosive Primasheet-1000 was conducted, where the detonation front velocity was measured at various electrical energies.

All experiments were conducted at an indoor facility. The actual experimental arrangement is shown in Figure 1. Figure 2 illustrates the high voltage power supply enclosed in a wooden box.



Figure 1. Experimental arrangement a) Outside the blast chamber and (b) Inside the blast chamber



Figure 2. High voltage power supply

The experimental arrangement of electromagnetic coupling with explosive rails shown in Figure 3 includes two copper plates separated by a 0.3 centimeter (cm) layer of Primasheet -1000 explosive. The plates are 2.54 cm wide by 50 cm long by 1.27 cm thick. 55 kilojoules (KJ) of energy is transferred from a capacitor to a 22- microhenry inductor. When the detonation front comes between the copper plates, an explosively opening switch (EOS) is ruptured and the energy stored in the inductor is rapidly transferred through the copper plates and into the conducting reaction zone of the detonation front.

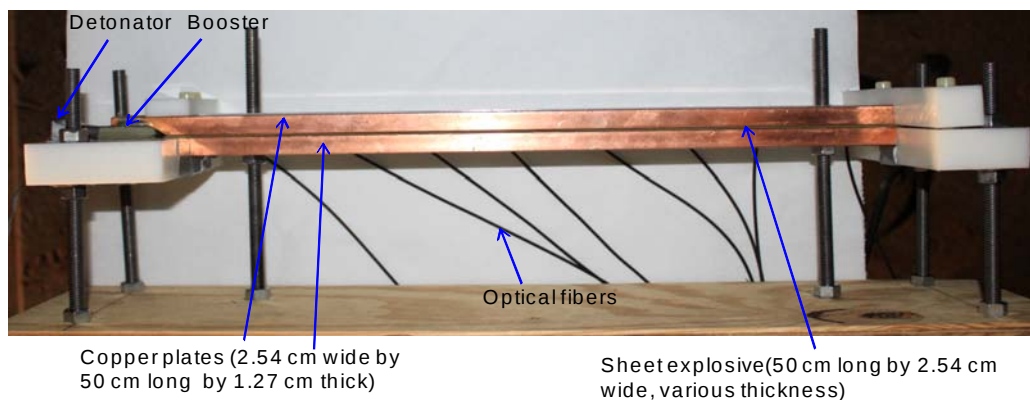


Figure 3. Electromagnetic coupling with explosive rails

An optical fiber system (shown in Figure 4) was designed and built in house to determine the detonation velocity of Primasheet-1000 in highly electrically charged environments. Eight Optimate plastic optical fibers (1 mm core diameter, 2.2 mm fiber jacket, Part # 501232-5, APM Inc., Harrisburg, PA) were cleaved and stripped back approximately 2mm. The straight edge of the fiber was mounted near the explosive being tested without having to be polished. There was a controlled air gap created

between the surface of the explosive and the cleaved end of the fiber to increase the light received from an explosion event. The fibers were evenly spaced 19.05 mm along the axis of the charge (Figure 4a). A piece of paper was placed between the fiber and the surface of the explosive to create an air gap of approximately 0.17mm (Figure 4b). The shock heating of the air gap provides the bright light required for the measurement. Light entering the optical fiber probe was transported through the fiber to a control room outside of the blast chamber (the fiber length approximately 20 feet). In the control room, light from the fiber was connected (SMA union) to a high speed DET10A-Si Biased photodetector (200-1100 nm wavelength, 1ns rise time, Thorlabs, Newton, NJ). Using the time of arrival for the evenly spaced fibers, captured by an oscilloscope, the incremental detonation velocities were determined. After each test, several feet of fibers were damaged. The fibers were then trimmed, cleaved, visually inspected by passing light through the fibers, and reused for the next experiments.

