Experimental Study of Afterburning Explosive Charges

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Introduction

Afterburning explosives such as aluminized TNT have been used extensively as warhead fills since WW-I, however only recently has research has been conducted into the late-time combustion processes for such explosions in air. Delayed energy release is characteristic of multi-phase explosive mixtures, and it is now known that the coupling of reactive chemistry with the hydrodynamic processes during the entire expansion of the fireball affects the blast performance of such explosives [1,2]. The fireball dynamics and combustion processes are affected by the charge casing and shape, available ambient oxygen, as well as the interaction and quenching effects from confining surfaces. Hence many variables of the entire charge configuration require consideration in such studies beyond the intrinsic properties of the fill.

An exploratory series of blast field experiments are described in which new diagnostic methods have been applied to resolve the radiant characteristics of the expanding fireball as well as blast-wave generation from explosive charges exhibiting various degrees of afterburning. Results are given comparing the blast and fireball from charges of C4 (89%RDX, 11% wax), TNT, tritonal (80%TNT, 20%Al powder), and tritonal heavily-cased in steel. The results show distinctive differences in the fireball and blast characteristics from these charges, and give new insights into afterburning processes of non-ideal explosives. The utility of a special spectral imager as a remote-sensing diagnostic instrument is highlighted.

Field Trials

The field trials were staged on the Experimental Proving Ground of DRDC-Suffield, Canada, during September-October 2002. As shown in Fig. 1a, a test-bed was prepared with an orthogonal array of blast-pressure gauges extending to 30m distance; several imaging systems including high-speed video, Hycam high-speed filming, and motor-drive 35mm framing IR cameras were deployed to record fireball expansion in the visual and near-IR. A 10000fps video camera was applied to resolve the shock-front trajectory against a backdrop. Of prime interest was the fielding of a special imaging spectrometer, Pirate-3 which will described later, viewing the fireball development from 1.15km distance.

A generic charge configuration was designed using a standard 19-liter thin-wall industrial steel pail as container, supported at 1.4-m height-of-burst as shown in Fig. 1b. One charge was prepared with 12.5mm steel wall and massive steel bulkheads at the top and bottom to assess the effects of heavy confinement on the fireball and blast strength. The work of Ref. 1 had indicated that heavy casing may cause quenching of afterburning combustion in addition to the direct energy losses to fragment generation which would otherwise support blast pressures.

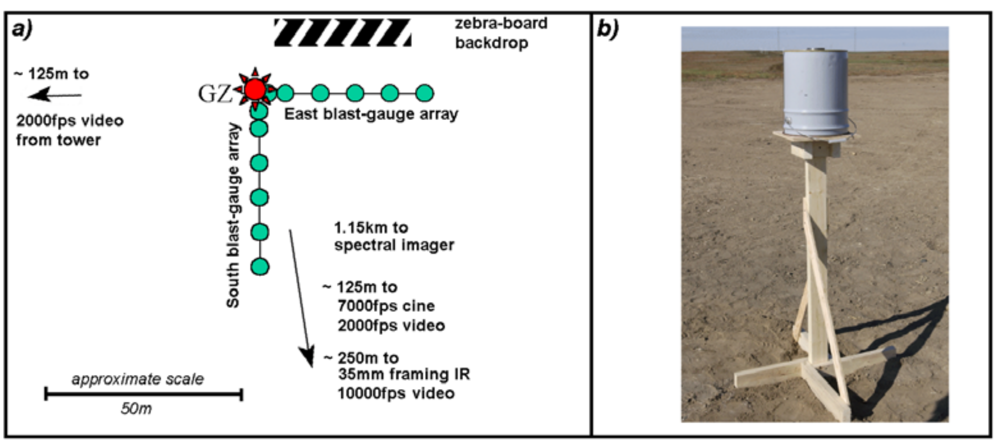

Figure 1. a) schematic of field test-bed layout; b) typical 25kg charge configuration.

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High-Speed Imaging
Successful diagnostic imaging was recovered from the various camera systems for all tests. For brevity only results for the TNT charge will be described in the following examples. Extracts from typical sequences of high-speed digital video are shown for illustration in Fig. 2. High-speed cinematography and video imagery is used to characterize the fireball appearance in the visual spectrum and also to track the shock propagation with distance from which blast-front parameters can be derived. The derived blast parameters are compared with measurements from the orthogonal array of blast gauges. For most charges, the near-field regime within the extent of the fireball expansion was subject to severe jetting producing localized flow anomalies which made many blast-gauge measurements difficult to interpret. Imaging methods allow ready identification of flow anomalies and offer a means to adjust for these by 'averaging' the shock-front propagation over the field of view. Imaging methods have the inherent advantage of being non-obtrusive to the flow, and allow assessment of the blast front propagation in 2D; however, it can be difficult to assess the full blast-time history at a desired location which is the advantage of gauges.

