A Critical Review of TNT Equivalency

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Abstract

The term TNT equivalency has been widely misused and misinterpreted when expressing energy yields from munitions and explosives. This paper will focus on how these approximate yields are an estimate of the actual output. This paper will also address how the values can change depending on many parameters and methods of measurement.

Background

For the military the ability to predict the effect of detonating or deflagrating energetic materials on the surroundings is of great interest. This is applicable for military field operations where the quantity and arrangement of explosive charges required to complete a mission must be in an easy to understand set of instructions. It is also important in safety planning in order to safely store, transport, and field munitions. The use of explosive equivalence is complicated by the variety of explosives that are available and their different explosive effects. An understanding of the utility and limits of relative equivalence is required.

The TNT equivalence, or Relative Effectiveness (RE) factor, is the ratio of the explosive to that of a known quantity of TNT that have the same effect, Equation 1. In the literature TNT equivalence and Relative Effectiveness factor are both used, RE is generally used for demolition[1] while TNT equivalence for safety evaluations.

$$RE = \frac{Amount\ of\ TNT}{Amount\ of\ Explosive} \qquad \text{Eq. 1}$$

The quantity of explosive required for the desired results is determined by dividing the amount of TNT needed by the RE value of the available explosive, Equation 2. The quantity of TNT required is known through military manuals, data bases, modeling, or experience. Higher performing explosives have a larger RE factor.

$$Amount\ of\ Explosive\ for\ Equal\ Effect = \frac{Established\ Quantity\ of\ TNT}{RE} \quad \text{Eq. 2}$$

There is a long history of using the performance of TNT as the basis of comparison between explosive materials. However, the US is greatly reducing the use of TNT for US military purposes, and its use will be stopped in the future due to safety concerns because of its poor response to cook-off reactions.

RE Estimation Methods

Many methods have been developed to calculate estimations for TNT equivalence. The methods used have varying degrees of success, even though they are based upon variables known to affect performance.

Berthelot Method[2]

This has also been referred to as the Characteristic Product and the Power Index. The first development of explosive equivalences was by the French researcher M. Berthelot around the turn of the last century. The method was later evaluated base upon Trinitrotoluene (TNT), a common explosive during the 20th century. The Berthelot method uses the ratio of equivalence factors based upon the heat of detonation and the amount of gases produced, Equation 3. Some researchers use rule of thumb estimations for the chemical species produced by the detonation, required to determine the molecular weight. Current thermochemical codes such as Jaguar or Cheetah would produce better estimations for the products of detonation.

$$RE = \frac{(Q\ V)_{Explosive}}{(Q\ V)_{TNT}} \quad \text{Eq. 3}$$

Where:

V=The Volume of the detonation Products at STP

Q= The Heat of Detonation

Maienschein[3]

This method uses the thermochemical code Cheetah to calculate the detonation energy for an explosive by summing the "mechanical energy of detonation" and the "thermal energy of detonation." This method should be considered an improvement over the Berthelot method.

Cooper Method[4]

Cooper used a hydrodynamic estimate and the Hugoniot equation to solve for the energy of detonation. Coopers development assumes $\Delta e = \frac{1}{2} P_{cj} v_{cj}$, an assumption that is not necessary as the Hugoniot, Equation 4, can be used.

From the Hugoniot equation:

$$\Delta e = \frac{1}{2} P_{cj} (v_0 - v_{cj}) \qquad \text{Eq. 4}$$

And the approximation:

$$v_{cj} \approx \frac{3}{4} v_0 \qquad \text{Eq. 5}$$

Then:

$$\Delta e = \frac{1}{32} D^2 \qquad \text{Eq. 6}$$

Then:

$$RE = \frac{\Delta e_{Explosive}}{\Delta e_{TNT}} = \frac{D^2{}_{Explosive}}{D^2{}_{TNT}} \qquad \text{Eq. 7}$$

CJ Pressure Ratio

A detonation is a shock driven chemical reaction of the explosive material. This chemical reaction is completed rapidly in a narrow reaction zone behind the shock wave. The pressure of the detonation wave (called the Chapman Jouget (CJ) pressure after the two independent developers) is related to the shattering or brisance of the explosive.

