

THE TROUBLE WITH TNT EQUIVALENCE

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When assessing a high explosive, most blast calculations require the mass as an equivalent charge of TNT, since TNT is used by many algorithms as the baseline. This equivalency is expected to give the same performance as the charge in question. Accurate equivalences are therefore key in determining performance. Unfortunately, there are no definitive methods or documents. Variability is found to be so significant that errors can be up to 50%, with 20% to 30% being typical. Three standard explosives (RDX, HMX and Comp B) were assessed in detail and their TNT equivalence calculated. Standard scaling theory indicates that TNT equivalence should be constant, this is shown as incorrect. UFC manuals recommend only the use of Heats of Detonation for equivalence, this and other functions such as Power Index and Hydrodynamic Work are assessed. This paper looks at the issues and recommends that Power Index is used to calculate the TNT equivalence for blast.

INTRODUCTION

When assessing the effects of a high explosive charge (e.g. RDX), many blast calculations require, as the key input parameter, the mass of the explosive under test expressed as an equivalent charge of TNT, as TNT is used by most computational algorithms as the baseline explosive. This is termed the TNT equivalent charge weight, which is expected to give the same performance as the charge in question. Accurate TNT equivalence factors are therefore key, determining charge performance and effectiveness, also determining safety requirements during manufacturing. Unfortunately there is no definitive method or document available that supplies accurate and consistent values. Figure 1, from Cheesman [1] gives an example of the problem, RDX varies from sources between 1 and 1.8.

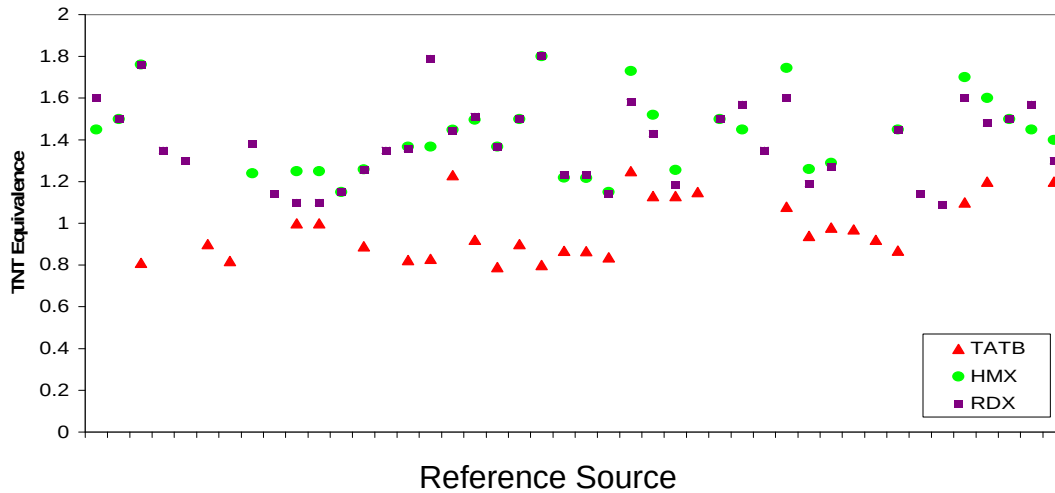


Figure 1. Variation in TNT equivalency of three high explosives TATB, HMX & RDX from a number of different techniques and sources. Reproduced with permission from Cheesman [1].

From Dusenberry [2] we have Tables I & II. These show the Equivalent TNT Masses for Airblast for both Pressure and Impulse. Values are also a function of density and valid over certain pressure ranges. The objective of this paper is to make the reader cautious in applying a value of TNT equivalence obtained from literature references and to show some inaccuracies present. The level of variability has been found to be so significant that errors in performance prediction can be as large as 50%, with 20% to 30% being typical. Some values are compared and give a reasonable and consistent level of prediction, albeit they are still not perfect.

