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26th International Ballistics Symposium

The Trouble with TNT Equivalence

Paper: 11770

Presented by

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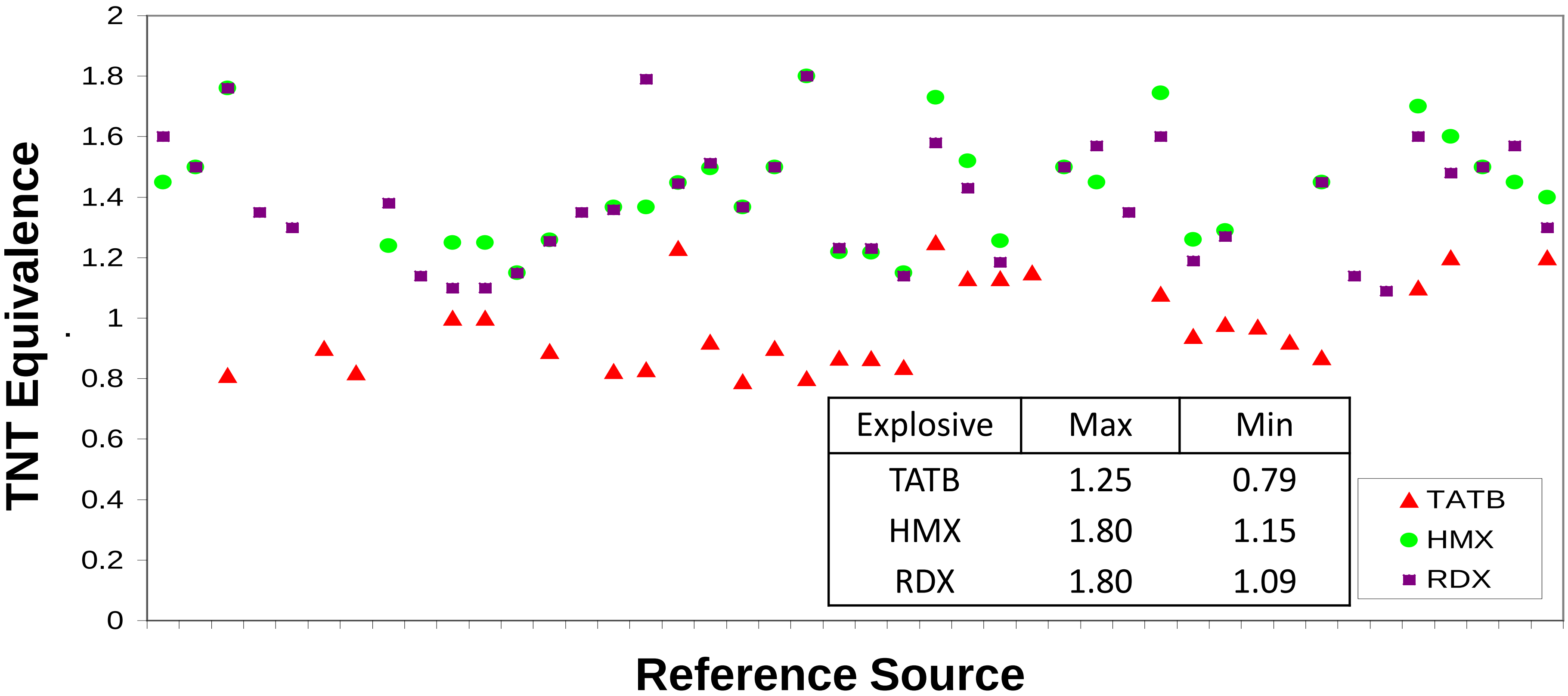
Outline

- The big problem with TNT Equivalence
  - Often used to compare explosives performance
  - Many models use TNT as the baseline explosive
  - 1 kg RDX = 1.6 kg TNT, so giving RDX an Equivalence of 1.6
  - 20% to 30% typical error, 50% has been found
- Scaling Laws
  - Scaled Distance, Scaled Impulse
- Trials techniques will not be discussed here -> see paper
- Theoretical Methods for TNT Equivalence
  - Secondary combustion / Aluminised explosives not covered
- Theoretical fit to trials data
  - Error Analysis
- Conclusions

The Problem

Figure 1. Variation in TNT equivalency of three high explosives TATB, HMX & RDX (from a number of different techniques and sources)



Explosive	Max	Min
TATB	1.25	0.79
HMX	1.80	1.15
RDX	1.80	1.09

(from Cheesman)

Scaling Laws

- Blast wave scaling laws are often called ‘Cube root scaling’
  - Hopkinson (1915) & Cranz (1926)

