On the Potential of RDX Dust Detonations for Minefield Breaching

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INTRODUCTION

Fuel-air explosives (FAE) have been used for a variety of military applications including minefield breaching. The operation of a FAE device is generally a two-step process in which liquid fuel is dispersed into a combustible droplet-vapour-air cloud during the first stage of the event, and detonation of the heterogeneous cloud is accomplished by a secondary high-explosive charge a short time later. A typical 50-litre FAE test device and accompanying secondary charge are shown in Figure 1. While FAE is attractive for applications in which large area coverage and high specific impulse are of interest, the detonation pressures generated by such clouds are generally low (e.g., 2 MPa) when typical hydrocarbon fuels are employed. Consequently, conventional FAE devices are not effective against deeply buried or blast-hardened anti-tank mines. Two ways of achieving higher pressures are: (i) to employ more energetic materials in a higher loading density configuration, and (ii) to release the available energy more effectively.

The present study was intended to assess the potential of high-explosive (HE) dusts for generating high detonation pressures. Various candidate canister designs incorporating such dusts are illustrated in Figure 2. A typical FAE device containing a central circular fuel dispersal charge is pictured in Figure 2a. A similar device containing HE dust and incorporating a liquid-filled buffer surrounding the dispersal charge is shown in Figure 2b. The purpose of the buffer is to prevent premature ignition or detonation of the dust during its explosive dispersal. The buffer material is ideally an energetic liquid such as a conventional FAE fuel (e.g., propylene oxide). A third concept is a compartmentalized canister (Fig. 2c) intended to produce a layered cloud consisting of a HE dust ground layer and a conventional FAE "covering" cloud above it (see the inset diagram). In this so-called "bimodal" concept [1, 2], the ground layer is initiated by the detonation wave in the covering cloud.

If the proposed canister designs are to work reliably, it is necessary to have knowledge about the detonability

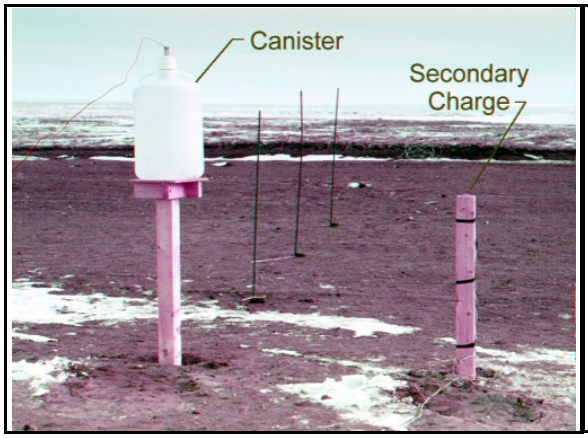

Figure 1. Photograph of typical canister and secondary charge used in detonation experiments.

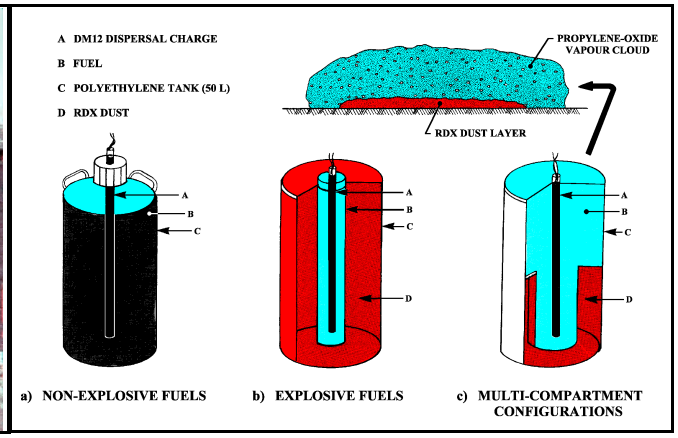

Figure 2. Canister configurations for: (a) non-explosive fuels, (b) high-explosive fuels, and (c) hybrid fuels.

of these dust clouds and to quantify the relevant performance parameters over the range of dust concentrations anticipated in practice. In the first part of this study, a vertical detonation tube is described in which quasi-stationary dust clouds are formed and detonated. The critical charge mass for direct initiation of detonation is established and both the detonation velocity and pressure are measured as a function of dust concentration. In the second part of the study, a rigid detonation tube is used to simulate a portion of the dust layer and covering cloud depicted in Figure 2 under carefully controlled laboratory conditions. It is shown that the highest pressures are realized in this scenario when deflagration-to-detonation transition (DDT) takes place in the vicinity of the outer edge of the dust layer.