SCALING LAWS

Blast wave scaling laws were developed to compare charges and were derived by Hopkinson [3] and Cranz [4] independently. They state that charge performance is a function of the Scaled Distance (Z). Both peak overpressure and scaled impulse are directly related to scaled distance. Where:

$$\text{Scaled Distance (Z)} = \text{Range} / \text{Charge mass}^{1/3} \quad (1)$$

$$\text{Scaled Impulse} = \text{Impulse} / \text{Charge mass}^{1/3} \quad (2)$$

This is described in more detail by Baker [5] and Smith [6].

TNT ASSESSMENT

TNT equivalency can be assessed by trials or theory. However, most openly published trials seem to have been carried out at sub-scale, which sometimes cannot be extrapolated to full scale. Theoretical predictions often do not take into account the effects of secondary combustion, this can apply to explosives containing

aluminium or which produce a high degree of fuel rich gases such as from TNT. Hence TNT is a poor explosive to use as the standard baseline explosive.

TABLE I. EQUIVALENT TNT MASSES FOR AIRBLAST FROM DUSENBERRY [2] PART A.

Explosive	Density (g/cc)	Equivalence for Pressure	Equivalence for Impulse	Pressure Range (MPa)
Amatol (50/50)	1.59	0.97	0.87	NA ¹
Ammonia Dynamite (50%)	NA ¹	0.90	0.90 ²	NA ¹
Ammonia Dynamite (20%)	NA ¹	0.70	0.70 ²	NA ¹
ANFO (94/6)	NA ¹	0.87	0.87 ²	0.03 - 6.90
AFX-644	1.75	0.73 ²	0.73 ²	NA ¹
AFX-920	1.59	1.01 ²	1.01 ²	NA ¹
AFX-931	1.61	1.04 ²	1.04 ²	NA ¹
Comp A3	1.65	1.09	1.07	0.03 – 0.35
Comp B	1.65	1.11	0.98	0.03 – 0.35
		1.20	1.30	0.69 – 6.90
Comp C3	1.60	1.05	1.09	NA ¹
Comp C4	1.59	1.20	1.19	0.07 – 1.38
		1.37	1.19	1.38 – 20.70
Cyclotol (RDX/TNT) (75/25)	1.71	1.11	1.26	NA ¹
(70/30)	1.73	1.14	1.09	0.03 -0.35
(60/40)	1.74	1.04	1.16	NA ¹
DATB	1.80	0.87	0.96	NA ¹
Explosive D	1.72	0.85 ²	0.81	0.01 – 0.30
Gelatin Dynamite (50%)	NA ¹	0.80	0.80 ²	NA ¹
Gelatin Dynamite (20%)	NA ¹	0.70	0.70 ²	NA ¹
H-6	1.76	1.38	1.15	0.03 - 0.70
HBX-1	1.76	1.17	1.16	0.03 – 0.14
HBX-3	1.85	1.14	0.97	0.03 – 0.17
HMX	NA ¹	1.25	1.25 ²	NA ¹
LX-14	NA ¹	1.80	1.80 ²	NA ¹
MINOL II	1.82	1.20	1.11	0.02 – 0.14
Nitrocellulose	1.65 – 1.70	0.50	0.50 ²	NA ¹
NG Dynamite (50%)	NA ¹	0.90	0.90 ²	NA ¹
Nitroguanidine (NQ)	1.72	1.00	1.00 ²	NA ¹
Nitromethane	NA ¹	1.00	1.00 ²	NA ¹

TRIALS

TNT Equivalence by trials have been well described by Cheesman, Cooper [7] and Dobratz [8]. So they are only briefly described here. Few techniques consider the combined explosive effects of shock, thermal energy and the work done during expansion of the products.

Sand Crush Test

A small charge of explosive is detonated within sand. Performance is a measure of the mass of sand that passes through a mesh. Results are material dependent.

