Scaling of light emission from detonating bare Composition B, 2,4,6-trinitrotoluene [$C_7H_5(NO_2)_3$], and PE4 plastic explosive charges

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It is well known that an intense flash of light is emitted when an explosive charge is detonated. The light emission continues well beyond the actual detonation process due to shock excitation of the air molecules around the charge, as well as post-detonation reactions in the expanding products of the detonation. Various researchers have studied these emissions, and it has been established that there are features in such emission spectra that can be regarded as characteristic for a specific explosive composition and configuration. In this study, the emission characteristics at wavelengths between 650 and 940 nm were experimentally investigated for cylindrical bare Composition B, 2,4,6-trinitrotoluene [$C_7H_5(NO_2)_3$], and PE4 plastic explosive charges in the mass (M) range of 0.5 kg to 4 kg. The results show that the light emission parameters scale to $M^{1/3}$ consistent with other explosive blast parameters such as pressure and impulse (so-called Hopkinson's scaling). It is also shown that for bare charges, two distinct regions in time can be distinguished for the light emission, namely, light from the early time frame, while the charge is detonating (and slightly beyond), and light from the expanding products of the explosive (the "fireball"). It is argued that in the first region, ionization effects and shock excitation of the air molecules around the charge dominate the light emission. The dominance of these effects fizzles out rapidly as the blast wave expands from the charge, leaving only light emission from the expanding products of the detonation. © *2011 American Institute of Physics*. [doi:10.1063/1.3645040]

INTRODUCTION

In contrast to propellant sources, with which a significant amount of experimental work has been performed,[1] light emission from detonating explosive charges has been sparsely studied experimentally in the past. This is mainly due to the very short time frame and the non-linear nature of a detonation event, which make the applicability of conventional diagnostic tools limited. For a cylindrical explosive charge of 1 kg and L/D ~ 1, the detonation time is typically less than 20 μs, and the time for full expansion of the explosive products is several hundred microseconds. During this time, the pressure next to the charge changes from atmospheric pressure to several GPa in less than a microsecond, and thereafter it decays back to atmospheric pressure in a few milliseconds. Similarly, temperature fluctuations of several thousands of degrees Kelvin occur. It is this temperature evolution with time that is of specific interest experimentally, because predictions from theoretical models based on different equations of state models vary on a wide scale.[2]

During the past two decades, advances in electro-optical technology have led to renewed interest in the experimental measurement of light emission from explosive charges. It is also not surprising that many of the studies have focused on new experimental adaptations of the optical pyrometry technique[2–5] in order to derive temperature measurements from experimental data. However, several workers also applied spectroscopic methods in order to characterize the light emission.[6–9]

The use of photodiodes to record light emission from post-detonation "fireballs" at a standoff distance was reported as early as 2001.[2] At the Council for Scientific and Industrial Research facility, novel low cost detectors using photodiodes were developed in 2005 and used routinely to record light emission at extended standoff distances (5 to 30 m) during tests with explosive configurations. Similar devices were also reported to have been used recently in prompt flash impact experiments.[10] In such experiments, the source size (i.e., the expanding products from the detonation or the fireball) changes with time and has a prominent bearing on the output measured by the detector. It is also generally accepted by most investigators that the light emission from detonating conventional explosive charges can be represented by some form of the Planckian distribution for a gray body when the emissivity is unknown and when both the temperature and the emissivity change with time.[2,4,7] This is probably not a bad assumption during the detonation phase and the early stages of the expansion of the fireball, when the density of the detonation products is still fairly high. It does, however, also logically raise the question of the scaling of light emission parameters for geometrically similar charges of the same composition. Although it is common knowledge that other explosive blast properties adhere to Hopkinson's scaling law,[11] there is only limited reference to the scaling of light emission. One reference could be found that applied a scaling law to the temperature of post-detonation fireballs based on the light emission from detonating explosive

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charges.[7] It is the aim of this paper to investigate the scaling of the light emission parameters captured by the photodiode detectors at extended standoff distances in experimental tests with three different explosive compositions. Although it is accepted that in these experimental tests the light emission from the explosive product reactions, as well as from the secondary excitation sources (such as shock excitation of the air around the charge or ionisation effects), is observed in an integrated way, the aim is to ascertain whether these emissions can be scaled with the charge mass.

