The Velocity of Detonation of High Explosives.

by Dave Everest.

Abstract: The Velocities of Detonation of High Explosives depend on a number of factors. These factors are examined for a number of High Explosives.

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Suggestions, information, constructive criticism and corrections are welcome. Please e-mail them to me at: davidreverest@ntlworld.com

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Amendment List

Amendment number	Affecting paragraph numbers / page numbers	Date of amendment
Draft issue		
1	Insertion of CAS# in table 3.10.	28 Apr2008
2	Addition of Abstract on Title page	11 Sept 2008

1. **Introduction**

1.1.1 When a High Explosive detonates, a shock wave is projected through the explosive, compressing the explosive material and causing a chemical reaction, which liberates gas and heat. The shock wave is then maintained by the chemical energy being liberated within the reaction zone, just behind the shock front. During the very short reaction time, typically one tenth of a millisecond, the temperature of the gaseous products of the reaction can reach 5000 K, the volume of the gases produced can be typically 80 litres per hundred grams of explosive (at Normal Temperatures and Pressures) and the pressure can reach 1500 MPa (about 100 tons/square inch). Detonation sets up exceptionally stable and steady conditions and each High Explosive has a characteristic velocity, termed the Velocity of Detonation. This velocity varies from explosive to explosive, and is typically between 3000 and 8000 metres per second.

1.1.2. The Velocity of Detonation of a High Explosive may be measured by a variety of techniques, the best of which use photographic methods, and these are accurate to within about ± 1%.

1.2. **Definitions used in this paper**.

1.2.1 **Stable detonation.** A stable detonation is defined as one that proceeds as a shock wave at a steady velocity over an appreciable length of explosive (several charge diameters in length) and that the detonation wave is maintained by the chemical energy liberated in the shock front.

1.2.2 **The Limiting parameters.**

1.2.2.1 The **Limiting Velocity of Detonation** of a given explosive is the highest attainable velocity that can be established in a stable detonation.

This corresponds to the theoretical Velocity of Detonation.

1.2.2.2 The **Limiting Diameter** of an explosive charge is the minimum diameter of the chargethat gives rise to the limiting Velocity of Detonation.

1.2.3. **<u>The Boundary parameters</u>**.

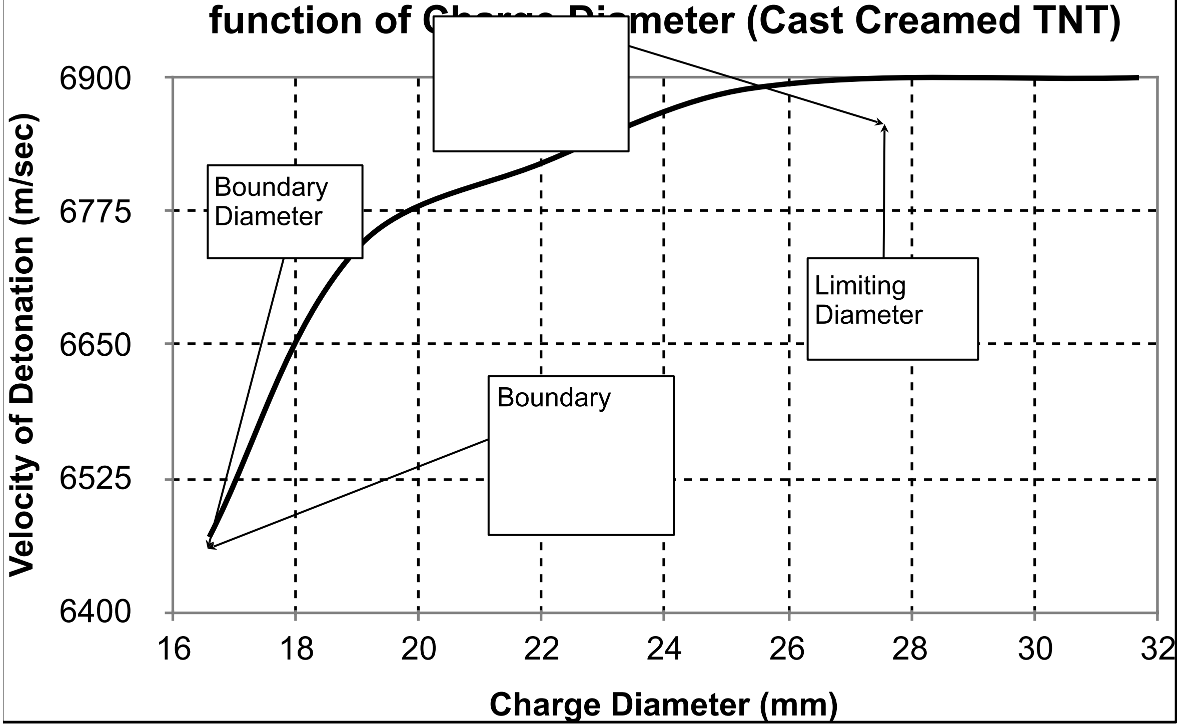
The Boundary parameters are not as sharply defined as the Limiting parameters.

1.2.3.1 The **Boundary Diameter** of an explosive charge is the smallest diameter of the charge in which detonation can be sustained.

1.2.3.2 The **Boundary Velocity of Detonation** is the velocity achieved in a charge with the boundary diameter.

1.2.4. These Limiting and Boundary parameters may be seen in Figure 1, below, where the Limiting Velocity of Detonation is 6900 m/sec, at the Limiting charge diameter of 27.5 mm. The Boundary Velocity of Detonation is 6470 m/sec at a Boundary diameter of 16.6 mm.

Figure 1. Graph showing the Boundary and Limiting Parameters for the Velocity of Detonation as a function of Charge Diameter (Cast Creamed TNT)



2. Factors that have an effect on the Velocity of Detonation of a given High Explosive.

2.1 The purity of the explosive.
2.2 The density of the explosive.
2.3 The diameter of the explosive charge.
2.4 The degree of confinement of the explosive charge.
2.5 The addition of compounds or elements to the explosive.
2.6 The aging of the explosive (particularly for gelatinous explosives).
2.7 The strength of the initiating source.
2.8 The "grist" size.
2.9 The statistical consistency within a batch of explosive charges.
2.10 The oxygen balance of the explosive.

3. The effects of the factors on the Velocity of Detonation

3.1 The purity of the explosive.

3.1.1. TNT/DNT. An example of the effects of the impurities of creamed cast TNT on the limiting Velocity of Detonation is shown in Table 3.1 and Figure 3.1 (Creamed TNT is prepared by agitating molten TNT to form a slurry. Ten percent by weight of powdered TNT is then added, while still agitating. The thickened melt, which is a cream color, is then poured as a casting.) The impurity in this case is the presence of incompletely nitrated TNT (i.e. dinitrotoluene)

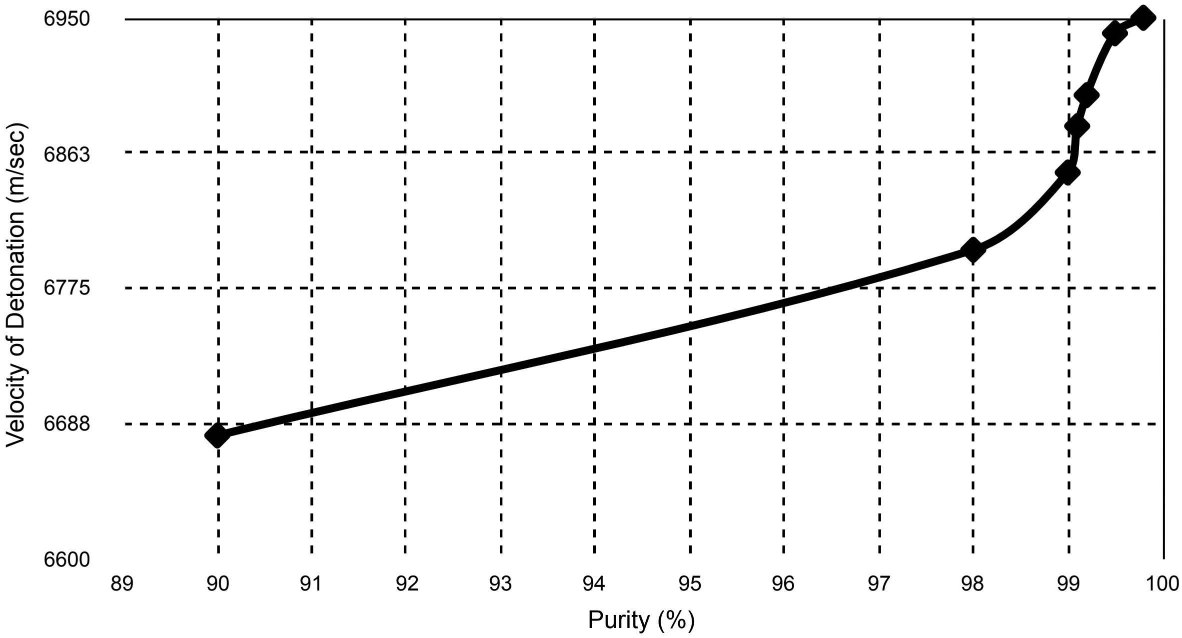
Table 3.1.1.The effects of impurities on the limiting Velocity of Detonation of creamed cast TNT

Purity (%)	90	90	98	99	99.1	99.2	99.5	99.8
Mean Velocity of Detonation (m/s)	6680	6680	6800	6850	6880	6900	6940	6950
Number of experiments	6	6	6	10	24	18	6	6
Range (m/s)	77	127	47	94	62	35	42	59
Standard Deviation (m/s)	34	48	20	27	17	12	16	22
Density (grams/cc)	1.51	1.57	1.61	1.62	1.62	1.62	1.62	1.62

3.1.2. Hydrazoic Acid/Water

The effects on the Velocity of Propagation with increasing concentration of

Figure 3.1 Mean Limiting Velocity of Detonation of Creamed Cast TNT as a function of Purity



hydrazoic acid (HN_3) in water is shown in Table 3.1.2

Table 3.1.2. Velocity of Propagation of Explosion in Hydrazoic Acid Solutions.

