# ENERGETIC RESIDUES FROM THE DETONATION OF COMMON US ORDNANCE

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*Munitions containing high explosives are used on military ranges during training. The detonation of these munitions leaves varying amounts of energetic residues on the ranges. Measuring individual detonation residues has been difficult because of the danger from unexploded ordnance on active ranges, the presence of energetics from past activities, and difficulties processing and analyzing soils containing minute quantities of explosives. A method has been developed whereby it is possible to measure energetic residues from the detonation of individual rounds. Two types of ranges have been used: snow-covered ranges underlain by frozen soil or ice. Both present a pristine sampling surface with a simple sampling matrix: snow. Using multi-increment sampling methods, we tested 11 types of munitions and looked at four scenarios: high- and low-order live-fire detonations, blow-in-place detonations, and the effect of a high-order detonation on a close-proximity unexploded ordnance item. Explosives residues deposition rates varied from $10^{-6}$% for high-order detonations to over 50% for close-proximity detonations resulting in partial detonation of the ordnance item. Implications for the range management community include groundwater contamination, security risks from unsecured high explosives, and environmental degradation leading to eventual loss of the range facilities.*

**KEY WORDS:** *explosives, residues, deposition rates, military munitions, detonations, energetic residues from the detonation of common US ordnance*

## 1. INTRODUCTION

Members of armed services worldwide need to train with live munitions to maintain combat proficiency. Training with these munitions requires the use of energetic materials, either as propellants, explosives loads, markers, or burster charges. In some cases, ranges have been closed or activities curtailed because of contamination from these munitions compounds (Clausen *et al.*, 2009; Racine *et al.*, 1992). To avoid closures, range managers need to know what the impact is from the use of live ordnance. Testing in the field is problematic because of the presence of residues from past range activities. Residues are distributed heterogeneously as nonuniform particles, and concentrations can be very low, leading to difficulties in obtaining representative samples (Pitard, 1993; Jenkins *et al.*, 1999; Walsh, M.E., *et al.*, 2001; Jenkins *et al.*, 2006). Unexploded ordnance (UXO) presents an obvious obstacle to almost any activity on impact ranges. An alternative method for characterizing detonations, the use of detonation chambers, is difficult, expensive, does not represent the environmental conditions in which the ordnance is used, and the results are not very reproducible (Ampleman *et al.*, 2008; Larson *et al.*, 2009).

Rounds that contain explosives can only be fired into specific impact ranges. These ranges are limited in number and thus heavily used. The soils on these ranges contain measureable amounts of energetic materials that will be difficult to separate from test activities that may result in very low concentrations of analyte. Using conventional sampling techniques, sampling error, typically the greatest source of error when characterizing an area for contaminants, becomes untenable (Rasemann, 2000). Over the past 10 years, the US Army Cold Regions Research and Engineering Laboratory (CRREL) has developed methods for obtaining deposition data for live-fire and other detonating events (Collins *et al.*, 1995; Jenkins *et al.*, 2002; Walsh, M.R. *et al.*, 2005a; Walsh, M.R. *et al.*, 2007). Snow is used as the collection medium, and on ranges covered in seasonal ice, access to detonations is possible because of the stabilization of and separation from the UXO by the ice cover. The collection medium, snow, is clean and consists only of water, which makes sampling and sample processing and analyses much easier and reduces the dilution experienced with soil samples.

This paper will present the results of research into the deposition of high explosives on military training ranges. Operations described include live-fire high- and low-order detonations, single-round blow-in-place operations (BIP), the effect on unexploded ordnance from the detonation of a close-proximity high-explosive munition, and detonation of demolitions munitions. This work follows that of Jenkins *et al.* (2002) and Hewitt *et al.* (2005), implementing new sampling and quality assurance techniques for improved reproducibility of results. Some considerations of the presence of high explosives on ranges will be discussed.

