

## Understanding the explosion risk presented by ammonium nitrate and aluminium home-made explosives detonated as surface charges in hexahedral main charge containers

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### Abstract

Ammonium nitrate and aluminium (AN–Al) has been used as a typical homemade explosive (HME) by non-state actors since the turn of the century. Despite the regulation applied to ammonium nitrate above 16% nitrogen content and an aluminium particle size below 200  $\mu\text{m}$ , their use has been widespread in Afghanistan, Columbia, Iraq, Syria and Yemen. Containers used to utilise AN–Al as a man-portable improvised explosive device (IED) are typically hexahedral in shape, not the spherical or hemispherical geometries used to theorise risk mitigation. This is particularly important in post-blast investigation where explosives of a non-ideal nature are often used in non-spherical containers.

Given the breadth of HME available to criminals, the explosion performance of forty hexahedral containers filled with AN–Al of unknown manufacture is examined. Performance of the AN–Al is determined through the surface detonation of these containers on alluvial soil, with apparent crater volume compared to theoretical calculations for spherical charges of TNT detonated in that same medium. A conversion factor for hexahedral main charges to spherical charges is then established to achieve more accurate predictions of the explosion risk using Kingery-Bulmash and Bowen curves. The paper provides worked examples for practical application and a methodology by which predictions of charge mass in other mediums such as asphalt can be determined.

**Keywords** Home-made explosive · Crater · Hexahedral charge container · Alluvial soil · Asphalt

## 1 Introduction

The prolific use of ammonium nitrate (AN) within man-portable improvised explosive devices (IEDs) has recently undergone literature review [1, 2], with aluminium (Al) as a metallic fuel rising in ascendance since the turn of the century in conflict-affected states such as Afghanistan, Columbia, Iraq, Syria and Yemen [3–5]. The addition of Al to AN is of significance, given its ability to make AN more sensitive to detonation than other types of AN-based HME, such as AN and fuel oil (ANFO) [6]. For example, the addition of Al to AN at a certain percentage and particle size is reported to reduce critical diameters from 60 to 20 mm, with detonation velocities above  $3850 \text{ ms}^{-1}$  achieved [7].

Whilst regulation does apply to both AN (above 16% nitrogen content) and Al (below a particle size of  $200 \mu\text{m}$ ) [8], the United Nations General Assembly (UNGA) is now focusing on the regulation of ECP used to manufacture HME [9], since supply chains continue to facilitate their amalgamation into viable IEDs [2]. As such, HME performance poses a

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significant challenge to the scientific community given their non-ideal nature [10], relative ease of manufacture [11], and simplicity of placement [12]. Therefore, it is of great importance to understand the explosive power of such compositions to increase knowledge of their effects on people and structures and to represent that knowledge within recognised blast terminology such as Friedlander Blast Waves [13], Scaled Distance [14, 15], Pressure–Time curves [16–18] and TNT equivalence ( $TNT_e$ ) [19].

Most historical data for blast in air examines the criteria surrounding a surface (or near surface) detonation of spherical or hemispherical charges [18], and does not consider containment. However, most IEDs comprising AN–Al utilise everyday hexahedral explosive charge containers, such as HDPE jerrycans, palm oil and water carriers (see Fig. 1). Their use as a man-portable explosive device is purely ergonomic—they must be easy to carry, easy to conceal, and simple to place. Less exposure during emplacement means less chance of being caught [20]. As such, IEDs are often found lying horizontally on the surface (if command-activated) or buried just beneath the surface (if victim-activated) [21]. Open-source military counter-IED literature also refers to HME containers of a hexahedral form being the most widely used in recent conflicts of Western interest [22].

Limited instrumentation within conflict-affected states makes scientific measurement of explosive performance and determining the composition of HME difficult. Therefore, a significant amount of information is lost to risk managers when practical measurement, such as crater size and crater volume from controlled detonations of confiscated items, would be an appropriate methodology to calculate  $TNT_e$  of actual compositions, not those made in ideal conditions for small-scale tests where exact properties (such as density of loading) are known. As such, crater formation is a suitable tool to study blast phenomena, the behaviour and destructive power of different HME, and the response of soil and rock under this type of loading when technology is the limiting factor [23].

However, the mechanism of crater formation is a complex subject and relates to the dynamic physical properties of air, soil, the soil–air interface, and the location of the explosive charge relevant to the soil–air interface [24]. For even the most carefully performed cratering experiments, there can be deviations in dimensional measurements in the region of 10%, up to as much as 40% [25]. As such, large sample sizes are necessary to reduce margins of error and improve coefficients of determination ( $R^2$ ). It is also desirable to perform trials where similarities in soil type to previous academic work exists; this provides consistency. This paper therefore considers 40 surface firings of AN–Al main charge compositions confiscated during security operations in alluvial soil (a soil medium commonly reported in cratering literature). Given their confiscation, the threat posed by their explosive properties and ageing is unknown.

**Fig. 1** Examples of containers used in trial © BCL & Artios Global



**Fig. 2** Crater dimensions considered during trial © Cranfield University

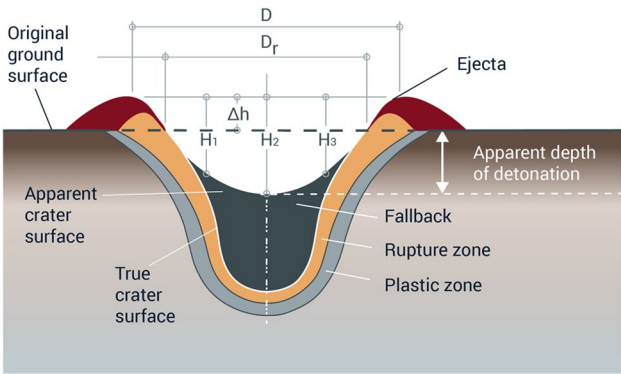


**Table 1** Empirical formulae available for crater calculations

| Author                         | Soil type     | Charge shape           | Charge position | Empirical formula                   | Equation number |
|--------------------------------|---------------|------------------------|-----------------|-------------------------------------|-----------------|
| Ambrosini [26]                 | Various       | Spherical              | Surface         | $D = 0.51M^{1/3}$                   | (1)             |
| Bjelovuk [31]                  | Asphalt       | Hexahedral (L:H 1–1.5) | Surface         | $M = 617.952V_b^{0.794}p_k^{0.309}$ | (2)             |
| Cooper [30]                    | Alluvial soil | Spherical              | Surface         | $H_2 = 0.5V_c^{1/3}$                | (3)             |
|                                |               |                        |                 | $R_a = 1.2V_c^{1/3}$                | (4)             |
| Cooper [27]                    | Alluvial soil | Spherical              | Surface         | $D = 2K_{alluvium}(2E_{CR}M)^{1/3}$ | (5)             |
| Kinney and Graham [18]         | Various       | Spherical              | Surface         | $D_r = 0.8M^{1/3}$                  | (6)             |
| Adushkin and Khristoforov [29] | Various       | Spherical              | Surface         | $D = 0.606M^{0.34}$                 | (7)             |
|                                |               |                        |                 | $V_a = 0.0143M^{1.038}$             | (8)             |
|                                |               |                        |                 | $H_2 = 0.152M^{0.331}$              | (9)             |
| Nagy [28]                      | Clay          | Spherical              | Surface         | $D_r = 0.55679M^{1/3}$              | (10)            |

2 Literature review

The most recent papers relating to surface explosions of spherical charges have been published by Ambrosini [26], Cooper [27], Nagy [28] and Adushkin [29]. These trials were built on the considerable work conducted by Cooper in alluvial soil during the Cold War [30]. However, the only publication that addresses non-spherical surface charges is that of Bjelovuk [31], who conducted numerous trials using hexahedral charges on asphalt. No literature on other soil types using hexahedral charges, or where a comparison to spherical charges has been attempted, can be identified by the authors of this paper.