A number of methods can be used to estimate CJ pressure, this simplistic model developed by Cooper, Equation 8, can be used to provide an estimate for TNT equivalence values, equation 9.

$$P_{cj} = \rho_0 D^2(1 - .5405{\rho_0}^{0.04}) \qquad \text{Eq. 8}$$

Where:

P_{cj}= CJ Pressure (Pa)

ρ_0= Initial Density [Kg/m3]

D = Detonation Velocity [m/s]

$$RE = \frac{{P_{cj}}_{TNT}}{{P_{cj}}_{he}} = \frac{\rho_0 D^2(1 - .5405{\rho_0}^{0.04})_{TNT}}{\rho_0 D^2(1 - .5405{\rho_0}^{0.04})_{he}} \qquad \text{Eq. 9}$$

An Explosive's Ability to Accelerate Materials

R. W. Gurney examined the velocity of fragmenting munitions during WWII. The development assumes that there is an energy, the Gurney Energy E, that can be converted to kinetic energy. Gurney assumes that the gaseous detonation products expand uniformly with constant density and a linear velocity distribution. The application of the conservation equations (mass, momentum, and energy) has been applied to various geometries, many of which are available in the literature. Despite the estimations made, the method has been successfully used in predicting fragmentation.

Open Faced Sandwich Configuration

The Gurney equation for an open faced sandwich configuration, Equation 10, is an approximate match to some configurations used in demolitions, as it represents an explosive placed on a plate without tamping. While cylindrical and spherical configurations of the Gurney equation exist, they are not used here as the internal volume is set prohibiting the unconstrained variations in mass.

$$V = \frac{\sqrt{2E}}{\left(\frac{1+\left(1+2\left(\frac{M}{C}\right)\right)^3}{6\left(1+\left(\frac{M}{C}\right)\right)}+\left(\frac{M}{C}\right)\right)^{1/2}} \qquad \text{Eq. 10}$$

Where:

V=Velocity

M= Mass of the Cylinder

C = Mass of the Explosive Charge

$\sqrt{2E}$ = Gurney Constant, units of velocity

In order to determine the amount of explosive needed to achieve the same velocity as a known TNT charge the velocities are set equal.

$$V_{TNT} = V_{HE} \qquad \text{Eq. 11}$$

$$\frac{\sqrt{2E}_{TNT}}{\left(\frac{1+\left(1+2\left(\frac{M}{C}\right)_{TNT}\right)^3}{6\left(1+\left(\frac{M}{C}\right)_{TNT}\right)}+\left(\frac{M}{C}\right)_{TNT}\right)^{1/2}} = \frac{\sqrt{2E}_{he}}{\left(\frac{1+\left(1+2\left(\frac{M}{C}\right)_{he}\right)^3}{6\left(1+\left(\frac{M}{C}\right)_{he}\right)}+\left(\frac{M}{C}\right)_{he}\right)^{1/2}} \qquad \text{Eq. 12}$$

The above equation must be solved numerically; the results of a Matlab® program are shown below in Figures 1 and 2. The range of Gurney values used represent the expected range seen in demolitions. The Relative Effectiveness (RE) is taken as the mass of TNT divided by the mass of the explosive to achieve the same velocity, Equation 13.

$$RE = \frac{C_{TNT}}{C_{he}} = \frac{\left(\frac{M}{C}\right)_{TNT}}{\left(\frac{M}{C}\right)_{he}} \qquad \text{Eq. 13}$$

