Always a Step Ahead
ARDEC
ARMAMENTS

Explosive Equivalence

Dr. Brian Fuchs — US ARMY ARDEC
Dr. Josephine Covino — DDESB
Dr. Ernest Baker — MSIAC

International Explosives Safety Symposium & Exposition
6-9 August 2018
San Diego, CA

UNPARALLELED COMMITMENT & SOLUTIONS

Act like someone's life depends on what we do.

U.S. ARMY
U.S. ARMY RDECOM

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT & ENGINEERING CENTER

INTRODUCTION

Explosive equivalence is a simple concept of how much of an available explosive has the same effects as a reference explosive. It is used in:

- safety evaluations: a magazine was designed to safely hold x pounds of a reference explosive …what quantities of available materials can be stored

- military field operations: what quantity of available explosives is required to complete the mission when x pounds is required with a reference material

An easy to understand set of instructions for computing the relative equivalence is desired. This is complicated by the variety of explosives that are available and their different explosive effects.

Relative Effectiveness
Introduction

RE Factor

- The Relative Effectiveness (RE) factor, or TNT equivalence, is a design tool that allows computation of the effects of various explosives or explosives formulations. The RE factor is based upon a known quantity of TNT.

$$RE = \frac{Amount\ of\ TNT}{Amount\ of\ Explosive}$$ For the same Effect

Relative Effectiveness

Introduction

Some of the Methods to Compute RE

- Ratio of CJ Pressures $$\frac{P_{cj}\, explosive}{P_{cj}\, TNT}$$

- Berthelot Method $$\frac{(QV)_{Explosive}}{(QV)_{TNT}}$$

Where:

Q= The Heat of Detonation

V=The Volume of the detonation Products at STP

Relative Effectiveness Computations

Some of the Methods to Compute RE

- Maienschein

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 of the approximate Berthelot and Power Index methods.

- Cooper Method

$$\frac{D^2{}_{Explosive}}{D^2{}_{TNT}}$$

Where:

D=The Detonation Velocity

Evaluation Based on Flyer Plates

- The Gurney Equation for an Open Faced Sandwich configuration is an appropriate match to the configurations for fragmentation.

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

Where: $\left(\frac{M}{C}\right)$=The mass ratio of liner to explosive charge

Early work output (metal pushing …not blast)

Relative Effectiveness Computations

U.S. ARMY RDECOM

Evaluation Based on Flyer Plates

ARDEC

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

$$V_{TNT} = V_{HE}$$

$$\frac{\sqrt{2E}_{TNT}}{\left(\frac{1+\left(1+2\left(\frac{M}{C}\right)_{TNT}\right)^{3}}{6\left(1+\left(\frac{M}{C}\right)_{TNT}\right)}+\left(\frac{M}{C}\right)_{TNT}\right)^{1/2}} = \frac{\sqrt{2E}_{HE}}{\left(\frac{1+\left(1+2\left(\frac{M}{C}\right)_{HE}\right)^{3}}{6\left(1+\left(\frac{M}{C}\right)_{HE}\right)}+\left(\frac{M}{C}\right)_{HE}\right)^{1/2}}$$

Which can be solved iteratively

Relative Effectiveness Computations

Evaluation Based on Flyer Plates

$$RE = \frac{C_{TNT}}{C_{he}} = \frac{\left(\frac{M}{C}\right)_{TNT}}{\left(\frac{M}{C}\right)_{he}}$$

$$RE \xrightarrow{as\ \frac{M}{C}\ goes\ to\ \infty} \frac{\sqrt{2E}_{HE}}{\sqrt{2E}_{TNT}}$$

