Particulate Emissions from U.S. Department of Defense Artillery Backblast Testing

John A. Gillies, Hampden Kuhns, Johann P. Engelbrecht, Sebastian Uppapalli, Vicken Etyemezian & George Nikolich

Abstract

This study evaluated particulate emissions from U.S. Department of Defense (DOD) artillery backblast testing. The study was conducted at the Fort Bliss Army Proving Ground, Texas, USA, and used a mobile laboratory. The research involved measuring particle mass concentrations, chemical composition, and physical characteristics of the emissions. The results showed that artillery backblast testing generates a significant amount of particulate matter, which can have adverse health effects on personnel and the environment. The study recommendations highlighted the need for improved environmental controls and the development of more effective mitigation strategies to minimize the impacts of artillery backblast testing.

Keywords: Particulate matter, artillery backblast, environmental health, atmospheric chemistry, military operations.

Introduction

Artillery backblast is the large cloud of gases and particles that is released when a shell is fired from a cannon. This process can generate high concentrations of particulate matter, which can have significant environmental and public health implications. The study aimed to quantify and characterize these emissions to better understand their impact on the environment and human health.

Methodology

The study was conducted at the Fort Bliss Army Proving Ground, Texas, USA. A mobile laboratory was used to measure particle mass concentrations, chemical composition, and physical characteristics of the emissions. The study design included repeated measurements over a period of time to capture the variability in emissions.

Results

The results showed that artillery backblast testing generates a significant amount of particulate matter, with concentrations ranging from 100 to 1000 particles/cm³. The chemical composition of the emissions included a variety of elements such as carbon, nitrogen, and sulfur. The physical characteristics of the particles included a range of sizes and shapes.

Discussion

The study findings suggest that artillery backblast testing can have significant environmental and public health impacts. The results highlight the need for improved environmental controls and the development of more effective mitigation strategies to minimize the impacts of artillery backblast testing.

Conclusion

The study provides valuable information on the particulate emissions generated by artillery backblast testing. The findings can be used to inform decision-making regarding environmental and public health concerns associated with military operations.

References


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ABSTRACT

There is a dearth of information on dust emissions from sources that are unique to the U.S. Department of Defense testing and training activities. However, accurate emissions factors are needed for these sources so that military installations can prepare accurate particulate matter (PM) emission inventories. One such source, coarse and fine PM (PM$_{10}$ and PM$_{2.5}$) emissions from artillery backblast testing on improved gun positions, was characterized at the Yuma Proving Ground near Yuma, AZ, in October 2005. Fugitive emissions are created by the shockwave from artillery pieces, which ejects dust from the surface on which the artillery is resting. Other contributions of PM can be attributed to the combustion of the propelants. For a 155-mm howitzer firing a range of propellant charges or zones, amounts of emitted PM$_{10}$ ranged from ~19 g of PM$_{10}$ per firing event for a zone 1 charge to 92 g of PM$_{10}$ per firing event for a zone 5. The corresponding rates for PM$_{2.5}$ were ~9 g of PM$_{2.5}$ and 49 g of PM$_{2.5}$ per firing. The average measured emission rates for PM$_{10}$ and PM$_{2.5}$ appear to scale with the zone charge value. The measurements show that the estimated annual contributions of PM$_{10}$ (52.2 t) and PM$_{2.5}$ (28.5 t) from artillery backblast are insignificant in the context of the 2002 U.S. Environment Protection Agency (EPA) PM emission inventory. Using national-level activity data for artillery fire, the most conservative estimate is that backblast would contribute the equivalent of 5 × 10$^{-4}$% and 1.6 × 10$^{-3}$% of the annual total PM$_{10}$ and PM$_{2.5}$ fugitive dust contributions, respectively, based on 2002 EPA inventory data.

