Effect of Confinement on the Velocity of Detonation (VOD) of Explosives by Employing Fibre Optic Technique

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Effect of Confinement on the Velocity of Detonation (VOD) of Explosives by Employing Fibre Optic Technique

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بسم الله الرحمن الرحيم

Dedication

This work is dedicated to my beloved family

Parents, Wife & Kids

Whose efforts, sacrifices, prayers, encouragement, appreciation which excelled my courage, zeal and helped me to achieve this task

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الحَمْدُ للهِ الَّذَي لاَ يَبْلُغُ مِدْحَتَهُ القَائِلُونَ، وَلاِ يُحْصِي نَعْمَاءَهُ العَادُّونَ، ولاَ يُؤَدِّي حَقَّهُ الُمجْتَهِدُونَ، الَّذِي لاَ يُدْرِكُهُ بُعْدُ الهِمَمِ، وَلاَ يَنَالُهُ غَوْصُ الفِطَنِ، الَّذِي لَيْسَ لِصِفَتِهِ حَدٌّ مَحْدُودٌ، وَلاَ نَعْتٌ مَوْجُودٌ، وَلا وَقْتٌ مَعْدُودٌ، وَلا أَجَلٌ مَمْدُودٌ. فَطَرَ الخَلائِقَ بِقُدْرَتِهِ، وَنَشَرَ الرِّيَاحَ بِرَحْمَتِهِ، وَوَتَّدَ بِالصُّخُورِ مَيَدَانَ أَرْضِهِ.

Praise is due to the Allah whose value cannot be defined by orators, whose abundances cannot be calculated by calculators and whose claim (to obedience) cannot be satisfied by those who attempt to do so, whom the height of intellectual courage cannot appreciate, and the divines of understanding cannot reach; He for whose description no limit has been laid down, no eulogy exists, no time is ordained and no duration is fixed. He took forth creation through his Supremacy, dispersed winds through His Compassion, and made firm the shaking earth with rocks.

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(MUHAMMAD ALI)

Abstract

The velocity of detonation termed as VOD of an explosives is a vital characteristic in the arena of energetic materials. It is measurement of the velocity at which the detonation reaction proceeds within an explosive when initiated by a desired activation energy. The detonation reaction is the combine effect of shock wave generated by detonation further induces the swift combustion of the energetic material and that of a reaction zone which enhances/stabilizes the propagation of shock-front. The VOD of an explosive is directly proportional to the power index of the explosive; hence its applications are best suited for that particular explosive. So far various methods have been established & being applied for measurement of VOD of an explosive experimentally or theoretically, nonetheless the one of precise method for this research topic is the use of optical fibre technique to measure the VOD with the help of "eplomet-fo-2000" instrument which uses optic fibre and records the delay time between two probs. The VOD of an explosive is influenced by its confinement with different materials and its influence is function of the density of confinement & weight ratio of explosives vis-a-viz material of confinement. Usually explosives are processed at lower densities that of TMD (Theoretical maximum density) of that particular explosives reducing the detonation performance characteristics mainly the VOD. The confinement with higher density & hardness materials tend to increase the VOD near to its TMD values. In the present work Tetryl pellets with density of 1.5~1.51 g/cm3 have been used and detonated in different confinements. The VOD recorded with the help of explomet-fo-2000. This instrument records the time interval/delay-time and analyses the VOD accordingly. The achieved results are in fair agreement with theoretical values having variation less than 3%. The upshot of this study is that the confinement of explosive charge considerably enhances the VOD which in turn helps to enhance the performance of the explosive.

Keywords: Explosives; Velocity of Detonation; Shock Velocity/wave. Theoretical maximum density

Abbreviations

Abbreviation	Extension /Word
ANFO	Ammonium nitrate fuel oil
CJ	Chapman Jouget
DDT	Deflagration to detonation
fps	Feet per second
NC	Nitrocellulose
NG	Nitro-glycerine
PETN	Pentaerythritol-Tetranitrate
RBE	Relative bubble energy
RDX	1,3,5-Trinitroperhydro-1,3,5-triazine
Tetryl/CE	2,4,6-Trinitrophenylmethylnitramine
TMD	Theoretical Maximum Density
TNT	2,4,6-Trinitrotoluene
VOD	Velocity of Detonation
HMX	1,3,5,7-Tetranitro-1,3,5,7-tetrazoctane
N_3	Azide
°C	Centigrade
mm	Millimetre
ml	Millilitre
m/s	Meter per second
P	Density
$\Delta D/\Delta T$	detonation velocity per unit change in temperature
DFC	Detonating Fuse Cord
w.r.t	With respect to
VISAR	Velocity Interferometer System for Any Reflector
PMMA	Poly (methyl methacrylate)
PDV	Photon Doppler Velocimetry
FFT	Fast Fourier Transform

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Chapter 1

Introduction

1.1. Background:

The performance parameters mainly the VOD of an explosive is greatly influenced by various factors including density, diameter & mass of explosive and confinement vis-a-viz confinement material made on the explosive charge. All explosives have its crystal or theoretical maximum density known as TMD and the performance is maximum at this density but the achievement of TMD is somewhat difficult due to certain limitation mainly due to safety reasons ultimately compromising the performance. The depletion of detonation performance of an explosive can be improved by different methods the one of the most practical is confinement.

1.2. Definition of Terms

1.2.1 Explosive:

The term energetic material now being widely used is an explosive substance either a single or a mixture of compound(s), is capable to yield an detonation by using its own energy or materials which can undergo exothermic chemical reaction at an extremely uncontrolled rate resultantly decomposes to low molecular weight gaseous products at high pressure and temperature. The energy so released is characteristically mechanical in nature, producing a shockwave, kinetic energy of fragments and a huge volume of gases and heat energy.

1.2.2 Identification of Explosive by its Features/Characteristics:

a. Rate of Reaction

There are so many chemical reactions termed as exothermic reactions, which releases energy/heat even more than explosives but proceeds leisurely, the energy so released will be dissipated due to low release rate, thus causes limited effects of increased and controllable system temperature. Quickness of reaction and its subsequent/tremendous rate of release of energy distinguishes the explosive reaction from an ordinary high energy combustion reaction e.g. unit mass of motor gasoline may releases more energy on combustion than the similar amount TNT or a unit mass of charcoal yields 5x times more heat that produced by of nitroglycerin using similar quantity but only difference is the rate of decomposition and succeeding rate of release of heat energy thus the later substances in either cases detonate and cause a discontinuity in the medium. The phenomenon is due the fact that most of heat and expanding gases dissipate in the medium continuously rather to sudden intensification of system parameters mainly temperature, pressure and volume; hence no explosion or discontinuity occurs. Contrary to ordinary combustion, if the reaction proceeds very hastily and energy is released so abruptly that rather to dissipate, the energy will sudden increase the system parameters (temperature, pressure and gas volume) cause a discontinuity in medium hence shocked up, the same can generate a shock-wave associated with fragments at speed of thousands of meter in a second.

b. Initiation of Reaction:

An explosive must be reliable enough that it should not undergoes any chemical reaction without a suitable initiation stimulus is applied and essentially be able to be initiated by a suitable initiation like shock, heat or electricity to minute amount of the explosive's material.

c. Formation of Gases:

The reaction must be violent; the conversion of explosive substance /molecules into gaseous products /molecules must either be complete or nearly complete and the same occurs in variety of ways. When an ordinary high energy substance/fuel like firewood or coal is scorched, the carbon, hydrogen in combustible substance mixed together with oxygen of air to convert into carbon dioxide and water vapours, associated with flame vis-a-viz smoke. Contrary to this, in an explosive reaction proceeds where the carbon and hydrogen in the explosive substance uses its own oxygen rather to take it from atmosphere, subsequently the explosive material is transformed to very hot, dense, pressurized with lighter molecular substances in gases phase. These explosion products primarily develop a very high velocities and try to reach equilibrium with atmospheric conditions, results into generation of a shock-front or shockwave. A shockwave primarily consists of extremely compressed air, proceeding outward from the source of detonation at supersonic velocities. Pressure so produced by an explosion is due to the gases evolved and is dependent on their volume and temperature.

d. Evolution of Heat:

In an explosive decomposition, the reaction is exothermic i.e. it generates and releases a large amount of heat associated with a tremendous rate. This rapid liberation of heat is responsible for sudden expansion of gaseous products of reaction and generates high pressures which further leads to a detonation. It is worth to mention that the release of heat at a deficient rate will not serve the purpose hence no explosion at all. The work potential (brisance) of explosives depend chiefly on the quantity of heat energy evolved at extremely high rate.

e. Self-Sustaining Reactivity:

As already stated ibid, the reaction must be self-sustaining without requirement for an external oxygen source or energy, except that required for initiation of the reaction. All explosives possess their own oxygen termed as oxygen No and the same is utilized in chemical reaction/ detonation process.

1.3 Classification of Explosive:

Explosive substances are classified in different ways, mainly by virtue of its chemical characteristics and their applications. We can distinguish the chemical individual substances and mixtures:

1.3.1 The Classification Based on Chemical Characteristics:

a. Nitro Compounds.
b. Nitric Esters.
c. Nitramines.
d. Derivatives from Chloric and Perchloric Acids
e. Azides

1.3.2 Classification Based on Rate of Reaction:

a. Explosives:

Explosives undergo a swift reaction, generating tremendous amount of heat associated with high gas volume & pressure and creates a shock in the surrounding medium due to discontinuity or jump conditions. The parameters jump from an ambient condition to thousands within microseconds.

b. Propellants:

In propellants, the low rate reaction produces a large amount of heat & considerable volume of gases with lower pressure hold over a longer time as compared to high explosives. This amount of sustained pressure generated in combustion reaction can be controlled, thus used to propel bullets, shells mortars and missiles.

c. Pyrotechnics:

Pyrotechnics are metal based inorganic mixtures, undergoes a chemical decomposition when oxidizers are added to it as these are not sustainable.

1.3.3 Classification Based on Usage:

a. Propellants or low explosives:

Propellants are used to get a desired effect mainly to propel a bullet out of barrel or a rocket to throw above the surface. The black powders, smokeless powders and composite powders are examples of this group. The burn rate as well as energy delivery rate of this explosive class differs widely among itself. Propellants are either slow or fast can be used for different purposes. They are differentiated as single-base propellants (SBP), double-base propellants (DBP), triple-base propellant (TBP) and composite propellants. The selection criteria of a propellant for a dedicated application is analyzed by ballistic and physical requirements rather on basis of its ingredients. A specific propellant composition may be appropriate for use in multiple applications depending on need of application and performance characteristic of propellant.

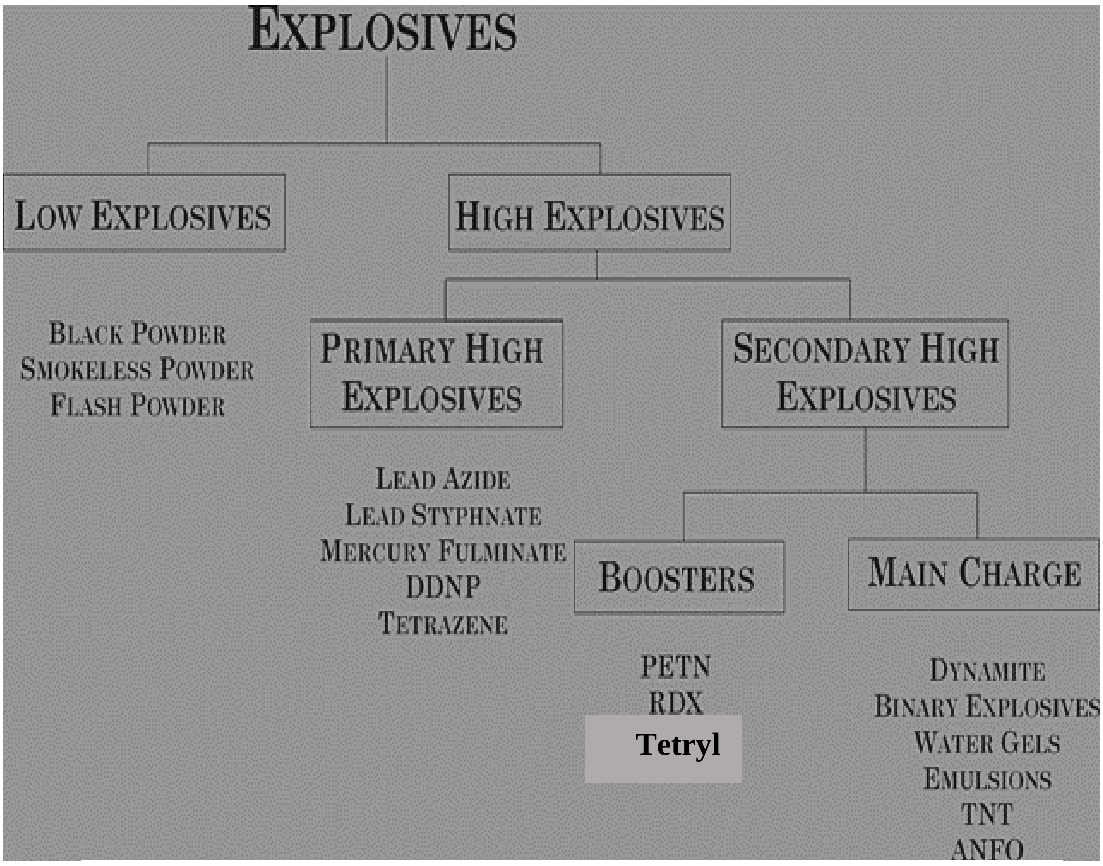


Figure 1.1: Classification of Explosives by virtue of its usage

b. Primary High Explosives or Initiators:

These are sensitive explosives which can be exploded or detonated when triggered by a low energy in form of heat, friction, shock or electricity (even a static charge may trigger such explosives). Contrary to a secondary high explosive, it undergoes a rapid changeover from deflagration to detonation DDT and has capability to transmit it to an intermediate or insensitive high explosive. These consist of Lead Azide (service and dextrinated), lead-Trinitroresorcinol (Lead Styphnate), Tetracene, Nickel Hydrazine Nitrate and Dinitrobenzofuraxane and used in initiatory caps, primers and detonators. Primary high explosives possess low figure of insensitivity (F of I) and power index (PI) as compared to secondary high explosives.

c. Secondary High explosives:

These are energetic materials which are less sensitive and more powerful than primary HE & Low explosives; thus, unable to detonate readily by heat and shock and needs primary explosives to initiate/detonate. Examples: 2,4,6-Trinitrotoluene (TNT), (CE), (Picric Acid), Nitrocellulose (NC), Nitroglycerin (NG), (Hexogen or RDX (HMX), (PETN) and Nitroguanidine are common military high explosives. These are further classified as Booster and Main Charge Explosives. PETN, Tetryl and RDX are being used as booster explosives whereas HMX, RDX, TNT and their mixtures are widely used as main charge explosives.

1.4 Physical Characteristics of Explosives.

Determination of appropriateness of an explosive material for any application is subject to their known characteristics. The fruitfulness of these materials can only be valued when the characteristics of substance and end effects of the same are entirely known. Various explosives/energetic substances have been evaluated in the past to find out their appropriateness for defence & commercial uses. Out of all evaluated, many suitable explosives shown certain undesirable characteristics, therefore, restricts their worth in certain uses. The qualification criteria of an explosive material for a dedicated application is rigorous, thus a very limited explosives materials qualify all the anticipated properties necessary to make them acceptable for a dedicated use and standardization. Various vital and key features are discussed in following paras.

1.4.1 Cost effectiveness and Abundance:

All the raw materials required for manufacturing of such explosives must be cheap, nonstrategic and readily available in enough quantity. The manufacturing processes must rationally be gentle, inexpensive, and safe.

1.4.2 Sensitivity & Insensitivity:

For an energetic substance, the terms insensitivity and sensitivity states that how easily can an explosive be ignited or detonated with the help of a suitable stimulus mainly shock, friction, heat and charge/electricity. The sensitivity of a specific explosive to percussion or impact may differ considerably from its sensitivity to stimulation. Few methods applied to determine sensitivity are as follows:

a Sensitivity to Impact/Percussion:

b Sensitivity to Friction:

c Sensitivity to Heat

d. Sensitivity to Static or Dynamic Electric Charge

1.4.3 Stability

The stability of an explosive substance is its ability to be stored without deterioration when stored for a long period of time. In order keep it safe, it should be stable enough that it should not decompose. The factors affecting the stability of an explosive are stated as follows:

a. Chemical Composition & Structure:

It is well known that unstable chemical compounds can undergo chemical decomposition exposed to sympathetic conditions particularly when heated due to unstable structures/bonding. Similarly, explosives of certain groups having unstable structures like nitrates (NO_2), nitrites (NO_3), and Azides (N_3), are inherently remains in an internal strain. The said strain may further increased & elevated by heating which further leads abrupt disturbance of the molecule causing subsequent explosion. For instance, some of explosive materials are in a state of molecular uncertainty thus decomposition of material starts. All propellants are molecularly unstable and undergoes decomposition under storage; hence stabilizers are necessarily added these materials.

b. The Storage Temperature:

Temperatures inversely affects the shelf life of explosive in storage. The decomposition rates an explosives material raises with rise of temperature. Although all military explosives are considered to be safe at operational temperatures of -40°C ~ +70°C, whereas storage must be made under a controlled range of temperature upto 35°C so as to minimize the decomposition rate ultimately prolonging the shelf life of explosive.

c. Sunlight Exposure:

The ultraviolet rays of sunlight may cause to decompose the explosive compound more rapidly than normal storage conditions particularly the compounds containing nitrogen groups, tends to reduce the stability of explosives.