Relative Effectiveness
Computations

U.S. ARMY RDECOM®

HISTORIC METHODS

ARDEC

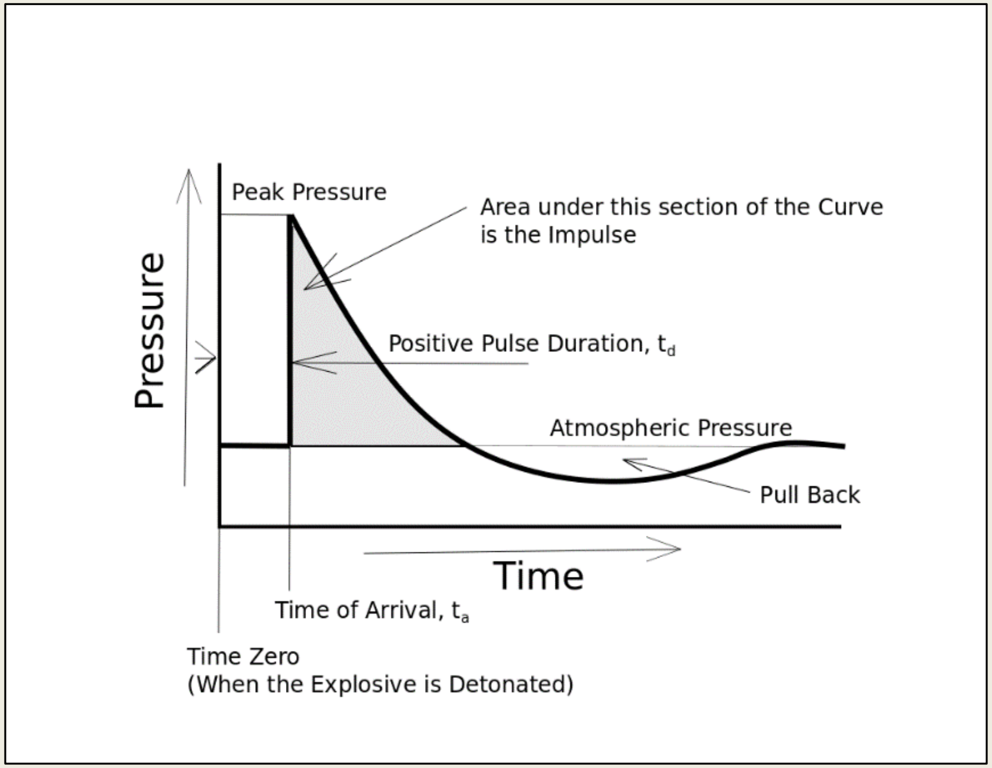
• Ballistic Mortar	The height which a weight (mortar) suspended on an arm is raised by an initiated sample.
• Dent Plate	The dent depth in a Plate caused by an initiated sample, this is approximately linear to CJ pressure.
Sand Crush Test	Measures the Relative Weight of Sand Crushed.
• Trauzl	Measures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

These Methods are no longer suggested as better analysis is available.

Relative Effectiveness
Historic Methods

BLAST

The direct measurement of blast waves is the best direct measure of Relative Effectiveness, for blast.



Relative Effectiveness
Blast

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.

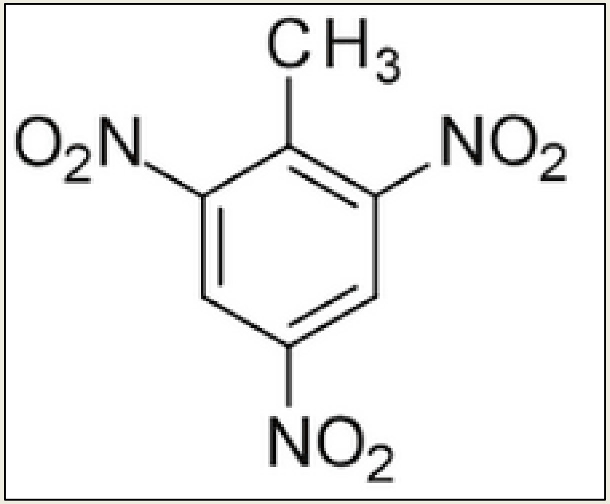
The percentages also change with geometry, size, and reflections off obstructions.

Relative Effectiveness
After Burn

Maienschein, J. L. Estimating equivalency of explosives through a thermochemical approach. No. UCRL-JC-147683. Lawrence Livermore National Lab., CA (US), 2002.