TABLE II. EQUIVALENT TNT MASSES FOR AIRBLAST FROM DUSENBERRY [2] PART B.

Explosive	Density (g/cc)	Equivalence for Pressure	Equivalence for Impulse	Pressure Range (MPa)
Octol (HMX/TNT) (75/25)	1.81	1.02	1.06	NA ¹
Octol (70/30)	1.14	1.09	1.09 ²	0.01 – 0.30
PBX-9010	1.80	1.29	1.29 ²	0.03 – 0.21
PBX-9404	1.81	1.13	1.13 ²	0.03 – 0.69
		1.70	1.70	0.69 – 6.90
PBX-9502	1.89	1.00	1.00	NA ¹
PBXC-129	1.71	1.10	1.10 ²	NA ¹
PBXN-4	1.71	0.83	0.85	NA ¹
PBXN-107	1.64	1.05 ²	1.05 ²	NA ¹
PBXN-109	1.67	1.05 ²	1.05 ²	NA ¹
PBXW-9	NA ¹	1.30	1.30 ²	NA ¹
PBXW-125	1.80	1.02 ²	1.02 ²	NA ¹
	1.64	1.42	1.00	0.03 – 0.69
Pentolite (Cast)	1.68	1.38	1.14	0.03 – 4.14
	NA ¹	1.50	1.00	0.69 – 6.90
PETN	1.77	1.27	1.27 ²	0.03 – 0.69
Picrotol (Exp D/TNT) (52/48)	1.63	0.90	0.93	0.03 – 4.10
RDX	NA ¹	1.10	1.10 ²	NA ¹
RDX/Wax (98/2)	1.92	1.16	1.16 ²	NA ¹
RDX/AL/Wax (74/21/5)	NA ¹	1.30	1.30 ²	NA ¹
TATB	NA ¹	1.00	1.00 ²	NA ¹
Tetryl	1.73	1.07	1.07 ²	0.02 – 0.14
Tetrytol (Tetryl/TNT) (75/25)	1.59	1.06	1.06 ²	NA ¹
TNETB	1.69	1.13	0.96	0.03 – 0.69
TNETB/AL (90/10)	1.75	1.23	1.11	0.03 – 0.69
(78/22)	1.18	1.32	1.32 ²	NA ¹
(65/35)	1.23	1.38	1.38 ²	NA ¹
TNT	1.63	1.00	1.00	Standard
Torpex	1.85	1.23	1.28	0.01 – 0.30
Tritonal (TNT/AL) (80/20)	1.72	1.07	0.96	0.03 – 0.69

NA¹ – Not Available, ² - Estimated

Lead Block (Trauzl) Test

A small charge is mounted within a lead block, the metal deforms, the volume and energy due to plastic deformation is assessed.

Ballistic Mortar Test

A small charge is placed inside a chamber and loaded with a heavy short nosed mortar projectile, the height of the swing of the mortar is measured. It does not measure the work done by gas expansion. Difficult to remove experimental variables.

Ballistic Pendulum Test

An explosive charge is fired near a pendulum and its swing measured. Problems with gas clearing around the pendulum. Difficult to remove experimental variables.

Plate Dent Test

Charges of the same mass are detonated on a steel plate, the depth of indentation is then compared. Produces a good comparison with CJ Pressure.

Cylinder Test

High speed photography measures the radial velocity of an explosive filled metal cylinder. Measuring case effects, the CJ Pressure and Detonation Velocity. Gives performance under shock conditions, doesn't cover work energy available.

Airblast Test

Charges are detonated in the free field, incident pressure and impulse are recorded at various distances. This is discussed in detail by the author in [9].

