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14. ABSTRACT

To achieve sustainable range management and avoid or minimize environmental contamination, the Army needs to know the amount of explosives deposited on ranges from different munitions and how these are degraded and transported under different geological and climatic conditions. The physical form of the deposited explosives has a bearing on this problem, yet the shapes and size distributions of the explosive particles remaining after detonations are not known. We collected residues from 8 high-order and 6 low-order non-tactical detonations of TNT-filled 155-mm rounds. We found significant variation in the amount of TNT scattered from the high-order detonations, ranging from 0.00001 to 2% of the TNT in the original shell. All low-order detonations scattered percent-level amounts of TNT. We imaged thousands of TNT particles and determined the size, mass and surface-area distributions of particles collected from one high-order and one low-order detonation. For the high-order detonation, particles smaller than 1 mm contribute most of the mass and surface area of the TNT scattered. For the low-order detonation, most of the scattered TNT mass was in the form of un-heated, centimeter-sized pieces whereas most of the surface area was again from particles smaller than 1 mm. We also observed that the large pieces of TNT disintegrate readily, giving rise to many smaller particles that can quickly dissolve. We suggest picking up the large pieces of TNT before they disintegrate to become point sources of contamination.

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TNT particle size distributions from detonated 155-mm howitzer rounds

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Abstract

To achieve sustainable range management and avoid or minimize environmental contamination, the Army needs to know the amount of explosives deposited on ranges from different munitions and how these are degraded and transported under different geological and climatic conditions. The physical form of the deposited explosives has a bearing on this problem, yet the shapes and size distributions of the explosive particles remaining after detonations are not known.

We collected residues from 8 high-order and 6 low-order non-tactical detonations of TNT-filled 155-mm rounds. We found significant variation in the amount of TNT scattered from the high-order detonations, ranging from 0.00001 to 2% of the TNT in the original shell. All low-order detonations scattered percent-level amounts of TNT. We imaged thousands of TNT particles and determined the size, mass and surface-area distributions of particles collected from one high-order and one low-order detonation. For the high-order detonation, particles smaller than 1 mm contribute most of the mass and surface area of the TNT scattered. For the low-order detonation, most of the scattered TNT mass was in the form of un-heated, centimeter-sized pieces whereas most of the surface area was again from particles smaller than 1 mm. We also observed that the large pieces of TNT disintegrate readily, giving rise to many smaller particles that can quickly dissolve. We suggest picking up the large pieces of TNT before they disintegrate to become point sources of contamination.

Keywords: Blow-in-place detonations; TNT particles; SEM; Size distribution; Surface area; Mass recovered

1. Introduction

Firing ranges provide soldiers the opportunity to train using a variety of munitions. However, as a result of training, unexploded ordnance (UXO), low-order detonations (where a significant fraction of the explosive remains un-detonated) and the explosive residues from live fire detonations may contaminate the soil and the groundwater, and consequently pose environmental and

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human health risks. Estimating the load of explosives on DOD training ranges is a difficult task (Jenkins et al., 2001; Pennington et al., 2002). It requires information on how much explosive residue is deposited after different munitions are fired into an area and the variation in this deposition due to how the munition detonates (dud, low-order or high-order, Dauphin and Doyle, 2000). Once on the ground, the rate of degradation of the deposited explosive particles probably depends on their size distribution and surface areas as well as weather and soil conditions (Ro et al., 1996; Lynch et al., 2001, 2002).

In this paper we use the term detonation residue to describe material collected after an explosion. The residue may or may not contain explosives. The TNT we collected during this study was in the form of particles and large pieces that had been scattered. We refer to them as TNT particles or scattered TNT. The yield of the detonation is the proportion of the explosive mass that detonates. In principle, it can be quantified based on air-blast parameters (Kingery and Bulmash, 1984). A detonation may be measurably less than 100% yield if the detonation wave does not propagate properly owing to defects in the shell casing or if the explosive was not packed or poured properly into the shell. The method used to initiate the detonation may also affect its yield. The term "order" is a subjective classification of explosive yield. An observer would classify as high-order any explosion indistinguishable from 100% yield and as low-order an explosion clearly sounding or looking different than 100% yield.

Detonations conducted in a blast chamber are used to assess gases produced during a detonation. If the chamber could be adequately cleaned between blasts and if the explosion itself were not modified by the confined space and limited air, a blast chamber would be a good place to measure the amount of explosives remaining after a detonation. Because of these issues, however, field detonations are used despite the difficulties involved in field sampling.

To estimate the mass of explosives remaining after high-order detonations, Jenkins et al. (2000a) collected and analyzed residue-covered snow samples from wintertime detonations at Camp Ethan Allen, Vermont. The frozen ground minimized soil contamination, and the snow provided a clean sampling background that decreased the chances of cross-contamination from prior range activities. The snow also made the dark detonation residue highly visible, allowing the residue plume to be mapped and measured.

To estimate the mass of explosives remaining after low-order detonations, Pennington et al. (2003) sampled the residues from detonations on a large tarp at Blossom Point, Maryland. The tarp also helped minimize cross-contamination from previous tests. The air-blast characteristics from each detonation were also measured to determine the relationship between detonation yield and the mass of remaining residue.

