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FAR-FIELD POSITIVE PHASE BLAST PARAMETER CHARACTERISATION OF SMALL-SCALE AMMONIUM NITRATE BASED EXPLOSIVES

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ABSTRACT

The behaviour of "ideal" explosives, where the energy release is almost entirely facilitated by the process of detonation, is relatively well known. The mechanism of energy release is relatively simple, and consequently it is usually relatively easy to characterise and predict the properties of blast waves resulting from such explosives. With non-ideal explosives, the situation is more complex. Here, at best only part of the energy release is facilitated by a detonation process, and some or all is released via a secondary, usually slower, reaction. This, in addition to the fact that the rates of reactions are often highly sensitive to the thermodynamic state of the partially and fully-reacted products makes characterisation and prediction of blast waves resulting from non-ideal explosives significantly more challenging.

Ammonium nitrate/fuel oil (ANFO) is such a non-ideal explosive. When initiated, the ammonium nitrate detonates, with the resulting products including a small amount of excess oxygen which is able to react with the fuel oil component. A relatively large amount of data exists from tests involving the detonation of large (>>100kg) ANFO charges. In such tests, the velocity of detonation (VoD) tends towards a limit of around 4.5km/s, and the resulting blast waves can be approximated as being equivalent to those from a TNT charge of 0.8-0.85 times the mass of the ANFO charge. However, significantly less information exists on the mechanisms of energy release and the resulting blast waves from detonations of much smaller ANFO charges.

This paper presents blast experimental work through detonation of small scale ANFO (Ammonium Nitrate 94.5% and Fuel Oil 5.5% mixtures) hemispherical charges to assess the validity of current assumptions made about the non-ideal explosive which are currently integrated within best practice modelling methods. Comparisons will be made to detonation of ideal plastic explosives conducting the same methodology and analyse to validate the present ANFO data.

Keywords: Blast Parameter Variability; Far-field; Positive Phase, Non-ideal, ANFO

INTRODUCTION

In 1963, the Nuclear Test Ban Treaty was enacted, which prohibited the detonation of nuclear weapons for any form of research. This caused problems for departments of defence and security across the globe due to an essential requirement to better understand the effects of devastating explosions on both military and civilian infrastructure. Large scale trials were conducted using TNT-stacked charges and provided data which is held in high regard for its accuracy and was used to develop fast-running empirical models still used today [1].

Historically, the problem with testing regimes undertaken using ideal explosives has been the cost associated with the large-scale trials. It was therefore an incentive to explore the use of an inexpensive and readily available alternative, ANFO, a non-ideal explosive. This composition was investigated through large scale trials (18,000-572,000kg) conducted from the 1970s onwards to compare the results directly with tests conducted using TNT, which could then be scaled for geometrically smaller scenarios [2-6]. The findings from these tests began to characterise the general behaviour of ANFO when detonated, which led to an empirical equivalency of TNTe=0.82 becoming established as a standard, derived from techniques comparing the blast waves to those of TNT given by semi-empirical prediction tools [5].

Despite ANFO being used in mining and quarrying processes, alongside being a common explosive for terror threats, there seems to be relatively little available published data characterising the explosive in free air across a range of scaled distances for small charge sizes [7,8]. This lack of data results in uncertainties on how best to model and predict the blast waves emerging from detonations of small ANFO charges. Specifically, we currently cannot say definitively if the TNTe value for ANFO is consistent across scales, or whether the reaction mechanics are affected by the physical length scale over which the detonation wave transits.

This article will compare historical data from ideal high explosives, which have exhibited high levels of consistency and comparison to Kingery and Bulmash (KB) predictions, against newly generated arena tests using small-scale (250g) hemispherical ANFO charges, implementing nominally identical experimental and analytical techniques discussed in by Farrimond et al[12]. The main aim of this article is to characterise the explosive yields of small scaled ANFO charges and to demonstrate their agreement non-ideal blast load parameters with semi-empirical approaches.

HISTORICAL DATA

Extracted published positive phase data recorded during large scale ANFO blast trials [2-6] are presented in Figures 1a-d, which have been scaled to a 1kg TNT hemispherical charge using a shape factor of 1.8 [9,10], if relevant to convert spherical charges to hemispherical, and a TNT equivalency of 0.82 as discussed in [5]. It is clear across each positive phase blast parameter that KB predictions capture the scaled experimental data with reasonable consistency across the entire scale distance range tested, which provides a reasonable justification as to why researchers in the blast community have concluded on a generalised TNT equivalency for ANFO. Despite this, each parameter tends to exhibit larger variability than experienced when detonating ideal explosives, which has been analytically discussed in Figures 1 and 2 of [11]. The variability from similar trials does tend to increase with lower scaled distances in line with the determinability regions of shock wave development hypothesis detailed by Tyas [12]. Although a fascinating area of research, the near-field region will not be discussed further in this report.