After Burn

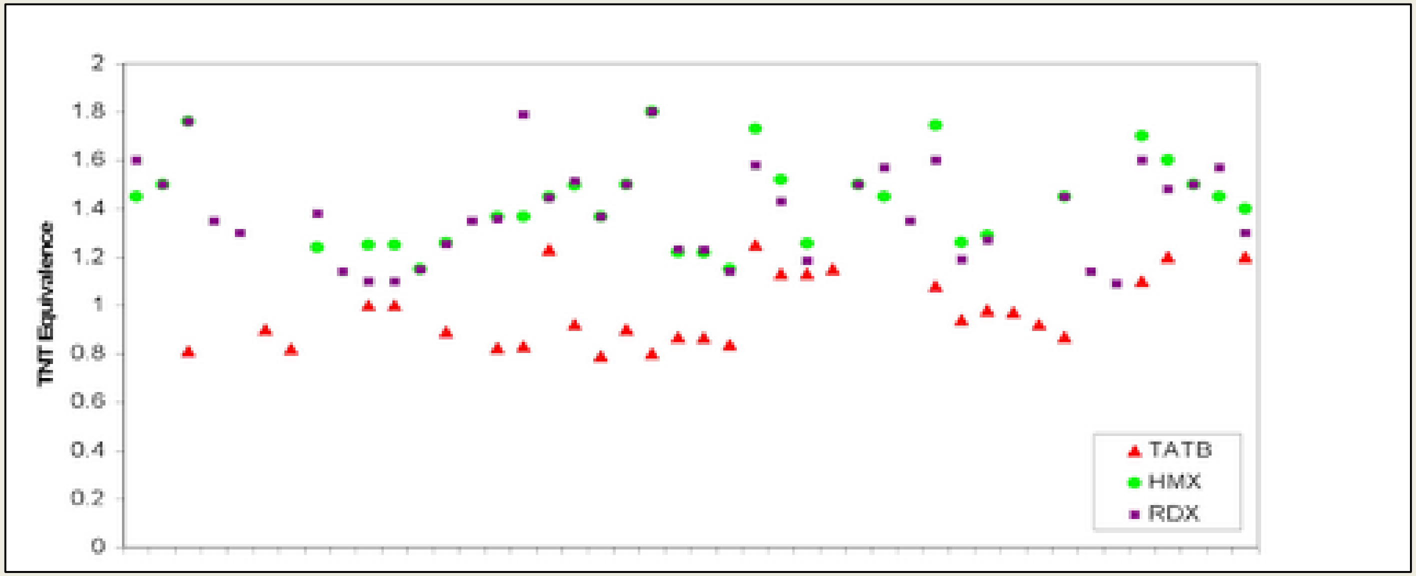
TNT is strongly oxygen deficient. As such the pressure pulse depends upon the geometry, size, and reflections off obstructions. For this reason it is an extremely poor choice upon which to base Explosive Equivalence.



Relative Effectiveness
After Burn

How Good are our RE Values

In reviewing the literature many variations in RE 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 attributed the figure below to Chessman, that illustrates the degree of difficulty in determining a RE factor.