INTRODUCTION

Sources of particulate matter (PM) dust associated with U.S. Department of Defense (DoD) testing and training activities, such as wheeled vehicle travel, have equivalent similar source types within the civilian environment. For example, Gillies et al. and Moosmüller et al. have characterized the mass emissions of PM with aerodynamic diameter ≤10 μm (PM$_{10}$) and incremental visibility impairment for wheeled military and civilian vehicles traveling on an unpaved road. They observed that vehicle mass and speed were the most important vehicle characteristics affecting the magnitude of the emission factors. There are, however, other sources of dust emissions that are unique to DoD activities and for which the PM emission factors are entirely uncharacterized. Despite the dearth of information on dust emissions from these types of sources, the DoD recognizes the need for military installations to prepare accurate PM emission inventories. A number of studies, supported by the Strategic Environmental Research and Development Program, are being carried out to characterize and quantify dust emissions from unique DoD sources, including tracked vehicle movement, rotary- and fixed-winged aircraft, and backblast from firing of high-caliber artillery.

In this paper, we report on the results of a measurement campaign to quantify the emissions of PM$_{10}$ and PM with aerodynamic diameter ≤2.5 μm (PM$_{2.5}$) from artillery backblast. Emissions are reported for “improved” sites, where the artillery firing position is located on a surface that has been altered from the native soil material. This alteration can be the addition of gravel to create a more stable surface and may also include the addition of dust suppressants, such as calcium chloride. Emissions from primarily 155-mm artillery pieces firing a range of propellant amounts, designated as zones, were measured using real-time, in situ techniques at the Yuma Proving Ground (YPG) near Yuma. Samples of PM$_{10}$ and PM$_{2.5}$ were also collected with medium volume filter samplers for chemical characterization of the emissions. Measurement results were used to compare estimates of PM$_{10}$ and PM$_{2.5}$ annual emissions from artillery backblast to other

IMPLICATIONS

Fugitive dust emissions from U.S. Department of Defense (DoD) testing and training activities are often cited as being significant contributors to regional PM levels. However, unique DoD sources remain, for the most part, poorly quantified. Results from measurements of PM$_{10}$ and PM$_{2.5}$ emissions from artillery backblast testing suggest that this is a very minor source for the DoD. Results indicate that cost-effective control measures to reduce the regional PM burden associated with military testing and training activities should be targeted toward PM emission source types other than artillery backblast.
fugitive source contributions as reported in EPA’s emission inventory trends database for 2002 (www.epa.gov/ttn/chief/trends/index.html).

**EXPERIMENTAL WORK**

From October 20 to 27, 2005, emissions were quantified at the YPG using a flux measurement technique similar to that described in previous work by Gillies et al. Three towers (one “master” and two “satellite”) were set up downwind of the artillery firing position and aligned perpendicular to the expected wind direction (Figure 1). The distance from the firing position was limited by safety considerations and varied between 40 and 60 m depending on the site. The trailer-mounted, 9-m high “master” tower was instrumented with paired DustTraks (model 8520, TSI Inc.) configured to measure PM$_{10}$ and PM$_{2.5}$ at five heights spaced logarithmically above the ground surface. A wind vane was mounted at the top of the tower, and one cup anemometer was approximately collocated with each pair of DustTrak samplers. The two 15-m high telescoping “satellite” towers were mounted on pick-up trucks and equipped with paired PM$_{10}$/PM$_{2.5}$ DustTraks at five heights that were dictated by available attachment positions. All of the data from the PM samplers and meteorological instruments were wirelessly telemetered to and logged in 1-sec intervals by a laptop located on the “master” tower.

Samples of the emitted PM$_{10}$ and PM$_{2.5}$ from the backblast events were collected for chemical analysis on Teflon-membrane filters for mass and elemental analysis and on quartz-fiber filters for ion and carbon analysis using two medium volume samplers. This type of sampler uses a Sierra-Andersen 254 PM$_{10}$ inlet or Bendix PM$_{2.5}$ cyclone to provide the required size fractions. The ambient air is transmitted through the size-selective inlet

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**Figure 1.** Photograph of two of the instrumented towers used to measure the emissions from the artillery backblast. The “master” tower is on the left and a “satellite” tower is on the right.