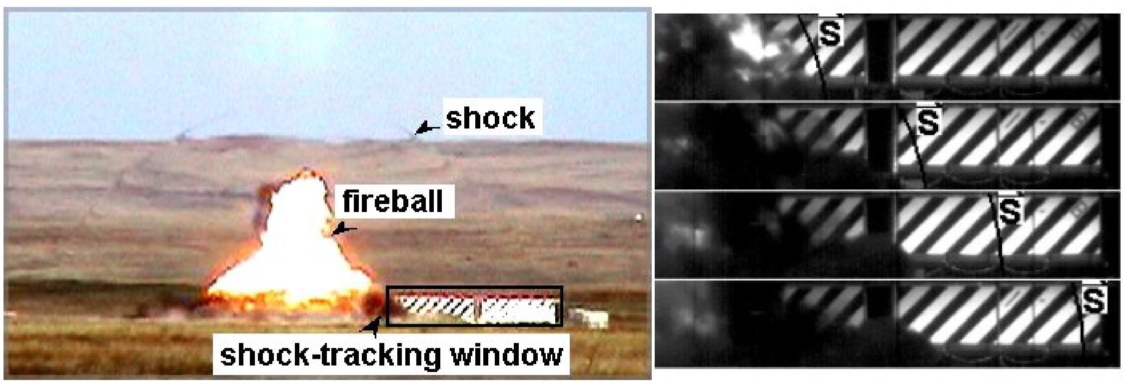

Figure 2. Example of visual imagery from TNT blast showing 1000fps color video (left) and 10000fps b/w shock-tracking video (right). The orange fireball and final sooty product cloud is typical of TNT explosions. The shock-tracking technique is used for direct correlation of the 2D blast propagation with computational modeling and for extracting shock-front measurements using the Rankine-Hugoniot relations.

Spectral Imaging
'Pirate-3' is a custom-designed spectral imaging system for field deployments developed by DRDC-Valcartier, a research laboratory of the Canadian Department of National Defence. This system is unique in its ability for spatial and temporal resolution of spectral data using an 8x8 element detector array. The single pixel field-of-view is 5.23mrad, equating to 6m in the plane of the observed fireball in these trials. The spectral band covered is 2-5.3 microns, and measurement rates are adjustable by trading spectral resolution for sampling speed. For example, at a sampling rate of 25Hz a resolution of 16cm^{-1} (wavenumber) is possible. At these sampling rates, it was not expected to resolve spectral data directly correlating to explosive processes as they develop, however important clues of the blast processes are evident in the spectral 'aftermath'.
A considerable range and depth of data concerning emission spectrum and spatial distribution through time can be recovered and displayed within minutes of an event. The following data products have been derived for the fireball development for each charge:

- total radiometric intensity *vs* time over the total field of view (48m x 48m)
- total apparent temperature *vs* time over the total field of view
- selected in-band image intensity representations (equivalent to thermal imagery)
- total spectral signature variation *vs* time to identify spectral components
- separation of gray-body and molecular species emissions
- spatial variation of apparent temperature *vs* time
- spatial variation of spectral properties *vs* time

The total radiant intensity variation of the fireball with time for the waveband 2 - 5.3 micron for the TNT charge is given in Fig. 3. The contribution of gray-body radiance (hot solid particles such as carbon soot) and gaseous species (carbon dioxide and water vapor) are distinguished, and it is apparent the gray-body radiance dominates the signature by about 5-fold in amplitude. The lag of the gaseous contribution is noteworthy indicating such products are being evolved at relatively late time or alternatively, heat is being transferred back to these cooled gases from the hot soot particles which had retained their heat during the fireball expansion. For perspective, the blast-wave has propagated out of the field of view within 50ms.

