National Institute of Justice Final Report: Development of Nanothermite Projectile for Improvised Explosive Device (IED) and Vehicle-Borne Improvised Explosive Device (VBIED) Neutralization

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The University of Texas at Austin

September 2008

IAT.R 0549

NIJ Grant #2007-DE-BX-K002

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
September 2008

3. REPORT TYPE AND DATES COVERED
Final report, 2008

4. TITLE AND SUBTITLE
National Institute of Justice Final Report: Development of Nanothermite Projectile for Improvised Explosive Device (IED) and Vehicle-Borne Improvised Explosive Device (VBIED) Neutralization

5. FUNDING NUMBERS
NIJ Grant #2007-DE-BX-K002

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Advanced Technology
The University of Texas at Austin
3925 W. Braker Lane, Suite 400
Austin, TX 78759-5316

8. PERFORMING ORGANIZATION REPORT NUMBER
IAT.R 0549

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of Justice, Office of Justice Programs, National Institute of Justice
810 7th St. NW
Washington DC 20531

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
ANFO, reactive material

15. NUMBER OF PAGES
49

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

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Executive Summary

The program objective of this nine-month feasibility study was to demonstrate a new technology for neutralization of explosives that are expected in vehicle-borne improvised explosive device (VBIED) scenarios. The explosive selected for the feasibility study was commercial grade ammonium nitrate–fuel oil (ANFO). The program requirements were that: (1) the solution must neutralize the explosive with minimal collateral damage, which implies that the ANFO must not detonate; and (2) the solution must be compatible with bomb squad operational tactics and tools. Additional requirements, which we used in developing our technology, were that the solution should improve:

- The bomb squad’s ability to defeat (render safe) confirmed or suspected VBIEDs at a safe standoff distance.
- The bomb squad’s ability to rapidly service targets.
- Response time from identification to neutralization of IEDs and VBIEDs.
- Post mortem forensic analysis.

The neutralization method selected was a projectile carrying a specialized reactive material (RM) fired into an explosive to cause a vented deflagration. The concept relies upon the shock from the ballistic impact to initiate the RM, which subsequently produces a controlled self-propagating reaction, e.g., deflagration, of the ANFO. The final RM projectile that was tested was fired from a commercial 12-gauge percussion-actuated nonelectric (PAN) disruptor used by bomb squads. Furthermore, initial testing at subscale indicated that a 0.50 caliber version is also probably feasible.

Our approach combined laboratory-scale experiments and modeling to help understand the thermophysical mechanisms and culminated with free-field tests. Experimental testing demonstrated that the RM projectile causes a controlled reaction of a sufficient mass of ANFO so that the resulting pressurization of the container causes the container to rupture, thus producing a render-safe solution. Several free-field shots demonstrated that both plastic and steel containers containing between 40 lb and 110 lb of ANFO could be successfully rendered safe.

Based upon these results, we believe the feasibility program has taken the concept to a technology readiness level (TRL) 4 maturity. Furthermore, we believe that the approach could be taken to mature technology (TRL 9), capable of countering the threat of terrorists to inflict casualties by providing an effective, inexpensive, and robust render-safe solution against a wide range of homemade explosives. The next steps required to achieve maturity are detailed in the final section of the report.

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Development of Nanothermite Projectile for Improvised Explosive Device (IED) and Vehicle-Borne Improvised Explosive Device (VBIED) Neutralization

***Abstract*—**It has been shown that ammonium nitrate-fuel oil (ANFO) charges in the range of several pounds to 80 pounds can be neutralized by impact of projectiles containing small amounts of a reactive material. The mechanism is that limited deflagration of the ANFO creates sufficient pressure to rupture plastic or steel containers.

1 Introduction

Vehicle-borne improvised explosive devices (VBIEDs) have been used by terrorists with increasing effect in recent years. A brief history of this evolving threat is provided in Appendix A. In the US, neutralization of explosive devices is the role of bomb-disposal squads, which form part of the domestic first-responder network. However, there is at present no protocol for responding to VBIEDs. The percussion-actuated nonelectric (PAN) disruptor technologies currently used by domestic bomb squads are not suited for a vehicle-borne device in which the detonation train is not readily accessible. Solutions developed in Europe involve large amounts of explosives to drive water disruptors, which cause collateral damage that is probably unacceptable in many US urban areas.

Against this background, the National Institute of Justice (NIJ) issued a call for proposals in 2006 to develop innovative techniques for responding to VBIED threats. The intent was to develop tools that could be put into the hands of local responders and that would permit relatively rapid and safe neutralization of VBIED threats.

The Institute for Advanced Technology (IAT) and Energetic Materials and Products, Inc. (EMPI) responded to this call based on technologies that have been under joint development for several years.

IAT is an Army university affiliated research center (UARC). IAT's main mission for several years has been to develop technology to support electromagnetic guns. As part of this effort, IAT has been investigating novel energetic materials that might replace explosives. The need for testing these and other projectiles led IAT to develop a world-class impact and explosive research facility, described at www.iat.utexas.edu.

EMPI was established with a core business aimed at developing advanced energetic materials for force protection. IAT and EMPI have collaborated on the core UARC mission, as well as several other efforts funded by the Space and Missile Defense Command (SMDC), the Defense Threat Reduction Agency (DTRA), and the Defense Advanced Research Projects Agency (DARPA) that included advanced energetics.

Funded and unfunded studies have shown that among their many useful properties, reactive materials that were thermite-based or contained metastable intermetallic compounds (MIC) could be packaged to react on impact and, when striking high explosive targets, can cause deflagration instead of detonation. A particularly dramatic example of this is shown in Figure 1.1. Here, an 81 mm mortar shell was struck by only 6 g of nanothermite mixture. The resulting deflagration caused the shell to split open.

Figure 1.1. 81 mm mortar after deflagration caused by impact of a thermite-containing projectile.

Based on this experience, IAT and EMPI responded to the NIJ proposal request with a plan to render VBIEDs safe by causing explosives to burn, so that a detonation would no longer be possible. This was to be accomplished by developing a reactive material (RM) projectile. This projectile would be able to penetrate obstacles between the shooter and the explosive. The RM would only be initiated on impact with the explosive target. The proposal was developed in consultation with the Austin, TX, Police Department bomb squad, which would participate to help ensure that solutions were compatible with present concepts of operation (CONOPS) and equipment. The proposal was selected for funding by NIJ.

A kickoff meeting was held with NIJ personnel on October 10, 2007, in which the goals of the program were focused on a scenario deemed to be particularly relevant to homeland security: The target was specified as a 55-gallon drum of ammonium nitrate–fuel oil (ANFO). IAT and EMPI were also instructed that their solution should be compatible with a conventional 12-gauge PAN disruptor. Lastly, IAT and EMPI were directed to develop a CONOPS that is compatible with the proposed render-safe technology.

2 Technical Approach

The target 55-gallon drums are usually constructed from 1/16-inch steel. Requirements for RM-containing projectiles in this program included that they must penetrate 1/16-inch steel. Interaction with the steel must cause ignition of the RM. The RM must ignite a low-order reaction in the ANFO that leads to a render-safe condition. A sequence of tasks was planned to meet this goal.

2.1 Concept of Operations (CONOPS) Task

A CONOPS must be developed that explains how a VBIED would be neutralized, given successful RM projectile development.

2.2 Experimental Task 1: Studies of ANFO Deflagration

An RM composition should be developed that, once initiated, leads to a controlled reaction of the ANFO capable of producing a render-safe condition in an ANFO target. This requires demonstration that ANFO will burn, but not detonate, when exposed to the RM source and, furthermore, that the reaction leads to a controlled rupture of the ANFO container.

2.3 Experimental Task 2: Projectile RM Development

An RM-containing projectile should be developed so the RM can withstand launch setback loads, pass through a 1/16-inch steel sheet, and then react behind the sheet.

2.4 Experimental Task 3: Small-Scale Impact Tests

It should be verified that an RM-containing projectile will initiate ANFO behind a 1/16-inch steel plate. The reaction should be low order and likely to result in a render-safe condition in larger targets.

2.5 Experimental Task 4: Intermediate-Scale Impact Tests

Full-scale RM projectiles should be fired at larger amounts of ANFO, which occupy volumes considerably larger than the zone immediately affected by the impact. Success will give more confidence before scaling up.

3 Concept of Operations

A CONOPS was developed in which use of the new RM disruptor is preceded by an exposure process. Arguments were that development of a rocket-propelled grenade (RPG) type device containing a reactive material that would create modest overpressure, sufficient to blow the sides off a panel truck, was well within the state of the art. The CONOPS was described in a report submitted to NIJ in February 2008 entitled "The VBIED Threat, Proposed Technology Solution, and CONOPS (IAT.R 0522)." An edited version of this report is included here as Appendix A.

4 Studies of ANFO Deflagration

Static tests were added to the program in order to quickly screen potential reactive materials using a *static test* protocol. The static tests involved initiation of the reactive material (RM) by a detonator, which ignited and injected the RM into the ANFO.

In order for the static tests to provide meaningful data, the static tests should duplicate the relevant conditions created by the shock produced by a ballistic impact. We determined that the applicable parameters for static tests were that the energy flux and power flux created by a ballistic impact shock should be duplicated as closely as possible by the detonator. Using this criterion, an RP-502 detonator was selected to initiate the RM.

Commercial ANFO prill was obtained from a local source. The density was measured to be 0.8 g/cm3. The tests conducted in Experimental Task 1 were intended to learn about the initiation of ANFO using reactive materials and are listed in Table I. The experiments were conducted at the IAT laboratory. The smaller ANFO mass tests were tested in an explosive tank designed to contain 1.5 pounds trinitrotoluene (TNT) equivalent. Those tests that used larger amounts of ANFO were tested in an explosive tank designed to contain 5 kg of TNT equivalent.

Table I. Tests Conducted in Experimental Task 1

Test #	Case	Reactive Material	RM Mass, g	Initiator Type	Cartridge	ANFO Mass, g	Effect on ANFO	Effect on Case
NIJ 1	Plastic bottle	Commercial thermite		Electric match	NA	454	Some melted	Melted
NIJ 2	Metal can	Commercial thermite		Electric match	NA	454	Some melted	Slightly burnt
NIJ 3	Metal can	Commercial thermite		Resistor	NA	454	Some melted	1 hole and slightly burnt
NIJ 4	3" D × 3" L pipe	APEX 17/17	2.26	RP-502 detonator	Plastic; 0.25" D cavity	325	No effect	None
NIJ 5	3" D × 3" L pipe	APEX 17/17	5.5	RP-502 detonator	Steel 0.625" D cavity	327	Deflagration	Cap blew off, base deformed
NIJ 6	3" D × 3" L pipe	Poster putty	4.5	RP-502 detonator	Steel 0.625" D cavity	325	Slightly compressed	None
NIJ 7	3" D × 3" L pipe	APEX 17/17	5.56	RP-502 detonator	Steel 0.625" D cavity	330	Deflagration	Cap blew off, base highly deformed
NIJ 8	3" D × 6" L pipe	APEX 17/17	6.07	RP-502 detonator	Steel 0.625" D cavity	630	Deflagration, ~400 g left	Cap blew off, thk. base slightly deformed
NIJ 9	3" D × 6" L pipe	APEX 17/17	5.5	RP-502 detonator	Steel 0.625" D cavity	630	Deflagration	Cap blew off, thk. base slightly deformed
NIJ 10	3" D × 6" L pipe	APEX 17/17	10.7	RP-502 detonator	Steel 0.625" D cavity	630	Deflagration	Cap blew off, thk. base slightly deformed
NIJ 11	4" D × 6" L PVC pipe	NA	NA	RP-80 det, 0.10 g Detasheet	NA	1000	Not detonated	Broken, cracked
NIJ 12	4" D × 6" L PVC pipe	NA	NA	RP-502 det, 16 g Detasheet	NA	1000	Detonation	Disintegrated
NIJ 13	5-gallon bucket	APEX 17/17	10	RP-502 detonator	1" steel bolt	1814	Non-propagating deflagration	Bottom bulged, nut sheared through
NIJ 14	5-gallon bucket	APEX 17/17	10	RP-502 detonator	1" steel bolt	0	NA	Bottom bulged
NIJ 15	5-gallon bucket, 1/8" base plate	APEX 17/17	10	RP-502 detonator	1" steel bolt	2000	Non-propagating deflagration	Base deformation
NIJ 16	5-gallon bucket, 1/4" base plate, nut support	APEX 17/17	10	RP-502 detonator	1" steel bolt	2000	Non-propagating deflagration	No deformation
NIJ 17	5-gallon bucket, 1/4" base plate	APEX 17/17	13	RP-502 detonator	1-1/4" steel bolt	2000	Non-propagating deflagration	Base sidewall bulged, bottom plate popped open
NIJ 18	5-gallon bucket, 1/4" base plate	APEX 17/17	13	RP-502 detonator	1-1/4" steel bolt	0	NA	No deformation
NIJ 19	5-gallon bucket, 1/4" base plate, center charge	APEX 17/17	13	RP-502 detonator	1-1/4" steel bolt	2000	Non-propagating Deflagration	Lid w/ 3" steel blew off, bucket center bulged

It was quickly established that conventional thermites would not ignite unconfined ANFO (tests 1–3). One pound of ANFO was placed in various containers. The thermites were ignited with an electric match and deposited enough energy into the ANFO to melt a substantial volume, but there was no reaction.

After those initial trials, approximately 330 g (3/4 lb) of ANFO was placed in a pipe bomb and initiation experiments were conducted with various special thermites. A review of literature on ANFO detonation was conducted[1,2], from which it was concluded that a 3-inch diameter pipe filled with ANFO should support a detonation. Therefore, the pipe bomb was constructed from a 3-inch diameter steel pipe. The pipe flange was bolted to a thick steel plate on one end. The cap on the other end contained a chamber into which various amounts of experimental reactive materials were placed. Figure 4.1 illustrates the test sequence for the 3-inch diameter, 3-inch long pipe bomb. The very first static test was successful, in that most of the ANFO was deflagrated and the pipe bomb deformed without rupturing.