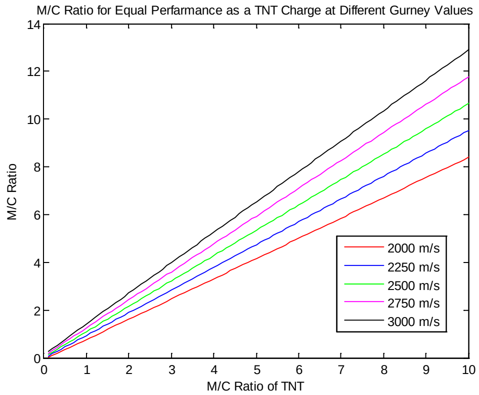

Figure 1

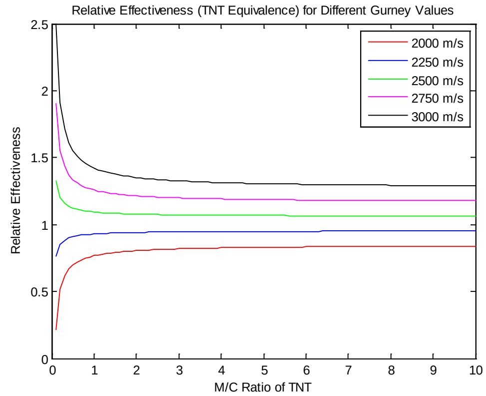

Figure 2

From Figure 1 the ratios of $\frac{M}{C}$ appear to have a linear relationship to each other. However when plotted as a function of RE the divergence from a linear relationship can be seen. It is noted that the effectiveness asymptotes to a constant value for large $\frac{M}{C}$ ratios. Additionally for materials with a higher performance than TNT, the RE increases with decreasing $\frac{M}{C}$ ratios. The asymptotic values for RE can be computed from equation 12.

$$\left(\frac{\sqrt{2E}_{TNT}}{\sqrt{2E}_{he}}\right)^2 \left(\frac{1+\left(1+2\left(\frac{M}{C}\right)^3_{he}\right)}{6+\left(1+\left(\frac{M}{C}\right)_{he}\right)} + \left(\frac{M}{C}\right)_{he}\right) = \left(\frac{1+\left(1+2\left(\frac{M}{C}\right)^3_{TNT}\right)}{6+\left(1+\left(\frac{M}{C}\right)_{TNT}\right)} + \left(\frac{M}{C}\right)_{TNT}\right) \qquad \text{Eq. 14}$$

As $\frac{M}{C} \xrightarrow{goes\ to\ \infty}$

$$\left(\frac{\sqrt{2E}_{TNT}}{\sqrt{2E}_{he}}\right)^2\left(\frac{8\left(\frac{M}{C}\right)^3_{he}}{6\left(\frac{M}{C}\right)_{he}}\right)=\left(\frac{8\left(\frac{M}{C}\right)^3_{TNT}}{6\left(\frac{M}{C}\right)_{TNT}}\right) \qquad \text{Eq. 15}$$

$$\left(\frac{\sqrt{2E}_{TNT}}{\sqrt{2E}_{he}}\right)^2\left(\frac{M}{C}\right)^2_{he}=\left(\frac{M}{C}\right)^2_{TNT} \qquad \text{Eq. 16}$$

Then

$$RE\xrightarrow{\frac{M}{C}\,goes\ to\ \infty}\frac{\sqrt{2E}_{he}}{\sqrt{2E}_{TNT}} \qquad \text{Eq. 17}$$

The asymptotic values are plotted with the RE values for the high and low Gurney values used in Figure 3.

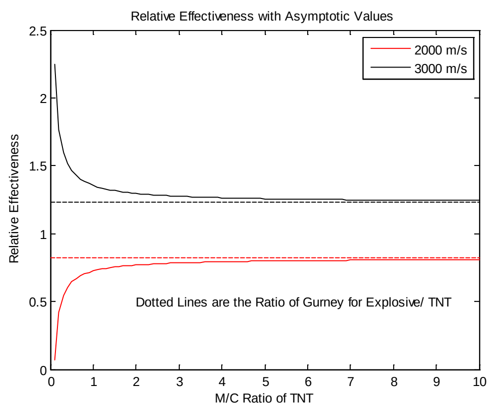

Figure 3

Symmetrical Sandwich Configuration

The Gurney Equation for a symmetric sandwich configuration, Equation 18, is another approximate match to some configurations used in demolitions, as it represents an explosive placed on a plate with tamping.

$$V = \frac{\sqrt{2E}}{\left(\frac{M}{C} + \frac{1}{3}\right)^{1/2}} \qquad \text{Eq. } 18$$

The asymptotic values for RE can be computed from equation 19.