1.4.4 Explosive Power:

The term power of an explosive material is a performance indicator which determines its shattering capability. Practically the term power or power index is defined as capacity of an explosive to get the desired effect in form of optimized fragments in a high explosive projectile, required penetration in h HEAT round and scabbing effect in a HESH round. Determination of explosive's power is being evaluated with help of different tests or a series of tests. The explosives with higher Power Index (PI) are CL-20, HMX and RDX are currently gaining favour for use in main charges particularly shape charges for the chemical energy penetration. The most common tests are elaborated in following paras:

a. Expansion of Cylinder Test:

In a copper cylinder, a predefined quantity of explosive is loaded. When the explosive detonated, the cylinder's expansion in radial direction peak wall velocity is obtained.

b. Fragmentation of Cylinder Test:

A definite quantity of explosive is fed into a metal (steel) cylinder and then detonated in a sawdust pit. The fragments caused by detonation are collected and the same is analysed based on size distribution.

c. CJ Pressure of Detonation:

The maximum dynamic pressure within a shock front is called the CJ Pressure of detonation pressure. It is derived by the shockwaves transmitted into water by the detonation of cylindrical explosive charges of a definite size. The CJ state is drawn & defined accordingly.

d. Critical Diameter:

Critical diameter of an explosive is a vital parameter which defines the least physical size of an explosive charge of a particular explosive where the detonation/ shock wave can be sustained. In this technique a series of explosive charges of dissimilar diameters are fired until the propagation of detonation wave is not self-sustainable further. The diameter where the detonation wave is no more selfsustained is known as critical diameter of that particular explosive. This value varies from explosive to explosive and condition to condition.

e. Pressure versus scaled distance:

A specific size charge is detonated, and pressure is measured at a standard distance. The values obtained in the tests are then compared with the known values of TNT.

f. Distance to Impulse:

It is a method to determine the detonation intensity and expressed in TNT equivalent. A predetermined size of explosive charge is detonated and its impulse at the area of pressure-time curve is recorded by virtue of distance.

g. Relative Bubble Energy (RBE):

In this technique a considerable amount of explosive charge ranging from 5.0 kgs to 50.0 kgs, is detonated well inside water. With the help of piezoelectric gauges, the time constant, peak pressure, the impulse, and energy are measured.

1.4.5 Brisance:

It is the ability of an explosive to shatter, determines chiefly by its pressure is called its brisance. It is distinguished by its a total work contribution. It is a vital parameter of performance which in turn determines the effectiveness of detonation of a specific explosive to create a desired fragmentation in Arty Shells, Bombs, Grenades etc. The ability or rate of an explosive to attains its peak pressure reflects the brisance of that particular explosive. This characteristic is primarily being employed and practiced by French and Russians. A good high explosive can be characterized by its ability to shatter the container in which it is confined.

1.4.6 Loading Density:

Loading Density of an explosive is its maximum workable or achievable density and expressed in the mass per unit volume commonly represented in g/cm^3. This density is being achieved by using various methods particularly press loading, pellet loading or cast loading. Although the loading density is lower than that of TMD, and depending on the method employed, 70-96% TMD can be achieved. At an elevated density the sensitivity may be reduced to make the explosive resistant to internal frictions and if density is augmented further the crystals of explosive may be crushed, leading to a vulnerable condition of sensitivity or instability of explosive may cause incidents.

1.4.7 Volatility:

Volatility of an explosive tends to increase its internal pressure which further leads to rise the temperature, resultantly reducing the stability and is not a desirable characteristic in military explosives. All types of explosives must be minutely volatile at the loading and storage temperature. The excessive volatility of an explosive particularly propellants causes the disturbance in the chemical composition of the explosive leading to considerable reduction in stabilizer percentage. The volatility must not be more than 2.0 ml of gas evolved in 48.0 hours.

1.4.8 Hygroscopicity:

The tendency to absorb moisture by an explosive is a strong demerit of an explosive as it reduces the significant parameters of explosive like sensitivity, strength, and VOD. It is a measure of a explosives tendency to absorb water from the moisture of surrounding air or with contact of water itself. The moisture of an explosive performs as inert material, absorbs heat leading to undesired chemical reactions; thus adversely affect the output characteristics of explosive. It also compromises the stability of explosive and corrosion to the explosive's container or component in which it is filled.

1.4.9 Explosive's Toxicity:

Explosives due to their specific chemical structure, are mostly toxic in nature and its effect may vary from a mild to severe based on exposure and type of explosive. In order to maintain good health conditions for workers, the toxicity of military explosives must be controlled to bare minimum by adopting safety procedures and wearing safety gears.

1.4.10. Velocity of Detonation:

Detonation velocity is a vital performance parameter of an explosive. When an explosive is detonated it generates a shock wave moving into unreacted explosive, a chemical reaction and the leading edge of rarefaction wave are in equilibrium and move in a same direction at a speed known as Velocity of Detonation denoted by D or VOD.

1.5 Detonation & Velocity of Detonation:

Practical explosives (energetic materials) are either single or mixture compounds. Most of the explosives contain oxygen together with fuel elements carbon & hydrogen and nitrogen, the system is thus capable of producing instantaneous & large amount of gases mainly carbon dioxide, carbon monoxide, water and nitrogen. As the reaction is extremely exothermic, hence the process produces a tremendous amount of heat known as "heat of explosion". Since the energetic materials (explosives) is a self-contained chemical system (compound) and by virtue of law of conservation of energy, it is obvious that the energy is contained within the material waiting for release at different rates when initiated by a stimulus known as "the activation energy". An explosive, upon initiation, releases energy by one of two possible combustion process, the burning or detonation. As the burning is out of scope of this research hence the same will not be deliberated further and the only focus will be detonation and related parameters mainly detonation velocity vis-à-vis effect of confinement on VOD.

1.5.1. The Detonation Process:

In contrast to the low explosive, the explosives detonate upon achieving desired condition rather to deflagrate /burn. Detonation is termed as a microsecond / discontinuous phenomenon and caused by sudden decomposition of material exothermically followed by a shock front in the explosive along with a abrupt release of tremendous amount of heat & gas. The main features of detonation are production of self-sustaining shock front which proceeds within an explosive substance at an increased speed. It is a discontinuous phenomenon and the shock wave velocity also known as velocity of detonation (VOD). When a shock wave is generated, it creates a discontinuity in the medium and all the detonation output parameters like pressure including density & temperature of system are suddenly changed from a lower level to highest level through a jump condition. This discontinuous change is propagated at a supersonic speed. Looking at the detonation process, there are some general phenomena that seem to apply to all explosives:

a. Density Pressure, temperature and Internal energy of explosive rises as shock waves proceed through it.
b. When the wave assumes the vertical front, it is called shockwave.
c. The transition is not smooth in the front of wave to the matter behind the wave but jumps from un-shocked to shocked state and called discontinuity.
d. Three different velocities are being generated, the pressure/propagation wave, particle and sound velocities.
e. The propagating shock wave velocity is higher than the speed of sound in the unreacted material through which the wave is traveling at a predetermined density.
f. The wave velocity is sum of sound velocity in that material and particle velocity.
g. In any given specimen of explosive, the wave velocity always remains constant.
h. In a specific explosive material, the wave velocity is a function of the density of that explosive material.

i. In a specific explosive the wave velocity is function of diameter of that specific explosive material and propagation completely falls below some minimum diameter known as critical diameter.
j. It is also noticed that the diameter above which wave speed no longer increases is different for each explosive.
k. The particle velocity is defined as the speed achieved by the decomposition material as a result of the acceleration of the shock wave.

The particle velocity and shock velocity both move in same direction

1.5.2 **Detonation Phenomena:**

Based on above observations, can be further divided into two broader categories:

i. Ideal Detonation:

Where the cross reaction of explosive is large enough to have no diameter effect.

ii. Non Ideal Detonation:

Where the dimension of the charge affects the characteristics of detonation. For most of the common military explosives the diameter is quite small from a mm to a few tens of mm, whereas for commercial explosives, the diameter may be in the range of several centimeters and for blasting agents, it may be a meter or more.

Detonation in a non-ideal condition is achieved either by direct detonation with a help of shock wave and termed as "shock to detonation" or by indirect detonation when necessary conditions are met and termed as "deflagration to detonation" DDT. Detonation of an Arty Shell and a Detonator are examples of SDT & DDT respectively.

1.5.3. Velocity of Detonation (VOD):

It is one of the most vital property of an explosive and indicates performance of that particular explosives in real time. It is the velocity of shock wave generated by a detonation reaction proceeds within the unreacted explosive. It can be expressed for confined or unconfined conditions with a measuring unit of feet per second (fps) or meter per second (m/s). The development of blast monitoring systems enables the continuous monitoring VOD through a reliable system.

1.5.4. Effect of Various Parameters on VOD:

a. Diameter Effects:

The diameter of an explosive composition effects directly on the detonation velocity upto a limiting value beyond which the diameter doesn't influence the VOD. The detonation wave or shock front for a cylindrical pellet at steady state conditions is not flat but curved and the VOD slowly weakens from the midpoint of the pellet to its outer surface outward due to losses energy at the outer surface of explosive column. In the higher diameter pellets, the diameter of surface does not influence the VOD to a same level as for lower diameter pellets. It is observed that there is a finite value for the diameter of the pellet where the surface influence are so high that the shock wave front will not sustain any more due to relatively large energy losses and is called the critical diameter, beyond which detonation fails to transmit further. The Detonation velocity (VOD) of an explosive charge is a function of the charge diameter (d), loading density (ρ), and grain size of explosives. The hydrodynamic theory of detonation being used to predict the explosive characteristics does not include charge diameter, thus the velocity of detonation (VOD) estimated or predicted will be for an imaginary charge with an infinite diameter. In this procedure a series of explosive charges having constant density and structure, but different diameters are fired. The detonation velocities (VOD) so recorded are combined to predict the detonation velocity of explosive charge at infinite diameter.

b. Density Effect:

VOD of an explosive has a direct and linear relationship with the density of processed explosive as shown in Fig 1.1. The same is maximum at infinite density or at TMD (Theoretical Maximum Density) and decreases as the density recedes. The affect, however, may vary for different types of explosives e.g. for a homogeneous military explosives, To achieve the maximum VOD for a homogeneous explosive, it is essential to achieve the maximum density of explosive compound and for a heterogeneous commercial explosive the VOD increases and then decreases as the density of the explosive composition increases. The compaction of heterogeneous explosives makes the transition from deflagration to detonation difficult. In case of a crystalline explosive, the density of compaction is dependent on the adopted technique of processing whether it is pressing, casting or extrusion and the limiting density is the density of the explosive crystal. SG Murray & A Bailey states that the VOD (velocity of detonation) can be estimated from the densities of the explosive composition using Equation $V\rho1 = V\rho2 + 3500 (\rho1 - \rho2)$. In order to get an optimum result a proper adjustment would be required to get an appropriate detonation velocity for any intended use. Moreover primary high explosives are used to initiate the secondary low (Propellants & Black Powders) or high explosives (main payload explosives like TNT, Tetryl, RDX and HMX etc and the initiation is solely dependent on the optimum density of primary explosive that it should not be as low as to ignite the secondary explosive nor should be as high as to safely processed; hence an optimum density must be worked out and applied.

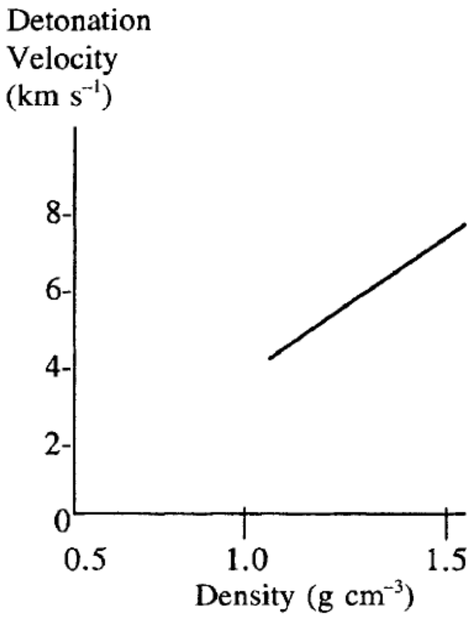


Figure 1.2: Change in VOD as function of density for a secondary explosive

c. Effect of Explosive Material:

In a detonation process, a wave with shock-front proceeds into the un-reacted zone of explosive with a constant velocity of detonation D, where it is followed by a region of chemical decomposition reaction. In order to proceed the detonation wave ahead, and the velocity in the reaction zone must be equal to the sigma of velocities of sound in that particular material and flowing explosive materials/medium ($D = U + c$) where c is the velocity of a sound wave in that particular medium, U is the velocity of the flowing particles and D is the steady state velocity of the wave front. If the particle velocity (U) of explosive decomposition particles is too low then it is difficult to maintain velocity (D) self-sustained as the shockwave generated in the process will be weak enough that it will approaches/equalizes to speed of sound. Under such conditions no detonation will take place. Conversely when the velocity of the explosive particles (U) is high, the shock front of wave will travel at a much higher speed that of sound and under such conditions, the detonation takes place. The basic physical properties of conservation of energy, mass and momentum across the shockwave with the equation of state for the explosive ingredients (describing the way, how fundamental parameters affects each other) are practically applied, then it may be observed /seen that VOD is found by the material constituting the explosive and the velocity of material itself.

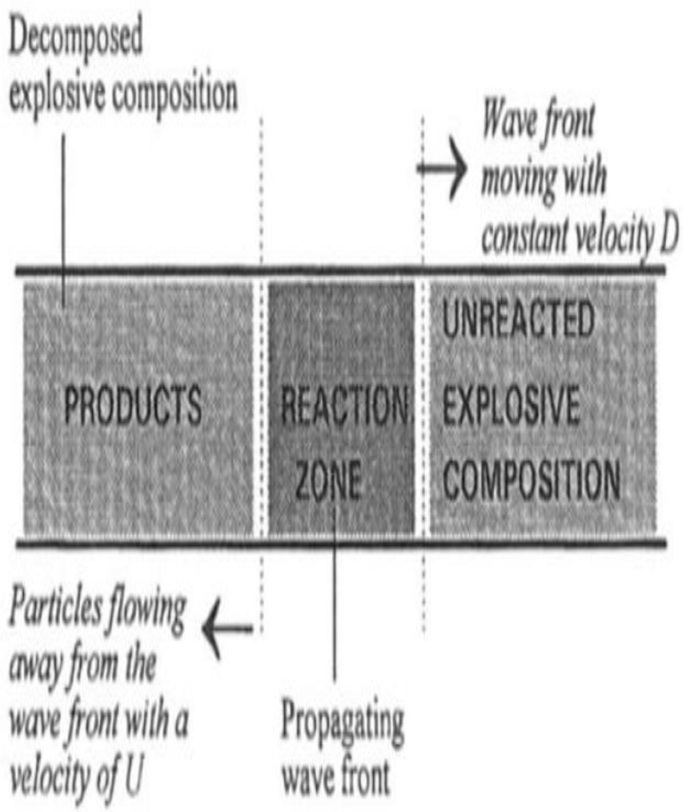


Figure 1.3: Detonation wave.

d. Temperature Effect:

VOD has inversely proportional to the temperature as the temperature increases, the density of explosive material decreases thus the reducing the velocity of detonation. Although the effect is small enough that normally doesn't cater in the evaluation & calculations, typically various data reveals that the change in detonation velocity per unit change in temperature ($\Delta D/\Delta T$) is in the range from -0.4 x 10^3 to -4.0 x 10^3 km/s/°C.

e. Geometry (L/D) Effect:

When a cylindrical explosive pellet is initiated from one end while placing the detonator on the center, it is expected to grow the detonation spherically outside from the point of initiation (center) initial stages, but after going certain distance the detonation ends to raise any more spherically and preserves a constant radius of curvature at detonation front. If the radius or diameter of explosive charge is increased, the point travelled out more but the relationship of radius of curvature to charge diameter remains constant. The rate of change of this ratio is different for various explosives and depends probably the reaction –zone length (etc) of that particular explosive.

f. Effect of Confinement:

The Velocity of Detonation (VOD) is a strong function not only of the charge radius but also the nature and thickness of the confining material. Confinement of an explosive in an external material housing while detonating increases the detonation velocity and bring it closer to ideal performance. It helps reduce explosive quantity to an optimum level of maximum performance, avoids wastage at the same time. As explosives are generally used with some confinement, the confined value of VOD is of more important. Upon detonation of an explosive charge without any confinement, the low molecular gaseous products of detonation expand quickly and due to lighter medium of air rarefaction waves tailor the shock front very soon resultantly VOD is reduced. In contrary to above, when an explosive is detonated in confinement, shock front or detonation waves reflects from walls of confinement. This quick reflection of the shock-wave from opposite walls, results into multiple punch effect on another wall. Moreover, confinement slows down the retardation of temperature and pressure just behind the detonation/shock front, thus increases the rate of reaction consequently increasing velocity of detonation. In this research we will try to find out the effect of confinement of VOD of a selected explosive. All the parameters like density, diameter, explosive, geometry and temperature will keep constant whereas medium of confinement will be varied by using unconfined, confined with paper, polymer, aluminum and steel. The achieved parameters (VOD) will be analyzed and results would be concluded accordingly.

1.6. Aim of Present Study:

As already mentioned, that VOD of an explosive is greatly influenced by various parameters mainly density, diameter & mass of explosive and confinement & confinement material made on the explosive charge. Aim of this study is to examine & analyse the effect of confinement on the VOD in comparison to unconfinement and to evaluate the effect of type of confining material and its characteristics mainly density of that material. The VOD of Tetryl an high explosive has been theoretically estimated, measured experimentally and analysed. The explosive /Tetryl has been prepared by keeping its diameter, mass and length thus density constant and the confining material have been changed by using paper, polymer, aluminium and steel respectively. The degree of accuracy achieved also been evaluated when an fibre optic based VOD meter is used as in such type of instrument the data sensing and transmission is being carried out at the speed of light.