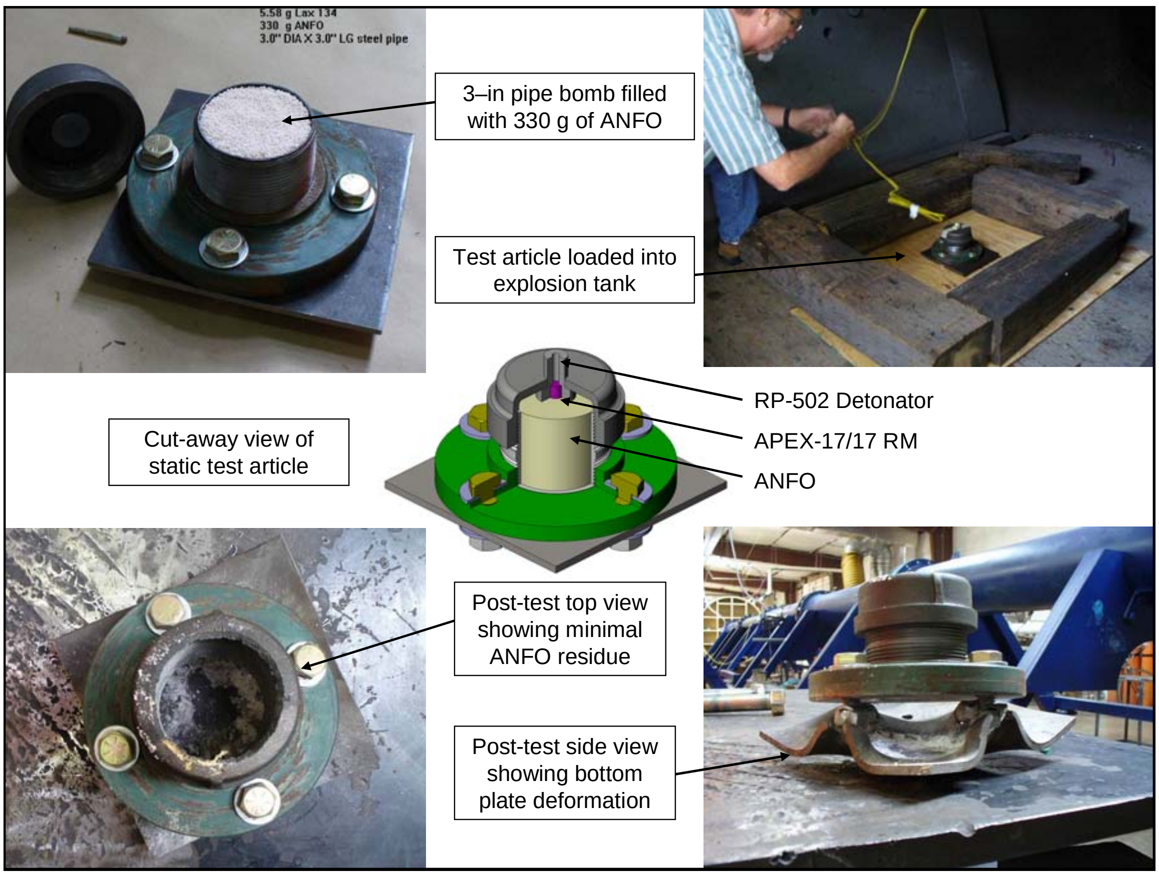

Figure 4.1. Three-inch pipe bomb test article.

Based on success in other IAT-EMPI programs[3], the RM selected for these tests was APEX-17/17. This is an EMPI proprietary material similar to LAX-134 originally developed at Los Alamos National Laboratory. Its density is approximately 2.1 g/cm^3. It is comprised of perfluoropolyether mixed with aluminum. In the EMPI APEX-17/17 formulation, the aluminum component of this material has been modified to increase reactivity. In lieu of impact initiation in these tests, the RM was ignited with RP-502 detonators.

A separate test (NIJ 6) was conducted with an inert fill replacing the RM to ensure that the detonator itself was not responsible for ANFO ignition. It was not. A test (NIJ 14) was also conducted without ANFO to ensure that the pipe-bomb rupture was not caused by the APEX. In that test, there was little damage to the 5-gallon metal bucket.

In the series of experiments described in Table I, it was established that 6 g of APEX-17/17 consistently gave rise to a propagating reaction in the ANFO in which a quarter to half of the ANFO was consumed in a deflagration. Most importantly, a render-safe principle was established. It was found that only a few hundred grams of burning ANFO produced sufficient gas to rupture the pipe bomb without fragmentation. It was decided to test a longer pipe bomb in order to allow for a possible deflagration-to-detonation transition (DDT). For this test, a six-inch pipe bomb was used, which contained 660 g (1.5 lb) of ANFO. A total of six tests demonstrated a repeatable deflagration with fracture of the pipe bomb (see Figure 4.2).

Assembled pipe bomb with 660 g of ANFO (3-in Diameter x 6-in Length)

Test article loaded into explosion tank

Top view of post-test pipe bomb with minimal ANFO residue

Side view showing ¼ - in base plate deformation but no detonation

Figure 4.2. The six-inch pipe bomb rendered safe by rupture due to overpressure developed during ANFO deflagration. The quarter-inch steel plate showed minimal deformation.

In NIJ 11, a 4-inch PVC pipe was used. Results were the same, so the relatively heavy confinement from the steel pipe was not a prerequisite to ANFO initiation.

When this configuration was used with Detasheet explosive instead of APEX, the result was a high-order detonation (NIJ 12). This was an important experiment, for it demonstrated that the lack of detonation in APEX-driven reactions was not due to the small quantity of ANFO, but rather to the thermal (as opposed to shock) excitation of the ANFO by the APEX.

Thus, the CONOPS associated with the use of RM projectiles was refined. It was realized that it was not necessary and probably not feasible to create a reaction that would consume tens of pounds of ANFO. Rather, the gas liberated from burning even a few hundred grams of ANFO is sufficient to cause local structural failure of a container, which disperses the remaining ANFO. In an ideal scenario, the ANFO would be dispersed in a thin layer that would not support a detonation. However, this assumption will need to be verified in a follow-on program with an ANFO drum that has a detonator/booster with a live explosive train.

In the next series of tests, the ANFO container was made more realistic. Five-gallon steel buckets were filled with 2 kg of ANFO. Drilled-out bolts containing RM and the detonators were inserted into 1/4-inch base plates which were placed inside the bucket, against the bottom lid. After the first trials, the upper lids of the buckets were weighed down with a 3-inch steel plate. The ANFO was contained in a lightweight plastic food container and placed next to the RM-containing bolt. The remaining volume of the bucket was then filled with cat litter, which was found to have the same approximate density as ANFO. Figure 4.3 illustrates the experiment layout. The inert cat litter provided inertial confinement to the ANFO that was ignited by the RM charge. In one test, NIJ 19, the ANFO and APEX were placed in the center of the bucket.

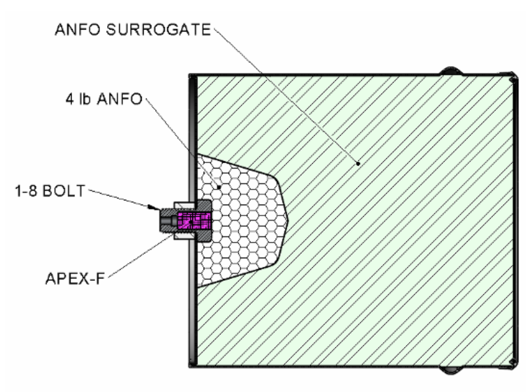

Figure 4.3. Static 5-gallon bucket test geometry.

The results of these experiments were consistent with the smaller scale pipe-bomb tests. Thirteen grams of APEX 17/17 RM was found to reliably deflagrate sufficient ANFO to open the container. However, all the ANFO was never consumed in these tests. Figure 4.4 provides a pictorial summary of the results of these experiments.

Figure 4.4. Results of tests 17–19. In test 17, APEX placed in the base plate ignited the ANFO, which blew the base open as shown. In test 18, the bucket was filled with inert material. There was insufficient overpressure from the APEX to remove the lid, and the bucket was undeformed. In test 19, the APEX and ANFO were in the center of the bucket, instead of against the base plate. Overpressure bulged the midsection of the bucket, although the bottom plate was not blown off.

In one set of experiments, carbon gauges were placed in the ANFO. The gauges are designed to withstand and record extremely high pressures, typical of condensed phase detonations. The objective was to use the carbon gauges to differentiate between a violent deflagration and a detonation event. Data was recorded during a series of tests; however, due to electrical noise, the results were not conclusive. Attempts to improve the quality of the data were unsuccessful and it was decided to abandon carbon gauges in further testing and rely instead upon high-speed images of the event and post-mortem investigation to determine deflagration vs. detonation on the ANFO.

5 Projectile Development

In order to proceed with projectile development, launch experiments were conducted using the small-caliber range at IAT. In the impact experiments, targets were 1/16-inch steel plates, and diagnostics were an open-shutter camera to record light emission from any reactions. Tests were also performed for determining the projectile accuracy and powder loading for obtaining correct velocities. Table II lists the shots conducted in these series.

Table II. Experiments Conducted to Support Development of RM Projectiles

Test #	Projectile	Reactive Material	RM Mass, g	Projectile Total Mass, g	Powder Mass, g	Velocity, m/s	Target	Result
SCR 1058	Projectile 1 CB01	APEX 17/17	5.19	18.67			1/16" steel plate	No evidence of reaction, witness Lexan showed splattered RM
SCR 1059	Projectile 1 CB02	APEX 17/17	5.16	18.7			1/16" steel plate	Slight evidence of reaction on camera, witness Lexan showed splattered RM
SCR 1060	Projectile 1 CB03	APEX 17/17	4.96	18.63	14.7	1001	3/4" steel plate	Camera image showed reaction plume uprange of target
SCR 1061	Projectile 1 CB04	APEX 17/17	5.07	18.74	12.81	853	1/16" steel plate	Camera image showed reaction plume behind target
SCR 1062	Projectile 1 CB05	APEX 17/17	4.86	18.59		862	1/16" steel plate	Camera image showed reaction plume behind target
SCR 1063	Projectile 1 CB07	APEX 34/0	4.9	18.34	13.29	877	1/16" steel plate	Projectile came apart; camera image showed reaction plume in front and behind target
SCR 1072	Projectile 1 CB09	PTFE, MoO_3 (Inert)	4.36	17.95	12.51	Not measured	Rag box	Accuracy test—hit mostly straight, ~105 mm north, ~25 mm up
SCR 1073	Projectile 1 CB10	PTFE, MoO_3 (Inert)	4.77	18.41	12.52	Not measured	Rag box	Accuracy test—hit highly yawed ~80 mm north, ~5 mm up
SCR 1074	Projectile 1 CB11	PTFE, MoO_3 (Inert)	4.98	18.65	12.52	Not measured	Rag box	Accuracy test—hit highly yawed, ~120 mm north, ~5 mm down
SCR 1075	Projectile 1 CB12	PTFE, MoO_3 (Inert)	4.86	18.52	12.52	Not measured	Rag box	Accuracy test—hit highly yawed, ~35 mm north, ~30 mm up
SCR 1076	Projectile 1 CB06	APEX 17/17	5.1	18.46	12.52	Not measured	1/16" steel plate, empty box behind	No reaction of RM behind plate from highly yawed projectile
SCR 1093	PAN Al slug	NA	0	26.19	4.86 (Blue Dot)	705.4	Rag box	Velocity test
SCR 1094	PAN Al slug	NA	0	26.21	6.48 (Blue Dot)	782	Rag box	Velocity test
SCR 1095	PAN Al slug	NA	0	26.23	8.11 (Blue Dot)	873	Rag box	Velocity test
SCR 1096	PAN Al slug	NA	0	26.23	7.30 (Blue Dot)	804	Rag box	Velocity test

Shots 1058 through 1076 (Table II) were fired from a 0.50-caliber smooth-bore rifle. A variety of projectiles were used. The ultimate projectile design, called projectile 1, was a brass tube with a thin brass cap (shown in Figure 5.1 inside the cartridge). The empty projectile 1 weighed ~13.5 g, and it could be filled with ~5 g of RM.

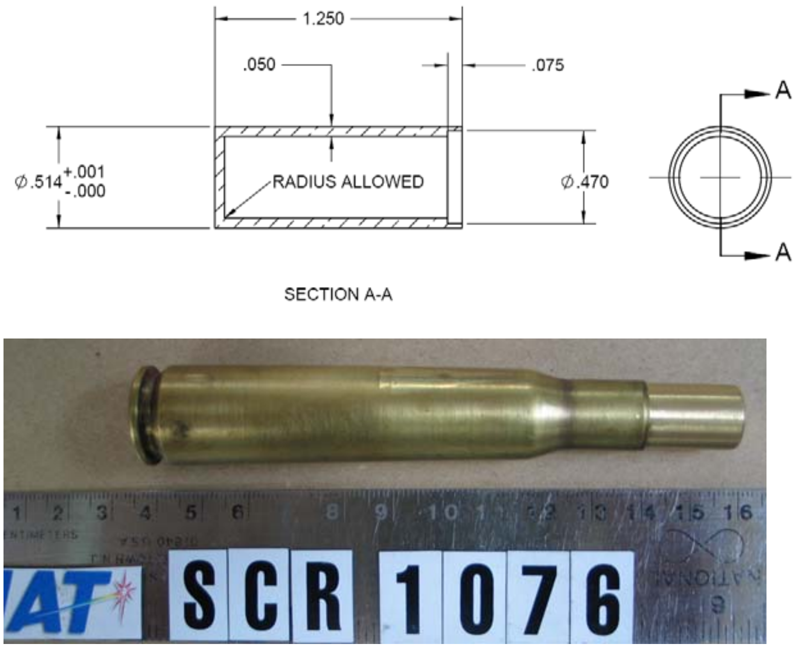

Figure 5.1. Projectile 1, a brass case filled with APEX, shown here crimped to 0.50 case.

