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TNT Equivalency of Unconfined Aerosols of Propylene Oxide

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ABSTRACT

The unconfined aerosols of propylene oxide (PO) are formed by dispersing the fuel in air. These aerosols undergo detonation by suitable initiation and produce high impulse blast. Tri-nitro Toluene (TNT) equivalence is an important parameter used to represent the power of explosive materials and compare their relative damage effects wrt TNT. The parameters commonly used for estimation of TNT equivalency are total energy of explosive source and properties of resulting blast wave, viz., blast peak overpressure and positive impulse. In the present study, the unconfined aerosols of 4.2 kg PO were formed by breaking open the cylindrical canister with the help of axially positioned central burster charge and then detonated using a secondary explosive charge after a preset time delay. The resulting blast profiles were recorded and the blast parameters were analysed. Being a non-ideal explosive source, the TNT equivalency depends on fraction of total energy utilised for blast formation, the rate of energy release, cloud dimensions, and concentration of fuel. Hence, various approaches based on energy release, experimental blast profiles, triangulated blast parameters, and ground reflected blast parameters were considered to determine the TNT equivalency of unconfined PO aerosols. It was observed that the TNT equivalency is not a single value but vary with distance. The paper provides various options for weapon designer to choose a suitable approach for considering TNT equivalency. The scaling laws established from the experimental data of unconfined aerosols of PO for blast peak over pressure and scaled impulse help in predicting the performance for different values of fuel weight and distance.

Keywords: Aerosol, propylene oxide, TNT equivalency, blast data, positive impulse

1. INTRODUCTION

Tri-nitro Toluene (TNT) equivalency, an important parameter, indicates the power of explosive materials and helps in comparing their relative damage effects wrt TNT. The primary reason for using TNT equivalency is the availability of well documented theoretical and experimental blast data of TNT under various conditions like free air, reflected, ground burst, and surface blast, etc[1]. Hence, TNT equivalency is used as an input parameter for design of weapons and blast-proof structures as well as evaluation of explosion hazards of unknown materials. The parameters commonly used for estimation of TNT equivalency are total energy of an explosion source and properties of resulting blast wave such as peak overpressure, positive impulse, etc[2].

The TNT equivalency of an explosive computed based on the weight and the energy release wrt corresponding values of TNT is found reasonably good for high explosives which are considered to be ideal explosion sources where the rate of energy release and energy density are very high[2]. In these cases, the high explosives make use of available oxygen in the molecule for combustion/explosion. Studies of Held[3] on computation of TNT equivalence for cylindrical high explosives have shown that bridge waves are generated along with primary and secondary shocks resulting in multiple peaks in the blast profiles. This phenomenon, thus, indicates that cylindrical high explosive charges are also non-ideal energy sources. Since a fraction of total energy released by the explosion source is utilised for blast formation, the rate of energy release plays significant role on the properties of resulting blast wave. It is observed that high explosives having high rates of energy release (velocity of detonation (VoD) - 7 km/s - 10 km/s) produce high blast peak overpressures at near distances from source and decays faster at longer distances. The unconfined fuel aerosols known as fuel-air explosives (FAE) are non-ideal explosion sources produce relatively low energy density with low rate of energy release (VoD – 2 km/s). The unconfined fuel aerosol detonation is caused by dispersal of fuel in air to form aerosol and subsequent initiation by secondary explosive charge termed as initiator resulting in generation of high impulse blast owing to the high heat of combustion of fuel. Various researchers[2,4,5] reported TNT equivalents for explosives and fuel-air mixtures. A variety of models have also been developed for prediction of blast effects for vapour cloud explosions[6,7]. Most of the researchers considered explosion of hemispherical clouds for predicting the TNT equivalency. The hemispherical explosions are likely to produce reflected blast waves which may superimpose with the primary blast wave, leading to produce higher blast effects and higher TNT equivalency.