## 2. EXPERIMENTAL

CRREL researchers have developed a munitions testing method that utilizes the segregating properties of snow and ice (Jenkins *et al.*, 2002; Walsh, M.R. *et al.*, In press). A clean layer of ice or snow over an impact area can separate past activities from current, isolating previous contamination and presenting an essentially clean environment in which tests can be conducted. On snow-covered ranges, with a thick (>60 cm) layer of snow compacted to add strength, several weapon systems can be tested, including smaller caliber and direct-fire armaments to some BIP operations. For tests that involve large detonations, such as live-fire and larger-caliber BIP operations, a thick (>30 cm) layer of ice is required to prevent the exposure of soils and contaminants from past activities. Added benefits to sampling on snow surfaces include an easily defined contamination plume; easily conducted quality assurance procedures, including sampling outside the defined plume (OTP) to confirm the plume demarcation and sampling beneath previously sampled points to ensure correct depth of sampling; having only water (snow) and not soils to process; minimizing dilution from the sampling matrix; and, most importantly, being able to conduct replicate sampling (Walsh *et al.,* In press). Problems associated with the subsampling of soils are also avoided (Walsh, M.E., *et al.*, 2007).

Working with Charles Ramsey of Envirostat (Fort Collins, CO), we have adapted Multi-Increment® (MI) sampling to the collection of samples containing explosive residues. The MI sampling protocol calls for the collection of many increments from throughout a demarcated area that are combined and processed as a single sample to characterize that area. The result is a mean mass or concentration of the analyte for the unit area. Prior studies relied on a single "discrete" sample or an average of a few discrete samples to determine the quantity of analyte in a given area. When this protocol was used, concentrations differed by several orders of magnitude between samples that were less than 1 m apart (Walsh, M.R. *et al.*, 2005a). Spatial heterogeneity, one of the greatest contributors to sampling uncertainty as well as overall error for characterization of a site, can be greatly reduced through the MI sampling method (Hewitt *et al.*, 2009). Replicate sampling is a check on the success or failure of the methods' ability to overcome this error.

There was a concern when we adopted MI sampling that the concentration of analyte would be diluted by collecting increments in areas that appeared to have low concentrations of residues. We conducted a study on snow to determine the difference between composited discrete sampling and MI sampling and found that the mean value of the composited discrete samples typically underreports results compared to MI sampling (Walsh, M.R. *et al.*, 2005a). This was a surprising finding, as discrete sampling typically occurred within the darkest residues rather than representatively sampling the entire plume (Fig. 1).

**FIG. 1:** Discrete samples being taken from a highly loaded segment of a detonation plume

## 2.1 Tests Conducted

Explosive residue tests were conducted on a suite of common high-explosive (HE) military munitions. Four series of deposition rate tests were conducted and one site characterization was performed. The objective of the deposition rate tests was to determine a per-round deposition rate for the HE compounds contained within the subject munitions for various activities. These activities included high-order (HO) detonations, low-order (LO) detonations, BIP operations, and close-proximity detonation effects on UXO. Parallel with the demolitions study, we conducted deposition studies of unconfined donor charges (C4 blocks), Bangalore torpedoes, and an 18-kg (40-lb) shape charge. The objective of the characterization study was to derive an estimate of HE mass for a low-order detonation site on an active range. Table 1 contains a list of munitions tested over the course of this research.

**TABLE 1:** Munitions tested

| Weapon system | Munition tested[1] |
|---|---|
| Mortars | |
| 60 mm | M888 |
| 81 mm | M374 |
| 120 mm | M933 |
| Howitzers | |
| 105 mm | M1 |
| 155 mm | M107 |
| Rockets | |
| 227 mm | M31 |
| Demolitions munitions | |
| Bangalore torpedo | M1A2 |
| Shaped charge | M3A1 |
| Demolition block | M112 |

[1]US military designation.

## 2.2 Test Procedures

The following subsections describe in general terms how each category of test was set up. Sampling, sample processing, and sample analysis procedures are described in other publications and will not be covered here (Jenkins *et al.*, 2002; Walsh, M.R. *et al.*, 2005a, 2007; Hewitt *et al.*, 2005, 2009; Walsh, M.E. *et al.*, 2007). All tests described in this paper were conducted at either the Eagle River Flats impact range (ERF) or the

Demolitions Training Range III (Demo III) on Fort Richardson, AK; the Washington Range at the Donnelly Training Area (DTA) near Fort Greely, AK; at Fort Drum, NY; or at the Camp Ethan Allen Firing Range (EAFR) in VT. Most tests were conducted in winter, generally in February or March when the amount of snow and ice is thickest and the days are long enough to provide sufficient light to complete most tests. For the low-order test, we conducted the sampling during summer months.