EXPERIMENTAL SETUP AND PROCEDURE

Because the light detectors were used routinely in many different tests with explosive charges and the detector design evolved with time, only results from test series that were recorded in complimentary conditions and from detectors with identical characteristics were selected for this paper. Two specific test series were selected, namely, one in which Composition B charges with masses (M) ranging from 0.5 kg to 3 kg in steps of 250 g were used to commission a semi-confined blast chamber, and another in which Composition B, 2,4,6-trinitrotoluene [$C_7H_5(NO_2)_3$] (TNT), and PE4 plastic explosive charges were fired in open air. In the latter series, 0.5 kg, 1 kg, 2 kg, and 4 kg charges of Composition B and TNT explosives were used, whereas only 0.5 kg and 1 kg charges of PE4 were used. All of the charges were unconfined and cylindrical with a length-to-diameter ratio (L/D) of 1. In all cases, the charges were viewed perpendicular to the cylindrical symmetry axis (i.e., side-on). The cylinder symmetry axis was also the initiation direction. In the case of the blast chamber series, the charges were suspended from a wire cradle in the center of the 5 m diameter and 6 m long cylindrical chamber. The detectors viewed the event 20 m from the firing point through the open end of the chamber. In the case of the open-air firings, the charges were fastened on top of a 50 mm diameter rigidly supported polyvinyl chloride (PVC) tube with duct tape, 1 m above the ground, and viewed from 10 m, 20 m, and 30 m. The charges were initiated by 30 g to 100 g boosters, with the booster mass never exceeding 6% of the charge mass. Standard military detonators were used.

The primary element of all of the detectors was a BPW34 Si *p-i-n* diode, used in the photoconductive mode for fast rise time. The diodes together with driving electronics were packaged into 50 mm diameter steel tubes with 10 mm diameter apertures in the front end of the tubes. The diode is specified with a spectral bandwidth of 0.6 μm to 1.05 μm with a reasonably linear responsivity between 0.65 μm and 0.95 μm. In order to affect sensitivity at a specific wavelength only, optical narrow bandpass filters were positioned in front of the diodes in the tubes. All of the detectors were therefore identical except for the various bandpass filters included. The bandpass filters that were used had maximum transmittance at 650 nm, 780 nm, 850 nm, and 940 nm, with a close to normal transmittance distribution around these peaks and a one sigma value of approximately 10 nm. For the sake of simplicity, only the maximum transmittance value is referred to hereinafter. The aperture size, the positioning of the filters and the diodes within the tube, and the careful selection of the standoff distance of the detectors from the charge enabled the observation of the complete fireball for the duration of the experiment. The electronic interface with the photodiodes was also designed in such a way that the output of the detector reflected directly the energy collected by the diode at any given time. Digital storage oscilloscopes sampled the signals obtained from the detectors.

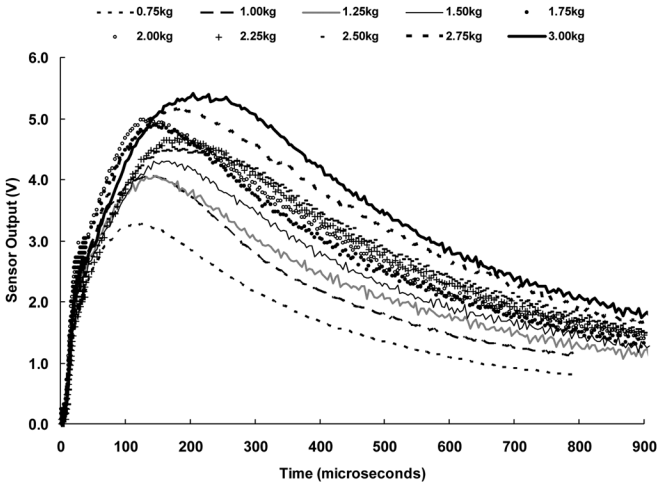

FIG. 1. Light emission recordings at 650 nm for Composition B charges in the semi-enclosed blast chamber.