$$\frac{\sqrt{2E}_{he}}{\left(\left(\frac{M}{C}\right)_{he} + \frac{1}{3}\right)^{1/2}} = \frac{\sqrt{2E}_{tnt}}{\left(\left(\frac{M}{C}\right)_{tnt} + \frac{1}{3}\right)^{1/2}} \qquad \text{Eq. } 19$$

$$\left(\frac{\sqrt{2E}_{he}}{\sqrt{2E}_{tnt}}\right)^2 = \frac{\left(\left(\frac{M}{C}\right)_{he} + \frac{1}{3}\right)}{\left(\left(\frac{M}{C}\right)_{tnt} + \frac{1}{3}\right)} \qquad \text{Eq. } 20$$

As $\frac{M}{C} \xrightarrow{goes\ to\ \infty}$

$$RE \xrightarrow{\frac{M}{C}\ goes\ to\ \infty} \left(\frac{\sqrt{2E}_{he}}{\sqrt{2E}_{tnt}}\right)^2 \qquad \text{Eq. } 21$$

Cooper has proposed the following approximation for the Gurney Constant[5]

$$\sqrt{2E} \approx {}^{D}/_{2.97} \qquad \text{Eq. } 22$$

$$RE \xrightarrow{\frac{M}{C}\ goes\ to\ \infty} \left(\frac{D_{he}}{D_{tnt}}\right)^2 \qquad \text{Eq. } 23$$

The Symmetrical Sandwich Configuration Asymptotes to the Cooper Approximation, Eq. 7.

The relationship for the Relative Equivalence for the symmetric sandwich are very similar to that of the open face sandwich.

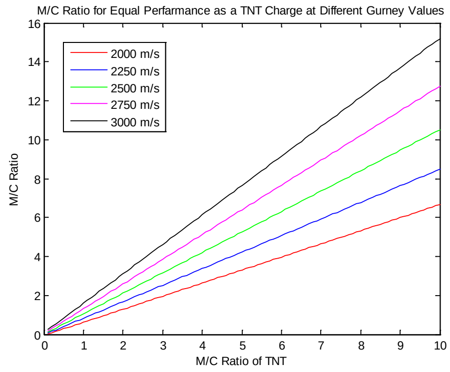

Figure 4

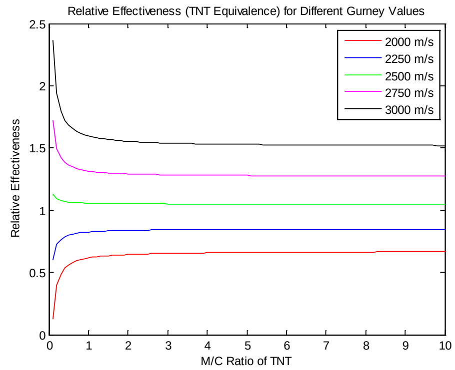

Figure 5

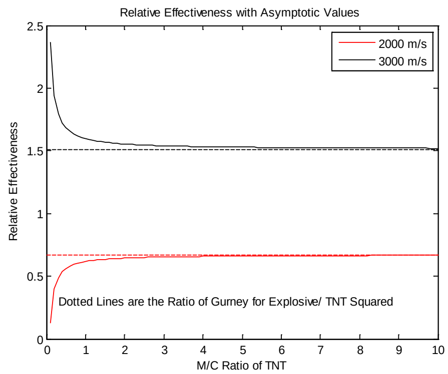

Figure 6

Measurement

Many methods exist to experimentally determine the relative equivalence of an explosive. Some, like the Dent Plate and Sand Crush test are closely related to CJ Pressure, and others such as Ballistic Mortar and open field air pressure gauge measurements are more closely related to blast effects.

Historic Methods

Ballistic Mortar	The height which a weight (mortar) suspended on an arm is raised by an initiated sample.
Dent Plate	The dent depth in a Plate caused by an initiated sample, this is approximately linear to CJ pressure.
Sand Crush Test	Measures the Relative Weight of Sand Crushed by an initiated sample.
Trauzl	Measures the increase in volume of a hole in a lead test fixture in which the explosive has been detonated.

These Methods above are not suggested, as better analysis is available, such as direct blast wave measurements and cylinder expansion testing.