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In general, the TNT equivalency is considered as a single value for ideal explosions. The vapour cloud explosions being non-ideal nature, it may not be possible to have a single value for TNT equivalence for various distances from source because of superimposition of secondary blast waves on primary blast wave. The findings of Kliene[8], *et al.* indicate that the TNT equivalency is not a single value but vary with distance from source. According to Cooper[9], a single TNT equivalence value assigned for an explosive by computing with the same weight of TNT may lead to variations of about 20 per cent. Moreover, aluminised explosive compositions produce blast waves with relatively low peak overpressure but with high impulse because of late stage reactions of aluminium with detonation products[3]. Thus, it is not sufficient to compute TNT equivalency based on blast peak overpressure alone but positive impulse also needed to be considered.

In the present study, unconfined aerosols of propylene oxide (PO) were formed through dispersion of propylene oxide by breaking cylindrical fuel container with the help of axially positioned central burster charge. The aerosols were detonated subsequently, using a secondary explosive charge. Aerosols based on PO, being non ideal energy source, a single method like energy scaling cannot represent the realistic TNT equivalency. Hence, efforts have been made to compute TNT equivalency for FAE based on PO using various methods like energy scaling, experimental incident (side-on) blast parameters, triangulated blast parameters, and ground reflected blast parameters. These TNT equivalencies, thus, computed will help weapon designers with various options to choose for their applications. In addition, scaling laws have also been derived for blast peak overpressure and positive impulse as a function of scaled distance.

2. EXPERIMENTAL

2.1 Materials/Chemicals

The commercially available propylene oxide having purity of 99 per cent and explosive limits of 3.1 vol. per cent to 27.5 vol. per cent has been selected as the fuel. Nitroguanidine, NQ (purity – 99 per cent, Spec. No. -JSS 1376-03:2002), was used for the preparation of burster charge on account of low energetics and flashless nature[1]. Shock initiation method for aerosol initiation was adopted in the experiments and hence, RDX/wax (95/5) [Spec. No. – IND/ME/816(a)] pellet was chosen as secondary explosive charge.

2.2 Preparation of Explosive Charges

The burster charges based on NQ were prepared by incremental filling method so as to have a loading density of 410 kg/m^3 and VoD of 4350 m/s, whereas secondary explosive charges based on RDX/Wax (95/5) pellets (density - 1600 kg/m^3, VoD - 8000 m/s) were made with the help of hydraulic press (load-1500 kg).

2.3 Canister and Buster Tube

A 5 l capacity mild steel canister (φ180 X 225 X 1.6 mm) provided with 24 equi-spaced longitudinal serrations (root thickness -1.0 mm) and central co-axial burster tube (mat - GI, φ31 X 240 X 0.6 mm) as shown in Fig. 1, was selected for experiments of aerosol formation and detonation. The longitudinal serrations help in dispersion of fuel uniformly in all directions.

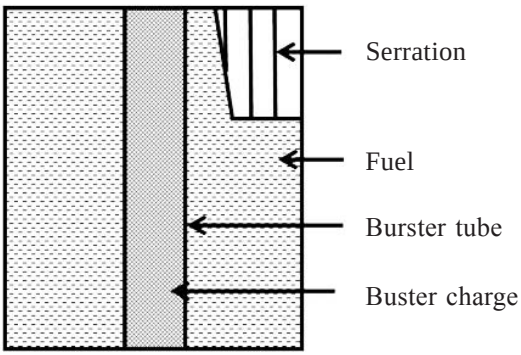

Figure 1. Canister with burster tube (Canister- φ180 X 225 X 1.6 mm, Burster tube: φ31 X 240 X 0.6mm).

2.4 Instrumentation Details

Aerodynamically shaped free field air blast pressure gauges of PCB piezo electronics make have been used for recording the blast profiles. The gauge is of voltage mode transducer which converts electric charge developed by quartz crystal in response to blast pressure, into a high voltage low impedance output (≤ 100 Ω) with the help of inbuilt amplifier (response time - 1 μs and rise time - 1 μs). A multi-channel digital data acquisition system having programmable digitising rate of 10 MS/s to 1000 MS/s was chosen for recording the blast profiles. In addition, the trial events were recorded using video cameras.