The first series of tests (SCR 1058–1063) were fired at steel plate targets to see if the RM would react when the projectile perforated a thin plate. Earlier work against half-inch-thick steel plates showed reaction upon impact. It was unknown whether the RM could be made to react when it struck the thin side of a drum. In these tests, images were taken of the impact zone to see if there was a reaction plume from the RM initiating. Figure 5.2 shows a sample image showing a reaction plume behind a 1/16" thick steel target. Two different reactive materials were fired in this study, but ultimately APEX 17/17 was chosen. The other composition (APEX 34/0) was fired in SCR 1063, but it was so sensitive that it initiated under the launch acceleration.

Figure 5.2. Reaction plume behind a 1/16" steel plate.

The previously discussed tests were fired at targets that were about 5 m from the gun in an open range. The testing against the ANFO containing targets was to be carried out in an explosive chamber with the gun about 20 m away from the targets. Since these projectiles were not spin stabilized, there was concern about how straight and accurate the projectiles would fly. Therefore, a second series of tests were fired (SCR 1072–1076) that used the same projectile design filled with a similar-density, inert fill material composed of Teflon and moly-trioxide. It was found that under this longer flight distance, the projectiles were unstable in flight; they frequently struck with large angles of attack and were inaccurate, having dispersions of tens of centimeters. The outcome of these tests forced us to place the gun much closer to the target than planned.

Another projectile development test series was aimed at launching a scaled-up projectile to be fired using a 12-gauge PAN launcher that was acquired by EMPI and installed on the IAT range. Projectile 2 was for the most part a scaled-up version of projectile 1, except for the switch to aluminum from brass. The empty projectile weighed about 10 g and allowed about 16 g of RM to be carried on board. This can be seen in Figure 5.3. To provide a powder loading curve for this projectile, an aluminum slug that had the same mass as projectile 2 was designed and tested. These were tests SCR 1093–1096. A powder load was developed for shooting at 700 to 850 m/s.

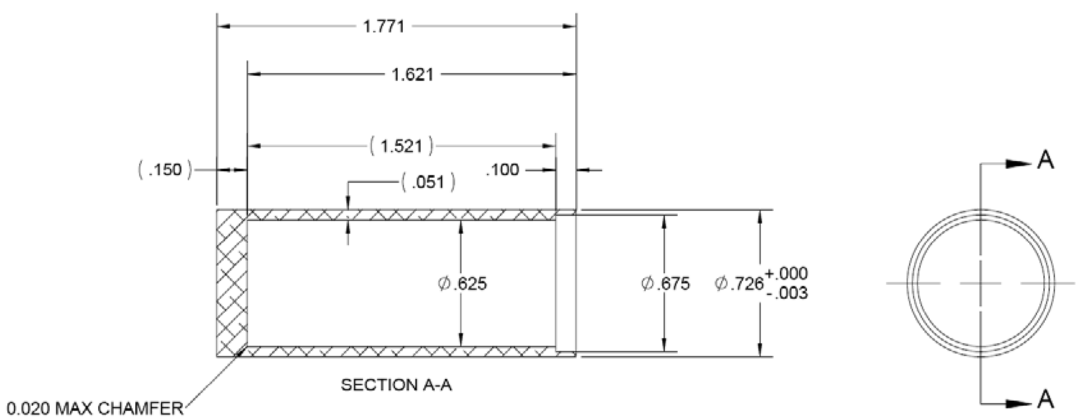

Figure 5.3. Projectile 2, designed for PAN launch.

A commercially available fin-stabilized projectile was also identified and procured from the Special Cartridge Company in London, UK. The steel body is normally supplied with an explosive fill, but it was purchased empty for these tests. A new, aluminum front chamber with a larger volume was designed and built to hold the reactive material payload. This projectile, designated projectile 3, and the UK projectile are shown in Figure 5.4. Its empty mass is 18.1 g, and it can hold about 8.5 g of APEX 17/17.

Figure 5.4. Fin-stabilized 12-gauge projectile from Special Cartridge Company shown in photograph on left and projectile 3 shown on right.

To make sure that it would initiate on a thin steel plate, it was tested in shots 1101 and 1102 against a 1/16” plate. In shot 1101, it launched to only 448 m/s because of blow-by over the body, which was subcaliber to accommodate the folded fins. High-speed photos showed that parts of the projectile separated from the body in flight. Nevertheless, it reacted with the 1/16” target plate, as shown in Figure 5.5. In the second shot (1102), the projectile held together, but impact velocity was only 360 m/s. It also reacted with the plate. Clearly, this projectile could be redesigned, but doing so was felt to be unnecessary in order to accomplish present program goals.

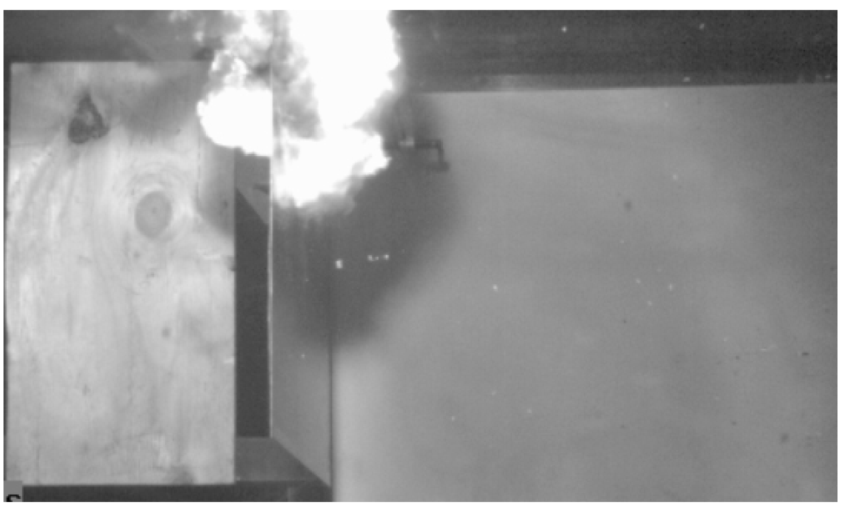

Figure 5.5. Reaction of fin-stabilized projectile with the target plate. The projectile is traveling from left to right.

6 Small-Scale Impact Tests

This series of tests was conducted in the large explosive tank at IAT, rated for 5 kg of TNT. A gun mount was designed and fabricated so that the 0.50-caliber or PAN launcher could shoot into targets contained in this tank. Two sizes of metal containers were used. In an effort to test against a target that was filled completely with ANFO, much of this testing was conducted using a half-gallon metal bucket. This smaller target required approximately 1540 g of ANFO to fill its volume. The other test used a 5-gallon metal bucket that contained 2000 g of ANFO with the remaining volume being filled with the surrogate material (cat litter). Figure 6.1 illustrates the test geometry for the test using the 5-gallon bucket.

The projectile used for most of these tests was projectile 1, and it was filled with the APEX 17/17 reactive material developed earlier. Two tests (SCR 1092 and 1097) used an inert material (Teflon with moly-trioxide) to see its effect on the target. This test series also included tests using the PAN launcher projectile, projectile 2. Finally, a 0.50-caliber ball round was fired at a half-gallon bucket to see the effect of a standard projectile. This test series is described in Table III.

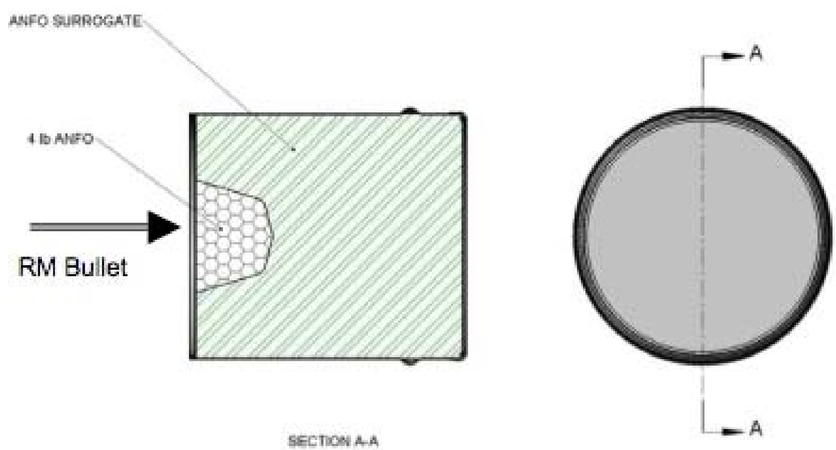

Figure 6.1. Small-scale impact test geometry.

Table III. Small-Scale Impact Tests

Test #	Projectile	Reactive Material	RM Mass, g	Projectile Total Mass, g	Powder Mass, g	Velocity, m/s	Target	Result
SCR 1077	Projectile 1 CB13	APEX 17/17	5.15	18.6	14.9	987	1/2-gallon can, 1500 g ANFO w/ 1/16" steel cover plate	Apparent detonation, can destroyed, All ANFO consumed
SCR 1078	Projectile 1 CB14	APEX 17/17	5.15	18.8	14.9	981	1/2-gallon can, 1500 g ANFO w/ 1/16" steel cover plate	Apparent detonation, can destroyed, All ANFO consumed
SCR 1079	Projectile 1 CB15	APEX 17/17	5	18.5	12.81	821	1/2-gallon can, 1500 g ANFO w/ 1/16" steel cover plate	Apparent deflagration, can split, ~50% ANFO consumed
SCR 1091	Projectile 1 CB20	APEX 17/17	5.06	18.81	11	748	1/2-gallon can, 1540 g ANFO w/ 1/16" steel cover plate	Apparent deflagration, can split, ~10% ANFO consumed
SCR 1092	Projectile 1 CB17	PTFE, MoO3 (Inert)	4.8	18.46	14.9	983	1/2-gallon can, 1540 g ANFO w/ 1/16" steel cover plate	Apparent detonation, can destroyed, All ANFO consumed
SCR 1097	Projectile 1 CB18	PTFE, MoO3 (Inert)	4.93	18.61	12.8	846	1/2-gallon can, 1540 g ANFO w/ 1/16" steel cover plate	Apparent detonation, can destroyed, All ANFO consumed
SCR 1098	Projectile 2 CB101	APEX 17/17	15.93	26.57	7.50 (Blue Dot)	765	5-gallon bucket, 2000g ANFO w/ 1/16" steel cover plate	Plate and bucket base perforated but little reaction, bucket completely intact
SCR 1099	.50 Caliber Ball	NA	0	42	12	789	1/2-gallon can, 1540 g ANFO w/ 1/16" steel cover plate	Bucket only perfed, no ANFO reaction
SCR 1100	Projectile 2 CB102	APEX 17/17	16.1	26.02	8.0 (Blue Dot)	800	1/2-gallon can, 1540 g ANFO w/ 1/16" steel cover plate	Apparent deflagration, can split, ~10% ANFO consumed

Projectile 1 was fired with APEX-17/17 in tests SCR 1077–1079 and 1091, with the only change being the impact velocity. The velocity varied from 987 to 748 m/s. For the two tests above 900 m/s, it is assumed that the ANFO detonated, as only fragments of the half-gallon bucket and 1/16-inch cover plate were recovered after the test, and all the ANFO was consumed. The two tests that had impact velocities below 900 m/s split open the bucket and only partially consumed the ANFO. The fraction of consumed ANFO was greater for the test at 821 m/s than for the test at 748 m/s. A comparison of the recovered bucket pieces can be seen in Figure 6.2. Even if the higher velocity tests did not actually detonate the ANFO, it is clear that there was a much more energetic reaction. The fact that the amount of consumed ANFO decreased with decreasing velocity also indicates that the impact velocity is a very important variable for a render-safe solution.

Figure 6.2. Recovered bucket parts: SCR 1078, V=981 m/s (at left) and SCR 1079, V=821 m/s.

Two tests were performed using projectile 1 with an inert material fill composed of Teflon paste and molybdenum trioxide (moly-triox) powder to simulate the same density as the APEX 17/17. The goal of these tests was to see if the mechanical breakup of the projectile and subsequent dispersal of the fill material into the ANFO medium would have any effect. Surprisingly, both of the tests (SCR 1092 and 1097) led to a violent ANFO reaction similar to what was seen in the high-velocity, APEX-filled tests SCR 1077 and 1078. In both tests, all the ANFO was consumed, and the bucket was highly fragmented. Recovered pieces of the bucket and cover plate from SCR 1097 can be seen in Figure 6.3. The only explanation for this result is that the breakup of the projectile and dispersal of the fill material created heat, which caused the Teflon to react with molybdenum. Moly-triox is known to dissociate at relatively low temperatures into molybdenum and oxygen, and it is possible that the reaction and the liberated oxygen caused a violent ANFO reaction. A totally inert powder like Al_2O_3 would have been a better choice.

Figure 6.3. Recovered bucket and cover plate pieces from SCR 1097.

While the projectiles that had the supposedly inert material fills caused an ANFO reaction, the 0.50 caliber ball (SCR 1099) projectile simply perforated the bucket and ANFO with no reaction. The bucket lid did come off, and ANFO was scattered about the tank interior. This was the expected result. Figure 6.4 shows the bucket after the test with holes through the lid and bucket base.