Those historic crater trials derive a specific formula for crater dimension based on charge geometry and proximity to the soil surface (buried, surface or near-surface). For example, Westine [32], Rickman et al. [33], Payne et al. [34] and Luccioni [24, 35] have focused upon deriving formulae to determine crater size for buried charges, whilst the works of Cooper [30] and Kinney and Graham [18] focus on surface or near surface laid charges.

To facilitate a useful trial of this nature, there must be commonality in reference data. As such, the formation of a crater from a surface explosion (and its measurement) must be described to obtain consistent and usable data. The crater dimensions defined by Kinney and Graham [18] and Cooper [27] are therefore used in this paper (see Fig. 2), where  $D$  [m] represents the apparent crater diameter (that which can be seen in the post-blast phase),  $D_r$  [m] the actual crater diameter (that which cannot be seen), and  $H_2$  [m] the apparent depth of the crater (another visible measurement).

The formulae of interest to this paper are described in Table 1 and have been derived over 50 years from the cratering methodology described at Fig. 2. Sometimes expressed as  $W$  in equations,  $M$  refers to the explosive mass of TNT [kg],  $V_a$  is the apparent crater volume [m<sup>3</sup>],  $D$  is the apparent crater diameter [m],  $D_r$  the actual crater diameter [m],

$E_{CR}$  the cratering efficiency of the soil type [27], and  $P_k$  the area of hexahedron (length  $\times$  height  $[L \times H]$ ) of the charge in direct contact with the soil surface  $[m^2]$  [31]:

These empirical equations achieve relatively consistent results for ideal explosives such as TNT, PETN and TATB. However, limited data exists on non-ideal explosives such as AN–Al under similar circumstances, whose properties can vary dependent upon the nature of the AN and Al used (such as fertiliser grade or technical grade AN, powder or flake aluminium), the booster explosive [36], the stoichiometry of the composition, the loading density applied, the type of confinement [37], moisture ingress and ageing [38, 39].

For example, ANFO is a non-ideal explosive [40] and does not possess the shattering or brisance effect that one would experience from TNT when in direct contact with rock. ANFO has a longer detonation reaction zone than TNT, thereby giving up its explosive energy over microseconds as opposed to sub-microseconds [41, 42]. This slower energy release results in much lower detonation pressures ( $P_{CJ}$ ) and therefore less brisance than TNT, which promotes the cracking as opposed to shattering of rock. ANFO also generates a greater gas volume than TNT [43], thereby creating a ‘heave’ effect within the medium as the gaseous products of detonation seep into cracks formed in the soil [13].

The realistic physical properties of unknown HME recovered from security operations, and their ageing, is evident in Fig. 1. These are the IEDs that terrorists build, not benign laboratory grade samples. Recent work by Collett et al. [44] also improves understanding of non-ideal explosive behaviours, allowing predictions of  $TNT_e$  within 10% for heat of explosion ( $Q_e$ ). Performance is determined from the following equation relating to oxygen balance and respective heats of formation from Hess’ Law:

$$\Omega = \frac{15.999 \left( d - 2a - \frac{b}{2} + \left( 2 \sum \text{Valence } (\pm 4) + \frac{3}{2} \sum \text{Valence } (\pm 3) + \sum \text{Valence } (\pm 2) + \frac{1}{2} \sum \text{Valence } (\pm 1) + \dots \right) \right)}{\text{molecular weight}} \times 100, \quad (11)$$

$$\Delta H_{\text{reaction}}^{\theta} = \sum \Delta H_{f(\text{products})}^{\theta} - \sum \Delta H_{f(\text{reactants})}^{\theta}. \quad (12)$$

As such, there exists a gap in academic knowledge concerning:

- 1) formulae to predict the size of an explosive charge used based on non-spherical containers;
- 2) how such formulae can be applied to charge position (buried, surface or near surface) and soil medium; and
- 3) risk to life posed by non-ideal explosives confined within non-spherical containers.

This paper aims to address these criteria for surface-laid IED charges recovered and disposed of by humanitarian agencies in a conflict affected state.

### 3 Methodology

Working closely with the United Nations Development Programme (UNDP), 40 hexahedral containers comprising AN–Al of unknown explosive performance recovered from security-led operations, were detonated on an undisclosed demolition area between 18 December 2019 and 21 March 2021. The sample size of containers can be seen in Table 2, with the dimensions of each container, and the mass of the explosive filling, shown in Table 3.

Each container was laid in a configuration typical of their original placement (see Fig. 3) with detonation achieved using a 100 g plastic explosive donor charge (85% RDX, 15% wax) and an ‘Electric Instant’ detonator (450 mg PETN) at the centre face. Given the limited explosive mass of initiator and donor charge (100.45 g) compared to main charge mass, they are not included in overall NEQ calculations.

The donor charge was placed in the location of the ‘20’ on the figure shown above. This is the intersection of the opposing corner diagonals (the centre of the container face). For safety reasons, no attempt was made to remove the yellow or blue detonating cord within the container cap of any IED, or to use the detonating cord as the means of initiation.

The soil type in the experimental area was determined from geological tables as dry compacted alluvial soil. For ethical reasons the precise location is not disclosed. However, the properties of that soil type are shown in Table 4, which is similar to those used by Cooper [27, 30], Kinney and Graham [18] and Ambrosini [26] to determine diameter ( $D$ ), ( $D_r$ ), radius ( $R$ , or  $D/2$ ), and apparent crater depth ( $H_2$ ) for many hundreds of surface detonations, thereby facilitating an appropriate trial data set.