We sampled detonation residues from 155-mm howitzer rounds detonated at Camp Ethan Allen and at Blossom Point. These rounds contained 6.76 kg of 2,4,6-trinitrotoluene (TNT). Our goals were to (1) determine the mass of scattered TNT particles and the resulting size distributions, and (2) estimate surface areas for these particles using their measured lengths and widths. These data are needed as input parameters for models that determine the mass transfer of TNT from the solid phase to solution in water, a rate-limiting step that occurs prior to aqueous transport or biodegradation. The rounds were blown-in-place and not fired from a howitzer as designed (tactically detonated). This set up made it possible for us to place trays around the detonation point but may produce different results than tactically detonated rounds. Our results may be germane to tactically detonated rounds provided that the yield of a detonation, not the initiation process, governs the amount and the size distribution of the scattered explosives.

2. Methods

2.1. Particle sampling

2.1.1. Camp Ethan Allen (CEA), Vermont

On 28 February 2002 seven 155-mm howitzer shells were detonated to collect data on high-order detonations for the SERDP CP1155 project. The 155-mm shells were hung about 1 m off the snow surface from a wooden frame. A 0.57-kg (1.25-lb) block of C4 was taped to the side of the shells and initiated electronically. We mapped the resulting residue plumes using a geopositioning system (GPS) and sampled 100-×100-×2.5-cm sections of the snow surface to obtain an average explosive concentration.

We bagged the snow samples, brought them back to the laboratory, and set them out at room temperature to melt. We filtered each water sample through a Whatman glass micro-fiber filter (47 mm, grade GF/A) and extracted the water and the filter separately. The samples were then analyzed for explosives with a Reverse phase High Performance Liquid Chromatograph (RP-HPLC) following method 8330 (EPA, 1994). The latter is the standard method for determining explosive concentration in water and in soil.

To collect scattered TNT particles, we set out four, 66-×46-cm aluminum trays around two of the 155-mm rounds (Tests 1 and 5). By using the trays, we minimized the amount of snow collected with the residue. The GPS was also used to measure the distance between the sample points and the crater. Fig. 1 shows the location of the snow samples and the trays (marked by triangles)

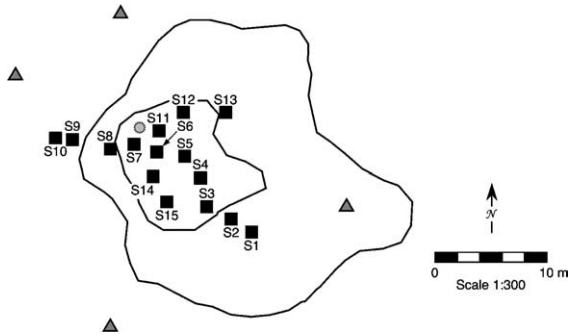

Fig. 1. The positions of the snow samples and the trays (marked by triangles) at Camp Ethan Allen relative to the detonation point. A 5-m/s west blowing wind was responsible for the shape of the plume (soot darkened areas of snow). The sootiest area of the plume is delineated by the inner line and the visible plume by the outer line.

relative to the detonation point for Test 1. We also examined the residue on the filter used for snow sample S1 (1 m^2) from Test 1.

After each detonation, the trays were placed in clear plastic bags and brought back to the laboratory. Any snow on the trays was allowed to melt and evaporate. We moved the residue from each tray down to a corner of the tray using a small paintbrush. The residue was then transferred onto weigh paper, weighed, and then stored in a 40-ml amber vial. Each tray was then wiped down with a cotton ball soaked with approximately 3-ml of acetone. The cotton balls, up to three for each tray, were placed in a separate amber vial.

2.1.2. Blossom Point (BP), Maryland

In May 2002, we sampled from low-order detonations conducted at the Blossom Point test site, an Army Research Laboratory facility (Pennington et al., 2003). All seven 155-mm rounds were detonated using a main charge disruptor, a tool that pierces the shell of the round using a small shape charge containing 50–230 g of C4. Based on shock-wave measurements one of the detonations was essentially 100% yield and the others ranged between 23% and 47% yield (Pennington et al., 2003). The munitions were detonated on a 184-× 230-×6-cm thick steel slab on top of an 86-cm-high wooden base centered on a 15- by 15-m (50- by 50-ft) white, flame resistant tarp. For each detonation, aluminum trays (66-×46-cm) were placed in a set pattern around the detonation point (Fig. 2). The furthest tray was 9 m from the detonation point and extended past the flame resistant tarp. After each detonation, we visually inspected both the tarp and the surrounding area to locate any centimeter-size pieces of explosive ejected from the round. These pieces were weighed and photographed in the field.

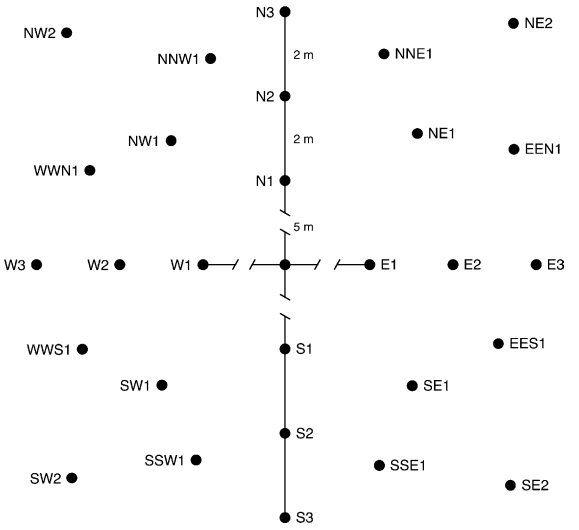

Fig. 2. Drawing that shows the position of trays at Blossom Point relative to the detonation point. Our data comes from the N, W, S and E trays.

