

CHAPTER 1

INTRODUCTION

1.2 EXPLOSIVE SUBSTANCES

1. Explosive is a substance which, when subjected to the action of initiation, produces a quantity of gas under such conditions that the energy of the reaction is sufficient to cause a rapid expansion of the material, which may be accompanied by a shock wave and a high rate of propagation of the reaction.

2. Initiating agent. Explosive is a substance which, when subjected to the action of initiation, produces a quantity of gas under such conditions that the energy of the reaction is sufficient to cause a rapid expansion of the material, which may be accompanied by a shock wave and a high rate of propagation of the reaction.

3. Detonation. Detonation is a specific exothermic reaction which is associated with a shock wave. The chemical reaction starts because of the heat which is a result of the compression by the shock wave. The energy liberated in the reaction sustains the shock wave. An important characteristic of the detonation is that the reaction products have initially a higher density than the unreacted substance.

4. Combustion or Burning of condensed matter means an exothermic reaction taking place at the surface of the grains which compose the material. This reaction is maintained by the heat transmitted from the gaseous reaction products.

5. Explosion is a rapid expansion of matter into a volume greater than the its original volume.

1.1 DEFINITIONS

In the following a few definitions useful in attending the course will be given⁽¹⁾:

Combustion or Burning of condensed matter means an exothermic reaction taking place at the surface of the grains which compose the material. This reaction is maintained by the heat transmitted from the gaseous reaction products.

Detonation is a specific exothermic reaction which is associated with a shock wave. The chemical reaction starts because of the heat which is a result of the compression by the shock wave. The energy liberated in the reaction sustains the shock wave. An important characteristic of the detonation is that the reaction products have initially a higher density than the unreacted substance.

Explosion is a rapid expansion of matter into a volume greater than the its original volume.

EXPLOSIVE SUBSTANCES

1.2 EXPLOSIVE SUBSTANCES

An explosive can either burn or detonate according to the method of initiation or the quantity of the material involved. According to Taylor⁽²⁾ if the mass of the explosive is small, thermal ignition usually leads to burning. However if the mass exceeds a critical value it is possible that the burning becomes so rapid that a shock wave propagates and detonation occurs. The critical mass depends on the explosive.

i. Initiating explosives. Explosives such as mercury fulminate or lead azide in which burning results in a detonation even in small quantities are called initiating explosives. These explosives are used in initiators (blasting caps). Another name for these explosives is primary explosives. Primary explosives are very dangerous since they are readily ignited by direct contact with flame or electric sparks. They impose significant problems in the manufacture since extreme care has to be exercised.

ii. Secondary explosives. They are called high explosives as well. They are less easily detonable; however they are handled in much larger quantities than primary explosives. Typical high explosives are TNT, RDX, PETN etc.

iii. Commercial explosives. Usually they are Ammonium Nitrate based mixes. They are considered to be safer than high explosives. However one should be extra careful so that one

interprets the available sensitivity data properly. For example, although drop tests indicate that cap sensitive slurries are less sensitive than cast TNT, projectile impact tests and gap

sensitivity tests show the opposite.

In this course the main emphasis will be placed on the commercial explosives since they are of primary interest in the mining and construction industries.

Commercial explosives are manufactured so that they are oxygen balanced. As a result the gases which are produced are non-toxic and the energy of the reaction between oxidizer and fuel is utilized fully.

The oxygen balance of oxygen rich compositions is expressed in weight percent as the amount of oxygen liberated as a result of complete conversion of the explosive material to CO_2 , H_2O , Al_2O_3 etc. (positive oxygen balance)⁽⁵⁾. If the amount of oxygen is insufficient for the oxidation reaction, the amount of oxygen needed (again as a weight percent) is reported with a negative sign⁽⁵⁾.

Example:

RDX ($\text{C}_3\text{H}_6\text{N}_6\text{O}_6$). In order to convert the material to CO_2 , N_2 , H_2O oxygen is needed. This could be expressed as:

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In other words 48g of oxygen is needed per mole of RDX or in weight percent 21.6%. Therefore the oxygen balance of RDX is -21.6%.

The oxygen balance is usually calculated on the unwrapped explosive. However a part of the wrapper takes part in the chemical reaction^(2,3).

Both negative and positive oxygen balance can produce toxic gases; carbon monoxide and nitrogen oxides respectively. This is shown in Table 1 where the calculated products of decomposition of AN/FO (Ammonium Nitrate/Fuel Oil) at various values of Oxygen Balance are shown.

1.3 SAFETY

Safety is a major concern of the explosives manufacturer and the explosives user. Various mechanical and thermal tests are used. The tests are simple indicators of the explosives sensitivity to various kinds of stimuli.

i. Mechanical tests. They test the explosive to shocks produced by mechanical means. These tests are:

- The drop weight test
- The friction test
- The projectile impact test
- The gap test

ii. Thermal tests. They provide the risk associated with accidental fires. Usually the explosive is heated confined. The degree of mechanical damage to the container indicates the event.

iii. Stability tests. They test the explosive in long term storage by measuring the amount of explosive decomposed as a function of time at various temperatures.