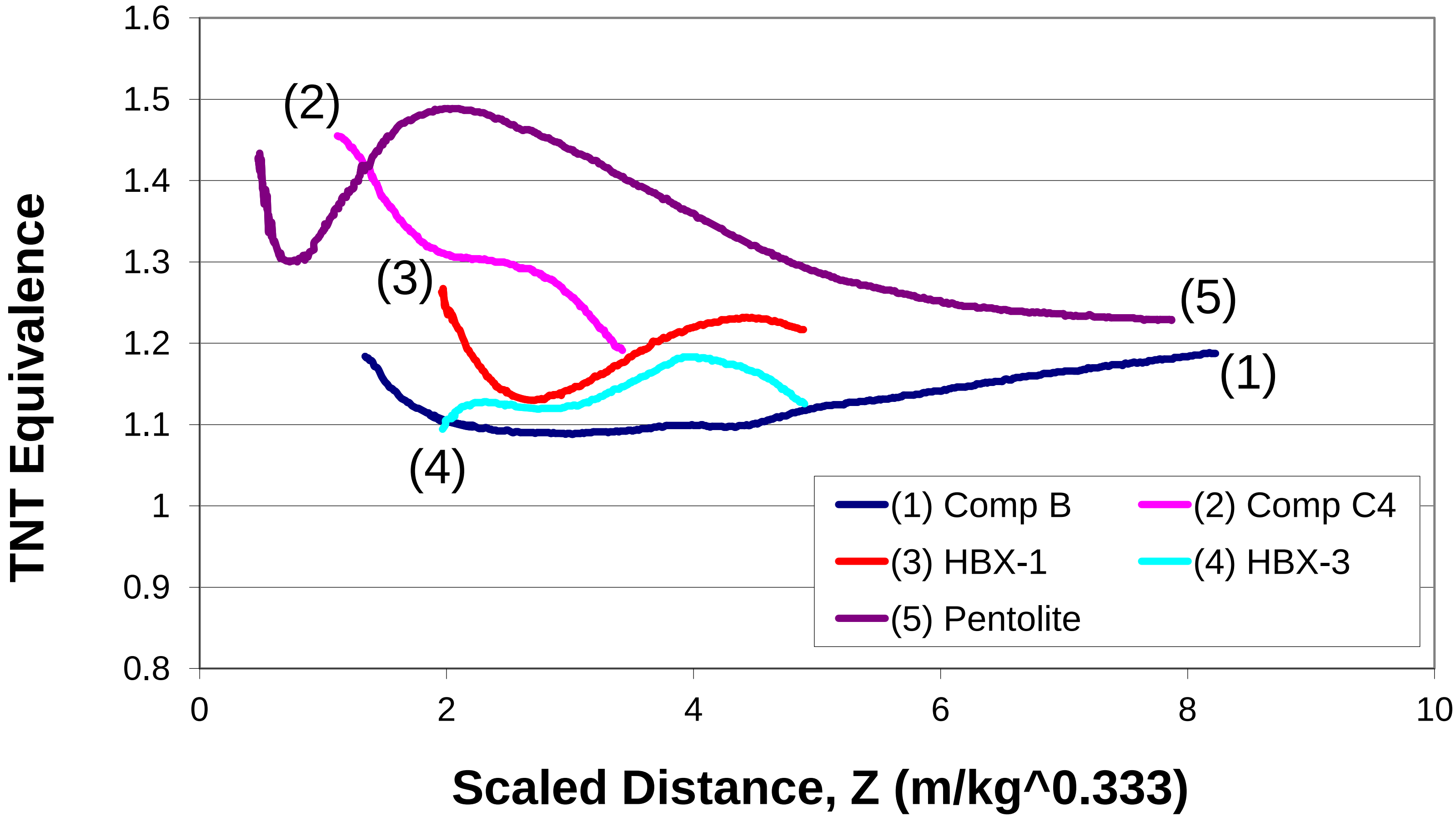
- Charge performance is a function of Scaled Distance (Z)

- Both peak overpressure & Scaled Impulse are directly related to Scaled Distance

Scaled Distance (Z) = Range / Charge mass ^ (1/3)

Scaled Impulse = Impulse / Charge mass ^ (1/3)

Figure 2. Variation of TNT Equivalence with Scaled Distance by Cooper



(from Air Blast Calculations and trials by Swisdak)

Figure 3. TNT Equivalence for Peak Positive Incident Pressure

(from UFC 3-340-02 data)

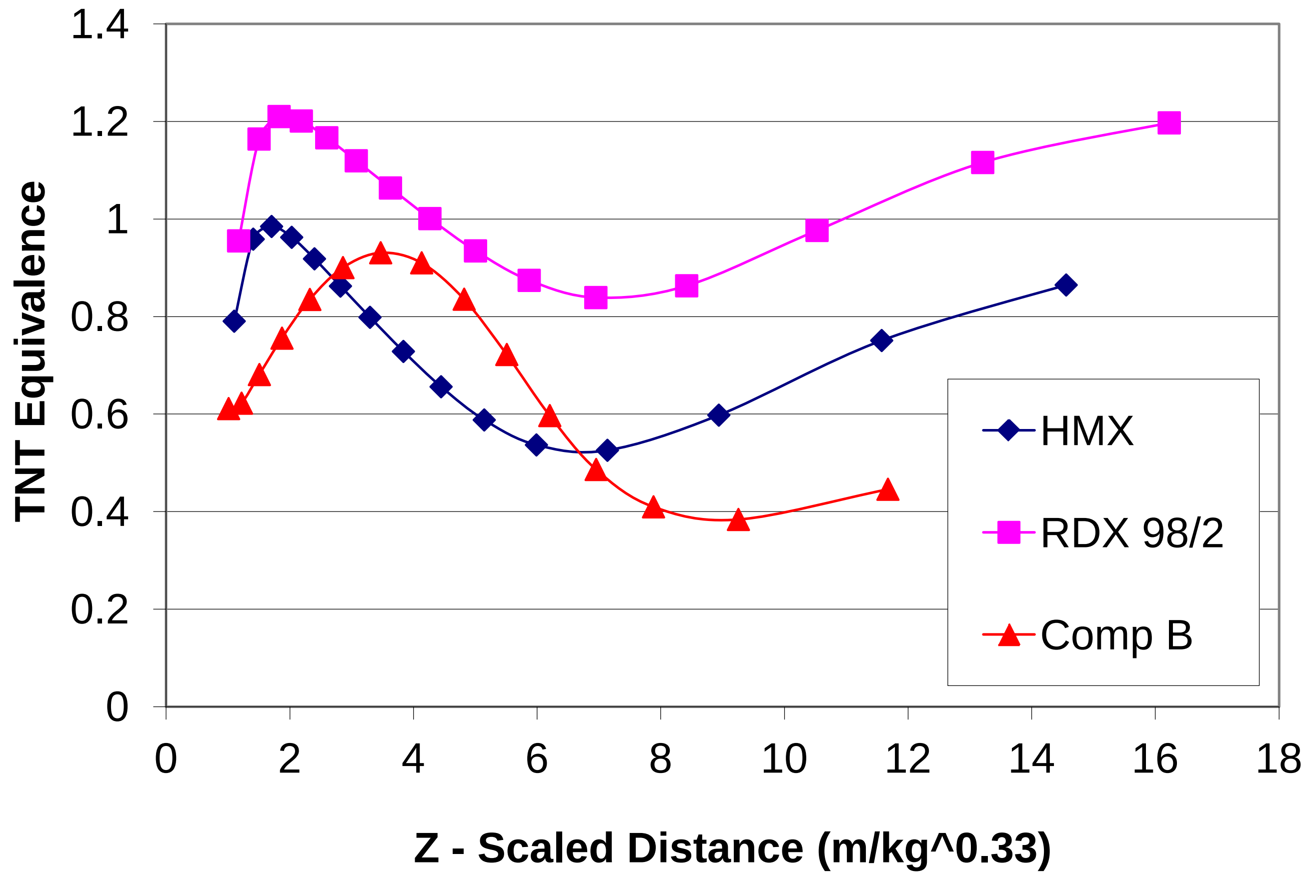


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Figure 4. TNT Equivalence for Peak Positive Incident Pressure