Figure 6.4. Recovered bucket from 0.50-caliber ball test (SCR 1099).

The final tests that took place within this task fired projectile 2 (SCR 1098 and 1100) at half- and 5-gallon buckets to make sure that the scaled-up projectile would perform the same as projectile 1. These were fired from the PAN launcher. Figure 6.5 shows projectile 2 integrated into a shotgun cartridge prior to testing.

Figure 6.5. Projectile 2 with cartridge.

When projectile 2 was fired at the 5-gallon bucket (SCR 1098), the projectile perforated the cover plate and bucket base but did not react with the ANFO. There was evidence that the projectile may have struck a wooden support prior to hitting the target. This may have led to premature initiation of the RM so that it couldn’t react with the ANFO. In SCR 1100, projectile 2 was fired at a half-gallon bucket completely filled with 1540 g of ANFO. A half-gallon bucket was chosen as the target so that there wouldn’t be any complication from the presence of surrogate material. This was a successful test in that the bucket was completely opened up and the ANFO was scattered around the tank interior. This can be seen in Figure 6.6.

Figure 6.6. Bucket after test from SCR 1100.

This test series established the following:

1. Projectile 1 containing APEX 17/17 was able to render safe containers with approximately 3.5 pounds of ANFO.
2. There appears to be a critical velocity window for successful deflagration of the ANFO. In other words, if the velocity is too low, e.g., ~700, the APEX 17/17 does not fully ignite and react; if the velocity is too high, e.g., ~ 900 m/s, the reaction is high-order—producing overpressure and fragments.

7 Intermediate-Scale Tests

In order to extend the experiments to larger ANFO charges, a final test series was conducted in a quarry north of Austin. This allowed the various containers to be completely filled with ANFO and eliminated any concern about the effect of the surrogate on the reaction. The 12-gauge PAN disruptor was used for all the experiments. All projectiles were filled with APEX 17/17 reactive material. Most of the tests used projectile 2, but there were two additional tests with projectile 3 and one test that used a modified version of projectile 2. All the field tests were monitored with a high-speed video camera to record the interaction. Results are summarized in Table IV. Note that impact velocities were not generally measured in these tests, because there is so much error from measuring them on the high-speed video.

Table IV. Results from Intermediate-Scale Tests

Test #	Projectile	Reactive Material	RM Mass, g	Projectile Total Mass, g	Powder Mass, g	Velocity, m/s	Target	Result
FT 1	Projectile 2 CB105	APEX 17/17	15.806	26.498		Not measured	5-gallon bucket, 40 lb ANFO w/ 1/16" cover plate, bottom impact	Bucket ripped open, successful render safe
FT 2	Projectile 2 CB106	APEX 17/17	15.692	26.441		Not measured	5-gallon bucket, 40 lb ANFO, side impact	Bucket ripped open, successful render safe
FT 3	Projectile 3 CB203	APEX 17/17	8.147	26.232		Not measured	5-gallon bucket, 40 lb ANFO w/ 1/16" cover plate, bottom impact	Bucket didn't open, some reaction and bulging
FT 4	Projectile 3 CB204	APEX 17/17	8.463	26.388		Not measured	5-gallon bucket, 40 lb ANFO, side impact	Bucket didn't open, some reaction and bulging
FT 5	Projectile 2 CB103	APEX 17/17	15.326	25.863	8.1 (Blue Dot)	Not measured	8-gallon steel bucket, 60 lb ANFO, side impact, no cover plate	Bucket lid opened, reaction and bulging, no defeat
FT 6	Projectile 2 CB110	APEX 17/17	15.840	26.512	8.1 (Blue Dot)	Not measured	5-gallon plastic bucket, 40 lb ANFO, side impact, no cover plate	Bucket lid opened, reaction and bulging, no defeat
FT 7	Projectile 4 CB301	APEX 17/17	16.081	26.175	8.1 (Blue Dot)	Not measured	5-gallon plastic bucket, 40 lb ANFO, side impact, no cover plate	Bucket completely split, target defeated
FT 8	Projectile 2 CB111	APEX 17/17	15.820	26.371	8.1 (Blue Dot)	Not measured	15-gallon plastic bucket, 110 lb ANFO, side impact, no cover plt	Bucket lid not open, reaction and bulging, no defeat
FT 9	Projectile 2 CB113	APEX 17/17	15.499	26.326	8.1 (Blue Dot)	Not measured	8-gallon steel bucket, 60 lb ANFO, base impact, no cover plt	Bucket base blew off, ANFO partially emptied, partially successful defeat

In the first shot (FT 1), a 5-gallon steel bucket was filled with 40 pounds of ANFO. Projectile 2 was used. Impact was on the bottom of the bucket, which was reinforced with a 1/16-inch steel plate to simulate a 55-gallon drum wall thickness. There was 6 feet of flight distance from muzzle to target. The reactive material projectile caused the ANFO to initiate, which led to the bucket being burst open. Figure 7.1 shows the pre- and post-shot photographs of the bucket and PAN disruptor on the left side. Also shown in Figure 7.1 are selected frames from a high-speed camera, which recorded the event. This shot was considered a successful render-safe experiment.

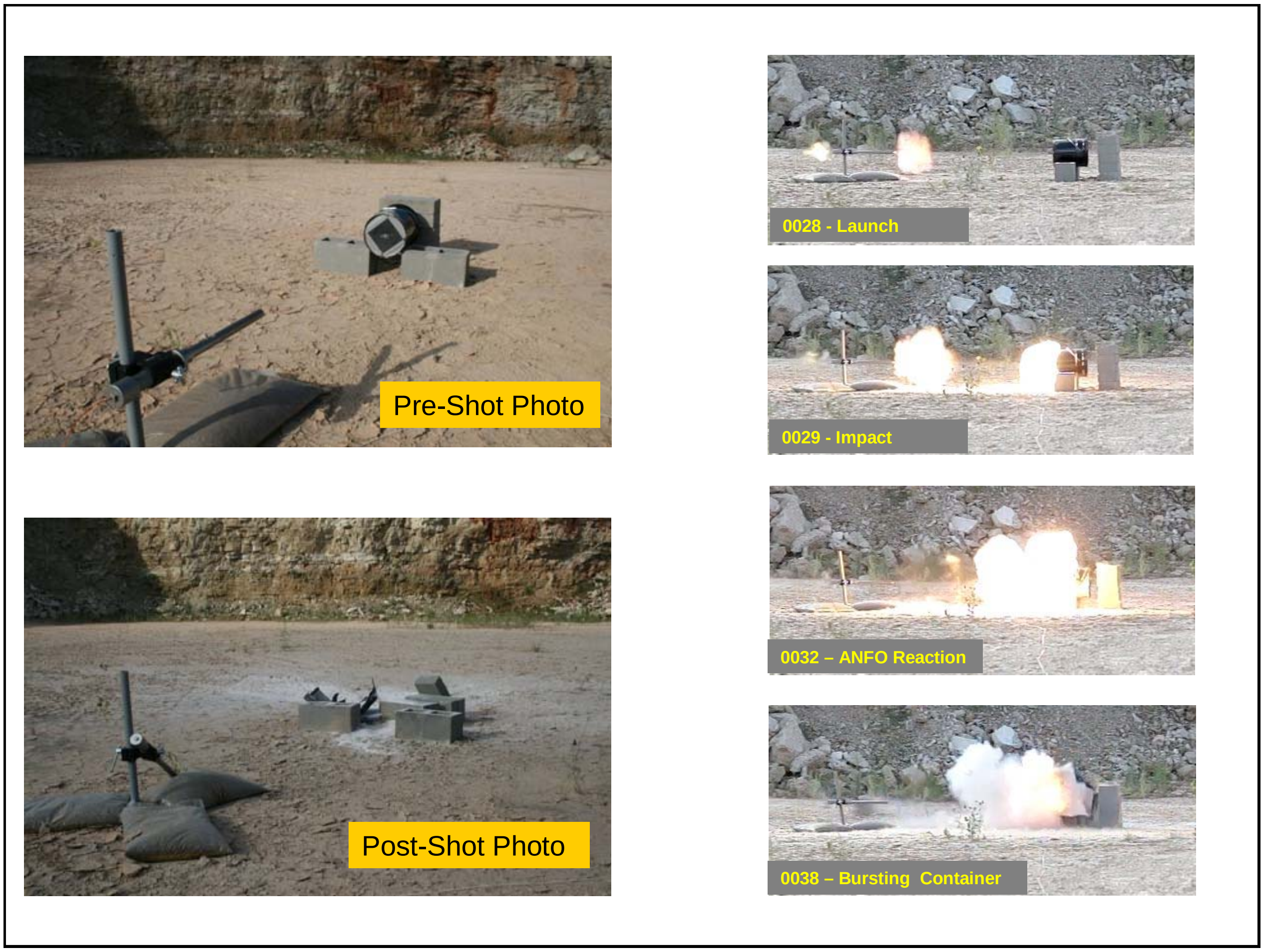

Figure 7.1. Results of the first field test, in which the target was rendered safe.

The second shot (FT 2) was a repeat of FT 1, except that the impact was into the round side of the steel bucket. Figure 7.2 shows the pre-shot and post-shot photographs of the bucket and PAN disruptor on the left side and selected frames from the high-speed camera. The bucket was split, and this was also considered a successful render-safe attempt.

Figure 7.2. Render-safe outcome in the second field test.

In the next two shots (FT 3 and FT 4), the previous tests were repeated, but using the fin-stabilized projectile 3. There was little or no reaction in either shot. In the enclosed range test, this projectile launched only to a maximum velocity of 448 m/s, and in the high-speed videos from this test, the speed was estimated at 550 m/s. Evidently, the velocity was too low to drive the APEX reaction with sufficient intensity. This result is consistent with the small-scale results, where lower velocities led to reduced amounts of consumed ANFO and thus reduced effects on the target. It also may be that at too low a striking velocity, only a small portion of the APEX is ignited by the impact-driven shock wave.

For the next series of tests, larger amounts of ANFO were employed. In FT 5, an 8-gallon steel drum with wall thickness comparable to a 55-gallon drum was selected and filled with 60 pounds of ANFO. Figure 7.3 shows the same series of pre-shot, post-shot and selected high-speed images. The container was split open by a crack driven from the impact site, and the lid popped open, as shown in Figure 7.3. This is probably a render-safe outcome. It is doubtful that the ANFO would still be detonable. ANFO needs a critical diameter of approximately 3 inches to support a detonation, and a thin layer of ANFO scattered as shown above most likely would not support a detonation. Certainly, the container would be vulnerable to a follow-up neutralization by additional impacts.

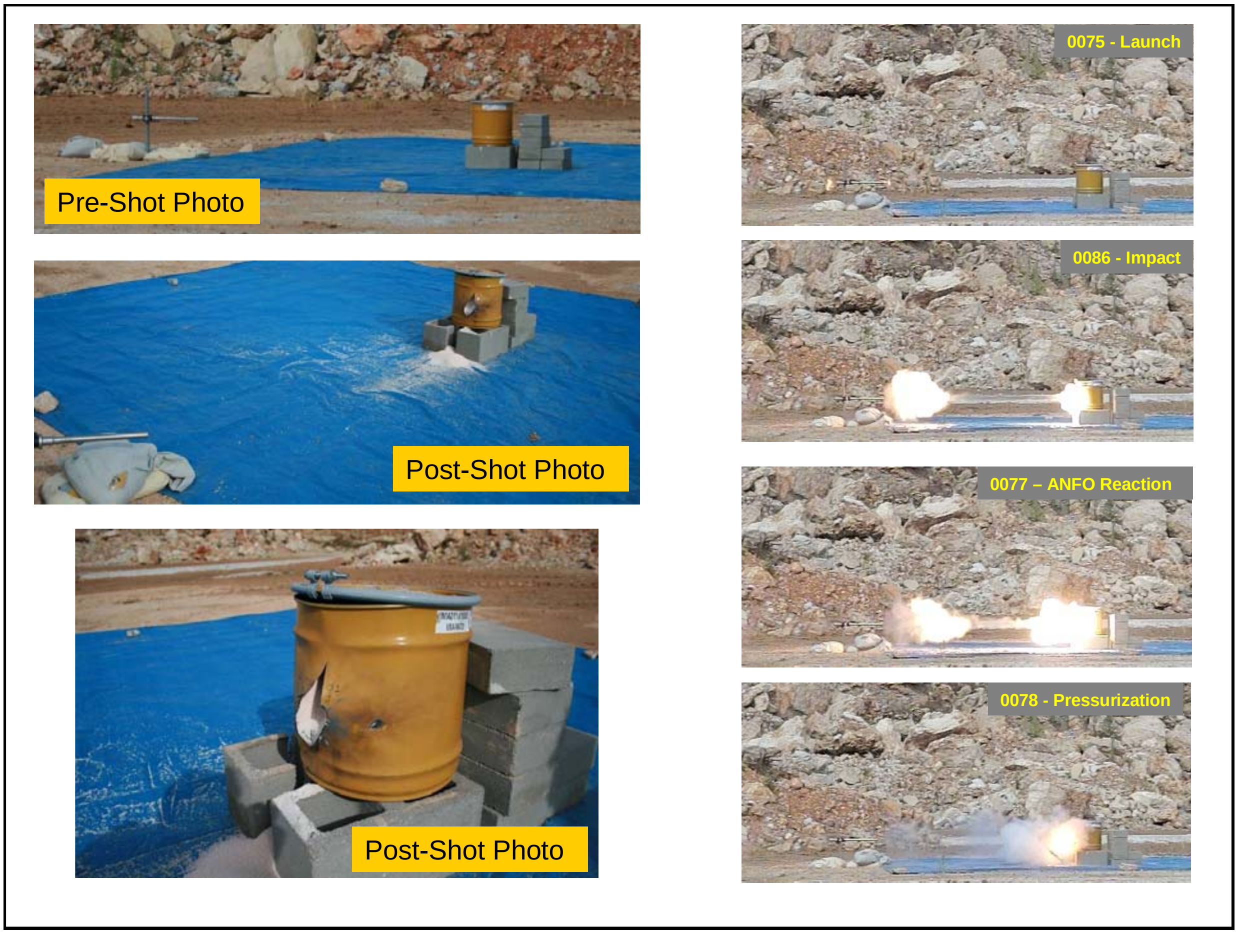

Figure 7.3. Render-safe solution in a shot into 60 pounds of ANFO in FT 5.