*2.2.1 High-Order Detonation Tests*

High-order detonations occur when a round fully functions as designed. We define a high-order detonation as the consumption of a minimum of 99.99% of the explosive load during detonation, although we have yet to find a standard definition in the literature. The reason for this is likely because deposition tests for energetics have not been successfully carried out before this research was conducted. For our tests, all rounds were either fired onto ice at ERF or onto the frozen riverbed at a newly opened section of the Washington Range at DTA. Point-detonating super-quick fuzes were used on all ordnance to minimize penetration of the round on impact. The goal was to fire at least seven rounds of a specific type of HE ordnance into the area, separating the impact points such that each detonation created a distinct plume. This was not always accomplished, as the weapon systems tested were indirect fire and placement of the rounds is difficult, especially with the smaller mortar ordnance, the trajectory of which is subject to atmospheric influence. Rounds were fired into areas where no activity had been reported for that winter to minimize exposure to UXO and contamination. The ice protected us from existing UXO from prewinter activities. In areas of thick ice, roads were plowed to the test areas to facilitate access. Snowmobiles with sleds were utilized for access to individual test areas. Following the cessation of firing, a UXO technician preceded us to the site to sweep for unexploded ordnance.

*2.2.2 Blow-in-Place Tests*

All blow-in-place tests were conducted on the ice-covered ERF impact area. After checking ice thickness and sweeping for UXO with a magnetometer, over-ice access roads were plowed to areas where no activity had occurred that winter. Detonation points were then set up with the use of range finders, with separation between detonation points approximated to not have interfering plumes (≈50–100 m). For larger ordnance items, blocks of ice 50- to 60-cm thick were cut from a nearby freshwater lake and used as standoffs between the ice surface and the ordnance item to reduce the amount of blast and fragmentation penetration of the ice cover (Fig. 2). A minimum of seven rounds was used in each test to enable the use of statistical analysis for the results. All rounds were initiated using an M112 demolition block and detonated remotely at once. The test area was cleared by a UXO technician prior to accessing the detonation sites.

**FIG. 2:** BIP setup for a fuzed large ordnance item. Donor block is placed on nose.

*2.2.3 Low-Order Detonations*

Deposition rate studies and UXO studies conducted by CRREL indicated that the two actions that will result in the largest mass of energetics on a range are low-order detonations and breaching of rounds from close-proximity detonations to UXO. We define a low-order detonation as one in which a round detonates, fragmenting most of the projectile body, but does not consume the full explosive load, leaving up to 25% behind. The low-order detonation of several rounds was observed during a firing exercise of 120-mm HE mortar cartridges on ERF. At the time, we were not scheduled for range access and could not sample the impact points. The following summer, we relocated the impact points for several of the rounds and did a site characterization by taking MI soil samples to roughly determine the amount of HE resulting from the LO detonations. These are the only results reported in this article that were not derived from snow surface sampling. This site has been monitored since then as part of a separate fate and transport study of HE (Walsh, M.E. *et al.*, 2010).

*2.2.4 Close-Proximity Detonations*

Close-proximity detonation tests were conducted on a demolitions training range (Demo III) at Fort Richardson using 81-mm mortar projectiles. A detonating device that screws into the fuze well was designed and successfully tested, allowing us to simulate a high-order-detonating incoming round. The detonating round was placed either vertically or horizontally on the snow with up to five projectiles simulating UXO placed at fixed distances and orientations to the detonating round (Fig. 3). The UXO had plugs in the fuze wells in place of live fuzes to confine the explosive filler and to reduce the chance of post-test detonation during sampling. Following each test, the area was cleared by military explosive ordnance disposal (EOD) specialists and a UXO technician.

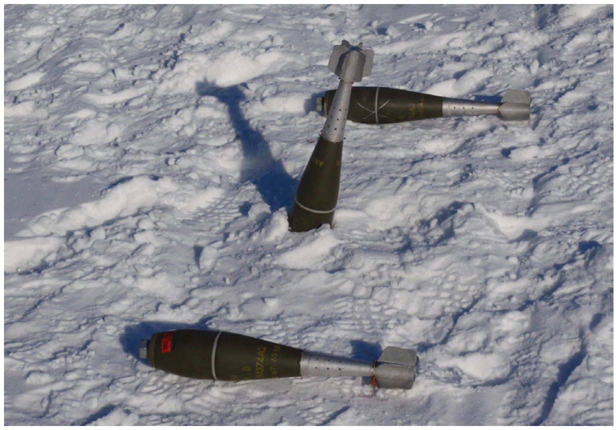

**FIG. 3:** Close-proximity detonation test setup. The center round will detonate, simulating a functioning round. Horizontal rounds simulate unexploded ordnance.