TRIALS ASSESSMENT

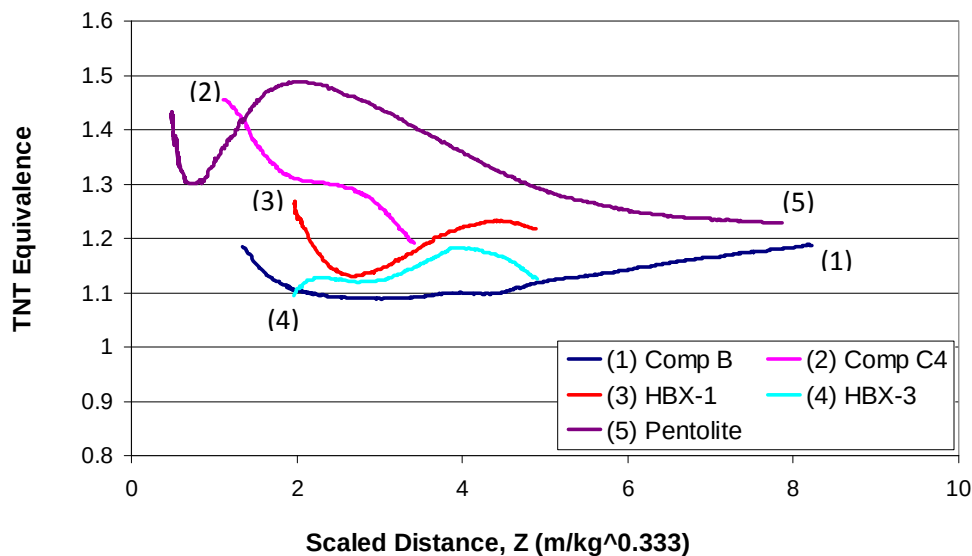


Figure 2. Variation of TNT Equivalence with Scaled Distance by Cooper [7], from Air Blast Calculations and trials by Swisdak [10].

Cooper first suggested that TNT Equivalence might change with Scaled Distance, as shown in Figure 2. This concept has been further developed at the suggestion of Cheesman [11] by fully assessing the performance of three standard explosives RDX, HMX and Comp B, which are then compared with a charge of TNT, shown in Figures 3-6.