At Blossom Point the solid debris on each plate was brushed into a 120-ml, wide-mouth, amber glass jar using a cotton ball. A small amount of acetone was then poured onto the cotton ball and it was used to wipe the tray. One to three acetone-wetted swipes were used for each tray to remove the residues before we reuse the trays for sampling. The cotton balls from each tray were placed into separate 20-ml amber glass vials.

2.2. Particle identification and analysis

For the size distributions we processed particles obtained from one high-order and one low-order test, Test 1 at Camp Ethan Allen and Test LO7 at Blossom Point, respectively. We dry-sieved the samples into <53-, 53–106-, 106–125-, 125–180-, 180–250-, 250–500-, and >500-μm size-fractions. The sieved samples were re-weighed and placed into labeled vials. Between samples, the sieves were cleaned using a brush and pressurized air to remove material caught in the mesh.

Sub-samples of each size fraction were examined under a light microscope. To establish that certain classes of particles were TNT we used tetra-butyl-ammonium hydroxide, a reagent that reacts with TNT to form a red product. Using a light microscope, we then separated out all the explosive grains from the 250–500- to >500-μm size-fractions. For Camp Ethan Allen-Test 1, we measured 122 TNT particles from the east tray sample and 1296 TNT particles from the filtered snow sample S1. For Blossom Point-LO7, we measured 3225 TNT particles collected from 12 sample trays placed along the main compass headings (N, S, E, W) and 207-cm-sized pieces hand collected from the tarp and the

nearby vicinity. The particles were measured in the following manner. We first photographed all the TNT particles using a digital camera attached to the light microscope (or a digital camera only, for the centimeter-sized particles) and transferred the images to a Macintosh computer. Then we used NIH image, a public domain program developed at the US National Institutes of Health and available on the Internet at http://rsb.info.nih.gov/nih-image/) to process each image and obtain the number of TNT particles, as well as the length of the major and minor axes for each particle.

We used the axes measurements to calculate average diameter (average of major and minor axes lengths) and aspect ratio (major/minor length ratio) for each particle. We estimated particle mass and surface area using two simple shape approximations: sphere (based on average diameter) and prolate spheroid (major > minor = unmeasured third axis). We also imaged the surfaces of some of the >250 μm TNT grains using a scanning electron microscope (SEM) to get a visual record of their surface roughness.

To estimate the number of TNT particles in the five size fractions smaller than 250 μm, we dissolved all or a large sub-sample of the residue in acetonitrile, agitated the sample overnight and analyzed a fraction of the sample with a RP-HPLC following EPA method 8330 (EPA, 1994). From the measured TNT concentration, we calculated the TNT mass in each size fraction. When only a sub-sample was analyzed, we assumed it was representative of the entire size fraction. We then calculated the number of particles and the total surface area in each size fraction, using both sphere and prolate-spheroid approximations, by assuming an average diameter for each size fraction and using the average aspect ratio of the sized particles from that same test. The average diameters chosen were 40, 75, 110, 150 and 200 μm, respectively, for the <53-, 53–106-, 106–125-, 125–180- and 180–250-μm size-fractions. The measured aspect ratios were uncorrelated with particle size and averaged 1.44 ± 0.31 (1σ) and 1.42 ± 0.38 (1σ) for Camp Ethan Allen-Test 1 and Blossom Point-LO7, respectively. Lastly, we added the resulting numbers, masses and surface areas calculated from TNT concentrations to the binned results based on measured particle sizes to produce histograms.

3. Results

3.1. Appearance of TNT particles

The Camp Ethan Allen-Test 1 TNT particles were all opaque white to gray and often had a black carbon coating on part of their surfaces (Fig. 3). They differed from quartz grains, which were also found in the sample, by having a dull luster and an irregular, smooth and

Fig. 3. Optical image showing TNT particles (arrows) in residue from a 'high-order' detonation. The TNT particles are opaque white to gray and often have black soot patches on parts of their surfaces.

indented surface. Unlike the quartz grains, the TNT particles could be indented with a needle. The SEM images show that the surfaces are quite smooth, lumpy and non-porous. The underlying crystalline nature of the TNT can also be discerned (Fig. 4).

A wider variety of TNT particles were found after the Blossom Point-LO7 detonation (Fig. 5a–d). The larger ones tended to be yellow to pink crystalline particles that were very friable; they disaggregated into very small particles when touched by a needle or tweezers. We also observed white opaque particles, such as those previously described for the Camp Ethan Allen-Test 1 samples, yellow, lumpy particles, and spherical particles (Fig. 5d). It is clear that some of the TNT particles were still molten or hot when they landed on the aluminum trays. We saw TNT 'splat' marks on the trays, and we saw particles that had flat bottoms from landing on the tray while they were still hot and deformable.

The SEM and optical images and measured aspect ratios suggest that, for both the high and low-order test, the TNT particle are better approximated as prolate spheroids rather than spheres. Because sphere and prolate-spheroid shape approximations give essentially the same size distributions and less than 4% difference in mass and surface-area estimates, all of the analyses we show assume a prolate-spheroid shape.