The direct measurement of blast waves is the best direct measure of Relative Effectiveness when blast is the effect being determined. When analyzing the results care needs to be taken because the geometry of the charge, size, distance, and interactions with solid objects will affect the measurement. Isaballe Sochet has stated "If the explosion takes place in a complex environment like a closed zone, urban area or industrial facility, it becomes impossible to define a TNT equivalency"[6]. It is the authors opinion that testing and modeling the results from similar environments can be used to overcome this problem.

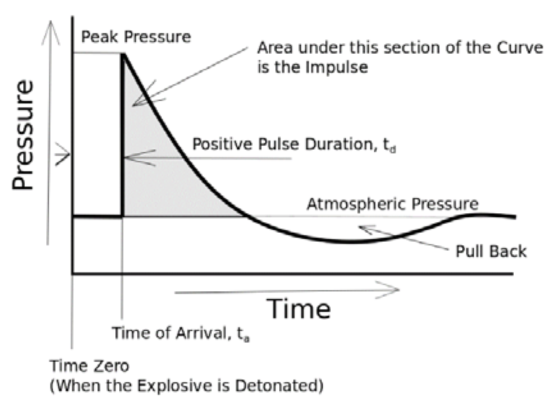

Figure 7 Air Shock

After Burn

Explosives with excess fuel (negative oxygen balance) can have significant post-detonative reactions as the hot fuels mix with air. These reactions can increase the impulse. Maienschein suggested the following rules of thumb:

For explosives with oxygen balance > 50%, assume 2/3rd of the aluminum reacts.

For explosives with oxygen balance <50%, assume 1/3rd of the aluminum reacts.

The percentages also change with geometry, size, and reflections off obstructions.

TNT is strongly oxygen deficient. As such the pressure pulse depends upon the geometry, size, and reflections off obstructions. For this reason it is a poor choice upon which to base Explosive Equivalence.

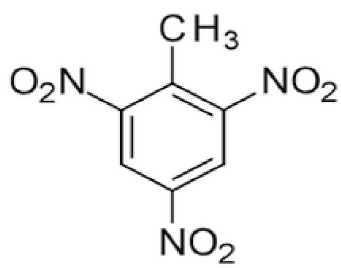

Figure 8 TNT Molecule

How Good are TNT Equivalence Values

In reviewing the literature many variations in TNT equivalence factors for the same explosive can be found. Some of these differences can be attributed to the method used to determine RE, others cannot. Locking[7] attributed the figure below to Chessman, which illustrates the degree of difficulty in determining a TNT equivalence factor.

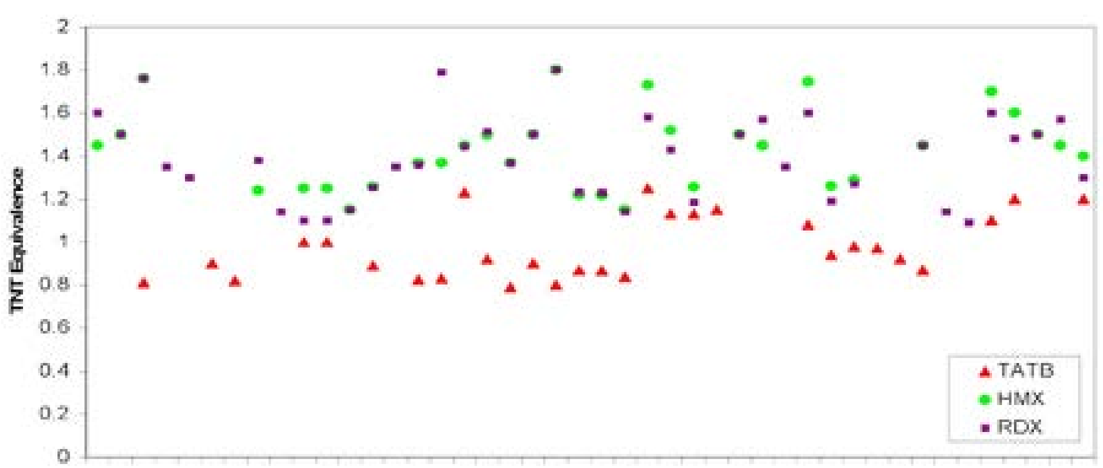

Figure 9 Various Report Values of TNT Equivalence

Cooper showed that Explosive Equivalence for blast waves in air changes with scaled distance[8],