Concentration of HN_3 (grams/100grams solution)	Normality of solution	Propagation Velocity (m/sec)
80	22.1	8500
70	18.0	7300
67	17.2	7100
65	16.8	1700
61	15.7	630
60	15.4	384
54	13.8	233
48	12.2	40
38	9.8	2.5
30	7.3	1.0
16.7	4.0	0.14

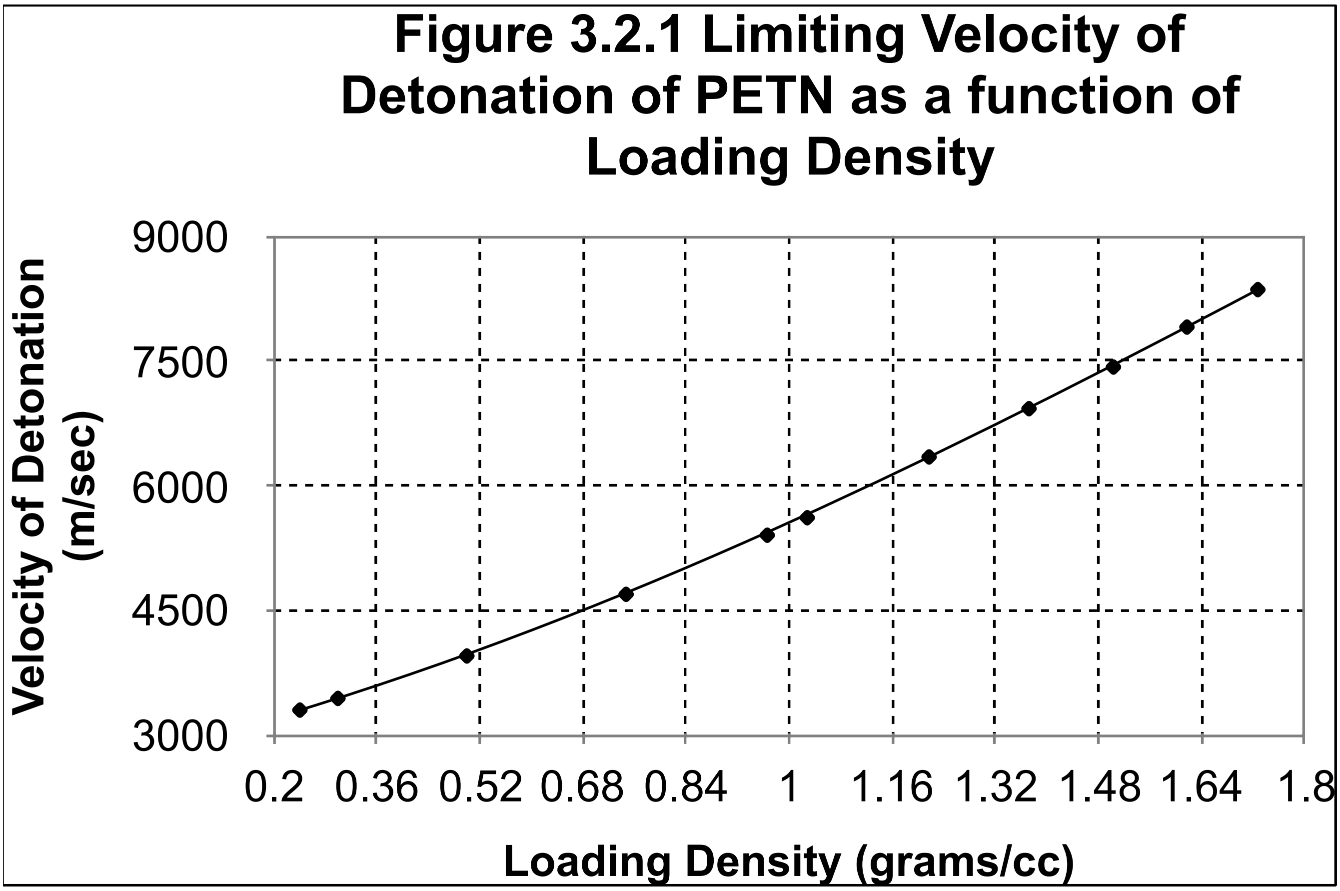
3.2 The density of the explosive.

3.2.1 The loading density of military explosives falls normally within the range of 0.3 to 2.0 grams/cc (with the exception of heavy metal salts such as lead azide and mercury fulminate).

An example of the limiting Velocity of Detonation of PETN with increasing density is shown in Table 3.2.1 and Figure 3.2.1

Table 3.2.1 The effects of Density on the Limiting Velocity of Detonation of PETN

Density (gram/cc)	0.241	0.300	0.500	0.747	0.966	1.028	1.217	1.372	1.503	1.617	1.727
Velocity of Detonation (m/sec)	3310	3450	3960	4700	5410	5620	6350	6930	7430	7910	8360



3.2.2.1. The relationship between the Limiting Velocity of Detonation and Density as shown in Figure 3.2.1 above is approximately linear over a range of densities. An estimate of the change of Limiting Velocity of Detonation with variation of density may be made from the following formula:

$$VofD_2 = VofD_1 + K(\rho_2 - \rho_1) \quad \text{.....................................Equation 1}$$

Where Vof D = Limiting Velocity of Detonation (in m/sec)

ρ = Explosive density (grams/cc)

K = a constant characteristic for a given explosive

subscript$_1$= values given in Table 3.2.2 below

subscript $_2$ = required value

Table 3.2.2 Limiting Velocity of Detonation and K values.

Explosive name	Density, ρ_1 (grams/cc)	Limiting Velocity of Detonation, $VofD_1$ (m/sec)	Value of the characteristic constant K
2.4.6 - TNT	1.61	6950	3100
Grade I TNT	1.61	6900	3100
Tetryl (CE)	1.50	7250	3220
Picric Acid	1.71	7260	3050
PETN	1.51	7520	3980
RDX	1.61	8240	3600
Fivonite	1.58	7250	3400
Sixolite	1.40	7010	3350
DINA	1.50	7700	3000
EDNA	1.47	7470	3280
CE/TNT (30/70)	1.62	7030	3400
CE/TNT (40/60)	1.62	7130	3450
Pentolite	1.68	7520	3100
RDX/TNT (60/40)	1.68	7800	3100
TNT/Al (80/20)	1.76	6750	3870
Torpex	1.82	7500	3600

3.2.2.2 K values for other explosives

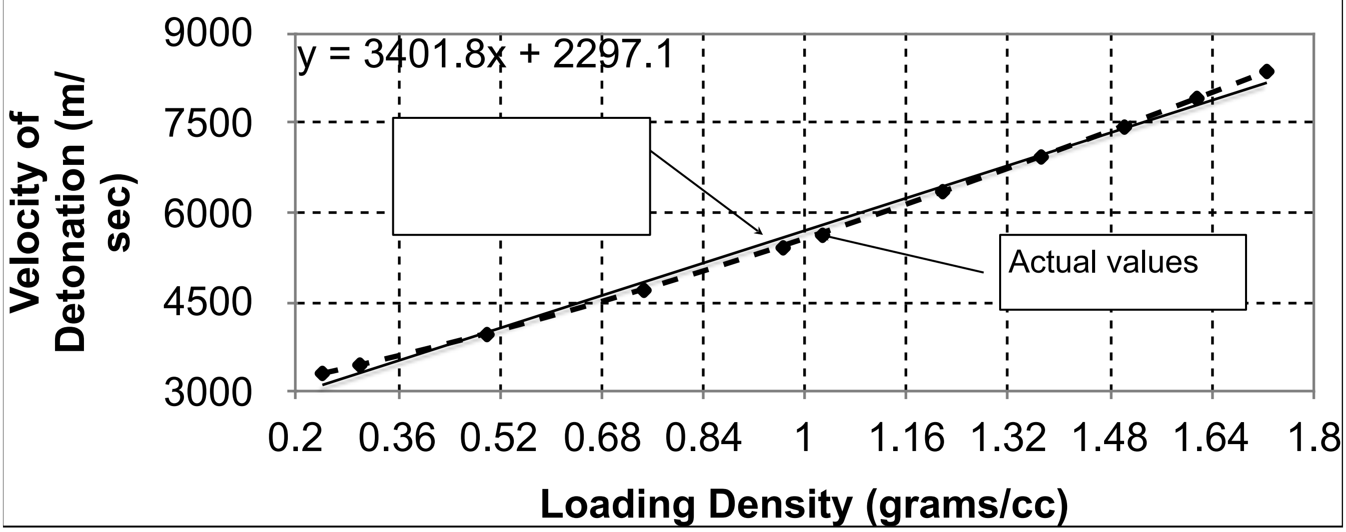
With the exception of RDX and PETN, using a K value of 3210 would introduce little error, independently of the chemical composition.

Figure 3.2.2 is reproduced below with the original values (shown dashed) from Figure 3.2.1, together with the linear relationship from Equation 1 above:

$$\text{Vof } D_2 = \text{Vof } D_1 + K(\rho_2 - \rho_1)$$

For PETN, K = 3980 and this becomes: $\text{Vof } D_2 = 7520 + 3980(\rho_2 - 1.51)$

Figure 3.2.2 Limiting Velocity of Detonation of PETN as a function of Loading Density together with linear trendline.

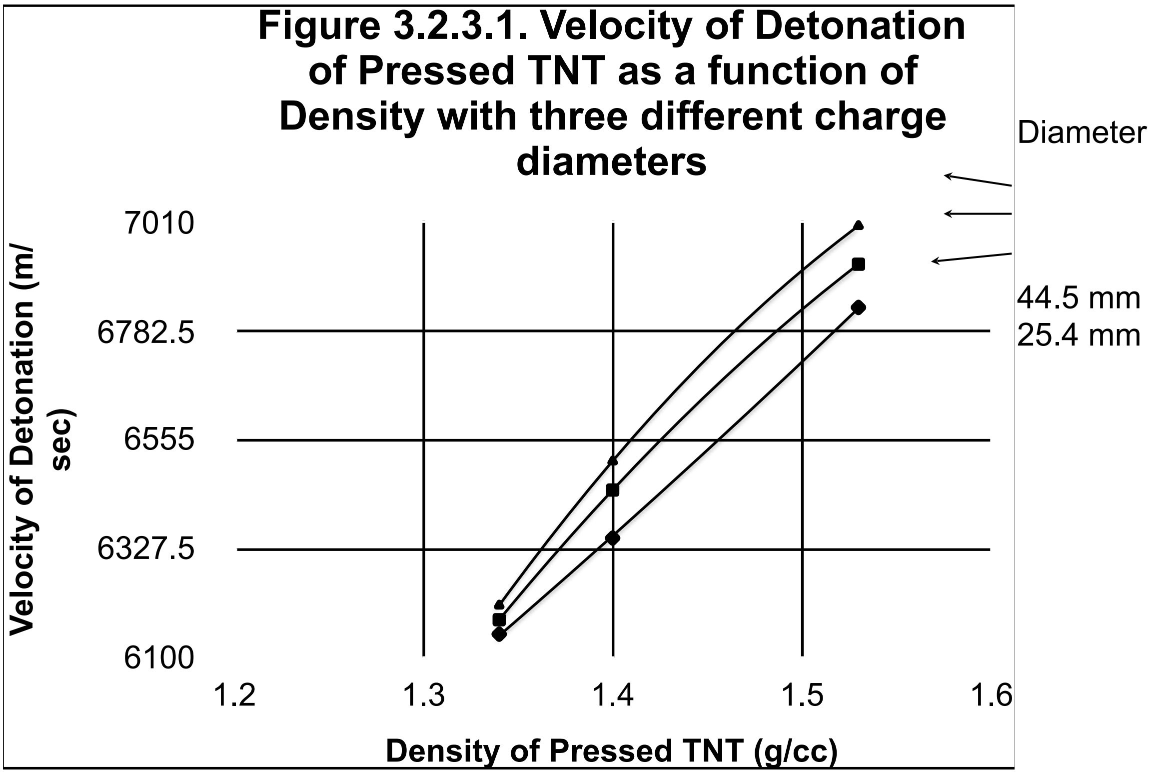


3.2.3. The Velocity of Detonation of Pressed TNT

Table 3.2.3.1. shows the Velocities of Detonation of TNT pressed to different densities. The charge diameters were 19, 25.4 and 44.5 mm.