2.5 Experimental Set-up

The canister is filled with 4.2 kg of PO whereas NQ based burster charge of 55 g was positioned in the central burster tube. Experiments were carried out by positioning the filled canister on a metallic stand of 2.0 m height. Secondary explosive charge, 100 g of RDX/Wax (95/5) was placed at a height of 2.1 m and 0.5 m away from the canister as shown in Fig 2. Four air blast pressure gauges fixed on metallic stands of 2 m height, are positioned at 5 m, 7 m, 9 m, and 11 m from the canister. The gauges are aligned in such a way that they record incident/side-on blast pressures. Wooden markers were

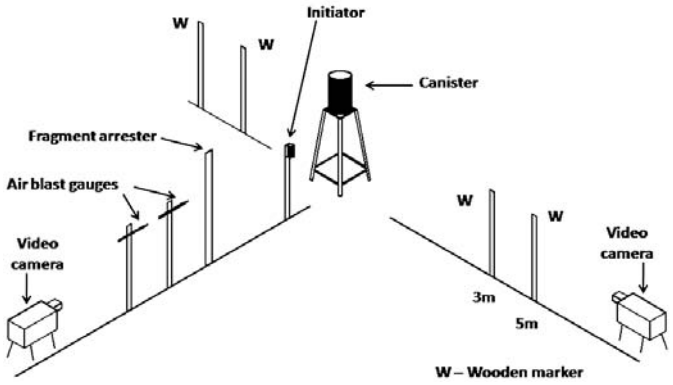

Figure 2. Experimental set-up for forming and detonating unconfined aerosols of propylene oxide.

used for measurement of aerosol dimensions. A time delay of 100 ms was given between the detonation of burster charge and secondary explosive charge for the fuel to attain detonable concentration limits in the aerosol. Both the explosive charges are detonated using electrical detonators. These experimental parameters have been extensively studied and optimised for obtaining consistent aerosol formation and detonation[10].

2.6 Experiments

A series of experiments have been carried out for aerosol formation and detonation using experimental setup shown in Fig. 2 and blast profiles were recorded at different distances, viz., 5 m, 7 m, 9 m, and 11 m. The propylene oxide aerosol was observed to be of pancake shape having about 10.4 m diameter, 2 m height and was about 1 m above the ground.

Typical blast profiles produced by 4.2 kg of unconfined propylene oxide aerosols at 5 m, 7 m, 9 m, and 11 m are presented in Fig. 3. The blast data has been analysed and the blast parameters, viz., average peak overpressure, positive time duration and impulse have been worked out and given in Table 1. The results given in Table 1 are consistent and reliable within the experimental limitations because of the high sensitive air blast pressure probes and the high response data acquisition system. Further, the calculated values of maximum coefficient of variation are 28.7 per cent for blast POP and 10.6 per cent for positive impulse which are well within the acceptable limit of 33 per cent.

3. RESULTS AND DISCUSSION

The TNT equivalencies of unconfined PO aerosols were computed using different methods, viz., energy scaling, incident blast pressure data, positive impulse, triangulated blast data and ground reflected blast data and the results are presented in Tables 2, 3, 4, and 5, respectively.

3.1 TNT Equivalency of Unconfined Aerosols of PO by Energy Scaling Method

The stoichiometric reaction of propylene oxide with atmospheric oxygen is given as

$$C_3H_6O + 4O_2 \rightarrow 3CO_2 + 3H_2O + 32.47MJ/Kg \quad (1)$$

One mole of propylene oxide requires four moles of oxygen from atmosphere for complete combustion in addition to the oxygen available within the molecule. The heat of combustion of propylene oxide[2] (E_{PO}) is 32.47 MJ/kg. Thus, the stoichiometric concentration of propylene oxide in air was worked out to be as 4.98 per cent by volume and 9.51 per cent by weight.