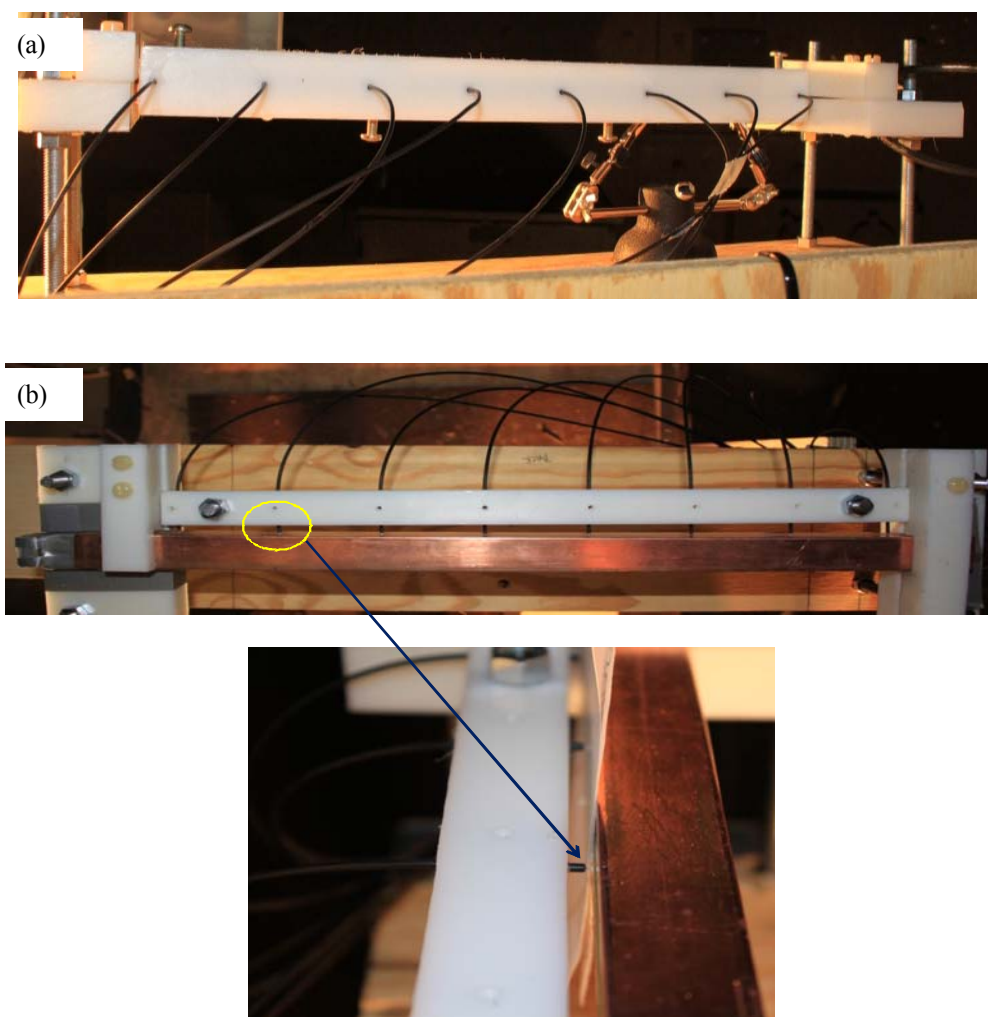


Figure 4 (a) Side and (b) top view of 8-channel optical fiber system

The Cordin Model 132B Synchronous streak camera (Cordin Company, Salt Lake City, Utah) is used to record the detonation front. The streak camera has a slit width of 0.6 mm and a maximum writing speed up to 20 mm/μs. Distance is shown vertically and time is shown horizontally (see Figure 5). Streak records were analyzed on a vertical beam optical comparator (S-T Industries, Inc. Model 4600) with 20X objective lens. For each streak record, the track was read from the original position (distance versus time) and slopes were recorded. The distance, time, and slope were recorded in order to calculate the detonation velocity. The detonation velocity is determined as followed

$$\text{Detonation Velocity} = \text{Scale Factor} * \text{Writing Speed of Camera} * \text{Tangent of the Angle} \quad (3)$$

$$= \text{Scale Factor} * (4000/\text{Camera Period}) * \text{Tangent of the Angle} \quad (4)$$

In addition, the high speed video camera images were captured with a resolution of 512x128 pixels using Photron FASTCAM SA5 high speed camera (Photron USA, Inc., San Diego, CA). The camera frame rate was 100,000 frames per second with an exposure time of 370 nanoseconds. Figure 5 shows the experimental setup of the Cordin streak camera and the high speed imaging Photron SA5 camera.