RESULTS

In Fig. 1, the full complement of the emission recordings from the 650 nm detector for the firings conducted in the semi-enclosed blast chamber are shown. Similar results were recorded for all of the other wavelengths.

The light emission recorded at each of the wavelengths displayed similar characteristic features for all of the firings, irrespective of the viewing distance. These features are discussed at the hand of Fig. 2, in which the detector outputs for all four wavelengths (signals corrected for the responsivity of the diode and transmittance factors of the optical filters) are shown for the 3 kg Composition B charge fired in the blast chamber. A fast rise of the signal is observed in all cases up to

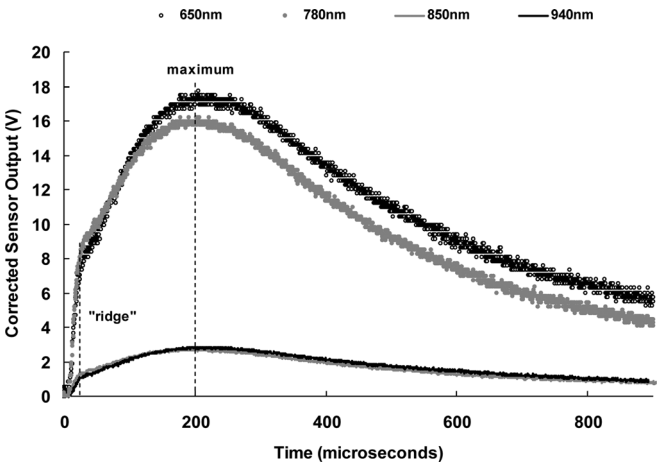

FIG. 2. Corrected detector output for all 4 wavelengths for the 3 kg Composition B charge fired in the blast chamber.

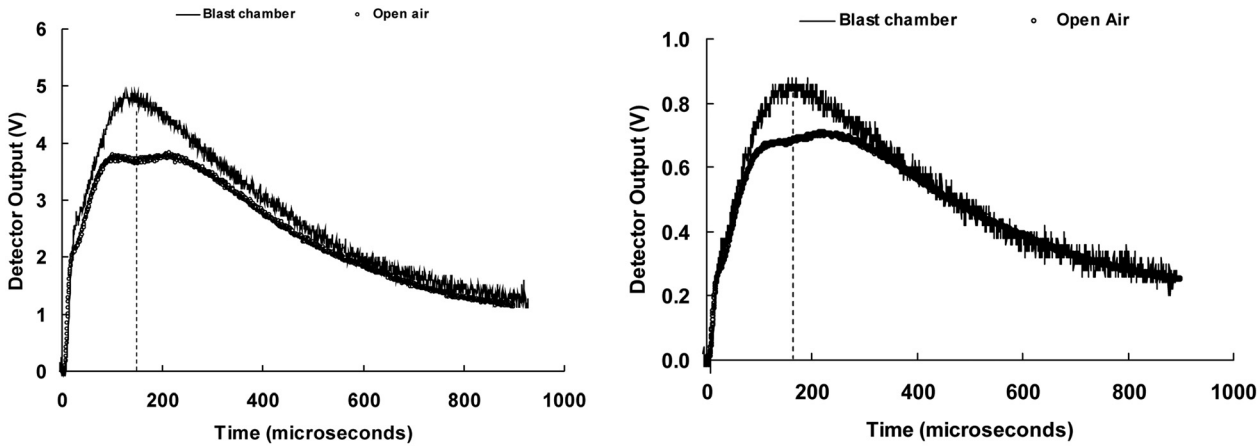

FIG. 3. Comparison of the 650 nm (left) and 940 nm (right) detector outputs for the 2 kg Composition B firings in the blast chamber and in open air at 20 m.

a point that is referred to hereinafter as the "ridge." The ridge time is similar for all of the wavelengths for a specific charge firing. Beyond the ridge, the signal rises more gradually until the signals for all of the wavelengths peak at similar times. This is followed by a gradual decay of the signals up to about 1 ms (the latter time was the maximum sampling time in the experiments). The output from the 650 nm detector gives the highest amplitude and is followed closely by the 780 nm detector, with the two longer wavelengths giving almost equal but much lower amplitudes.