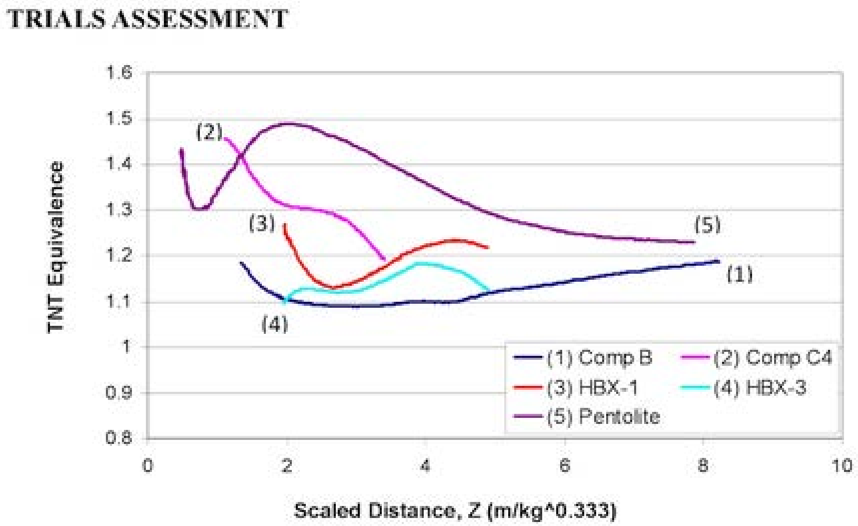

Figure 10

Locking showed that the Explosive Equivalence for blast waves in air change differently for peak pressure and impulse[9].