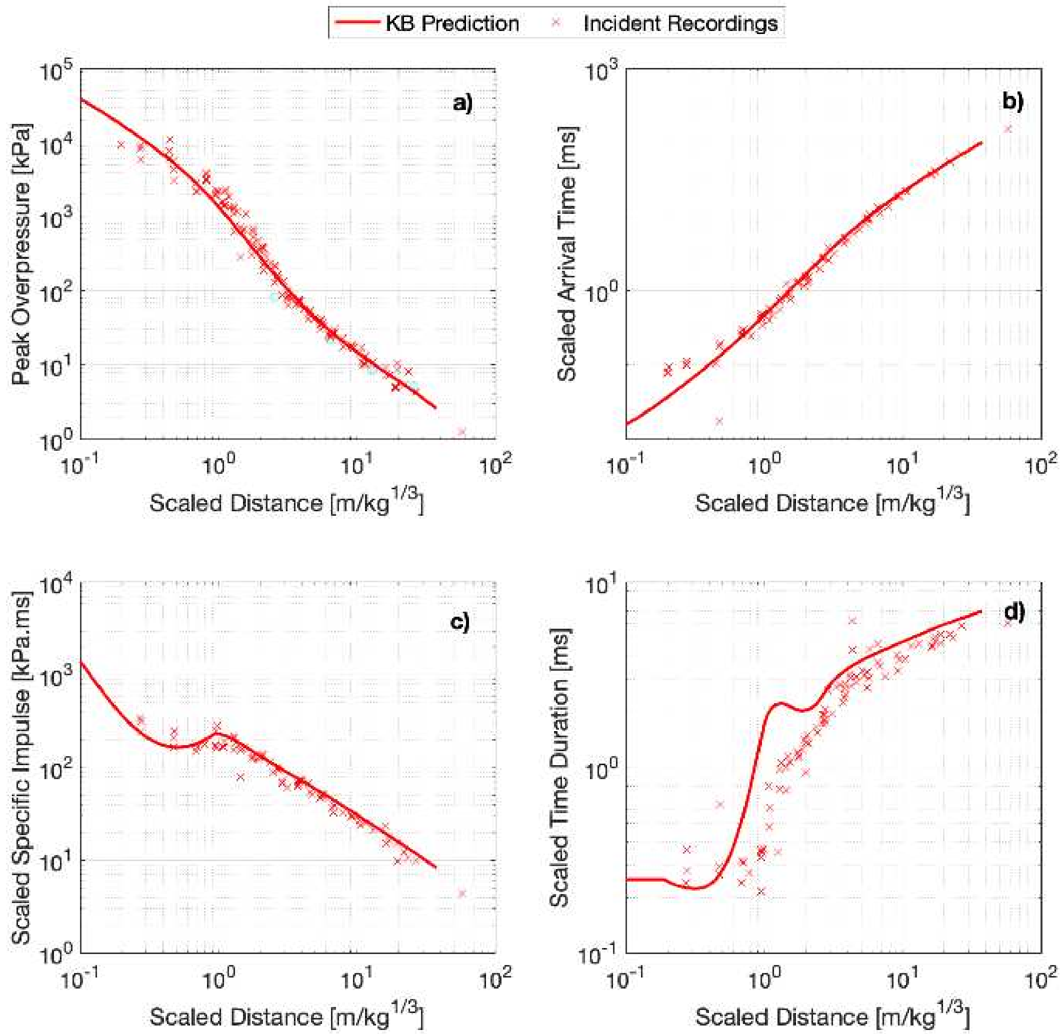

Figure 1: Compiled blast parameters from ANFO explosive trials [2-6] with varying mass as a function of scaled distance, which has been scaled to a 1kg equivalent hemispherical charge, using a shape scaling factor of 1.8, a TNTe=0.82 [5], and compared with KB Predictions: a) Peak Overpressure, b) Scaled Arrival Time, c) Scaled Peak Specific Impulse, d) Scaled Positive Phase Duration

Whilst the reasons for larger spreads in nominally identical tests is not currently certain, the authors have begun to draw conclusions on it being related to the difference in the meso-structure of ANFO when compared to more homogeneous explosives such as TNT and other plastic explosives. ANFO comes in prill form, meaning that regardless of charge preparation, there will be air voids between each individual prill with the overall formation being difficult to keep consistent. It is assumed that cellular disturbances of the detonation wave are generated when propagating through the prill structure, fostering multiple interactions within the complex meso-structure which disrupt the smooth isentropic expansion of the detonation products. Mie at al. [14] numerically modelled the shock-to-detonation transition in nitromethane, a non-ideal non-homogeneous explosive, when incorporating different arrangements of air voids and applying varying energy shocks to the medium to induce initiation. This model presented delays during the initiation process when cavities were present in comparison to a homogeneous mixture which provides further understanding to the complexity of the expansion of the shock wave and resulting detonation products, which could be related to the extra spread in the output data. It is highly likely that with an increased radius of a spherical/hemi-spherical ANFO charge, associated with larger masses, the bulk density would increase through self-weight compression and void collapse, which was suggested to result in higher detonation velocities and resulting blast parameters [5]. This provides another uncontrollable variable for the reason as to which the presented historical data may exhibit larger spreads than documented ideal explosives like TNT and plastic explosives.

In the absence of high quality experimental data from blast trials conducted with small (<10kg) ANFO charges, the validity of a constant TNT equivalence, unaffected by mass scale, becomes questionable. This is especially the case when detonating non-ideal explosives whose reaction zone lengths are in the order of 10s of mm, and therefore requiring an adequate charge radius to allow for an effective detonation. A clearly defined small-scale testing regime of hemispherical ANFO charges was therefore conducted to access the validity of published TNT equivalencies across the mass scale.

EXPERIMENTAL PROCEEDURE

A total of 67 far-field experiments were performed at the University of Sheffield (UoS) Blast and Impact Laboratory in Buxton, UK. These trials were conducted using surface detonated hemispherical charges of both ideal plastic explosives (PE4: 16 Tests, PE8: 7 Tests, PE10: 8 Tests) and non-ideal ammonium nitrate-based explosives (Ammonium Nitrate + Fuel Oil (ANFO): 35 tests and Ammonium Nitrate (AN): 2 tests). to facilitate the discussion of validated experimental methods. The ammonium nitrate-based explosives were commercially purchased from EPC-UK to provide comparable studies from a consistent supplier.

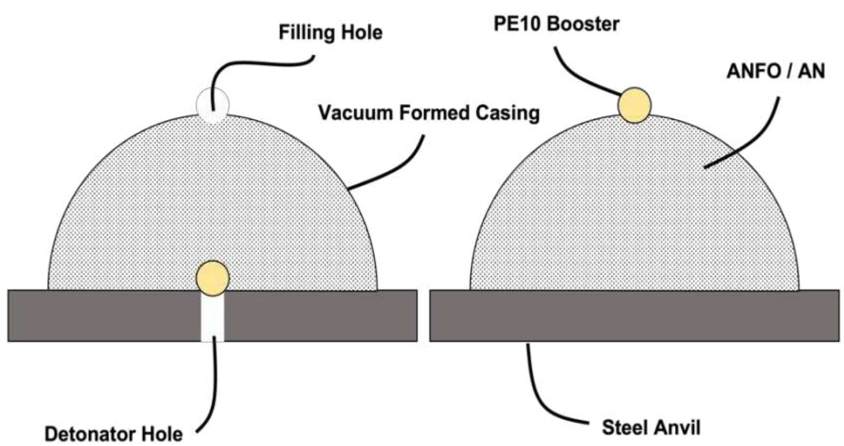

Figure 2: Schematic of the charge and booster locations through this testing regime