It is also important to compare the signals obtained in the open-air firings to those obtained in the blast chamber. In Fig. 3, two examples are shown (which are typical of all of the firings) for the 2 kg Composition B charge observed from 20 m in the different test series.

It is observed from Fig. 3 that the signals for both test series are similar at early and later times but differ at the peak part of the signals. This is thought to be a result of the way the charge was set up in the open-air firings (i.e., heavily strapped down with duct tape across the center of the charge onto the PVC tube and therefore constituting a constraint in that region) compared to the hanging of the charge in a thin wire cage in the blast chamber firings. In most of these comparisons, the peak value of the signal from the blast chamber recordings coincided with a small local minimum in the peak part of the signal of the open-air recordings. It was decided

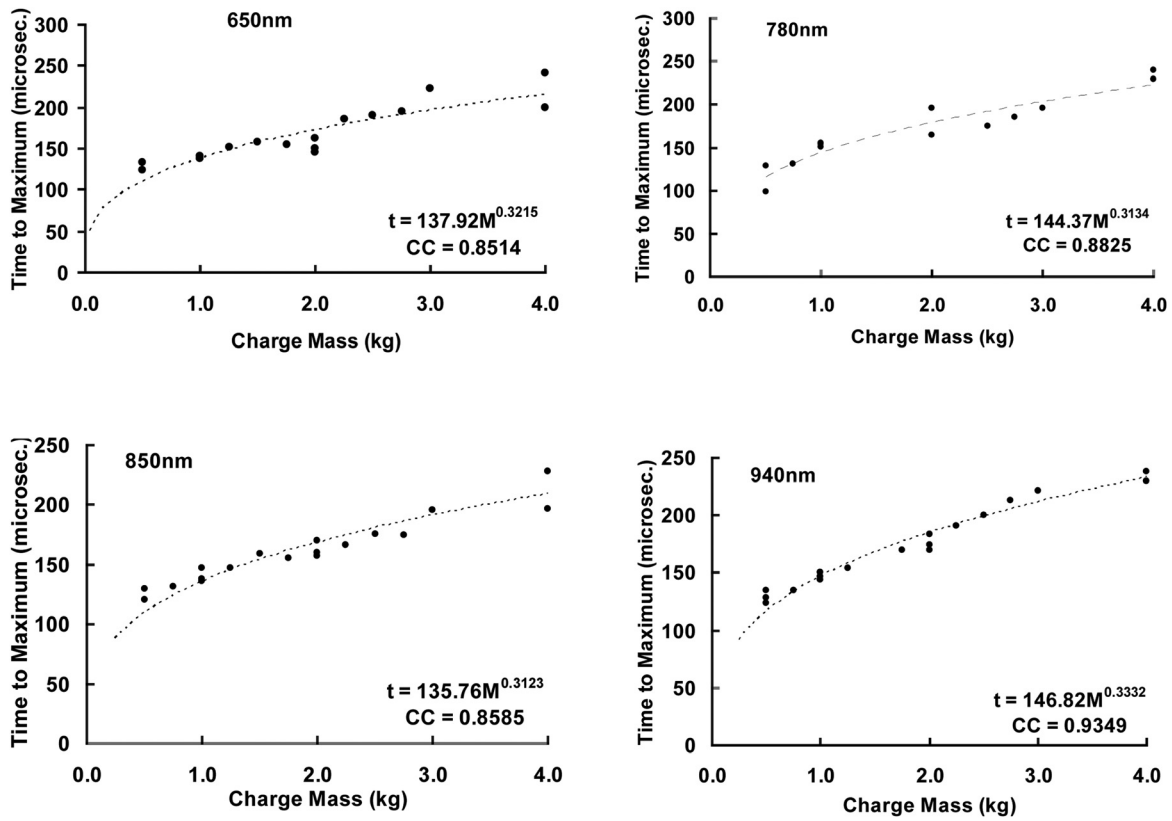

FIG. 4. The time to peak emission for the Composition B firings as a function of charge mass.