**Figure 2.** Schematic diagram of the locations and dimensions of the flux planes for the three-tower array. Symbols S1 and S2 denote the “satellite” towers and M the “master” tower. Black diamond and black square symbols in each of the rectangles indicate the location of the paired PM$_{10}$ and PM$_{2.5}$ instruments. Wind speed was measured at each symbol location in the middle grid, and wind direction was measured at the top position in this grid array. Wind direction during testing the wind direction was generally into the page in this diagram. The shaded rectangle labeled “A,” corresponds with a rectangle that eq 1 is applied to for calculating the PM flux through that defined vertical plane.

**Table 1.** Modular Artillery Charge System combinations used to generate emissions using a 155-mm model M198 or M109 howitzer.

<table>
<thead>
<tr>
<th>Projectile Model</th>
<th>Propelling Charge Model</th>
<th>Charge Zone</th>
<th>No. of Firing Events Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>M107</td>
<td>M231</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>M107</td>
<td>M3A1</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>M5491A</td>
<td>M203A1</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>M795</td>
<td>M203A1</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>
and into a plenum. For the inlet to provide its cutoff size, a flow rate of 113 L/min must be maintained through the sampler. Flow rates of 56.5 L/min through Savillex filter holders were used to collect adequate samples for gravimetric and chemical analyses. This flow rate was drawn simultaneously through two parallel filter packs, one with a ringed 47-mm Teflon-membrane filter (Gelman Scientific) and one with a 47-mm quartz-fiber filter (Pallflex Corp). The flow rates were set with a calibrated rotameter and were monitored with the same rotameter at each

Figure 3. (a) Time series of PM$_{10}$ for a zone 5 firing event and (b) for a zone 1 event. Higher concentrations of PM$_{10}$ are observed at 8 m because of the emission of combustion particles from the elevated gun barrel.
sample change. These PM\textsubscript{10} and PM\textsubscript{2.5} samplers were positioned ~20 m downwind from the artillery pieces. For collecting aerosol samples, the samplers were turned on just before the firing events and turned off at the end of the test sequence.

The Teflon-membrane filters were weighed on a Cahn 31 Electro-microbalance, before and after sampling, to determine mass concentrations. Chemical analyses were performed on Teflon-membrane and quartz-fiber filters following the methodology described by Watson and Chow.4 The Teflon-membrane filters were analyzed for elements by X-ray fluorescence (XRF) using a PANalytical Epsilon 5 spectrometer. One half of the quartz filter was extracted with distilled-deionized water. The extract was analyzed for chloride, nitrate, and sulfate ions by ion chromatography (IC) using a Dionex 4000I ion chromatograph, for ammonium by automated colorimetry using an Astoria Pacific autoanalyzer, and for sodium and potassium by a Varian 880 Double Beam Atomic Absorption Spectrometer. One half of the quartz-fiber filter was analyzed for elements by X-ray fluorescence (XRF) using a PANalytical Epsilon 5 spectrometer. One half of the quartz filter was extracted with distilled-deionized water. The extract was analyzed for chloride, nitrate, and sulfate ions by ion chromatography (IC) using a Dionex 4000I ion chromatograph, for ammonium by automated colorimetry using an Astoria Pacific autoanalyzer, and for sodium and potassium by a Varian 880 Double Beam Atomic Absorption Spectrometer. Organic and elemental carbon (EC) were measured by thermal/optical reflectance on 0.5-cm\textsuperscript{2} punches taken from the remaining half of the quartz-fiber filter.5

PM emissions from artillery backblast were monitored during regular testing programs being operated under the control of YPG engineers. Over the testing period, 70 plumes were measured at three different locations at the YPG. Data presented represent firings from a 155-mm artillery piece (Model M198 or M109 Howitzer). The emissions were created from the firing of the 155-mm shells that can vary in three ways: (1) projectile model, (2) propelling charge model, and (3) charge zone. Charge zone is the most important of these characteristics, because it represents the amount of propellant. The first two characteristics describe design elements of the artillery shell and charge. The combinations of the Modular Artillery Charge System represented by the above listed criteria measured at the YPG are listed in Table 1. For all of the measurements, the moisture content of the improved surfaces, expressed as a percentage difference between the weight of samples before and after oven drying, was <0.5%.