3.2. Size distribution of TNT particles

The size distributions of the TNT particles from Camp Ethan Allen-Test 1 and from Blossom Point-LO7

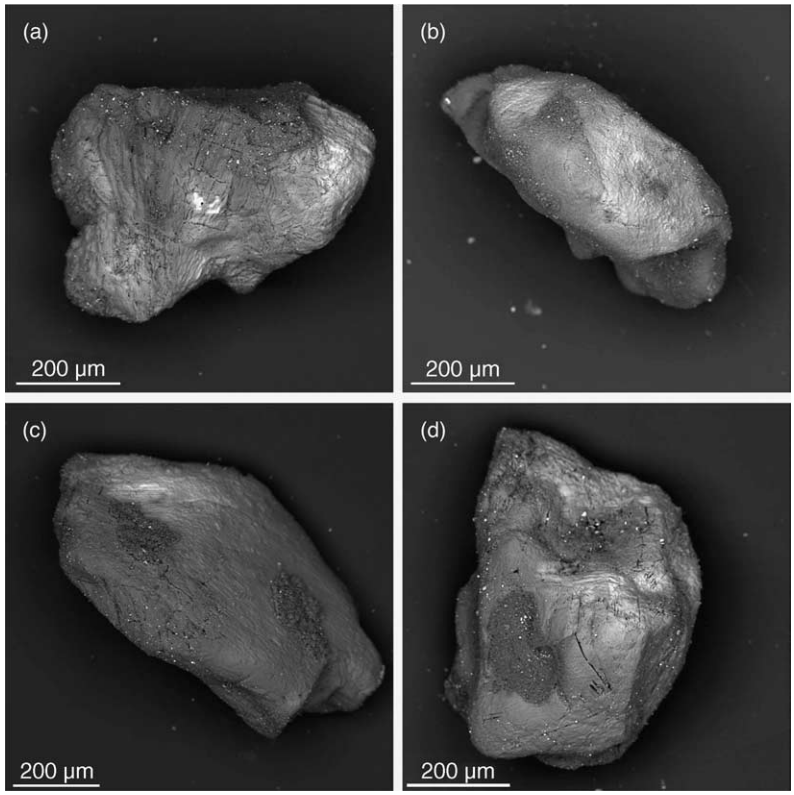

Fig. 4. Scanning electron micrographs of TNT particles from Camp Ethan Allen. Patches of different texture are soot like those seen in Fig. 3.

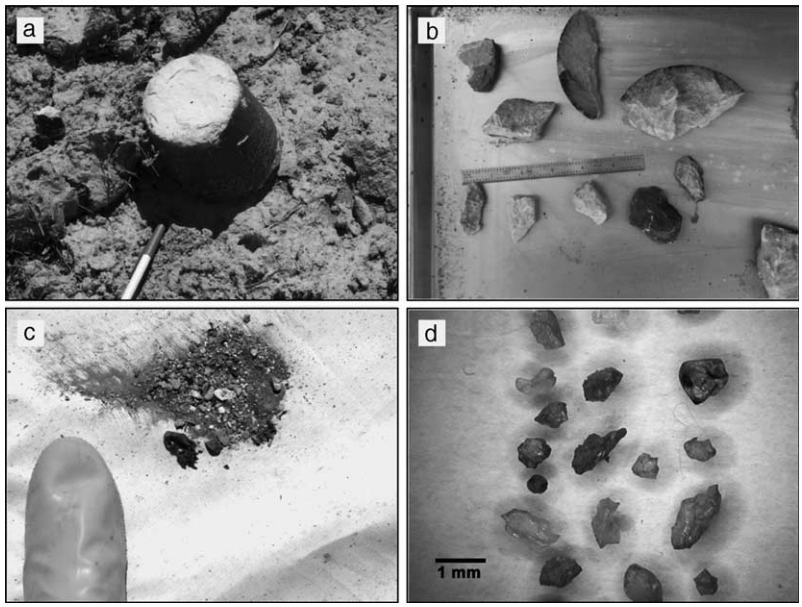

Fig. 5. Optical images of TNT pieces and particles collected after a low-order detonation (Blossom Point-LO7), (a) >1 kg piece, (b) assortment of 10–100 g pieces (15-cm ruler for scale), (c) material collected from SE quadrant (boot for scale), (d) TNT particles from trays.

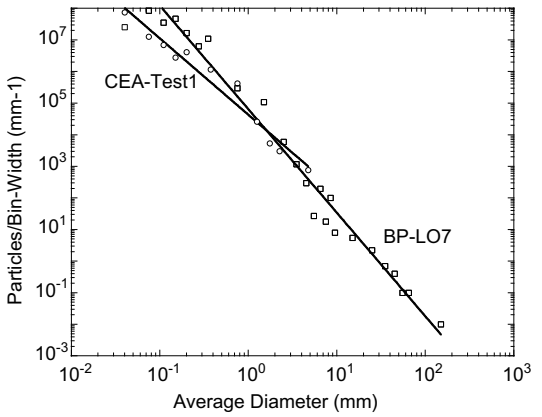

Fig. 6. Size distribution of TNT grains from the east tray sample and S1 snow sample, Camp Ethan Allen, VT (open circles) and from 12 trays samples, Blossom Point, MD (open squares). The slopes of the best-fit lines are −2.4 for the Camp Ethan Allen-Test 1 and −3.3 for Blossom Point-LO7, with R^2 of 0.99 and 0.83, respectively.

are shown in Fig. 6 and Table 1. The data are presented as the number of particles per bin width to account for the fact that the sieves, used to separate the samples, yielded variable size fractions. The low-order test (Blossom Point-LO7) scattered much larger TNT particles than the high-order test (Camp Ethan Allen-Test 1), including one exceeding 10 cm in size (Figs. 6 and 5a). Interestingly, the size distributions nearly overlap for particles smaller than a few millimeters.