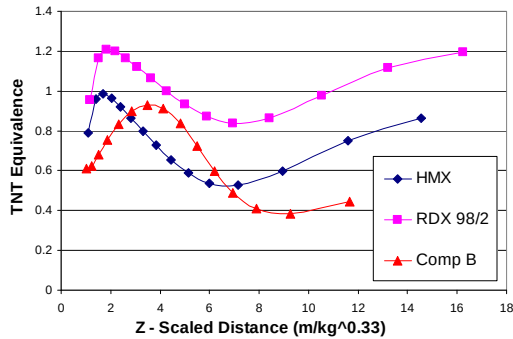


Figure 3. TNT Equivalence for Peak Positive Incident Pressure

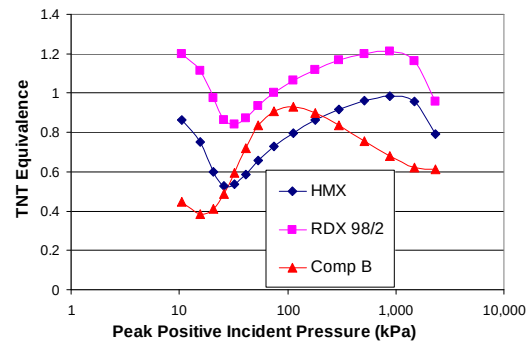


Figure 4. TNT Equivalence for Peak Positive Incident Pressure

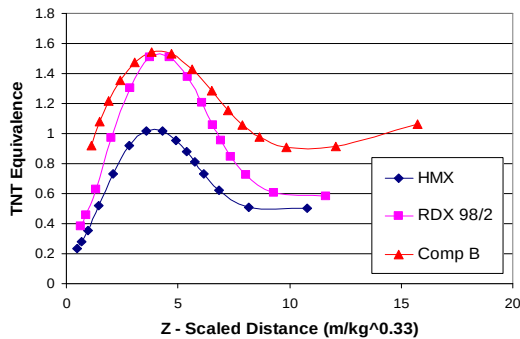


Figure 5. TNT Equivalence for Impulse

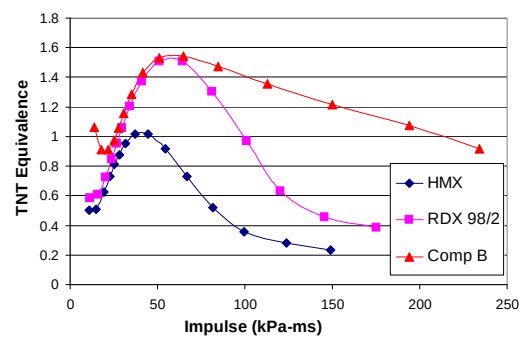


Figure 6. TNT Equivalence for Impulse

This original data was taken in electronic form from US DoD document Unified Facilities Criteria 'Structures to Resist the Effects of Accidental Explosions' (UFC) 3-340-02 [12], covering simple cylindrical charges fired on the surface at sea level. This data was logarithmically interpolated and then solutions found for the actual TNT equivalent charge determined for a unit charge of the particular explosive in question. These results show the TNT charge weight, which under the same condition, at the same location, would produce the same effects at the gauge in question.

TABLE III. TNT EQUIVALENCE FROM UFC DATA [12].

Explosive	TNT Equivalence (%)	
	Peak Incident Pressure	Peak Incident Impulse
HMX	99	102
RDX 98/2	121	151
Comp B	93	154

Figures 3-6 and Table III indicate that TNT equivalence is not constant with Scaled Distance, Pressure or even Impulse. Therefore it does not follow the standard scaling laws. This effectively states that the TNT equivalence should be a constant when plotted against Scaled Distance (Z) for both Pressure and Impulse. Figures 3-6 show that this is clearly not the case. However these results are based on small sub-scale charge firings.

For a particular scenario care should be taken when using TNT equivalence values and for safety cases it is recommended that the peak values of both Pressure and Impulse equivalences are used.

THEORETICAL METHODS

Five different theoretical methods are described here to calculate the TNT Equivalence. Simplifications are made in all cases to derive an empirical approximation that can be of use. The most common method is discussed last.

Berthelot Method

Berthelot [13] derived an equation for explosive comparison which has been updated giving:

$$\text{TNT Equivalent (\%)} = 840 \cdot \Delta n \cdot (-\Delta H_R^O) / \text{Molwt}_{\text{EXP}}^2 \quad (3)$$

Where:

Δn – Number of moles of gases released / moles of explosive (-)

ΔH_R^O – Heat of Detonation (kJ/mol)

$\text{Molwt}_{\text{EXP}}$ - Molecular weight of the Explosive (g/mol)

Cooper Method

Simply the ratio of square of the Detonation Velocity (D) from Cooper [14], so:

$$\text{TNT Equivalence} = D_{\text{EXP}}^2 / D_{\text{TNT}}^2 \quad (4)$$

Where:

D – Detonation Velocity (m/s)

From Cooper and Table IV, we can see the typical variations of these two methods. For which more detailed assessment work is ongoing.

TABLE IV. SOME TNT EQUIVALENCE COMPARISONS BY PERCENTAGE.

Explosive	From Expt	Berthelot Method	Difference Bethelot from Expt (%)	Cooper Method	Difference Cooper from Expt (%)
Ammon. Picrate	85	87	2	97	14
HBX-3	116	110	-5	99 to 102	-15 to -12
Pentolite (50/50)	105	156	49	115	10
Torpex	122	118	3	120	-2
Tritonal	110	89	-19	87 to 93	-21 to -15

Hydrodynamic Work

Working from the energy available that can do work on their surroundings, we can derive an isentropic expansion giving the energy available from the P_{CJ} to ambient pressure. This is called the hydrodynamic work function. This main issue in deriving this accurately is that the products are in a constant state of change during the expansion, changing from high pressure and temperature to low pressure and temperature, usually quoted as standard temperature and pressure (stp). The heat capacity of these products change from effectively constant volume to constant pressure and additionally the product composition also usually changes during the expansion process. Results are compared in Table V.