*2.2.5 Demolitions Range Characterization*

Previous research indicated that unconfined and lightly confined explosives and ordnance have a lower efficiency of detonation than ordnance with confined explosive loads such as mortar and howitzer projectiles. Large amounts of these less efficient ordnance items are consumed at engineering demolitions training ranges. To verify this observation, several demolitions items were detonated on snow or snow-covered ice to obtain an estimate of residues. The demolitions training range at Fort Richardson (Demo III) was also characterized to get an indication of the cumulative effect of the use of this type of facility. In both cases, we were accompanied by a UXO technician to ensure the safety of the operation.

## 3. RESULTS

For most tests, we obtained both plume size data as well as residues mass data. Plume size is a function not only of the round but the climatic conditions at the time of testing. Wind speed affects the residue distribution, so testing occurred when winds were the calmest. However, the detonation particles are for the most part so fine that even the slightest breeze will enlarge the plume. Precipitation also has an effect, with snow (or rain) reducing the dispersion of the residues as well as making plume delineation and sampling more difficult. None of our tests occurred during precipitation events. Deposition results are given in energetic analyte mass per round and are a total of the estimates for the demarcated plume and, when necessary, the estimated OTP and subsurface masses. Results for our tests are given below by activity.

### 3.1 High-Order Detonations

High-order detonation plumes for seven types of ordnance from six weapon systems ranging from 60-mm mortars to 230-mm rockets were tested for explosive residues. Table 2 contains the results for these tests. Results in this and following deposition rate tables are given as the mass of analyte in the detonation residue per round as well as the mass of analyte in the residue compared to the original total mass of the analyte in the rounds prior to detonation (percent of the original analyte remaining in the residue). For tests performed on mortar and artillery ordnance, averages are given over all the ordnance types. All results are given to two significant digits. Larger howitzer and mortar ordnance items tend to have thicker-walled projectile bodies. These munitions are designed to generate a high-pressure shock wave along with fragmentation particles (frag). The smaller mortar and rocket warheads are designed for localized small frag generation. The rocket warhead is tri-functional, designed for anti-personnel effects (frag), fortified structure destruction (blast), and light armor destruction (blast and frag). ND indicates non-detectable concentrations of analyte in the sample. Table 3 contains the field sampling QA results for these tests. Note that if 0.01% or less of the energetics remain after detonation, the activity is considered a high-order event (>99.99% efficient).

**TABLE 2:** High-order residue deposition rates for some standard weapon system ordnance (Walsh, 2007)

| Weapon system | Munition tested[1] | Number tested | Energetic material | Energetic compound | Mass[2] per round (g) | Residue[3] per round (mg:%) | |
|---|---|---|---|---|---|---|---|
| Mortars | | | | | | | |
| 60 mm | M888 | 7 | Comp B | RDX / HMX | 230 | 0.073 | $3.2\times10^{-5}$ |
| 81 mm | M374 | 14 | Comp B | RDX / HMX | 600 | 8.5 | $1.4\times10^{-3}$ |
| 120 mm | M933 | 8 | Comp B | RDX / HMX | 1800 | 19 | $1.1\times10^{-3}$ |
| Average | | | | | | | $8.3\times10^{-4}$ |
| Howitzers | | | | | | | |
| 105 mm | M1 | 13 | Comp B | RDX / HMX | 1300 | 0.095 | $7.3\times10^{-6}$ |
| 155 mm | M107 | 7 | Comp B | RDX / HMX | 4200 | 0.30 | $7.1\times10^{-6}$ |
| | M107 | 7 | TNT | TNT | 6600 | -ND- | — |
| Average | | | | | | | $7.2\times10^{-6}$ |
| Rockets | | | | | | | |
| 227 mm | M31 | 6 | PETN-109 | RDX | 15000 | -ND- | — |

[1]US military designation. [2]Initial mass of energetic compound in round. [3]Estimate of initial energetic compound remaining after detonation.

Table 4 contains the data for the residue areas generated by the detonation of the ordnance items. As described in the methods section, these areas are heavily influenced by weather conditions, especially winds. We attempted to test only when winds were at a minimum, but as most of these tests occurred during training exercises, we could not halt training to wait for the preferred test conditions. OTP measurements were not taken for some of these tests as the QA and sampling protocols were under development during this phase of the research.