Previous studies by Tulis *et al.* [3, 4] employing powerful initiators (between 2.8 and 30 grams A4 explosive) have shown that oxygen-deficient explosives such as TNT will detonate readily in air and in oxygen, but will not detonate in nitrogen. Other more oxygen-balanced explosives such as RDX are capable of detonating in nitrogen and will, in fact, transit to detonation rapidly in air if exposed to a flame or sufficient heat. Kauffman and co-workers at the University of Michigan [5-7] conducted similar shock tube experiments, but used a relatively weak initiator consisting of a helium-diluted hydrogen-oxygen detonation. These authors were unable to detonate RDX in nitrogen and could only detonate oxygen-enriched (12% O_2 addition) RDX-air using 37 or 150 μm particles. Similar mixtures containing smaller particles (i.e., 2 or 10 μm) did not detonate. Both theoretical and experimental results confirm that TNT gives superior detonation performance at low concentrations in comparison with RDX [3] or PETN [4] because the oxygen present in the air enhances the energy release of TNT. RDX dust (Class 5; 22 μm mean particle size) was used in the present work, primarily because of its increased detonation sensitivity over TNT.

EXPERIMENTAL RESULTS

Detonation of Quasi-Stationary RDX Dust Clouds

The dust detonation tube (Fig. 3) constructed by Mining Resource Engineering Limited (MREL) under contract to DRES consisted of a vertical column into which the RDX dust was dispersed. The column was constructed in most cases from a 0.13-mm thick polyethylene sock in order to minimize confinement effects. The circular cross section of the tube was maintained by cardboard rings which also gave the column rigidity for the purposes of securing it to support posts. In a few of the early tests, a cardboard tube having 1-cm thick walls was used instead. A perforated plastic sheet was placed over the top of the column to eliminate wind effects and to hold the C4 (91% RDX) initiation or "primer" charge in a central position. The bottom of the sock was connected to a fan via an elbow and a length of ducting. The fan provided a rising air flow which countered particle settling and permitted full dust dispersal before the primer was detonated. The majority of tests used a 1.83-metre tall by 30-cm diameter column. A 60-cm diameter column was employed in selected tests to further minimize confinement effects.

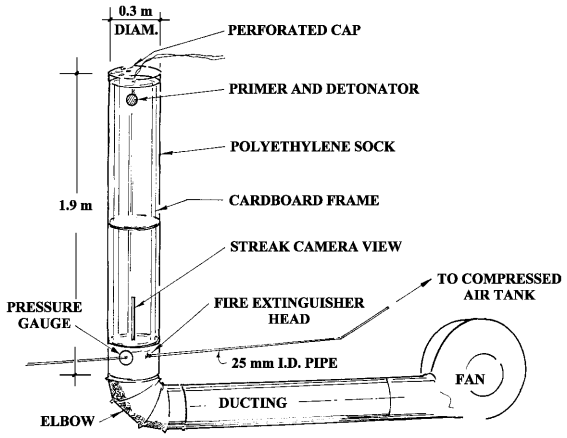

Figure 3. Pictorial of vertical detonation tube used in the RDX dust detonation studies.

The RDX dust was allowed to stand freely in a well ventilated area prior to testing in order to remove the alcohol present during shipping. The slurry was stirred occasionally. When the alcohol was no longer detectable, the dust was placed in an oven at 110 ^{0}C for one to two hours, stirring every quarter hour. Once the dust appeared to be dry, 2% tri-basic calcium phosphate desiccant was added and the mixture returned to the oven. Stirring was thereafter required every five to ten minutes to avoid melting of the desiccant. After fifteen to thirty additional minutes, the dust was considered to be effectively dry. It was then removed and screened through a 400-μm sieve while warm to break up any large agglomerates.

The dust was dispersed at the bottom of the column using a 3-metre long by 25-mm diameter dust-loaded plastic tube fitted with a fire-extinguisher head at one end. A flexible conduit connected the opposite end of this tube to a source of regulated compressed air. The fan speed and dispersal line pressure were adjusted to optimize the dispersal process. Estimates of the dust concentration were made knowing the quantity of powder dispersed and the volume of the column.

Three recording systems were used to monitor the events. The velocities of detonation (VODs) were recorded using a streak/framing camera. A domestic video camera was used to provide qualitative information about the uniformity of the cloud and to identify the optimal time delay between the start of dust dispersal and cloud detonation.