From theory:

$$E = \int_{P_{CJ}}^{P_{AMB}} P(V)_S \cdot dV \quad (5)$$

Giving:

$$E = 0.5 \cdot P_{CJ} / \rho_{CJ} \quad (6)$$

But from Cooper we have a good approximation of ρ_{CJ} as:

$$\rho_{CJ} = 1.386 \rho_0^{0.96} \quad (7)$$

So:

$$E = 0.36075 \cdot P_{CJ} / \rho_0^{0.96} \quad (8)$$

Thus only a standard explosive density (ρ_0) and P_{CJ} are required to give a good estimate of the work energy available.

Where:

- E = Hydrodynamic Work Available (J)
- P_{CJ} = Chapman-Jouguet (CJ) Detonation Pressure (Pa)
- ρ_{CJ} = Density of explosive at the CJ state (kg/m^3)
- ρ_0 = Density of unreacted explosive (kg/m^3)

Explosive Power

Explosive Power (EP) is related to the amount of energy available from an explosion than can do work on its surroundings. As such it is proportional to the total amount of gases produced and the amount of heat available to expand these gases. Power Index (PI) is the ratio of an explosives power to that of Picric Acid, and hence its equivalence [15]. Results are compared in Table V. A modified derivation is supplied here.

From the ideal gas laws we have:

$$EP = n \cdot R \cdot T \quad (9)$$

Where n is the moles of gas per unit mass of explosive and V_{MOL} is the molar volume:

$$n = V / V_{MOL} \quad (10)$$

The Heat of Detonation (Q) per unit mass is:

$$Q = C \cdot T \quad (11)$$

So:

$$EP = Q \cdot V \cdot R / (V_{MOL} \cdot C) \quad (12)$$

TABLE V. COMPARISON OF WORK TNT EQUIVALENCE PREDICTIONS.

Explosive	Density (g/cc)	Heat of Detonation (MJ/kg)	CJ Pressure (GPa)	TNT Equivalence (%)				
				Expt	Calc from E	Difference, from E to Expt	Calc from PI	Difference, from PI to Expt
Non-Aluminised								
Ammon. Picrate	1.55	3.349	19.3	85	98	15.1	92	8.4
Amatol 60/40	1.50	2.638	13.3	95	69	-26.9	112	17.4
Amatol 50/50	1.55	2.931	16.4	97	84	-13.9	114	17.3
Comp A-3	1.59	4.605	27.5	109	136	25.1	141	29.5
Comp B	1.68	5.192	26.9	110	127	15.3	131	18.7
Comp C-3	1.60	6.071	24.5	105	121	15.0	135	28.7
Cyclotol 75/25	1.71	5.150	28.3	111	131	18.4	137	23.8
Cyclotol 70/30	1.73	5.066	29.1	110	134	21.4	135	22.5
Cyclotol 60/40	1.72	5.024	27.8	104	128	23.4	130	24.5
Ednatol 55/45	1.63	5.610	23.0	108	112	3.3	122	13.3
Pentolite 50/50	1.66	5.108	24.2	105	115	9.7	122	16.0
Picratol 52/48	1.63	4.564	20.8	100	101	0.6	103	3.3
PTX-1	1.64	6.364	25.2	111	121	9.3	123	10.7
PTX-2	1.70	6.531	28.8	113	134	18.6	133	17.5
Aluminised								
DBX	1.65	7.118	18.8	118	90	-23.7	143	21.3
HBX-3	1.81	8.834	22.3	116	98	-15.6	74	-36.3
MINOL-2	1.68	6.783	14.8	115	70	-39.2	145	25.7
MOX-2B	2.00	6.155	11.3	102	45	-55.8	49	-52.3
Torpex	1.81	7.536	26.1	122	115	-5.9	143	17.5
Tritonal	1.72	7.411	19.3	110	89	-18.8	120	9.1
Mean Absolute Difference						18.8		20.7