The TNT equivalency of propylene oxide (E_{PO}) can be expressed as

$$E_{eqv} = E_{PO} / E_{TNT} \quad (2)$$

where (E_{TNT}) is the heat of explosion of TNT [2] is 4.184 MJ/kg

$$(E_{eqv}) = 32.47/4.184 = 7.76 \quad (3)$$

It implies that 1 kg of propylene oxide will produce blast effects at stoichiometric concentration same as that of 7.76 kg of TNT. This estimation is based on the assumption that the concentration of propylene oxide in unconfined aerosol is stoichiometric throughout the aerosol which is not true because the concentration of fuel will deviate from the stoichiometric value in spatial coordinates but will be within detonable concentration limits in the aerosol. Hence, this energy scaling

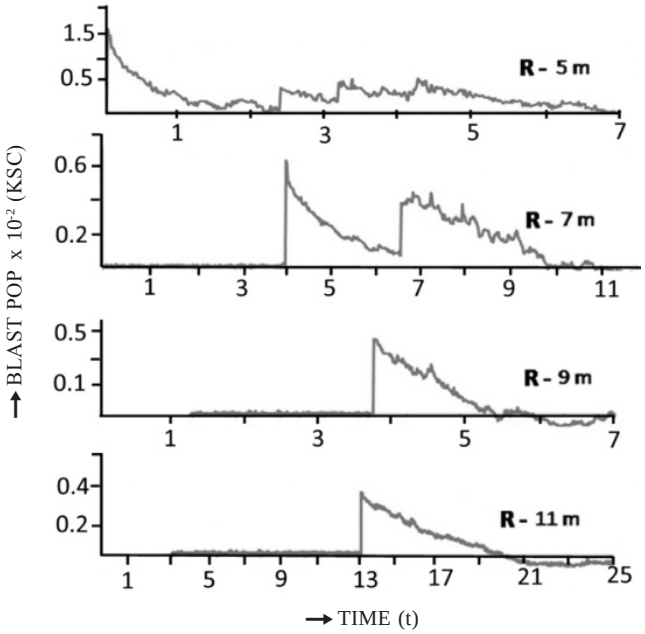

Figure 3. Blast profiles of unconfined aerosol of 4.2 kg Propylene oxide at different distances (Fuel: 4.2 kg Propylene oxide, Burster charge : 55 g NQ, Initiator : 100 g RDX/wax (95/5), Time delay : 100 ms), R – distance from the source.

Table 1. Blast data of unconfined aerosol of 4.2 kg propylene oxide[a]

Distance R (m)	Scaled distance $\overline{R}$ (m/kg$^{1/3}$)	Avg. blast peak over pressure, P (kPa)	Positive time duration t^+ (ms)	Avg. positive impulse, i^+ (Pa.s)
5	3.1	153.0 (98.1 - 245.3)	2.5 (1.5 - 3.0)	167.8 (137.3 - 184.4)
7	4.3	77.7 (65.7 - 100.1)	3.0 (2.6 - 3.4)	156.7 (141.6 - 179)
9	5.6	49.4 (47.1 - 52.0)	3.4 (3.3 - 3.5)	115.7 (101.8 - 135.1)
11	6.8	38.3 (37.3 - 39.2)	3.8 (3.7 - 3.9)	96.9 (92.8 - 101.9)

[a]Canister - ϕ 180 x 225 x 1.6 mm, Burster charge- 55 g NQ, Initiator – 100 g of RDX/Wax (95/5), Delay - 100 ms

method may not be suitable for computing TNT equivalency for PO aerosols.

3.2 Blast Profiles of Unconfined Aerosols of PO

The experimental blast profiles shown in Fig. 3 indicate that the blast profiles recorded at rear distances have primary and secondary peaks. Later, the primary and secondary shocks merged at longer distances (9 m and 11 m). The merger of primary and secondary peaks did not show any significant increase in amplitude (peak overpressure) whereas there was appreciable increase in positive time duration. The analysis of the blast profiles reveals that the primary shock waves originated from top, bottom and side surfaces of the cylindrical aerosol whereas secondary shock waves are originated from the corners/edges of the fuel aerosol. The secondary shock waves follow behind the primary shock waves with a time lag as is evident from Fig. 3. This nature of blast profiles of propylene oxide aerosols is in agreement with the blast profiles obtained by Held[3] for cylindrical high explosive charges.