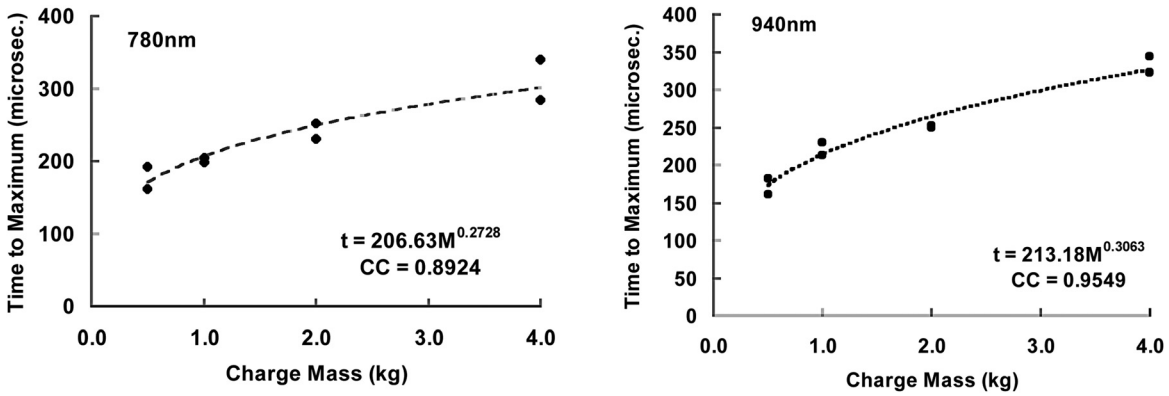

FIG. 5. The time to peak emission for TNT as a function of charge mass (left: 780 nm; right: 940 nm).

that we should regard this local minimum value as the real representative peak emission time for the open-air firings. It is also deduced from the results shown in Fig. 3 that the contribution of reflected light from the walls of the chamber to the light collected by the detector is small.

ANALYSIS

Three parameters of the light emission recorded by the detectors were investigated for scaling with explosive mass, namely, the time from initiation to peak light emission, the ridge time, and the maximum amplitude of the emission signal recorded by the detectors. In Fig. 4, the "peak emission time" is shown for all of the Composition B firings (both test series together) as measured at the wavelengths.

Because the time to peak emission must be zero for a zero charge mass, a simple power law could be fitted through the points. This is shown in Fig. 4, in which the best-fit parameters are given together with the correlation coefficient of the fit (CC). Experimental error bars are excluded in the data because it is difficult to estimate this error based on a single firing at each standoff distance. However, if it is assumed that the parameters are independent of standoff, an indication of experimental error is obtained from the deviation of the results from those of similar charge mass firings at the different standoffs. This value is 12% on average for all of the firings.

It is noted that the power coefficient in the best fits for all of the wavelengths is close to 1/3. The correlation coefficients are viewed as reasonable, considering the fact that the parameter analyzed depends to a large extent on the expansion of the source. This in turn depends on the symmetry of the initiation and detonation processes. Fewer data are available for the TNT and PE4 firings, but similar curves can be obtained, as is shown in Figs. 5 and 6. In Fig. 6, the liberty was taken of including results obtained from previous small scale firings performed with 20 g PE4 cylindrical charges at the Blast Impact and Survivability Research Unit facility of the University of Cape Town.

For the TNT results, the best-fit power coefficients are slightly lower than 1/3. However, it has to be remembered that small TNT charges are notoriously difficult to fully initiate and that this might have some influence on these results.

The "ridge time" of each emission curve was estimated from the data and is shown in Fig. 7 for all four of the wavelengths of all the Composition B firings. There is a fair amount of scatter in the data in Fig. 7, but again the best fit through the data points shows scaling behavior similar to $M^{1/3}$ for the general trend of the ridge time. Similar graphs can be generated for TNT and PE4.