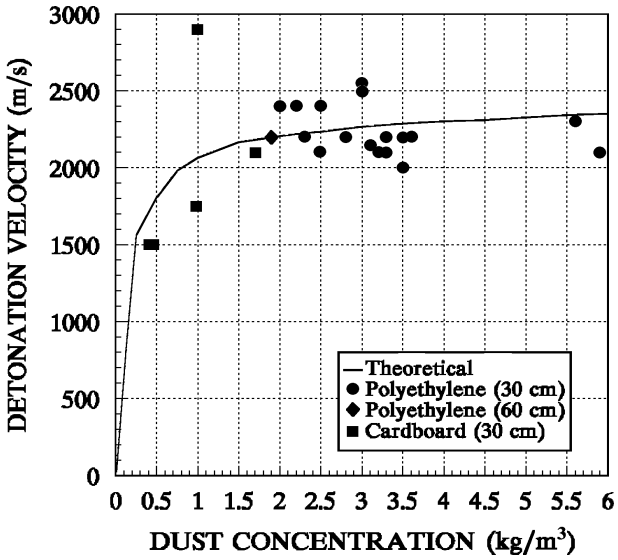

Figure 4. Detonation velocity versus dust concentration for RDX-air mixtures.

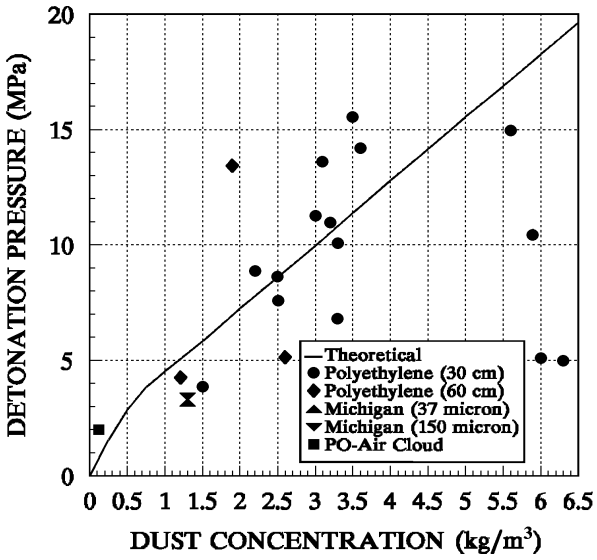

Figure 5. Detonation pressure versus dust concentration for RDX-air mixtures.

Piezoelectric pressure transducers in "lollipop" mounts were used to measure side-on detonation pressure in the column.

The experimental detonation velocities and pressures are plotted as a function of dust concentration in Figures 4 and 5, respectively. Some earlier data from the Michigan group's oxygen enriched tests [6, 7] have been included for comparison. In general, agreement between the experimental VODs and the theoretical values based on the mean dust concentrations indicated by the TIGER code [8] was within ±13%. However, the measured detonation pressures did not correlate with the theoretical values nearly as well. The likely reason for this discrepancy is that the VOD is an average quantity computed over a significant length of the tube, whereas the detonation pressure is more a function of the local conditions in the immediate vicinity of the transducer. A similar conclusion was reached during the study of high-explosive droplet-vapour-air clouds employing nitromethane monopropellant [9]. Despite the scatter in the data, the results show that the RDX clouds have high blast potential. Detonation of a fuel dust such as aluminum requires a sufficient amount of oxidizing gas and mixing rate, and therefore an upper limit in dust concentration exists. In contrast, the detonation velocity and pressure of appropriately sized RDX dust, as a molecular explosive dust, are expected to increase monotonically toward the values for a solid explosive as the dust concentration approached the solid density. The present experimental results confirm this notion in the lower range of dust concentration.

The data from selected tests to determine the critical energy (i.e., critical charge mass) for direct initiation of detonation as a function of dust concentration are plotted in Figure 6. Most of the data are from tests employing the apparatus pictured in Figure 3. However, the data at the top left of the graph were obtained from canister tests based on the design in Figure 2b. In these tests [1], RDX dust (20 kg) and propylene oxide (18.5 kg) were co-dispersed into clouds having a volume of 335 m^3 ± 10% based on estimates from high-speed film records. Assuming a homogeneous cloud, the corresponding mean dust concentration was 0.06 kg/m^3 ± 10%. The clouds were successfully detonated by a 1-kg secondary charge in both experiments. However, pressure measurements indicated that the RDX did not participate in the detonation reaction. The fact that the propylene-oxide detonation did not induce detonation of the RDX is consistent with the observation by Kauffman *et al.* [5-7] that the stronger shock from a helium-diluted hydrogen-oxygen initiator ($\Delta P/P_0 = 28$) was unable to initiate RDX-air at the much higher

