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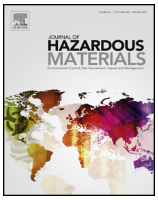

The spatial distribution patterns of condensed phase post-blast explosive residues formed during detonation

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HIGHLIGHTS

- Particle distribution patterns from explosive releases are analyte specific.
- Applications of mathematical models to particle movement are unsuitable.
- The dominant particle dispersal mechanism is the smoke plume, governed by the wind.

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ABSTRACT

The continued usage of explosive devices, as well as the ever growing threat of 'dirty' bombs necessitates a comprehensive understanding of particle dispersal during detonation events in order to develop effectual methods for targeting explosive and/or additive remediation efforts. Herein, the distribution of explosive analytes from controlled detonations of aluminised ammonium nitrate and an RDX-based explosive composition were established by systematically sampling sites positioned around each firing. This is the first experimental study to produce evidence that the post-blast residue mass can distribute according to an approximate inverse-square law model, while also demonstrating for the first time that distribution trends can vary depending on individual analytes. Furthermore, by incorporating blast-wave overpressure measurements, high-speed imaging for fireball volume recordings, and monitoring of environmental conditions, it was determined that the principle factor affecting all analyte dispersals was the wind direction, with other factors affecting specific analytes to varying degrees. The dispersal *mechanism* for explosive residue is primarily the smoke cloud, a finding which in itself has wider impacts on the environment and fundamental detonation theory.

1. Introduction

The majority of research related to post-blast chemical data is centred on the development of novel sampling techniques and optimisation of analytical methods for trace explosive residues. Whilst these are necessary and important research foci, a distinctly disproportionate amount of research has been conducted in establishing the types of trace chemicals that may remain following detonation in the first instance. For example, how do explosive residues remain in their undecomposed form during detonation, how do they disperse, and therefore where can they be found in the environment? By answering such questions, we would be better placed to act in the aftermath of a radiological dispersive device ('dirty' bomb) or improvised explosive device modified to contain chemical or biological warfare agents, for example. Knowledge regarding the dispersal and fate of particles would not only benefit environmental decontamination efforts but would also assist in forensic investigations. Undetonated explosive particles that remain after detonation can provide critical intelligence regarding the explosive charge used and indicate the perpetrators of an explosive attack [1]. Current knowledge regarding post-blast residue location has developed with experience over time but the prevailing requirement to be prepared to face new threats [2], as well as validate and strengthen the scientific underpinning of forensic practices [3], calls for further research.

Given the impracticalities of experimenting with explosive charges modified with hazardous additives, we first focus on monitoring the distribution trends of known explosive ana-

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lytes during detonation. In doing so, it will become possible to develop models that can assist in elucidating the particle dispersal behaviours of other, more harmful, potential additives. Both 1,3,5-Trinitroperhydro-1,3,5-triazine (RDX) and ammonium nitrate (AN) are widely used explosives, in both military and criminal contexts, which leave undetonated residues and for which the decomposition mechanisms have been studied extensively. In the solid state, the most supported mechanism for the initial unimolecular decomposition step of RDX begins with the loss of a single NO_2 molecule [4] via homolytic cleavage of an N—NO_2 bond [5,6], which is followed by the rupture of the chain into intermediate products. The final gaseous products formed through these decompositions are energetically stable and form strongly bonded species such as CO_2, H_2O and N_2 [7] (Eq. (1)).

$$C_3H_6N_6O_{6(s)} \rightarrow 3CO_{(g)} + 3H_2O_{(g)} + 3N_{2(g)} \quad (1)$$

Whilst RDX has a deficient number of oxidising atoms for complete combustion (oxygen balance (OB) of −21.6%), theoretically, no parent explosive molecules should remain following detonation. The energy release is increased as the fuel-rich product gases undergo afterburning with atmospheric oxygen, which is facilitated by turbulent mixing within the fireball [8].

The decomposition of the bimolecular AN has been studied broadly but is not understood as well [9]. Investigations into the effect of the shock stimulus on AN decomposition have indicated the break-up of the $NH_4{}^+$ ion occurs initially, possibly followed by decomposition of the $NO_3{}^-$ ion [10]. Ultimately, the gaseous products formed are N_2, H_2O and O_2 [7]. As a fuel-lean explosive (OB of +20%) AN combusts fully (Eq. (2)).

$$NH_4NO_{3(s)} \rightarrow N_{2(g)} + 2H_2O_{(g)} + \tfrac{1}{2}O_{2(g)} \quad (2)$$

The addition of combustible light metals (e.g. aluminium) to non-ideal explosives such as AN, improves their energetic efficiency by increasing the reaction velocity and temperature [7,11]. In the case of aluminised ammonium nitrate (AlAN), the high temperature AN decomposition products heat the aluminium particles, which evaporate upon reaching their ignition temperature and react in the gaseous phase; either aerobically with oxygen in shock compressed air or anaerobically with oxidants in the detonation products [12,13]. Reactions occur behind the principle reaction front during the expansion of the gases [13–16], with the main combustion product being aluminium oxide [14,15]. Given that the afterburning of aluminium releases more energy, which further enhances the blast effects by increasing the overpressure impulse produced [12,15,17], it is again counter-intuitive to expect any undecomposed AN molecules to remain post-blast.