In order to check the robustness of these results, shot FT 6 was against a 5-gallon plastic bucket containing 40 pounds of ANFO. In this shot, it was clear that the projectile did indeed initiate upon impact with the plastic wall. However, it appeared from the high-speed videos that the projectile was damaged by launch and may have lost some of its APEX fill. Only a relatively small volume of ANFO reacted. The target may still be vulnerable to second impact, but because little ANFO was spilled, this first shot is probably not a successful render-safe outcome, since most likely the container may have still been detonable. The post-test target is shown in Figure 7.4.

Figure 7.4. Results from Shot FT 6, striking a 5-gallon plastic bucket filled with ANFO.

In the next shot (FT 7), also against a plastic container, the projectile was modified with a thicker nose and thinner sidewalls. The projectile sidewalls were thinned out to make it easier for them to burst upon impact and allow the initiating RM to spread out inside the ANFO. A schematic of the revised version, designated projectile 2A, is shown in Figure 7.5. This modification proved to be successful.

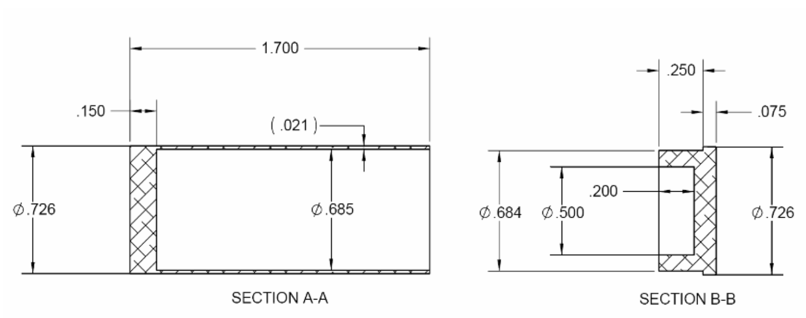

Figure 7.5. Projectile 2A, modified from projectile 2 so as to react on lighter barriers.

Figure 7.6 shows the same series of pre-shot, post-shot and selected high-speed images of the event. The target was successfully ruptured, being split symmetrically, dispersing ANFO over a 40-foot diameter region, as shown in Figure 7.6.

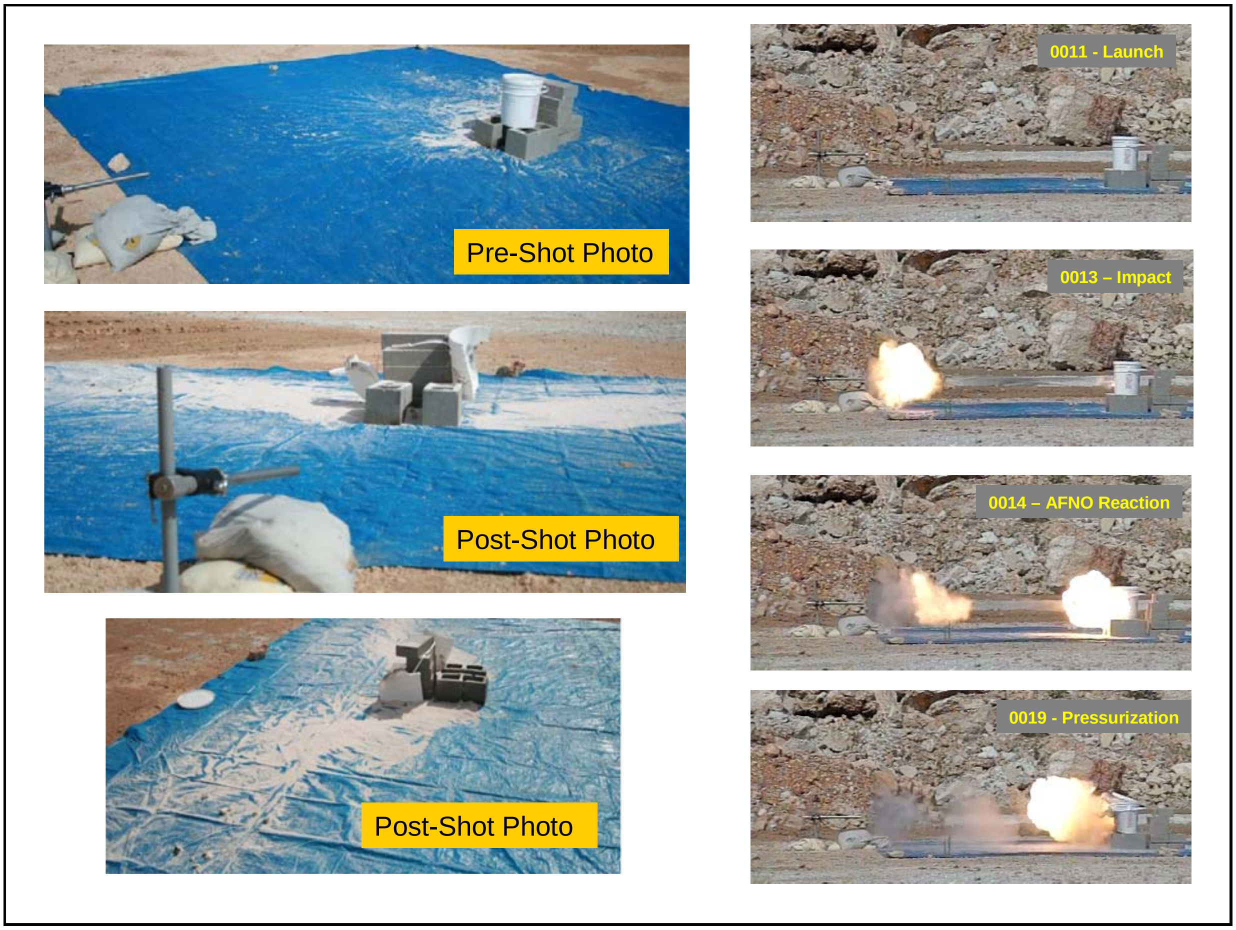

Figure 7.6. Results of FT 7, firing the modified projectile 2A at a plastic drum: clearly a render-safe outcome.

In order to determine if a larger amount of ANFO in plastic containers would give similar results, in shot FT 8, a 15-gallon plastic drum was used that contained 110 pounds of ANFO. It was shot with projectile 2 from a distance of 8 feet. Projectile 2A was not used because only one of them was available on the testing day. Figure 7.6 shows the same series of pre-shot, post-shot, and selected high-speed images of the event. The APEX initiated on impact with the target, and the drum was split both vertically and axially, as shown in Figure 7.7. The reaction and pressurization and post-test damage are very similar to that shown in Figure 7.4. Apparently, the local effect on the container is relatively independent of the size of the container. The amount of ANFO ejected was similar to the previous shot, which left a considerable amount of explosive still in the container. Thus, this target may have still been detonable. The large entrance hole would have made the target vulnerable to water attack.

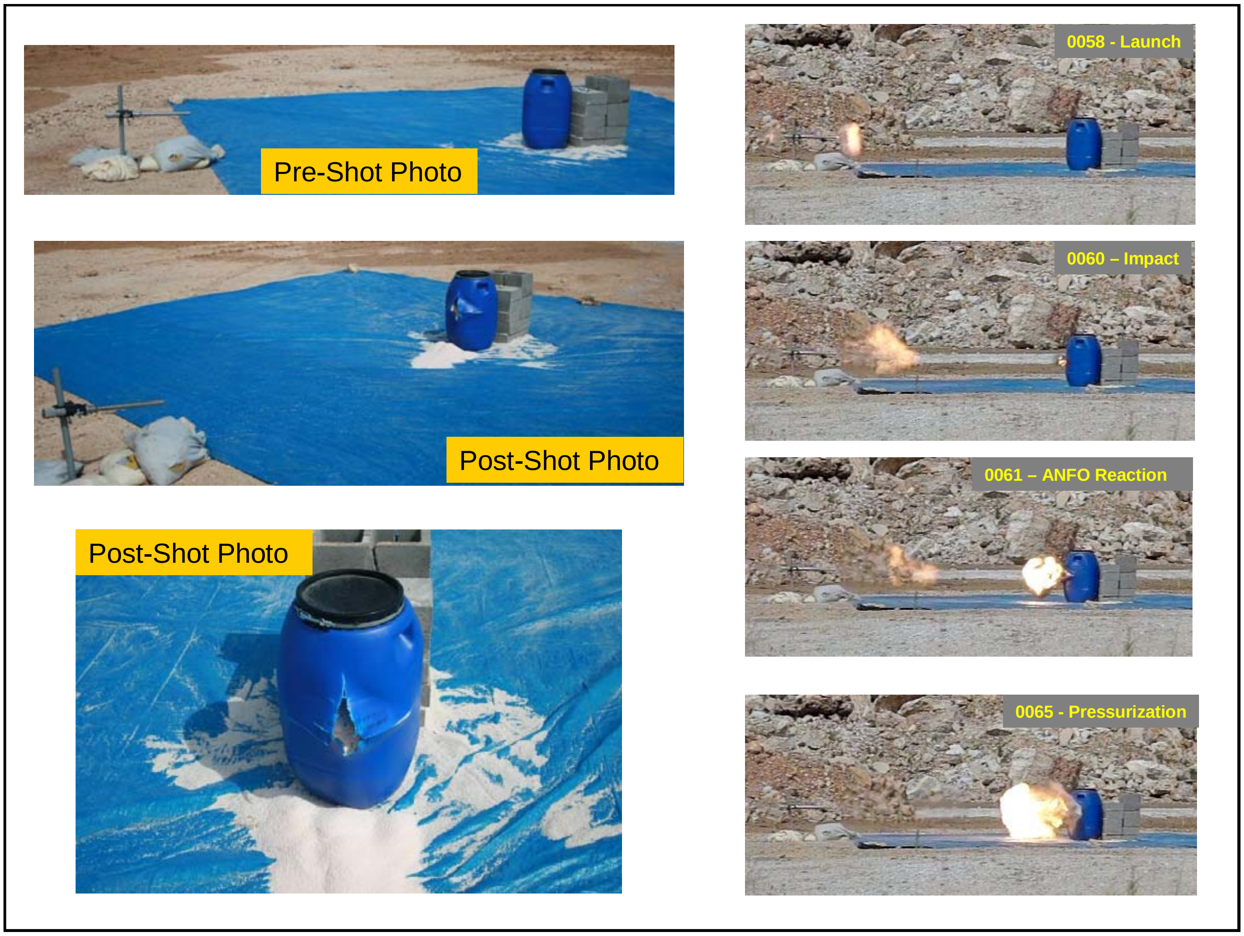

Figure 7.7. Damage to a 15-gallon plastic drum. Local structural failure, but much ANFO remains in the target.

The last shot conducted in this program, FT 9, was a repeat of FT 5 (8-gallon steel barrel filled with 60 pounds of ANFO) except that the impact was against the base. There was a violent reaction that detached the base and threw it approximately 100 feet. The ANFO spilled out all around the drum. Figure 7.8 shows the pre-shot and post-shot condition of the target and the ANFO reaction, which appears to be more energetic than test FT 5. However, if a detonator were present at the other end of the target, it may have been possible to detonate the remaining ANFO. So again, a one-stage render-safe outcome was not achieved. Perhaps for relatively large targets such as this one, a different RM projectile is required that releases the RM payload after more penetration into the ANFO fill.