Defining the ‘Characteristic Product’ of the explosive as:

$$CP = Q \cdot V / C \quad (13)$$

So:

$$EP = CP \cdot (R / V_{MOL}) \quad (14)$$

Difficulties arise with comparisons of CP, as the mean heat capacity (C) is difficult to quantify. However, if we assume k is a constant, so that:

$$k = R / (V_{MOL} \cdot C) \quad (15)$$

This assumes that the expanded products are approximately of similar composition, such that the mean heat capacities are relatively constant.

$$EP = k \cdot Q \cdot V \quad (16)$$

Taking Explosive Power relative to TNT as the standard reference explosive, rather than the using the normal convention of Picric Acid, we can then redefine the Power Index:

$$\text{Power Index} = EP_{\text{EXP}} / EP_{\text{TNT}} \quad (17)$$

$$\text{Power Index} = Q_{\text{EXP}} \cdot V_{\text{EXP}} / Q_{\text{TNT}} \cdot V_{\text{TNT}} \quad (18)$$

Where:

C = Mean Heat capacity of gases from detonation to stp (J/kg/K)

CP = Characteristic Product of explosive (m³K/kg)

k = Gas constant (kg/m³)

n = Moles of gas / Mass of explosive (mol/kg)

EP = Explosive Power (J/kg)

EP_{EXP} = Explosive Power of explosive for comparison (J/kg)

EP_{TNT} = Explosive Power of TNT (J/kg)

Q = Heat of Detonation (J/kg)

Q_{EXP} = Heat of Detonation of explosive for comparison (J/kg)

Q_{TNT} = Heat of Detonation of TNT (J/kg)

R = 8.3143 = Universal gas constant (J/mol/K)

T = Temperature of explosion (K)

V = Volume of gases at stp / Mass of explosive (m³/kg)

V_{EXP} = Volume of gases at stp / Mass of explosive for comparison (m³/kg)

V_{MOL} = 22.4 = Molar volume of any gas at stp (m³/mol)

V_{TNT} = Volume of gases at stp / Mass of TNT (m³/kg)

TNT Equivalence by Heat of Detonation

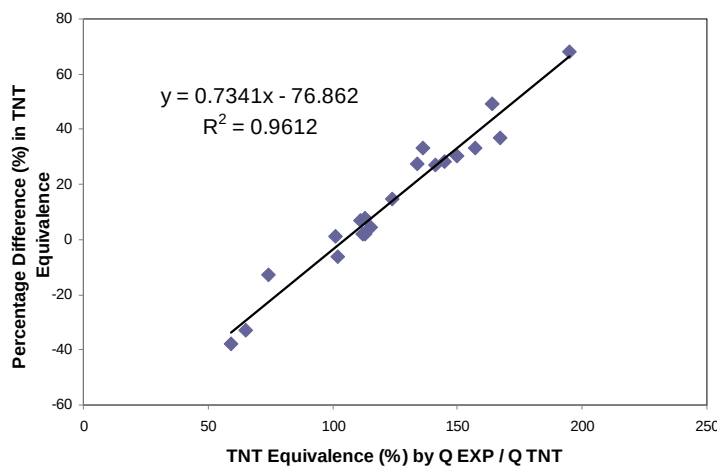


Figure 7. Percentage Difference in TNT Equivalence by Heat (Q)

This is the most commonly used method for comparison of explosive performance comparison and is based solely on the Heat of Detonation ratio. Its virtue is its pure simplicity. UFC manuals recommend this for the TNT equivalence of an unconfined charge. But use of Heat of Detonation fails to

account for the effects of secondary combustion, expansion of gases and volumes of gases produced. So inaccuracy is not surprising. When plotting the tabulated data looking for trends, it was found that a linear relationship exists between the percentage difference in TNT equivalence experimentally to that calculated using the standard formula (Figure 7). Assuming that the experimental Heat of Detonation measurements are in fact accurate, rather than being subject to some systematic error, we can apply a simple correction to the standard TNT equivalence prediction method (19), making it significantly more reliable for the explosive types studied.