**Table 2** Quantity of containers available for trial

| Container size (L) | Quantity | Comment                                                                                                                                                                                           |
|--------------------|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 5                  | 10       | Intelligence reporting identified AN–Al HME manufactured in bulk, but the precise AN–Al stoichiometry was unknown. 20 L containers were by far the most readily available within the supply chain |
| 10                 | 10       |                                                                                                                                                                                                   |
| 20                 | 15       |                                                                                                                                                                                                   |
| 40                 | 5        |                                                                                                                                                                                                   |

**Table 3** Container dimensions used for trial

| Container size (L) | L [m] | W [m] | H [m] | Area [m <sup>2</sup> ]<br>$P_k$ | Volume (m <sup>3</sup> ) | Mass of AN–Al [kg] | H:L ratio |
|--------------------|-------|-------|-------|---------------------------------|--------------------------|--------------------|-----------|
| 5                  | 230   | 100   | 270   | 0.0621                          | 0.00621                  | 7.1                | 1.17      |
| 10                 | 226   | 194   | 324   | 0.0732                          | 0.01421                  | 16.3               | 1.43      |
| 20                 | 290   | 240   | 400   | 0.1160                          | 0.02784                  | 32.6               | 1.38      |
| 40                 | 400   | 240   | 580   | 0.2320                          | 0.05568                  | 65.2               | 1.45      |

Where  $L$ ,  $W$  and  $H$  [m] represent the length, width and height dimensions of the container;  $P_k$  [m<sup>2</sup>] represents the area of container ( $L \times H$ ) laid on the surface of the soil; volume [m<sup>3</sup>] represents the  $L \times W \times H$  of each container; and H:L represents the ratio of H divided by L for each container

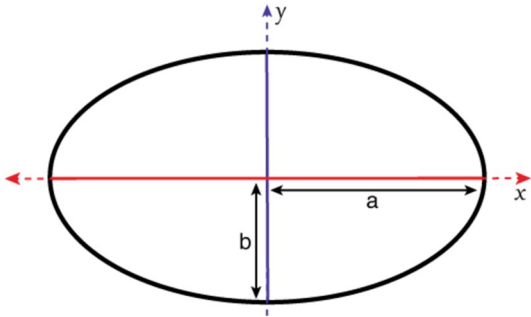
**Fig. 3** Position of containers on surface—representative of a 20 L container and its condition © BCL



**Table 4** Properties of alluvial soil used in trial

| Soil property                                | Value       |
|----------------------------------------------|-------------|
| Specific gravity [Gs]                        | 2.6         |
| Minimum void ratio                           | 0.48        |
| Maximum void ratio                           | 0.91        |
| Maximum dry unit weight [kNm <sup>-3</sup> ] | 19.66       |
| Moisture content [%]                         | 10.66       |
| Liquid limit [LL%]                           | Non-plastic |
| Plastic limit [PL%]                          | Non-plastic |
| Cratering efficiency $E_{CR}$                | 0.5         |

**Fig. 4** Representative crater shape from trials



However, it was noted that the detonation of each hexahedral container produced an elliptical crater, not a hemisphere (see Fig. 4), which was similar to the findings of Bjelovuk [31] for asphalt. As such, it was necessary to determine the apparent crater diameter ( $D$ ) and apparent crater volume ( $V_a$ ) using the following equations, where  $a$  and  $b$  are the major and minor axes of a semi-ellipse:

$$D = 2\sqrt{\left(\frac{a}{2} \cdot \frac{b}{2}\right)}, \quad (13)$$

$$V_a = \frac{1}{2} \cdot \frac{4}{3} \pi \left(\frac{a}{2} \cdot \frac{b}{2}\right) H_2, \quad (14)$$

$$\therefore V_a = \frac{\pi ab H_2}{6}. \quad (15)$$

Post detonation,  $a$ ,  $b$  and  $H_2$  measurements were calculated [m] using a laser measure. Each dimension was recorded to 2 significant figures. No material was removed from the crater to determine actual crater depth. The reasons for this were threefold:

- Safety—the area used for the controlled demolition was a historical range of many decades;
- Environment—heat and humidity precluded spending long periods out in the open; and
- Security—minimising time out in the open due to ongoing conflict.

The apparent crater volume was determined using Eq. (15).

Apparent crater volumes were then compared to the calculations offered by Cooper [27, 30] for the same soil type in Table 1 (Eqs. 3–5). Given that results for Adushkin, Ambrosini, and Nagy were obtained for clay-type soils and asphalt, their data was discounted. However, given the similarities in crater shape between these trials and the results of Bjelovuk, a correlation between surface detonations on asphalt and alluvial soil was attempted for hexahedral explosive charges using Eq. (2) [31]. The aspiration was to achieve a methodology by which hexahedral detonations in alluvial soil could be used to determine crater sizes from hexahedral charges in asphalt.

Once trials were completed, 10 × 100 g samples of AN–Al were removed from surplus environmentally damaged containers awaiting bulk disposal to determine the composition of the HME and its likely TNT<sub>e</sub> based on the predicted heat of explosion ( $Q$ ). Sampling was carried out by UNDP explosive experts, with a Scanning Electron Microscope (SEM) utilised at the University of Wales Trinity Saint David (UWTSD) to determine whether the Al was a fine powder, flake, or a mixture of both.

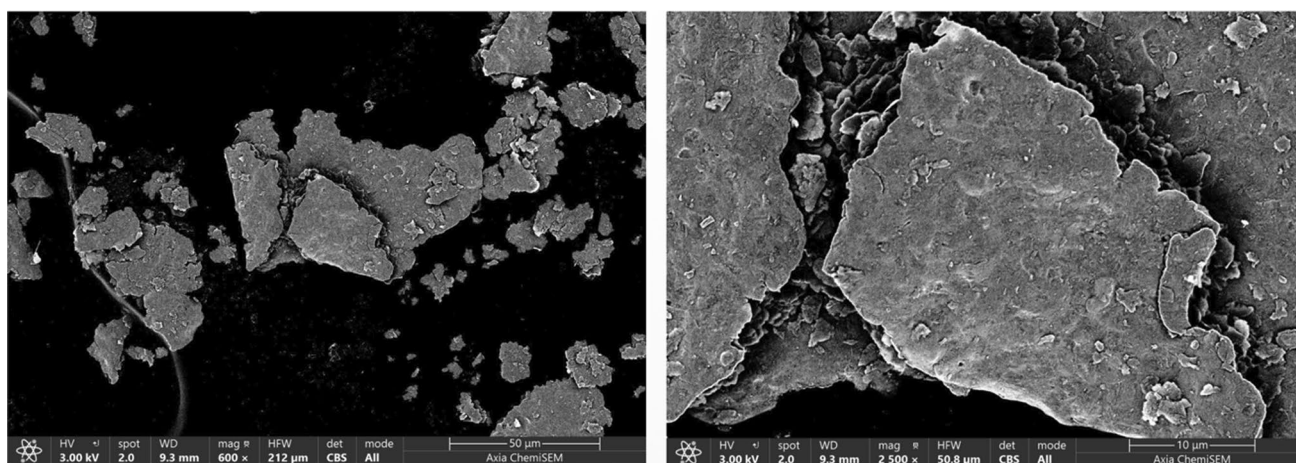


**Fig. 5** SEM results for aluminium composition (the grey flakes) within AN–Al at magnification 600 (left) and 2500 (right)