It is observed (see Fig. 1) that there is a general trend of increasing maximum amplitude of the signals with increasing charge mass. However, the analysis in this study is complicated by the aberrations in the peak region of the signals

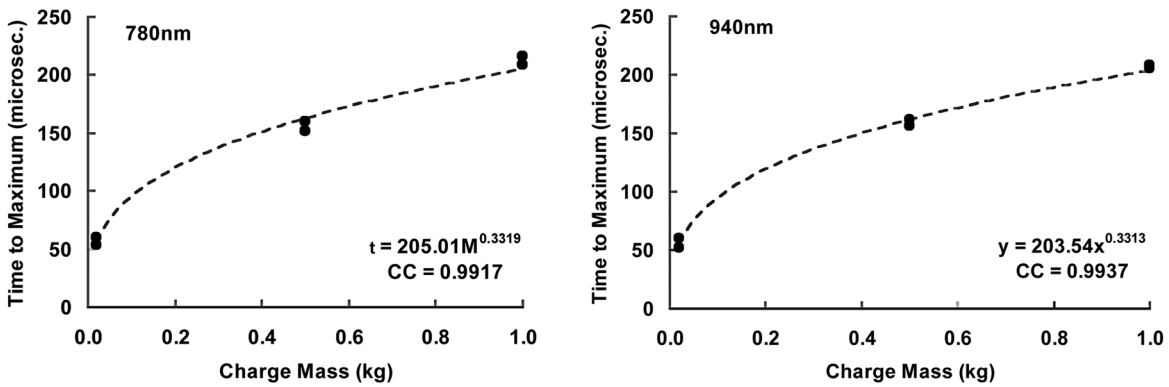

FIG. 6. The time to peak emission for PE4 as a function of charge mass (left: 780 nm; right: 940 nm).

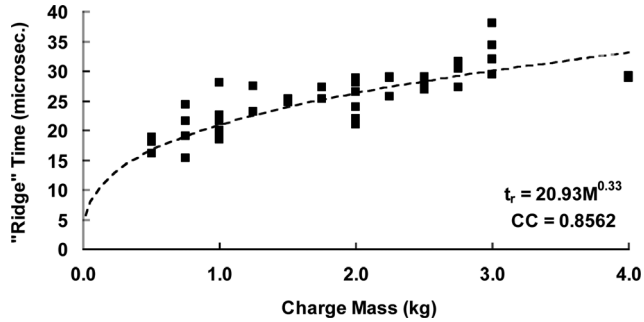

FIG. 7. Ridge time for all wavelengths of all of the Composition B firings.

obtained in the open-air firings. In general, the measured increase was haphazard, with sometimes larger charges yielding slightly lower maximum amplitudes than smaller charges. In Fig. 8, the maximum amplitude for only the Composition B firings from the test series fired in the blast chamber is shown as a function of charge mass for the 650 nm bandwidth. It can be noted that even with the relatively large data scatter, the general trend is consistent with $M^{1/3}$ scaling.

DISCUSSION

In line with other blast parameters of explosive charges, it would appear from this analysis that light emission parameters during and immediately after the detonation process scale with M^x, where x is approximately 1/3. For the three explosive charge compositions and the masses tested, similar features were observed in the emission signals: a fast rise of the signal to a point referred to as the ridge, a maximum amplitude within a few hundred microseconds, and a slower decay of the signal that ranges over the millisecond range. It is important to point out that the data obtained with the detectors in these experiments cannot be used to discern between light emission from the compressed and heated air layer of the outward moving shock (blast) front and the fireball itself. The signal is an integrated result of all of the light emanating from the event. However, this in fact highlights the prominence of the ridge and the subsequent discontinuity in the signal. Although the integrated signal is of interest in this scaling study (i.e., not necessarily clarifying the origin of the light emission, but investigating its scaling behavior), the results do suggest a change in the source character at the ridge junction.

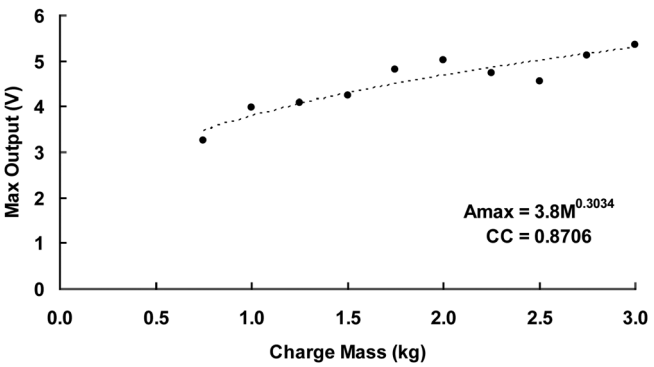

FIG. 8. Maximum detector output for the Composition B firings in the blast chamber at 650 nm.