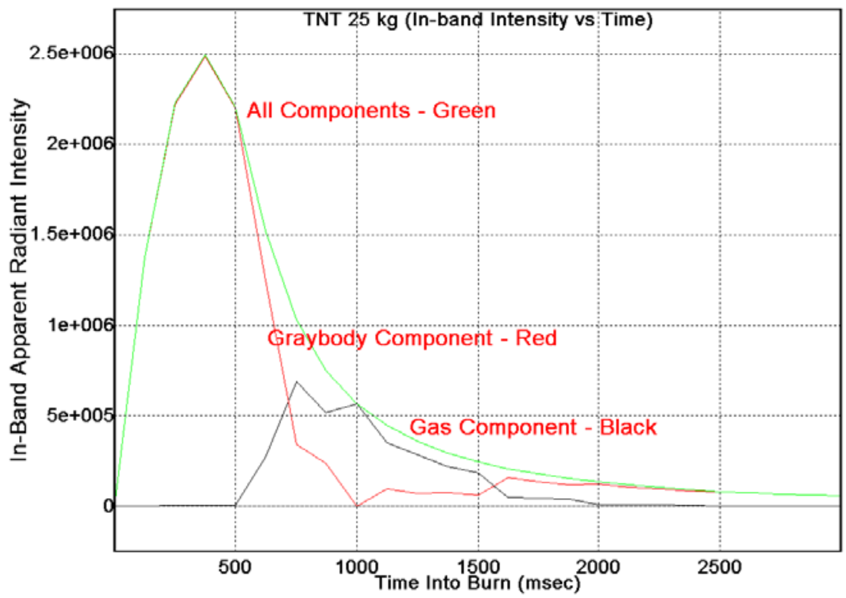

Figure 3. Total intensity variation with time into burn, separating contributions from gray-body sources and gaseous species.

Figure 4 shows the spatial distribution of apparent temperature variation with time and merits special discussion. A 'halo' of high-temperature air with a radial thickness of about 1m is evident just *beyond* the visible fireball. Although the fireball is highly visible and radiant due to the presence of hot carbon particles, temperatures of these combustion products are only about 1650C being mostly expanded and cooled explosion products. In comparison, the annular shell of shock-heated air ahead of the fireball (which had been adjacent to the charge when it was initiated) remains above 3000C; unlike the gaseous products, the shock-heated air is not adiabatically cooled as it is expanded outwards. To the authors' knowledge this is the first graphical experimental evidence of the shock-heated zone predicted by computational modeling. This annular zone of very high-temperature air would likely have an important role in promoting combustion of any fuel material which may be projected through the nominal edge of the visible fireball. Indeed, jets of material projecting through the fireball from many types of explosive charges are often seen as intensely luminous; this may well be due to their encounter with the shock-heated zone as much as due to their prior combustion state before penetrating through the fireball contact surface.

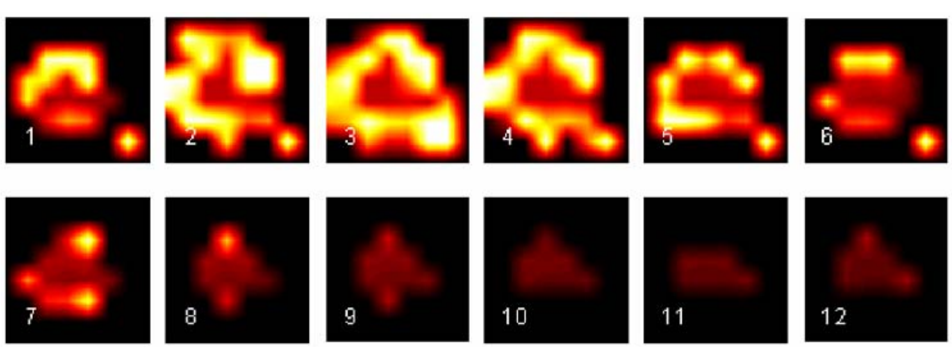

Figure 4. Time sequence showing spatially resolved apparent temperature. Each image shows the total FOV spanning 48m at 40ms intervals. The "halo" of shock-heated air is evident beyond the edge of the fireball. Although more radiant, the fireball shows as a cooler zone within this halo.