Table 5 Mean results of each container detonation

| Explosive                      | Mass [kg] | $\rho$ [gcm <sup>-3</sup> ] | TNTe [kg] | $M_{tnt}^{1/3}$ [kg <sup>1/3</sup> ] | D <sub>Exp</sub> [m] | D <sub>Cooper</sub> [m] | H <sub>2Exp</sub> [m] | H <sub>2Cooper</sub> [m] | H <sub>2Exp</sub> /H <sub>2C</sub> (%) | V <sub>e</sub> [m <sup>3</sup> ] | V <sub>c</sub> [m <sup>3</sup> ] | V <sub>e</sub> /V <sub>c</sub> (%) |
|--------------------------------|-----------|-----------------------------|-----------|--------------------------------------|----------------------|-------------------------|-----------------------|--------------------------|----------------------------------------|----------------------------------|----------------------------------|------------------------------------|
| AN–Al                          | 5.68      | 0.914                       | 5.91      | 1.81                                 | 0.498                | 0.759                   | 0.219                 | 0.158                    | 138                                    | 0.028                            | 0.032                            | 88                                 |
|                                | 13.04     | 0.917                       | 13.56     | 2.38                                 | 0.617                | 1.002                   | 0.340                 | 0.209                    | 162                                    | 0.067                            | 0.073                            | 92                                 |
|                                | 26.08     | 0.936                       | 26.08     | 3.00                                 | 0.741                | 1.262                   | 0.440                 | 0.263                    | 168                                    | 0.127                            | 0.145                            | 88                                 |
|                                | 52.16     | 0.936                       | 52.16     | 3.79                                 | 1.010                | 1.590                   | 0.490                 | 0.331                    | 147                                    | 0.261                            | 0.291                            | 90                                 |
| Mean value over all 40 firings |           |                             |           |                                      |                      |                         |                       |                          |                                        |                                  |                                  |                                    |
| 0.926                          |           |                             |           |                                      |                      |                         |                       |                          |                                        |                                  |                                  |                                    |
| 156                            |           |                             |           |                                      |                      |                         |                       |                          |                                        |                                  |                                  |                                    |
| 89                             |           |                             |           |                                      |                      |                         |                       |                          |                                        |                                  |                                  |                                    |

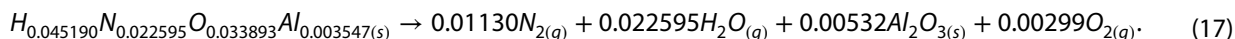
## 4 Results and discussion

### 4.1 TNT equivalence

From the 1000 g sample collected, the mean stoichiometric composition of the AN–Al was determined from the dissolution of AN to be 90.43/9.57 AN–Al. Using this composition and the methodology offered by Collett et al. [44], the molecular formula of the AN–Al was determined as:

$$H_{0.045190}N_{0.022595}O_{0.033893}Al_{0.003547(s)} \quad (16)$$

From this empirical formula, the products of detonation were calculated as follows, using a modified oxygen balance equation (see Eq. (11)) for non-ideal explosives [44]:



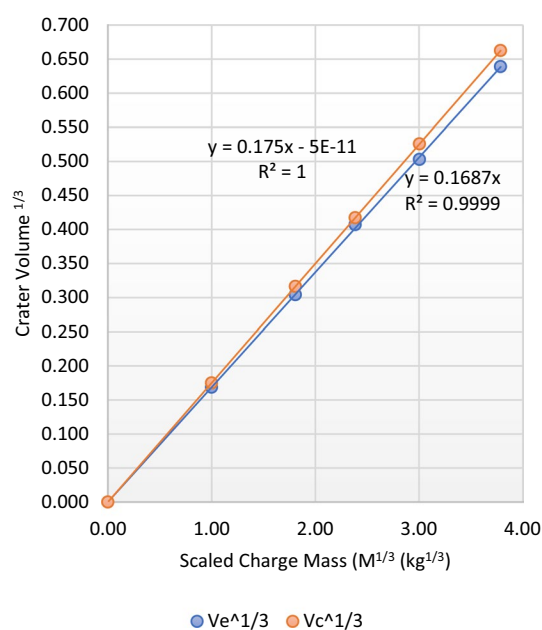
From this molecular formula and using the enthalpies of formation identified by the authors [44], Hess' Law (Eq. 12) determined the heat of explosion ( $Q$ ) of the AN–Al to be  $-4272.93 \text{ kJ kg}^{-1}$ , with an associated oxygen balance of  $+9.56\%$ . This equates to a TNT<sub>e</sub> of 1.04 (see Eq. (18)), where the  $Q$  value for TNT is taken as  $-4091.63 \text{ kJ kg}^{-1}$  from literature [43]:

$$TNT_e = \frac{Q_{ANAL}}{Q_{TNT}} = \frac{-4272.93}{-4091.63} = 1.04. \quad (18)$$

Results of SEM analysis (see Fig. 5) identified that no specific particle size criteria was applied to the selection of aluminium for this HME, but rather the availability of that aluminium within the supply chain. The aluminium used was a crude product, likely obtained from the sluff of engineering applications, with a particle size ranging between 10 and 100  $\mu\text{m}$  and a mean particle size distribution of 63  $\mu\text{m}$ . However, the particle size was within the scope of regulatory prohibition ( $< 200 \mu\text{m}$ ), suggesting that waste Al from engineering applications should, perhaps, be graded before disposal [1].

The SEM also identified that the aluminium flakes had a coating of  $Al_2O_{3(s)}$ , suggesting that the AN–Al had been mixed with the AN and exposed to the environment for some time. This was also evident from the degradation of some containers where the HDPE had split longitudinally due to loss of ductility [45] and the explosive filling expanding [21]. It was impossible to determine the precise length of environmental exposure, other than to confirm with the authorities that containers had been recovered in August 2018, with disposals commencing in December 2019, and the trials concluding in March 2021. As such, the IEDs had been exposed to diurnal cycling in a largely arid sub-tropical country for about

**Fig. 6** Graphical representation of experimental crater volumes for rectangular charge containers compared to theoretical volumes obtained from spherical charges



18 months before disposal. This would allow for the HDPE containers to degrade, for moisture uptake, for oxidation of the aluminium, and ‘caking’ of the explosive filling. ‘Caking’ causes AN-based explosives to lose their durability and explosive properties over time through loss of porosity [46, 47], thereby reducing detonation velocity up to 50% [48].

All of these findings support explosion theory predictions that the performance of the AN–Al would be less than that of HME compositions comprising fine Al powder [49] made for trials, but still capable of achieving theoretical detonation velocities in the order of 3160–3850 ms<sup>−1</sup>, and detonation pressures ( $P_c$ ) between 2.1 and 3.5 GPa [7].

## 4.2 Cratering performance and explosive characteristics

The results of each firing are available at <https://doi.org/10.17862/cranfield.rd.25047764>, with their mean values highlighted in Table 5 below. The columns from left to right determine:

- the mean mass of AN–Al within each container size [kg];
- the mean density of AN–Al from each container size [g cm<sup>−3</sup>];
- the mean TNT equivalence for each container size [kg];
- the mean scaled charge mass  $M_{\text{tnt}}^{1/3}$  [kg<sup>1/3</sup>];
- the mean experimental widths ( $D_{\text{Exp}}$ ) and depths ( $H_{2\text{Exp}}$ ) of craters for each container size [m] compared to Cooper’s theoretical values for a spherical surface detonation ( $D_{\text{Cooper}}$  and  $H_{2\text{Cooper}}$ ) [m];
- the mean apparent crater volumes ( $V_e$ ) for each container size compared to theoretical values for Cooper ( $V_c$ ) [m<sup>3</sup>];
- the ratio of mean experimental crater depths compared to Cooper ( $H_{2\text{Exp}}/H_{2C}$ ); and
- experimental crater volume ( $V_e$ ) for hexahedral charges compared to Cooper ( $V_e/V_c$ ).