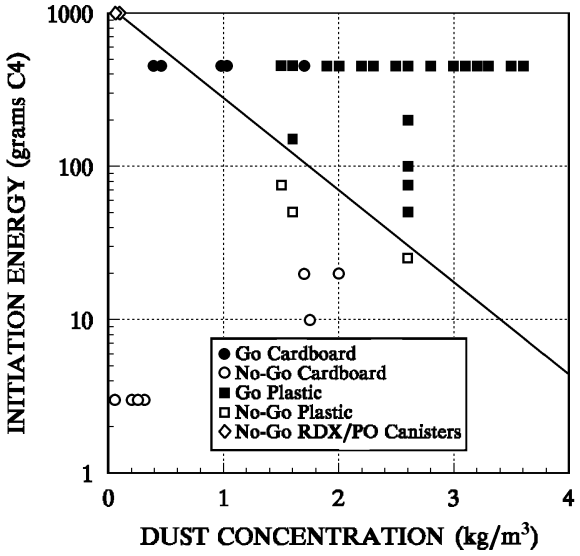

Figure 6. Initiation energy versus dust concentration for RDX-air mixtures.

concentration of 1.3 kg/m^3. The data in Figure 6 show that the critical charge mass varies from approximately 1 kg for a dust concentration in the 0.1 kg/m^3 range to about 20 grams for a dust concentration of 3 kg/m^3. Note that the dust in the cardboard tube could be initiated somewhat more easily.

Deflagration-to-Detonation Transition in a RDX Dust Laden Fuel-Air Mixture

The second part of this study, carried out by Combustion Dynamics Limited under contract to DRES, was intended to reveal whether or not a more effective energy release process might be possible in a fuel-air mixture incorporating a ground layer of RDX dust. Of specific interest was the possibility of inducing deflagration-to-detonation transition (DDT) in the mixture with participation from the RDX.

It is well known that the most violent form of DDT in a gas-filled tube is the so-called Craven-Greig scenario [10]. Under these conditions, the precursor shock wave ahead of a weakly ignited flame is reflected from the end wall of the tube. Subsequently, DDT occurs ahead of the flame, resulting in a detonation wave which propagates forward through the doubly-shocked gas and reflects once again from the end wall. A Hugoniot analysis indicates that the reflected detonation pressure can reach a value more than 10 times that of the reflected detonation in the initial mixture.

When a dust slug is present near the end wall, the process is more complex as indicated in the wave diagram of Figure 7. In this case, the precursor shock (S_1) impacts on the multiphase slug, generating a transmitted shock (S_{1a}) into the slug and a reflected shock (S_2) backwards into the precompressed gas. The transmitted shock (S_{1a}) is then reflected from the end wall as S_{3a}, which propagates back into the multiphase slug. Owing to the interactions between the gas and solid particles, the pressure behind S_{3a} can be several times higher than that for a normal rigid wall reflection without dust. As the reflected shock (S_{3a}) arrives at the gas-slug interface, the rarefaction there generates a transmitted shock (S_3) in the gas and a reflected expansion (R_{4a}) backwards into the slug. If the onset of detonation takes place via localized auto-explosions ahead of the flame front, the resultant detonation (D_{5a}) propagates into the multiphase slug. The pressure of the reflected detonation (S_{6a}) on the end wall is again enhanced by the interactions between the two phases. It is possible in some cases for multiple reflections to occur inside the slug before the arrival of the detonation wave [11].

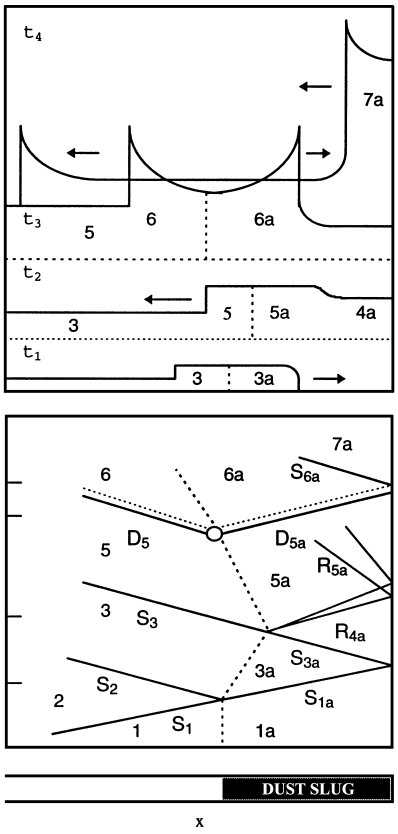

Figure 7. Wave diagram for DDT in an end multiphase slug.