The AN-based charges were boosted with a 3g sphere of PE10 to ensure reliable shot-to-shot detonation. It is important to note that a secondary objective from these trials considered the position of the booster/detonator and their effects on non-ideal explosive yield, therefore 16 of the trials were top detonated and 21 bottom detonated. The hemispherical idealised plastic explosives were formed using a 3D-printed mould to ensure consistency in charge preparation and shape. Figure 2 is a schematic displaying the different booster and detonator positions adopted for the AN testing regime. For each of the AN-based far-field trials, clear plastic sheets were heated and vacuum-formed around a 3D printed hemispherical mould, to provide a lightweight casing to facilitate negligible confinement of the ANFO prill but keeping a consistent test-to-test shape to avoid systematic errors in experimental methodology [11]. A small circular cut was made in the top of the vacuum formed plastic casing to enable a consistent method of filling the charge with prill.

The explosive charges were detonated at varying stand-off distances, perpendicular to two rigid reflective surfaces in the form of a reinforced concrete bunker and a blockwork wall, separated exactly 10.0m apart. Kulite HKM-375 piezo-resistive pressure gauges were used to record the reflected pressure history in each test at both locations. The gauges were made flush to the surface of a small steel plate (approximately 110 × 150 × 10mm) which was fixed to these walls. The charges were placed on a small steel plate (150 × 150 × 25mm) prior to detonation, to avoid repeated damage to the concrete testing pad. For bottom detonated trials, the steel anvil had a machined hole through the centre to allow for the detonator to be in contact with the PE10 booster. The pressure was recorded using a 16-bit digital oscilloscope and TiePie software, with a typical sampling rate of 195kHz at 16-bit resolution. The recording was triggered automatically using TiePie's 'out window' signal trigger on a bespoke break-wire signal, formed by a wire wrapped around the detonator. The 'out window' trigger initiated with a voltage drop outside the normal electrical noise experienced in the break-wire. This coincides with the detonation of the charge breaking the circuit. The data was recorded using piezo-resistive pressure gauges in the historic tests and current tests and were processed using the automated techniques described in [11,13].

The explosive charges were situated between a Photron FASTCAM SA-Z high speed video camera, fitted with a Tamron SP AF70 70-200mm zoom (F2.8) lens, and a zebra board which ran perpendicular to the two reflective walls. The zebra board provides a high contrast background such that distortions in light, caused by changes in refractive index of the propagating shock front, would feature as sharp dark bands in the HSV recording [13]. The frame rates of the recordings and exposure time were 32,000 frames per second and 2.5-15microseconds due to varying weather/light conditions. Exposure times were altered before each test to maximise the contrast of the zebra board stripes, and the sharpness of the propagating shock front.

RESULTS

Before analysis of the ANFO trial data, it is instructive to consider results from similar tests conducted at University of Sheffield, using PETN and RDX based plastic explosives, as examples of the results obtained from "ideal" explosives. Full details are presented in [11,13]; we will show typical examples here, from tests involving plasticised PETN explosive PE10. Similar findings were obtained in tests using plasticised RDX (PE4 and PE8).

Figure 3 displays the compilation of as-recorded positive phase pressure-time history profiles for 250g hemispherical PE10 detonations at various stand-off distances. Since pressure was recorded at two stand-off distances for each test (2m to the bunker wall and 8m to the blockwork wall in test 1; 3 m to the bunker wall and 7 m to the blockwork wall in test 2; etc.), the results from different tests but identical stand-off distances can be compared. Qualitatively, each pair of results are in excellent agreement, with minimal variations in the blast pressure histories. The raw peak pressures at 2 m stand-off exhibits a higher level of variability when compared to the other pairings, which agrees with the working hypothesis of enhanced variability in the regions described by Tyas [12], hypothesised to be due to Rayleigh-Taylor [15,16] and Richymyer-Meshkov [17,18] surface instabilities affecting the uniformity of the blast wave front at these scaled distances and lower. Similar profiles and relationships between nominal tests are seen for both PE4 and PE8. The results presented within Figure 3 shows qualitatively striking test-to-test consistency for ideal explosives when adopting the testing methodology discussed in [13].

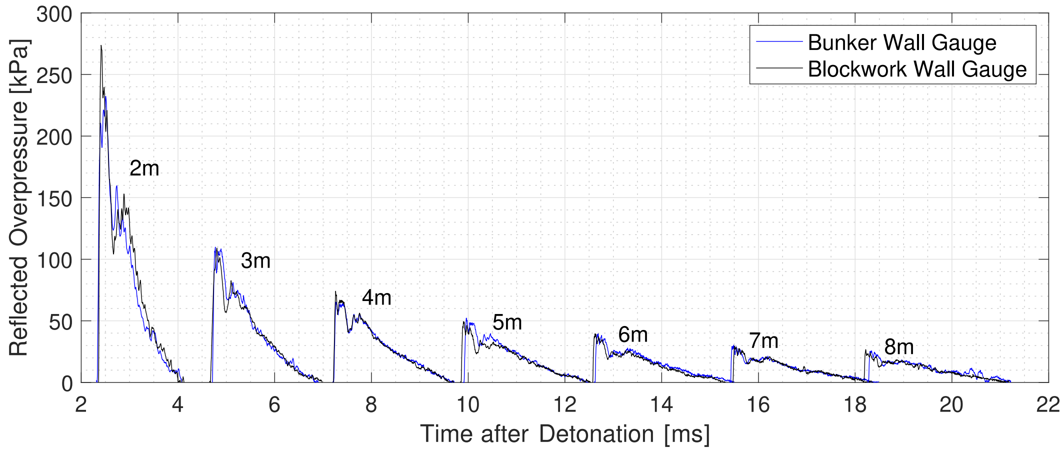

Figure 3: Compilation of the 14 raw pressure-time histories of 250 g PE10 hemispherical ground burst comprising of two recordings at each standoff distance, displaying the positive phase only.