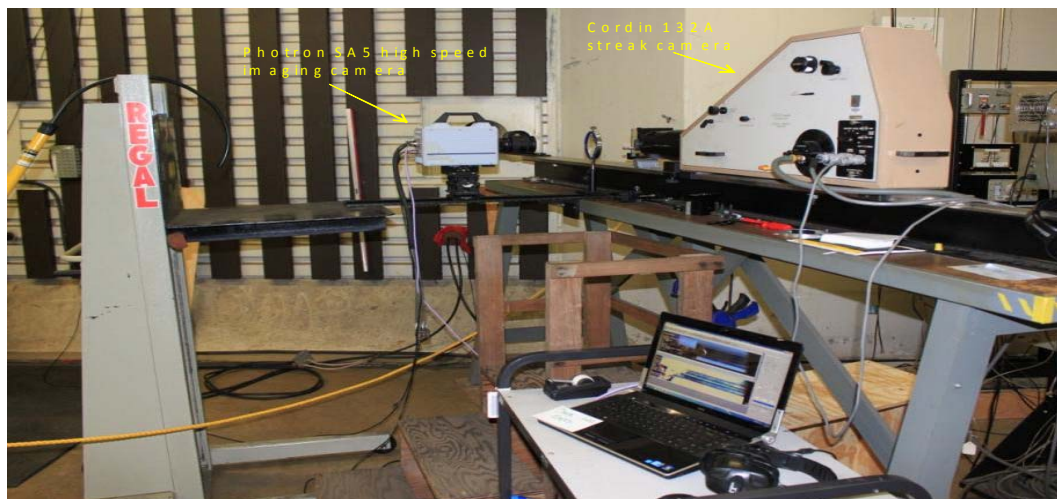


Figure 5. High speed imaging experimental setup

RESULTS

Figure 6 shows a series of high speed digital images following initiation of 1 mm thick Primasheet-1000 without high voltage electrical input. Figure 7 shows a series of high speed digital images of 1 mm thick Primasheet-1000 with high voltage electrical input.

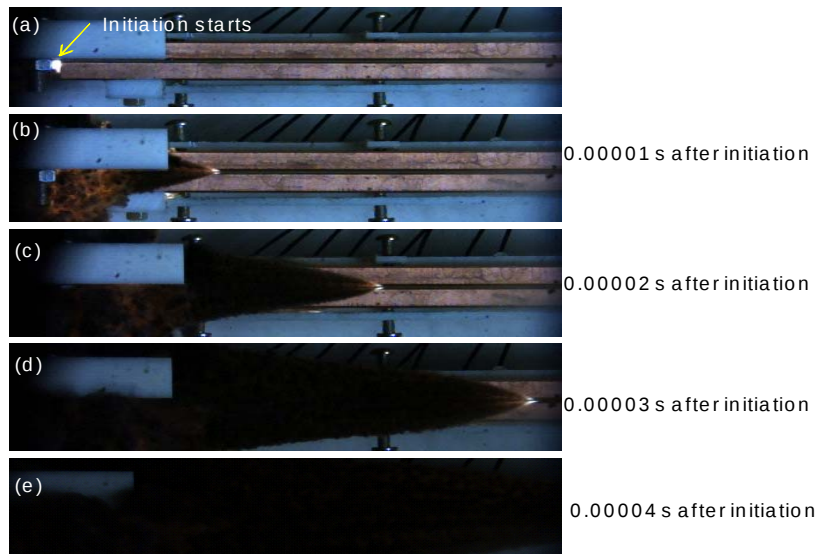


Figure 6. High speed digital images following initiation of 1 mm thick Primasheet-100 without high voltage electrical input