Chapter 2

Literature Review

Explosives are energetic materials and play a vital role in everyday life of the society. Its use rages from mining of important materials which includes metals and nonmetals and currently the mining industry uses about 90% of all explosives produced worldwide. [16]. Military uses for explosives are obvious and crucial, but there are hundreds of other uses that may not be as obvious: explosive welding, inflation of airbags in vehicles, avalanche control, opening oil wells, and demolition of structures, among hundreds of other uses. Modern life would not be the same without the use of explosives VOD is measured either by estimating theoretically by using available empirical methods with the help of characteristics of an explosive or experimentally by employing various methods.

Various important parameters characterize the performance of an energetic material, but one of precise interest is the velocity of detonation (VOD) or detonation velocity (D). Commonly explaining as the speed at which a reaction proceeds within an explosive and scientifically stated as "the shock front, chemical reaction and the leading edge of rarefaction wave are at equilibrium and moving in same direction is called detonation velocity". The detonation reaction consists of a shock wave immediately followed by a reaction zone moving into unreacted material and explosion products moving away from reaction zone. The shock wave initiates the chemical reaction in the explosive which rapidly changes the explosive compound into its product gases in the reaction zone [4]. The detonation velocity of an explosive is directly related to the power index of the detonation a key characteristic thus determines its engineering applications suitable for that specific explosive [17][18]. There are several factors which influence the VOD of an explosive which includes explosive material, diameter, density, geometry and confinement at a direct proportion and temperature in a reverse proportion. Moreover, there are several ways to measure velocity of detonation including fibre optic technique. The interest of this study is the use of various confinements and use of fibre optic technique. The fibre optic methods are attractive because they senses and transmitted the signals at speed of light and are relatively simple to use, inexpensive (provided that the test facility has a high speed camera), and can be used for a wide variety of scales [14] .

Since the early era of study mainly 1940s, many methods have been developed to determine the detonation velocity of explosives. Several traditional ways are presented, concluding with the unique fibre optic techniques employed for this research. VOD of various explosives are well established at its TMD and processed densities too. In this study Tetryl has been used and its VOD at TMD is predetermined as 7570 m/s whereas the VOD of same explosive at processed density of 1.5 g/cm^3 (approximate) is narrated the value ranging from 7080 m/s [15] and 7160 m/s [10]. The estimated values by using theoretical methods for same explosive at same density found to be 6870 m/s [10], 7174 m/s [12] and 7267 m/s [4]. The VOD under confinement has been studied by Paul Cooper [4] and H Jones [23]. Validation of the VOD under confinement for commercial explosives has widely been studied for a single type of confinement whereas study for a military high explosive the same is somewhat limited as the same has either not conducted or conducted with single confinement only.

2.1 Estimation of VOD by Theoretical Methods:

VOD of an explosive can be estimated theoretically rather detonating the explosive experimentally. Several methods have been proposed by various authors which includes Rothstein, Xiong, Stein, Keshavarz, SG Murray, Cooper, Terry Gibs, P. Clark Souers and Jones [4][8][10][12][21] and can be used for conventional explosive molecules like Tetryl. These methods are good starting points and help finding the detonation velocity, and few of which may be accurate or close to accurate, while some may not due to certain constraints in the applications. The estimation method of calculations set by Rothstein applies the chemical formulae, chemical structure, and physical condition of the explosive material to determine velocity of detonation at the TMD of the explosive compound. The data required is the formula, nature of molecular compound that whether the compound is aromatic, and physical state that whether it is a liquid or solid. As the density has an important relationship with detonation velocity, particularly the density differences for a single explosive compound. The relationship of VOD is somewhat linear for many explosives for a rational variety of density. Paul A Cooper states that “a” and “b” are two empirical coefficients which are dedicated to the explosive itself, are the basic parameters required to estimate velocity of detonation (D) subject to the fact that density (ρ) is known. The formula is:

$$D = a + b\rho \qquad (2.1)$$

However various other formulae are also valid for VOD calculations at a given density other than its TMD and stated as under:

$$D_1 = D_2 + 3500\,(\rho_1 - \rho_2) \qquad (2.2)$$

$$D = 2742 + 2935\,(\rho_o) \qquad (2.3)$$

$$D = Di - a\,\frac{Di}{d} \qquad (2.4)$$

Equations (2.2 to 2.4) have been suggested by SG Murray, Terry Gibbs and Paul Cooper respectively [10][12] [4]. Other methods set by Kalmet [22] are based on specific order to determine the detonation decomposition products and to calculate velocity of detonation. In order to get a reliable result, the chemical reaction involved in detonation process must be balanced on both side of equation and heats of detonation with initial explosive density and molecular weights are parameters must be known. All of these methods calculate the VOD of an explosive at a given density which is achievable and usually lower than TMD.

In order to calculate VOD with confinement, methods suggested by Paul Cooper & Jones [4][23] give practical approach and can be verified experimentally with the help of a single or multiple methods /instruments. The equations studied by aforesaid authors are as under:

$$D = Di\,\{1 - 8.7\,(\frac{We}{Wc})\,(\frac{a}{d})^2\} \qquad (2.5)$$

$$We = \pi\,\rho_o\,Ro^2 \qquad (2.6)$$

$$Wc = 2\,\rho_m\,R_o\,\mathbf{x} \qquad (2.7)$$

2.2 Experimental Techniques:

Velocities of detonation were first measured by Berthelot and Vieille,4 who worked first with gaseous explosives and later with liquids and solids [24]. The VOD calculation methods on experimental basis are relied purely on physical characteristics of that particular explosive which only occurs upon detonation and the basis of these resultant output characteristics of explosion which could be:

a. Emission of various light beams like infrared, visible, ultraviolet.
b. Bang or blast Sound.
c. Pressure - Shock wave
d. Air ionization
e. High temperature

All the aforesaid parameters, progress in synchronization/association with the detonation wave less the sound waves; hence any of parameters stated ibid, could be used to determine the VOD (velocity of detonation). The sensors detecting the detonation/shock wave front depends on various physical output characteristics such as the illumination produced at or near the detonation front, the pressure that causes a discontinuity in the impedance of a sensing cable or some form of electrical continuity due to air ionization caused by explosion or disruption formed by the propagating wave front. Data so obtained from such measurements is then plotted against the time period of explosion thus VOD can be calculated. Derivation of accurate VOD by the appropriate measurement methods will consequently reduce the consumption of explosive materials. Although measurement of VOD by experimental method is time consuming, costly and safety risk, but the value obtained are much accurate than that obtained from theoretical methods. Although the accuracy may vary from instrument to instrument or method to method in addition to the fact that precision of test arrangements including data feeding, connectivity, placement of samples also play vital role in gaining a reliable and accurate results. Such factors have almost overcome by development of latest instruments mainly photonic and fiber-optic based instruments. These instruments are trouble free, easy handling and user friendly in addition to its reliability.

2.2.1 Boulenge Chronograph

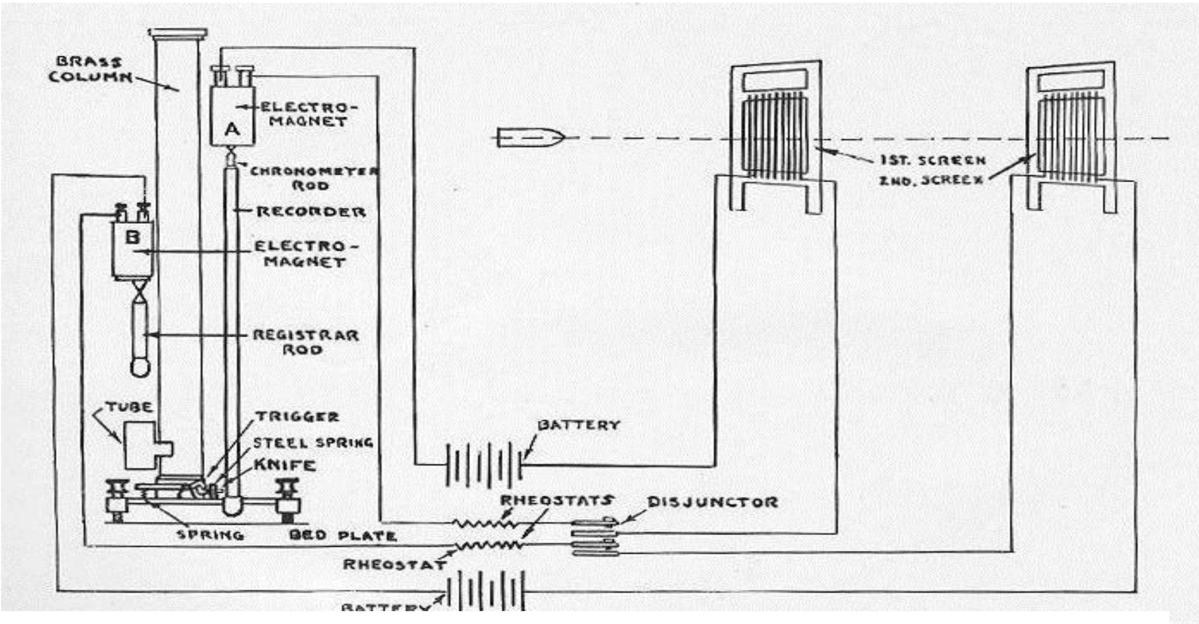


Figure 2.1: A Boulenge Chronograph

VOD was measured 1st time with gaseous explosives and later on with liquids and solid explosives by using a Boulenge. Chronograph. The precision of this instrument was such that they have to employ long columns of the explosives. Tests have been outlined by Tenney L Davis and Munroe & Tiffany [24]. The same was later on replaced by Mettegang Recorder is being commonly used for such measurements is a gadget of better accuracy and enables to record velocity of detonation by using a shorter cartridge of the explosives. This apparatus consists heavy cylinder of steel essentially strong, smartly turned and balanced, is rotated by an electric motor at a high but known velocity. The explosive under test is loaded in a cylindrical cartridge. When the explosive is fired by means of an electric detonator at the end of the cartridge, the wires of chronograph is broken by the explosion, and two spots are marked on the rotating drum. The distance between these marked spots of smoke is measured with a precision measuring instrument like micrometer. The time duration corresponding to movement of surface of the rotating drum is calculated, and this is time which is required for the detonation of the explosive column of identified lengths laying among the 2 x cables. The velocity of detonation VOD can be is computed in m/s.

2.2.2 Dautriche Method:

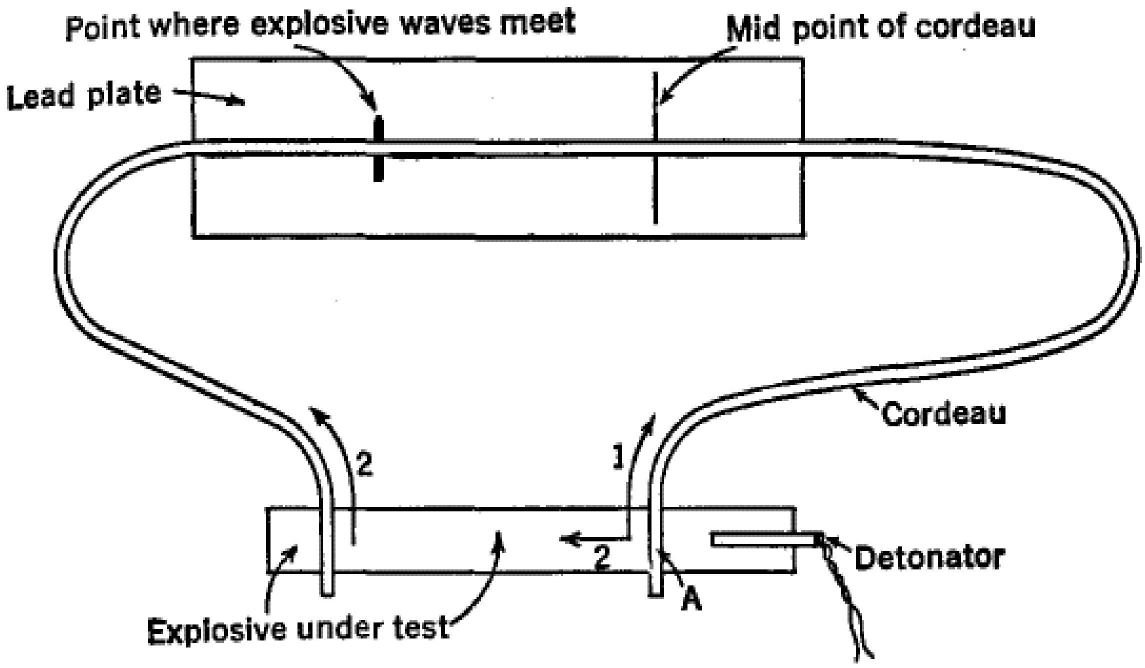


Figure 2.2: Dautriche Method of Measuring Velocity of Detonation.

Chronographs being heavy, difficult to assemble, time consuming and expensive, method of Dautriche described by Munroe & Tiffany and Tenney L Davis, has a wide application. This is among one of the oldest methods, easy to operate and reasonably accurate is used extensively all over the world. In this method a known length of Detonating Fuse Cord (DFC) approximately 2 meters with a predetermined VOD is identified and its mid-point is marked, placed / bound to an aluminum plate with the centre point marked on the plate at one end. The opposite ends of the DFC are then inserted in the explosive cartridge at a redecided distance from each other. The detonation wave in the explosive cartridge initiates the two DFC ends chronologically. The shock wave thus induced by detonation in DFC collides at a point on the aluminum plate. This collision distance is marked and measured from midpoint and is directly proportional to VOD. The formula is VOD = V x (m/2a) [24].

2.2.3. Discrete Point VOD Systems

This equipment is an improved and digital version of Dautriche method in which the digitally supported start and stop timer is used rather the dent impression and worked as chronometric principle. The 1st end of cable is implanted into the explosive column at predetermined points and another end to the VOD recorder where the digital signals of start and stop are recorded. Upon reaching signal at first sensor timer clock starts and while reaching at the next sensor, the clock is stopped. The timer interval (t) between start & stop is recorded. Since the distance (d) between sensors is known; hence VOD is calculated with simple relationship of distance over time.

2.2.4 Resistance Wire Continuous VOD System.

Based on Ohm's Law, continuous resistance wire VOD measurement system works on voltage drop. The pressure of explosion provides electric short continuously along the sensor path, instigating a reduction in sensor length ultimately continuous voltage drop under constant current excitation. The measurement and recording of the voltage drop w.r.t time gives the VOD at any instant. This enables to record a continuous VOD.

2.2.5 Time Domain Reflectometer

This method works on the generation of a narrow electric pulse & recording of reflected pulse. This method is a cable free sensing system and is one of the safest methods used with any military or commercial explosive. The instrument as well as the method is appropriate to measure the VOD in numerous slums within a explosion. In order to keep the instrument safe due care must be observed with respect to the initiation order and the likelihood of cut-offs that may disturb the cable. Experiments have been carried out with VOD sensors constructed by a high resistance Ni-Cr wire with a 1.6 mm diameter, 90 cm long brass tube and crimping both at one end to ensure electrical connection with the brass tube acting as a return lead.

2.2.6 Sliffer Continuous VOD System

This system based on oscillation frequency, mainly contains of reduced length of co-axial wire as a sensor in the explosive which is further linked to the oscillating circuit. This minute device displays the occurrence as a function of sensor length in the explosive column with a revers rate, as the length of wire reduced the frequency of oscillation increases. The frequency then can be measured as a function of time and the rate of cable length change, leading the direct measurement of VOD. The system remained limited to laboratory work only.

2.2.7 Rate Stick or Cylinder Test Method:

Figure 2.3: Rate stick demonstration cylinder

The rate stick method is a VOD measuring instrument and is among the one of most common instruments or methods to measure detonation velocity or cylinder test, outlined by “Paul A Cooper and “Karnowski”[4]. In this method a copper cylinder with predrilled holes is loaded with a known explosive. There are several pins which are being hold by pre-drilled holes of cylinder at known distances apart from each other. The detonation proceeds down from one end, the pressure probs are activated, and the time is measured by an analyzer attached to the sensing probes /wire. As the times and distance between the pins are known thus velocity can be calculated.

2.2.8 Velocity Interferometer System for Any Reflector (VISAR):

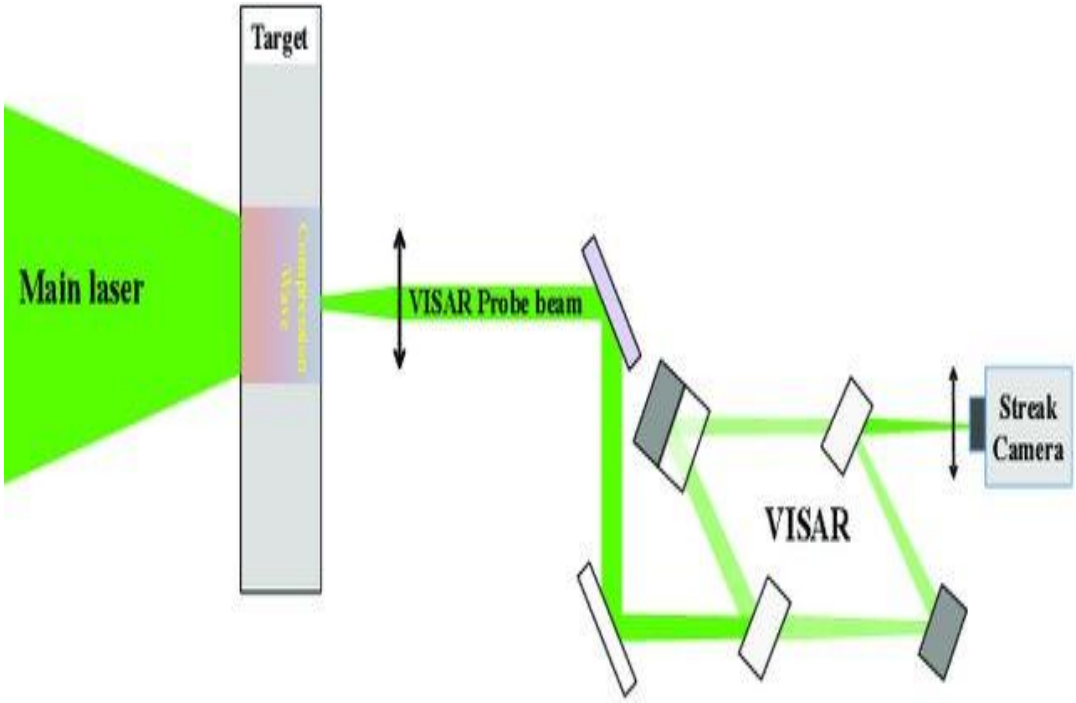


Figure 2.4: Schematic experimental set up where a Velocity Interferometer System for Any Reflector (VISAR) was used to record the target free surface.