Except for the <53-μm size fraction for Blossom Point-LO7, the size distributions are well represented by power-laws (straight lines on log–log plots, Fig. 6). The slopes of these lines are −2.4 for the Camp Ethan Allen-Test 1 and −3.3 for Blossom Point-LO7, with R^2 of 0.99 and 0.83, respectively. As explained in the Discussion, the slope of the size distribution will change as the particles weather and the way in which the slope changes provides information on the dominant process altering the scattered particles.

Note that we have scaled the sample results to estimate the total number of particles expected to have been scattered by each detonation. For Camp Ethan Allen-Test 1, we assume that the plume approximates the areal extent of the scattered TNT particles. The east tray and snow-sample S1 were the only samples located within the 496-m^2 plume. We therefore combined and scaled their histograms by the area ratio 496 m^2/1.30 m^2 to estimate the particle content of the entire plume. These two samples had a combined TNT mass of 321 mg. While the south and west trays had insignificant TNT quantities (<0.1 and 3.5 μg, respectively), the north tray had three large particles of TNT (average diameters of 4, 3, and 1 mm) and a TNT mass of about 8 mg. Clearly, the plume did not contain all the scattered TNT particles, but the small number and mass of particles missed should have a minor effect on the results presented here.

For Blossom Point-LO7, we produced a histogram for the combined 12-tray sample and scaled this to the 18-m × 18-m pattern covered by the trays (324 m^2/3.62 m^2). We then added in the 207-cm-sized hand-collected pieces to the scaled histogram. Essentially this procedure assumes that the 12 tray samples adequately represent the population of scattered TNT particles smaller than about 1 cm, and that the hand-collected pieces constitute the entire population of >1 cm TNT particles. We estimate that this procedure adequately represents the size distribution for Blossom Point-LO7 within the uncertainty of the experiment.

3.3. Cumulative distributions for mass and surface area

We plotted the cumulative distributions for TNT particle mass and surface area versus average diameter for Camp Ethan Allen-Test 1 and Blossom Point-LO7 (Fig. 7). As with the size distributions, the results shown are scaled to approximate the total mass and surface area of particles scattered by the two detonations. For ease of comparison, we normalized the curves by dividing by these calculated totals (0.133 kg and 0.566 m^2 for Camp Ethan Allen-Test 1, 2.95 kg and 1.94 m^2 for Blossom Point-LO7). Table 1 presents the cumulative masses and surface areas before normalization.

For Camp Ethan Allen-Test 1, particles smaller than 1 mm contribute most of the cumulative mass and surface area. For Blossom Point-LO7, particles larger than 1 cm contribute most of the cumulative mass while particles smaller than 1 mm again contribute most of the cumulative surface area. The larger surface area of the small particles indicates that this size fraction will interact with available water and dissolve. With time, these smaller particles will disappear and only larger particles of TNT will remain in the soil.

3.4. Total TNT mass deposited

3.4.1. Camp Ethan Allen high-order tests

We measured the TNT concentrations for the 15 snow samples collected after Test 1 (Table 2). Except for sample S1, where we measured the TNT particles, the other 14 snow samples were extracted and analyzed for TNT. The average TNT concentration thus obtained was 0.220 g/m^2 of snow, which, when multiplied by the 496 m^2 area of the visible plume, yields a TNT mass of 109 g. Adding 1.80 g calculated for the crater produces an estimate of 111 g of TNT scattered from this detonation. This is 1.64% of the 6.76 kg of TNT contained in a 155-mm shell. However, the uncertainty in the calculated TNT quantity could be ±50%, owing to the large range among the 15 measured TNT concentrations. That is, the concentration measurements suggest that

Table 1
Binned results for particle numbers, mass and surface area for Camp Ethan Allen-Test 1 and Blossom Point-LO7