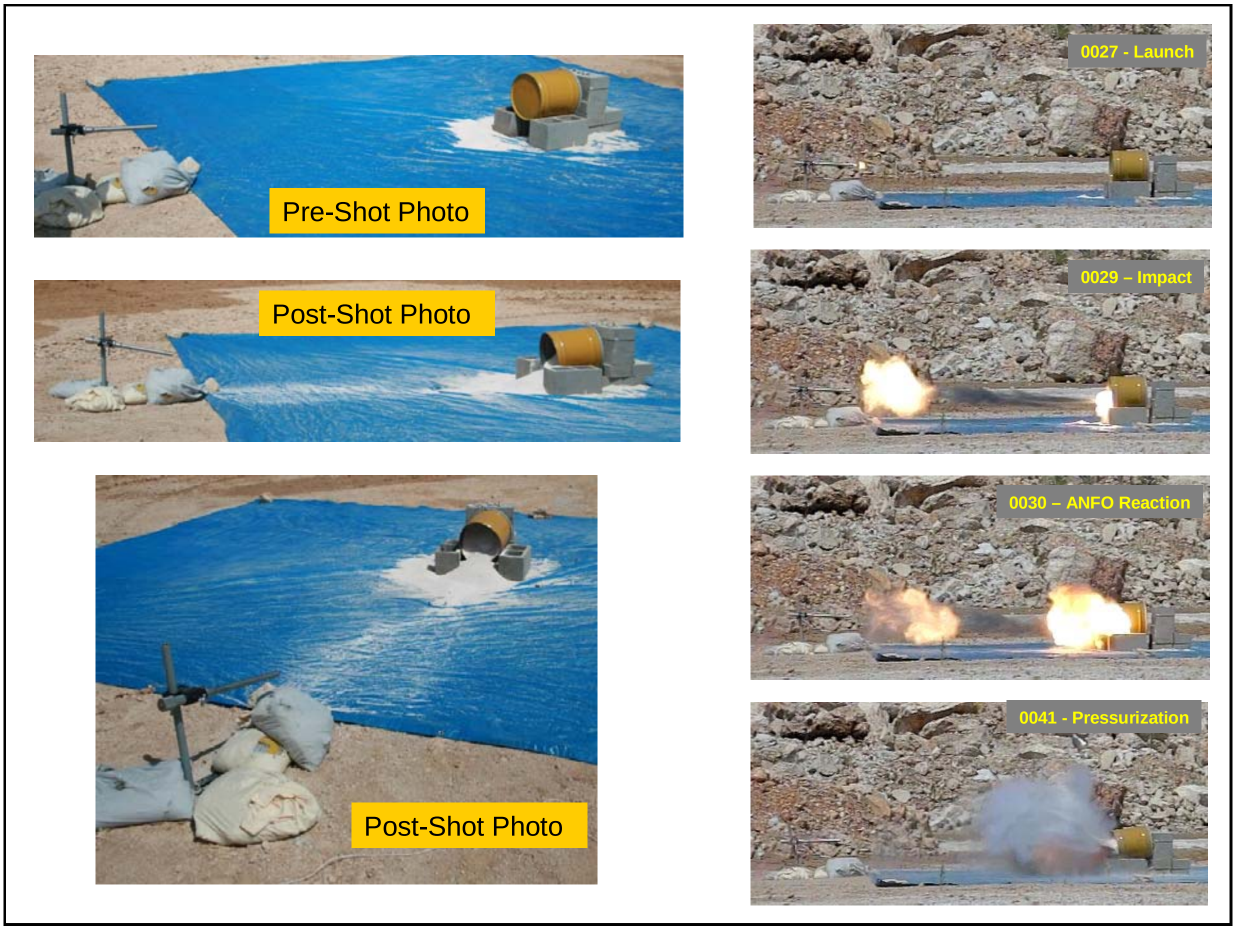

Figure 7.8. Results from FT9, against the face of a plastic drum containing 60 pounds of ANFO. The contents are exposed, but some ANFO remains in the target.

Finite difference calculations were run in order to clarify the difference between steel-walled and plastic-walled containers. The results of the calculations are included in Appendix B. The conclusion from the calculations was that the main difference between steel and plastic buckets is that when projectile 2 passes into steel buckets, there is a more violent expulsion of the RM payload laterally away from the nominal trajectory. Thus, a larger amount of ANFO is engaged, leading to a more violent reaction.

8 Conclusions

The findings and results from the nine-month feasibility study are summarized below:

- Fast-track static screening demonstrated that the APEX family of reactive materials are excellent candidates for safely neutralizing commercial-grade ANFO.
- Laboratory-scale dynamic testing demonstrated
  - Impact ignition thresholds for APEX RM ignition.
  - Upper limit of impact velocity to avoid possible detonation of ANFO.
  - Similar results can be obtained with smaller diameter projectiles.

- Initial field testing with 12 gauge PAN disruptor is very encouraging
  - Render safe with ANFO mass ranging from 40 lb to 110 lb.
  - Steel and plastic containers produced successful render-safe solutions.
- The feasibility study has taken concept to technology readiness level (TRL) 4/5 maturation.

The CONOPS study developed an operational response to VBIEDs based on use of projectiles containing reactive materials. A possible CONOPS for ANFO explosive would be as follows:

1) **Exposure—**The proposed neutralization technology requires visual access to the VBIED. The walls of the truck must be opened up. This might be accomplished using conventional robots. Another possibility (described in Appendix A) is a low-speed projectile containing a low-pressure explosive that would be fired into the vehicle. Reaction within the vehicle would remove the sides of the cargo compartment of the vehicle, revealing the contents to a line-of-sight PAN disruptor.

2) **Neutralization—**If the firing circuit is visible, the next step would be to attack the circuit with conventional PAN disruptor projectiles. But if the circuit is not visible, the next step will be to render safe each of the exposed containers of ANFO. This would be done by shooting each container with an RM-filled projectile. The outcome of the impact will either be massive spillage of ANFO from the container, or at the very least a large hole into the container. If any particular target drum is deemed still detonable, it could be struck a second or even a third time. In its final implementation, a family of RM projectiles would probably be available that is designed for different barrier penetration and different light-of-sight explosive depths.

9 Suggestions for Further Work

We believe that a logical continuation of the work completed so far would result in a prototype projectile that could be field-tested by government personnel. The additional required tasks would be driven by the requirements that were detailed in the reviewer's comments and are summarized below.

- Larger scale testing, using 55 gallon drums full of ANFO.
- Testing on multiple drums stacked together, working up to perhaps 18 drums in a 3 × 3 configuration, stacked two high.
- Determine the effects of the deflagration on circuit components.
- Testing on other explosives, starting with the least sensitive and working toward the most sensitive.
- Develop projectiles that are scaled for different barrier materials, such as truck cargo box walls, bags, or loose fill.

These requirements would then be translated into a set of tasks to accomplish the overall program goals as illustrated below.

1) Extension of the projectile design and investigation of additional reactive materials for different target sets, e.g., different containers and different explosives within the containers. It

may be necessary to have more than one 12 GA round to address different containers, such as steel or plastic, with very different wall thicknesses. In addition, it may be necessary to have different reactive materials with different activation energies and reaction kinetics.

2) Refinement of design and CONOPS through testing against targets that contain several drums of ANFO as well as a detonator/booster explosive train. Here, the goal would be to show definitively that activation of the firing circuit no longer leads to an explosion.

Among the deliverables in this next phase of the effort should be publication as an FBI Special Technicians Bulletin.

Further work should focus on neutralization of relatively insensitive (military grade) high explosives (IHE) as well as more sensitive homemade explosives (HME). In the case of IHE, the follow-on work can benefit from research currently being conducted by EMPI and the Joint IED Defeat Organization (JIEDDO).

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Acknowledgment

The research reported in this document was performed in connection with Grant #2007-DE-BX-K002 with the National Institute of Justice (NIJ). The views and conclusions contained in this document are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of NIJ or the US Government unless so designated by other authorized documents. Citation of manufacturers or trade names does not constitute an official endorsement or approval of the use thereof. The US Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation hereon.

Appendix A: The VBIED Threat, Proposed Technology Solution, and CONOPS

Table of Contents

The VBIED Threat, Proposed Technology Solution, and CONOPS

Dennis Wilson[1] and Stephan Bless[2]

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Abstract**—**This report summarizes: (1) the vehicle-borne improvised explosive device (VBIED) tactics used by terrorists; (2) the physical characteristics of the IED and VBIED threat; (3) the current policy and operational issues of the bomb squad and explosive ordnance disposal (EOD) community; (4) the current technology and industry providers; (5) our concept and a concept of operations (CONOPS); and (6) a brief summary of our research plan.

1 Introduction

As the name implies, vehicle borne improvised explosive devices (VBIEDs) use a vehicle as the package or container for the improvised explosive device (IED). The IEDs come in all shapes and sizes, which vary by the type of vehicles available, e.g. small sedans to large cargo trucks. The following statement from the Department of Homeland Security (DHS) Bulletin No: 021-03 on 14 November 2003 succinctly summarizes the threat posed by VBIEDs.

> "The use of VBIEDs allow terrorists to place large amounts of explosives against hard or soft targets with a high degree of mobility – in effect turning these VBIEDs into precision weapons that cause mass casualties and physical destruction. VBIED attacks require less coordination, planning, expertise, material, and money than the more spectacular type of terrorist methods, such as aircraft hijackings or employment of weapons of mass destruction, yet still can achieve the mass casualty objective." [1].

2 Tactics: Historical Background

According to the FBI Bomb Data Center [2], approximately 70 percent of all terrorist incidents worldwide involve the use of explosives and incendiary agents. The most prevalent form of explosive device used by terrorists today is the improvised explosive device (IED). IEDs are homemade, nonconventional explosive devices that are used to destroy, incapacitate, or harass. IEDs can be fabricated from either military or commercial grade explosives (through theft or purchase) or from explosives that have been manufactured by combining common chemicals. Terrorist incidents within the United States have been mostly limited to smaller IEDs, such as pipe bomb and briefcase size attacks. However, there are two incidents that demonstrated the potential destructive power of a vehicle-borne IED (VBIED). The relevant details are summarized below.

- **Murrah Federal Building in Oklahoma City, April 19, 1995:** Right-wing extremists Timothy McVeigh and Terry Nichols destroyed the Federal Building in

Oklahoma City with a massive truck bomb that killed 166 and injured hundreds more in what was up to then the largest terrorist attack on American soil.

- **World Trade Center Bombing, February 26, 1993:** The World Trade Center in New York City was badly damaged when a car bomb planted by Islamic terrorists exploded in an underground garage. The bomb left six people dead and 1,000 injured. The men carrying out the attack were followers of Umar Abd al-Rahman, an Egyptian cleric who preached in the New York City area.

In 1999, another incident was averted when alert customs agents searched al Qaeda terrorist Ahmed Ressam's explosives-laden truck as it rolled off a ferry from Canada. In addition to these domestic incidents, there have been numerous attacks against US assets abroad. A few of the more notable incidents are outlined below.

- **Bombing of US Embassy in Beirut, April 18, 1983:** Sixty-three people—including the CIA's Middle East director—were killed, and 120 were injured in a 400-pound suicide truck-bomb attack on the US Embassy in Beirut, Lebanon. Islamic Jihad claimed responsibility.
- **Bombing of Marine Barracks, Beirut, October 23, 1983:** Simultaneous suicide truck-bomb attacks were made on American and French compounds in Beirut, Lebanon. A 12,000-pound bomb destroyed the US compound, killing 242 Americans, while 58 French troops were killed when a 400-pound device destroyed a French base. Islamic Jihad claimed responsibility.
- **Khobar Towers Bombing, June 25, 1996:** A fuel truck carrying a bomb exploded outside the US military's Khobar Towers housing facility in Dhahran, killing 19 US military personnel and wounding 515 persons, including 240 US personnel. Several groups claimed responsibility for the attack.
- **US Embassy Bombings in East Africa, August 7, 1998:** A bomb exploded at the rear entrance of the US Embassy in Nairobi, Kenya, killing 12 US citizens, 32 Foreign Service Nationals (FSNs), and 247 Kenyan citizens. Approximately 5,000 Kenyans, six US citizens, and 13 FSNs were injured. The US Embassy building sustained extensive structural damage. Almost simultaneously, a bomb detonated outside the US Embassy in Dar es Salaam, Tanzania, killing seven FSNs and three Tanzanian citizens and injuring one US citizen and 76 Tanzanians. The explosion caused major structural damage to the US Embassy facility. The US government held Osama Bin Laden responsible.

These incidents and other similar attacks can be used as case studies to aid in developing a taxonomy of the operational and tactical issues associated with the VBIED threat. In addition to published reports, we have attended open and classified briefings and conducted interviews with experts in the IED defeat community in order to gain a understanding of the tactics and the physical characteristics of the IED and VBIED threat and the current capability of the Bomb Squad and EOD community to deal with the threat.

3 Physical Characteristics of the VBIED Threat

3.1 Lethality

The VBIED problem poses a much more serious threat than small-scale IEDs and a more challenging problem for domestic first responders. The major difference is the size of the device, which produces a much more extensive blast and fragmentation radius. Figure 1 (produced by the Bureau of Alcohol, Tobacco, and Firearms) illustrates the extent of the lethal blast radius for several different types of VBIEDs.

BATF Explosive Standards

ATF	Vehicle Description	Maximum Explosives Capacity	Lethal Air Blast Range	Minimum Evacuation Distance	Falling Glass Hazard
	Compact Sedan	500 pounds 227 Kilos (In Trunk)	100 Feet 30 Meters	1,500 Feet 457 Meters	1,250 Feet 381 Meters
	Full Size Sedan	1,000 Pounds 455 Kilos (In Trunk)	125 Feet 38 Meters	1,750 Feet 534 Meters	1,750 Feet 534 Meters
	Passenger Van or Cargo Van	4,000 Pounds 1,818 Kilos	200 Feet 61 Meters	2,750 Feet 838 Meters	2,750 Feet 838 Meters
	Small Box Van (14 Ft. box)	10,000 Pounds 4,545 Kilos	300 Feet 91 Meters	3,750 Feet 1,143 Meters	3,750 Feet 1,143 Meters
	Box Van or Water/Fuel Truck	30,000 Pounds 13,636 Kilos	450 Feet 137 Meters	6,500 Feet 1,982 Meters	6,500 Feet 1,982 Meters
	Semi-Trailer	60,000 Pounds 27,273 Kilos	600 Feet 183 Meters	7,000 Feet 2,134 Meters	7,000 Feet 2,134 Meters

Figure 1. Bureau of Alcohol, Tobacco, and Firearms chart estimating VBIED lethality.

The expanded lethality radius from the VBIED threat has resulted in a new set of operational requirements and the need for a significantly different technology to address this threat. Before discussing these issues, the next section lists the major classes of explosives that are likely to be used.

3.2 Major Classes of Explosives

Unlike IED and VBIED incidents in Iraq and Afghanistan, a domestic VBIED incident will most likely not employ military-grade high explosives (HE). Instead, the terrorists will most likely manufacture the explosive from precursors in a clandestine laboratory. These explosives can be produced from common products found in retail stores in virtually any town in the United States, or as the Pakistani Terrorist Training Manual states, "…from easily available substances anywhere on the market or anywhere across the globe." Based upon previous VBIED incidents and an understanding of the synthesis process for explosives, the following four classes of explosives emerge as the most likely threat, with ammonium nitrate fuel oil (ANFO) being the number one threat.