**TABLE 3:** Field sample QA results for live-fire high-order detonations

| Weapon | Munition tested[1] | Number tested | Number of OTPs | Percent residues in OTPs | Number of subsurface samples[2] | Percent residues in subsurface samples |
|---|---|---|---|---|---|---|
| Mortars | | | | | | |
| 60 mm | M888 | 7 | 7 | BDL[3] | 1 | BDL[3] |
| 120 mm | M933 | 8 | 2 | 15% | — | — |
| Howitzers | | | | | | |
| 155 mm | M107 (TNT) | 7 | 7 | BDL | — | — |
| | M107 (Comp B) | 7 | 7 | BDL | — | — |

[1]US Military designation. [2]Samples were taken below locations where sample increments were previously taken. [3]BDL: Below detection limits. For 155-mm Comp B OTPs, TNT at detection limits was found in three samples but not in all the replicates.

**TABLE 4:** High-order detonation residue plume areas

| Weapon | Munition tested[1] | Number tested | Plume area[2] ($m^2$) | OTP area[3] ($m^2$) | Reference |
|---|---|---|---|---|---|
| Mortars | | | | | |
| 60 mm | M888 | 7 | 214 | 193 | Walsh *et al.*, 2006 |
| 81 mm | M374 | 14 | 230 | — | Hewitt *et al.*, 2003 |
| 120 mm | M933 | 8 | 450 | 350 | Walsh *et al.*, 2005c |
| Howitzers | | | | | |
| 105 mm | M1 | 13 | 530 | — | Hewitt *et al.*, 2003 |
| 155 mm | M107 (TNT) | 7 | 757 | 390 | Walsh *et al.*, 2005b |
| | M107 (Comp B) | 7 | 938 | 450 | Walsh *et al.*, 2005b |
| Rockets | | | | | |
| 227 mm | M31 | 6 | — | — | — |

[1]US military designation. [2]Main area of residue deposition (detonation plume). [3]Annular area outside the detonation plume.

### 3.2 Blow-in-Place Detonations

Blow-in-place detonations reported here were conducted specifically for this study. Projectiles up to 105 mm were detonated on the ice surface. The 120-mm and 155-mm rounds were placed on ice blocks prior to detonation. Seven of each munition were detonated for these tests. Table 5 contains the results for six types of ordnance used by five different weapon systems. As with high-order detonations, the thicker casing of the projectile bodies of the larger ordnance results in more efficient consumption of the HE filler. The energetic mass per round differs from those in Table 2 because of the addition of the RDX from the donor charge. It is interesting to note the contribution to the residues from the unconfined donor charge, which can clearly be seen for the 155-mm TNT round.

**TABLE 5: Blow-in-place residue deposition rates for some standard weapon system ordnance.**

| Weapon system | Munition tested[1] | Energetic material | Energetic compound | Mass[2] per round (g) | Residue[3] per round (mg:%) | | Reference |
|---|---|---|---|---|---|---|---|
| Mortars | | | | | | | |
| 60 mm | M888 | Comp B | RDX / HMX | 750 | 200 | $2.7\times10^{-2}$ | Walsh *et al.*, 2008 |
| 81 mm | M374 | Comp B | RDX / HMX | 1100 | 150 | $1.4\times10^{-2}$ | Walsh *et al.*, 2005a |
| 120 mm | M933 | Comp B | RDX / HMX | 2300 | 25 | $1.1\times10^{-3}$ | Walsh *et al.*, 2008 |
| Average | | | | | | $1.4\times10^{-2}$ | |
| Howitzers | | | | | | | |
| 105 mm | M1 | Comp B | RDX / HMX | 1800 | 50 | $2.8\times10^{-3}$ | Walsh *et al.*, 2005a |
| 155 mm | M107 | Comp B | RDX / HMX | 4700 | 15 | $3.2\times10^{-6}$ | Walsh *et al.*, 2005a |
| | M107 | TNT | TNT | 6600 | 5.9 | $8.9\times10^{-5}$ | Walsh *et al.*, 2005a |
| Average | | | | | | $9.6\times10^{-4}$ | |

[1]US military designation. [2]Initial mass of energetic compound in round. [3]Estimate of initial energetic compound remaining after detonation.