(from UFC 3-340-02 data)

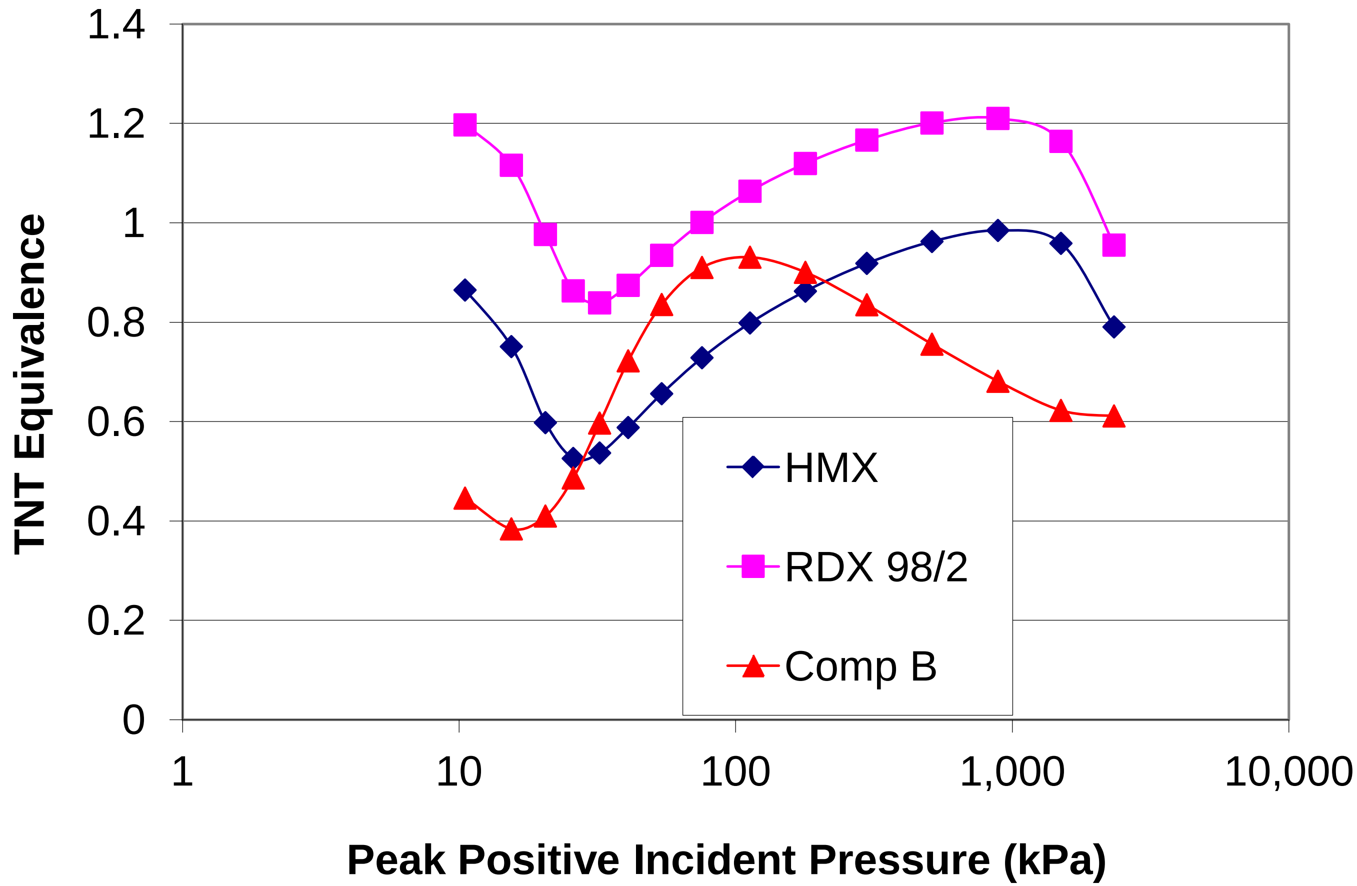

Figure 5. TNT Equivalence for Impulse

(from UFC 3-340-02 data)