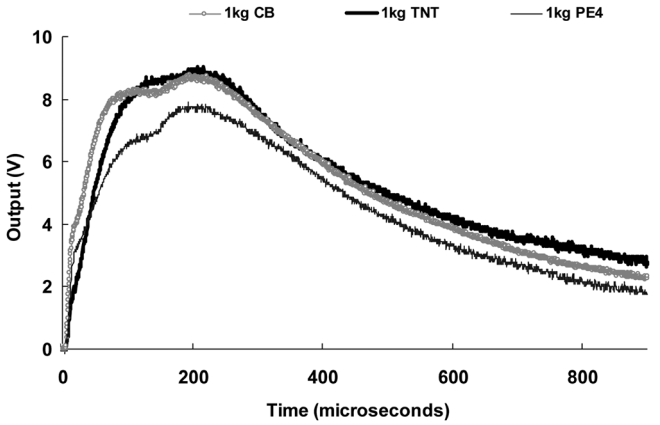

FIG. 9. Emission curves for 1 kg Composition B, TNT, and PE4 at 650 nm.

A direct comparison can be made by considering the signals obtained from the 650 nm detector for the 1 kg firings of all three explosive types, shown in Fig. 9. It is noted that the ridge height is lowest for TNT. This is seen as a strong indication that the ridge emission is due to pressure effects around the charge, as the detonation pressure of TNT is less than that of the other two explosive compositions. It is also seen from the data that the time to the ridge is slightly longer than the detonation time (approximately 21 μs for a 1 kg Composition B charge, whereas the detonation time is approximately 12 μs). This implies that there is a lingering emission after the passage of the detonation front through the charge. This in turn suggests that this emission is partly due to shock excitation of the air by the shock wave. This particular emission character disappears rapidly as the pressure in the shock front decay and the blast wave separates from the explosive products. The maximum amplitude and the time to peak emission are slightly higher for TNT. This is consistent with the fact that TNT is more oxygen deficient than the other two explosives and displays afterburning behavior when the explosive products mix with the surrounding air. This can lead to higher luminosity in the expanding products of the detonation at later times, as well as prolonged expansion of the products themselves, despite the lower initial detonation pressure.

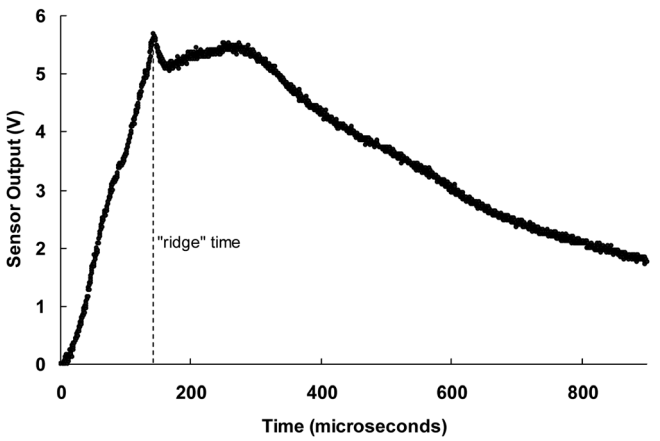

FIG. 10. Emission recording at 650 nm from a 1.5 kg (L/D = 33) PE4 charge firing at 10 m standoff.