Bin range (μm)	Bin diameter (μm)	Number of particles	Mass (g)	Surface area (mm^2)
Camp Ethan Allen-Test 1				
<0.053	0.040	3.95E+06	0.173	1.74E+04
0.053–0.106	0.075	6.74E+05	0.195	1.04E+04
0.106–0.125	0.110	1.33E+05	0.122	4.44E+03
0.125–0.180	0.150	1.52E+05	0.355	9.47E+03
0.180–0.250	0.200	2.86E+05	1.60	3.18E+04
0.250–0.500	0.375	2.91E+05	14.3	1.35E+05
0.500–1.0	0.750	2.11E+05	41.9	2.44E+05
1.0–1.5	1.25	1.30E+04	14.7	4.91E+04
1.5–2.0	1.75	2.67E+03	8.33	2.01E+04
2.0–2.5	2.25	1.52E+03	9.61	1.85E+04
2.5–3.0	2.75	0	0	0
3.0–3.5	3.25	0	0	0
3.5–4.0	3.75	0	0	0
4.0–4.5	4.25	0	0	0
4.5–5.0	4.75	3.81E+02	30.8	2.47E+04
Blossom Point-LO7				
<0.053	0.040	1.35E+06	0.0599	5.98E+03
0.053–0.106	0.075	4.52E+06	1.32	7.03E+04
0.106–0.125	0.110	6.70E+05	0.618	2.24E+04
0.125–0.180	0.150	2.59E+06	6.06	1.61E+05
0.180–0.250	0.200	1.16E+06	6.45	1.29E+05
0.250–0.300	0.275	3.18E+05	4.58	6.66E+04
0.300–0.425	0.350	8.21E+05	24.4	2.78E+05
0.425–1.0	0.750	1.72E+05	71.8	3.33E+05
1.0–2.0	1.5	1.08E+05	166	4.93E+05
2.0–3.0	2.5	5.99E+03	52.9	8.96E+04
3.0–4.0	3.5	1.17E+03	29.1	3.54E+04
4.0–5.0	4.5	2.96E+02	19.4	1.68E+04
5.0–6.0	5.5	27	3.97	2.65E+03
6.0–7.0	6.5	196	30.0	2.01E+04
7.0–8.0	7.5	18	6.61	3.26E+03
8.0–9.0	8.5	100	48.8	2.18E+04
9.0–10	9.5	8	5.77	2.27E+03
10–20	15	55	146	3.60E+04
20–30	25	22	244	3.81E+04
30–40	35	7	293	2.98E+04
40–50	45	4	369	2.87E+04
50–60	55	1	108	8.02E+03
60–70	65	1	221	1.29E+04
70–80	75	0	0	0
80–90	85	0	0	0
90–100	95	0	0	0
100–200	150	1	1087	3.74E+04

the detonation scattered about $2 \pm 1\%$ of the explosive charge.

If instead we use the number of TNT particles we found in *S*1 and the east tray (Table 1) to estimate the TNT mass scattered by the detonation we obtain an average TNT concentration of 0.268 g/m^2 in the snow which when multiplied by 496 m^2 yields 133 g. This mass is 1.96% of the TNT charge in the shell, but we should also allow ±50% uncertainty in this method and report the result as $2 \pm 1\%$. The agreement between these two estimates is satisfying but possibly fortuitous given the large uncertainties involved.

We also list the concentration measurements obtained for Test 4, another high-order detonation of a 155-mm round (Table 2). For this test, the average TNT concentration from nine snow samples gave a total deposited TNT mass of 0.5 ± 0.3 mg, roughly 5 orders of magnitude lower than Test 1. The masses of TNT estimated for the other 155-mm tests conducted at Camp Ethan Allen, based on concentration measurements of

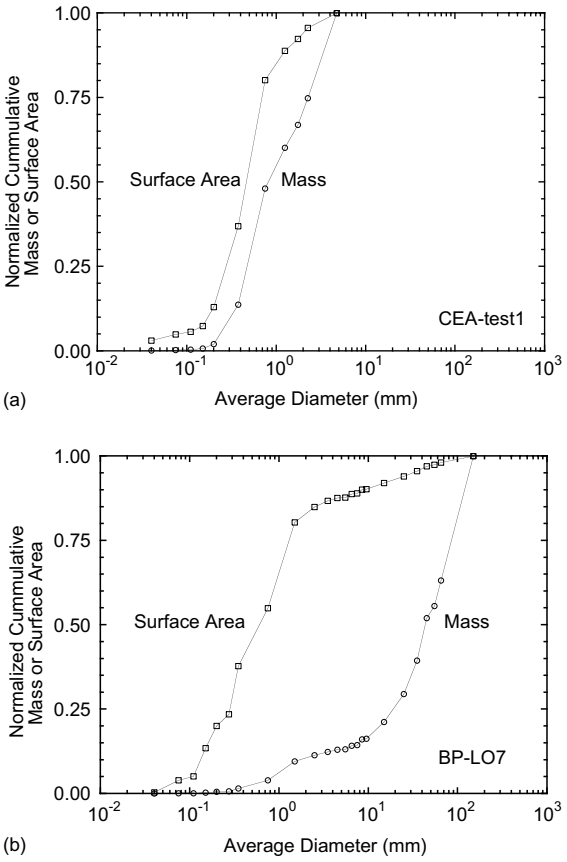

Fig. 7. Normalized cumulative mass and surface area, as a function of particle diameter, for TNT collected from (a) Test 1 at Camp Ethan Allen, Vermont and (b) LO7 at Blossom Point, Maryland. The masses and surface areas were calculated based on a prolate particle shape. To make it easier to compare the distribution shapes we normalized the counts by the total mass and surface area calculated for each test. The total mass at Camp Ethan Allen was 0.133 kg and at Blossom Point 2.95 kg. The total surface area was 0.566 m^2 for Camp Ethan Allen-Test 1 and 1.94 m^2 for Blossom Point-LO7.

the snow samples, fall between the values for these two tests (Table 3).

3.4.2. Blossom Point-LO7

Our estimate for the mass of TNT scattered by test LO7 consists of two calculations. The mass of TNT particles collected on the 12 trays was scaled by the area of the tarp to obtain an estimate for the small sized particles of 0.45 ± 0.22 kg. To this we added the mass of the >1-cm pieces that we picked up from the entire tarp and its vicinity, 2.5 ± 0.2 kg. The sum of these is 2.9 ± 0.3 kg or $44 \pm 4\%$ of the TNT in the round. Although we again allowed $\pm 50\%$ uncertainty in the mass scaled from the 12 trays, the total scattered mass for this test is dominated by the picked up chunks that we collected from the entire surface of the tarp and consequently were not scaled.