The comparison with Cooper [27, 30] is calculated using Eqs. (3), (4), (13), and (15).

These results identify a hexahedral to a spherical relationship of apparent crater volume ( $V_e/V_c$ ) in the alluvial soil of 89%, where the ratio of container in contact with the surface (H:L) lies between 1 and 1.5 (see above). Similarly, apparent crater depth provided a relationship of 156% ( $H_{2\text{Exp}}/H_{2C}$ ). As such, it is possible to predict, based on  $M^{1/3}$  and the properties of alluvial soil, that hexahedral charges in alluvial soil display a relationship to spherical charges in alluvial soil of:

$$V_e = 0.89V_c. \quad (19)$$

Graphically (see Fig. 6) the equations for  $V_e$ ,  $V_c$  and  $M$  can be represented as:

$$V_e^{1/3} = 0.1687M^{1/3}, \quad (20)$$

$$V_c^{1/3} = 0.175M^{1/3} - 5 \times 10^{-11} \cong 0.175M^{1/3}. \quad (21)$$

Note that  $R^2$  for the trials achieves unity.

With the cratering comparison complete, the data set (<https://doi.org/10.17862/cranfield.rd.25047764>) also determined the average density of the AN–Al explosive to be 0.926 g cm<sup>−3</sup>. This was calculated by taking the mean value of density in Table 5. Given that the mixture comprises approximately 90/10 AN/Al from dissolution, the detonation velocity ( $v_{\text{mix}}$ ) can be determined from the characteristic velocities ( $D_i$ ) of both AN [50] and Al [27], and their theoretical maximum densities ( $\rho_{\text{TMD}}$ ) of 1700 and 2700 g cm<sup>−3</sup> respectively [27, 51].

**Table 6** Comparison of experimental crater volumes in alluvial soil and asphalt

| Explosive | Mass [kg]                  | TNTe [kg] | $M_{\text{tnt}}^{1/3}$ [kg <sup>1/3</sup> ] | $V_e$ [m <sup>3</sup> ] | $V_b$ [m <sup>3</sup> ] | $V_e/V_b$ (%) | $V_c/V_b$ (%) |
|-----------|----------------------------|-----------|---------------------------------------------|-------------------------|-------------------------|---------------|---------------|
| AN–Al     | 5.68                       | 5.91      | 1.81                                        | 0.028                   | 0.0084                  | 334           | 375           |
|           | 13.04                      | 13.56     | 2.38                                        | 0.067                   | 0.0225                  | 299           | 323           |
|           | 26.08                      | 27.12     | 3.00                                        | 0.127                   | 0.0451                  | 282           | 322           |
|           | 52.16                      | 54.25     | 3.79                                        | 0.261                   | 0.082456                | 316           | 353           |
|           | Mean value over 40 firings |           |                                             |                         |                         | 304           | 339           |

The velocity of detonation  $v_d$  [ $\text{ms}^{-1}$ ] and detonation pressure ( $P_{cj}$ ) [GPa] of this composition are therefore predicted from the actual and theoretical maximum density (TMD) as follows:

$$v_{mix} = \sum D_{iAN} D_{iAl} = (0.9 \times 5050) + (0.1 \times 6850) = 5230 \text{ ms}^{-1}, \quad (22)$$

$$\rho_{TMD} = \sum \rho_{iAN} \rho_{iAl} = (0.9 \times 1700) + (0.1 \times 2700) = 1.8 \text{ gcm}^{-3}, \quad (23)$$

$$\therefore v_d = v_{mix} \left( \frac{\rho}{\rho_{TMD}} \right) + 1.5 \left( 1 - \frac{\rho}{\rho_{TMD}} \right) = 5.230 \left( \frac{0.926}{1.8} \right) + 1.5 \left( 1 - \frac{0.926}{1.8} \right), \quad (24)$$

$$\therefore v_d = 3419 \text{ ms}^{-1}, \quad (25)$$

And detonation pressure  $P_{cj}$  [7, 27]:

$$P_{cj} = \rho \frac{v_d^2}{4} = 0.926 \left( \frac{3.419^2}{4} \right) = 2.84 \text{ GPa}. \quad (26)$$

Both values lie within the detonation velocity and detonation pressure reported for AN–Al compositions in the region of 90% AN and 10% Al [6, 52, 53].

### 4.3 Comparisons with other soil mediums

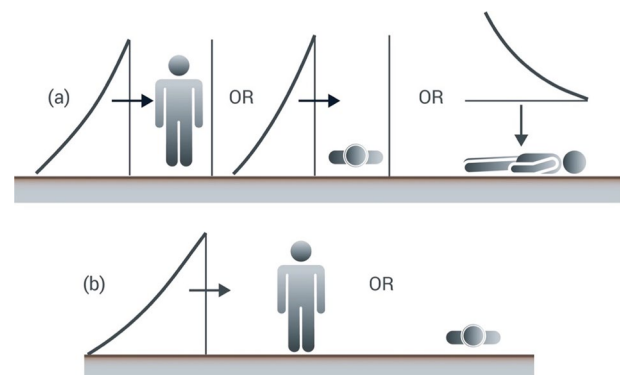
Bjelovuk reports [31] that the mass of explosive  $M$  [kg] (in terms of TNTe) is proportional to the apparent crater volume  $V_b$  [ $\text{m}^3$ ] and the surface area of the charge in contact with the ground  $P_k$  [ $\text{m}^2$ ] for container L:H ratios of 1:1.5 on asphalt.

Asphalt was chosen by Bjelovuk given that most IEDs within Europe present as surface or above surface detonations within this medium [2, 54]—it is difficult and time-consuming for a terrorist to dig into asphalt. As such, a man-portable IED container is likely to be placed on the ground or worn as a person-borne IED (PBIED), whilst an IED within a vehicle may be above the ground by some distance 'x' (determined by the height of the load-carrying area) [2]. Bjelovuk's supposition can be further supported by international community concerns over the increased presence of IEDs within urban settings [55].

The correlation of apparent crater volume between alluvial soil and asphalt for hexahedral containers is summarised below (Table 6), where the columns from left to right represent:

- the mean mass of AN–Al within each container size [kg];
- the TNT equivalence of that mass of AN–Al [kg];
- the mean scaled charge mass for each container  $M_{tnt}^{1/3}$  [ $\text{kg}^{1/3}$ ];
- the mean apparent experimental crater volumes ( $V_e$ ) for each container size in alluvial soil;
- the theoretical values for Bjelovuk in asphalt ( $V_b$ ) [ $\text{m}^3$ ]; and
- the ratio of mean experimental crater volumes in alluvial soil compared to Bjelovuk ( $V_e/V_b$ ) and Cooper ( $V_e/V_c$ ) in asphalt.