Using validated curve fitting methods, discussed in both [13,19], which make use of the Friedlander equation (1), fitting to the positive phase of the pressure-time history. The entire data set of plastic explosives was analysed and compared directly to KB predictions to establish a confidence in the analytical methods developed. For a more detailed explanation to the approaches see the aforementioned articles.

$$P(t) = P_{max}\left(1 - \frac{t}{t_d}\right) * e^{-b*\frac{t}{t_d}} \tag{1}$$

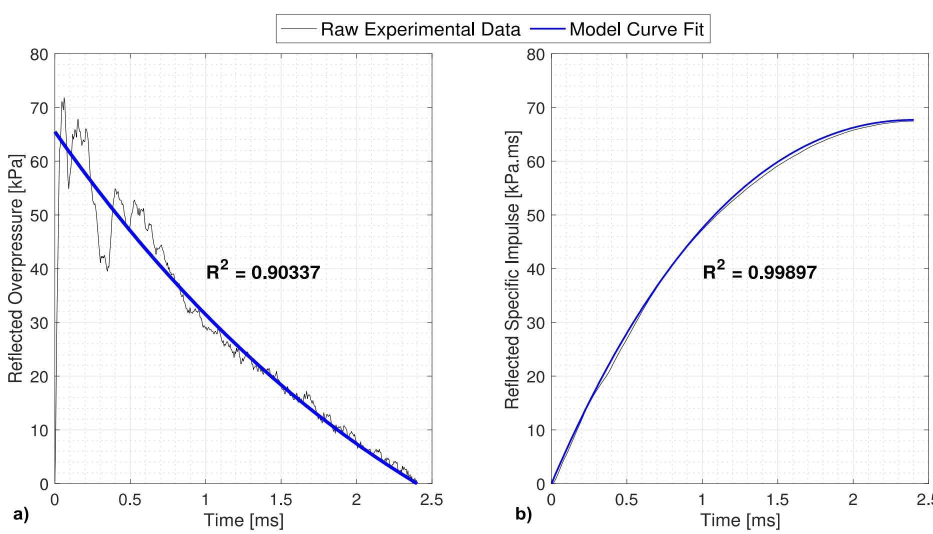

Figure 4: Example test result using a 250g PE4 hemispherical charge at 4m standoff with optimal curve fits overlain: a) Reflected overpressure, and b) Reflected specific impulse

The results from the curve fitting approach from a single trial is given as an example in Figures 4a-b. The high coefficients of determination, R^2, shown on each figure, indicate that the generalised model fits compare well to the raw data and therefore can be used with confidence to provide robust and accurate representations of the recorded pressure histories. The presented optimal fits from a single given test are evaluated from a large number of different potential fits and a statistical approach was taken to evaluate the best representation. These fits were checked and any potential outliers from the general data set were revisited and manually analysed.

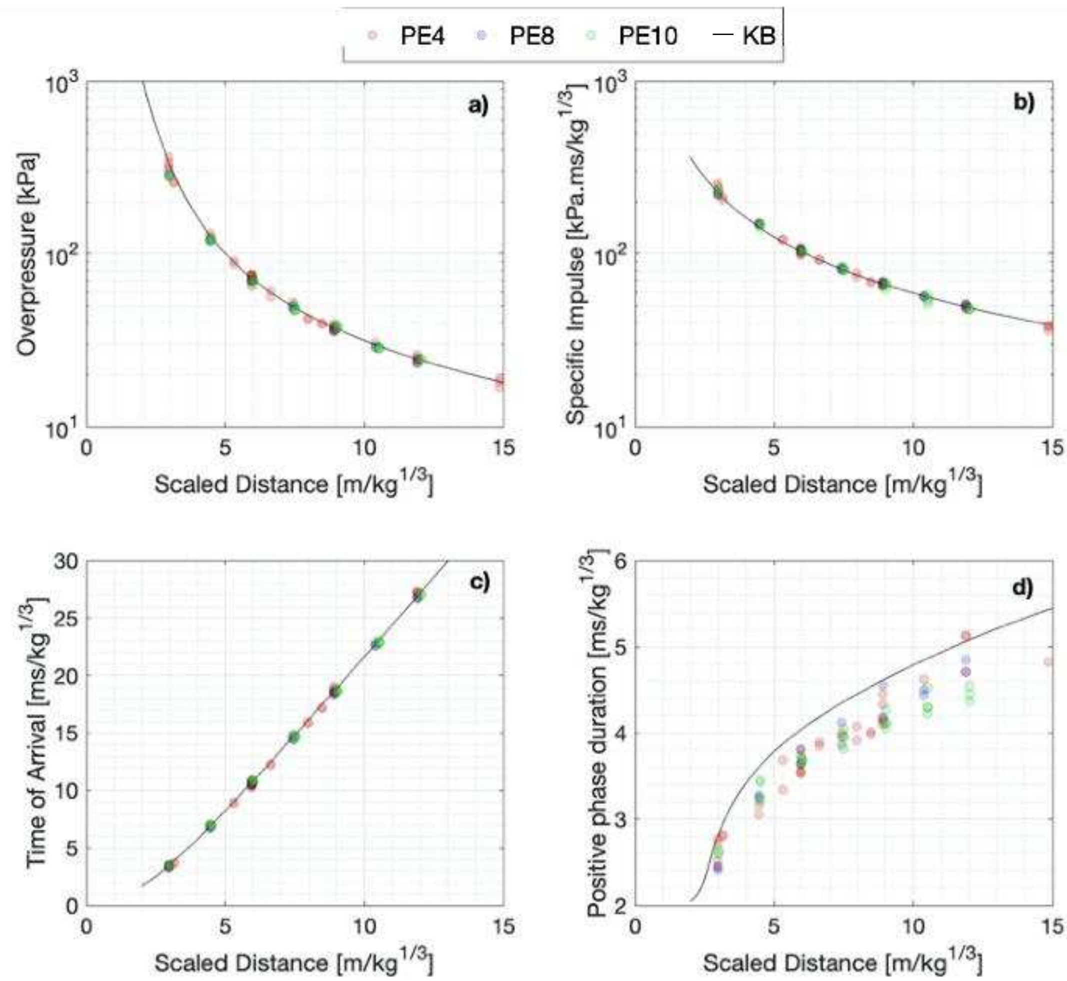

Figure 5: Compiled blast parameters from RDX and PETN based explosive trials as a function scaled distance, compared with KB predictions: a) Peak reflected overpressure; b) Scaled reflected peak specific impulse; c) Scaled arrival time; d) Scaled positive phase duration

To access the robustness of the KB prediction method and the accuracy of the data presented, a Mean Absolute Error (MAE) analysis was undertaken between the results from each explosive and those predicted for varying quantities of TNT to establish a TNT equivalence value for each explosive. It is expected that due to the three explosives in question being designed to result in similar explosive yields on detonation, that the TNT equivalence values for far-field free air scenarios should be similar across all explosives tested. The results presented in Figure 5b shows that generally, the positive phase duration tends to exhibit higher levels of variability due to the difficulty in assigning a specific value to the parameter due to noise in the signal making the true point at which conditions return briefly back to atmospheric difficult to determine.