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1.4 REFERENCES

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TABLE 1

EXPLOSION STATE PRODUCTS OF AN/FO AT VARIOUS
VALUES OF OXYGEN BALANCE OF THE COMPOSITION

PRODUCT	CONCENTRATION (moles/Kg of explosive)		
	OXYGEN BALANCE (%)		
	+9.0	0.0	-16.2
H ₂ O	26.4	27.5	27.2
N ₂	9.3	11.8	11.2
NO	5.7	0.0	0.0
CO ₂	2.1	3.9	2.7
CO	0.0	0.0	1.1
CH ₄	0.0	0.0	0.2
H ₂	0.0	0.0	1.9
NH ₃	0.0	0.0	0.1

CHAPTER 2

THE DETONATION
PROCESS

2.1 INTRODUCTION

According to Persson⁽¹⁾ steady state detonation along a cylindrical charge can be regarded as a self propagating process in which the axial compressive effect of the shock front discontinuity changes the state of the explosive so that exothermic reaction sets in with the requisite velocity.

This reaction in homogeneous liquid explosives such as nitroglycerin is completed in a time interval of the order of 10^{-12} seconds⁽¹⁾. In high explosives, such as RDX and PETN it is completed in about 1 μ sec. In composite explosives containing

AN the reaction times are considerably longer resulting in long reaction zones and non ideal performance.

2.2 SHOCK WAVES

Compressional waves of small intensity are propagated in gases at the velocity of the sound. Let us suppose that a column of gas is set in motion by a piston which is accelerated into it. Let us also consider that the velocity of the piston is a staircase function of time. Each step transmits a small compressional wave which advances through the gas already set in forward motion and heated by the previous waves. Since the velocity of the wave is larger at elevated temperatures, the new wave overtakes the previous⁽²⁾. Therefore the velocity, pressure and temperature gradients in the front of the wave grow steeper with time. If there is no dissipative mechanism (e.g. heat diffusion) the gradients become infinite⁽²⁾.

This type of wave, in which a discontinuity has developed is known as a shock wave. The area of pressure rise is called the shock front. The front advances with a speed higher than the sound speed. The shock velocity depends on the conditions behind. If the piston continues accelerating so does the front. If the piston maintains a constant velocity, the front maintains a constant velocity as well. If the piston decelerates a wave of rarefaction is formed ahead of it. Finally this wave overtakes and weakens the shock front.

It follows that the velocity of the front is determined by the conditions behind the front. The wave does not maintain itself. Rather it depends on the support provided by the piston.

2.3 DETONATION WAVES

However from our experience we know that steady detonation waves exist. In this case the role of the piston is played by the reaction taking place in the detonation wave.

Let us consider a plane detonation wave which has been established in an explosive (Figure 1). The wave front advances into the unconsumed explosive with a constant velocity D and it is followed by the reaction zone. If an observer is moving with the velocity D of such a front, the wave will appear to him/her as in Figure 1. Undetonated explosive flows into the shock front AA' with constant velocity $U = -D$. Its pressure, temperature and density and internal energy per unit mass are P_1, T_1, ρ_1, E_1 at all points to the right of AA' . The wave front is considered to be a discontinuity in comparison to the changes occurring behind it. Therefore at AA' these values change to values P_2, T_2, ρ_2, E_2 . These values change at some later stage.

The apparent velocity of the mass leaving the front is $-(D - U_p)$ where U_p is the particle velocity (mass velocity) in the zone between AA', BB' , relative to the fixed coordinates.

If we consider a region of flow surrounded by a tube of unit sectional area and two planes, one just before the detonation front and one right after it, the mass flowing in must equal the mass flowing out (conservation of mass). The mass flowing in per unit time is $\rho_1 D dt$. The mass flowing out is $\rho_2 (D - U_p) dt$. Therefore :

$$\rho_2 D = \rho_2 (D - U_p) \quad (\text{EQ 1})$$

Furthermore the difference in momentum should be equal to the impulse of the net force. Thus:

$$\rho_1 D dt D - \rho_1 D dt (D - U_p) = (P_2 - P_1) dt \quad (\text{EQ 2})$$

or

$$P_2 - P_1 = \rho_1 D U_p \quad (\text{EQ 3})$$

P_1 is very small compared to the detonation pressure. Therefore it can be ignored and equation (3) can be written as :

$$P_2 = \rho_1 D U_p \quad (\text{EQ 4})$$

From equation (1), one can obtain:

$$U_p = (1 - \rho_1 / \rho_2) D \quad (\text{EQ 5})$$

According to Cook⁽³⁾ U_p / D and ρ_1 / ρ_2 are slowly variable functions of the original density. Thus:

$$U_p = f(\rho_1) D \quad (\text{EQ 6})$$

where

$$f(\rho_1) = 1 - \rho_1 / \rho_2 \quad (\text{EQ 7})$$

Therefore equation (4) can be written as:

$$P_2 = \rho_1 f(\rho_1) D^2 \quad (\text{EQ 8})$$

For most cases (explosives having a density between 0.9 - 1.4g/cc) it is sufficiently accurate to assume $f(\rho_1) = 4.0$. Under this approximation, the detonation pressure in atmospheres when the velocity of detonation is given in meters per second, is given by the following equation⁽⁸⁾ :

$$P_2 = 0.00987 \rho_1 \frac{D^2}{4} \quad (\text{EQ 9})$$

This is a relationship of great practical value. It allows the estimation of the detonation pressure when only the detonation velocity and the initial density are known. It is worth mentioning that the detonation velocity can be measured accurately in the laboratory.