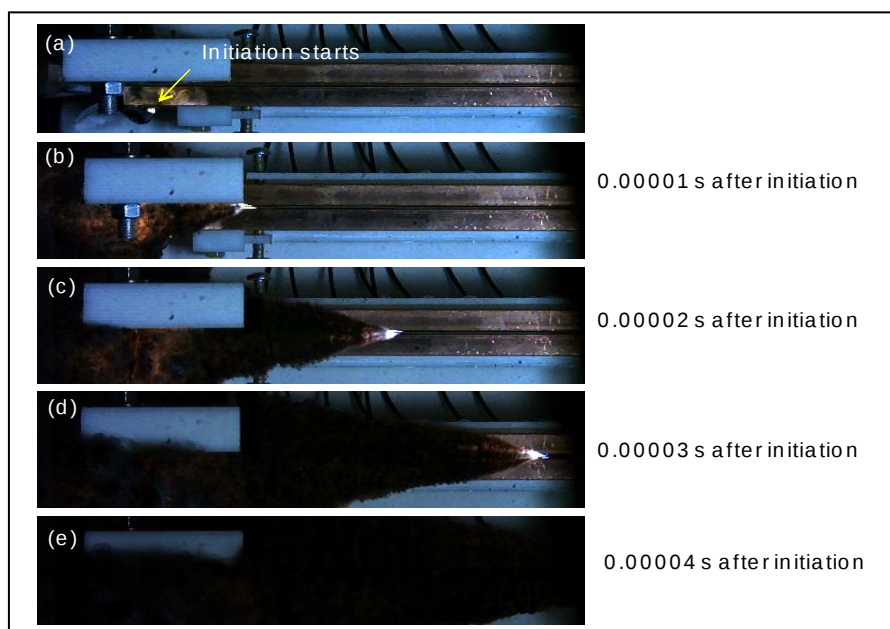


Figure 7. High speed digital images following initiation of 1 mm thick Primasheet-100 with 160.33 kJoules electrical input

Figure 6(a) and 7 (a) show an initial flash from the onset of detonation. As shown in Figure 7(c) and 7(d), the upper edge and lower edge of the Primasheet-1000 show a brighter leading luminous trace compared to the leading edges of Primasheet-1000 in Figure 6(c) and 6(d) when there was no high voltage electrical input. It is speculated that the luminosity happened due to the jetting of the shockwave along the explosive/copper interface rather than a high voltage discharge spark. The random nature of this is what contributes to errors in measuring the streak camera records for the detonation velocity.

Figure 8 shows a typical streak camera record in which the maximum available energy in the circuit deposited in the explosive. The reference detonation velocity was measured for each different explosive thickness testing in the same setup only without supplying electric energy. The results of detonation velocity tests are illustrated in Table 1 together with the electrical input.



Figure 8. A typical streak record with an electric energy input of 160.33 kJoules

A velocity increase determined from the fiber optic records was 4.2% for 1 mm thick Primasheet-1000 and 2.6% for 2mm thick Primasheet-1000. On the other hand, the velocity increase rate from the streak camera records was determined to be 2.32% for 1mm thick Primasheet-1000 and 2.62% for 2mm thick Primasheet-1000 (shown in Table 1). It is noted that the energy input is the energy stored in the capacitor, not the energy delivered to the explosive.

TABLE 1: DETONATION VELOCITY OF PRIMASHEET-1000 WITHOUT (W/O) AND WITH (W/) HIGH VOLTAGE ELECTRICAL INPUT

Explosive thickness (mm)	Detonation velocity measured from streak camera record (mm/ μ s)			Detonation velocity measured from optical fiber record (mm/ μ s)			Energy input (KJ)
	W/OHV	W/HV	%Enhancement	W/OHV	W/HV	% Enhancement	
1	6.90	7.06 $\pm$ 0.16	2.32 %	6.90	7.19 $\pm$ 0.16	4.20 %	160.33KJ (@5.5KV
2	6.87	7.05 $\pm$ 0.14	2.62 %	6.92	7.10 $\pm$ 0.03	2.60 %	160.33KJ (@5.5KV
3	6.99	6.91 $\pm$ 0.11	0	-	-	-	160.33KJ (@5.5KV