Field-quality assurance tests were conducted on the main detonation plume for most of the tests (Table 6). Results are quite good, with OTPs less than 1.5% in all but one case and subsurface samples containing little if any of the overall residues in the main plume. Most of these tests were conducted later during our research than the live-fire detonation tests and reflect an improvement over time in our methods. Table 7 contains data for the average areas of the various sampling units demarcated during the tests. See Table 5 for original source references. Although wind had a different influence on each set of tests, the plume sizes generally follow the explosive load sizes.

**TABLE 6:** Field sample QA results–BIPs

| Weapon | Munition tested[1] | Energetic compound | Number of OTPs | Residues in OTPs | Number of subsurface samples[2] | Residues in subsurface samples |
|---|---|---|---|---|---|---|
| Mortars | | | | | | |
| 60 mm | M888 | RDX | 7 | 0.42% | 2 | 0.54% |
| | | HMX | 7 | 0.45% | 2 | 0.10% |
| 81 mm | M374 | RDX | 4 | 0.09% | — | — |
| | | HMX | 4 | 0.4% | — | — |
| 120 mm | M933 | RDX | 7 | 1.2% | 2 | BDL[3] |
| | | HMX | 7 | BDL[3] | 2 | BDL |
| Howitzers | | | | | | |
| 105 mm | M1 | RDX | 3 | 3.6% | — | — |
| | | HMX | 3 | 1.4% | — | — |
| 155 mm | M107 | RDX | 6 | BDL | 2 | BDL |
| | | HMX | 6 | BDL | 2 | BDL |

[1]US Military designation. [2]Samples were taken below locations where sample increments were previously taken. [3]BDL: Below detection limits. For 155-mm Comp B OTPs, TNT at detection limits was found in three samples but not in all the replicates.

**TABLE 7:** BIP detonation residue plume areas

| Weapon | Munition tested[1] | Plume area[2] ($m^2$) | OTP area[3] ($m^2$) |
|---|---|---|---|
| Mortars | | | |
| 60 mm | M888 | 500 | 230 |
| 81 mm | M374 | 820 | 410 |
| 120 mm | M933 | 1500 | 480 |
| Howitzers | | | |
| 105 mm | M1 | 860 | 450 |
| 155 mm | M107 | 1600 | 750[4] |

[1]US military designation. [2]Main area of residue deposition (detonation plume). [3]Annular area outside the detonation plume. [4]Includes six 0–3-m and two 0–6-m OTPs.

### 3.3 Low-Order Detonations

The low-order detonations in this study occurred while we were observing a winter live-fire training exercise with 120-mm HE mortar munitions. We define a low-order detonation as a detonation that propagates incorrectly, fragmenting most of the ordnance and consuming around 75% to 99.99% of the HE load. The data used in this analysis are from a study by M.E. Walsh *et al.* (2010) on the persistence of Comp B particles in the environment. The total mass of Comp B in each round was 2900 g, and the analytes of interest were RDX, HMX, and TNT, the energetic constituents of Comp B (HMX occurs as a manufacturing byproduct of RDX and can constitute up to 6% of the energetics in Comp B). Three events were characterized in this study. The results are given in Table 8. Visible pieces of Comp B were not removed from sites LO2 and LO3, so the data presented are for sediments only in those cases, although some particles were collected with the samples. Characterization of the sites occurred 2–3 months following the detonation events. Plume areas are included in this table.

**TABLE 8:** Low-order (LO) residue deposition for M933 120-mm HE mortar projectiles (Walsh *et al.*, 2010)

| LO site | Mass collected prior to sampling (mg) | Residues recovered from sediment (mg) | Energetics recovered | Plume area ($m^2$) |
|---|---|---|---|---|
| 1 | 120000 | 9900[1] | 4.4% | 250 |
| 2 | — | 450000[2] | 15% | 150 |
| 3 | — | 650000[2] | 22% | 380 |

[1]Collected after particles and chunks removed from area. [2]Surface particles not removed.