It is one of those methods which determines VOD by measuring particle velocity. A PMMA (a transparent thermoplastic) mirror is placed onto a window facing the explosive. A laser is bombarded on the reflecting glass and the same is mirrored back to the recorder. As the detonation wave approaches the reflecting glass, the same moves, and the frequency of laser is somewhat lifted due to the doppler effect and sensed through VISAR instrument. The mirrored velocity can be calculated from the Doppler change. This data is transformed to the interface versus time waveform.

2.2.9 Photon Doppler Based Velocimetry (PDV)

It is one of novel technique which replaced the VISAR and other interferometry techniques in various applications. This method is fundamentally a Michelson interferometer functioning at very high speed and is totally walled in an fiber optical system. Instead of relying only on single laser in previous method, double light bases are joint together. 1st is used as a reference light source that is not being Doppler shifted whereas 2nd illuminating source is reflected back from the moving exterior and is influence by a Doppler shift. The signals are documented and examined with a high-speed digital analyzer using Fast Fourier Transform (FFT) technique then frequency versus time data is displayed as output. VOD is found by multiplying this frequency with ½ wavelength. The system due to its small size, portability, wide VOD measurement capability and good resolution has advantages over other techniques thus are being used extensively for measurement of VOD.

Figure 2.5 Photonic Doppler Velocimetry Module

2.2.10 Fiber-Optic Method

This particular method uses a fibre optic wire which is proficient of initially detecting (probe sensing) and subsequently conveying a light signal associated with detonation wave front. The method is a point-to-point chronometric type instrument where the 1st cable signals the start whereas the 2nd cable placed at a known fixed distance stops the timer of chronometer. The predetermined distance between two fibreoptic probes is rated by the timed clock directly calculates & displays the VOD. Explomet-Fo-2000 works on electro-optical method tailored with a electronic timer or chronometer. The device can measure VOD between one segment to five segments with the help of two to six probes/cables. The method measures time between the start & stop of detonation and analyses VOD with the help of already fed distance between two points. The key advantage of fibre-optic based system is that the data/incidence is sensed and transmitted to the electronic chronometer at the speed of light causing less variation due to change of distance /length of test setups or any other reason extremely low least measurability of time up to 10 sec with precision of ± 0.1 μs thus resulting into most accurate and consistent results of measurements. The Explomet-fo-2000 is calibration free instruments and works in two modes:

a. Time only:

The optic fibres are illuminated randomly. The instrument measures the time period between the illumination of 1st and 2nd probe /fibre, then between 2nd & 3rd one and so on until last /6th fibre. In this mode the instrument only displays time interval between each incident and VOD can be calculated manually when the distance between each segment/incidence is known by using the simple formula of V = S/t.

b. Velocity and Time:

In this mode the 1st optic fibre is illuminated 1st which starts the time cycle and the last fibre (either 2nd or 6th whatever is the condition) stopes the chronometer/analyser. The distance between all segments is fed before firing. The instrument measures time intervals between the illumination of two consecutive optic fibre probes then subsequently calculates the VOD of each segment in m/s. In this mode the distance between each segment should be fed into the meter /analyser. The illumination must be made sequentially in ascending order. If it is desired to measure VOD by using 2 probes for a single incidence than 1st Prob must be illuminated first by placing the same at the face of explosive and 2nd one at base end.

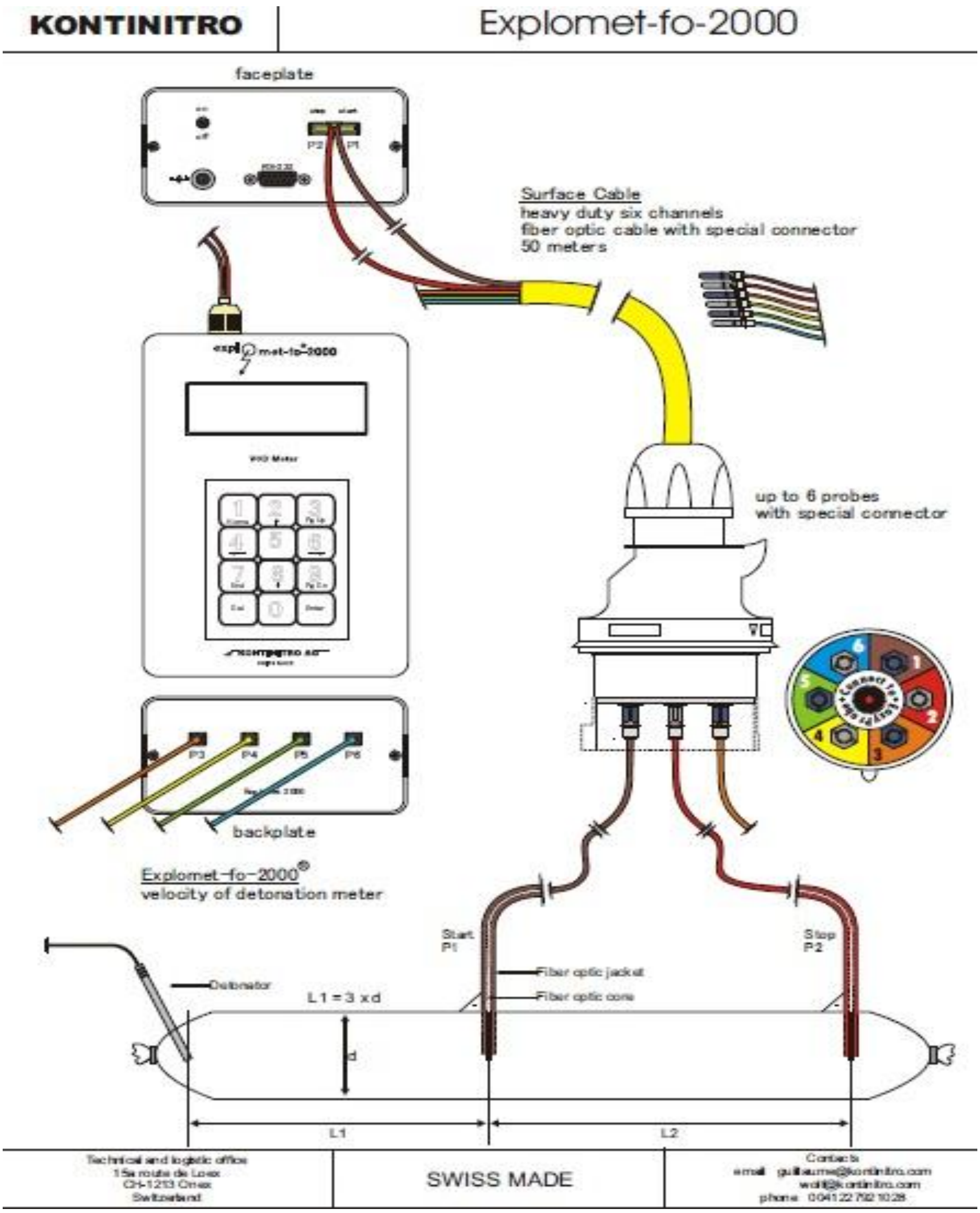


Figure 2.6 A fibreoptic based Swiss Made VOD meter Explomet-fo-2000

Chapter 3

Experimental

3.1 Theoretical Method for Estimation of VOD:

3.1.1 Unconfined Estimation:

The Velocity of Detonation of Tetryl has been estimated theoretically by using various methods or empirical formulae as already discussed in Chapter 3. Various known values have also been taken from available literature and works including SG Murray in “Explosives, Propellants & Pyrotechnics”. The values estimated theoretically obtained are tabulated in Table 4.1. The VOD of tetryl at its theoretical maximum density TMD has been taken as 7570 m/s whereas the value mentioned by SG Murray in aforesaid book is 7160 m/s at density of 1.5 g/cm^3. Different values have been measured theoretically by using various methods and available data. The calculations and data are as under:

a- Known Data unconfined values:

VOD of Tetryl at TMD = 7570 m/s -----------------(1)

VOD of Tetryl at 1.5 g/cm^3 = 7160 m/s ----------------(2) [10]

VOD of tetryl at 1.55 g/cm^3 = 7080 m/s -----------------(3) [15]

b- Measurements for unconfined values:

i- $D_1 = D_2 + 3500 (\rho_1 - \rho_2)$ [10]

$D_1 = 7570 + 3500 (1.51-1.71) = 7570 -700$

$D_1 = 6870$ m/s ----------------(4)

ii- D= 2742 + 2935(ρo) [12]

D= 2742 + 2935 (1.71)

D = 7174 m/s -------------(5)

iii- $D = Di - a \frac{Di}{d}$ [4]

$$D = 7570 – 1.0 (7570/25)$$

$$D= 7267 \text{ m/s} \qquad \text{---------------(6)}$$

As already stated ibid, VOD of Tetryl at TMD of 1.71 ~ 1.73 g/cm3 has been taken from available literature which is 7570 m/s and based on this, the unconfined VOD of same explosive at processed density of 1.51 g/cm^3 has been calculated. Various unconfined VOD are mentioned in table 4.1.

Table 3.1: The unconfined VOD of Tetryl from available data or theoretically measured

VOD	Equation/Method used	Density g/cm^3	VOD m/s
(1)	TMD	1.71 ~ 1.73	7570
(2)	SG Murray Table 2.3	1.50	7160
(3)	J Akhavan Table 3.2	1.55	7080
(4)	Equation 2.2	1.51	6870
(5)	Equation 2.3	1.51	7174
(6)	Equation 2.4	1.51	7267

VOD so obtained by Equation 2.3 has been taken as the VOD of pressed Tetryl at a density of 1.51 g/cm^3 and further calculations has been carried out on the basis of equation 2.5. the values of weight ratios per unit length of explosives have been calculated by using equation 2.6 & 2.7. Values so calculated are stated in table 3.2 & 3.3. The results in same tables reveal that VOD of an explosive simultaneously decreases as its density decreases and at the processable density, the VOD is substantially decreased. The VOD of Tetryl at density of 1.71 g/cm^3 (near to TMD) is 7570 m/s whereas measured VOD at density of ~1.51 g/cm^3 by employing available theoretical methods resulted as 6870~ 7267 m/s or 92~96 % of VOD at TMD.

3.1.2 Confined Estimation:

In order to analyse the effect of confinement theoretically major characteristics of confining materials have been sought and based on these data and employing the known methods the confined VOD have been estimated /calculated. The confining materials used are Paper, Polymer (PET based X-Ray Sheet), Aluminium & Steel. The only characteristic used in estimation is the density of confining material. Formulae mentioned by P Cooper's in Explosive Engineering [4], Also stated in equation (Eq 2.5) ibid has been used to estimate confined VOD theoretically.

$$D = Di \left\{ 1 - 8.7 \left(\frac{We}{Wc}\right) \left(\frac{a}{d}\right)^2 \right\} \qquad [4]$$

The We/Wc known as the weight ratios of explosive and confining materials have been calculated by using formula stated by P Clark Sours & Eyring as stated below:

$$We = \pi \rho_o Ro^2 \qquad [12]$$

$$Wc = 2 \rho_m R_o x \qquad [12]$$

We & Wc are narrated as weight per unit length of explosive and confining material respectively. The π is constant whereas ρ_o Ro^2, ρ_m and x are density of explosive, radius of explosive and density of confining material. and nd the weight ratios of explosive to confining material were calculated by using equations 2.6 & 2.7 described by P Clark Souers. In order to calculate the confined VOD, method described by P Cooper has been used, whereas the weight ratios have been calculated by using formula stated by P Clark Souers. The calculated values are as under:

$We = \pi \rho_o Ro^2 = 3.14 \times 1.51 \times (1.25)^2 = 7.41$ g/cm

$Wc = 2 \rho_m R_o x$

Steel = 2 x 7.8 x 1.25 x 1.5 = 29.4 g/cm

Aluminum = 2 x 2.8x 1.25 x 1.5 = 10.5 g/cm

Polymer = 2 x 1.5x 1.25 x 1.5 = 6.625 g/cm

Paper = 2 x 1.15x 1.25 x 1.5 = 4.125 g/cm

Consequently, the weight ratios We/Wc for different confinements have been calculated and tabulated in Table 3.2.

Table 3.2: Values of We/Wc for different confining materials

S#	Material	We/Wc
1	Paper	1.796
2	PET	1.317
3	Aluminium	0.706
4	Steel	0.2517

When these values of We/Wc and other values have been substituted in equation 3.5, the confined VOD for different confinements calculated and tabulated in Table 3.3. As an example, the calculation for steel confinement is given below:

$$D = Di \left\{ 1 - 8.7 \left(\frac{We}{Wc}\right) \left(\frac{a}{d}\right)^2 \right\}$$

$$D = 7570\{1-8.7(0.2517)(1/25)^2\}$$

$$D = 7543 \text{ m/s.}$$

Table 3.3: VOD with different confinements

S#	Confining Material	Density of confining material g/cm^3	VOD (confined) m/s
1	Paper	0.7	7380
2	PET	1	7431
3	Aluminium	3	7495
4	Steel	8	7543

3.2. Experimental Method for measurement of VOD:

Experiments have been performed by detonating the explosive pellet of Tetryl unconfined and by employing various confinement with the help of a fibre-optic based VOD meter. The results achieved have been analysed and compared with each other as well as with estimated confined & unconfined values. All the materials used for this study has been tabulated in tables 4.4 and confinements shown in figure 3.1.

Table 3.4: Bill of detail of Materials, Components & Test Setups.

S#	Component /materials	Spec/ Density g/cm^3	Source
1	Paper	1.15	General Trade items
2	PET	1.5	
3	Aluminium	2.8	
4	Steel	7.85	
5	Det holder wooden	General items	
6	Wire		
7	Electric Source		
8	Detonator	Det No 8 Electrical	POF made
9	Explosive	Pressed Tetryl	
10	VOD Meter	Explomet-fo-2000	NUST

The general / specific characteristics of all materials, explosives and equipment used have been deliberate and given in following tables. All the parameters of materials used have been have kept constant so as make the study reliable. In all 5 samples of each series all materials of confinement, explosives, initiators were used having same characteristics.

3.2.1 Specification of Materials:

The specifications & characteristics of all direct materials i.e Explosive, Detonator, Pellet and Materials of Confinements have been worked out and shown in tables 3.5 to 3.7.

Table 3.5: Specification of Tetryl

Name	2,4,6-Trinitrophenylmethylnitramine	
Grade	Granualted	
CAS No	479-45-8	
Appearance	Yellow crystalline solid	
Odor	Odorless	
Molecular formulae	$C_7H_5N_5O_8$	
Molar Mass	287.15 g/mol	
Density (Max)	1.71~1.73 g/cm^3	
Melting Point	129.5 °C	
Boiling Point	187 °C	
Figure of Insensitivity	90~100	
Power Index	123	
Heat of Explosion	4350 J/g	
Lead Block Expansion	340	
Ignition Temperature	180°C	
Uses	Booster Charge	

Table 3.6: Specification of Detonator 8E

Ingredients	AS Composition (14% Lead Styphnate & 86% Dextrinated Lead Azide)	350 mg
	PETN	675 mg
Functioning Parameters	Resistance	0.9 ~1.6 Ω
	Current	0.8 Amp
	Voltage	1.3 V

Table 3.7: Specifications Confining Materials

a- Aluminium		
Grade	LY11CZ	
Diameter	32mm	
Tensile Strength	372 MPa	
Yield Strength	215 MPa	
Elongation	12%	
Density	2.8 g/cm^3	
Ingredients %	Si	0.7
	Fe	0.7
	Cu	3.8~4.8
	Mn	0.4~0.8
	Mg	0.4~0.8
	Cr(Fe+Ni)	0.7
	Ni	0.1
	Zn	0.3
	Ti	0.15
	Total Impurities	0.1

b- Steel		
Grade	WMD305-1-5	
Diameter	32mm	
Tensile Strength	600 MPa	
Hardness	≤ 241 HB	
Elongation	≥6.5%	
Shrinkage	35%	
Desnity	7.8 g/cm^3	
Ingredients %	Si	≤0.2
	C	0.32~0.39
	Mg	≤0.6
	S	≤0.04
	P	≤0.035

c- **Kraft Paper**				
Characteristics	**Units**	**Condition**		**Values**
Basis Weight	lbsf/msf	-	-	50
Density	g/cm^3	-	-	1.15
Mullen	Psi	T403	Nominal	41
Percent Moisture	%	T412	Minimum	5
Elmendrof Dry Tear	Gf	T414	MD Nominal	117
			MD Minimum	75
			CD Nominal	126
			CD Minimum	85
Wet Tensile	lbf/inch	T494	MD Nominal	7
			CD Nominal	4

d- Polymer /PET based X Ray Sheet.
X-Ray Sheets display a radiographic image when exposed to a radioghraphic source. The X-Ray Sheets have various grades based on their utility mainly industrial & medical based sheets are extensively being used. It consists of silver halide (silver bromide ($AgBr$) emulsified in a cellulose triacetate or in a PET polyester which when exposed to radiographic rays, produces a Silver Ion (Ag^+) and an Electron. The electron so produced is further attached to the sensitivity flecks and attract the silver ions. Subsequently, the silver ions got attached and clusters of metallic silver (black) shades are formed Layers • Base: Cellulose Triacetate or Polyester • Substratum: An Adhesive layer containing gelatin and solvents that bind emulsion and base • Emulsion: Silver Halide and gelatin, with some hardening agents • Protective Layer: Gelatin • Density: 1.5 g/cm^3 The total thickness of the film is about 0.25 mm.