Table 3.2.3.1.Velocity of Detonation of Pressed TNT

Density of Pressed TNT (grams/cc)	Velocity of Detonation (m/sec) for 19 mm charge diameter	Velocity of Detonation (m/sec) for 25.4 mm charge diameter	Velocity of Detonation (m/sec) for 44.5 mm charge diameter
1.34	6150	6180	6210
1.40	6350	6450	6510
1.53	6830	6920	7000



3.3 <u>The diameter of the explosive charge.</u>

In an explosive charge without any confinement, then as the diameter of the charge is increased, the Velocity of Detonation also increases, asymptotically, due to decreasing lateral losses.

3.3.1. Table 3.3.1. shows the Velocities of Detonation of TNT of charge diameters from 12.6 to 31.7 mm.

<u>Table 3.3.1 The effects of Charge Diameter (six charges at each diameter) on the Velocity of Detonation of creamed cast TNT</u>

Diameter (mm)	12.6	16.6	19.0	22.0	25.4	31.7
Density (gram/cc)	No detonation	1.605	1.610	1.615	1.615	1.620
Mean Velocity of Detonation (m/s)	No detonation	6470	6740	6820	6890	6900
Range (m/s)	No detonation	116	35	53	30	35
Standard Deviation (m/s)	No detonation	42	12	22	11	14

3.3.2. <u>Velocity of Detonation of Pressed TNT</u>

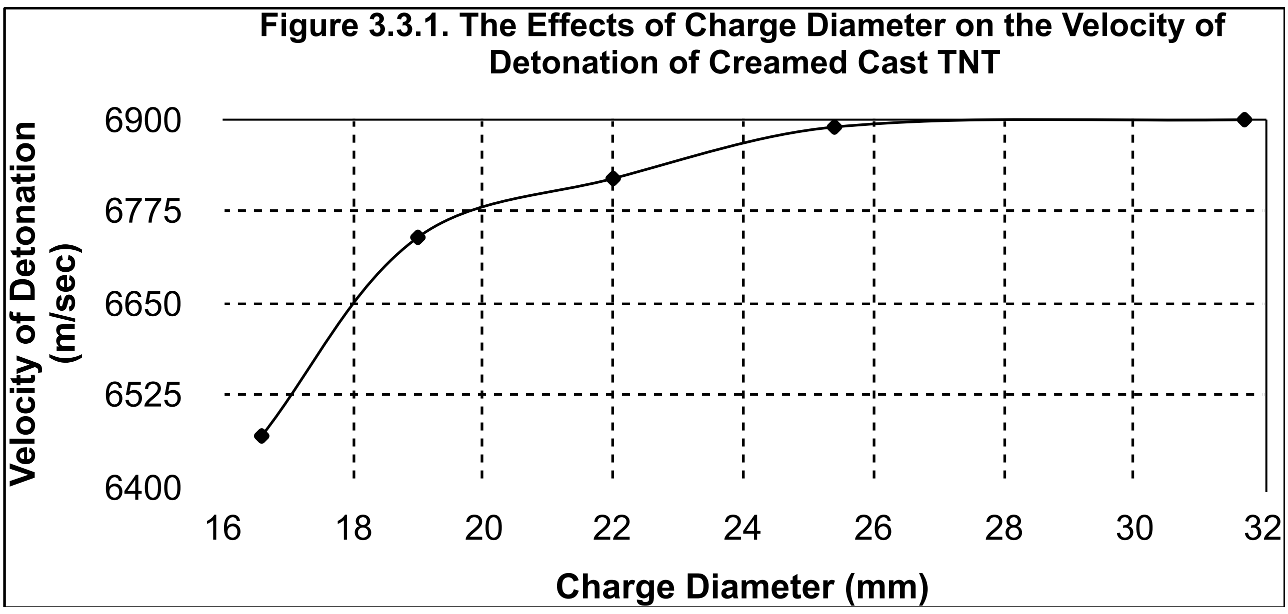


Table 3.3.2. shows the Velocities of Detonation of TNT of charge diameters 19, 25.4 and 44.5 mm. Each charge was pressed to three different densities.

Table 3.3.2 Velocity of Detonation as a function of Charge Diameter.

Charge Diameter (mm)	Velocity of Detonation (m/sec) for Density of 1.34 grams/cc	Velocity of Detonation (m/sec) for Density of 1.40 grams/cc	Velocity of Detonation (m/sec) for Density of 1.53 grams/cc
19	6150	6350	6830
25.4	6180	6450	6920
44.5	6210	6510	7000