A steel detonation tube of 4.5-m length and 80-mm diameter was employed for the experiments. The tube was filled to atmospheric pressure with a lean acetylene-air mixture containing 6.75% C_2H_2. Acetylene was chosen as the fuel because of its high sensitivity and therefore favourable conditions for DDT. Acetylene is also a gas at atmospheric conditions, thereby eliminating the need for a heated tube. A 100-mm long RDX dust slug was created at the end wall of the tube to simulate a ground layer. The dust suspension was formed via a counterflow injection system. Various weak ignition schemes were used to tune the transition distance. Pressure measurements were made using a pair of Kistler gauges; one mounted on the end wall of the tube and the other mounted on the side wall 38 mm from the end.

In an earlier study by the authors [11], wall pressures of between 26 and 30 MPa were reported for DDT in lean acetylene-air. These were seen to approximately double when a 100-mm slug of 5-μm aluminum particles in the concentration range between 5 and 10 kg/m^3 was present near the wall. The results were found to be very sensitive to the slug length, the particle size, and the dust concentration. Pressure data from the present RDX experiments are compared with the earlier aluminum results and the case of "no dust" in Figure 8. In general, it can be seen that RDX is more effective than aluminum at enhancing the hybrid detonation. As expected, the peak pressure increases approximately monotonically with the RDX dust concentration and without an upper limit of hybrid detonation being realized because of the molecular explosive nature of the dust. The RDX dust was completely consumed during the reaction, whereas in contrast to the earlier aluminum tests, a thin layer of unburned aluminum "foil" could be peeled from the end wall following each test due to the very rich aluminum dust mixture. Figure 8 also includes the data from four experiments in which a combination of aluminum and RDX particles were used. The RDX dust concentration was 13.9 kg/m^3 in all four tests, while the aluminum concentration was 6 kg/m^3 in two such tests and 10 kg/m^3 in the two remaining

tests. The detonability limits were extended in these tests as well, but the peak pressures were lower than if the total dust concentration had been pure RDX. The peak pressure achieved during the end slug DDT is more than twice the usual detonation pressure for RDX-air mixtures as depicted in Figure 5.

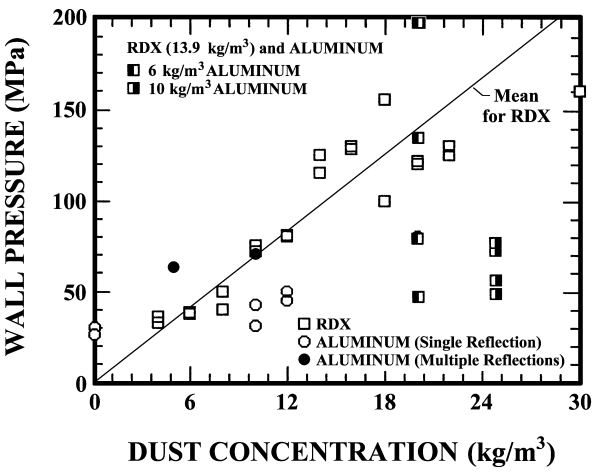

Figure 8. Peak wall pressure versus dust concentration in 6.75% acetylene-air with a 100-mm end slug of RDX or aluminum dust.

CONCLUSIONS

The results of the present investigation have shown that weakly confined RDX dust suspensions in air will detonate readily under controlled conditions providing that a large enough initiation charge is used. While the measured VODs and average detonation pressures were found to be in general agreement with the Chapman-Jouguet theory, there was considerable variability in the pressure data, suggesting that the local dust concentration in the vicinity of the transducer had a dominant effect on the measurement. The critical secondary charge mass for direct initiation of detonation has been determined and found to decrease monotonically with increasing dust concentration.

The present work has also extended the results of an earlier shock tube investigation of DDT phenomena in acetylene-air mixtures with and without an end multiphase slug containing aluminum particles. In that study, the experimentally measured peak pressures near the end wall during the Craven-Greig DDT scenario were approximately 26 to 30 MPa. These were found to more than double in experiments with the addition of a 100-mm slug of 5-μm aluminum near the wall in concentrations between 5 and 10 kg/m^3. In the present experiments with RDX dust, the peak pressures were observed to increase yet again and in approximately linear fashion with dust concentration due to the nature of the molecular explosive dust. In summary, the potential of RDX dust detonations for minefield breaching operations has been demonstrated from a fundamental perspective. However, the ability to reliably generate a ground layer of high dust concentration would be critical in any practical application.

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