It is noted that KB predictions of time duration are generally around 10% greater than experimentally recorded results which would cause any MAE analysis for a TNT equivalence value to be skewed[1]. With this noted, positive phase duration was omitted from the MAE analysis.

It was found through comparing the MAE values for pressure, specific impulse and arrival time at all far-field scaled distances that the three explosives tested all resulted in very similar TNT equivalency factors: PE4 and PE10 resulting in an equivalence of 1.22; and PE8 resulting in an equivalence of 1.24. This provided confidence and validation in both the experimental and data analysis techniques adopted for these trials as the three explosives were designed to have the same explosive yield. The TNT equivalence factors were applied to each of their corresponding compositions and subsequent recorded blast parameters presented in Figures 5a-d. The scaled results show a striking agreement between each blast parameter (expressed as a 1kg hemispherical TNT charge), and KB predictions, for all three explosives across the far-field range considered which disregards claims that far-field free-air blast parameters are inherently variable. With this background, we now consider the ANFO trials results.

Having little knowledge on the yield and characteristics of small scale ANFO charges, it was essential to establish an understanding on the general behaviour recorded during testing to assess if these non-ideal explosives behave as consistently as ideal explosives seen in Figure 3. Presented in Figure 6 are a selection of the 33 hemispherical ANFO detonations considering the consistency of the data across the standoff range tested. Between 2 - 9m, it is evident that although a discrepancy in the arrival times is consistently recorded between top and bottom detonated, with the overall trends in the positive phase of the pressure-time histories show considerable agreement, suggesting that in far-field regions, a similar level of consistency should be experienced when compared to ideal explosives. The traces at 1m standoff do present variability in the overall peak overpressure recorded which has been directly linked to the spherical uniformity and irregularity of the detonation cloud breakout related to bottom and top detonated tests respectively.

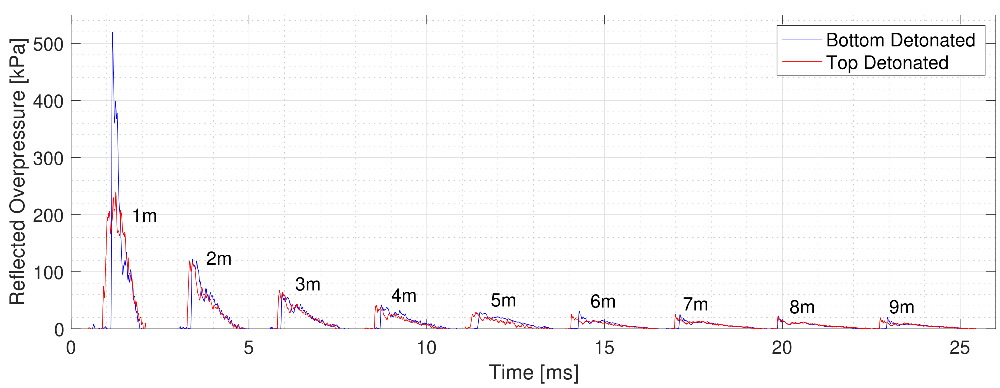

Figure 6: Compilation of 18 raw pressure-time histories of 250g ANFO hemispherical ground bursts, comprising of both top and bottom detonated charges, across the entire range of standoff distances tested in this regime. Positive phase is presented only.

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[1] The authors have found this to be a consistent discrepancy with several different explosives. Interestingly, when comparing measured and KB-predicted modified Friedlander traces, this positive duration discrepancy is not obviously noticeable by eye. It appears that any error in the KB prediction for positive duration may be compensated for by the choice of Friedlander decay coefficient *b*.

To establish the behaviour of small scale ANFO explosives, it was important to adopt the same experimental analysis tools validated for ideal explosives to assess how they perform for non-ideal explosive detonations. To access the TNT equivalency of small scaled ANFO shots, the unscaled processed results were again subjected to a similar MAE analysis comparing the data set to semi-empirical predictions based on varying masses of TNT. In line with variability regions hypothesised [12], the MAE analysis was performed on all AN-based tests within the definitive far-field range, with the the aim to attribute a TNTe factor at which the shock wave is no longer affected by propagation and fireball instabilities. To establish the effects of detonator position and charge mass, the MAE analysis was undertaken for the data when separated into nominally identical tests alongside the full data set in its entirety. The results from the MAE analysis converged on a TNTe = 0.395 for reflected pressure and specific impulse across the entire range of scaled distances, for both, charge mass and detonator position groupings.