Measurements of the blast wave for this low-order test gave an estimated yield of 37% of the original TNT mass in the round (Reed, 2002, based on Kingery and Bulmash, 1984). Although an uncertainty was not given, the high-order detonations varied by almost 20% in estimated yields. The asymmetric nature of a low-order detonation probably significantly increases the uncertainty in its yield estimated from blast-wave measurements. Consequently, we may estimate the yield of Blossom Point-LO7 as $40 \pm 20\%$.

These two measurements allow us to account for $80 \pm 20\%$ of the original explosive mass in the round: $44 \pm 4\%$ scattered mass and $40 \pm 20\%$ yield mass, rounded to reflect the high uncertainty in the yield estimate. Some TNT was left in the shell but we were not allowed to remove it, some TNT may have been burned in the fireball and we may not have recovered all of the centimeter-sized scattered particles.

4. Discussion

The results presented here are, to our knowledge, the first reported size, mass and surface-area distributions for explosive particles scattered by detonations. Once we identified the types of TNT particles collected, they were relatively easy to pick out from the explosive residue and soil collected on the trays. However, the time-intensive nature of imaging the particles to produce size distributions limited the results presented here to just two detonations. Note also that the detonations were triggered by methods used for blow-in-place operations. It is unclear at present how closely these results will apply to tactically detonated rounds.

The variety of sizes, colors and textures of the scattered TNT particles are the result of differential heating, with the crystalline particles being the least heated and the spheres having been totally melted during the detonation. TNT particles that have been heated or melted tend also to have smooth surfaces whereas the unmelted crystalline particles have rougher surfaces. Also, the crystalline particles are friable and readily break apart into smaller pieces.

The measured size distributions for Camp Ethan Allen-Test 1 and Blossom Point-LO7 nearly overlap for particles smaller than a few millimeters. The high-order Camp Ethan Allen-Test 1 scattered small TNT particles with characteristics similar to those scattered by the low-order Blossom Point-LO7 with a yield of only $40 \pm 20\%$. The low-order test differed primarily by scattering a few large particles that represent most of the scattered mass.

We saw TNT particles in the smallest size fractions from both Camp Ethan Allen-Test 1 and Blossom Point-LO7. We expect that these small, ubiquitous TNT grains

Table 2
TNT snow sample concentrations for two, 'high-order', 155-mm detonations conducted at Camp Ethan Allen, VT

Sample Test 1	Distance to crater (m)	Sample area (m^2)	TNT conc. (mg/m^2)
S-1[a]	12.6	1.0	184
S-2	10.0	1.0	49.0
S-3	8.3	1.0	170
S-4	6.2	1.0	200
S-5	3.8	1.0	530
S-6	1.8	1.0	330
S-7	2.0	1.0	19.0
S-8	4.4	1.0	1.00
S-9	6.0	1.0	3.20
S-10	8.0	1.0	4.30
S-11	1.5	1.0	1300
S-12	4.0	1.0	340
S-13	6.6	1.0	140
S-14	4.6	1.0	15.0
S-15	6.8	1.0	21.0
Crater (not included in ave.)	–	1.0	1800
Ave. $n=15$			220
Std. dev.			337
Area of soot plume		496	
Sample Test 4	**Distance to crater (m)**	**Sample area (m^2)**	**TNT conc. ($\mu g/m^2$)**
1	0.6	0.64	0.47
2	6.6	0.55	0.82
3	9.1	0.68	bd[b]
4	6.0	0.72	1.50
5	2.5	0.33	1.90
6	1.7	0.42	7.50
7	4.8	0.55	0.39
8	6.4	0.60	0.42
9	4.0	0.63	0.22
Crater (not included in ave.)	–	0.65	5.20
Ave. $n=9$			1.47
Std. dev.			2.34
Area of soot plume		344	

[a] Estimated from particle counts in the filter and TNT concentration in the melt.
[b] The practical detection limit for the water samples was 0.5 ppb.

Table 3
Variability in the average TNT concentrations among residue from 7, high-order, 155-mm rounds detonated at Camp Ethan Allen, VT

Test #	# Samples averaged	Ave TNT conc.	Std. dev.	Plume area (m^2)	Plume mass	Crater mass	% Recovered
1	15	220 mg/m^2	337 mg/m^2	496	109 g	1.8 g	1.64E+00
2	9	124 mg/m^2	203 mg/m^2	311	38.3 g	0.11 g	5.68E−01
3	11	118 $\mu g/m^2$	222 $\mu g/m^2$	345	40.4 mg	7.1 μg	5.98E−04
4	9	1.47 $\mu g/m^2$	2.34 $\mu g/m^2$	344	0.5 mg	3.64 μg	7.40E−06
5	11	16.9 mg/m^2	12.6 mg/m^2	406	6.8 mg	19 mg	1.01E−01
6	10	679 $\mu g/m^2$	1774 $\mu g/m^2$	301	204 mg	0.4 μg	3.02E−03
7	11	168 $\mu g/m^2$	243 $\mu g/m^2$	476	79.8 mg	0.2 μg	1.18E−03

The original 155-mm rounds each contain 6.76 kg of TNT.

will dissolve rapidly during weathering leaving larger, randomly distributed, millimeter-sized, particles behind. In fact Radtke et al. (2002) observed that millimeter-sized TNT grains made up most of the explosive contamination at a site that had not been used for over 50 years. Preferential dissolution of small particles will

flatten the slope of the size distribution (i.e., the exponent of the power-law distribution will become less negative). However, the slope of the distribution will steepen if new particles are created by dissaggregation of large pieces into many smaller ones. The net change in the shape and magnitude of the size distribution will depend on the relative rates of these two processes.