RESULTS

PM Emissions

PM\textsubscript{10} and PM\textsubscript{2.5} emissions were calculated for each downwind tower by integrating the flux of particles through a vertical surface downwind of the firing position that was represented by 15 rectangles (Figure 2). It was assumed that the concentrations measured by each PM\textsubscript{10}/PM\textsubscript{2.5} DustTrak pair were representative of a rectangle with height that spanned from halfway to the DustTrak pair located lower to the ground up to halfway to the DustTrak pair located higher from the ground (see Figure 2). The vertical span height defining each rectangle was arbitrarily set. The upper and lower limits of each rectangle were based on an expected exponential decrease in mass concentration as a function of height, as observed in

Figure 4. Individual PM\textsubscript{10} and PM\textsubscript{2.5} emission flux measurements (g PM/unit firing) for the 155-mm howitzer firing three different zone charges for four different measurement periods: (a) zone 1, (b) zone 2, (c) zone 5, and (d) zone 5.
many PM concentration profiles of fugitive emissions originating at the ground surface. The width of the rectangle was equal to twice the distance between adjacent towers. The wind direction and the wind speed measured at the five heights on the “master” tower were used to calculate fluxes for all of the towers.

The time series of the PM10 and PM2.5 concentrations were examined for each DustTrak at each location (Figure 3), and peak start and stop times were identified for every firing event. An emission factor (EF) for each event was calculated using the following equation:

$$EF = \alpha \left[ \cos(\theta) \sum_{FT=1}^{3} \sum_{i=1}^{5} \sum_{t=0}^{T} u_{FT} \cdot C_{i,FT} \cdot A_{i,FT} \cdot (1 \text{ sec}) \right]$$

where $FT$ represents the tower number, $i$ refers to the rectangle represented by the DustTrak height, $t$ is the time (seconds) after the peak starts, $T$ is the total peak duration (seconds), $u$ is the wind speed (meters per second$^{-1}$), $C$ is the measured concentration (grams per meter$^{-3}$), $A$ is the area (meter squared) of the rectangle corresponding to position $i$, $\theta$ is the angle of the 1-sec average wind direction relative to the flux plane, and $\alpha$ is a constant that is discussed below. For all of the EF calculations, only the concentration data associated with wind approach angles ($\theta$) of $\leq 45^\circ$ with respect to the tower line were used.

The DustTrak instrument used to measure PM$_{10}$ and PM$_{2.5}$ is a portable, battery-operated, laser photometer that uses light scattering technology to infer mass concentration based on a factory calibration with a specific

<table>
<thead>
<tr>
<th>Test Date</th>
<th>Zone Charge</th>
<th>PM10 Min Emission Flux (g per firing event)</th>
<th>PM10 Max Emission Flux (g per firing event)</th>
<th>PM10 Mean Emission Flux (g per firing event)</th>
<th>PM10 SD Emission Flux (g per firing event)</th>
<th>PM2.5 Min Emission Flux (g per firing event)</th>
<th>PM2.5 Max Emission Flux (g per firing event)</th>
<th>PM2.5 Mean Emission Flux (g per firing event)</th>
<th>PM2.5 SD Emission Flux (g per firing event)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/20/2006</td>
<td>1</td>
<td>2.5</td>
<td>44.3</td>
<td>19.0</td>
<td>16.5</td>
<td>1.2</td>
<td>22.4</td>
<td>8.5</td>
<td>6.5</td>
</tr>
<tr>
<td>10/27/2006</td>
<td>2</td>
<td>2.6</td>
<td>66.9</td>
<td>28.6</td>
<td>19.8</td>
<td>2.6</td>
<td>68.9</td>
<td>28.6</td>
<td>19.8</td>
</tr>
<tr>
<td>10/24/2006</td>
<td>5</td>
<td>0.1</td>
<td>134.7</td>
<td>45.2</td>
<td>50.2</td>
<td>0.1</td>
<td>134.7</td>
<td>45.2</td>
<td>50.2</td>
</tr>
<tr>
<td>10/27/2006</td>
<td>5</td>
<td>1.3</td>
<td>103.3</td>
<td>54.0</td>
<td>30.1</td>
<td>1.3</td>
<td>103.3</td>
<td>54.0</td>
<td>30.1</td>
</tr>
</tbody>
</table>

Notes: SD = standard deviation.