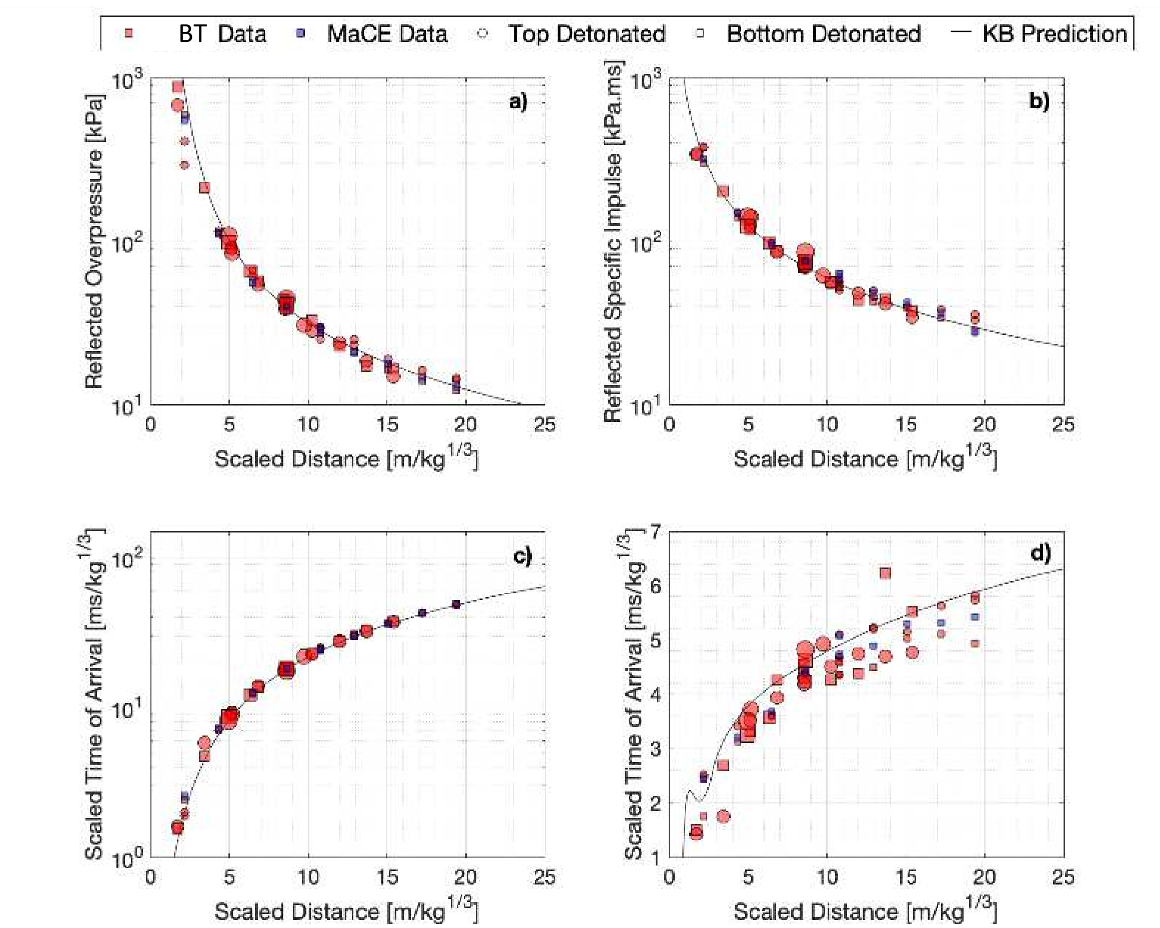

Figure 7: Compiled scaled blast parameters from ANFO explosive trials as a function of scaled distance, compared with KB predictions, using a TNTe=0.395, with increasing marker sizes to indicate the mass of the charge: a) Peak reflected overpressure, b) Scaled peak specific impulse, c) Scaled arrival time, d) Scaled positive phase duration.

This factor was applied to each of the recorded blast parameters and presented in Figures 6a-d which show a striking agreement between each experimentally recorded blast parameter (expressed as a TNT equivalent mass), and the KB predictions. It is important to note that there were 2 preliminary trials which resulted in much lower explosives yields related to not using a PE10 booster.

The results presented in Figures 7a-d completely contradict quoted values of TNTe for ANFO being around 0.82 across all scaled distances and masses and therefore has implications for numerical modelling which have incorporated these assumptions within simulations. Across a multitude of experimental trials, pressure gauges were changed depending on where the charge was situated, meaning the ower than expected results presented are not a feature of the equipment used and a real physical mechanism.

With the gauge results displaying discrepancies to the historic data in terms of yield, it was important to validate the gauge recordings using High Speed Video shock wave tracking methods developed in [13], which are able to obtain a larger quantity of arrival time data along virtual spokes from the charge centre. Figure 8 shows the HSV data extracted from a single video in comparison to a KB prediction for TNT, assuming an equivalence of 0.3, which parallels the findings from the MAE analysis undertaken on the pressure gauge data evaluating a lower TNTe factor (TNTe=0.28) for arrival time when compared to other blast parameters (TNTe=0.395). Figure 9 shows the results of plotting KB predictions assuming a TNTe=0.395, alongside raw experimental data recordings. Whilst both the pressure and impulse trends are captured reasonably well[2], the arrival of the recorded shock waves is much later than an equivalent TNT blast.

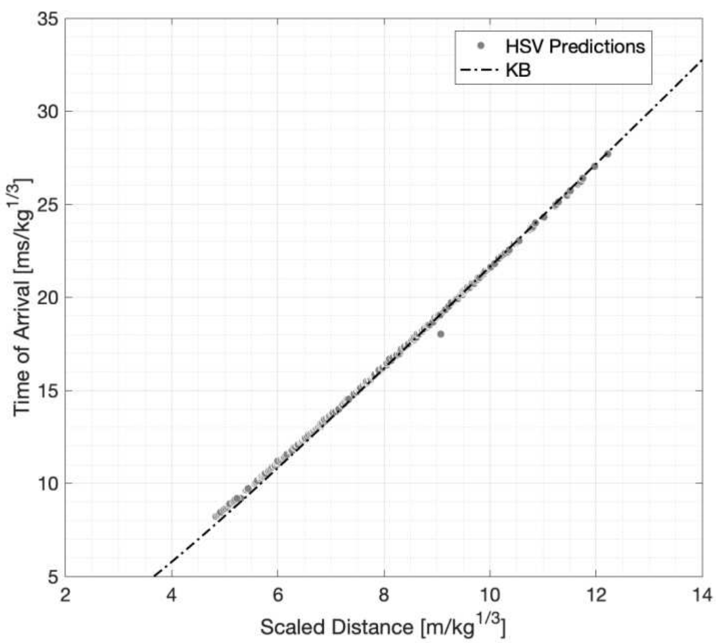

Figure 8: Shock front arrival time from a bottom detonated 250g ANFO hemispherical charge placed at a 5 m stand-off, recorded using HSV and scaled using TNT equivalence factor of 0.3 to compare to KB predictions

[2] The specific impulse trend would tend towards the KB when using the validated curve fit to omit the gauge plate clearing phenomena, the raw data will always show to under-predict for these trials.

