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Aerostat-based sampling of emissions from open burning and open detonation of military ordnance

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HIGHLIGHTS

- PM emission factors were higher for soil-covered vs surface detonations.
- Large amounts of soil were ejected during detonations and entrained into the plumes.
- Energetics in the detonation plumes were less than 0.0005% of original munitions.
- Al-containing AP propellants showed that 7–17% of Al partitioned to the emissions.

GRAPHICAL ABSTRACT

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ABSTRACT

Emissions from open detonation (OD), open burning (OB), and static firing (SF) of obsolete military munitions were collected using an aerostat-lofted sampling instrument maneuvered into the plumes with remotely controlled tether winches. $PM_{2.5}$, PM_{10}, metals, volatile organic compounds (VOCs), energetics, and polyaromatic hydrocarbons (PAHs) were characterized from 121 trials of three different munitions (Composition B (hereafter, "Comp B"), V453, V548), 152 trials of five different propellants (M31A1E1, M26, SPCF, Arc 451, 452A), and 12 trials with static firing of ammonium perchlorate-containing Sparrow rocket motors. Sampling was conducted with operational charge sizes and under open area conditions to determine emission levels representative of actual disposal practices. The successful application of the tethered aerostat and sampling instruments demonstrated the ability to sample for and determine the first ever emission factors for static firing of rocket motors and buried and metal-cased OD, as well as the first measurements of $PM_{2.5}$ for OB and for surface OD.

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1. Introduction

Open burning (OB) and open detonation (OD) are used to dispose of obsolete military munitions, and static firing (SF) is used to destroy obsolete rocket motors. In OB, the materials are placed in a steel pan and ignited. In SF, the rocket motor is placed either vertically, facing down, or held in place horizontally and fired. Explosives are destroyed at ground level (surface detonation) or buried under a soil cover. In the U.S., most demilitarization facilities use the buried detonation method because they are located near population centers and want to minimize blast noise, blast overpressure, and shrapnel travel distance.

In the U.S., OB, OD and static firing are regulated under environmental permits that use pollutant dispersion models and emission factors (EFs) to set limits on the quantities of the munitions and rocket motors that can be destroyed over a specified time period. The EFs used for these permits were derived through a series of OB and uncovered OD emission plume characterization studies conducted at Dugway Proving Ground, UT (DPG) between 1989 and 1995 [1,2] and at the Nevada Test Site, NV, between 1997 and 2000 [3,4] that attempted to simulate real-world OB and OD operations. Some of the EFs were derived by flying an instrumented aircraft through OB and OD plumes produced on an open test range, but most of the EFs were derived by sampling OB and OD plumes held in a detonation chamber (BangBox). However, these efforts did not credibly address EFs for buried detonations and static fire events, and there were no $PM_{2.5}$ (particulate matter (PM) with an aerodynamic diameter less than or equal to 2.5 μm) EFs for OB events [5], leading the U.S. Department of Defense (DOD) to conclude that open test range experiments were needed to derive the missing EFs [6].

The difficulty of open atmosphere sampling [7] and questions regarding the representativeness of small-charge and enclosed conditions from BangBox tests [8] have prompted efforts to determine and further validate representative emission factors. These efforts must address the inherent difficulty of sampling OB/OD emission plumes: rapid dispersion, short event duration, heterogeneous emission concentrations, large plume lift, soil entrainment, and explosive safety restrictions. Improvements to the sampling methods and equipment for conducting open atmosphere emissions testing for OB/OD can help to develop and verify these emission factors as well as produce a larger set of high quality emission factors that address known data gaps.