**Fig. 7** Orientations of human to friedlander blast waves ((a) denotes human near reflecting surface, (b) denotes human in the free field) [13, 50]



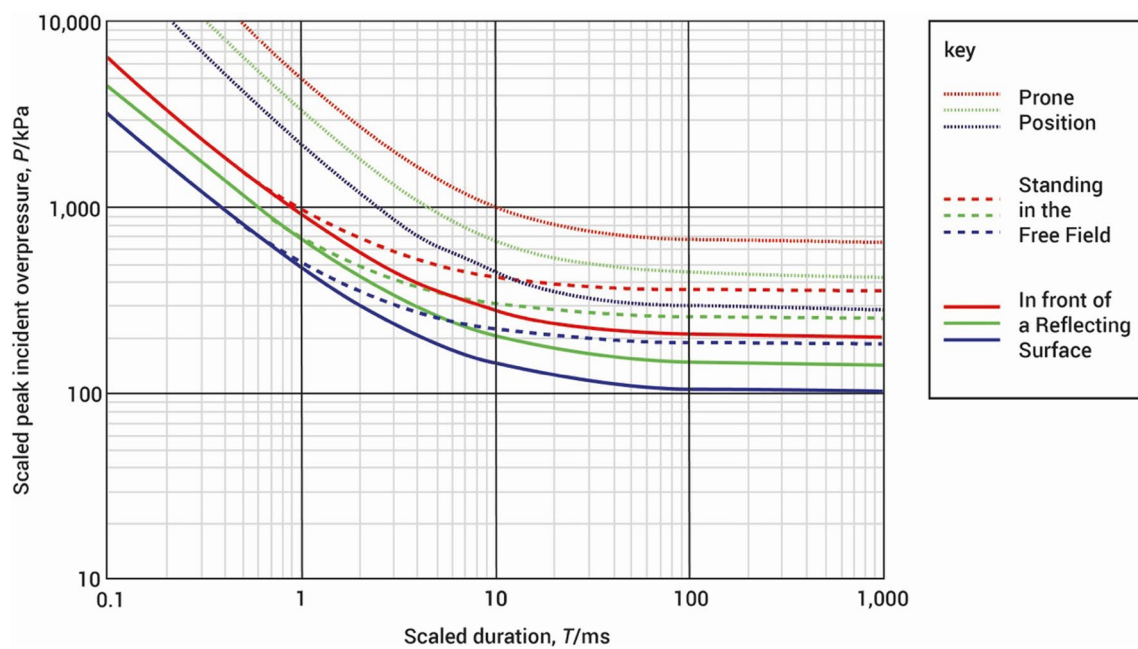


**Fig. 8** New standard: scaled incident peak overpressure versus scaled duration for three lethality levels (1, 50 and 99%) in front of a reflecting surface, prone and standing in the free field [63] © Cranfield

**Table 7** Blast consequences for worked example 2

| Range (R) [m]                                | 1         | 5      | 10     | 20     |
|----------------------------------------------|-----------|--------|--------|--------|
| NEQ (kg)                                     | 28        | 28     | 28     | 28     |
| TNTe (kg)                                    | 24.36     | 24.36  | 24.36  | 24.36  |
| Peak incident pressure (Ps) [kPa]            | 7293.10   | 271.54 | 61.71  | 18.72  |
| Incident impulse (Is) [kPa ms]               | 408.73    | 305.88 | 164.81 | 87.17  |
| Peak reflected pressure (Pr) [kPa]           | 64,912.97 | 994.37 | 153.60 | 40.14  |
| Reflected impulse (Ir) [kPa ms]              | 7366.60   | 816.39 | 364.08 | 170.66 |
| Shock front velocity (U) [ms <sup>-1</sup> ] | 2609.78   | 617.21 | 419.63 | 370.59 |
| Arrival time (Ta) [ms]                       | 0.245     | 4.28   | 14.60  | 41.03  |
| Positive phase duration (T+) [ms]            | 0.575     | 4.93   | 8.34   | 10.81  |
| Decibel level                                | 189.79    | 161.82 | 149.79 | 137.75 |

Table 6 demonstrates that (based on the *TNTe* for the AN-Al used in the trials) the crater volumes produced by hexahedral surface charges on alluvial soil ( $V_e$ ) are roughly 300% larger than those calculated for asphalt (the ratio of  $V_e/V_b$ ). Calculations further suggest that the volume relationship between spherical and hexahedral charges in alluvial soil is 339% than that in asphalt for the same mass  $M$  [kg] of explosive.

The results demonstrate that cratering in asphalt and alluvial soil for rectangular surface charges can be expressed as follows:

$$M_{asphalt} = 617.952V_b^{0.794}P_k^{0.309}, \quad (27)$$

$$V_b = 0.339V_c, \quad (28)$$

$$V_a = 0.89V_c, \quad (29)$$

$$V_a \approx 3V_b, \quad (30)$$

**Table 8** Incident overpressure inflicted upon male at distance

| Distance R [m] | 1       | 5      | 10    | 20    |
|----------------|---------|--------|-------|-------|
| Ps [kPa]       | 7293.10 | 271.54 | 61.71 | 18.72 |
| T+ [ms]        | 0.575   | 4.93   | 8.34  | 10.81 |
| Lethality      | ≥ 99%   | ≥ 50%  | < 1%  | < 1%  |
| Lung damage    | Yes     | Yes    | Yes   | Yes   |

**Table 9** The actual impact on a human male—70 kg

| Distance R [m]  | 1                            | 5                                                                         | 10                | 20                |
|-----------------|------------------------------|---------------------------------------------------------------------------|-------------------|-------------------|
| Ps [kPa] Bulson | 7293.10                      | 271.54                                                                    | 61.71             | 18.72             |
| T+ [ms]         | 0.575                        | 4.93                                                                      | 8.34              | 10.81             |
| Lethality       | ≥ 99% even in prone position | ≥ 50% in front of a reflecting surface or ≥ 1% standing in the free field | < 1% in all cases | < 1% in all cases |

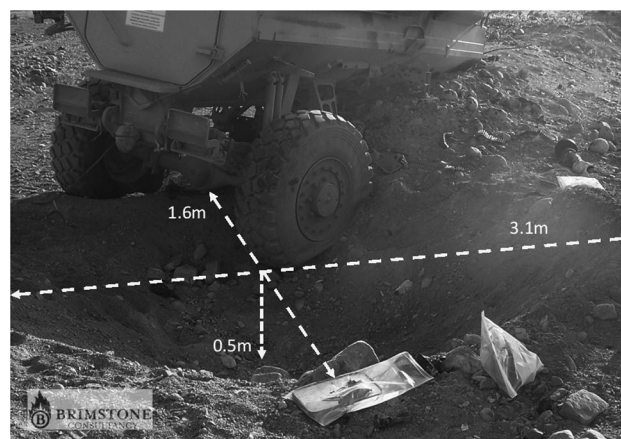
where:

- $M_{asphalt}$  = the mass of explosive [TNT<sub>e</sub> in kg];
- $V_b$  = the apparent crater volume [m<sup>3</sup>] created by the detonation of a hexahedral surface charge in asphalt;
- $P_k$  = the area of the container in contact with the surface [m<sup>2</sup>];
- $V_c$  = the theoretical apparent crater volume from Cooper in alluvial soil [m<sup>3</sup>];
- $V_a$  = the apparent crater volume from the surface detonation of a hexahedral container in alluvial soil [m<sup>3</sup>];
- the ratio of mean experimental crater depth ( $H_{2Exp}/H_{2C}$ ) and crater volume compared to Cooper ( $V_e/V_c$ ).
- the H:L ratio of the hexahedral charge lies between 1.0 and 1.5.