The fact that a lower TNTe has been empirically established for arrival time, through two different methods of experimental work and analysis, is a finding which ties up with the arrival time of the shock wave being slower than TNT predictions at smaller scaled distances seen in Figures 1b and 7c. The main reason for a potential offset in the arrival time has been attributed to the slower detonation velocities associated with ANFO once the detonation wave reaches the extents of the charge, the shock wave forms and propagates away from the charge and takes detonation products with it. TNT has a detonation velocity of around 6800m/s when compared to the published figure of approximately 4800m/s for ANFO, again related to large scale trials and a maximum velocity. However, TNT reaches this quoted maximum speed effectively instantaneously due to its ideal-like detonation characteristics, but ANFO requires a specific amount of time in which the charge sustains detonation without losing energy through propagation of products (i.e., similar to being confined) to allow for the full chemical reaction to occur, thus reaching the quoted velocity of detonation. It is therefore a safe assumption that comparing the near-field conditions of ANFO to TNT will result in slower arrival times until a point at which maximum possible velocity of the detonated charge, related to radius and the time it takes to reach its extent, is achieved, at which the free-air shock will be comparable to one from a TNT detonation.

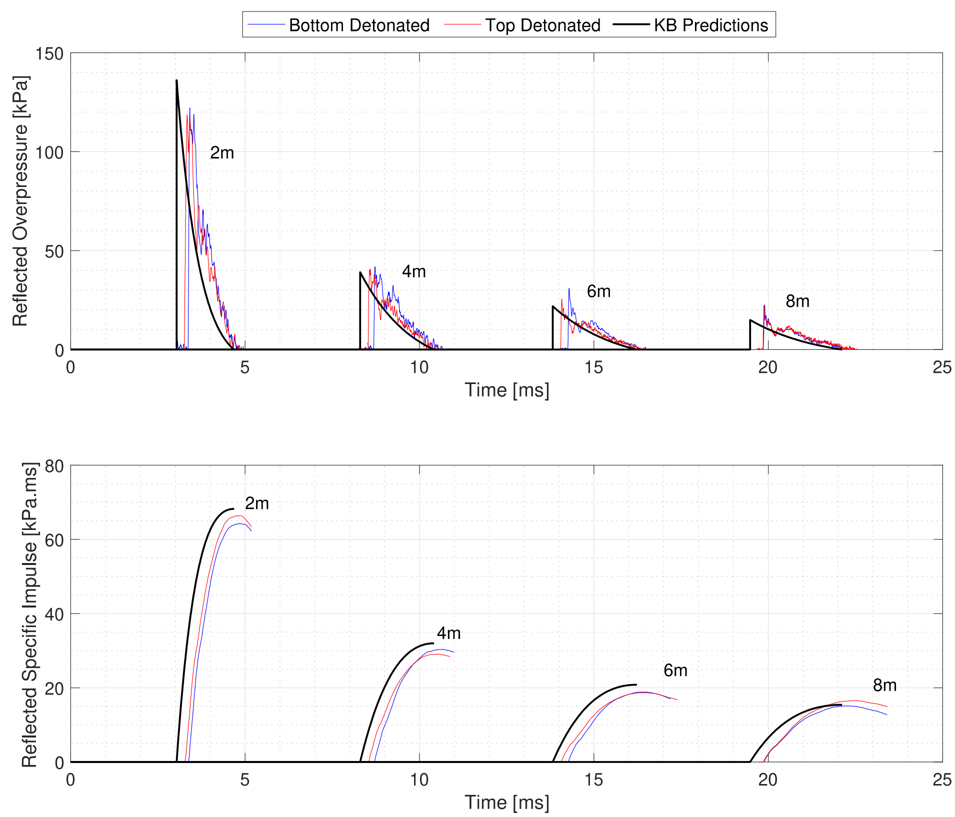

Figure 9: Compiled raw data from both top and bottom detonated trials at 2m, 4m, 6m and 8m standoff distance compared to KB predictions assuming a TNTe=0.395: a) Pressure-time history and b) Impulse-time history, showing only positive phase

HYPOTHESIS

The fact that this small-scale testing regime resulted in a generally low TNT equivalence (TNTe ≈ 0.4) for ANFO is a considerable deviation from the widely accepted figure of approximately 0.8 within the available published literature. Giglio et al [1] undertook a testing regime consisting of the detonation of three large scale, 20-100 Ton, hemispherical ANFO charges to which recorded blast parameters using pressure transducers and magnetic tape-recording systems, were processed and resulted in a TNTe = 0.834. Petes et al [5] expressed the desirability to use ANFO for explosive testing and provided a detailed compilation of historic testing which concluded on the idea that ANFO had approximately 80% of the energetic output of TNT. The findings from the current tests led the authors to discuss the hypotheses around why the tested ANFO presented a much lower energetic output than previously reported.

- ***Was the composition of the explosive actually ANFO?:*** Findings from published literature detail that a pure ammonium nitrate detonation results in a TNTe = 0.32-0.4 [18-22] which led the authors to consider the possibility that the composition did not contain fuel oil as requested on purchase. The composition of the explosive was chemically assessed by separating the substance in pentane and undertaking a gravimetric analysis resulted in a yield of 5.55±0.09% and 94.45±0.09% of the tested mass was found to be fuel oil and ammonium nitrate respectively. This finding was able to remove this hypothesis from consideration.