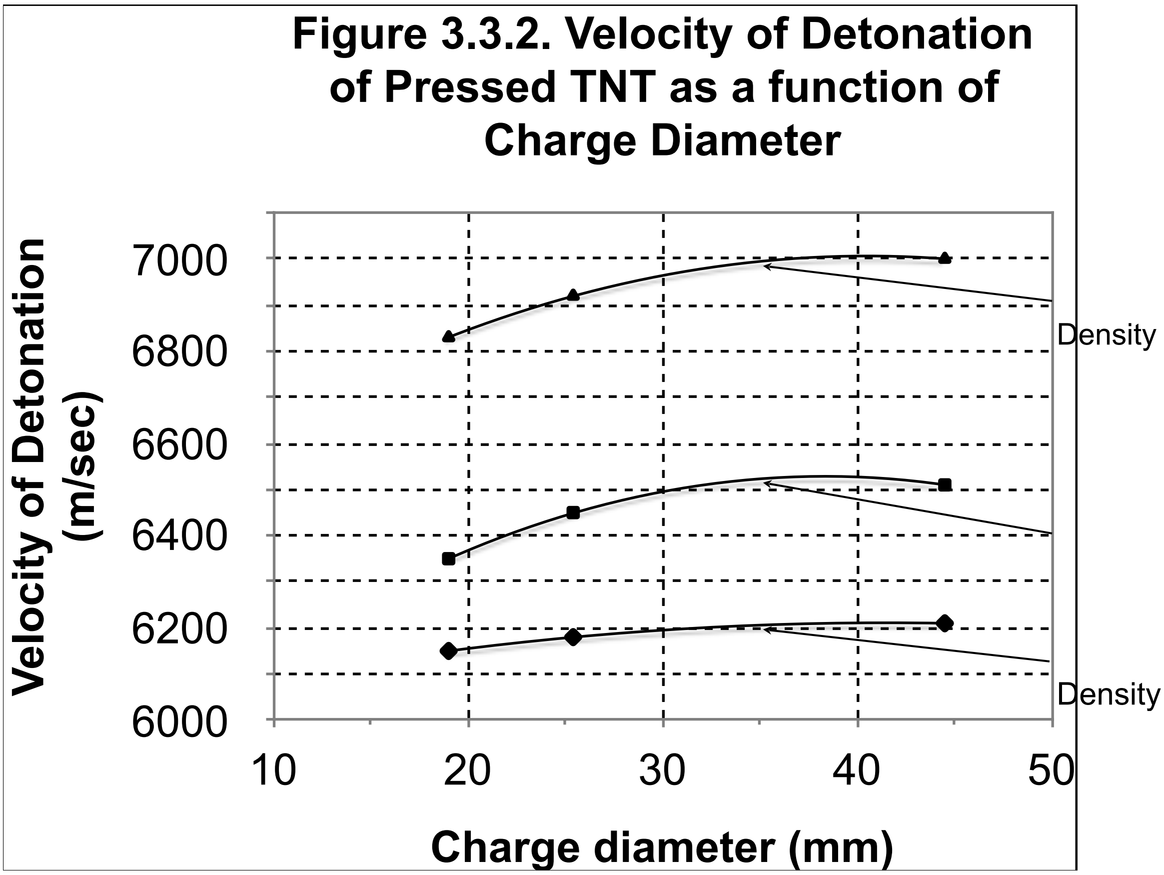


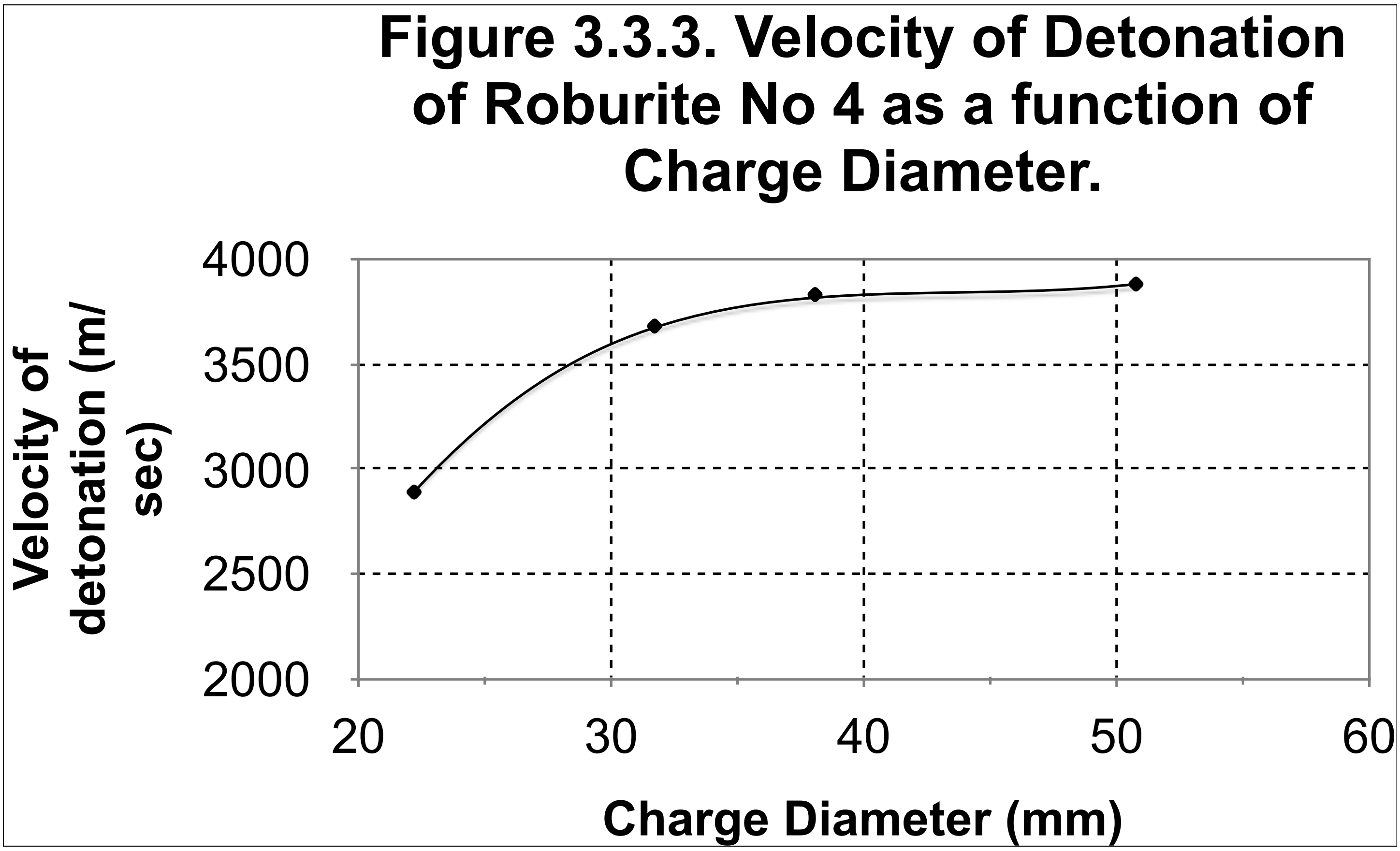
Figure 3.3.2. Velocity of Detonation of Pressed TNT as a function of Charge Diameter

3.3.3. <u>Velocity of Detonation of Roburite No 4.</u>

Table 3.3.3. shows the Velocities of Detonation of Roburite No 4 with 0.875, 1.25, 1.5 and 2 inch Charge Diameters.
Roburite No 4 consists of TNT/Ammonium Nitrate/Salt (16/60/24)

Table 3.3.3. Velocity of Detonation of Roburite No 4 as a function of Charge Diameter

Diameter (mm)	22.23	31.75	38.1	50.8
Velocity of detonation (m/sec)	2890	3680	3830	3880



3.3.4. Velocity of Detonation of Amatol.

Table 3.3.4. shows the Velocities of Detonation of Amatols with 0.75, 1.0 and 1.25 inch Charge Diameters. The loading density varied from 1.66 grams/cc (70/30 Amatol) to 1.55 grams/cc (0/100 Amatol).

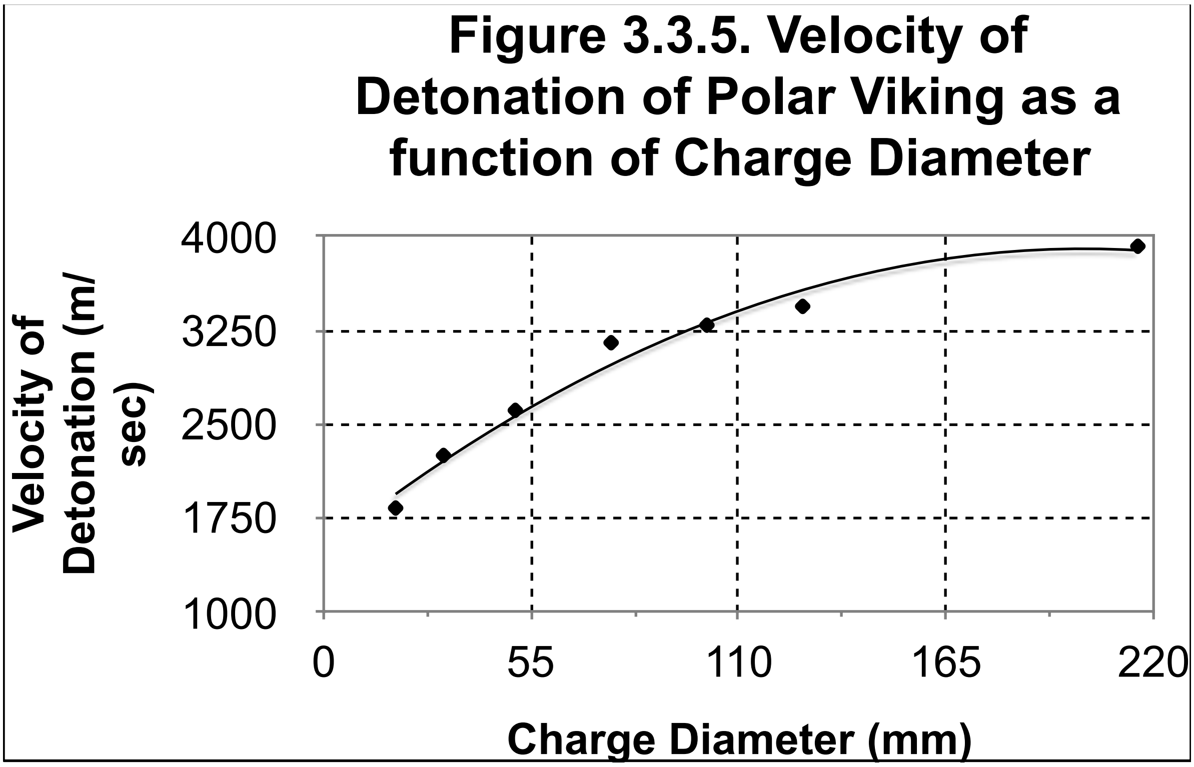
Table 3.3.4. Velocity of Detonation of Amatols

Composition AN/TNT (%)	Velocity of Detonation (m/sec) for 19 mm diameter	Velocity of Detonation (m/sec) for 25.4mm diameter	Velocity of Detonation (m/sec) for 44.5mm diameter
70/30	-	5510	5720
60/40	5780	6020	6120
50/50	6100	6270	6350
40/60	6440	6470	6600
30/70	6570	6700	6720
20/80	6690	6810	6880
10/90	6790	6870	6960
0/100	6830	6920	7130

3.3.5. <u>Velocity of Detonation of Polar Viking.</u>
Table 3.3.5. shows the Velocities of Detonation of Polar Viking with 0.75, 1.25, 2.0, 3.0, 4.0, 5.0 and 8.5 inch Charge Diameters at a loading density of 0.98 grams/cc. Polar Viking has the composition NG/Nitroglycol/Wood cellulose/Ammonium Nitrate/Salt (8.4/2.1/8.8/70.7/10.0).

<u>Table 3.3.5. Velocity of Detonation of Polar Viking.</u>

Diameter (mm)	19.05	31.75	50.8	76.2	101.6	127	215.9
Detonation Velocity (m/sec)	1830	2250	2610	3150	3290	3440	3920

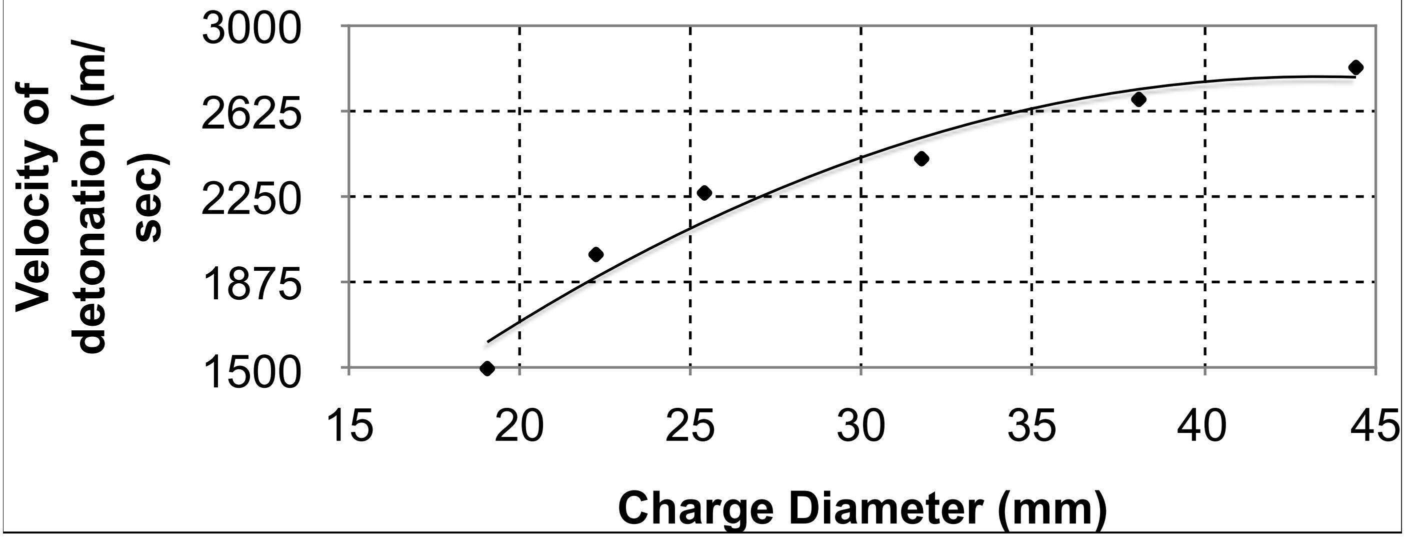


3.3.6. Velocity of Detonation of Blasting Gelatin.
Table 3.3.6. shows the Velocities of Detonation of Blasting Gelatin with 0.75, 0.875, 1, 1.25, 1.5 and 1.75 inch Charge Diameters.