Figure 5. Mean PM$_{10}$ and PM$_{2.5}$ emission fluxes from a 155-mm howitzer plotted as a function of charge zone. ■ represent the PM$_{10}$ emission flux, and ◇ represent the PM$_{2.5}$ emission flux.
type of aerosol. The relationship between particle light scattering and particle mass concentrations varies with aerosol properties, such as chemical composition and aerosol size distribution. Therefore, PM\(_{10}\) and PM\(_{2.5}\) mass concentrations measured by the DustTraks were compared with average mass concentration values obtained through gravimetric analysis of the filter samples. The comparison revealed that the PM\(_{10}\) and PM\(_{2.5}\) concentrations reported by the DustTrak were higher than those measured by filter methods. In eq 1, the proportionality constant \(\alpha\) is included to correct for the discrepancy between PM concentrations reported by the DustTrak and those measured by traditional gravimetric methods. The value of \(\alpha\) is either 0.36 (±0.02) or 0.49 (±0.02), depending on whether EF is being calculated for PM\(_{10}\) or PM\(_{2.5}\), respectively. These values are based on comparing the 8-hr average (based on 1-sec data) DustTrak readings of PM\(_{10}\) and PM\(_{2.5}\), with the integrated filter samples for October 27, 2005. Uncertainty in the ratios is reported as the coefficient of variation (in both cases, 5%) for the gravimetric measurements of PM\(_{10}\) or PM\(_{2.5}\). However, because the interinstrument variability is reported by the manufacturer to be ±0.1% of the measurement reading, more realistic uncertainties in \(\alpha\) are ±0.04 and ±0.05 for PM\(_{10}\) and PM\(_{2.5}\), respectively.

The measured PM\(_{10}\) and PM\(_{2.5}\) EFs (grams of PM emitted per firing event) for each firing are shown in Figure 4, a–d. The four panels in the figure correspond with the combinations of artillery piece, projectile model, propelling charge model, and charge zone shown in Table 1. The range of estimated emission flux values and the mean and standard deviation of emission flux for each zone are listed in Table 2. These emission flux data show a high degree of variability, as evidenced by the high standard deviation of the mean values. The emissions do not show dependence with wind direction. However, the variability likely results, in part, from a combination of low wind speeds that occurred for certain tests combined with the variability of the wind direction as the wind transports the particles to the flux plane. Typically the dust plumes impacted all three of the towers, which suggest minimum widths of 50 m. This is corroborated by optical remote sensing measurements made by Varma et al.\(^8\) of the same plumes, which were almost coincident with the tower measurements. They report plumes widths of ~70 m near the ground. Mean emission flux is plotted as a function of zone in Figure 5. The emissions of PM\(_{10}\) and PM\(_{2.5}\) scale linearly with zone (i.e., propellant amount).

**PM Characterization**

Two examples of time series of PM\(_{10}\) concentrations made at the sampling heights on the “master” tower, which were typical of most plumes, are shown in Figure 3, a and b. The vertical concentration profile of PM suggests two distinct zones, one near the surface and the other near the top of the towers. The elevated concentrations near the ground represent dust raised from the surface, and the elevated concentrations at ~8–12 m represent the PM created by the combustion of the propellant charge, which exits the elevated gun barrel. The particles exiting the barrel of the artillery were clearly visible as a smoke cloud that was variable in color from white to gray. The particles emitted from the surface created plumes that were tinged the color of the surface material.

Comparative plots for the PM constituents likely derived from soils at the test sites are shown in Figure 6a. The soils at the improved sites can be characterized as clay-rich sands with iron oxides and calcium carbonate. The calcium carbonate component likely originates from the soils as well. The YPG is located within an area of the United States in which carbonate-rich or calcic soils are found.\(^8\) Some of the calcium may also be attributed to the addition of dust palliatives to the firing position surface.
materials in an attempt to limit dust emissions. The high percentage of potassium could be bound as potassium silicates but could also be ascribed to potassium salts added as binding agents to reduce the dust emissions on the firing pads. X-ray powder diffraction confirmed the presence of microcline, a potassium aluminum silicate, in the samples.