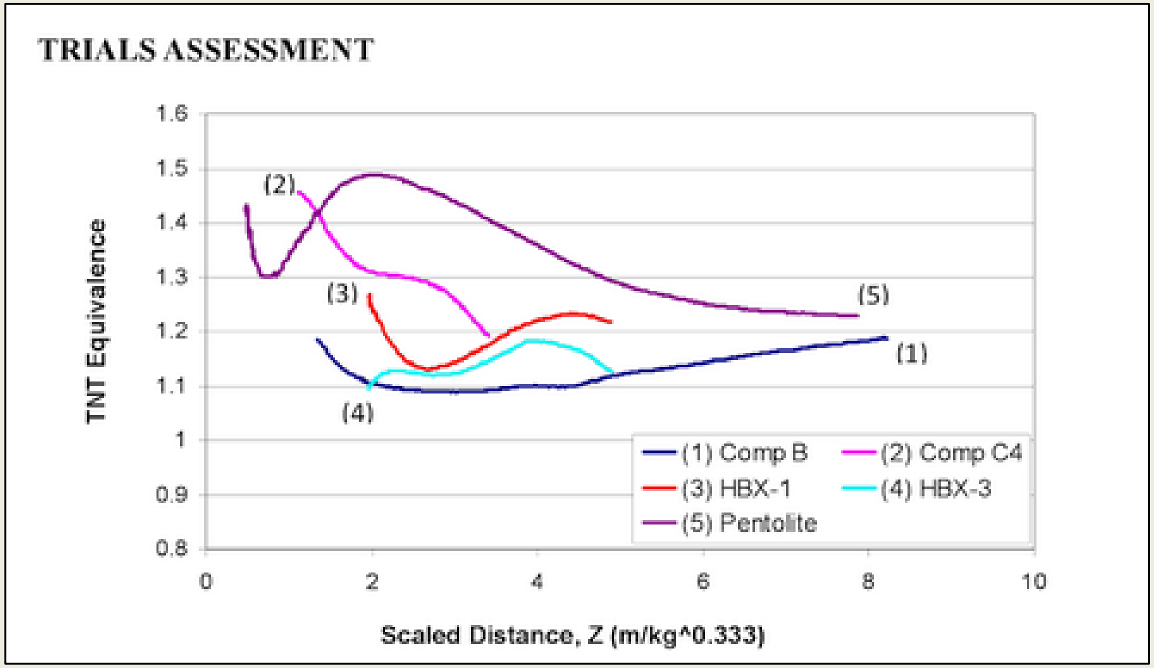


Relative Effectiveness Problems

Locking, Paul M. "The trouble with TNT equivalence." In *26th International Ballistics Symposium*, pp. 143-154. 2011.

How Good are our RE Values

Cooper showed that RE factors change with scaled distance,



Relative Effectiveness

Problems

Cooper, Paul W. *Comments on TNT equivalence*. No. SAND--94-1614C; CONF-940776--6. Sandia National Labs., Albuquerque, NM (United States), 1994.

How Good are our RE Values

and that the RE factors change differently for peak pressure and impulse.