Table 3.3.6. Velocity of Detonation of Blasting Gelatin

Charge Diameter (mm)	Velocity of Detonation (m/sec)
19.05	1500
22.23	2000
25.4	2270
31.75	2420
38.1	2680
44.45	2820

Figure 3.3.6. Velocity of Detonation of Blasting Gelatine as a function of Charge Diameter



3.3.7. <u>Velocity of Detonation of Nitroglycerine/Salt mixture.</u>
Table 3.3.7. shows the Velocities of Detonation (Low Velocity regime) of a Nitroglycerine/Salt mixture (15/85)

<u>Table 3.3.7 Velocities of detonation of a Nitroglycerine/Salt mixture.</u>

Diameter (mm)	6.3	8.2	9.6	12.7	22	31.7	44.5	100.8	∞
Velocity of detonation (m/sec)	1170	1250	1310	1370	1430	1450	1550	1620	1650

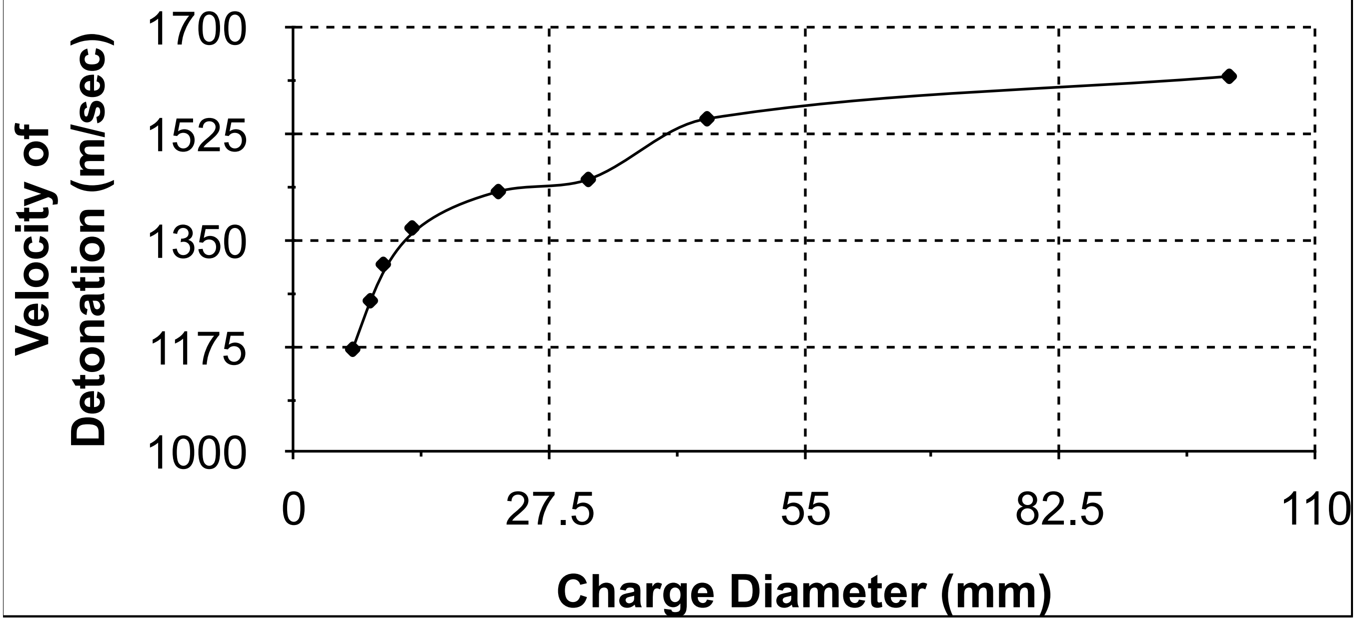


Figure 3.3.7. Velocity of Detonation (Low Velocity Regime) of Nitroglycerine/Salt

3.4 <u>The degree of confinement of the explosive charge.</u>

3.4.1 When a charge is confined, the Velocity of Detonation is greater than with an unconfined charge of the same diameter. For confinement within a thin skin, confinement mass per unit area is the controlling factor. For a thicker containment, the compressibility of the confining material is the controlling factor. The effect of confinement in steel tubes of different wall thickness on the Velocity of Detonation is shown in Table 3.4.1 and Figure 3.4.1

<u>Table 3.4.1 The effects of confinement in steel tubes of differing wall thicknesses (six charges each) on the Limiting Velocity of Detonation of creamed cast TNT</u>

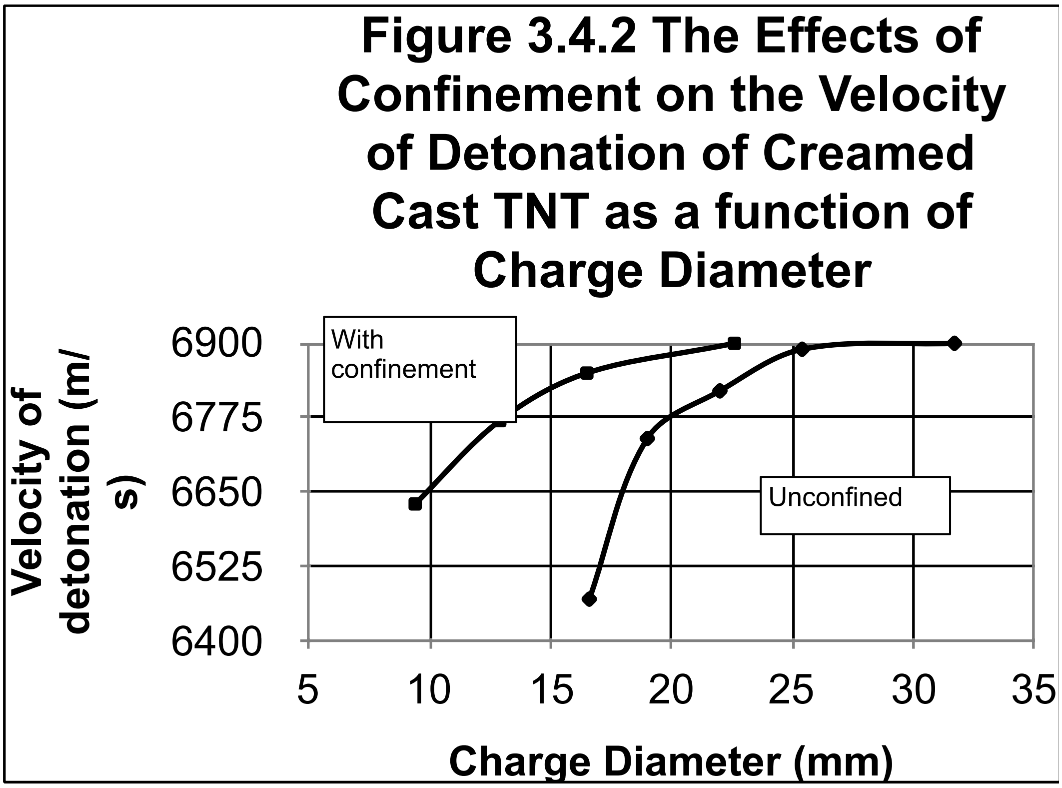
Diameter (mm)	16.6	16.5	16.5
Wall thickness (mm)	Unconfined	0.8	2.3
Case inertia (gram/cc)	Unconfined	0.66	2.07
TNT Density (gram/cc)	1.605	1.605	1.605
Mean Velocity of Detonation (m/s)	6470	6780	6850

Velocity of Detonation range (m/s)	116	49	51
Velocity of Detonation, standard deviation (m/s)	42	16	22

3.4.2 The effect of confinement in steel tubes of different diameters on the Velocity of Detonation is shown in Table 3.4.2 and Figure 3.4.2 Also shown are the unconfined values of Figure 3.3, for comparison. It can be seen that the confined charges reach the same Limiting Velocity of Detonation but at a smaller Limiting Diameter.

Table 3.4.2 The effects of confinement in steel tubes of differing diameters (six charges at each diameter) on the Limiting Velocity of Detonation of creamed cast TNT

Diameter mm)	9.4	12.9	16.5	22.6
Wall thickness (mm)	2.3	2.0	2.3	2.0
Case inertia gram/cc)	2.17	1.86	2.07	1.73
TNT Density (gram/cc)	1.600	1.605	1.60	1.610
Mean Velocity of Detonation m/s)	6630	6770	6850	6900
Velocity of Detonation range (m/s}	68	53	51	28
Velocity of Detonation standard deviation (m/	23	18	22	12



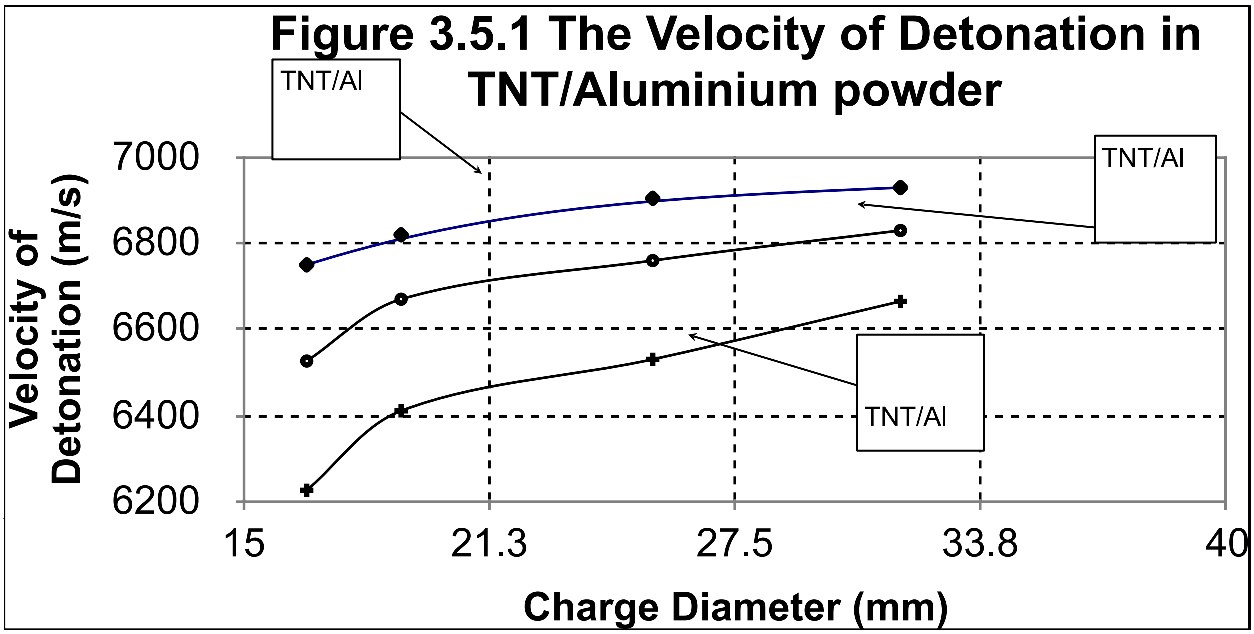
3.5 The addition of compounds or elements to the explosive.

3.5.1 Of many possible compounds or elements to be added to the many varieties of High Explosives, four of particular interest have been selected. These are: Aluminium to creamed cast TNT, Ammonium Nitrate to TNT, Aluminium to RDX and CE to TNT.