TABLE VI. COMPARISON OF HEAT (Q) TNT EQUIVALENCE PREDICTIONS.

Explosive	TNT Equivalence (%)				
	Expt	Standard Calc (19) from Heat	Difference, from Standard Q (19) to Expt	Updated Calc (23) from Heat	Difference, from Updated Q (23) to Expt
Non Aluminised					
Ammon. Picrate	85	74	-12.9	96	12.4
Amatol 60/40	95	59	-37.9	88	-6.9
Amatol 50/50	97	65	-33.0	92	-5.5
Comp A-3	109	102	-6.4	104	-4.6
Comp B	110	115	4.5	107	-2.8
Comp C-3	105	134	27.6	110	5.1
Cyclotol 75/25	111	113	1.8	107	-3.9
Cyclotol 70/30	110	112	1.8	106	-3.4
Cyclotol 60/40	104	111	6.7	106	2.0
Ednatol 55/45	108	124	14.8	109	0.6
Pentolite 50/50	105	113	7.6	107	1.4
Picratol 52/48	100	101	1.0	104	3.8
PTX-1	111	141	27.0	111	0.3
PTX-2	113	145	28.3	112	-1.0
Aluminised					
DBX	118	157	33.1	113	-3.8
HBX-3	116	195	68.1	117	1.1
MINOL-2	115	150	30.4	113	-2.1
MOX-2B	102	136	33.3	111	8.4
Torpex	122	167	36.9	115	-6.1
Tritonal	110	164	49.1	114	3.9
Mean Absolute Difference			23.1		4.0

The improvement (23) is simple to apply and results are given for comparison in Table VI. Taking a typical TNT Heat of Detonation (Q_{TNT}) of 4521 kJ/kg.

$$\text{TNT Equivalence (by Q)} = Q_{EXP} / Q_{TNT} \quad (19)$$

Taking the line fit gradient (m) and the intercept (i) from Figure 6. We have:

$$m = 0.7341 \quad (20)$$

$$i = -76.862 \quad (21)$$

$$\text{Letting:} \quad d = -i / 100 = 0.76862 \quad (22)$$

Giving us an updated TNT equivalence of:

$$\text{TNT Equivalence (by Q)} = Q_{\text{EXP}} / (Q_{\text{TNT}} (1 - d) + m \cdot Q_{\text{EXP}}) \quad (23)$$

Where:

d – Adjusted line intercept from Heat of Detonation TNT Equivalence

i – Line intercept from Heat of Detonation TNT Equivalence

m – Line gradient from Heat of Detonation TNT Equivalence

Q_{EXP} – Heat of Detonation of Explosive (J/kg)

Q_{TNT} – Heat of Detonation of TNT (J/kg)

CONCLUSION

Past trials data have been shown to be very variable when comparing TNT equivalences for blast modelling. TNT Equivalence is shown to change with Scaled Distance, Impulse and Pressure. Simple theoretical calculations of Hydrodynamic Work or Power Index can reliably be used for blast effects and are better than the Standard Heat of Detonation method. Power Index, which accounts for both the heat produced and also the work available, is considered the most reliable for blast effect modelling. Tables (V & VI) show similar accuracy for the various methods, with Aluminised explosives causing the largest discrepancies.

A proposed modification to the standard heat method (23) does give significantly improved predictions, with a mean difference of 4% across those explosives assessed, compared to a mean difference of 23% for the standard method (19). Further work is ongoing covering additional explosives and trials.

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