Selected Summary Results
Total radiometric output from the fireball as a function of time for the four charges of current interest are shown in Fig. 5. C4 produces the lowest IR emission intensity which peaks earliest and decays rapidly with expansion of the fireball. Separate assessment of apparent temperature (as distinct from radiance) shows a peak temperature of about 1400C. This observation would be expected for an efficient high-power explosive: the explosive combustion is completed almost entirely in the detonation phase after which the gaseous products adiabatically expand and cool. Little carbon soot is formed. Note that the peak output is a function of both the intensity and physical size of the fireball source. The TNT charge produces a peak radiant intensity 2.5-fold that of C4, occurring about 150ms after detonation, and the radiance persists proportionately longer. These features are expected of delayed and inefficient afterburning. As might be expected, the fireball radiance of aluminized TNT charges lags that for pure TNT and is slightly more persistent, likely due to the heat-sink effect of the metal oxides. The significantly increased persistence and decrease in peak radiance from the fireball for heavily-cased tritonal is consistent with the premise suggested in Ref. 1 that such casing impedes or quenches the important early afterburning phase. The radiance curves suggests residual partially decomposed fuels from the detonation are still burning and radiating when the product cloud is churning with the ambient air long after blast generation.

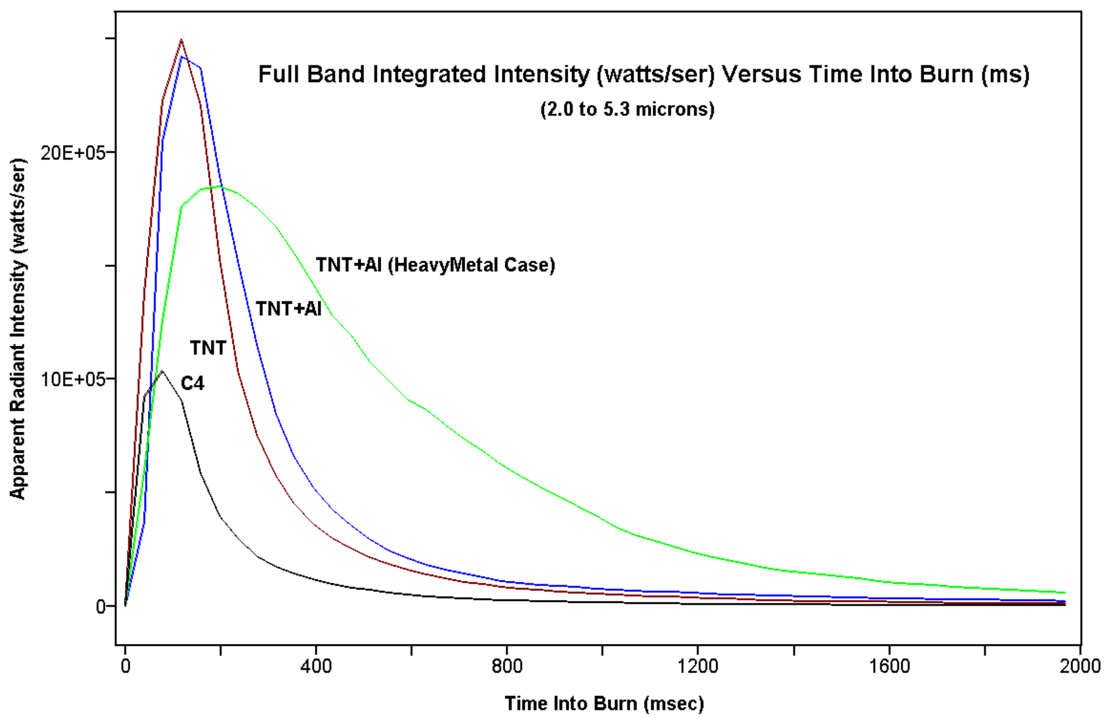

Figure 5. Comparison of total radiometric intensity with time, 2 - 5.3micron waveband.

Conclusion
The current project is considered an exploratory exercise both in trial techniques and diagnostics to investigate non-ideal explosive processes. Current observations should be considered preliminary, since the data is still being assessed in detail and in comparison to theory and modeling. The current data set is small, and systematic investigation of repeatability between charges, effects of charge size, and higher spatial resolution are planned for future trials. However, extremely valuable insights seem possible with current diagnostics in analyzing late-time combustion processes of non-ideal explosives using stand-off imaging systems. The utility of the Pirates-3 imaging spectrometer shows particular promise.

References

1. Needham, C.E., "The Influence of Delayed Energy Release in Aluminized Explosives", PA07, Military Aspects of Blast and Shock, MABS-15, Banff, Alberta, September 1997.
2. Thomsen, J.M., Rocco, J., Rinehart, E.J., "Dynamic Properties of Aluminized Explosives", SB05, Military Aspects of Blast and Shock, MABS-15, Banff, Alberta, September 1997.