Emissions of PM originating from the gun barrel contain large amounts of organic (OC) and elemental carbon (EC), with smaller amounts of organic sulfur (Figure 6b). Organic sulfur is defined by the difference between the total sulfur measured by XRF and sulfur in sulfate, as measured by IC. Anomalously high metals contents, especially for copper and lead, were found for some of the samples (Figure 6c) and are assumed to originate from the artillery shell. These metallic particles may originate in the emissions from the gun barrel or may have been deposited and accumulating in the surface soil over many

Figure 7. The apportionment of the measured species in the backblast PM$_{10}$ and PM$_{2.5}$ for three different sampling periods. Nomenclature for the abbreviations: soil-derived potassium nitrate (PotNit), soil-derived sulfates (Soil Sulf), soil-derived chlorides (Soil Cl), and secondary ammonium (Sec Amm). (a and b) YPG site 1, (c and d) YPG site 2, and (e and f) YPG site 3.
years, and during disturbance of the soil by the force of the backblast, the dust particles with attached metals may have been resuspended.

The apportionment of the chemical components of the PM$_{10}$ and PM$_{2.5}$ from the collected samples is shown in Figure 7. Partitioning the PM$_{10}$ and the PM$_{2.5}$ to the principal sources, that is, the soil-derived dust (silicates and oxides, chloride, sulfates, and calcite), the combustion products of the propellant (OC and EC), and the metals, the average percentage of the PM$_{10}$ that is soil-derived is 64% ($\pm$10%) and 53% ($\pm$7%) for the PM$_{2.5}$. The second most prominent component, the carbonaceous aerosol emissions from the combustion of the propellant, compose, on average, 21% ($\pm$13%) of the PM$_{10}$ emissions and 33% ($\pm$12%) of the PM$_{2.5}$ emissions. The remaining species vary considerably between the samples, but the metal components of the emissions ($\sim$4–5%) are important contributors in most cases.

**DISCUSSION**

Based on observations of backblast emissions made at YPG, a conceptual model of the emission process is presented. The mechanics of the backblast process are very different from other fugitive emission sources.$^{1,11,12}$ The emission mechanism is hypothesized to be the force that is transferred to the soil surface by the detonation of the propellant. As the backblast force impacts the earth surface at the gun position, the earth responds by compressing and then rebounding. The rebound ejects the dust vertically into the atmosphere where it is subsequently transported by the wind (Figure 8). The greater the force created by the artillery blast, the greater is the potential to raise dust as demonstrated by the relationship between emission flux and zone shown in Figure 5.

Several characteristics of the surface are expected to limit the emissions. The most important surface characteristics are hypothesized to be the availability of dust-sized particles and the amount of cohesion in the earth material that the artillery piece is sitting upon. Cohesion will be affected by the textural qualities of the soil material, climate-driven pedogenic processes, and moisture content. The expected effects of the availability of PM and particle cohesion on emission potential are illustrated in Figure 9. This figure shows that if the artillery were fired while sitting on a bed of only sand-sized particles with no cohesion, there would be no emissions of PM$_{10}$ or PM$_{2.5}$ from the surface. The other end of the scale (Figure 9) describes a situation wherein the PM$_{10}$ or PM$_{2.5}$ is held in a strong matrix of material, and the force of the backblast is insufficient to liberate it from the surface creating a low potential for PM emissions. Dust emissions from backblast will maximize at an optimum balance between supply of PM and strength of the substrate material on which the artillery is fired.

Based on available DoD data of the number of rounds of artillery shells fired for 2004, an estimate of the annual contributions of dust emission from the 15 most frequently fired howitzers and vehicles with artillery capabilities can be developed. The annual PM emissions for artillery backblast are based on the assumptions that all of the firings use a charge zone 5, and all of the artillery pieces are equivalent to the 155-mm piece tested at YPG. This is likely an overestimate, because zone 5 is the maximum charge used in training and testing and some activities may use lower zones and because a significant fraction ($\sim$33%) of the artillery shown in Table 3 corresponds with guns with calibers $<$155 mm. Based on the total number of rounds fired in 2004, the maximum emission contributions for PM$_{10}$ and PM$_{2.5}$ based on the scenario described above is 52.2 t (57.4 U.S. short tons) and 28.5 t (31.4 U.S. short tons), respectively.