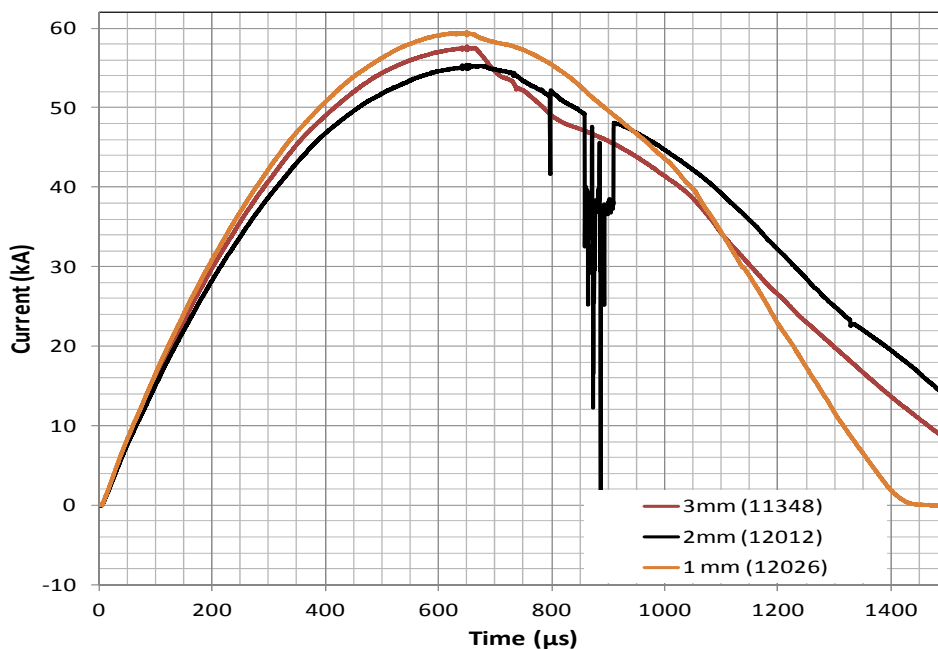


Figure 9. Current traces during tests for 1, 2, 3 mm thick Primasheet-1000

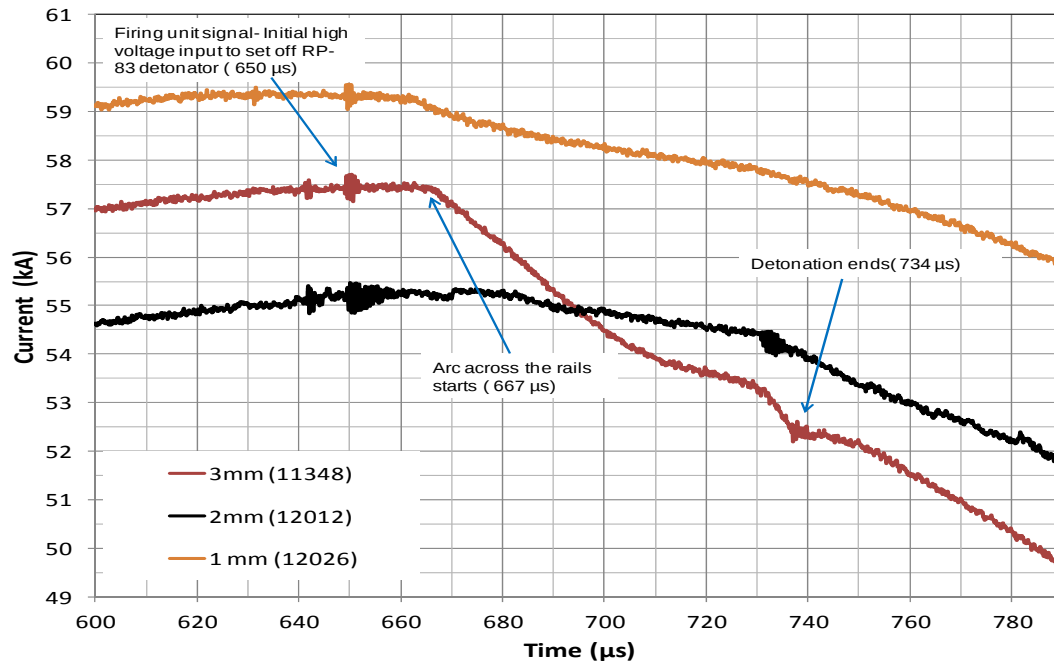


Figure 10: Current traces during the detonation of the 1, 2, and 3 mm thick Primasheet-1000

Figure 10 is the section of the current traces in Figure 9 between 600 μs and 780 μs . In this figure, there is a small noise pulse at 650 μs when the detonation circuit delivered a current pulse to the blasting cap. The slope of the current doesn't change, indicating that the resistance of the circuit has not changed. This is the time when the blasting cap is detonating a booster charge and when the 25 mm wide EOS is being opened by the explosive between the rails. The slope of the current does noticeably change at about 667 μs , indicating that the resistance of the circuit has increased. This additional resistance is due to the detonation front between the rails, which lasts until about 734 μs when there is a small noise pulse and a change in the slope of the current. When the detonation front reaches the end of the rails, there is still about 30.3 kJoules energy left in the inductor that must be dissipated by forming a discharge arc through the air that has a larger resistance. Given the detonation velocity of 7 mm/ μs that was measured by the streak camera and the light pipe data, the time for the detonation front to travel the length of the rails, 508 mm, is about 73 μs . Subtracting this time from the 734 μs , the time that the detonation front should start at about 661 μs , which is consistent with the change in the slope at about 667 μs .