ANFO: Ammonium nitrate (AN), when combined with fuel or diesel oil (FO), becomes the explosive known as ammonium nitrate fuel oil (ANFO). Both ammonium nitrate and fuel oil are common chemicals in regular use around the world. Ammonium nitrate is a very common form of fertilizer used extensively in agriculture. Fuel oil is used as both a heating source and a fuel in farm tractors. In the 1950s, ANFO became a common explosive. It was a truckload of this explosive that Timothy McVeigh used to destroy the Murrah Federal Building in Oklahoma City in 1995. Although McVeigh used aviation fuel rather than fuel oil, the manufacturing process was the same. ANFO is well known to makers of home-brewed explosives, since it is much cheaper and less sensitive than dynamite. Recent governmental controls now require commercial fertilizer manufactures to add a treatment to the ammonium nitrate to make it more difficult to make explosives. These manufacturers apply a coating to the pellets (prills) of AN to make a product that will continue to work as a fertilizer yet be less soluble in fuel oil (or other fuels) and thereby inert as an explosive. However, the industry has yet to be fully successful, as the pellets can be pulverized. To pulverize and prepare the hardened prills of the fertilizer, bomb makers have used commercial coffee grinders, which are very effective for the process of grinding. Gristmills for the crushing of barley or wheat are also effective.

Powdered Ammonium Nitrate and Aluminum Powder: Ammonium nitrate can be procured in powdered form—one example is a common cold pack. These use ammonium nitrate in either prill or powder. If ammonium nitrate is in prill form, as in fertilizer, it is a simple task to grind it into a powder as described above. The aluminum powder can be procured at a professional paint store or simply filed from an ingot. The explosive has 75% of the power of TNT and is sensitive to friction, impact, or electrostatic discharge (ESD). It requires only a blasting cap for initiation. This mixture of readily available chemicals has been used in very large IEDs. In 1997, the equivalent of 500 pounds of TNT of ammonium nitrate damaged three apartment complex buildings in Moscow. The devastating effects from each of those devices resulted in over 100 casualties per incident [2].

Urea Nitrate: Urea nitrate is also considered a type of fertilizer-based explosive, although its two precursors are nitric acid (one of the ten most produced chemicals in the world) and urea. A common source of urea is the prill used for de-icing sidewalks. Urea can also be derived from concentrated urine. This is a common variation used by terrorists in South America and the Middle East. Often, sulfuric acid is added to assist with catalyzing the constituents. A bucket containing the urea is used surrounded by an ice bath. The ice serves in assisting with the chemical conversion when the nitric acid is added. The resulting explosive can be blasting-cap sensitive. Urea nitrate has a destructive power similar to ammonium nitrate.

Peroxide-Based IED: Peroxide-based explosives have been used in IEDs by international terrorists for some time and are an emerging threat domestically. The two most common examples are hexamethylenetriperoxidediamine (HMTD) and triacetonetriperoxide (TATP). They are both extremely sensitive and are used by terrorists as both an initiator (blasting cap) and as a main charge.

TATP is commonly found as the main charge being employed by Middle East terrorists in suicide bombings [2]. It can be easily manufactured by combining acetone (fingernail polish remover), hydrogen peroxide (hair bleach), and sulfuric acid (drain cleaner or battery acid). TATP has ~ 80% to 90% of the power of trinitrotoluene (TNT).

HMTD has between 60–116% of the power of TNT and is comprised of peroxide (ideally 30% or above), citric acid, and hexamethylenediamine (heat tabs).

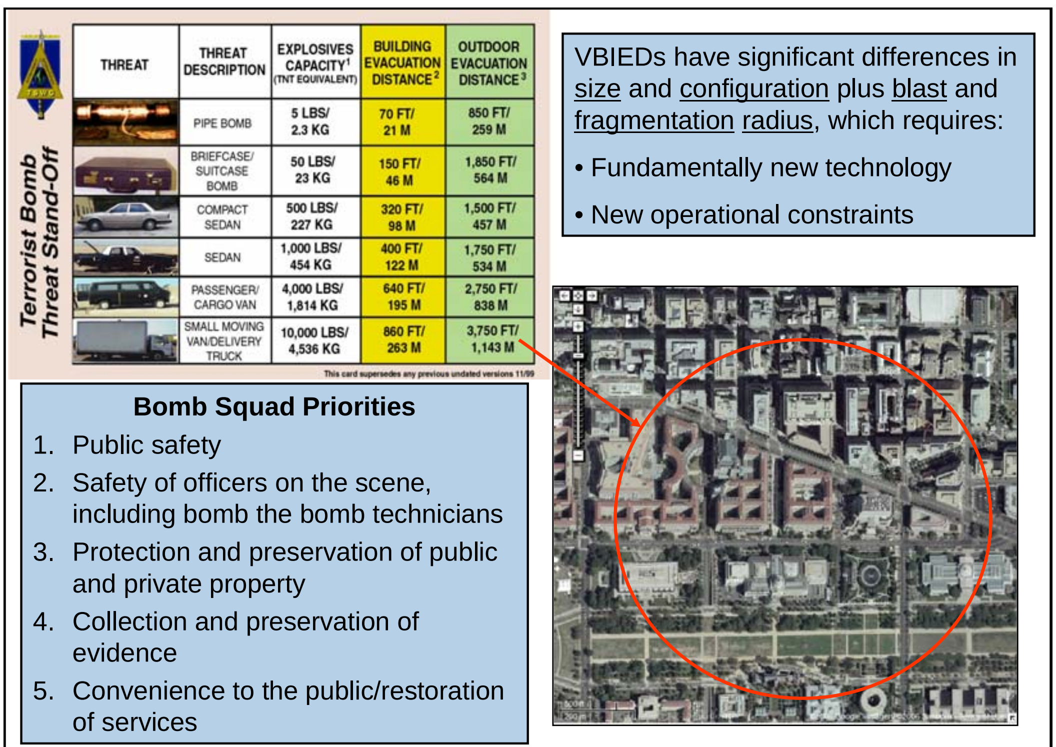
4 Policy and Operational Issues

According to a presentation by Jeff Fuller, Chairman, National Bomb Squad Commanders Advisory Board (NBSCAB) at the 8th Annual Technologies for Critical Incident Preparedness Conference and Exposition 2006 [3]:

- The (current) tools required for VBIED response produce more collateral damage than those used on general IEDs.
- Standard procedures need to be developed and approved in advance.

This presentation also summarized the adjustments in technology, specifically the need for (1) more powerful tools; and (2) tools capable of working at greater standoff distances. It also noted that adjustments in operations required (3) more urgent response and (4) fast attack procedures. Finally, the author stated that adjustments to current policies were needed.

In addition, the presentation addressed the need for new Bomb Squad priorities due to the increased lethality radius as summarized in Figure 2.



Terrorist Bomb Threat Stand-Off

THREAT	THREAT DESCRIPTION	EXPLOSIVES CAPACITY[1] (TNT EQUIVALENT)	BUILDING EVACUATION DISTANCE[2]	OUTDOOR EVACUATION DISTANCE[3]
	PIPE BOMB	5 LBS/ 2.3 KG	70 FT/ 21 M	850 FT/ 259 M
	BRIEFCASE/ SUITCASE BOMB	50 LBS/ 23 KG	150 FT/ 46 M	1,850 FT/ 564 M
	COMPACT SEDAN	500 LBS/ 227 KG	320 FT/ 98 M	1,500 FT/ 457 M
	SEDAN	1,000 LBS/ 454 KG	400 FT/ 122 M	1,750 FT/ 534 M
	PASSENGER/ CARGO VAN	4,000 LBS/ 1,814 KG	640 FT/ 195 M	2,750 FT/ 838 M
	SMALL MOVING VAN/DELIVERY TRUCK	10,000 LBS/ 4,536 KG	860 FT/ 263 M	3,750 FT/ 1,143 M

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Figure 1. VBIED Problems

Figure 2. VBIED problems.

In August 2007, one of the authors (Dr. Dennis Wilson) attended the International Association of Bomb Technicians & Investigators (IABTI) and met with: subject-matter experts (SMEs), program and policy experts, first responders (e.g., bomb squad and EOD personnel), investigators, and solution providers from over a dozen companies. These individuals included Sgt. Jim Hansen, Everett Johnson, Sidney Alford of Alford Technologies, and Jeff Wight of MREL. The following is a summary of the highlights from these meetings that are relevant to the VBIED problem and its solution. The comments made by these individuals have been paraphrased and as such should not be taken as actual quotes.

Comments by Jim Hansen, Vice-Chairman Equipment Subcommittee of NBSCAB

- The US has no unified policy to attack VBIED because it lacks a technology that can avoid large-scale collateral damage.
  - The EMPI/IAT reactive projectile-vented deflagration solution has the potential to overcome these issues.
- The UK has years of IRA car/truck bombs and has an aggressive policy to attack the VBIED.
  - The US public has not seen this level of attack and as such is not conditioned to accept these aggressive tactics.
- The explosive in a VBIED can be anything from ANFO (very insensitive) to TATP (very sensitive), but most likely the load in VBIED attacks will be ANFO or some commercial-grade HE or LE.

Comments by Everett Johnson

- The first responder community needs a low-collateral-damage solution.
- The solution should minimize time from command post (CP) to incident site—the system should be ready to go.
- We should get the Austin Bomb Squad (ABS) involved with our program.
  - We have had multiple meetings with the ABS to brief them on our solution and get their input.

5 Current Technology and Industry Providers

5.1 Current Technology

Based upon discussions with SMEs and a survey of the current technologies, the following conclusions can be drawn.

- In general, the current policy/tactic is to attack the detonator train, which may be a timing power unit (TPU) or simply a switch that connects the vehicle battery to the detonator.

    - Approximately 90% of VBIED have a control element or switch in the cab or driver's area.
    - These solutions use overpressure or physical disruption in order to neutralize the threat, i.e., "render safe."

- The industry standard is to use water and water-based slurries as the preferred disruption medium to attack IEDs and VBIEDs. These can be grouped into the following categories:

1. Small, precision/directed energy tools, e.g., the percussion-actuated nonelectric (PAN) disruptor.
    - The PAN disrupter is a success story, but it is limited to small IEDs.
    - The PAN disruptor uses a propellant to accelerate water or a variety of slugs to disrupt the TPU.
    - Our technology will utilize the existing PAN disruptor tool by providing a new reactive round to deflagrate large ANFO or HE loads.
2. Large, VBIED tools, e.g., explosive launch of 1–55-gallon containers of water.
    - These solutions are designed to disrupt and scatter the contents.
    - Velocities of 500 m/s to 1500 m/s at close (tens of centimeters) range.
    - The Romanian Intelligence & Anti-terrorist Brigade is developing a missile with a 50-m range that carries tens of kilograms of water toward the VBIED.

The second category, large disruption tools, can be further refined into two subgroups. This produces the following three categories for water-based disruption tools.

1. Surgical disruption, e.g., focused and directional effects to attack the TPU or smaller car-trunk bombs.
2. Overpressure, e.g., attack the TPU with the addition of a water-based slurry containing abrasive.
3. Expulsion, e.g., large-scale, explosively launched water or similar medium shots to attack the main charge.

Figure 3 contains additional details and photographs of the "surgical" disruption tools that are available to the users.

Similarly, Figures 4 and 5 contain photographs and additional details on overpressure and expulsion tools.

Focused / Directional Devices

- **Geometry 1:** Small, surgical strike gun system for “suitcase” IEDs, e.g., PAN disruptor.
- **Geometry 2:** Large, explosively launched system for VBIED targets, e.g., modular large vehicle disruptor (MLVD).

PAN Disruptor Kit

Ideal Products

MLVD

Alford Technologies

Figure 3. IED and VBIED tools.

Omni-directional, Overpressure Devices: Inserted into the vehicle cab to attack the TPU

- **Geometry**: Typically a center core explosive with water-based “slurry” of abrasives, e.g., dolomite or large gravel to cut wires and disrupt TPU
- **Examples:** Rapid Access Neutralization Tool (RANT) and Rapid Access & Disruption Equipment (RADE)

RANT being positioned by robot inside car

Post-detonation of car

Figure 4. More IED and VBIED tools.

3. Expulsion, Massive Disruption Systems: Attacks the main explosive charge
   - **Geometry:** 55 gal water drum with 9 lb center charge explosive
     - Examples: Large Vehicle Bomb Disruption System (LVBDS)
     - High Energy Access Disruption (HEAD)

Major Disadvantages
- Time from CP to incident site is too long
- Collateral damage is unacceptable
- Logistic train is complex
- Destroys forensic evidence

Figure 5. More IED and VBIED tools.

5.2 Industry Providers

We have conducted a survey of the technology solutions provided by the industry and have drawn the following conclusions.

- Most companies provide low-tech solutions
  - The solutions are mostly water based disruption tools
  - There is very little differentiation between companies
- The high-tech leaders appear to be
  - Alford Technologies, a UK-based company specializing in explosive applications, for EOD, breaching and explosives engineering.
  - MREL, a Canadian company providing explosives, blasting expertise, and products to the blasting, defense, and EOD communities.
  - Raytheon, Northup Grumman, and SAIC are new high-tech entrants.
- In general, the current policy/tactic is to attack timing power unit (TPU)
  - Approximately 90% of TPUs are in the front seat of a car or cab of a truck.
  - These solutions use overpressure or physical disruption in order to neutralize the threat, i.e., render safe.

The next section briefly outlines our concept of operations and describes our innovative approach to providing a reactive round that can be fired from a conventional PAN disruptor to neutralize or render safe a large container, e.g., a 55-gallon drum, of ANFO or similar insensitive explosive.