Note: Worked examples for these equations are provided at Appendix 1, with supporting figures and tables at Appendix Fig. 9 and Appendix Table 10 respectively.

These equations hold true for any explosive, not just AN–Al, if the explosive mass is presented as a TNT<sub>e</sub>.

Given that the cratering efficiency ( $E_{CR}$ ) for a vast number of soil types has been calculated over the years and is available within literature [27, 56], further work may be able to utilise the following equation of Cooper to deliver approximations for other media given that the crater radius ( $R_d$ ),  $P_{cj}$  and  $M^{1/3}$  can be determined by simple calculation (see Eqs. 1–6 and 18):

**Fig. 9** Crater remaining from surface IED blast

$$R_a = (0.46 + 0.027P_{cj})(2E_{CR}M)^{1/3}. \quad (31)$$

#### 4.4 The impact on people and structures

Given that the performance of HME in spherical or hexahedral containers can be determined from crater size in alluvial soil and asphalt, these parameters can now be applied to the impact of such explosions on people and structures, or the safe cordon and evacuation distances that would be required should a device be discovered.

Whilst explosions have varied effects on engineering structures [57–59], the physiological response of civilians to blast, who are often the unintended victims of IEDs, can be much harder to determine. The most vulnerable organs in the body to blast are our lungs and ears, which through many decades of testing on animal species has led to an empirical scaling for humans [27]. Designed by Bowen in 1968 [60], empirical scaling predicts the lethality from a Friedlander blast wave for persons in front of a reflecting surface, or in the free field (see Fig. 7).

In Fig. 7 the adult male at (a) is set against a reflecting surface in the standing and prone position. The Friedlander blast wave approaches left to right and top down respectively. At position (b) the adult male is standing or prone in the free-field. The Friedlander blast wave approaches from the left. Curves can also be demonstrated for babies (the most vulnerable class), small children, and women.

In recent years, Bowen's predictions have been updated by Bass [61] and Panzer [62] to determine that:

*"For blast waves with short positive phase durations ( $T < 2$  ms), the load on a person standing in the free field is comparable to that on a person in front of a reflecting surface. For long positive durations ( $T > 20$  ms), the load on a person standing in the free field is lower than for a person in front of a reflecting wall".*

Whilst these differences are minimal, the updated experimentation allows varying degrees of lethality (1%, 50% and 99%, for example) to be displayed graphically as one image (see Fig. 8), which is useful for comparison to calculated data:

To demonstrate the utility of such information to the first responder, suppose that forensic analysis determined that and explosive was indeed AN–AI, and that crater analysis determined the charge mass to be approximately 28 kg, with a TNTe of 24.36 kg. In this case, Table 7 uses detonation equations from Kingery and Bulmash [64], Bulson [65], Kinney and Graham [18] and Vasilis et al. [66] to calculate the scaled incident peak overpressure ( $P_s$ ) and scaled duration curves ( $T$ ) at distances of 1, 5, 10 and 20 m. These calculations are shown for completeness as an excel sheet at Appendix 2, Appendix Fig. 10, using the distance of 10 m as the calculation example.

From these new 'Bowen' curves, the impact of HME of unknown composition can be determined from the size of the crater they leave behind within a soil medium, which informs coroner inquests and cordon and evacuation distance for blast accordingly. For example, the calculated peak incident overpressures ( $P_s$ ) from Table 7 would inflict the likelihood of death on an individual standing in the free field as follows (see Table 8):

If these calculated values are then transposed to Bass' scaled graphical representation (Fig. 8), then additional information can be gleaned by the first responder as Table 9 demonstrates.

As can be seen, the original Bowen curves depict lethality based on lung damage, but the revised plot allows first responders to determine the effects of orientation at distance too. It may not, for example, be possible in open spaces (such as busy markets) for people to find hard cover, so what is the minimum distance required whereby a person would survive blast injury in the prone position?

## 5 Conclusion

The size and shape of a crater caused by ideal and/or non-ideal explosives are a practical method to determine the mass of explosives used in an explosion event.

Sadly, significant amounts of data are often lost due to the inability of nations to facilitate scientific collection, or through a lack of understanding by first responders of the complex theories involved.

Calculation is often based on spheres and hemispheres, not the actual geometry of the IED main charge container (or the warhead) used. However, comparing cratering efficiency is possible between classical spherical charge predictions

and hexahedral charges. In most cases, all that is required is a knowledge of the soil type, the apparent crater volume ( $V_a$ ) [ $\text{m}^3$ ] or the cross-sectional area of the container ( $P_k$ ) [ $\text{m}^2$ ] in contact with the surface to progress meaningful calculations.

This paper focuses solely on alluvial soil and asphalt, but existing equations in literature circulation can be adapted to provide efficiencies for other soil types. In each case, the crater size can determine the potential impact on people and structures using well-established methodologies such as Bowen and Bass curves.

**Author contributions** GC wrote the main manuscript and made substantial contributions to the design of the work and the acquisition, analysis, and interpretation of data. JA and RC revised successive drafts critically for important intellectual content and approved the version to be published. GC agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

**Data availability** Data supporting this study are openly available from CORD at <https://doi.org/10.17862/cranfield.rd.25047764>.

Declarations

**Competing interests** The authors declare no competing interests.

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Appendix 1: Worked examples—the detonation of hexahedral surface-laid charges in alluvial soil

Worked example 1

If a 25 kg hexahedral charge of AN–Al (*TNTe*—26 kg) were detonated on the surface of alluvial soil, what is the expected apparent crater volume?

$$V_a^{1/3} = 0.1687M^{1/3}, \tag{32}$$
$$\therefore V_a^{1/3} = 0.1687(26)^{1/3} = 0.4998,$$
$$\therefore V_a = 0.4998^3 = 0.124 \text{ m}^3.$$

What would be the expected crater volume if the medium were changed to asphalt?