3.5. 1.1 The addition of Aluminum to Creamed cast TNT

Table 3.5.1 The mean Velocity of Detonation of unconfined Aluminium/TNT mixtures as a function of the Charge Diameter.

TNT/A1 %	100/0	100/0	85/15	85/15	70/30	70/30
Diameter (mm)	Density (Grams/	Velocity of	Density (Grams/	Velocity of	Density (Grams/	Velocity of
31.7	1.62	6930	1.71	6830	1.82	6665
25.4	1.62	6905	1.71	6760	1.82	6530
19.0	1.62	6820	1.71	6670	1.81	6410
16.6	1.62	6750	1.71	6526	1.81	6255

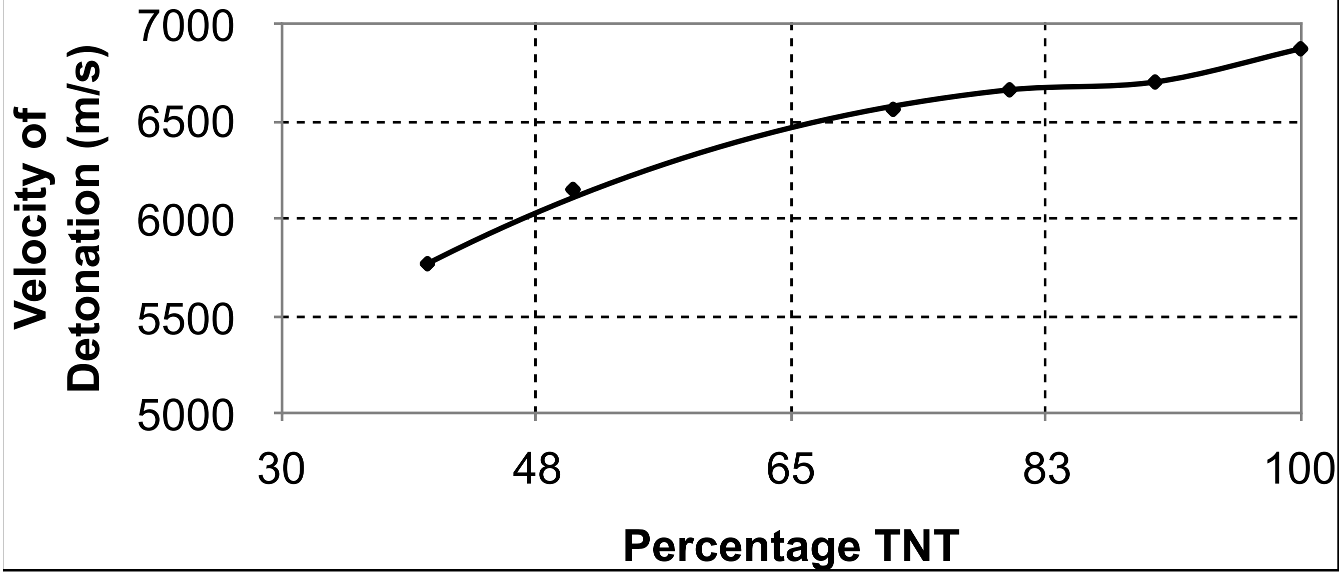


3.5.1.2 The addition of Ammonium Nitrate to Grade I cast TNT.

Table 3.5.2 The mean Velocity of Detonation of unconfined Ammonium Nitrate/TNT mixtures (Amatols). The effects of differing percentages.
(All charges 31.7 mm in diameter, 42 cm long, unconfined)

TNT/Al%	100/0	90/10	80/20	72/28	50/50	40/60
Density (Gram/cc)	1.6	1.6	1.59	1.59	1.58	1.55
Velocity of Detonation m/sec)	6870	6700	6660	6560	6150	5770

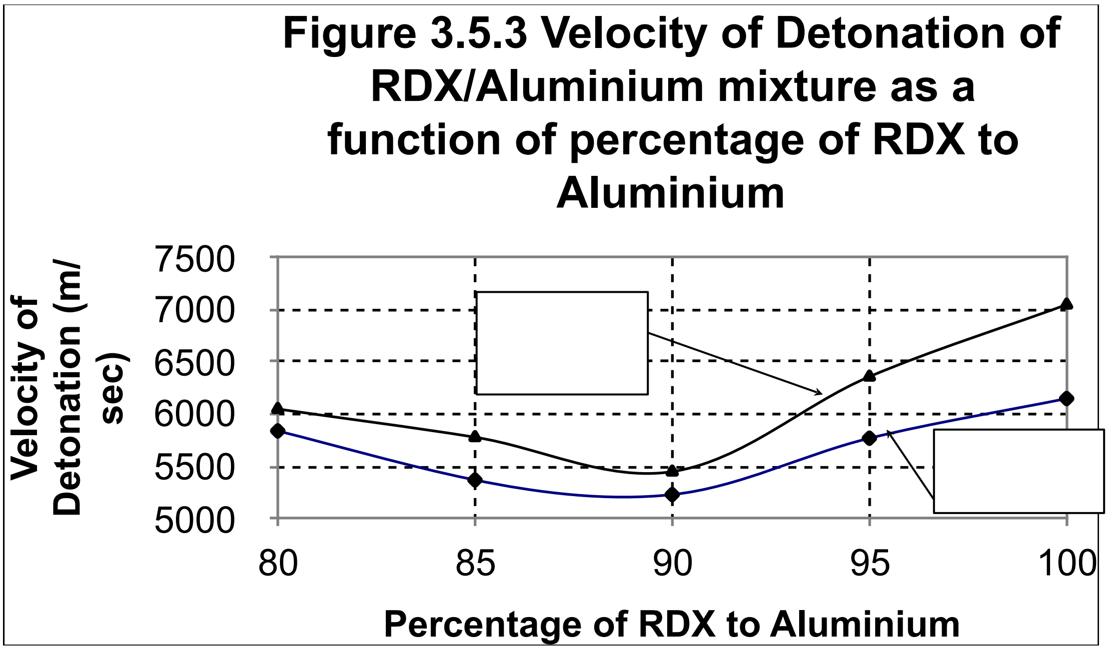
Figure 3.5.2 The Limiting Velocity of Detonation of Amatol as a function of percentage of TNT



3.5.1.3 The addition of Aluminium to RDX.

Table 3.5.3 The mean Velocity of Detonation of unconfined RDX /Aluminium mixtures. The effects of differing percentages.
(All charges 30 mm in diameter, unconfined)

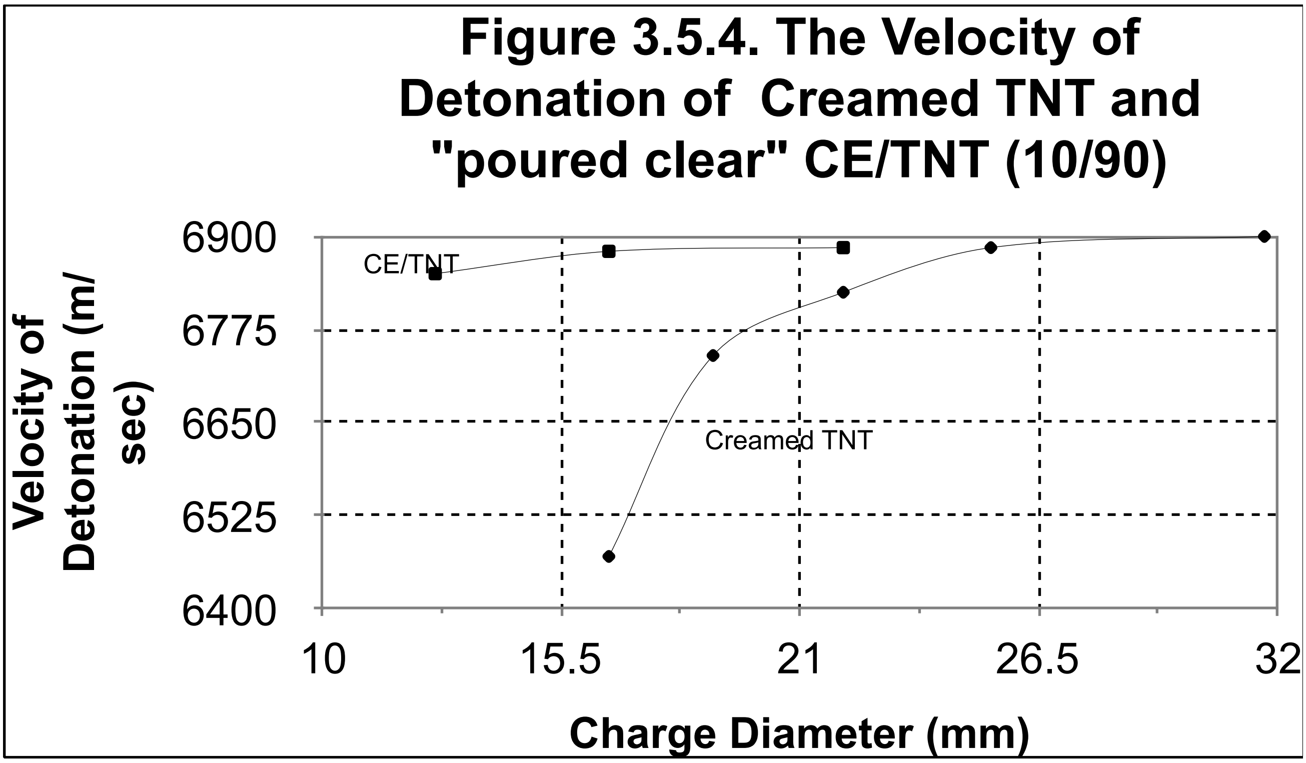
Density (Grams/cc)	100/0 RDX/Al (%)	95/5 RDX/Al (%)	90/10 RDX/Al (%)	85/15 RDX/Al (%)	80/20 RDX/Al (%)
1.10	6150	5770	5230	5370	5840
1.30	7050	6360	5450	5780	6050



3.5.1.4. The addition of CE to TNT.

Table 3.5.4. <u>The Velocity of Detonation of Creamed TNT and "poured clear" CE/TNT (10/90), unconfined charges of various Charge Diameters.</u>

Charge Diameter (mm)	10.0	12.6	16.6	19.0	22.0	25.4	31.7
Creamed TNT Velocity of Detonation (m/sec)	No detonation	No detonation	6470	6740	6825	6885	6900
10/90 CE/ TNT Velocity of Detonation (m/sec)	No detonation	6850	6880	-	6885	-	6905