The preferential dissolution of small TNT particles might also explain difficulties in obtaining representative samples of range soils where high concentrations are found in a few samples and blank or very low concentrations in most samples. Because the larger grains are much farther apart than the scale of individual samples, most samples are unlikely to contain an explosive grain. Laboratory particle weathering experiments would help quantify how the surface area of a group of grains changes and how quickly grains of different size are dissolved.

The large variety of particle shapes found in the samples makes it difficult to use a simple geometric approximation to calculate the surface area of TNT particles. Fortunately our two approximations for particle shape, sphere and prolate spheroid, yield estimates of total surface area that differ by less than 4%. The prolate-spheroid approximation better matched the observed shapes and average aspect ratios measured for the particles. Although the smooth, regularly shaped particles may have surface areas similar to our estimates, irregularly shaped, rough-surfaced particles are likely to have higher surface areas than estimated. A physical measurement of the surface areas of TNT grains, by gas absorption for example, is needed to calibrate the surface-area estimate made based on a simple geometric model and to determine the usefulness of such an estimate.

Jenkins et al. (2000a,b) used multiple snow samples, taken within the residue plume, to estimate the deposited mass of explosive from high-order detonations. The sampling has yielded consistently low explosive concentrations, $\mu g/m^2$ quantities, for a variety of tactically and non-tactically detonated munitions (Jenkins et al., 2000b). The high-order tests described here deposited 0.5 mg to 111 g or 0.00001% to 2% of the TNT in the shell onto the range. If these rounds had been tactically detonated (using the normal triggering sequence involved when these are fired from a howitzer) would the residual mass of TNT have been the same? Do the results simple scale according to yield or is the symmetry of the detonation critical? We do not know the answer to these questions and hope to determine the variability in the residual mass of TNT from tactically detonated 155-mm rounds. This information would help us better estimate the loads being delivered during training.

We probably obtained a minimum value for the mass of explosive scattered after a low-order detonation. There are a number of sampling issues that need to be considered when making these estimates. First, because most of the mass from the low-order detonations resides in the big pieces, and their distribution is non-symmetrical and non-uniform, if we miss a big piece it will cause a large error in our estimate. Second, because of their greater mass, the big pieces are the most likely to be ejected a long way. Third, because non-uniformity in range and azimuth appears to occur across all sizes, predicting the mass of small particles based on averages of sub-samples introduces large errors. Lastly, for low-orders there is often TNT left in the shell. To obtain more precise size and mass distributions for low-order detonations, tests would have to be conducted on an expansive, flat area, such as a large frozen lake or a huge concrete pad, where essentially all of the scattered particles could be retrieved. The amount of TNT remaining in the shell could be estimated by measuring the inside diameter of the shell and the fill depth or by weighing the TNT filled shell and re-weighing it once the TNT has been dissolved using acetone. The waste acetone could be disposed of safely by burning it along with the unexploded pieces.

5. Conclusions

This paper presented data on the appearance and size distribution of TNT grains found after blow-in-place detonations of 155-mm rounds. We found TNT particles from both high- and low-order detonations. Our results show significant variation in the amount of TNT remaining after high-order detonations. The values ranged from 0.5 mg to 111 g, representing 0.00001% to 2% of the TNT in the original shell. We also found particles of TNT outside of the soot plume suggesting that estimates of explosive concentrations are minimum values. We hope to examine residue from 155-mm rounds that are fired from a howitzer or are set in place but initiated using the normal detonation sequence to determine the amount of explosive remaining when the shells are fired under typical training conditions.

Low-order detonations scatter explosive particles and pieces on the ground and deposit much larger explosive particles than a high-order detonation. Most of the mass of the unexploded TNT is found in un-heated, large, centimeter-sized pieces whereas most of the surface area comes from particles <1 mm. We also observed that large pieces of TNT disintegrate easily so, although their initial surface area is small relative to their mass, these pieces can quickly give rise to many smaller pieces with a huge increase in overall surface area. Because the large particles have so much mass, they can become point sources of contamination.

SEM observation of TNT grains showed them to be smooth and non-porous suggesting that surface-area estimates based on measurements of major and minor

axes might be a good first approximation. We intend to improve the surface-area measurements by using gas absorption to physically measure the collective surface area of a group of TNT grains collected from field detonations. We also will section some particles to look at their internal structure.

Until we can better account for the many variables that affect the quantity and spatial distribution of explosives, the Army could greatly decrease the possibility of future contamination problems by practicing regular range maintenance. Because large pieces of explosives readily break down to many smaller, unrecoverable pieces, collecting, and disposing of, these large pieces would eliminate a large source of potential contamination. Large pieces of unexploded ordnance may also pose a security issue if not collected and disposed of properly.

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