3.3 Selection of TNT Blast Data

As TNT blast data is required for computing TNT equivalence of PO aerosol, the data generated by Baker[1], Henrych[11], and Kinney and Graham[12] have been studied. In addition, few inputs from reviewed data of Goel[13], *et al.* have also been considered. The comparative blast data in terms of blast peak overpressure (POP) and positive impulse wrt scaled distance are presented in Figs 4 and 5, respectively. It is seen from the blast data of PO aerosol (Table 1) that the scaled distance is the range of 3 to 7. Hence, the TNT blast data for the same range of scaled distances were considered for computing TNT equivalency of PO aerosol. It is seen from Fig. 4 that the blast POP values of Henrych, Kinney and Graham are higher at lower scaled distances and lower at longer scaled distances. On the other hand, the blast POP of Baker is moderate as is evident from Fig. 4. The positive impulse values reported by Henrych[11] and Kinney and Graham[12] are very high and very low respectively as is evident from Fig. 5. Hence, positive impulse values reported by Baker wrt scaled distance was selected for computing TNT equivalency of PO aerosols.

3.4 TNT Equivalency of Unconfined Aerosols of PO Based on Blast POP

Based on the blast POP measured at distances 5 m, 7 m, 9 m, and 11 m of PO aerosol detonated at a height of 1 m above the ground, the scaled distances and the wt. of TNT (W_{TNT}) required for getting equivalent blast POPs have been computed. The resultant TNT equivalency values (W_{TNT}/W_{PO}) have also been given in Table 2. The variation of blast POP wrt scaled distance for unconfined fuel aerosol and TNT are presented in Fig. 6. It is found from the results of Table 2 that the TNT equivalency is not a single value but vary from 3.7 to 4.5 with an average value of 4. The detonation studies of Liu[14], *et. al.* with 1.8 kg of PO and TNT based burster charge on ground indicate that the TNT equivalency is ranging from 2.46 to 4.29 between 3 m to 6 m from the source. Similarly the TNT equivalency values reported by Jinhua[2], *et. al.* are in the range of 3.27 to 5.98 between distances 4.09 m to 12.45 m for 3.9 kg of PO-air mixtures detonated on ground surface. In both the cases, the explosions are on ground surface and it is necessary to consider ground reflection factor of 1.8 for estimating the TNT equivalency values as has been adopted by Dewey[15] for detonation of hemispherical mixtures of propane and propane-air. If ground reflection is considered, the TNT equivalency values of PO will become smaller than that of reported values.

3.5 TNT Equivalency of Unconfined Aerosols of PO Based on Positive Impulse

Based on positive impulse values of PO aerosols, the

Table 2. TNT equivalency of unconfined aerosols of propylene oxide computed based on blast peak over pressure[a]

Distance, R (m)	Scaled distance, $\overline{R}$ (m/kg$^{1/3}$)	Wt of PO, W_{PO} (kg)	Blast peak over pressure, P (kPa)	Weight of TNT required for getting P, W_{TNT} (kg)	TNT equivalency, W_{TNT}/W_{PO}
5	3.1	4.2	153.0	16.7	4.0
7	4.3	4.2	77.7	15.5	3.7
9	5.6	4.2	49.4	16.0	3.8
11	6.8	4.2	38.3	18.8	4.5

[a]Propylene oxide- 4.2 kg, Canister - ϕ 180 x 225 x 1.6mm, Burster charge - 55 g NQ, Initiator – 100 g of RDX/Wax (95/5), Delay - 100ms

Table 3. TNT equivalence of unconfined propylene oxide aerosols computed based on positive impulse[a]

Distance, R (m)	Scaled distance, $\overline{R}$ (m/kg$^{1/3}$)	Wt of PO, W_{PO} (kg)	Positive impulse, i^+ (Pa.s)	Weight of TNT required for getting i^+, W_{TNT} (kg)	TNT equivalency, W_{TNT}/W_{PO}
5	3.1	4.2	167.8	26	6.2
7	4.3	4.2	156.7	56	13.3
9	5.6	4.2	115.7	46	11.0
11	6.8	4.2	96.9	50	11.9

[a] Propylene oxide - 4.2 kg, Canister - ϕ 180 x 225 x 1.6mm, Burster charge - 55 g NQ, Delay - 100 ms

TNT equivalency values have been computed considering the TNT data of Baker[1] and presented in Table 3. The values are observed to be very high, 6.2 to 13.3 between distances of 5 m to 11 m from the center of explosion source. The TNT equivalency of 13.3 at 7 m may be due to super imposition of secondary shock with the primary shock of PO aerosol. Similarly, the overlap of secondary peaks with the primary blast profile resulting in increased positive duration which is responsible for TNT equivalency values of 11 and 11.9 at 9 m and 11 m, respectively.