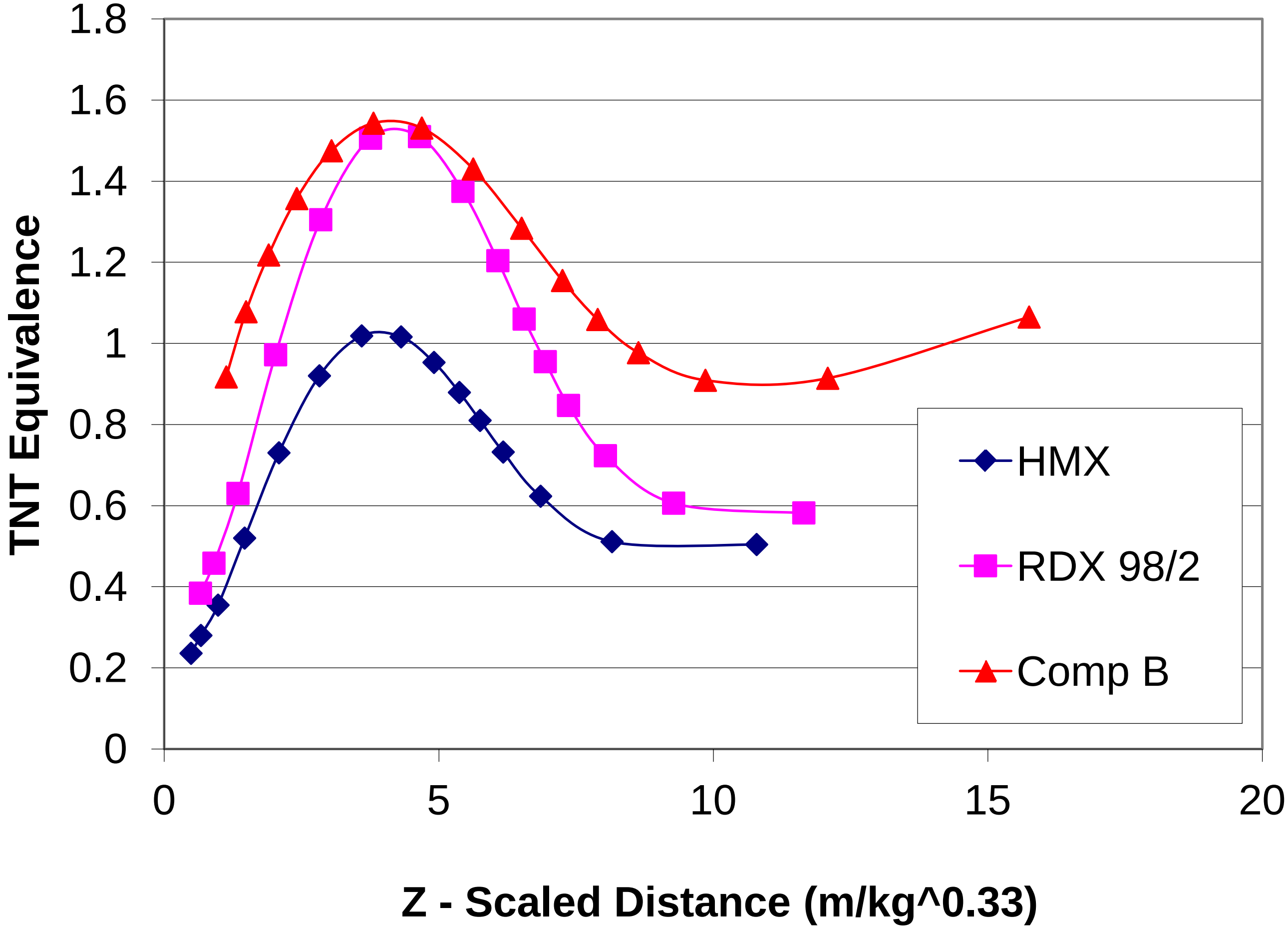

Figure 6. TNT Equivalence for Impulse

(from UFC 3-340-02 data)

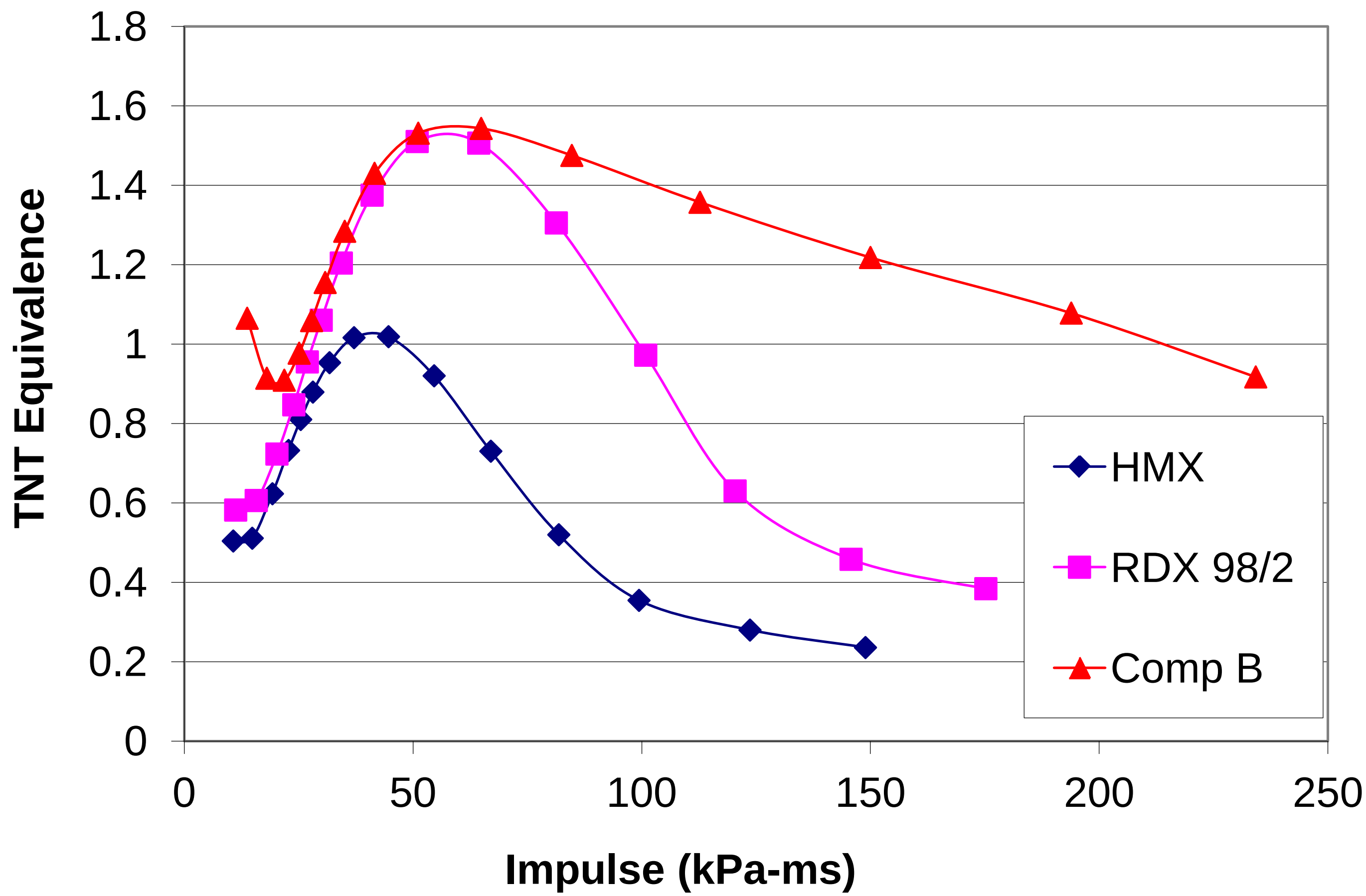

Table II. TNT Equivalence from UFC 3-340-02 Data

(from Figures 3 – 6)

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

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Theoretical Methods for TNT Equivalence (1 of 3)

- Berthelot Method (1892)
  - TNT Equivalent (%) = $840 \cdot \Delta n \cdot (-\Delta H_R^O) / Molwt_{EXP}{}^2$

    Where:

    Δn – Number of moles of gases / mol of explosive

    ΔH_R^O – Heat of Detonation (kJ/mol)

    $Molwt_{EXP}$ – Molecular weight of the Explosive (g/mol)

- Cooper Method (D^2)
  - TNT Equivalence = D^2_{EXP} / D^2_{TNT}

    Where:

    D – Detonation Velocity (m/s)

Theoretical Methods for TNT Equivalence (2 of 3)

- Hydrodynamic Work (E)

  - $E = \int_{P\,CJ}^{P\,AMB} P(V)_S \,.\, dV = 0.36075 \,.\, P_{CJ} / \rho_O \wedge 0.96$

  Where:

  P_{CJ} – Chapman-Jouguet (CJ) Detonation Pressure (Pa)

  ρ_O – Density of unreacted explosive (kg/m^3)

- Power Index (PI) – related to Explosive Power (EP) = $Q_{EXP} \,.\, V_{EXP} \,.\, R / (V_{MOL} \,.\, C)$
  - Power Index = $Q_{EXP} \,.\, V_{EXP} / Q_{TNT} \,.\, V_{TNT}$

  Where:

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

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

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

  V_{EXP} – Volume of gases at stp / Mass of explosive for comparison (m^3/kg)

  V_{MOL} = 22.4 – Molar volume of gas at stp (m^3/mol)

  V_{TNT} – Volume of gases at stp / Mass of TNT (m^3/kg)

Theoretical Methods for TNT Equivalence (3 of 3)

- Heat of Detonation (Q) – the TM / UFC Standard
  - TNT Equivalence (by Q) = Q_{EXP} / Q_{TNT}

    Where:

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

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

- Heat of Detonation (Q) – Updated method in paper
  - TNT Equivalence (by Q) = $Q_{EXP} / (Q_{TNT} (1 - d) + m . Q_{EXP})$

    Where:

    d – Line intercept = 0.76862

    m – Line gradient = 0.7341

Figure 7. TNT Equivalence Difference for Heat (Q)

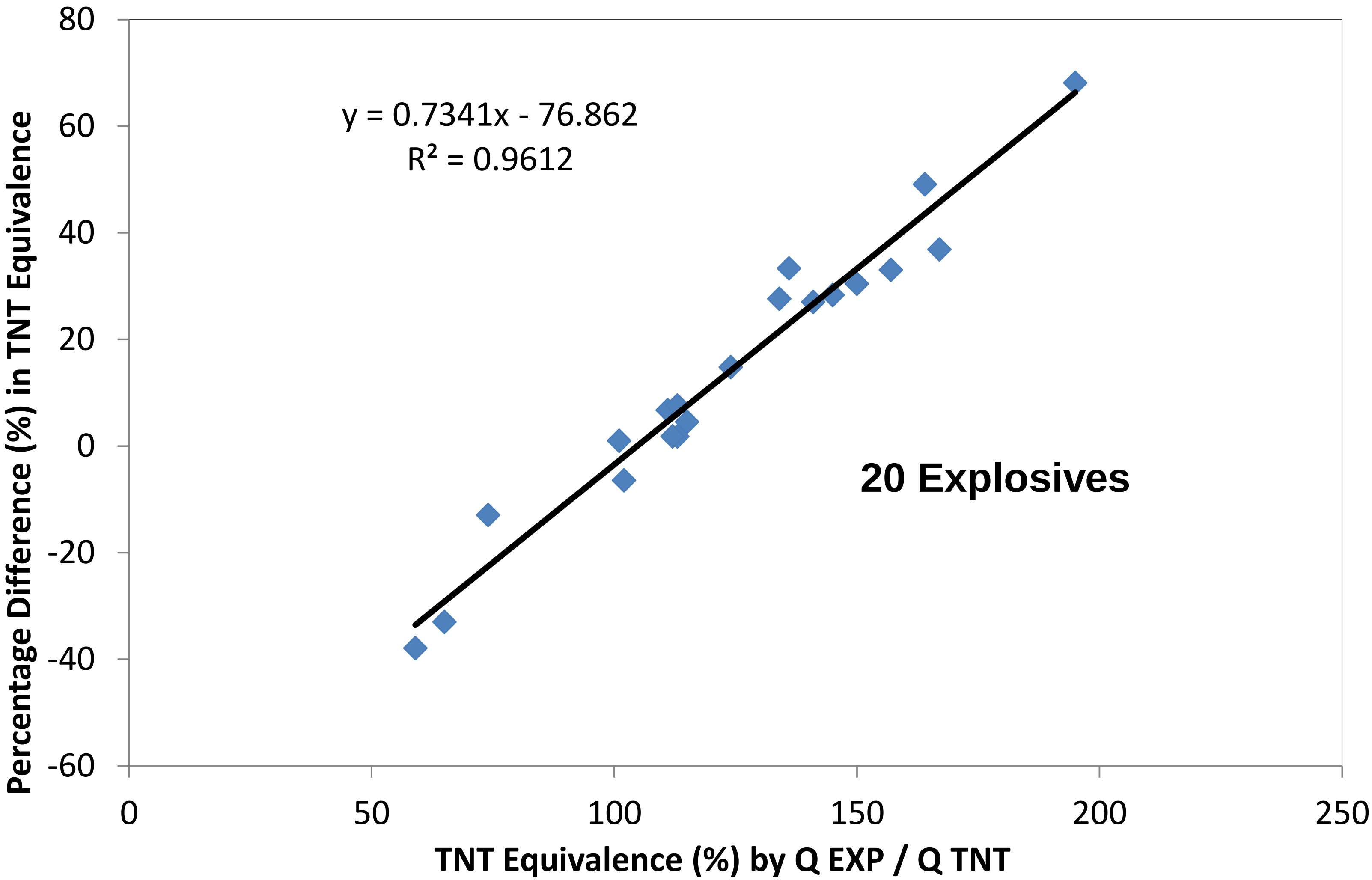

Figure 8. TNT Equivalence Difference for Heat (Q)