Table 10 Kingery-Bulmash data for UHP detonation

|                                              |        |
|----------------------------------------------|--------|
| Range (R) [m]                                | 10     |
| NEQ UHP (kg)                                 | 31.8   |
| TNT <sub>e</sub> (kg)                        | 17.5   |
| Peak incident pressure (Ps) [kPa]            | 69.78  |
| Incident impulse (Is) [kPa ms]               | 193.55 |
| Peak reflected pressure (Pr) [kPa]           | 176.99 |
| Reflected impulse (Ir) [kPa ms]              | 436.85 |
| Shock front velocity (U) [ms <sup>−1</sup> ] | 429.64 |
| Arrival time (Ta) [ms]                       | 14.11  |
| Positive phase duration (T+) [ms]            | 8.71   |

$$V_a = 0.89V_c,$$

$$\therefore \frac{0.124}{0.89} = V_c = 0.139 \text{ m}^3,$$

$$\text{and } V_b = 0.339V_c,$$

$$\therefore V_b = 0.339V_c = 0.339 \times 0.139 = 0.047 \text{ m}^3.$$

Check:

$$V_c^{1/3} = 0.175M^{1/3}, \quad (33)$$

$$V_c^{1/3} = 0.175(26)^{1/3} = 0.518,$$

$$\therefore V_c = 0.518^3 = 0.139 \text{ m}^3,$$

$$\therefore V_b = 0.339(0.139) = 0.047 \text{ m}^3.$$

## Worked Example 2

A 25 L oil container of dimensions length 304 mm, height 444 mm and width 240 mm is filled with AN–Al of density  $0.86 \text{ gcm}^{-3}$ . Assuming a TNTe of 0.87, what is the apparent volume of the crater that would be evident in asphalt and alluvial soil?

Volume of container =  $0.0324 \text{ m}^3$ ,

Mass of AN–Al =  $860 \times 0.0324 = 27.86 \text{ kg AN–Al}$ ,

$$\text{TNTe} = 24.23 \text{ kg},$$

$$M_{\text{asphalt}} = 617.952V_b^{0.794}P_k^{0.309},$$

$$\therefore 24.23 = 617.952V_b^{0.794}P_k^{0.309},$$

$$\therefore 0.039 = V_b^{0.794}(0.304 \times 0.444)^{0.309},$$

$$\therefore \frac{0.039}{0.539} = V_b^{0.794},$$

$$\therefore V_b = (0.072)^{1.259} = 0.036 \text{ m}^3,$$

$$\therefore V_a \approx 3(0.036) = 0.108 \text{ m}^3.$$

## Worked Example 3

A surface-laid IED in Afghanistan badly damages a troop-carrying vehicle—see Appendix Fig. 9. The crater dimensions are shown below, with the ground dry alluvial soil. Explosive sampling suggests an explosive comprising ammonium nitrate. The

v-shaped underbelly of the vehicle is smudged with a fine grey residue amongst the soil. It is determined from intelligence within the area, and the physical evidence recovered, that the likely explosive is AN-Al.

Determine the mass of the explosive used and the likely  $P_k$  dimensions of the container.

$$\begin{aligned}
 V_a &= \frac{\pi abH_2}{6}, \\
 \therefore V_a &= \frac{\pi \times 1.55 \times 0.8 \times 0.5}{6} = 0.32 \text{ m}^3, \\
 \therefore V_a^{1/3} &= 0.687, \\
 V_a^{1/3} &= 0.1687M^{1/3}, \\
 \therefore 0.687 &= 0.1687M^{1/3}, \\
 \therefore M^{1/3} &= 4.072, \\
 \therefore M &= 67.53 \text{ kg}, \\
 V_a &\approx 3V_b \therefore V_b \approx 0.106 \text{ m}^3, \\
 \therefore M_{\text{asphalt}} &= 617.952V_b^{0.794}P_k^{0.309}, \\
 \therefore 67.53 &= 617.952(0.106^{0.794})P_k^{0.309}, \\
 \therefore P_k^{0.309} &= 0.649, \\
 \therefore P_k &= 0.247 \text{ m}^2.
 \end{aligned} \tag{34}$$

This  $P_k$  value ( $L \times H$ ) is comparable to a 40 L container (see Table 3).

#### Worked Example 4

Urea Hydrogen Peroxide (UHP) is suspected of having been used in a bombing associated with criminality. The volume of the crater produced in the asphalt surface is  $0.028 \text{ m}^3$ . What is the mass of UHP likely to have been used in the attack?

A man lying against a wall 10 m away from the blast has been killed, but there are no obvious signs of death from shrapnel. What is the more likely cause of death—primary blast or tertiary blast?

$$\begin{aligned}
 V_a &\approx 3V_b, \\
 \therefore V_a &\approx 3 \times 0.028 \approx 0.084 \text{ m}^3, \\
 V_a^{1/3} &= 0.1687M^{1/3}, \\
 \therefore 0.084^{1/3} &= 0.1687M^{1/3},
 \end{aligned} \tag{35}$$

$\therefore 2.596 = M^{1/3},$

$\therefore M = 17.5 \text{ kg TNT}.$

Given that the  $TNT_e$  of UHP is provided in literature as 0.55 for overpressure [67], this would equate to a mass of UHP in the region of 31.8 kg. At 10 m, Kingery-Bulmash provides the following data (see Appendix Table 10). Applying  $P_s$  and  $T_+$  to the Bowen Curve for a reflecting surface (see Fig. 8), it is unlikely that the individual would have died from primary blast injuries with a UHP charge. However, the peak reflected pressure ( $P_r$ ) would have been sufficient to surpass the threshold for lung damage. It is therefore likely that the individual may have died from tertiary blast related injuries.

Appendix 2: Air blast parameters by distance, NEQ and TNT equivalence—AN/AL 90/10

See Fig. 10.

AIRBLAST PARAMETERS BY DISTANCE, BY NEQ & BY TNT EQUIVALENCE

Reference Documentation is:  
"Airblast Parameters from TNT Spherical Air Burst & Hemispherical Surface Burst" by  
Charles N Kingerey & Gerald Bulmash, Tech Report ARBRL-TR-02555 dated April 1984.

INPUTS

|                                   |       |
|-----------------------------------|-------|
| Actual Stand-off Distance (D) [m] | 10.00 |
| Nett Explosive Quantity (Q) [kg]  | 28.00 |
| TNT Equivalence Figure            | 0.87  |

OUTPUTS

|                                     | Air         | Surface     |
|-------------------------------------|-------------|-------------|
| Peak Incident Pressure (Ps) [kPa]   | 61.7140841  | 86.7478333  |
| Incident Impulse (Is) [kPa.msec]    | 164.8102195 | 237.8913889 |
| Peak Reflected Pressure (Pr) [kPa]  | 153.5985705 | 230.8430273 |
| Reflected Impulse (Ir) [kPa.msec]   | 364.0849378 | 553.2009279 |
| Shock Front Velocity (U) [m/msec]   | 0.4196341   | 0.4487118   |
| Arrival Time (Ta) [msec]            | 14.6023922  | 13.0862908  |
| Positive Phase Duration (T+) [msec] | 8.3489007   | 9.1056374   |

Fig. 10 Blast parameters by distance, NEQ and TNT equivalence

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## **Understanding the explosion risk presented by ammonium nitrate and aluminium home-made explosives detonated as surface charges in hexahedral main charge containers**

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