It is well known that the positive impulse produced by unconfined PO aerosol is responsible for inflicting the damage on the targets rather than the peak overpressure. Hence, it is suggested that TNT equivalency values estimated based on positive impulse shall be considered for design of blast resistant structures to have better factor of safety and those TNT equivalency values calculated from blast POP may be utilized for design of weapon systems for having conservative performance levels.

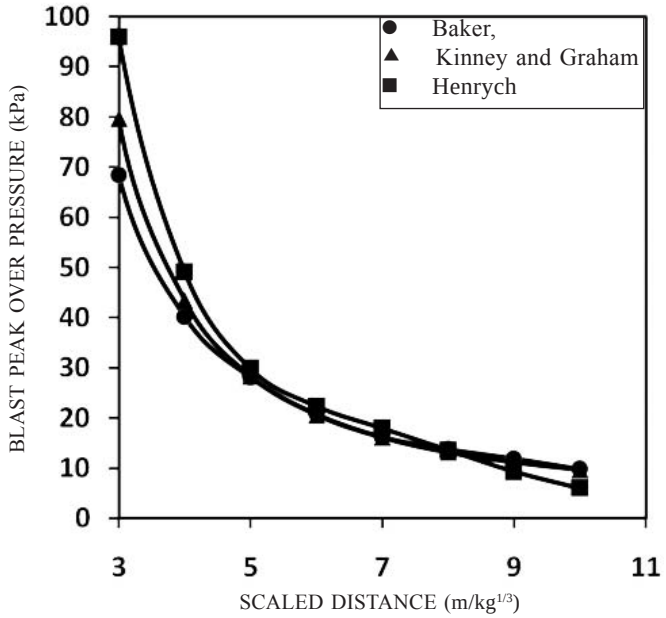

Figure 4. Variation of blast peak over pressure with scaled distance for spherical TNT charge[1,10,11,13].

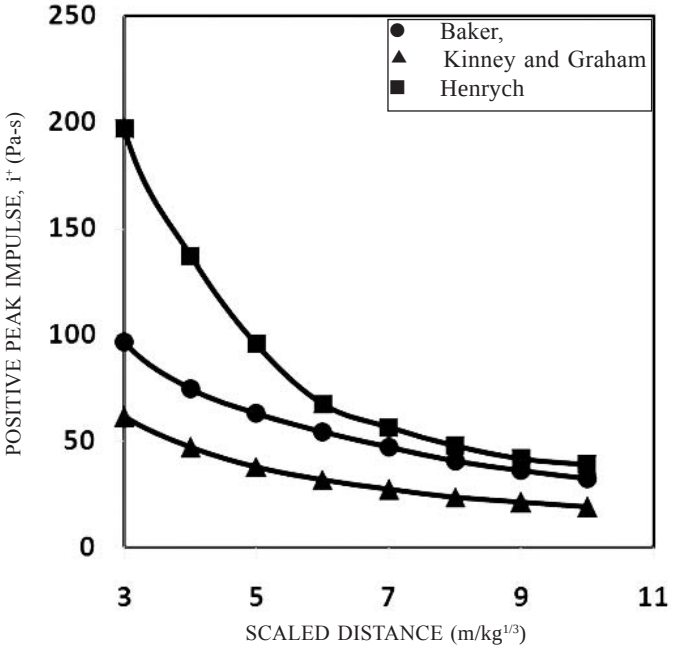

Figure 5. Variation of positive impulse with scaled distance for spherical TNT charge[11-14].