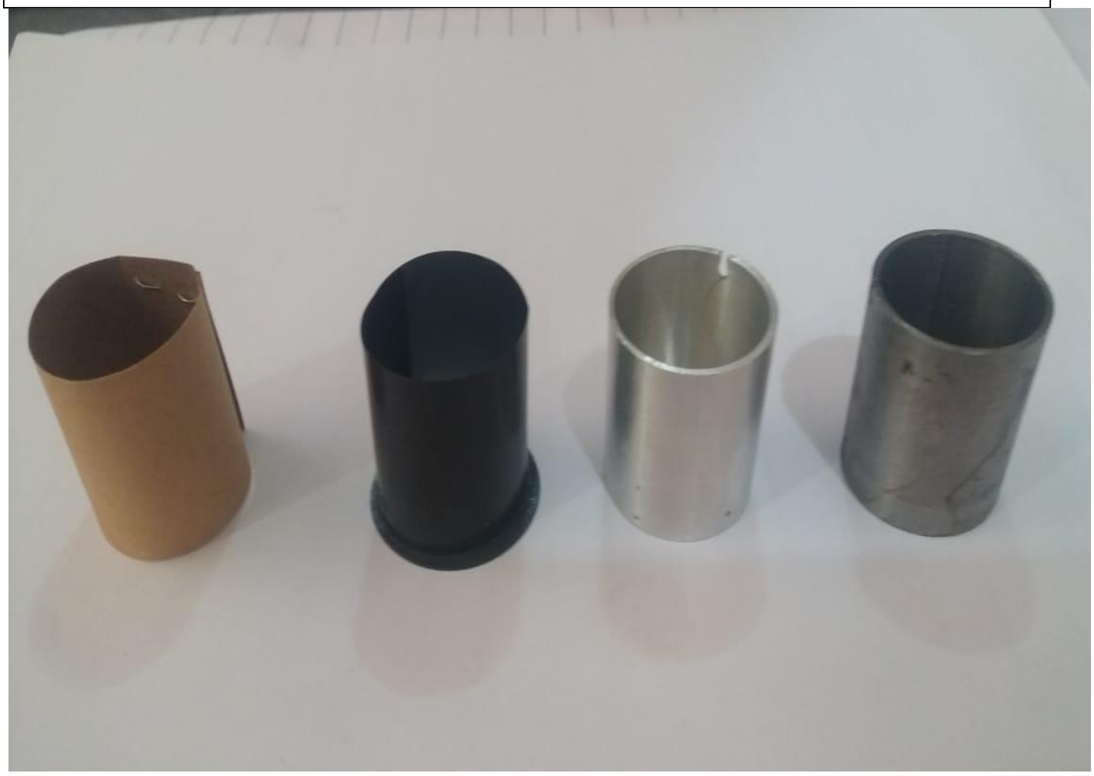


Figure 3.1: Confining materials with properly machined /fabricated.

Figure 3.2: Hydraulic Explosive Pressing Machine & Tools

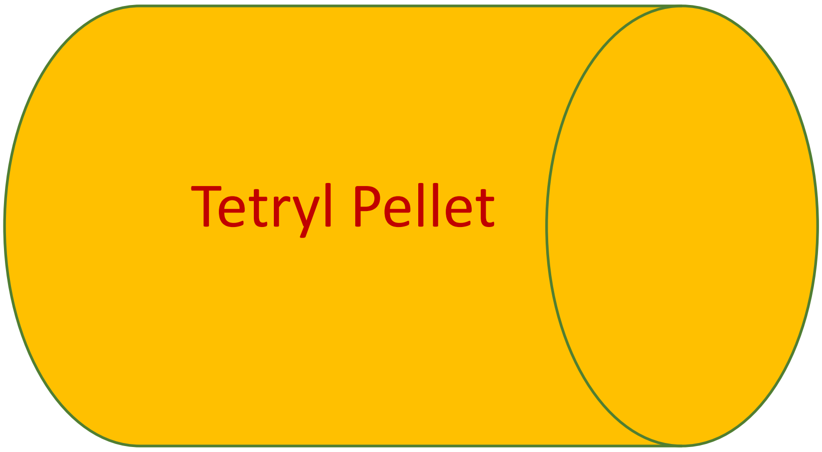


Figure 3.3: Pressed Tetryl Pellet at density 1.51 g/cm^3

Figure 3.4: Detonator Electric No 8E

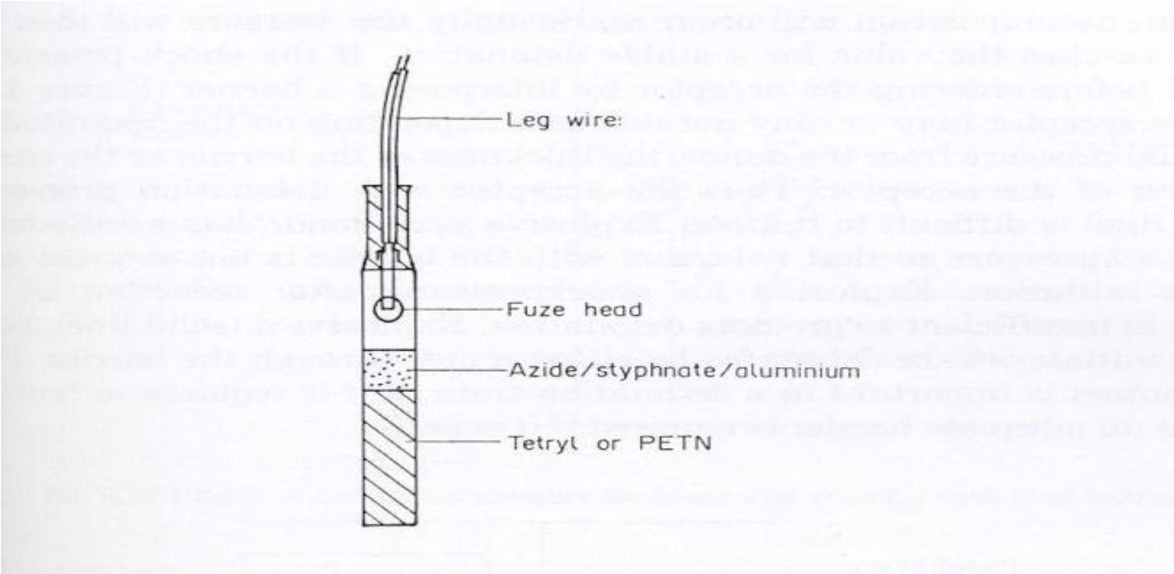
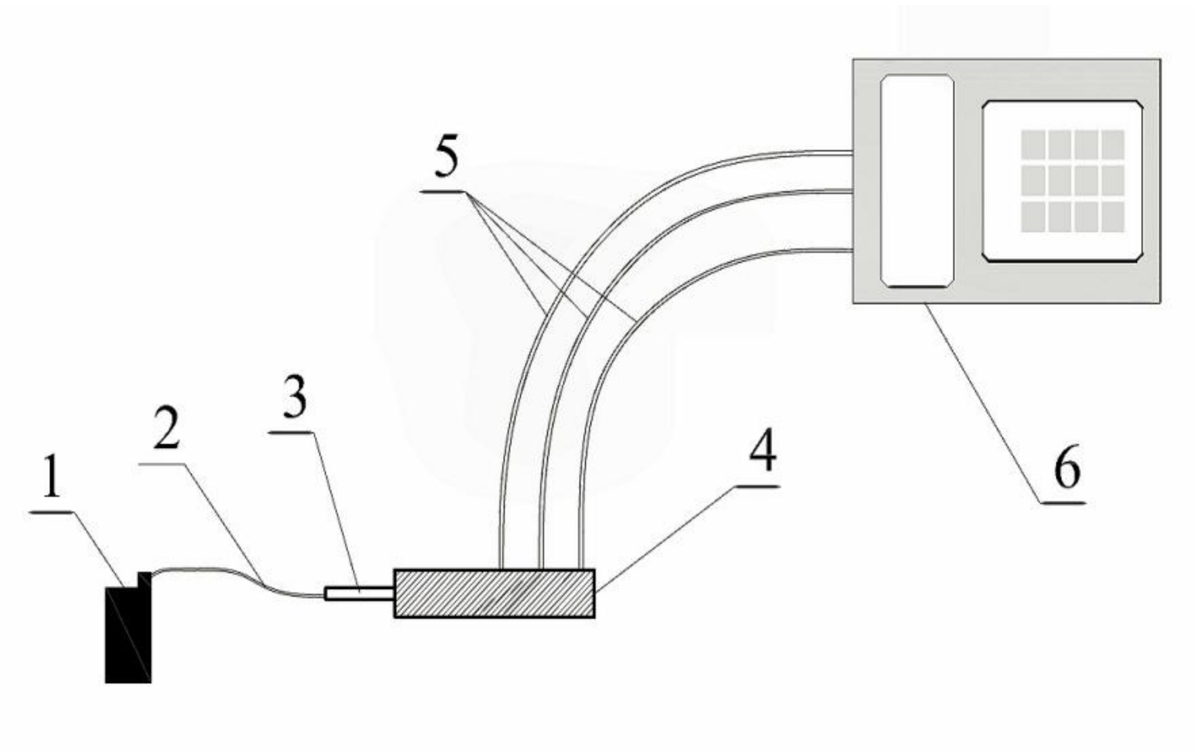


Figure 3.5: Detonator NO.8 (Electric) & Tetryl Pellet 22.3 g



1	Battery Low Voltage DC Electric Supply	2	Wire
3	Electrical Detonator 8E	4	Explosive Substance (Tetryl/CE Pellet)
5	Sensors (optical Fibre cables),	6	Explomet-fo-2000

Figure 3.6: Tests setup

The tests were conducted at POF Ranges Hasanabadal by following all safety & security SOPs.

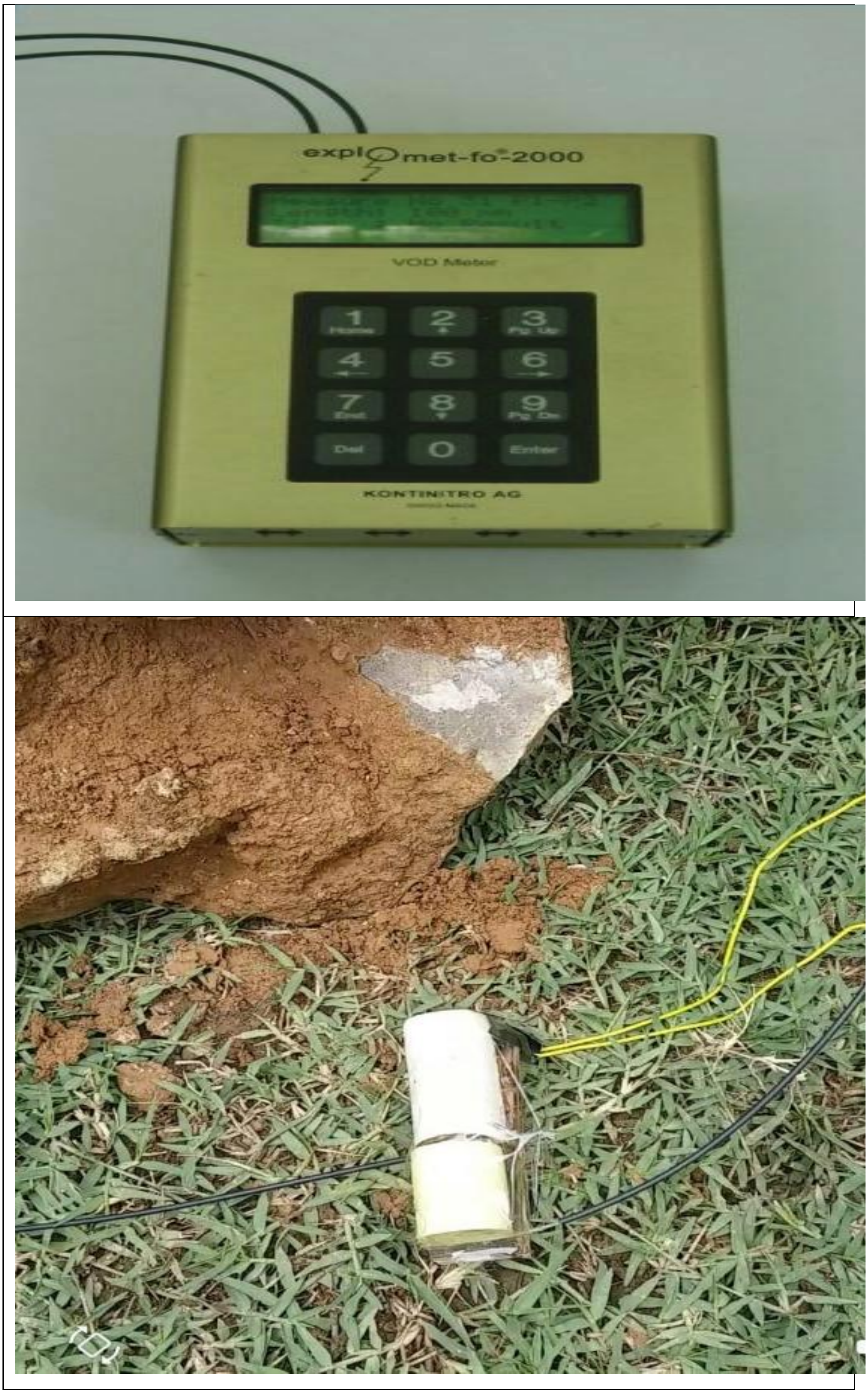


Figure 3.7: Explomet-fo-2000 & Test Sample ready to fire.

Tests were conducted in sequence given in Table 3.8:

Table 3.8: SOP/Sequence of fire.

1	Use Serviceable Tetryl duly qualified all tests mentioned in governing specification
2	Use machines & tools which are approved for designated pressing of tetryl.
3	Hydraulic System, instruments, weighing scales & Tools much be calibrated before use.
4	Ensure all safety measures during pressing & ejection of Tetryl pellets.
5	Measure the dimensions & weight of Tetryl Pellets and confinement materials.
6	Select Detonator Electric 8E from serviceable & qualified lot.
7	Counter check the resistance of electric squib of detonator, it should be within specified limits.
8	Pack all tetryl pellets & detonators in designated packings and seals must be affixed.
9	Arrange safe & secure transportation of energetic materials to POF Ranges Hasan-Abdal.
10	Make a survey of range and select a suitable & safe place for detonation.
11	Place the Tetryl pellet on the wooden detonator holder and fix it
12	Insert 1st prob at start face of pellet (between detonator & Pellet) and 2nd prob on the end face of pellet.
13	Insert Detonator in detonator holder, care must be observed that both terminals of wires must be tied to each other to ensure safety
14	Once the detonator is properly fixed open the wires and connect it electric supply. Safety procedure stated ibid must be followed in addition to that electric source /battery must be kept away until all individuals are protected. Must ensure that all individuals are under cover & Ambulance is ready.
15	Set Parameters on VOD meter and get it ready to measure
16	Give caution loudly or with a help of megaphone
17	Connect the wires with terminal of battery and push the fire button
18	Once the firing is done (Pellet detonated) get reading of time & VOD from the meter.