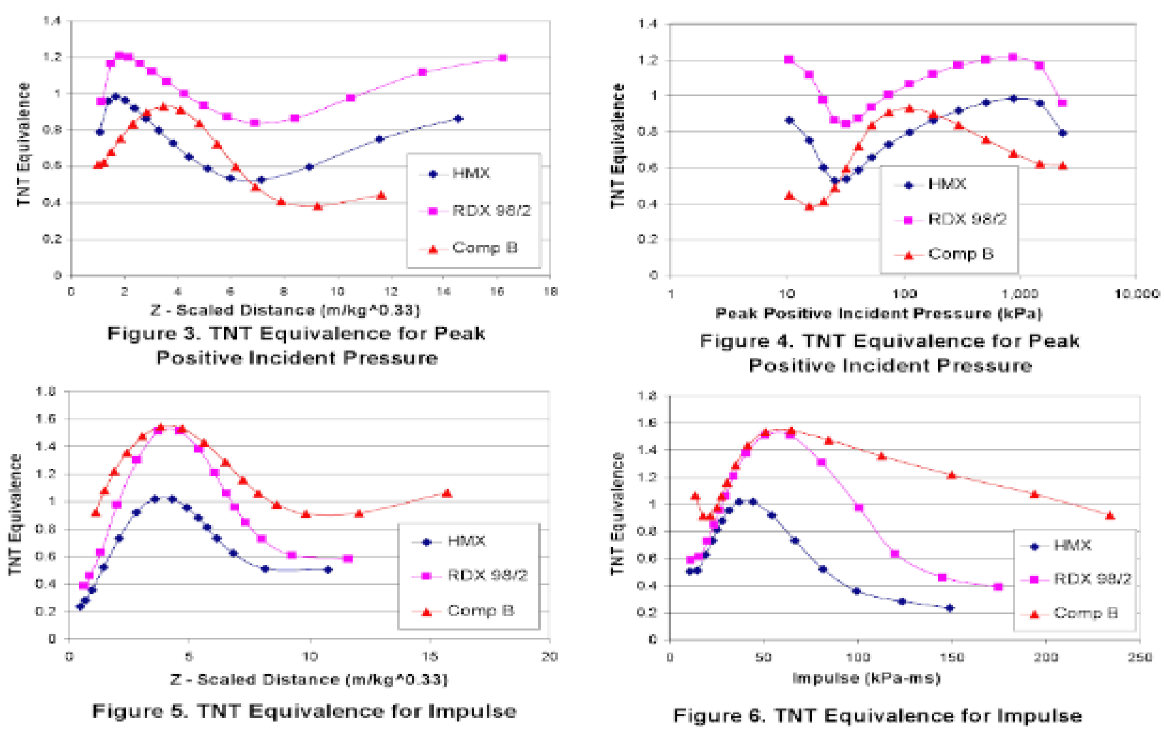

Figure 11

Energetic Materials not Designed for Detonation

Propellants and pyrotechnics are not designed to detonate, although they may, given the right circumstances. These systems vary in types of reactions and the violence of reactions. This does not eliminate the potential for destructive blast waves and fragmentation. In fact based on the accident data and testing with propellants and pyrotechnics the structural break up is different. There are larger lethal structural debris that might travel further than for a similar quantity of detonating explosives. Consequently explosive equivalency is not an accurate estimation of the hazards associated with pyrotechnics and propellants.

These systems have very complicated combustion hazards and energy functions. In many cases Explosive Equivalency does not address:

- System Geometry(ies)
- Initiation mechanism
- Rate of reaction
- Confinement effects
- "Work" function or damage mechanism
- Energy release as a function of time
- Type of reaction(s)
- Facilities Siting Hazards
- Realistic and likely hood of an event

Improved methods for handling burning propellants and pyrotechnics are needed. Rate dependent measurements are useful in order to assess behavior and energy release. Parameters such as loading density, confinement, geometry etc. become very important for assessing hazards.

All of the information available should be used in assessing the damage potential for an accident. This includes using Insensitive Munitions and Hazard Classification testing and assignments, however they are not sufficient for addressing all of the significant hazards required for siting. Some guidelines exist such as:

- Comprehensive risk assessments per the guidelines of NFPA 495 (2016) and Office of Management and Budget, Circular No. A-123 92016 should be conducted to identify the hazards and facilities should be designed to mitigate such hazards.
- OSHA 29 CFR 1910 "Process Safety Management"

– DDESB Technical Paper 23- "DoD Explosives Safety And Munitions Risk Management: Acquisition Lifecycle Considerations, Risk Assessment Process Framework, And Associated Tools" DRAFT

Suggestions

The use of the terms Relative Effectiveness or Explosive Equivalence are confusing as utilized, implying a greater degree of certainty than is warranted. Data shows that these values are usually approximate except under very limited situations. Instead the term Approximate Explosive Equivalence is suggested.

TNT is strongly oxygen deficient. As such the pressure pulse depends upon the geometry, size, and reflections off obstructions. For this reason it is a poor choice upon which to base Explosive Equivalence. The community should consider another basis of comparison, or develop or use a property that does not depend upon the comparison to any explosive.

Data used in tables for explosive equivalence are determined from many testing methods, which are often unspecified. This severely limits the utility as even crude adjustments for circumstances cannot be made. Standard test methods should be developed.

While the computational methods are continually developing, improvements for modeling blast and fragmentation are still needed.

For siting facilities all of the hazards need to be considered. Normalizing to a hazard classification does not address all of the hazards. The use of a simple TNT equivalency analysis overlooks the full hazards of a system and misses many of the effects and the overall work energy produced from a reaction that is much different than the work energy estimation made by an approximate TNT equivalency.

The Equivalence calculations should be matched to the desired results. Fragmentation and blast can have various relative strengths for different energetic materials. One size does not fit all, and safety site planning requires knowledgeable and experienced experts.

Conclusions

TNT Equivalency is simple in concept, but difficult to use properly. The use of the terms Relative Effectiveness or Explosive Equivalence are confusing as utilized, implying a greater degree of certainty than is warranted. The values change depending on the measuring techniques and environment. Data shows that these values are usually approximate except under very limited situations. Instead the term Approximate Explosive Equivalence is suggested. For siting facilities all of the hazards need to be considered. Normalizing to a hazard classification does not address all of the hazards. The use of a simple TNT equivalency analysis overlooks the full hazards of a system and misses many of the effects and the overall work energy produced from a reaction that is much different than the work energy estimation made by an approximate TNT equivalency.

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