Emissions of concern include $PM_{2.5}$ and PM_{10} (PM with an aerodynamic diameter less than or equal to 10 μm) metals, volatile organic compounds (VOCs), energetics, and polyaromatic hydrocarbons (PAHs). $PM_{2.5}$ can cause decreased visibility in the form of haze and is also a criteria pollutant regulated by the U.S. EPA due to its adverse health effects. VOCs are comprised of many compounds, a number of which are on the U.S. EPA's list of hazardous air pollutants (HAPs) [9]. For example, benzene is a VOC that is toxic to humans, and toluene can form ground level ozone, a criteria pollutant tied to respiratory ailments. PAHs are a large group of compounds, 16 of which are prioritized by U.S. EPA since some of them have mutagenic and carcinogenic properties [10]. Energetics such as 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) include toxics and possible human carcinogens [11–13].

The objective of this effort was to: (1) determine the applicability of an open air sampling methodology [14] to the first ever determination of emission factors from open detonations of metal-encased munitions and static firing of rocket motors; (2) determine distinctions in emissions from different methods of OB and OD disposal; and (3) develop methods for aerial sampling and quantification of semi-volatile energetics. Specifically, emission factors were derived for open pan burns of single-, double-, and triple-base propellants (comprised of nitrocellulose (NC), nitroglycerin (NG), and nitroguanidine (NQ) bases), open pan burns and static firing of perchlorate-based rocket propellants, open and buried detonations of bulk explosives, and buried detonations of metal-cased munitions. These munitions were selected for this testing based on their representativeness of the U.S. demililtarization stockpile, emission uncertainties, emission factor data quality issues, and uncertainties in the analyte-specific sampling methods. Sampling was performed using a lightweight, aerostat-lofted instrument/sampling apparatus maneuvered into the OB and OD plumes for continuous monitoring and batch sample collection.

2. Experimental method

Two three-week field campaigns for OB and OD of military munitions were conducted at the Tooele Army Depot, Utah, USA, March 2011 and June 2012, respectively.

2.1. Munitions

Air emissions from OD of three different munitions (Composition B hereafter, "Comp B", V453, V548), and OB of five different propellants (M31A1E1, M26, SPCF, Arc 451, and 452A) were characterized. In addition, air emissions from static firing of a rocket motor (Sparrow, SRM) were also characterized. Two of the propellants (Arc 451, 452A) and the rocket motor were ammonium perchlorate (AP)-based, while the SPCF was a single-base (94% NC), M26 was a double-base (67% NC and 25% NG), and M31A1E1 was a triple-base (22% NC, 18% NG, and 55% NQ). The composition of the propellants, munitions, and detonation donor charges are shown in Table 1.

2.2. Aerostat sampling method

An aerostat-borne instrument package named the "Flyer" (Fig. 1) was used to sample emissions from soil-covered and uncovered ODs, OB in pans, and static firing of rocket motors (Fig. 2). This aerial sampling method has been described in detail elsewhere [14–17]. In summary, the method used a 4.3 m-diameter helium-filled aerostat to loft the Flyer instrument package. Two all-terrain vehicles (ATVs), each mounted with a remotely controlled electric winch with 305 m-long tethers, were used to anchor and maneuver the aerostat into the emission plume. The instrumented Flyer contains an onboard computer with a data acquisition and control program and wireless communication which enables viewing data in real time as well as controlling the sampling process from the ground. During one exceptionally windy test day which precluded safe aerostat operation, two Flyers were attached to a forklift approximately 2.5 m above ground level to sample emissions.

2.3. Instrumentation, sampling and analytical methods

The instrumentation on the Flyer was varied depending on the composition of the different munition types (Table 2; Fig. 1). Carbon dioxide (CO_2) was measured continuously for all munition trials and was subject to daily three-point calibrations for CO_2 according to U.S. EPA Method 3A [18]. Energetics (HMX, RDX, and TNT) and by-product compounds were analyzed from the PM collected on a large (20.3 cm × 25.4 cm) quartz filter from the OD tests, as past experience with energetic sampling at Dugway Proving Ground [19] suggested that the airborne energetic compounds were solely associated with the particles. This assumption enabled collection of a large sample using the Flyer's high surface area filter and its high volume pump (1200 L min^{-1}) in an effort to minimize or eliminate non-detects. Composite samples for nitrobenzene and nitrotoluene