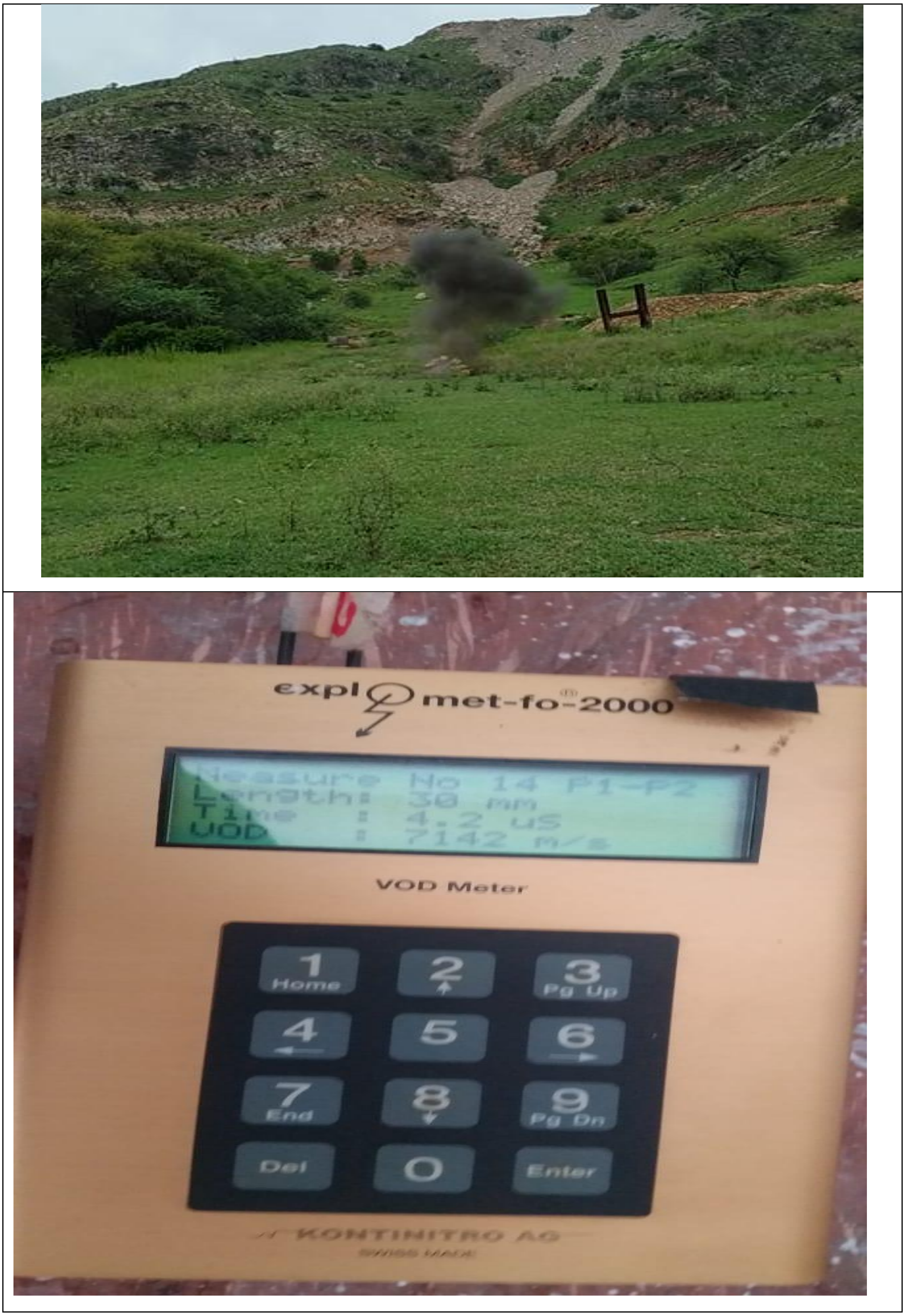


Figure 3.8: Firing & displayed/measured result.

Chapter 4

Results and Discussion

Velocity of Detonation (VOD or D) being an output physical parameter/characteristic of a detonation process of a high explosive is significantly influenced by various factors such as diameter, density, explosive type, temperature, Geometry (L/D) and confinement. The extend of effect has already been discussed in chapter 2. The research was aimed to evaluate the effect of confinement; hence the remaining factors were kept constant. Those influencing parameters of the explosive which have been kept constant during current research other than confinement has mentioned in Table 4.1.

Table 4.1: Characteristic of Explosive

S#	Characteristics	Units	Values
1	Diameter of charge	Mm	25
2	Length	Mm	30
3	Weight	G	22.3
4	Density	g/cm^3	1.51
5	Geometry L/D	---	1.2:1
6	Temperature	°C	(25~30) Ambient/Atmospheric
7	Type of Explosive	-----	Aromatic (Tetryl)

The confinement has been carried out by using Paper, Polymer sheet of PET, Aluminium and steel. The detailed specifications mentioned in table 3.7.

4.1 Empirical /Theoretical Results:

As per the available literature and known data, the VOD of Tetryl is 7570 m/s at TMD of 1.71 g/cm^3. The VOD at a processed density (1.51 g/cm^3 in this case) has either taken from known data or been worked out by applying the known methods /equations.

4.1.1. Estimation of unconfined VOD:

The values estimated by using different methods & formulae has already stated in Table 3.1. It is known and observed that the detonation performance thus the VOD of an explosive is directed related to its density. Theoretically the VOD of Tetryl an eminent high explosive mainly used as booster or intermediate at a density of ~1.5 g/cm3 drops significantly. The drop values fall within 300 to 600 m/s at corresponding fall in density of 0.2 g/cm^3, or expressly we can see that 4~8 % drop in VOD by drop of 12% of density. The VOD of Tetryl at processed density has variations from data source to source or estimation method to method. This variation in values are the results of non-verification of methods experimentally or use of less accurate and complex instruments for experiments & measurements. Such accuracy issues have been addressed by developing latest & accurate techniques with least variations particularly employing the fibre-optic technics as fibre optic cable has dual performance that is sensing & transmitting the data signals at the speed of light.

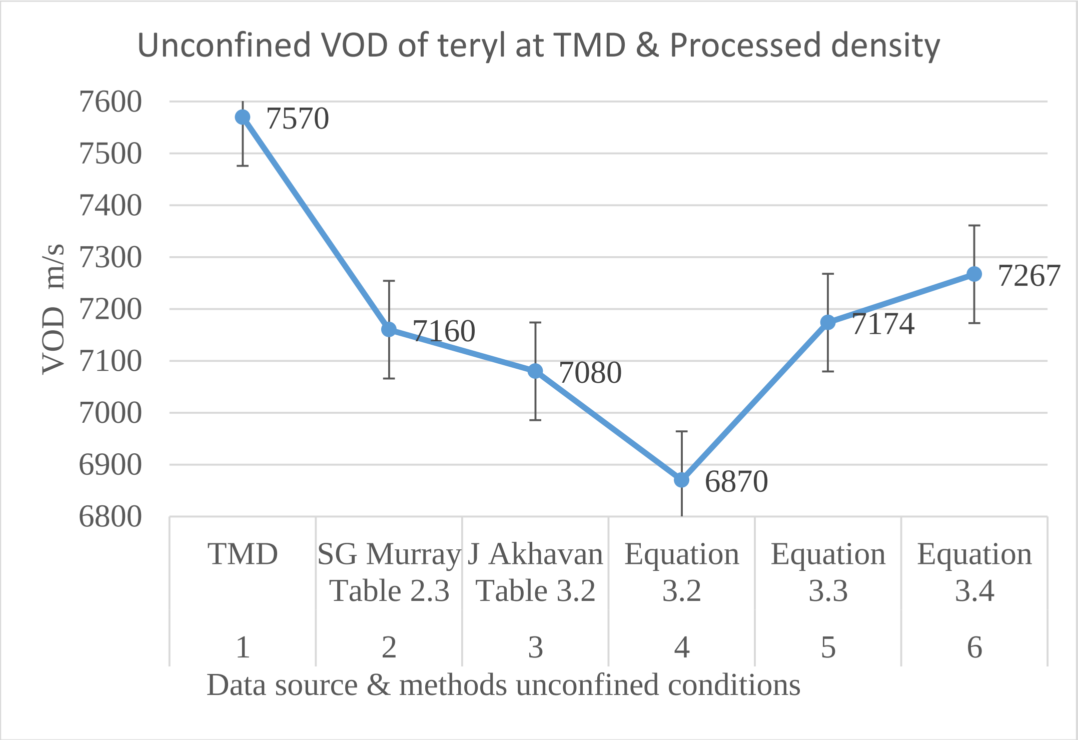


Figure 4.1: Variation of VOD at TMD vs estimated VOD at processed density and by applying different methods.

4.1.2 Estimation of confined VOD:

This reduced VOD ultimately compromises the detonation performance of explosive. In order to subjugate this issue of lowered performance of explosive, various performance enhancement methods have been studied out of which confinement of explosive is one of most suitable, safe and easy method. The use of estimation methods mainly stated by Paul A Cooper & P Clark Souers as shown in Table 3.3, reflects the results of confined VOD of Tetryl with different confinements. As we have already discussed that the VOD at a density of 1.51 g/cm^3 is less than that of at TMD by a value of approximately 300 ~600 m/s (4~8%) and by confining the same explosive in different confinement, the VOD recuperates its value near to its TMD value with an almost linear relationship but fluctuates substantially for different confinements. The major change is witnessed with the confinement of lowest density & strength material i.e paper. Later on the VOD tends to increase with increase in density & strength of material used, although relationship is linear but with a lesser rate. The highest value observed is for steel with highest density and hardness.

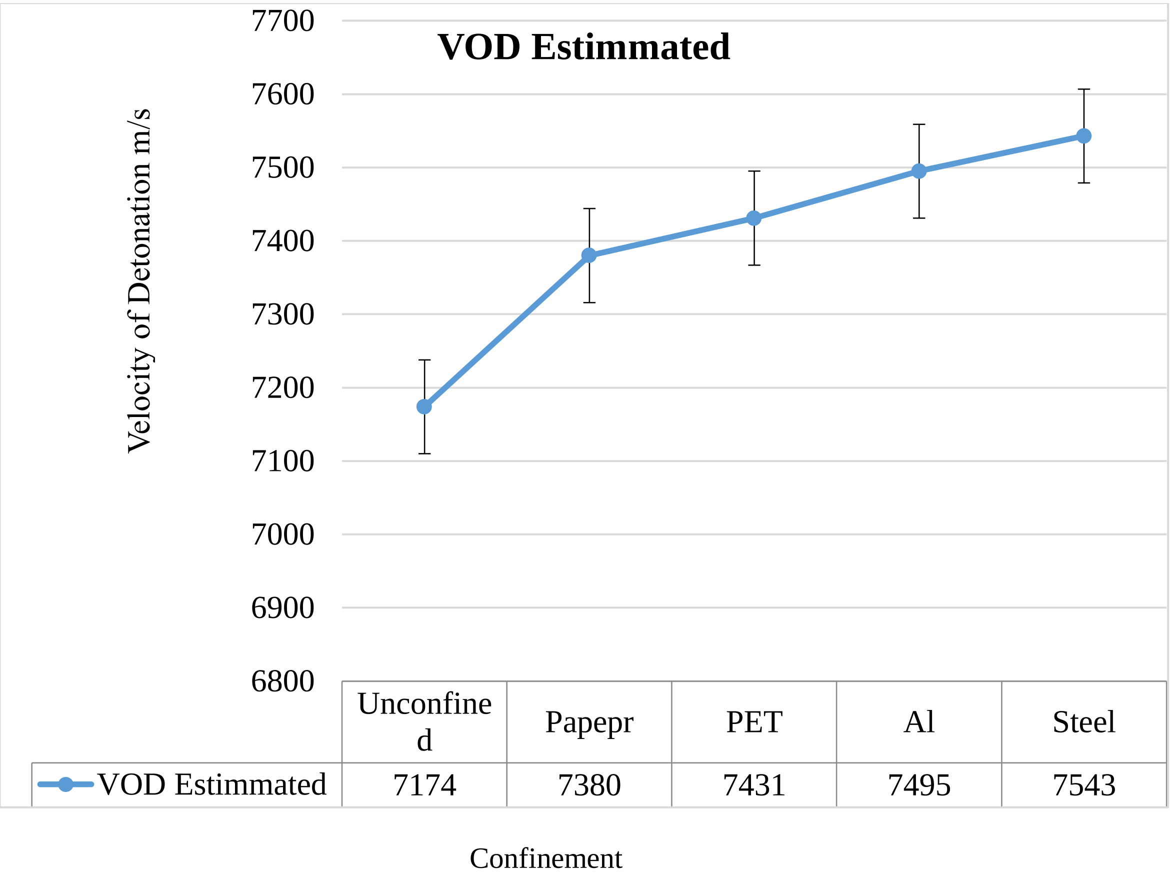


Figure 4.2: Effect of confinement on theoretical VOD of Tetryl

During estimation it has been observed that the density of confining material has a direct relationship with the estimated VOD of explosive whereas the We/Wc weight ratios of explosive to confining material has a reciprocal relationship with VOD. This relationship is described in Fig 4.3.

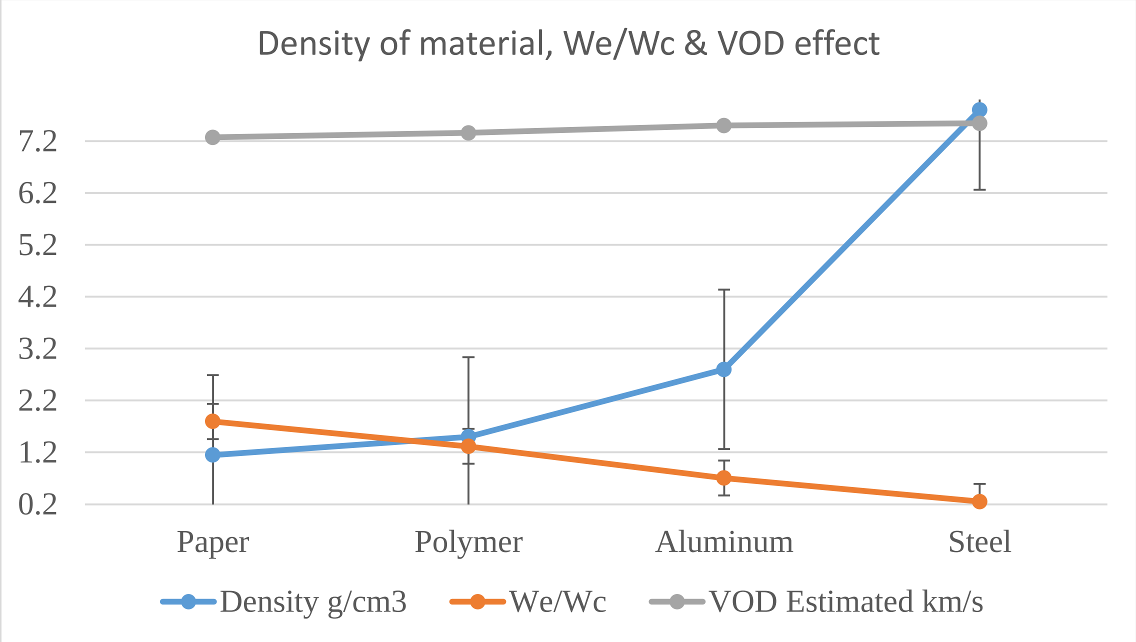


Figure 4.3: Relationship between confined VOD and density & weight ratios of confinement

4.2. Experimental Results:

In order to validate the values obtained from empirical method, various experiments have been conducted by employing different confinements on a single explosive. The measurements have been made by a fibre-optic based VOD meter Explomet-fo-2000. Accordingly 05 x samples with each combinations of unconfined, confined with paper, polymer, aluminium and steel were prepared and fired with the help of electric detonator No 8E by employing aforesaid fibre-optic based instrument the results so measured are tabulated in Table 4.2 and analysed the behaviour graphically in Fig 4.4. the graphical representation shown that the confinements have greatly influenced the VOD of tetryl. The enhancements in VOD are relatively lesser for paper & polymer i.e. non-metallic materials whereas the increased VOD for metallic confinement particularly with steel is significantly higher and near to its TMD values. The variation within measured values is least when the explosive is confined with steel.

Table 4.2: Experimental VOD with different confinement.

Sample No	VOD m/s				
	W/o Confinement	Paper	PET/Polymer	Aluminium	Steel
1	7142	7370	7365	7497	7535
2	7120	7395	7430	7479	7515
3	7185	7360	7405	7471	7509
4	7135	7325	7390	7463	7521
5	7150	7365	7410	7447	7565
Mean	7146	7363	7400	7471	7529
Variation	65	70	65	50	56

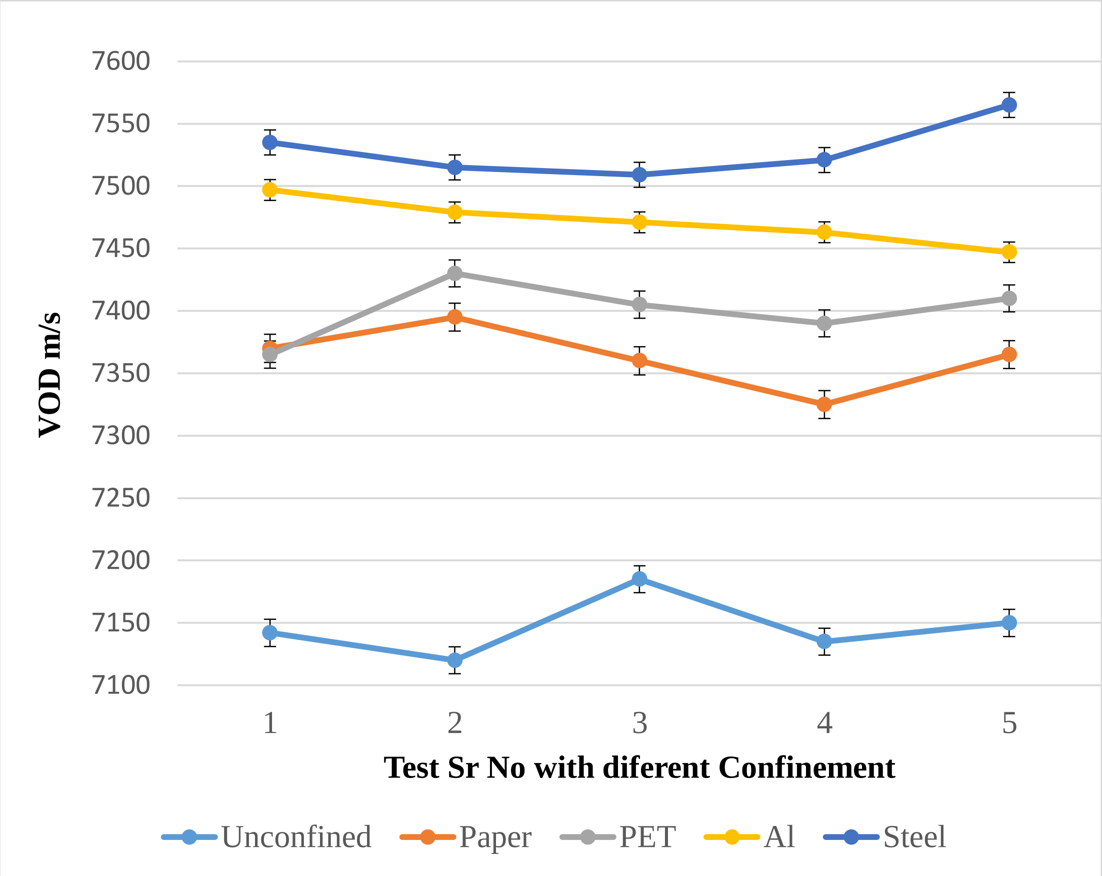


Figure 4.4: Effect of confinement on VOD of Tetryl.