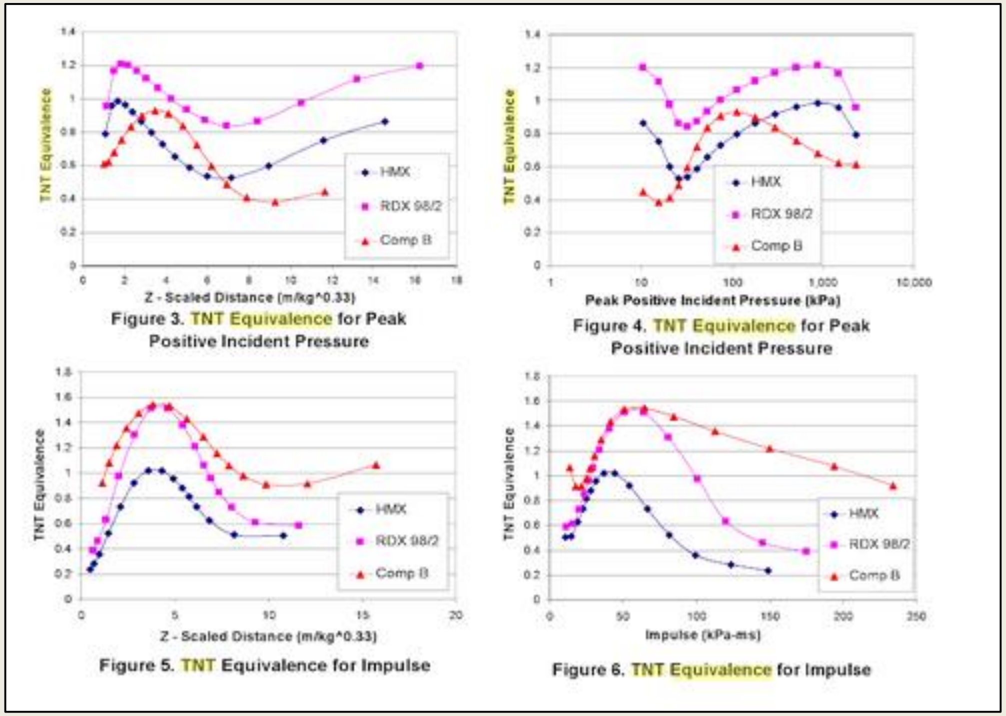


Figure 3. TNT Equivalence for Peak Positive Incident Pressure

Figure 4. TNT Equivalence for Peak Positive Incident Pressure

Figure 5. TNT Equivalence for Impulse

Figure 6. TNT Equivalence for Impulse

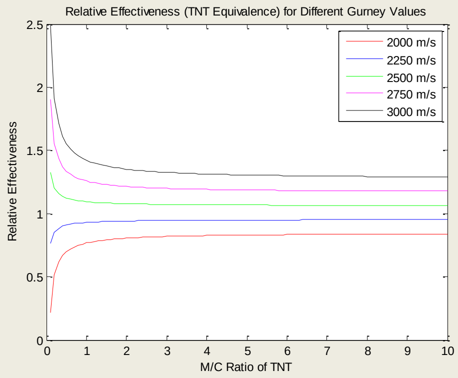
Relative Effectiveness

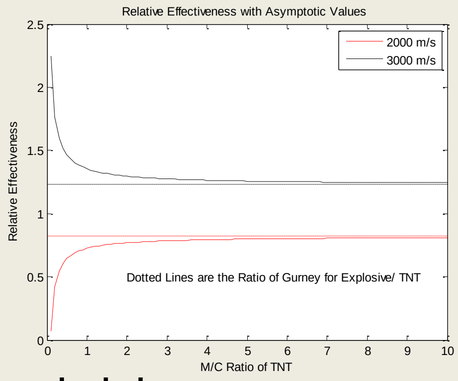
Problems

Cooper, Paul W. *Comments on TNT equivalence*. No. SAND--94-1614C; CONF-940776--6. Sandia National Labs., Albuquerque, NM (United States), 1994.

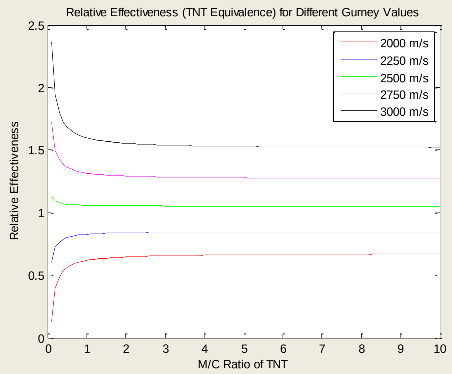
How Good are our RE Values

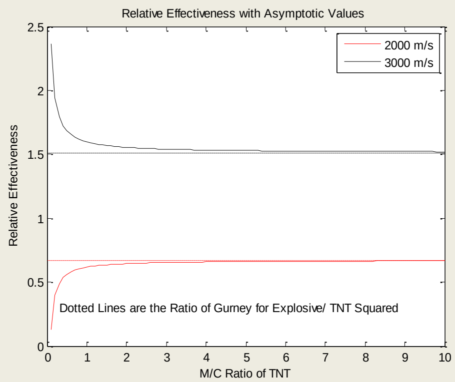
The Relative Equivalence Based upon the Gurney Values, solved iteratively from the equation developed earlier, is also non-linear.





Open Faced Sandwich





Symmetric Sandwich

Relative Effectiveness Problems

Other Problems

- Improved methods for handling burning propellants and pyrotechnics are needed.
- Based on the accident data and testing with propellants the structural break up is different. You get larger lethal structural debris that may travel further than from a detonation.

Pyrotechnics & Propellants

- Explosive equivalency is not a true 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 likelihood of an event

PYROTECHNICS & PROPELLANTS

- These systems vary in types of reaction and violence of reactions.
- 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 the hazards.
- Insensitive Munitions and Hazard Classification assignments can be used for hazard assessments but they do not address the significant hazards required for siting.
- Available References:
  - 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
  - Office of Management and Budget, Circular No. A-123, “Management's Responsibility for Enterprise Risk Management and Internal Control,” 15 July 2016.
  - **NFPA®** 495 Explosive Materials Code 2018 Edition

SUGGESTIONS

- Stop using the term Relative Effectiveness or Explosive Equivalence, instead use the Term Approximate Explosive Equivalence.
- Consider a different basis other than TNT, or just properties.
- Establish standard methods to measure.
- Improve the use of Computational Methods.

- For siting facilities one needs to consider the hazards and not attempt to normalize to a Hazard Classification. 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.

Relative Effectiveness
Suggestions

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.

The Equivalence calculations should be matched to the desired results. One size does not fit all. Safety site planning requires knowledgeable and experienced experts.

QUESTIONS