Due to the transient, dynamic nature of detonation, it is an understandably challenging task to experimentally investigate the means by which undetonated explosive residue 'survives' detonation; it is generally accepted that incomplete combustion will always occur to varying degrees depending on the explosive type. It may be possible to infer the mechanism(s) however, by investigating how distribution trends vary between different explosives. Our recent review [18] of explosive residue dispersion theories highlighted the effects of the blast-wave and ambient wind field as the two principal potential mechanisms by which explosive residue is dispersed – neither of which have been tested experimentally. The residue distribution patterns have been purported to be based on an inverse-square law distribution [19] (Eq. (3)); a seemingly logical theory for spherical explosive charges (if the particles are assumed to be ejected uniformly from the charge surface), but one that has not been verified.

$$\mathrm{Mass}_1/\mathrm{Mass}_2 = \mathrm{Distance}_2{}^2/\mathrm{Distance}_1{}^2 \quad (3)$$

One of the factors thought to affect the resulting detectable amount of explosive residue is the fireball [19]; the exposure of which onto nearby surfaces may cause degradation of any deposited intact explosive particles and therefore alter any preliminary inverse-square type distributions.

Experimental work to date is mainly limited to studies [20,21] conducted to understand residue distribution at ground-level in order to control explosives leaching through soil and into groundwater. Fewer studies have investigated particle distribution by incorporating perpendicularly positioned sampling sites around detonations of both military and improvised explosives. The few that have [22–25] found conflicting trends of both decreasing and increasing amounts of explosive residue as a function of increasing distance from the charge centre, where issues with sample analysis may have affected the results. Challenges with detecting post-blast residues have led to the use of taggant material as a marker for the explosive [26]; the question of the suitability of such markers in achieving this aim remains open however. Additionally, likely due to the cost of conducting firing trials, the inclusion of repeated firings are limited in previous work. In the limited cases where repeat firings have been possible, variations in the quantity of post-blast explosive residue detected on similar sites following firings of the same explosive charge, configured in the same manner, have demonstrated the unique nature of each detonation event [25].

Using a military and improvised explosive formulation, this study is the first to systematically assess the explosive residue distribution patterns formed following detonations. We incorporate repeated firings and measurement of blast overpressures, environmental conditions and fireball growth in order to test the variables hypothesised to affect explosive particle distribution.

2. Experimental

2.1. Materials

Fertilizer grade ammonium nitrate (AN) prills (Hydro Agri Ltd., UK) were ground to less than 1 mm in diameter using electric processors (average particle size; 0.8 mm). Aluminium powder (10 μm–150 μm average particle diameter, provided by Defence Science and Technology Laboratories, UK) was mixed into the AN in a 10:90 (mass fraction) Al:AN ratio to produce the improvised aluminised AN (AlAN) explosive charges. The military composition used was Plastic Explosive Number 4 (PE4), consisting of 1,3,5-Trinitroperhydro-1,3,5-triazine (RDX) (mass fraction of 88%) as the explosive ingredient and hydroxyl–terminated polybutadiene (HTPB) (mass fraction of ∼12%) as the binder (provided by Cranfield Defence Academy). Each explosive was moulded into six spheres of 0.5 ± 0.001 kg mass each in order to conduct repeat firings (approximately 81.79% and 91.89% theoretical mass density for the organic and inorganic charges respectively). SX2 booster charges (88% RDX and 12% non-explosive plasticiser) and No. 8 Instant Electric detonators (containing ∼0.7 g of Pentaerythritol tetranitrate) were used to produce detonation.

2.2. Experimental design

All firings were conducted at the Explosive Range and Demonstration Area (ERDA) at Cranfield Defence Academy. Charges were positioned atop wooden firing poles and secured in place with adhesive tape around the base of the charge and top of pole. In order to prevent crater formation, and therefore comply with range operating procedures, each charge was placed 2 m from the ground. New firing poles were used per detonation. Booster charges and detonators were positioned in the charge centres from underneath the charge (detonator tip pointing up) and initiation was therefore directed vertically upward in order to avoid directionally biased expansion of product gases in any of the horizontal orientations.