Line fit through origin

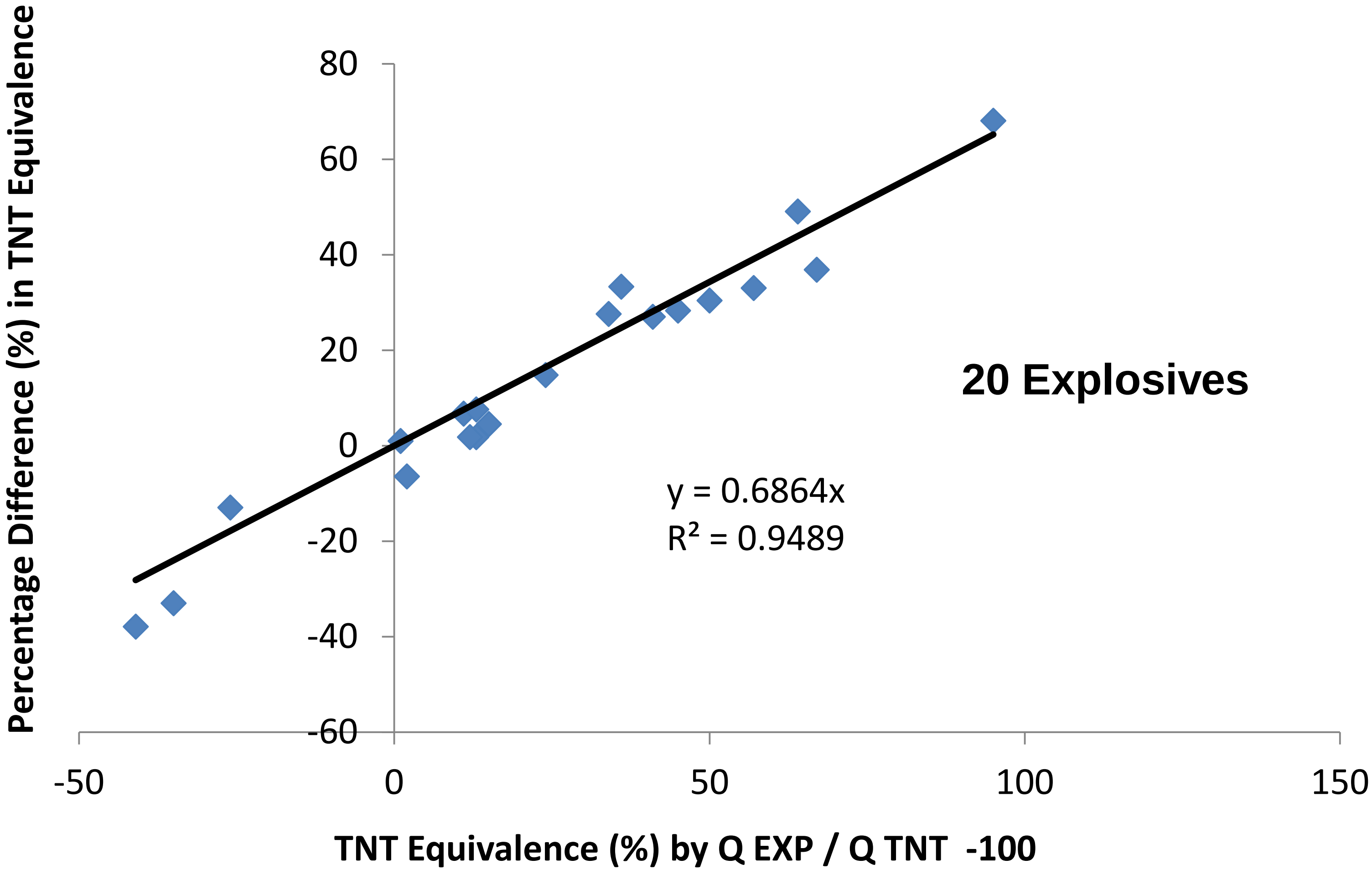

Table III. Some TNT Equivalence Comparisons by Percentage

Table III - has been updated and replaced by Table VI

Table IV. 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**

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Figure 9. TNT Equivalence Difference comparison for Work