This increment caused by confinement has been re-evaluated by ordering results achieved in experiment as stated in Table 4.3 & Fig 4.5.

Table 4.3: Variation of VOD in Different Conditions.

Confinement	Test Sample #	VOD m/s	Mean VOD m/s	Δ VOD w.r.t VOD TMD & Estimated at 1.51 g/cc
Unconfined @ (TMD)*	01	7570	7570	-
Unconfined @ 1.51 g/cc#	02	7174	7174	-396*
Unconfined	1	7142	7146	-424* -28#
	2	7120		
	3	7185		
	4	7135		
	5	7150		
Confined with Paper	6	7370	7363	-207* +189#
	7	7395		
	8	7360		
	9	7325		
	10	7365		
Confine with Polymer /PET	11	7365	7400	-170* +226#
	12	7430		
	13	7405		
	14	7390		
	15	7410		
Confined with Aluminium	16	7497	7471	-99* +297#
	17	7479		
	18	7471		
	19	7463		
	20	7447		

Confined with Steel	21	7535	7529	-41* +355[#]
	22	7515		
	23	7509		
	24	7521		
	25	7565		

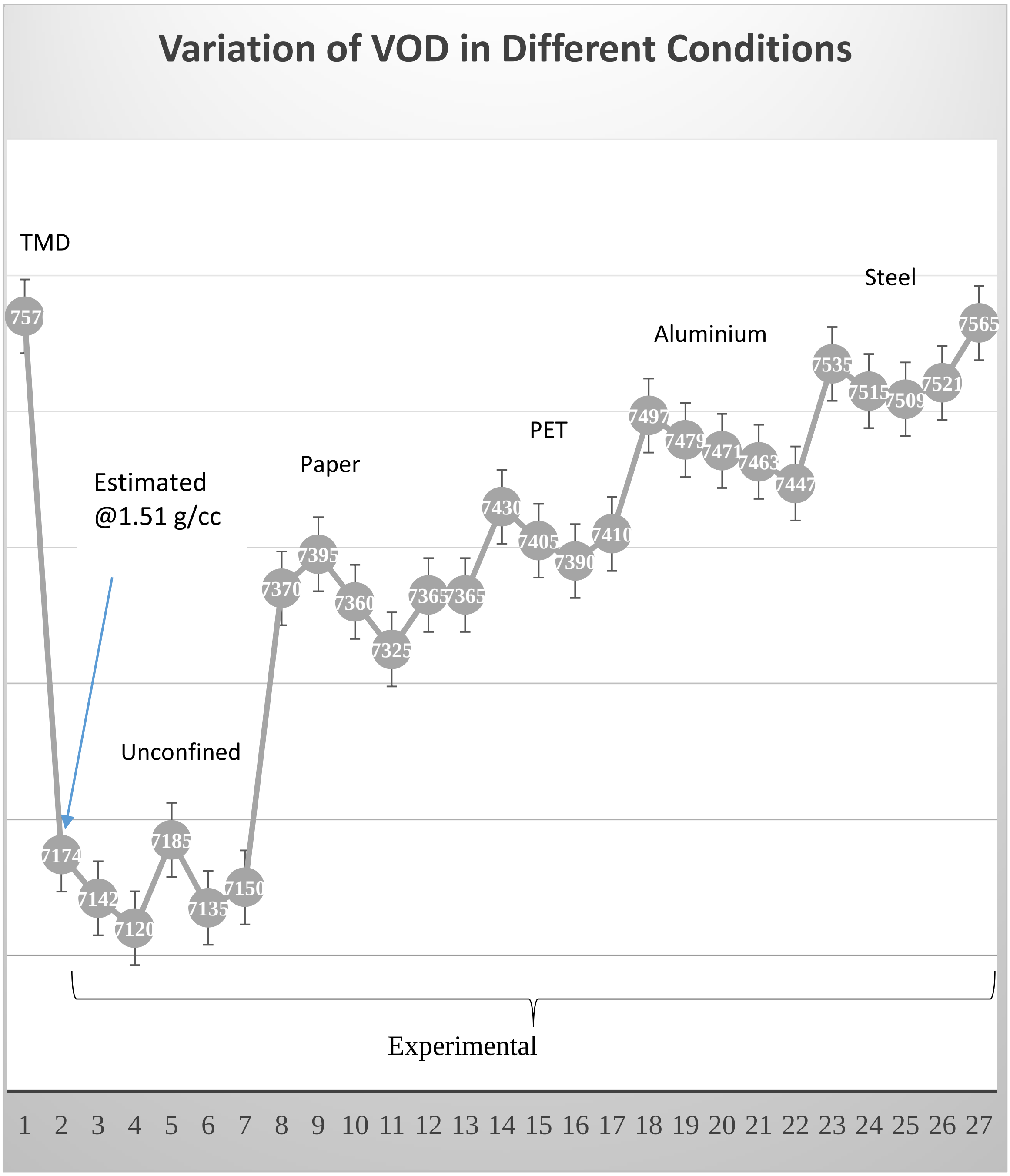


Figure 4.5: Variation of VOD at unconfined TMD, Theoretical unconfined at ρ_1 & Experimental confined at ρ_1 .

It has been observed that the VOD of Tetryl has substantially reduced due to reduction of density from theoretical maximum to a workable one, however the same is regained by confinement and effect of confinement on VOD is complex but experimental values of confinement shows somewhat linear relationship b/w type of confinement & increment in VOD at a constant density vis-a-viz other parameters. The effect of hardness of a single confining material and its subsequent thickness has not been evaluated nor discussed. The variation of theoretical vs experimental values for each confinement has similar effect. The reliable measurement was also ensured by keeping constant distance between the sensing probes. Table 4.3 & Figure 4.6 shows the comparison of values of estimation and mean vales of experimental results.

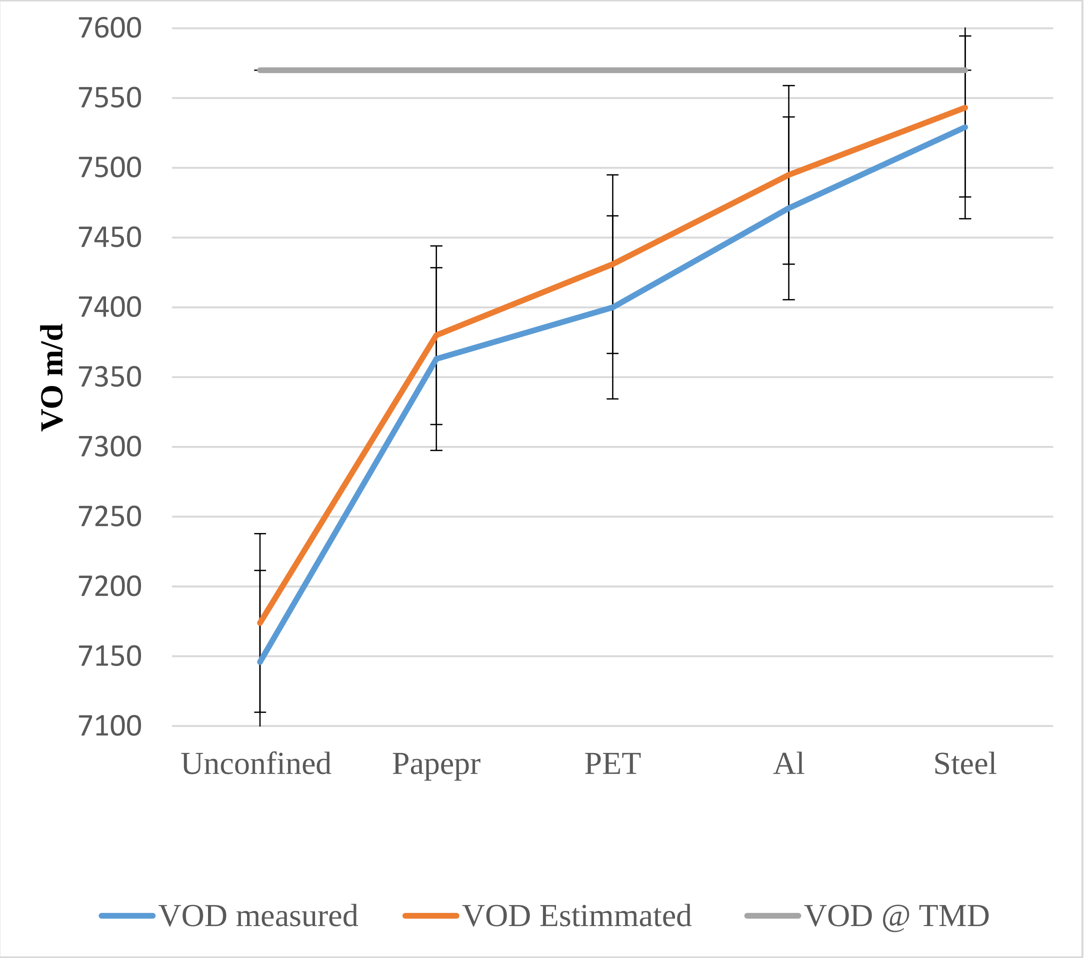
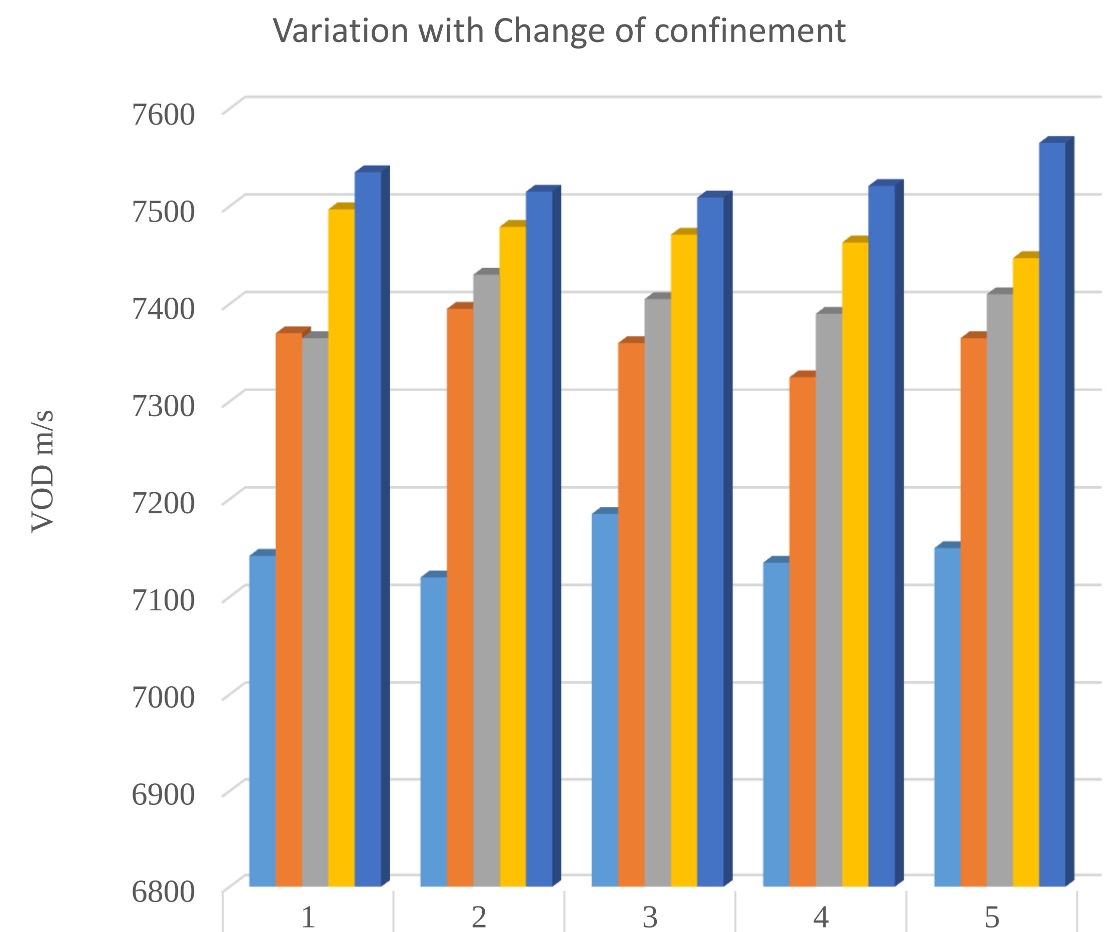


Figure 4.6: Comparison of average theoretical & experimental values

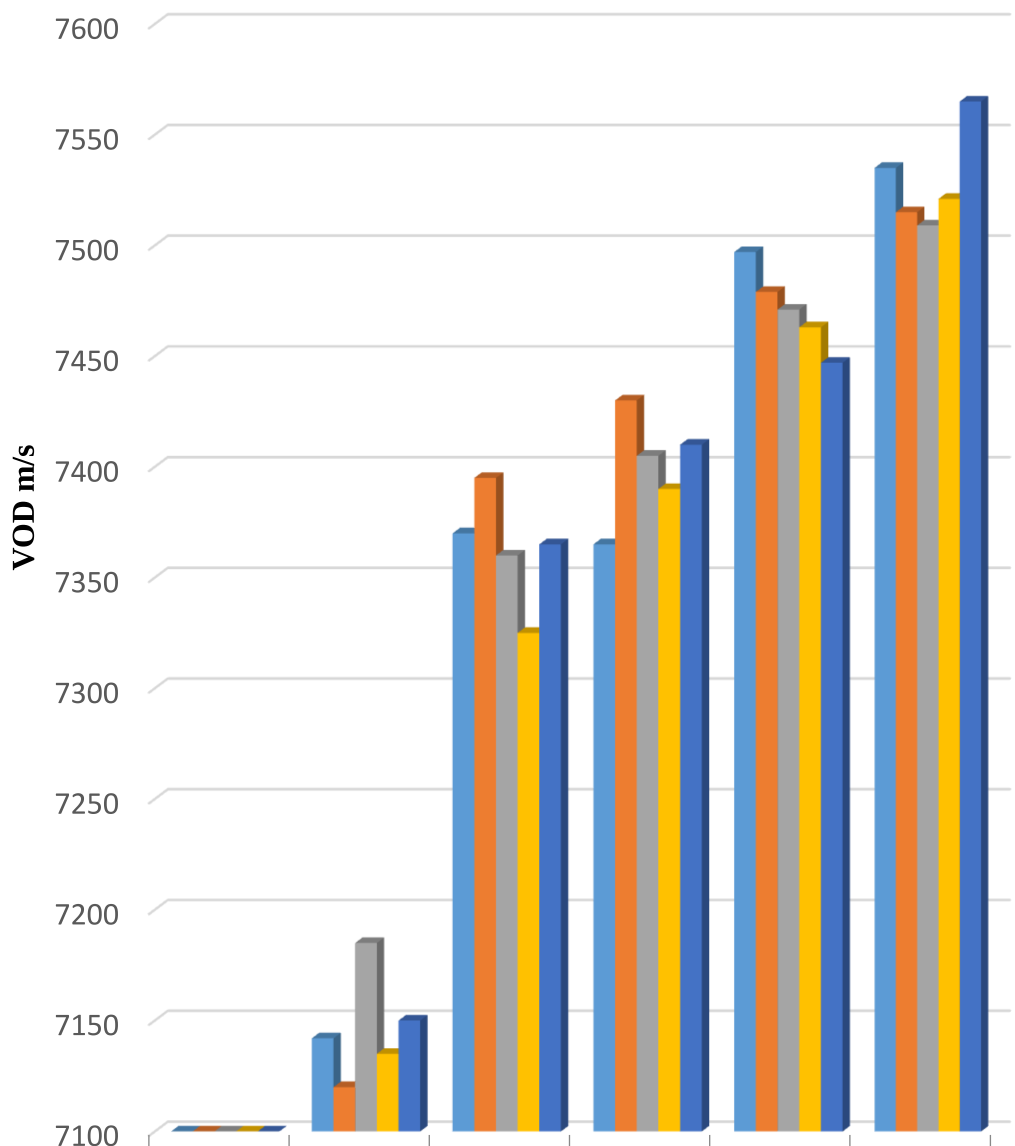


	1	2	3	4	5
Unconfined	7142	7120	7185	7135	7150
Paper	7370	7395	7360	7325	7365
PET	7365	7430	7405	7390	7410
Al	7497	7479	7471	7463	7447
Steel	7535	7515	7509	7521	7565

Unconfined Paper PET Al Steel

Figure 4.7: Pattern for different confinement.

Figures 4.7 shows, how the values of the VOD at different conditions varies and giving almost a similar pattern whereas Figure 4.8 represents the variation in results within a same confinement conditions reflecting accuracy & precision. It is further experienced that the use of fibreoptic based instrument caused least variation for sample to sample and condition to condition in addition to the fact that high density and hardness confinement resulted into more enhanced VOD near to its TMD value and precision as well.



	Test #	Unconfined	Paper	PET	Al	Steel
Series1	1	7142	7370	7365	7497	7535
Series2	2	7120	7395	7430	7479	7515
Series3	3	7185	7360	7405	7471	7509
Series4	4	7135	7325	7390	7463	7521
Series5	5	7150	7365	7410	7447	7565

Effect of Confinement & Variation within Series

Series1 Series2 Series3 Series4 Series5

Figure 4.8: Variation of readings for same type of confinement.