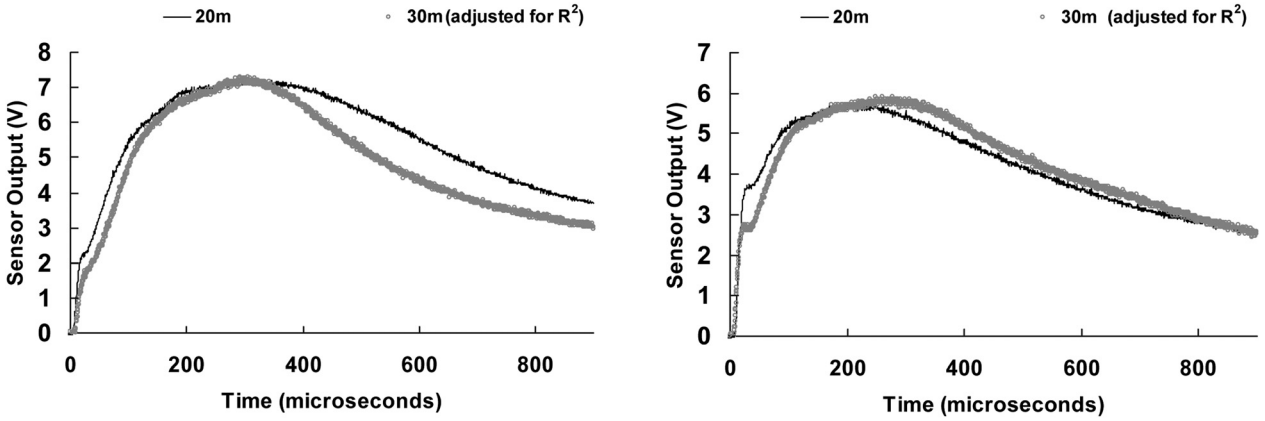

FIG. 11. Signals obtained by the 650 nm detectors for the 4 kg TNT (left) and Composition B (right) charges at 20 m and 30 m (the latter is adjusted by the square of the standoff ratio).

The proof that the ridge emission is directly linked to the detonation process and slightly beyond was obtained from a separate experimental firing (positioned on the ground and viewed from 10 m by identical detectors as discussed above) of a 1 m long, 1.5 kg PE4 charge (L/D = 33). The emission recording for the 650 nm detector is shown in Fig. 10. In Fig. 10 the ridge time can clearly be observed to compete with the time to peak emission. The time to the ridge is 145 μs, and the estimated detonation time of the charge is 120 μs.

Based on the data presented above, it is argued that the ridge emission is a direct consequence of pressure effects in and around the charge during, and slightly beyond, the detonation time. The most probable source of this emission is shock heating of the air around the charge, but ionisation effects cannot be ruled out. In this specific case, the "time to maximum" of the emission curve is very close to the ridge time, because only limited further expansion of the products will take place after such a long and small diameter charge has fully detonated, and therefore further reactions in the products will fizzle out rapidly.

In Fig. 11, the light emission for the 4 kg firings in open air for the TNT and Composition B firings are shown for 20 m and 30 m standoff as captured by the 650 nm detector. The data for the longer standoff recording are adjusted by the square of the standoff distance ratio (i.e., multiplied by 2.25) in order to normalize the data. It is observed that the signatures converge with slight differences in the ridge amplitude and some deviation in the late time signal of TNT.

The data show clearly that the emission signatures are characteristic for a particular charge. The differences in the longer time frame might be due to the non-symmetric expansion of the source (the late time behavior of the detonation products). The differences in the level of the ridge are interesting, but no explanation can currently be put forward. Note that the ridge and peak emission times are still coincidental.

The finding of a Hopkinson type scaling for the integrated light emission from the explosives used in this study can most probably be attributed to the fact that this integrated light emission is dictated by pressure effects. The time to maximum of the signals is dominated by the source expansion, which in turn depends on the pressure in the fireball. By assuming that the ridge characteristics are dominated by the detonation characteristics of the charge, it can also be concluded that these characteristics would be largely dominated by pressure effects. As it is well known that pressure adheres to Hopkinson scaling, it can be deduced that the integrated emission characteristics should follow this trend.

CONCLUSION

Light emission from detonating bare cylindrical Composition B, TNT, and PE4 explosive charges was studied using photodiode detectors. The emissions were studied in the 650 nm, 780 nm, 850 nm, and 940 nm wavelength regions and analyzed for scaling behavior. It was found that the prominent parameters of the emission scale according to $M^{1/3}$ (i.e., similar to Hopkinson's scaling). The scaling of the maximum output of the emission could not be conclusively verified, but indications of similar scaling behavior were found. It was also confirmed that certain light emission parameters can be regarded as characteristic of the specific composition and charge configuration. Similar studies of other explosive types should be conducted in order to ascertain whether such emission scaling can be generalized.

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