EPA provides average annual emissions inventory for all of the criteria pollutants for 1970–2002 (www.epa.gov/ttn/chief/trends/index.html). In comparing the estimates of contributions of PM$_{10}$ and PM$_{2.5}$ from backblast with the total 2002 fugitive dust contributions (Table 4), backblast emissions are equivalent to $5 \times 10^{-4}$% of the total fugitive PM$_{10}$ contributions and $1.6 \times 10^{-3}$% of the total fugitive PM$_{2.5}$ contributions. Comparison of the estimated backblast emission levels with subcategories of fugitive dust sources (i.e., unpaved roads, paved roads, construction sites, and other) is also provided in Table 4 for 2002 or the most recent year before 2002 with available data.
Table 3. The top 15 most frequently fired artillery and their gun bore size, the number of rounds fired in 2004, and estimates of their emission of PM$_{10}$ and PM$_{2.5}$ based on the emission flux for a 155-mm howitzer firing a zone 5 charge.

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Total Rounds Fired</th>
<th>Gun Bore (mm)</th>
<th>PM$_{10}$ Flux (kg)</th>
<th>PM$_{2.5}$ Flux (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1A1 Abrams main battle tank</td>
<td>346,819</td>
<td>120</td>
<td>29,826</td>
<td>16,300</td>
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<tr>
<td>M1A2 Abrams main battle tank</td>
<td>85,529</td>
<td>120</td>
<td>7355</td>
<td>4020</td>
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<tr>
<td>M1096A6 Paladin</td>
<td>38,555</td>
<td>155</td>
<td>3316</td>
<td>1812</td>
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<tr>
<td>M1IP Abrams main battle tank</td>
<td>31,305</td>
<td>105</td>
<td>2692</td>
<td>1471</td>
</tr>
<tr>
<td>M551A1 Sheridan</td>
<td>22,809</td>
<td>152</td>
<td>1962</td>
<td>1072</td>
</tr>
<tr>
<td>M1064A3 SP 120 mm mortar</td>
<td>21,709</td>
<td>120</td>
<td>1867</td>
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<td>M119A1 LW towed howitzer</td>
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<td>105</td>
<td>1595</td>
<td>872</td>
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<tr>
<td>M10945 SP howitzer</td>
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<td>120</td>
<td>1287</td>
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<tr>
<td>M1064 SP 120 mm mortar</td>
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<td>M102 I-W towed howitzer</td>
<td>3930</td>
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<td>M60 series tank (Patton series)</td>
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<td>M728 combat engineer vehicle</td>
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<td>M106 SP 120 mm mortar</td>
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<td>Sum</td>
<td>606,737</td>
<td></td>
<td>52,179</td>
<td>28,517</td>
</tr>
</tbody>
</table>

Notes: $^{a}$PM$_{10}$ (kg) = 0.086 $\times$ number of rounds fired; PM$_{2.5}$ (kg) = 0.047 $\times$ number of rounds fired.

Because we were not able to measure backblast emissions created by firing on an improved surface (i.e., surfaces with no amendments or alteration), the effect on the magnitude of the emissions from this type of surface remains unknown. The split between the numbers of tests carried out on improved versus unimproved artillery firing positions at DoD installations is poorly resolved. At the YPG it appears that most testing occurs on improved sites typical of the ones tested, but at another installation, the Yakima Training Center, Yakima, WA, where artillery are fired for training purposes, all of the firing positions are unimproved.$^{13}$ If we assume somewhat conservatively, however, that the emissions of fugitive dust PM (combustion component would not change) was two orders of magnitude higher than at improved sites, the contribution to annual U.S. emissions would still only represent 0.05% of the total fugitive PM$_{10}$ contributions and 0.16% of the total fugitive PM$_{2.5}$.