### 3.4 Close-Proximity Detonations

The close-proximity detonation tests were conducted with M374A2 81-mm mortar rounds containing 920 g of Comp B explosive (Walsh, M.R. *et al.*, 2011). The surrogate UXO rounds contained no booster charge but were capped at the end with either cast zinc shipping plugs or aluminum fuze simulators. Residues recovered were unreacted particles of Comp B. The test surface was snow, compacted prior to testing to a compressive strength of approximately 240 g/cm$^2$. Eleven tests were conducted with 23 rounds exposed to the blast effects of the detonating mortar round. Damage to the rounds is described in Table 9. For our purposes, pierced to HE filler indicates a breach of the body of the projectile to the filler without any reaction of the filler, which may lead to spillage of some filler material; partial detonation indicates some of the filler detonated but not enough to carry the detonation throughout the round, thus leaving a substantial portion of the projectile body intact with HE residues generally in the 25–75% range; low-order detonation indicates a round that detonates but does not consume all of its HE filler, resulting in lower blast pressure, creation of large sections of improperly fragmented body, and residues generally in the 0.01–25% range; and high-order detonations indicate proper detonation resulting of full-round fragmentation and Comp B filler consumption of at least 99.99% during detonation.

**TABLE 9:** Damage to UXO from a close-proximity detonation

| Damage descriptor | Number of rounds | Distance range from detonations |
|---|---|---|
| Intact–surface damage | 4 | 0.5–0.8 m |
| Pierced to HE filler | 9 | 0.5–1.2 m |
| Low-order or partial detonation | 7 | 0.3–0.6 m |
| High-order detonation | 1 | 0.5 m |
| Not recovered | 2 | 0.3–0.5 m |

Images of some of the test rounds are shown in Fig. 4. These are rounds described in the table below. There was great variability in the nature and extent of damage to the rounds, with those closer to the detonation point likely to sustain the greatest damage.


**FIG. 4:** Damage to surrugate UXO from close-proximity detonations. (a) Pierced (breached) round. (b) Partial detonation (left) with most of filler ejected. (c) Partial detonation with most of filler intact. (d) Low-order detonation with larger body pieces.

The more the body of the projectile was intact, the more likely the filler remained in the body as well. Pierced rounds generally had the least amount of ejected HE, while low-ordered rounds had the least remaining HE (Fig. 4). Partial detonations had highly variable amounts of ejected HE. The combined effects of the shock wave and frag impacts are the likely cause of this variance.

Of the 17 recovered rounds sustaining damage, five were characterized for the mass of HE ejected from the body of the projectile. Of these, the area of deposition for the particles was estimated for three (Table 10). It is interesting to note that for one partially detonated round (Fig. 4b), the carcass was recovered 124 m away from the detonation point and large chunks were found up to 73 m down range. The mass of the HE recovered does not include any HE that remains within the remnants of the body of the projectile, which can be substantial (Fig. 4c). Projectiles that were closer to the detonation point were more likely to detonate high or low order, resulting in destruction of the body of the round and filler material (Fig. 4d).

**TABLE 10:** Mass of ejected and recovered HE and the area of deposition for close-proximity detonations (det.).

| Round | Distance from detonation (m) | Post-det. condition | Pieces recovered | Mass of HE recovered (g) | Mass of largest piece (g) | Deposition area ($m^2$) |
|---|---|---|---|---|---|---|
| 4b | 0.3 | Partial det. | 839 | 220 | 9.3 | 600 |
| 8a | 0.5 | Low order | 12 | 26 | 3.1 | — |
| 8b | 0.5 | Pierced | 20 | 22 | 3.3 | 2 |
| 9a | 0.5 | Partial det. | 11 | 12 | 1.6 | — |
| 10a | 0.5 | Low order | 16 | 60 | 12 | 140 |

### 3.5 Demolitions Munitions

Demolitions training ranges are a special case for the detonation of munitions containing explosives. These ranges are periodically graded, mixing and entraining explosive residues in the soil column. Thus, although surface contamination may be low, these ranges are among the most highly contaminated that we have encountered. As an example, for a different study (Hewitt *et al.*, 2009) we collected C4 debris at one site prior to doing a site characterization (C4 explosive is 91% RDX/9% plasticizer). In less than an hour, four individuals recovered over 3 kg of C4 in centimeter-sized chunks and larger.

We tested three types of demolitions items: a Bangalore torpedo, a shaped charge, and blocks of C4 demolition explosive. The C4 blocks are used as donor charges for initiating detonation of HE projectiles during BIP tests and tests were conducted on excess charges. All three items are only lightly confined and none of them are fired from a weapon system. RDX was the analyte of interest. Table 11 contains the results for our tests of these items.