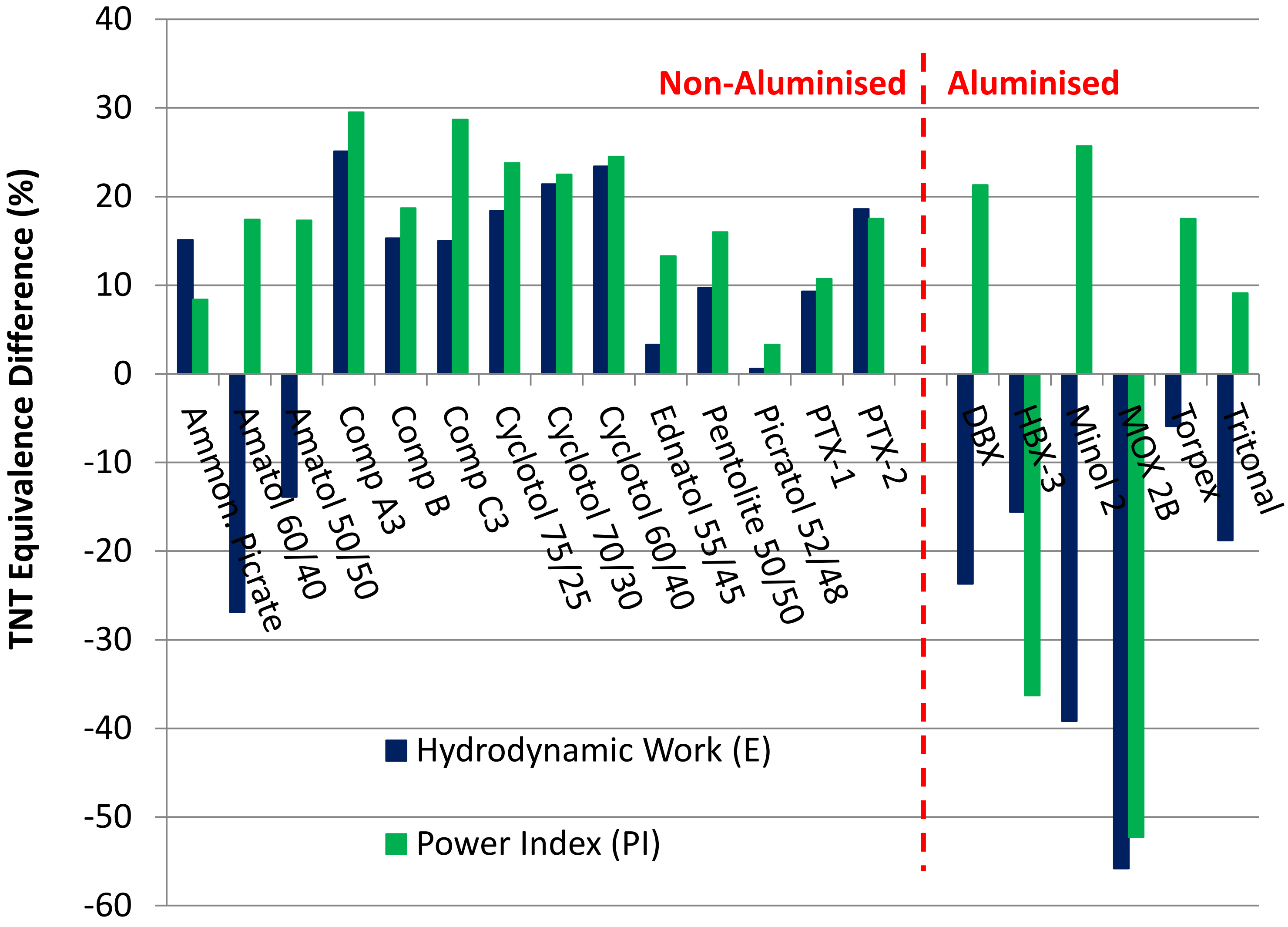

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Table V. Comparison of Heat TNT Equivalence Predictions

Explosive	TNT Equivalence (%)				
	Expt	Standard Calc from Heat (Q)	Difference, from Standard Q to Expt	Updated Calc from Heat (Q)	Difference, from Updated Q 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**

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Figure 10. TNT Equivalence Difference comparison for Heat

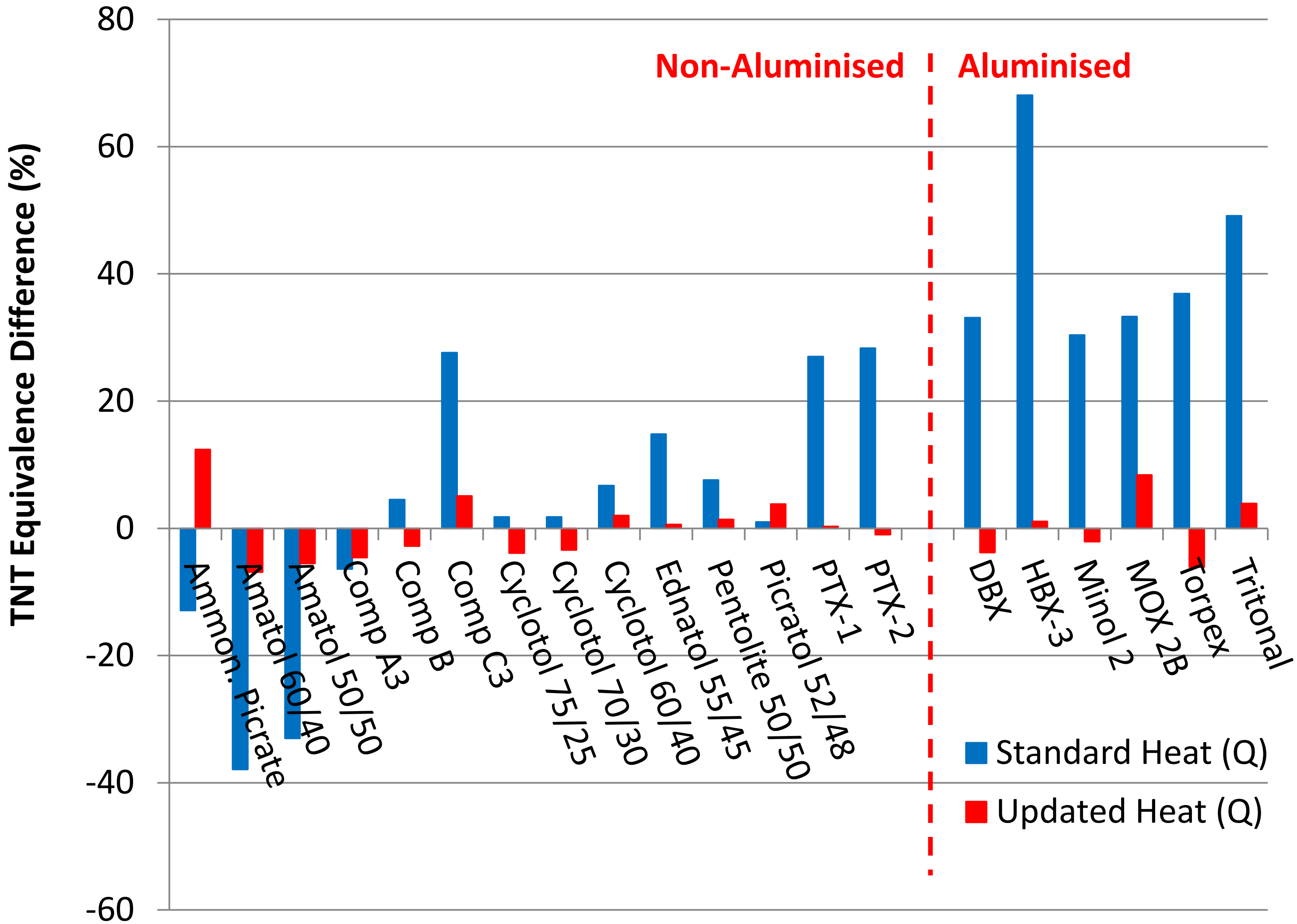

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Table VI. TNT Equivalence Comparisons by Percentage