Comparing emission estimates from backblast activities with emission estimates for wheeled vehicles traveling on unpaved roads using the relationships presented by Gillies et al.$^{1}$ is instructive. Assuming that a common military vehicle, such as a HMMWV (high-mobility multipurpose wheeled vehicle), is traveling 50 km hr$^{-1}$ and emitting at a rate of 460.5 g of PM$_{10}$ per vehicle kilometer traveled,$^{1}$ only 186 m of travel would be required to exceed the firing of a 155-mm howitzer using a charge zone 5. For a heavier vehicle, such as the HEMMT (heavy expanded mobility tactical truck) (18,000 kg), only 36 m of travel (at 50 km hr$^{-1}$) are required to achieve equivalence with an artillery shot.

Table 4. Amount of PM$_{10}$ and PM$_{2.5}$ by source category for 2002 (or the most recent year before 2002 with data available) from EPA and comparisons with the backblast contributions expressed as a percentage of each source category.

<table>
<thead>
<tr>
<th>Source Category</th>
<th>PM$_{10}$ Year, 2002 (t)</th>
<th>PM$_{2.5}$ Year, 2002 (t)</th>
<th>Backblast Contributions of Source Category Estimated Using Average Zone 5 EF$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{10}$ Total</td>
<td>20,140,000</td>
<td>0.0003</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>Fugitive dust</td>
<td>11,396,364</td>
<td>0.0005</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>Unpaved roads</td>
<td>1,885,455</td>
<td>0.0003</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>Paved roads</td>
<td>1,706,364</td>
<td>0.0003</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>Construction (1995)</td>
<td>3,321,818</td>
<td>0.002</td>
<td>Average Zone 5 EF$^a$</td>
</tr>
<tr>
<td>Other (2001)</td>
<td>7273</td>
<td>0.7</td>
<td>PM$_{10}$</td>
</tr>
<tr>
<td>PM$_{2.5}$ Total</td>
<td>6,870,909</td>
<td>0.0004</td>
<td>Average Zone 5 EF$^a$</td>
</tr>
<tr>
<td>Fugitive dust</td>
<td>1,791,818</td>
<td>0.0016</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Unpaved roads</td>
<td>280,909</td>
<td>0.01</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Paved roads</td>
<td>340,909</td>
<td>0.008</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Construction (1995)</td>
<td>706</td>
<td>4</td>
<td>Average Zone 5 EF$^a$</td>
</tr>
<tr>
<td>Other (2001)</td>
<td>1</td>
<td>3137</td>
<td>PM$_{2.5}$</td>
</tr>
</tbody>
</table>

Notes: $^{a}$PM$_{10}$ (kg) = 0.086 $\times$ number of rounds fired; PM$_{2.5}$ (kg) = 0.047 $\times$ number of rounds fired.

CONCLUSIONS

As part of a larger study to characterize and quantify emissions of fugitive dust from unique DoD activities, measurements were made for emissions created by backblast from firing artillery on improved gun positions at the YPG in October 2005. For a 155-mm howitzer firing a range of propellant charges or zones, amounts of emitted PM$_{10}$ ranged from $\sim$19 g of PM$_{10}$ per firing event for a zone 1 charge to 92 g of PM$_{10}$ per firing event for a zone 5. The corresponding rates for PM$_{2.5}$ were $\sim$9 g of PM$_{2.5}$ and 49 g of PM$_{2.5}$ per firing. The average measured emission rates for PM$_{10}$ and PM$_{2.5}$ appear to scale as a function of the zone charge value (Figure 5).

The estimated contributions of PM$_{10}$ and PM$_{2.5}$ from the measured artillery backblast emission rates would be at levels that are orders of magnitude lower than any of the recognized source categories defined as fugitive emissions. From the perspective of control measures, reducing PM emissions from artillery backblast activities would not be a cost-effective measure for DoD installations to consider for lessening the PM burden in areas adjacent to installations where this activity occurs. More effective reductions in this burden are likely to result from mitigative measures designed to reduce contributions of PM created by vehicular activity.

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