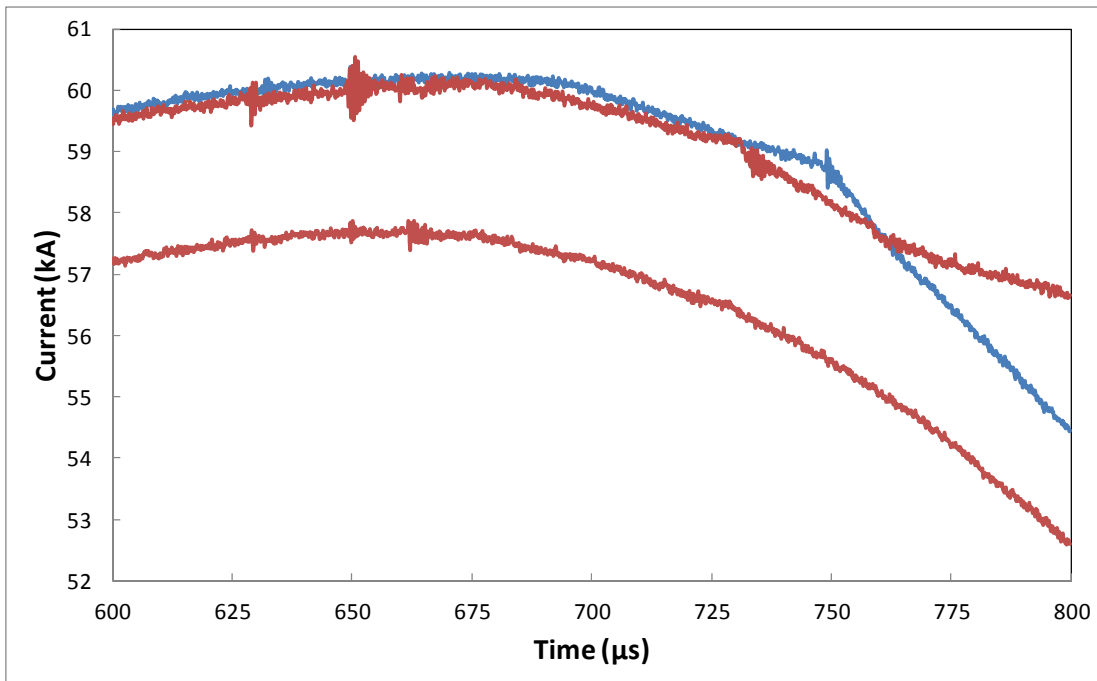


Figure 11: Current traces where the directions of the JxB force and the detonation velocity are in the opposite directions (red) and in the same direction (blue)

It is postulated that having the direction of the JxB force in the same direction as the direction of the detonation velocity would improve the coupling of the current with the detonation front. To test this postulation, several experiments were conducted using 1 mm thick Primasheet 1000 where the directions of the JxB force and the detonation velocity were in opposite directions. This was accomplished by simply connecting the wire leads to the opposite ends of the rails in Figure 3. The current traces for some of these experiments are shown in red in Figure 11. The blue trace is for a test where the JxB force and the detonation velocity are in the same direction as a comparison. The upper red trace has some weak features and the decay of the current is slower than all the other traces after 750 μs . This may indicate that part of the current is being delivered to the detonation front, but the resulting arc may be spread out over a large area to have such a low resistance. The lack of features in the lower red trace may indicate that none of the current was coupled to the detonation front, and all of the current was flowing through an arc that stayed at the end of the rails. Thus having opposing directions of the JxB force and the detonation velocity may not exclude the current from being coupled to the detonation front, but this coupling may be unreliable.

CONCLUSIONS

Initial results show that there was an increase of $\sim 4\%$ in the detonation velocity observed in a 0.1 cm thick layer of Primasheet-1000 while inputting the electric energy into the reaction zone. There was $\sim 2.6\%$ enhancement in the detonation velocity observed in a 0.2 cm thick layer of Primasheet-1000. No detonation velocity enhancement was observed in 0.3 cm thick layers of Primasheet-1000 explosive. It may be possible to use this electrical energy coupling technique to enhance detonation velocity of an explosive. Future works would be to measure the voltage wave forms, the breakdown voltage of the un-reacted Primasheet-1000, and the resistance of detonating Primasheet-1000. Further improvements in diagnostics are needed to obtain an accurate and reliable current data for analysis.

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- [2] D. Demske, "The experimental aspects of coupling electrical energy into a dense detonation wave: Part 1", NSWC TR 79-143, and May 1982.

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