6 CONOPS

6.1 Current Path

A high-priority goal within the anti-terrorism community is to develop a comprehensive policy, operational doctrine, and effective tools to deal with the VBIED threat. In other words, a CONOPS built around existing, commercial off-the-shelf (COTS) tools. Unfortunately, the existing disruption tools are not well suited to deal with the VBIED threat. In particular, their energy output can cause more collateral damage than is acceptable. According to a science and technology (S&T) stakeholder's conference sponsored by DHS in May 2007, one path forward is to:

> "Determine the impulse characteristics of the suite of disruption charges used to kinetically penetrate, access, and disrupt IEDs and VBIEDs and develop an electronic tool characterization guide for use in scenarios involving IEDs and VBIEDs to aid EOD and bomb technicians in the tactical decision making process for disabling the threat device."

It is our opinion that current water-based disruption tools are ineffective devices for opening and exposing the contents of a typical cargo truck or van and may cause an inadvertent detonation of the contents from the blast effects associated with using high impulse from explosively driven water systems. The photographs in Figure 6 show the aftermath of a trial using a modular large vehicle disruptor (MLVD) device.

Figure 6. MLVD device test.

An alternate approach, and the one we believe will yield the best solution, is to develop a new set of *precision tools* that are capable of rendering safe the contents inside a suspected or confirmed VBIED. The system is described below.

6.2 Proposed Concept of Operations

It is assumed that the vehicle is under surveillance, so close approach by bomb squad technicians is inadvisable. It is furthermore assumed that the terrorist has taken a few simple measures to defeat EOD attempts: the vehicle is securely locked and the TPU protected by barriers so that even if the vehicle is opened, visual access is not possible.

The proposed CONOPS is composed of two steps:

1. Uncover.
2. Neutralization.

The function of the first step is to open up line-of-sight access to the containers of explosives. The second step is to sequentially render safe the containers by controlled deflagration of their contents.

6.3 Exposure Tool

We have developed a conceptual design for an exposure tool that would rapidly (in tens of milliseconds) open the sides and top of a panel truck without initiating the main charge using a special thermobaric (TBX) type composition to create modest pressure (a few psi) to expose the contents without detonating the explosive. The concept involves using a newly developed modified explosive composition that can be tailored to produce a sustained overpressure sufficient to open the sides and top of a panel truck.

EMPI has developed these modified explosive compositions for enhanced blast effects in urban combat operations where *low collateral* effects are required. These enhanced blast explosives (EBX) compositions can and have been engineered to deliver different pressure and temperature outputs by varying the precursors. Figure 7 describes the overall exposure tool concept.

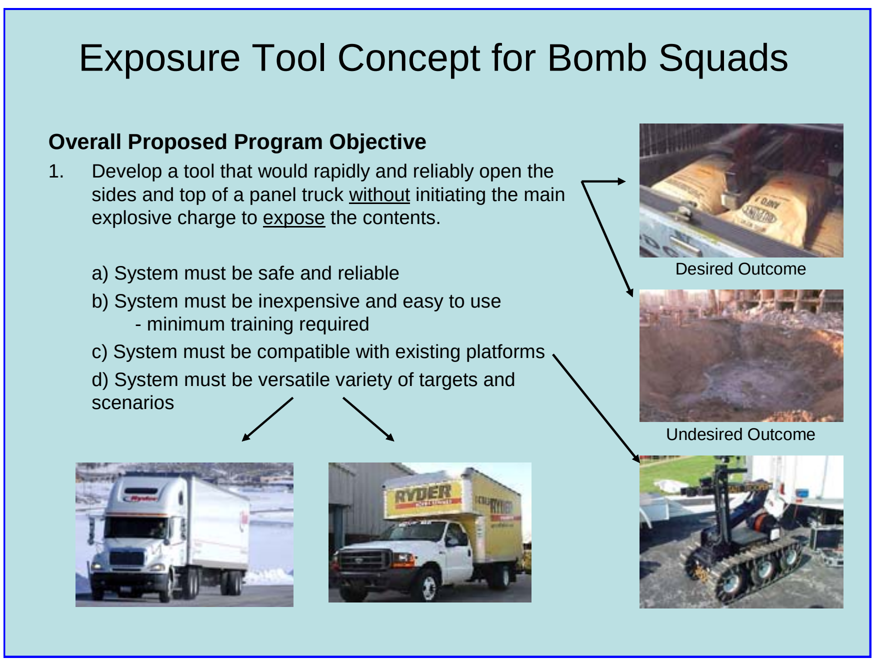

Figure 7. Exposure tool concept.

The concept involves launching a modified explosive charge through the sidewall of a panel truck to produce a sustained and controllable overpressure. EMPI has recently demonstrated the ability to control the pressure output by using multipoint initiation in an Air Force Dial-a-Yield program. The launching system could be a line rocket, rocket-propelled grenade (RPG) type device or other suitable platform. The features and advantages of this concept are listed below.

- System will minimize collateral effects by precision coupling of the energy (pressure output) to target.
- System will have a variable (Dial-A-Yield) energy output that can be selected at the incident site for different targets.
    - Only a single explosive charge is required; thus, the system reduces the EOD or bomb squad logistics train.
- EMPI has made progress in understanding the fundamental physics in the:
    - Lockheed Martin sponsored enhanced blast explosive program.
    - Air Force Research Laboratory (AFRL) Dial-A-Yield program.

Figure 8 illustrates the variety of pressure outputs that are available from these modified explosive charges. The feature that is most notable is that they do not have the initial high peak pressure exhibited by conventional explosives, such as TNT or cyclotetramethylene-tetranitramine (HMX).

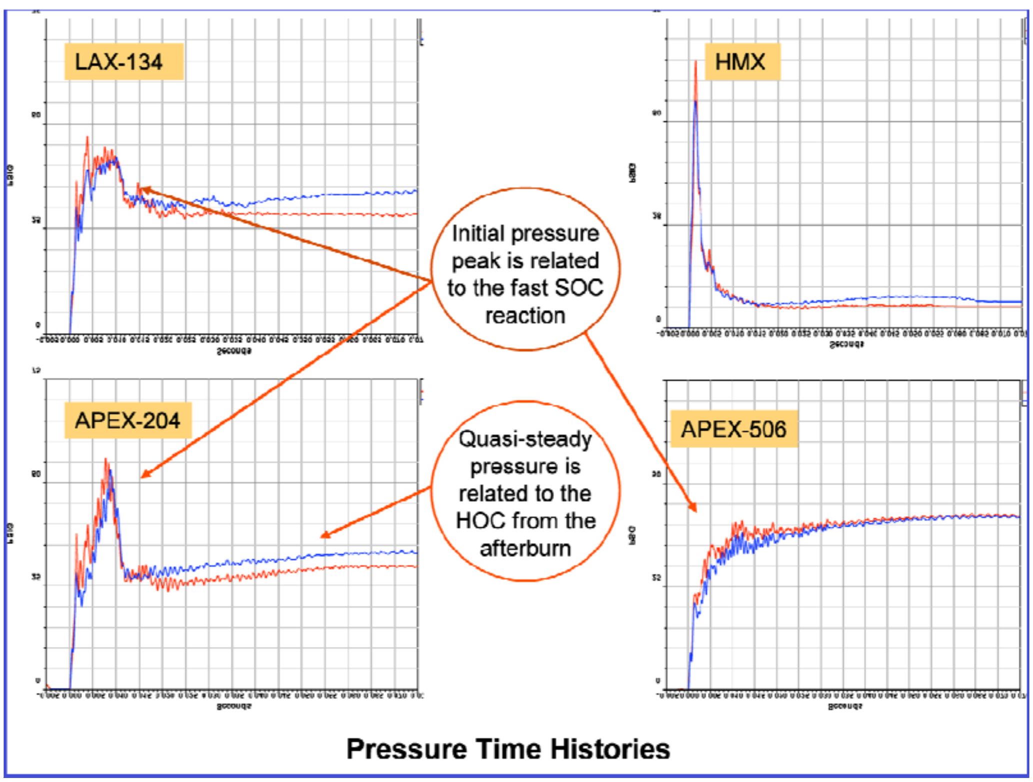

Figure 8. Variable pressure output from modified explosives. Initial pressure peak is related to fast, self-oxidized combustion (SOC); quasi-steady pressure is related to heat of combustion (HOC) from the afterburn.

We have made some preliminary calculations to determine the amount of modified explosive that would be necessary to open the sides of a panel truck based upon the simple equation below that relates the peak overpressure to the energy density of the modified explosive and the volume of the truck:

$$V_{\mathrm{T}} \Delta P = (\gamma - 1) \Delta E$$

Using a volume of 50 m^3 and an energy density of 34 kJ/cm^3 we find that a mass of approximately 460 g (1 lb) would create an overpressure of 5 psig. Furthermore, since the pressure output is a relatively slow, nearly monotonic increase, it is likely that the contents would not be disturbed but merely exposed.

In addition, Figure 9 illustrates that ability to control the output in real time through different initiation mechanisms, thus giving the bomb squad the ability to tailor the output for different size trucks.

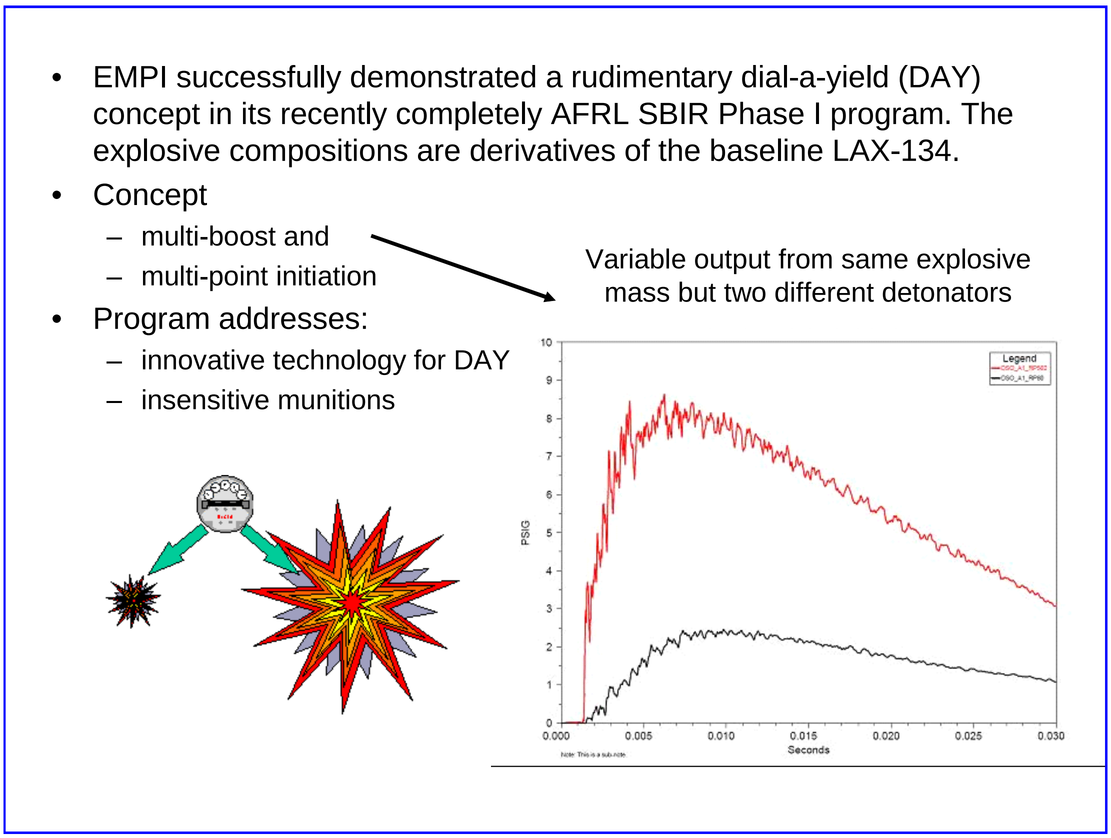

Figure 9. Variable pressure output.

It is also possible that a suitable backscatter x-ray imaging system could be used to identify the precise location of the drums within a panel truck. Once located, the drums could be targeted and a reactive round could be fired through the thin panel truck wall. This would, however, require the development of a frangible nose on the current design that would absorb the impact shock from the wall of the panel truck without causing a premature initiation of the reactive material in the round.

6.4 Explosive Neutralization

It is proposed to develop a family of projectiles for a robot-mounted PAN launcher. Each projectile is designed to penetrate a given barrier before releasing its RM payload. The shooting would start with the lowest-level penetrator, which is the subject of the current program. This penetrator activates its RM payload after passing through a 1/16-inch mild steel barrier and entering into a medium of specific gravity 0.8 or greater.

The action of the RM projectile causes a significant quantity of ANFO to rapidly deflagrate. The confined deflagration produces sufficient overpressure to split the container and release the contents. Spilled ANFO is then neutralized with a fire hose.

6.5 Proposed Plan

- Program Goal: **Neutralization of typical explosives in domestic VBIED scenarios by vented deflagration.**
- **Neutralization Method:** Projectile carrying a specialized reactive material (RM) fired into explosive.
    - Ballistic impact initiates RM, which subsequently produces a controlled self-propagating reaction, e.g., deflagration.
- Platform: **Develop a projectile compatible with common bomb-squad equipment, specifically the 12-gauge PAN disruptor.**
- **Test Plan:**
    - Static tests of RM against ANFO initiated by a detonator to simulate ballistic impact added to program to demonstrate proof of concept.
    - Dynamic tests of RM against ANFO
        1. Small-scale laboratory tests with diagnostics.
        2. Large scale—55 gal drum of ANFO.
- **Status:**
    - Static tests against ANFO have demonstrated successful render-safe solution, as shown in Figure 10.
    - Our concept has received favorable feedback from this community, and the consensus is that this technology can meet the current and evolving IED/VBIED threat.