3.6 <u>The aging of the explosive</u>

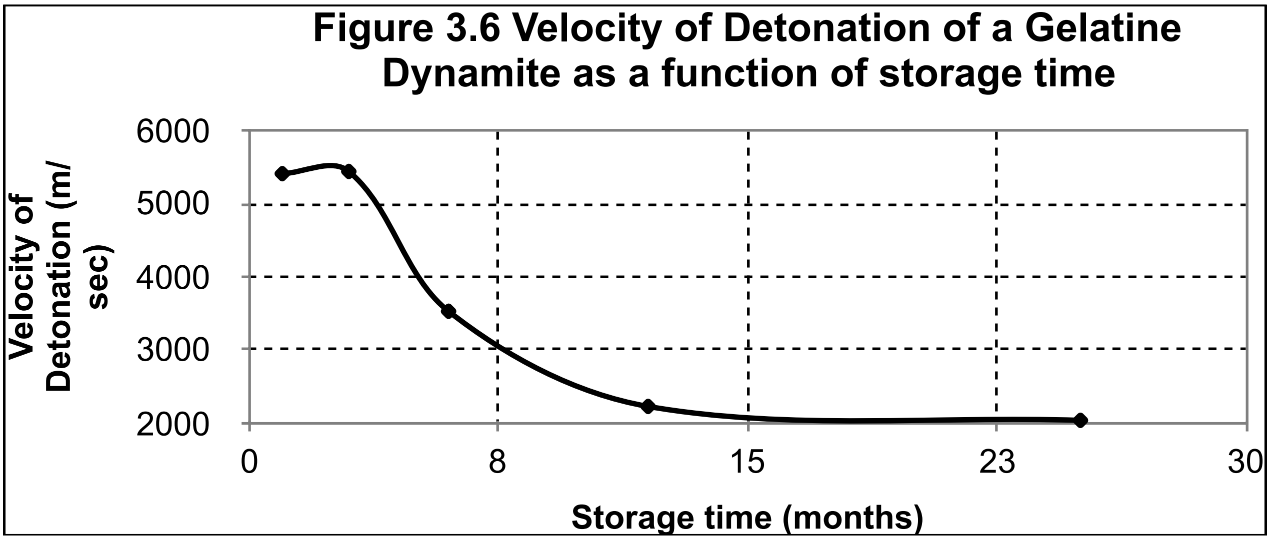
3.6.1 This is of particular importance for gelatinous explosives. During manufacture, minute air bubbles are entrained in the explosive. These bubbles become hot spots due to compression by the sonic wave. The sonic wave is caused by the initiating source traversing the charge. The hot spots assist in the decomposition of the explosive. During storage, these bubbles escape and the aerated structure is lost. The explosive in table 3.6 below is Ammon Gelatin Dynamite (36.1% nitropoly-glycerine, 0.7% nitrocellulose, 33.3% sodium nitrate, 1.2% calcium carbonate, 7.3% carbonaceous combustible and 20.3% ammonium nitrate). The cartridges were 1.25 inches in diameter and they were initiated by a No 6 detonator. The cartridges were 18 inches long and were unconfined. The density was 1.48 grams/cc.

Table 3.6. Velocity of Detonation of gelatine dynamite as a function of periods of storage

Storage (months)	1	3	6	12	25
Velocity of Detonation (m/sec)	5410	5440	3530	2230	2040

3.7 The strength of the initiating source

3.7. 1. The strength of the initiating source should theoretically have no



effect on the Limiting Velocity of Detonation of a given explosive, as by definition, this is the maximum velocity that can be established. However, both abnormally high and abnormally low Velocities of Detonation have been recorded.

3.7.2. Abnormally high Velocity of Detonation. With a strong initiator, the Velocity of Detonation can be greater than the Limiting Velocity of

Detonation, but only for a very short distance, after which, stable detonation at the Limiting Velocity of Detonation is established.

3.7.3. Abnormally low Velocity of Detonation. Particularly with nitro-glycerine based explosives, both a Low and a High Velocity of Detonation may occur. The High Velocity of Detonation is the Limiting value of about 8000 meters per second and the Low Velocity of Detonation is of the order of 1000 to 2000 meters per second. After a low velocity explosion, un-decomposed explosive is often found. The low velocity detonation can be relatively stable, or it can change into a high velocity detonation. This change from the low to the high velocity regime may occur abruptly or relatively gradually, with a period of acceleration from the low to the high velocity. The low order detonation in a liquid explosive is propagated by a discontinuous series of local explosions at a number of randomly positioned air bubbles in the rear of a sound wave moving through the liquid. The speed of sound through nitroglycerine is of the order of 1600 meters per second. Similar effects have also been seen with TNT (both crystalline and granulated) and tetryl. Again, the strength of the initiating source affects the velocity regime, as does the diameter of the cartridge. Table 3.7.1 and Figure 3.7.1 show the variation of the Velocity of Detonation of Nitro-glycerine with two initiators, one weak (No 6 Fulminate detonator) and the other strong (No 8 Briska detonator).

Table 3.7.2 and Figure 3.7.2 show the variation of the Velocity of Detonation of Nitro-glycerine Polar Saxonite with cartridge diameter.

Table 3.7.1. The Velocity of Detonation of Nitro-glycerine in glass tubes as a function of Detonator strength.

Diameter of charge (mm)	Velocity of Detonation (m/sec) with a No 6 Fulminate detonator	Velocity of Detonation (m/sec) with a No 8 Briska detonator
6.35	910	8130
12.7	2015	8700
19.05	2000	8320

25.4	2025	8130
31.75	1895	8140

Table 3.7.2 The Velocity of Detonation of Polar Saxonite No 3 (at a density of 1.53 grams/cc) by a No 6 detonator as a function of Charge Diameter.

Diameter (mm)	Velocity of Detonation (m/sec)
19.1	1970
22.2	1960
25.4	2380
31.8	2580
38.1	2850
47.6	5250
50.8	5410
63.5	5500
76.2	5530
127.0	5880
177.8	5670

Above 38.1 mm (1.5 inches) it was not possible to maintain the low velocity detonation. Velocities of Detonation of greater than 5000 metres per second were always obtained.

3.8 The "Grist" size

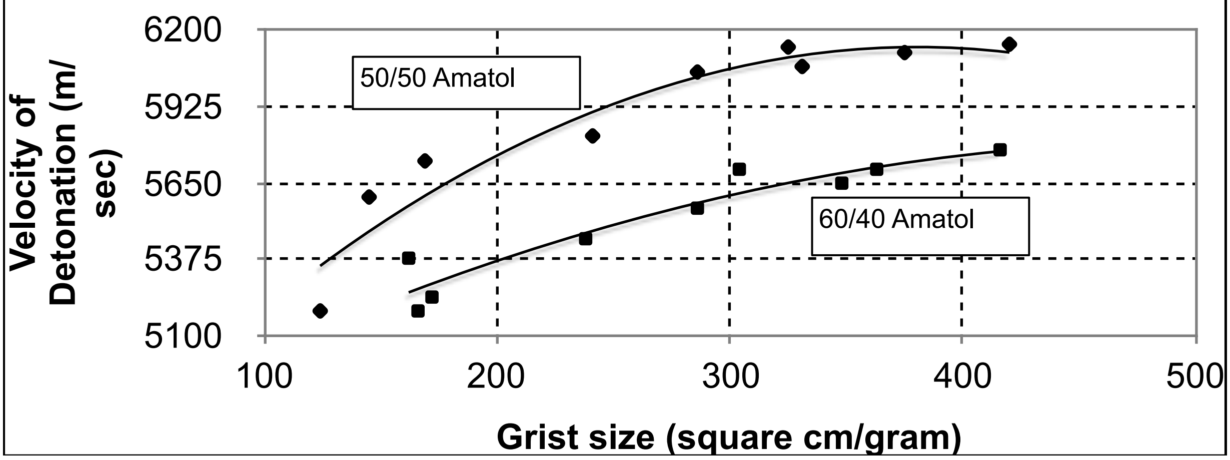
3.8.1. When Ammonium Nitrate, in crystal form with varying degrees of fineness, is added to cast TNT to form Amatol, the crystals retain their

identity in the TNT matrix. The "Grist" size is defined as the surface area of the Ammonium Nitrate in one gram of Amatol.
The Velocities of Detonation in various Amatols are shown in Table 3.8.1. All were Cast charges, 31.7 mm diameter, unconfined.

Table 3.8.1. Velocities of Detonation in Amatols.

50/50 Amatol	(Density 1.58)	60/40 Amatol	(Density 1.55)
Grist	Velocity of Detonation (m/sec)	Grist	Velocity of Detonation (m/sec)
420	6150	416	5770
375	6120	363	5700
331	6070	348	5650
325	6140	304	5700
286	6050	286	5560
241	5820	238	5450
169	5730	172	5240
145	5600	166	5190
124	5190	162	5380
93	No detonation	93	No detonation

Figure 3.8.1. Velocity of Detonation of Amatols as a function of "Grist" size



3.9. The statistical consistency within a batch of explosive charges.

Table 3.9 shows the consistency of the Velocity of Detonation with cartridges taken at random from a single batch from normal manufacture of a commercial blasting explosive, gelatin dynamite.

Table 3.9 Velocities of Detonation (meters/sec) measured on a sample of 24 cartridges

2320	2450	2480	2500	2540	2580
2370	2470	2480	2510	2540	2630
2420	2470	2490	2530	2550	2660
2420	2480	2490	2540	2550	2720

The mean Velocity of Detonation was 2508 metres per second and one standard deviation was 89 metres per second.