4.3 Effect of Confinement:

The explosives are normally instantiated by different means, but high explosives are mostly initiated by shock to detonation. In this method a shock wave from an a detonating charge "Electric Detonator No 8 E" may referred as initiator or donor was induced to the main charge under test called the receptor or exploding charge, practically a Tetryl pellet pressed at a density of 1.51 g/cm^3. Both charges placed and assembled in such a way that both were intact or nearly so. When the shock/detonation waves proceed through receptor charge the tetryl pellet, the same experienced compression and adiabatic heating, which further caused the following effects:

a. Evolved some of chemical energies, which has the effect of shifting natural retardation of the wave into acceleration, thus the pressure a key performance characteristic in the shock front is increased, more energy is liberated from explosive and the shock continued to accelerate until it approached the characteristic velocity of sound in the shocked medium of explosive.

b. An outburst of light signals, the onset of detonation.

c. In contrary to above, if the shock wave from donor charge is too feeble, or if other parameters are not met, the entering wave will fail to accelerate and die out without giving any proper detonation.

d. A proper initiating type of detonator with constant specification was therefore repeatedly used for all types of tests. Foregoing, when a high explosive is detonated in air (without confinement), a noticeable part of released energy is contained within the shockwave proceeding through the explosive charge. This shock front blow-outs laterally and frontally at far end of charge, into surrounding air, but retards brusquely and is overtaken within limited charge diameters by escalating gas front. This gas front suppresses the surrounding air ahead of it and produces a vigorous detonation wave, comprising much of the original energy of explosive.

e. Work by detonation is done while shocking /setting the air molecules in motion, but it is attained more by the internal energy of the expanding gases rather than the energy of the detonation shock wave. If the aforesaid identical explosive is detonated in a container or confinement instead of open air, the situation is somewhat different as the expanding gases are not free to move away straight /steadily.

f. The detonation shock wave is transmitted more efficiently by a dense solid such as steel, aluminium or rock etc. It proceeds freely within the energetic material, but the impulse that it imparts is not of kind which, by itself, may propel large fragments of confining material over a distance and thus do quantifiable work, rather it generates strong compression forces rapidly thus causing plastic and elastic flow in a uniform hard material. Consequence to this effect, the energy of wave is mostly dissipated as frictional energy or heat.

g. The fruitfulness of this wave lies in the fact that a fragile material will fail under severe compression, and even a harder one will fail in strain when the initial compression stage of wave is swiftly reversed by reflection. These extreme energies may cause spalling, scabbing and cracking effects even in the hardest materials, and the detonation product gases are then able to expand and heave the fragmented material in any desired direction. Thus, the energy liberated by a detonation process is partitioned among the shock wave and internal energy, this is actually the work capacity of the expanding gases behind it.

h. In some effects, such as exploding the isolated boulders, only the shock energy is useful, while for others, such as blowing the craters in soft land, the heaving action is much more important.

i. The confinement helped to partition the energy for a desired application. At a given detonation velocity, all high explosives display a particular partition of its energy, and it is therefore possible to choose the explosives and confinement best suitable for particular task.

j. Confining an explosive can cause significant improvements in its detonation behaviour, but the extend of confinement desired and the magnitude of the effect on parameters such as detonation velocity and failure thickness are largely unknown, however as the toughness of the confinement rises, lateral expansion adjacent to the primary reaction zone is restricted. This upholds the pressure and temperature at larger levels, and so increases the degree of detonation in the primary reaction zone. This increment further stabilizes the shock front which influences the velocity of detonation which in returned enhanced significantly.

k. These phenomena elucidate why explosives can detonate at a substantially higher detonation velocity in confinement than in air.

l. The explosive performance characteristics mainly heat of explosion, detonation velocity, pressure and temperature gave a clear vision and help the designers in selection of a proper explosive in certain conditions. Table 4.4 shows how an explosives falls from a higher group to its lower group due to processing at lower density as in this case the VOD of tetryl drops from 7570 m/s (very high) at its TMD to 7170 m/s (high) when pressed at a density of 1.51 g/cm^3 and on its confinement with steel it almost regained its TMD status i.e. 7529 m/s (very high). Reduction in the VOD of Tetryl at a density of 1.51 g/cm^3 handicaps its use for high energy purposes including weapons as its VOD drops from 7570 m/s to 7170 m/s, however the same explosive at same density is confined with a harder material like steel than its subsequent achievement of 7529 m/s near to its TMD value categorises the explosive as “Very High VOD” group ultimately enables its use for high energy weapon system.

m. Usually when an explosive can’t be processed at its ideal conditions thus can’t achieve the density at par of TMD, it loses its output performance and doesn’t fulfils the intended purpose particularly in Arty, Armour and tank Fuzes where due to limitation of space the basic explosive parameters influencing VOD mainly density, critical diameter, critical mass & length etc. The results of theoretical & experimental measurements mirrored that the deficiency in output parameters can greatly be overcome by a single factor of confinement as due to enhancement in VOD, the critical diameter, mass and length are greatly reduced.

n. Commercially when explosives are used in hard rocks of industrial quarries and mountainous construction sites, the hard rocks acts as confinement ultimately increasing the VOD thus the performance /blast of explosion needs to be addressed and cause to lower the consumption of reduced explosive for the desired purpose.

Table 4.4: Detonation Effect by virtue of its performance characteristics

S#	Characteristics		Uses	
	Heat of Explosion	**Detonation Velocity VOD**	**Military**	**Commercial**
1	High-Medium	Very High	Implosion charges for nuclear weapons, high-performance hollow charges, squash-head shells	Breaking metals
2	Medium	High	Filling for HE shells, mortar bombs, grenades, fragmentation warheads, ordinary hollow charges, exploders for less sensitive explosives.	Breaking of concrete, brick-work, hard rock, boosters for less sensitive explosives.
3	High	Medium	Cratering charges, blast warhead, aircraft bombs, torpedoes, sea mines	-
4	Medium	Medium-low	-	Blasting of average rock and overburdens
5	Low	Low	-	Blasting of coal under ground
6	Low	Medium	Detonators	Detonators

Value Ranges

No	Range	Q Values (J/g)	D Values (m/s)
a-	Very High	-	≥7500
b-	High	≥5500 J/g	6000~7500
c-	Medium	3500~5500	3500~6000
d-	Low	≤3500	≤3500

4.4 Role of Optic Fibre Technique:

The use of fibre-optic based measuring instrument /chronometers significantly proved to be encouraging as it truly exhibited more accurate results as compared to other instruments. Although only fibre-optic based VOD meter Explomet-fo-2000 has been used in this experiment but the measured values when compared with theoretically estimated and literatures values it is obvious that the variation within reading and with theoretical values are least. In the experiments, variations observed are least for aluminium & steel ranging from 60 & 63 m/s whereas highest is 96 m/s observed for unconfined conditions. The same is tabulated in Table 5.5 and graphically represented in Figures 5.9 & 5.10. it can further read-through that the variation in experimental measurement is less than 3% within a test series whereas variation observed in the experimental vs theoretical measurements are less than 1%.

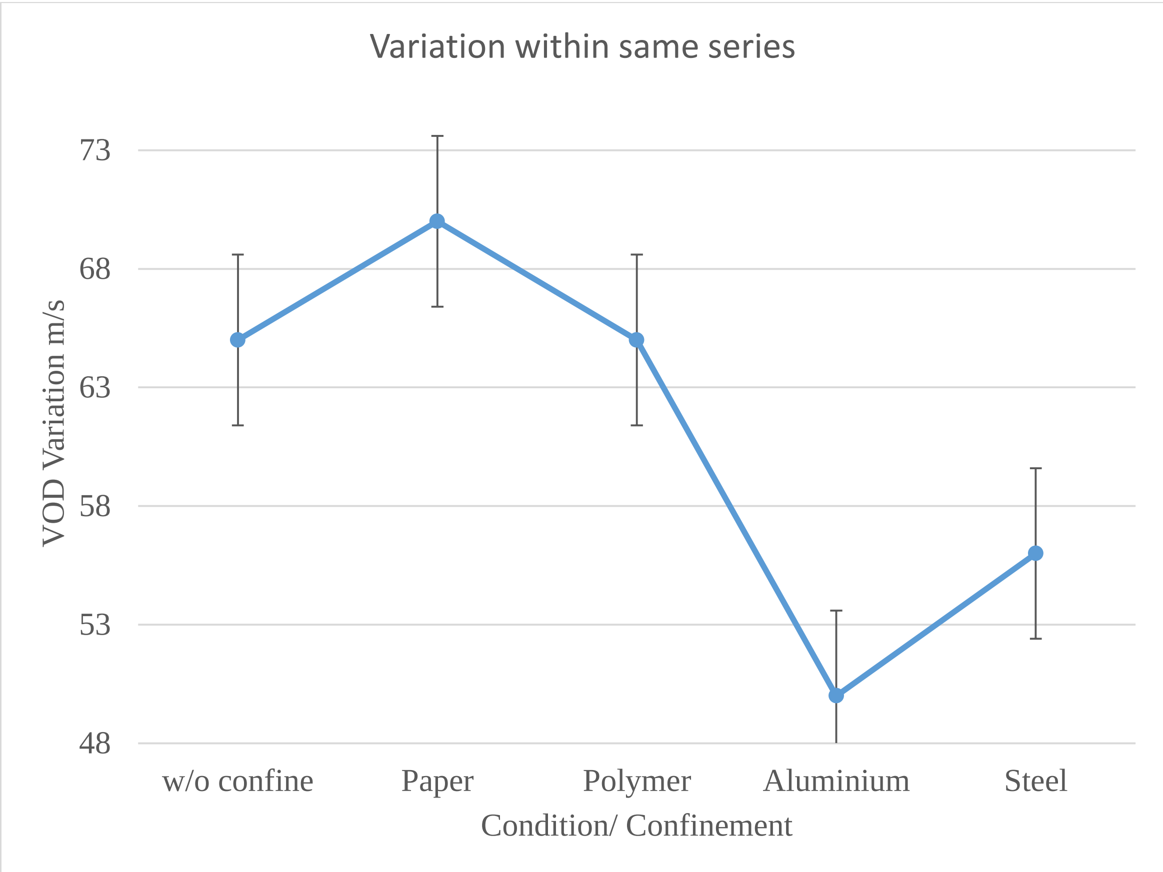


Figure 4.9: The variation in the VOD measured with different confinement.

Table 4.5: Variation in the Experimentally and Theoretically measured VOD.

S#:	Confinement Conditions	Variation in VOD within Series		Variation of Experimental vs Estimation	
		m/s	**%**	**m/s**	**%**
1	w/o	65	0.91	28	0.39
2	Paper	70	0.95	17	0.23
3	Polymer	65	0.88	31	0.42
4	Aluminium	50	0.67	24	0.32
5	Steel	56	0.74	14	0.19

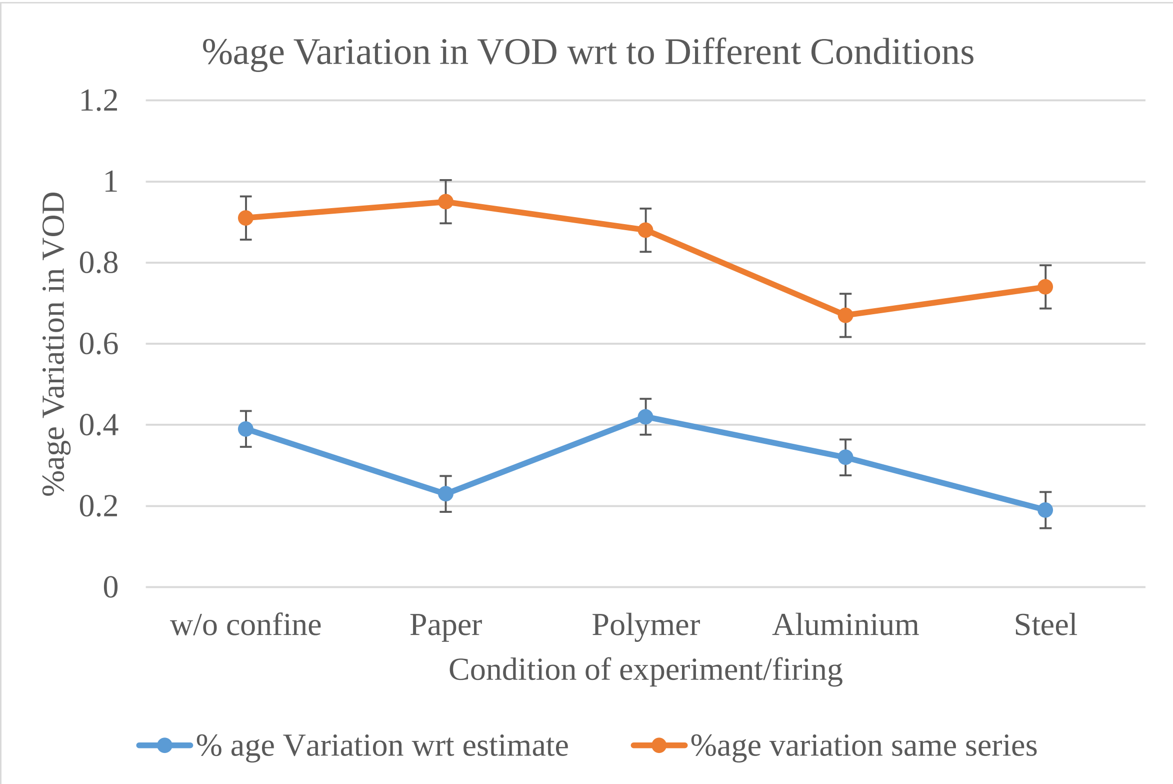


Figure 4.10, Comparison b/w the %age variation of VOD

The basic mechanism of fibre-optic based instrument which contributes in the accuracy and reliability of results are outlined as under:

a- Instrument Explomet-fo-2000 either doesn't require calibration or can easily be calibrated by just illuminating the probes.

b- Fibre-Optic cables works dually i.e. as a sensing probes and as a signal transmission medium. This feature eliminates the errors caused by various connections between sensing probes & transmission cables.

c- It senses and transmits data signals at the speed of light thus eliminates the distance related errors between the explosion /sensing point to analyser /VOD meter. This further makes it reliable to use and relates the experimental values performed even at different distances.

d- The insertion of fibre-optic prop due to its lower diameter of ~ 1.0 mm is more convenient that other methods having larger diameter sensing probes.

e- The precision between probe distances ensures proper and accurate VOD measurement, however if the data fed is not accurate than the VOD can be recalculated /confirmed with the help of time measured and actual distance.

f- In this experiment the two probes/cables method used and both were connected on each face of Tetryl Pellets, whereas the length of pellet were predetermined with help of a microammeter resulted into more consistent and accurate measurements.

g- In order to get proper insertion and distance measurement, the confining sleeves were drilled accurately for insertion of probes, thus got results with good precisions.

The overall variation in results are clear picture of this accuracy achieved by using fibre-optic based VOD meter "Explomet-fo-2000".

The results achieved so far found satisfactory and encouraging when an explosive charge is confined, and the VOD so achieved is improved /enhanced near to its TMD value with a better accuracy and precision due to use of fibreoptic method and

Explome-fo-2000. The influence of wall/container thickness of and hardness of confining material was out of scope of this research; hence not studied/evaluated.

As far as the effect of confinement is concerned it has been observed that the VOD of an explosive is being substantially reduced at a processing density which is lower that of TMD (Theoretical Maximum Density). By applying the confinements, the same can be reversed and an improved VOD near to TMD value can be achieved. For instance, the VOD of Tetryl at its TMD of 1.71 g/cm^3. Results validate the theory of confinement that when an explosive is detonated in confinement, shock /detonation waves reflects from walls of confinement. This swift mirroring of the wave from different walls, results a multiple punch effect on another wall. Moreover, confinement slowed down the retardation of pressure and temperature behind the detonation/shock front, thereby increased the reaction rate consequently got the increased velocity of detonation as reaction rate has direct relationship with pressure.

Conclusions and Future Recommendations

Conclusions

VOD of an explosive is its vital performance characteristic and depends on various factor. One of which is the density. Due to certain safety and operational limitations high explosives are processed, pressed or casted at a lower density than its theoretical maximum density TMD, this reduction in density causes to lower the detonation characteristics mainly pressure, heat and VOD. The reduced performance of explosives leads to compromise the terminal effect, and its enhancement is either possible with increased quantity of explosives or have to develop some technically valid option like confinement.

The objectives set-out have been achieved as follows:

a- Effect of confinement on the VOD of an explosive charge has been studied and measured theoretically & experimentally.

b- The comparison has been made for the VOD of an explosive in unconfined and confined environments with various materials of confinement including paper, polymer, aluminium and steel.

c- The density effect of the confinement has also been evaluated.

d- The validity of research is highly dependent on accuracy, reliability and precision of equipment/ instruments used for the evaluation of experimental data. The fibreoptic based instrument Explomet-fo-2000 shown its credibility by measuring and analysing the results of VOD consistently, accurately and reliably.

The nutshell result of the present study is that there is considerable enhancement in the VOD of an explosive under confinement. It has been observed that maximum enhancement in the VOD is achievable with steel manifested as 7174 to 7543 m/s is confirmed with steel confinement.

Future Recommendation

a. The extend of effectiveness of greater hardness or wall thickness are required to be worked out. Both are achievable parameters and may paly role in the enhancing performance of explosive.

b. The effect of similar type of performance on different explosives shall be worked out to select a suitable explosive with an optimum confinement to get maximum detonation performance.

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