Table 5. TNT equivalency computed for unconfined aerosols of propylene oxide based on ground reflection[a]

Distance, R (m)	Wt of PO, $W_{PO,}$ kg	Scaled distance, $\overline{R}$ (m/kg$^{1/3}$)	Equivalent weight, 1.8 $W_{PO,}$ kg	Blast peak over pressure, P (kPa)	Blast positive impulse, i^+ (Pa.s)	TNT Equivalence	
						Based on P	Based on i^+
5	4.2	3.1	7.56	153.0	167.8	2.2	3.4
7	4.2	4.3	7.56	77.7	156.7	2.1	7.4
9	4.2	5.6	7.56	49.4	115.7	2.1	6.1
11	4.2	6.8	7.56	38.3	96.9	2.5	6.6

[a] Propylene oxide – 4.2 kg, Canister - ϕ 180 x 225 x 1.6 mm, Burster charge- 55 g NQ, Delay - 100 ms

Table 4. TNT equivalency computed for unconfined aerosols of propylene oxide based on blast triangulation method[a]

Distance, R (m)	Blast parameters of primary shock			Weight of TNT required for getting blast data of PO aerosol W_{TNT} (kg)		TNT equivalency	
	P_{ps} (kPa)	t^+_{ps} (ms)	i^+_{ps} (Pa.s)	Based on P_{ps}	Based on i^+_{ps}	Based on P_{ps}	Based on i^+_{ps}
5	111.8	2.5	71.6	9.8	1.7	2.3	0.4
7	61.8	3	68.7	11.0	3.9	2.6	0.9
9	47.1	3.4	64.7	15.2	6.3	3.6	1.5
11	36.3	3.8	60.8	17.0	9.2	4.0	2.2

[a] Propylene oxide – 4.2 kg, Canister - ϕ 180 x 225 x 1.6 mm, Burster charge- 55 g NQ, Delay - 100 ms

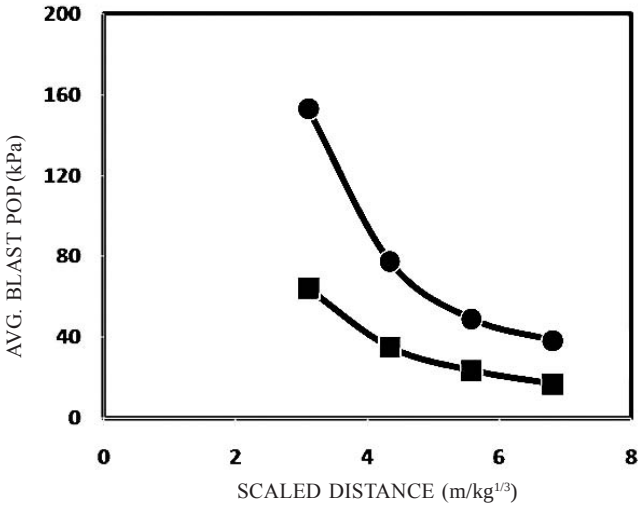

Figure 6. The variation of blast peak overpressure with scaled distance for unconfined aerosols of propylene oxide(●) and TNT(■) [Propylene oxide – 4.2 kg, Burster charge – 55g NQ, Initiator – 100g RDX/wax (95/5), Delay – 100ms][1].

3.6 TNT Equivalency of Unconfined Aerosols of PO by Triangulated Blast Parameters

The computation of TNT equivalency was also carried out by considering the blast POP and positive phase duration of the primary shock by approximating the blast profile into a triangle so as to minimize the effect of secondary shock[13]. A typical triangulated blast profile considering only primary shock is shown in Fig. 7.

Each triangulated blast profile was analyzed and the corresponding blast peak overpressure (P_{PS}), positive time duration (t^+_{PS}) and positive impulse (i^+_{PS}) were calculated and presented in Table 4. TNT equivalencies were computed in a similar method used earlier for blast peak overpressure and positive impulse. It is evident from the results of Table 4 that the TNT equivalencies of unconfined propylene oxide aerosols obtained from blast triangulation approach vary with distance and are very low for both peak overpressure and positive impulse as expected. Hence, the triangulation approach cannot be considered for representing the true TNT equivalency of unconfined PO aerosols.