Explosive	From Expt	Berthelot Method	Difference Bethelot from Expt (%)	D^2 Method	Difference D^2 from Expt (%)
Non-Aluminised					
Ammon. Picrate	85	110	**29.1**	109	**27.8**
Amatol 60/40	95	138	**45.6**	137	**43.8**
Amatol 50/50	97	136	**39.9**	128	**31.5**
Comp A-3	109	168	**54.5**	136	**24.5**
Comp B	110	156	**41.5**	132	**19.8**
Comp C-3	105	161	**53.5**	132	**26.1**
Cyclotol 75/25	111	164	**47.6**	139	**25.0**
Cyclotol 70/30	110	161	**46.1**	136	**23.4**
Cyclotol 60/40	104	154	**48.5**	130	**25.1**
Ednatol 55/45	108	99	**-7.9**	67	**-38.2**
Pentolite 50/50	105	145	**38.0**	119	**13.4**
Picratol 52/48	100	115	**14.5**	105	**4.5**
PTX-1	111	147	**32.0**	123	**10.8**
PTX-2	113	158	**40.1**	133	**17.4**
Aluminised					
DBX	118	171	**44.6**	115	**-2.7**
HBX-3	116	90	**-22.5**	86	**-26.0**
MINOL-2	115	171	**48.8**	115	**0.2**
MOX-2B	102	58	**-43.0**	126	**23.8**
Torpex	122	171	**40.1**	110	**-9.9**
Tritonal	110	143	**30.3**	85	**-22.5**
	Mean Absolute Difference		**38.4**		**20.8**

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Figure 11. TNT Equivalence Difference for Berthelot and Cooper (D^2)

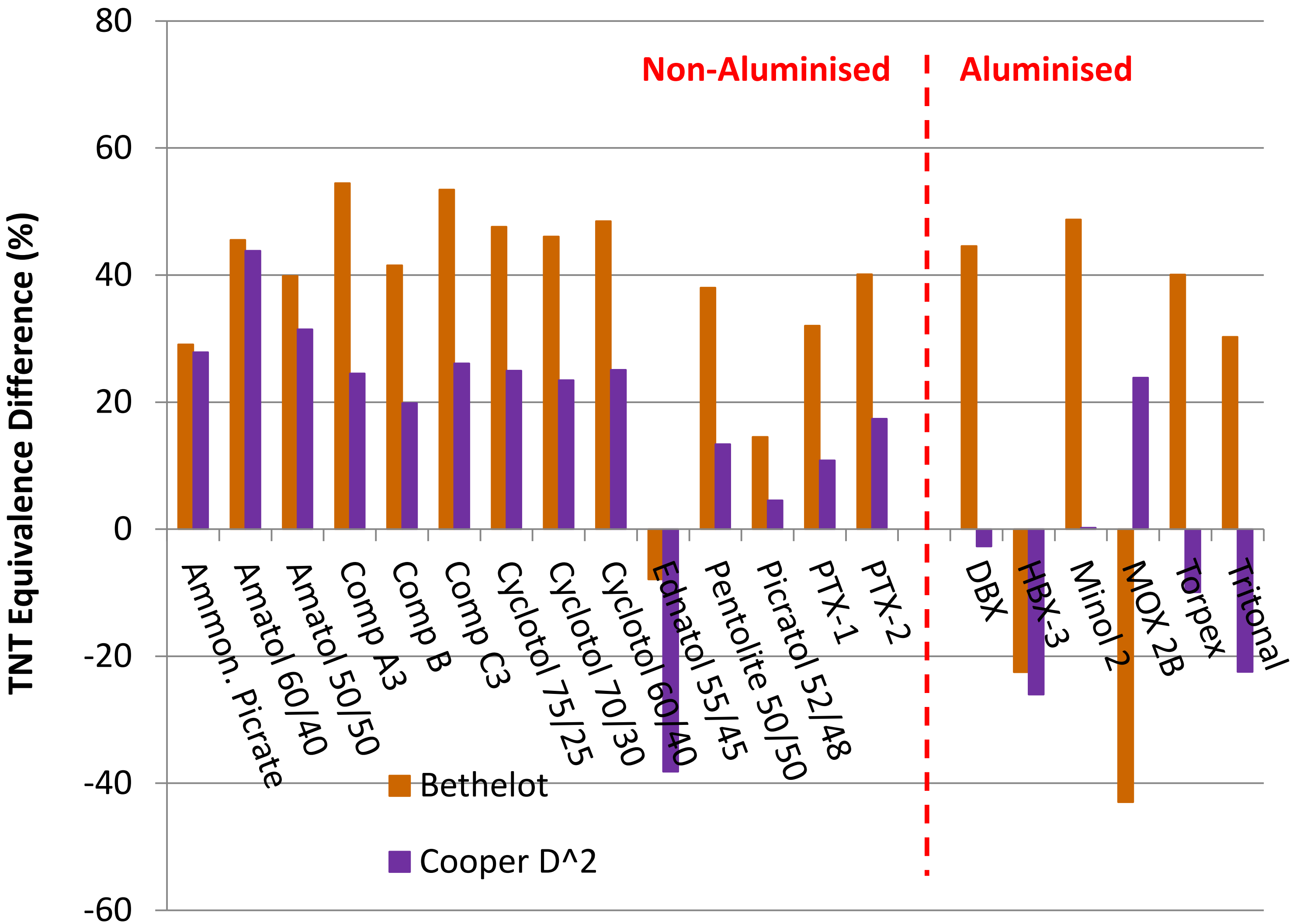

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Table VII. Error Level Analysis of Methods

TNT Equivalence Difference (%) across the Methods

Method	Mean Absolute Difference	Standard Deviation	Maximum Absolute Difference	Ratio of Absolute Difference to Standard Deviation
Berthelot	**38.4**	**26.3**	**54.5**	**2.1**
D^2 (Cooper)	**20.8**	**21.4**	**43.8**	**2.0**
Hydrodynamic Work Function (E)	**18.8**	**22.9**	**55.9**	**2.4**
Power Index (PI)	**20.7**	**20.5**	**52.3**	**2.6**
Standard Heat (Q)	**23.1**	**26.1**	**68.1**	**2.6**
Updated Heat (Q)	**4.0**	**5.0**	**12.4**	**2.5**
Updated Heat (Q) with fit through point (100,0)	18.4	23.4	55.8	2.4

Ratios of 2 - 3 are typical for a Normal Distribution from a small sample

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Conclusion

- A big problem with TNT Equivalence, typically 20% - 30% error
- Scaling Laws – they don't scale for Equivalence
- Five Theories have been detailed
- Theories compared to limited (open) trials data
- Power Index (PI) is the most reliable to date (21%)
  - Accounts for both Heat produced and Work available
- Recommended Standard Heat of Detonation (Q) is poor (26%)
  - But can be adjusted (Q update) to give the best of all fits (5%)

Any Questions ?

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