**TABLE 11:** RDX Residue mass for various demolition items (Walsh, 2007)

| Demolition item | Munition type | Number of tests | Energetic material | Energetic mass (kg) | RDX mass (g) | Recov-ered RDX (mg) | Recov-ered RDX (%) |
|---|---|---|---|---|---|---|---|
| Bangalore torpedo | M1A2 | 1 | Comp B4 | 4.86 | 1900 | 110 | 0.0032% |
| Shaped charge | M3A1 | 1 | Comp B | 13.4 | 5200 | 4200 | 0.011% |
| Demolition block | M112 | 11 | C4 | 0.57 | 510 | 19 | 0.0038% |

## 4. DISCUSSION

Environmental stewardship is becoming an important factor in the sustainability of modern military training ranges. Encroachment in the form of housing, businesses, or public facilities and public access to military lands, especially in Europe, is exposing people to contamination that results from the use of training munitions. In some cases, groundwater and drinking water aquifers have become contaminated, leading to range closures and massive, expensive clean-up projects. It is thus important that the range management community keep close track of not only what is being used on ranges but how effective the ordnance being used is performing.

The detonation of projectiles is a clean process when the ordnance functions as designed. Larger, heavier munitions tend to be cleaner detonating because of their thick steel bodies, which confines the shock propagation wave as it travels through the explosive load in the round. Even less robust ordnance items, such as hand grenades and Bangalore torpedoes, detonate cleanly, consuming over 99.99% of their HE filler. It is when the rounds do not function properly that problems occur. The largest source of explosive residue contamination thus comes not from the vast majority of normally detonating rounds fired into an impact area but from malfunctioning ordnance.

We examined several ordnance-related operations for energetic residues. Unexploded ordnance is obviously the largest potential point source for contamination, but the undamaged body of the projectile is very effective at containing the explosive load. Corrosion of the ferrous body is a slow process, and diffusion of the explosives through a thick oxide layer is slow, sometimes allowing the transformation or breakdown of the explosive compounds in the process. To be an environmental and health concern, the filler must be exposed to the environment. This is where low-order detonations, close-proximity detonation damage to UXO, and BIP operations on UXO come into play.

Residues from a single low-order detonation of a round will contaminate an impact area as much as 100,000 properly functioning rounds. A close-proximity detonation that badly breaches a UXO can be worse, exposing almost all the explosive load in small, easily dissolved particles over an area of a few square meters. Improper disposal of UXO can have similar results, especially if the objective is to render the munition safe rather than detonate for disposal. Improper use of demolitions can result in easily available large quantities of this very dangerous material. Thus, not only are there health and environmental issues associated with improperly functioning munitions, there are serious safety and security issues as well, especially on open or more accessible ranges.

These results follow those of Hewitt *et al.* (2005). Over the course of our research, which dates back to the early 1990s, the one factor that stands out that most urgently needs to be addressed is munitions accounting on the training range. More accurate records need to be maintained, not only of what ordnance is being used on ranges but what happens to it once it is fired. We have been on ranges in several countries, and the presence of UXO and munitions constituents is a common occurrence. Military forward observers are tasked to direct fire into a target zone as their primary mission, and accounting for munitions functionality is a secondary task if done at all. Dudding and low-order rounds are seldom reported. The consequences outlined above are not where the problem stops. Under-reporting of problematic rounds will have severe consequences on the battlefield, both during and after a battle. We strongly recommend that better observation of live-fire exercises be conducted along with more accurate round accounting. We also recommend that, whenever safely possible, UXO be removed from the impact areas and properly detonated. If movement of the UXO is not possible, the high-order detonation of the munition in the field should be the goal of the explosive ordnance specialists.

## 5. SUMMARY

The use of munitions containing high explosives will leave energetic residues on ranges. To avoid accumulation of these residues and subsequent environmental and regulatory problems, it is important to know what the possible sources of energetics on training are and how much these sources will contribute to any contamination problems. The research results described in this article will give the range and regulatory communities a clear indication of the activities and sources that will result in problems over time. The use of unconfined charges and the maintenance of demolitions training ranges can lead to concentrated sources of explosives such as RDX. Unexploded ordnance damaged by the close-proximity detonation of functioning rounds can be a significant point source of energetics, as can be low-order detonation of rounds. Ranges should be periodically swept for UXO as well as large chunks of explosives to avoid future environmental complications as well as security issues.

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