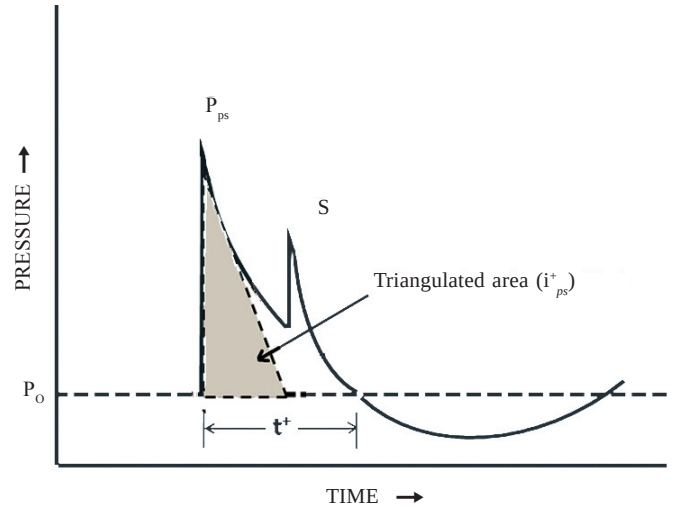

Figure 7. A typical blast profile of unconfined aerosol of propylene oxide consisting of primary and secondary shock (P_{ps} – Primary peak, S – Secondary peak, t^+ - Positive time duration, i^+_{PS} – triangulated area)

3.7 TNT Equivalency of Unconfined Aerosols of PO Based on Ground Reflection

When the vapour cloud explosion takes place on ground, the blast wave gets reflected from ground and the resulting blast wave is stronger than that of the original blast wave. The ground reflectivity is reported as 1.8 in practical conditions[13]. It implies that W kg of fuel in a vapour cloud explosion, produces blast equivalent to that of 1.8 W kg of fuel. In the present study, the unconfined aerosols of PO were detonated at about 1 m above the ground level. Due to higher height of burst, the effect of ground reflection may be possible at longer distances from the source beyond 11 m. However, TNT equivalency values for unconfined fuel aerosols have been computed by considering the ground reflectivity factor so as to understand the lower possible damage levels. The results given in Table 5 show that the TNT equivalency estimated considering ground reflectivity factor vary with distance and is not a single value. It is evident that the TNT equivalency values are lower than that observed with original blast profile as expected.

3.8 Determination of Scaling Laws for Blast Peak Overpressure and Positive Impulse of Unconfined Aerosols of PO

The blast data presented for unconfined propylene oxide aerosols in terms of peak overpressure and scaled impulse presented in previous paragraphs was numerically analyzed to derive the scaling laws for blast POP and scaled impulse for unconfined aerosols of PO. The general expression representing the behaviour of both the above parameters, fitted with least squares method is given below:

$$y = a_0 + \frac{a_1}{x} + \frac{a_2}{x^2} + \frac{a_3}{x^3} \quad (4)$$

where y is blast peak overpressure(P), kPa or scaled impulse (I), Pa.s.kg$^{-1/3}$, x is scaled distance, $\overline{R} = \frac{R}{W^{1/3}}$, m.kg$^{-1/3}$($3.1 \leq \overline{R} \leq 6.8$), R is distance (m), W is Weight of PO (kg), and a_o, a_1, a_2 and a_3 are the fitted coefficients and are given in Table 6. The scaling laws formulated will help in performance assessment of unconfined PO aerosols of different fuel quantities in terms of blast peak overpressure and positive impulse as a function of distance.

Table 6. Fitted coefficients of scaling laws for unconfined aerosols of propylene oxide

Parameter	Fitted co-efficients of scaling laws			
	a_o	a_1	a_2	a_3
Blast POP (P)	44.3	-355.5	2131.0	49.45
Scaled impulse (I)	-68.62	1138.0	-1864.0	0

4. CONCLUSIONS

The unconfined aerosols of propylene oxide being a non-ideal source, the TNT equivalence is not a single value but vary with distance. The computation of TNT equivalency is possible using different approaches by considering energy release, side-on (original) blast parameters, triangulated blast parameters and ground reflected blast parameters. TNT equivalency estimated based on blast peak pressure may be considered by weapon designers for conservative performance estimation whereas TNT equivalency computed based on positive impulse may be utilized for design of blast resistant structures. The established scaling laws from experimental data will help in predicting the blast performance of different quantities of propylene oxide at various distances.

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