- ***Does the scale of the charge affect the chemical reactions occurring during detonation?:*** During the detonation of ANFO, theoretically an ideal stoichiometrically balanced reaction occurs, meaning the oxygen molecules released as a result of the AN decomposition is enough to cause deflagration of the fuel oil. Due to the fact the fuel oil aspect of the composition is not chemically bonded to the AN, there is a lag in the time it takes for the fuel oil and oxygen molecules to come into contact within the reaction zone. If the detonation wave reaches the extent of the charge, or there is expansion of detonation products, prior to this chemical reaction fully occurring, the potential energy release is never fully achieved. In small scale charges, the authors discussed whether it possible that this reaction never actually occurs and that the yield of these tests is the result of only the AN detonating. To test this hypothesis, pure Ammonium Nitrate prill was purchased from the same provider and tested utilising an identical methodology to the ANFO shots, boosted with a 1g sphere of PE10, to which no detonation occurred. This result was evidence to suggest the fuel oil oxygen reaction had to be occurring to sustain the detonation at least at the instance of detonation in the ANFO trials. The fact that around 50% of the quoted potential energy from the ANFO was released could be inconclusively related to a lack of confinement or more closely related to small sizes charges, a lack of radius to sustain the continual rise in internal pressure, temperature and detonation velocity to reach the potential yields seen in large scale shots, effectively only detonating AN.

- ***Is the energy equivalence reduction related to unreacted ANFO prill projectiles?:*** The findings from testing the previous two hypotheses led the authors to draw a further theory, that the overall explosive yield reduction, compared to quoted values in literature, could be directly linked to the quoted reaction zones of non-ideal explosives being in the order ≈15mm. The authors ran a rudimental analysis which assessed a shell of this radius of un-reacted ANFO (e.g the outer surface of the hemispherical charge) would have on the apparent TNT equivalence for a variety of hemispherical charge sizes tested as seen in Figure 10.

  The analysis assumed a constant reaction zone size of 13mm, and TNTe=0.82, to compute a mass ratio of ANFO between the theoretically reacted charge, based on the un-reacted prill contained within the reaction zone effectively being ignored, compared to the actual mass tested. This ratio was multiplied by the quoted TNTe factor to evaluate a theoretical reacted TNTe for these small-scale trials when assuming un-reacted prill projectiles represented by the plotted curve in Figure 10.

The attenuation towards the TNTe=0.82 is related to a smaller proportion of unreacted prill to the reacted in large scale trials and therefore small-scale charges would be more sensitive to this mechanism. Presented on this curve is evaluated best TNTe factor for the pressure and impulse data relating to the actual masses tested within this series alongside those presented within [5] for large scale trials. Considering the small-scale tests alone, the range in TNTe=0.3-0.5, closely matches the variability seen in Figure 7a and 7b, alongside the large-scale charges also seeming to compare well to the theoretical curve. To achieve the TNTe=0.82 based on the unreacted projectile mechanism alone, a charge mass of 10^4kg would be required. It is important to note that the value of TNTe and the size of reaction zone has been chosen based on published values and appropriate fits to the available data. The few experimental recordings which are much lower than the quoted range of TNTe=0.3-0.5 are the result of being top detonated and within near-field scaled distances, $Z < 1m/kg^{1/3}$, to which the detonator position and fluid dynamic instabilities have a much greater influence on the recorded overpressure and thus the inferred TNTe values, but the peak specific impulse remains equivalent to a bottom detonated charge.

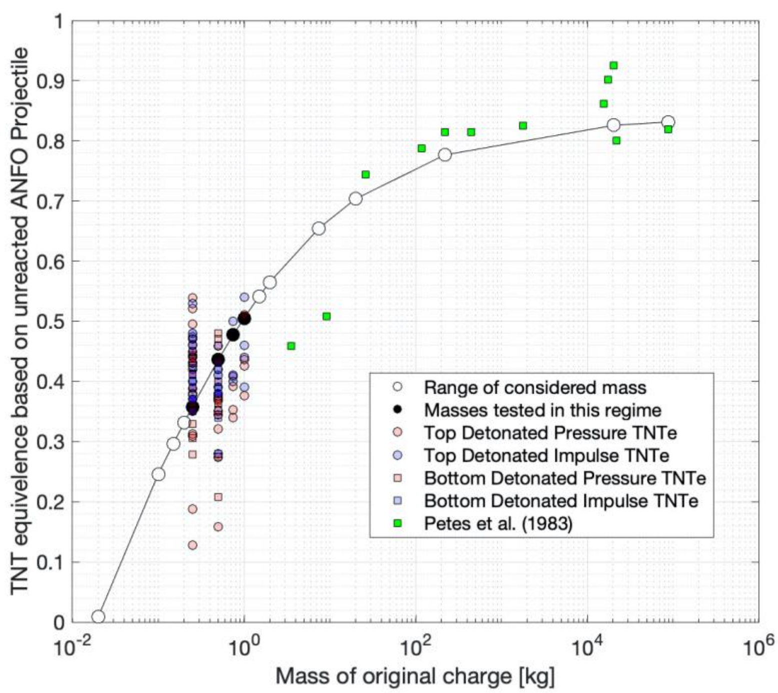

Figure 10: The results of applying a nominal 13mm reaction zone to a given ANFO charge and assuming this region has not detonated and instead is fired off as a projectile, therefore not adding to the yield of the detonation on the surface.

Whilst the last hypothesis has been validated using a reasonable theoretical assessment, it is still inconclusive as to whether this is the definitive mechanism as to why a lower TNTe value is experienced for small-scale ANFO charges. Future work will consider numerically modelling small-scale tests comparing detonations of ANFO and pure AN to help understand the fundamental mechanisms of the detonation process in these small-scale trials.

CONCLUSIONS

Through rigorous testing, this article established a TNTe = 0.395, for small scale hemispherical ANFO charges, within the mass range tested (250-1000g), which is around 50% of the industry recognised standard for ANFO (TNTe = 0.82). Whilst this finding suggests numerical methods are conservative when considering detonations of ANFO, it does however suggest that numerical simulations of small-scale non-ideal explosives are invalid if reliant on parameters extracted from historical large-scale shots. The observations were justified by considering the physical mechanisms ongoing during the detonation process of prill ANFO. The arrival time offset was directly related to the difference in velocity profiles between detonating ANFO, prior to steady-state conditions, and TNT believed to be caused by meso-structure and homogeneity of the explosive charges in question. The overall yield of the small scale ANFO charges was discussed to be a combination of unreacted prill projecting away from the charge and whether or not the timescale of detonation was enough for the fuel oil and oxygen reaction to occur prior to the detonation wave reaching the extents of the charge. The findings of the article aim to provide fundamental improvements to the knowledge of non-ideal explosions and to assist with capturing them accurately in simulations.

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