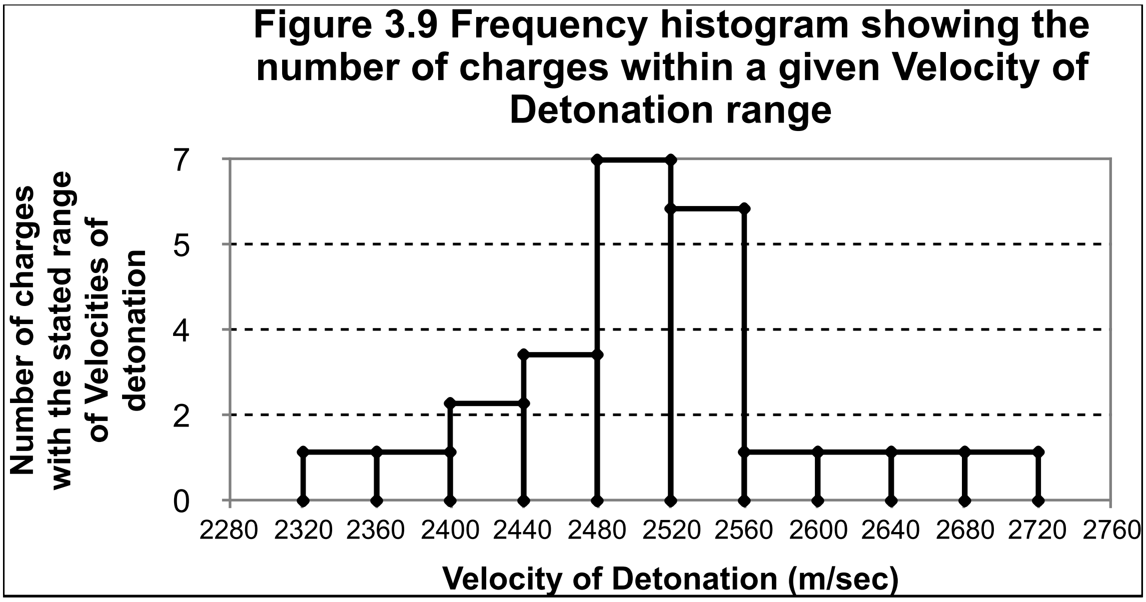


Figure 3.9 Frequency histogram showing the number of charges within a given Velocity of Detonation range

3.10. The oxygen balance of the explosive.

3.10.1. So far in this paper, the factors affecting the Velocity of Detonation have been purely descriptive, with no explanation as to why a given explosive has a given Velocity of Detonation. Some beginning of an explanation can now be given, relating to the Oxygen Balance of the explosive. An estimate may be made of the maximum Velocity of Detonation that can exist.

3.10.2. Explosives contain oxidizing and combustible ingredients, which can be combined in a single molecule or as different chemicals. The oxygen balance of an explosive is the percentage excess of oxygen in the composition. When the explosive is detonated, it breaks down into simpler chemical products, typically carbon dioxide, water vapor and nitrogen. If there is insufficient oxygen, the explosion products will contain carbon monoxide and hydrogen. The intrinsic strength of an explosive is associated with oxygen balance, increasing as the combustion is more complete. An explosive that is oxygen positive is weaker than one having the optimum oxygen balance.

3.10.3. The limiting Velocity of Detonation is also associated with the oxygen balance, as shown in Table 3.10 and Figure 3.10, below. All the Velocities of Detonation of the explosives have been calculated for a common density of 1.5 grams/cc, using Equation 2.

$$VofD_2 = VofD_1 + K(\rho_2 - \rho_1) \quad \text{...Equation 2}$$

which is the same equation as Equation 1, but the K value was increased to 3770.

Table 3.10. Limiting Velocity of Detonation of a number of explosives with differing oxygen balances, at a common density of 1.5 grams/cc.

Ident No.	Explosive name	Chemical Abstracts Service number (CAS#)	Oxygen balance (%)	Velocity of Detonation (m/sec)
1	Dinitrobenzene	99-65-0	-95	5990
2	Hexamethylenetriperoxide	283-66-9	-92	6600
3	Trinitroxylene	38677-56-4	-89.6	6425
4	Trinitroanisole	606-35-9	-78	6575
5	Trinitrotoluene (2,4,6)	118-96-7	-74	6620
6	Ethyl picrate	-	-63	6320
7	Trinitrocresol	602-99-3	-62.5	6400
8	Ethyl tetryl	-	-61.1	7700
9	Diazodinitrophenol	4682-03-5	-61	6600
10	Trinitrobenzene	99-35-4	-56.3	6760
11	Tetramethylolcyclohexanone	-	-56.2	7700
12	Hexanitrodiphenylamine	131-73-7	-52.8	6600
13	Ammonium picrate	131-74-8	-52	6650
14	Tetryl	479-45-8	-47.3	7250
15	Cyanuric triazide	-	-47	6925
16	Tetramethylolcyclopentanone	-	-45.8	6750
17	Picric Acid	88-89-1	-45.3	6750
18	Tetramethylolcyclohexanol	-	-45	7230
19	Diethylene glycol dinitrate	693-21-0	-40.8	7170
20	Dinitrodimethyloxamide	-	-38.8	7050
21	Azideoethyl nitrate	-	-36.3	6950
22	Trinitrophenylnitramineoethyl	-	-35.3	7150
23	Tetranitroaniline (TENA)	3698-54-2	-32.2	7250
24	Ethylene dinitramine	505-71-5	-32	7575
25	Nitroguanidine	556-88-7	-30.8	7430
26	Trimethylene glycol dinitrate	-	-28.9	7300
27	Dipentaerythitol tetranitrate	-	-27.5	7075
28	Cyclotrimethylenetrinitramine	121-82-4	-21.6	7950
29	Methyl nitrate	598-58-3	-10.4	7700
30	Pentaerythritol tetranitrate	78-11-5	-10.1	7525
31	Ethylene glycol dinitrate		0.0	7350
32	Trimethylolnitromethane		0.0	7330
33	Nitroglycerine	55-63-0	3.5	7385
34	Mannitol hexanitrate	15825-70-	7.1	7400

3.10.4. Some of the scatter of values seen in Figure 3.10 arises because some of the values are not in fact the limiting Velocities of Detonation. The constant K value of 3770 is also sometimes in error for some explosives. The dashed line shows a linear regression, and it can be seen that there is a general drift towards higher Velocities of Detonation as the oxygen balance improves.

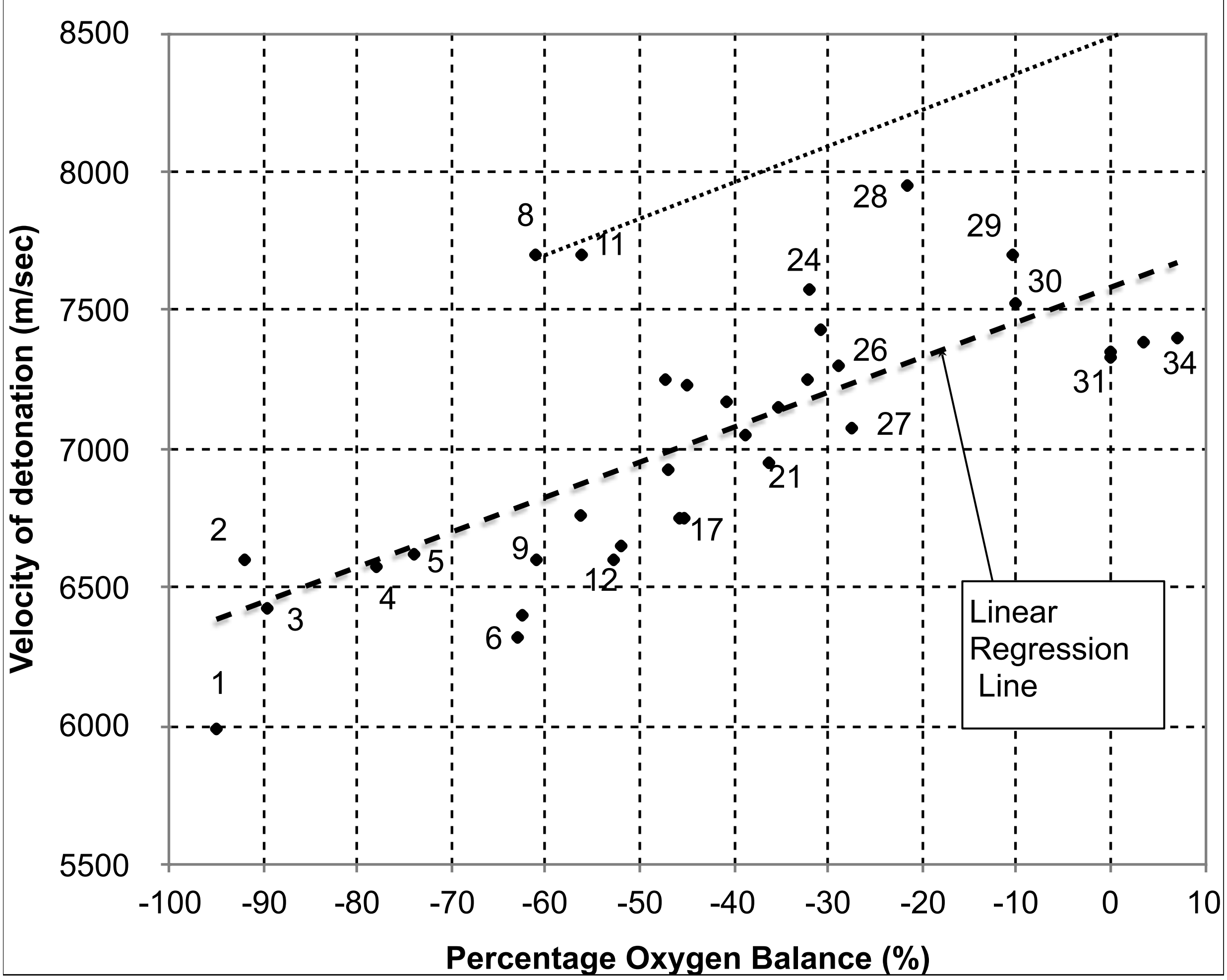


Figure 3.10. Velocity of Detonation as a function of percentage Oxygen Balance

3.10.5. An estimate can now be made of the ultimate Velocity of Detonation of oxygen based explosives. A line parallel to the regression line, drawn through the furthest value from the line towards a higher Velocity of Detonation (Ident No 8), shows an intercept with the zero oxygen balance at about 8500 meters per second. This is for a density of 1.5 grams per cc.

And as noted in paragraph 3.2.1, the loading density of military explosives falls normally within the range of 0.3 to 2.0 grams/cc. From Equation 1,

$$VofD_2 = VofD_1 + K(\rho_2 - \rho_1)$$

Where VofD = Limiting Velocity of Detonation (in m/sec)
ρ = Explosive density (grams/cc)
K = a constant characteristic for a given explosive
subscript 1 = existing value
subscript $_2$ = required value

then VofD, = 8500 meters per second
ρ_1= Explosive density of 1.5 grams/cc
ρ_2= Explosive density of 2.0 grams/cc
K = 3770

Then $VofD_2$ = 8500 + 3770 (2.0-1.5)
= 10,385 mètres per second

A theoretical explosive with this truly immense Velocity of Detonation could well have undesirable properties for military explosives, for instance extreme sensitivity or excessive corrosive effects in storage.

4. **Acknowledgments.**

4.1. Grateful acknowledgement is made to the authors of the publications in the references, below, from which the data for this paper has been abstracted.

5. References.

5.1 .1 "Science of Explosives" by C.E.H. Bawn and G. Rotter.
5.1.2. "Detonation in Condensed Explosives" by J. Taylor
5.1.3. "High Explosives and Propellants" second edition by S. Fordham

6. Disclaimer.

The comments and calculations in paragraph 3.9.5. are my own and should not be imputed to the authors in references of paragraph 5 above.

7. Index