Apart from equations (1) and (3) other equations are used in the theory of detonation. Many of these fall outside the area of interest of these notes. They are mentioned in the following to assist the reader in further studies.

The conservation of energy is expressed by the following equation:

$$E_2 - E_1 = \frac{1}{2} (P_2 + P_1) (V_2 - V_1) \quad (\text{EQ 10})$$

This is known as the Rankine-Hugoniot equation.

A fourth equation is the equation of state of the reaction products of the explosive.

The above four basic equations are not enough to calculate the five unknown quantities behind the detonation front (energy, density, detonation velocity, pressure and particle velocity). A fifth condition is necessary. This is the Chapman- Jouguet hypothesis stating that the detonation velocity equals the local sound speed plus the particle velocity at the detonation state. Therefore:

$$D = C + U_p \quad (\text{EQ 11})$$

Equations (1),(3),(10),(11) and the equation of state of the detonation products are essential for the calculation of the detonation parameters in the thermohydrodynamic codes.

2.4 THE DETONATION HEAD MODEL(3,4)

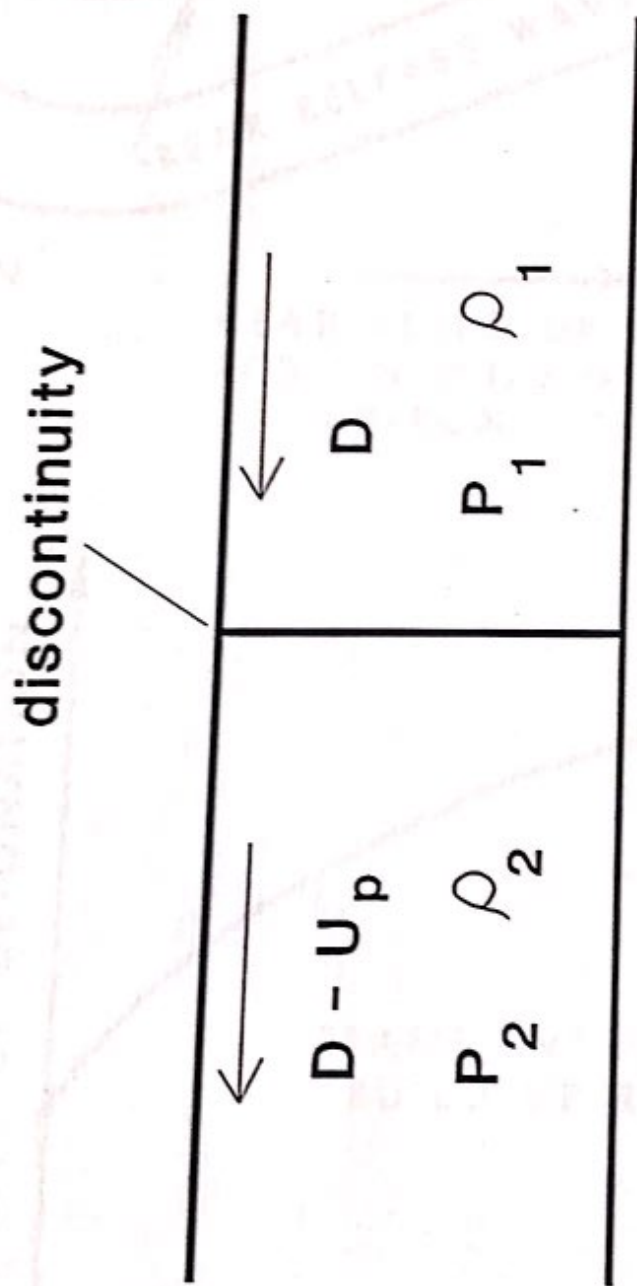
Practical explosives are used normally in the form of cylindrical charges. Cook's detonation head model illustrates the sequence of events taking place. Figure 2 shows the detonation head formation in a cylindrical unconfined charge. With strong priming a detonation wave travels out from the primer and along the charge. This is responsible for the promotion of the necessary exothermic detonation reactions within the explosive charge. At the back of the primer the high pressure gases expand into the surrounding air. As this expansion takes place it permits a release wave or a rarefaction wave to travel down the charge behind the detonation front. This always lags the detonation front for reasons which were explained earlier. In a similar manner at the sides of the charge immediately after the detonation wave the gases expand into the atmosphere. Again two release waves are travelling into the charge. The detonation front, rear release wave and side release waves define a region called the detonation head. The detonation head is a region associated with high pressure and high density. The shape of the detonation head depends on the geometry of the charge and changes as it travels out from the initiation source. This is due to the approximately constant relationship between the release wave velocity and the detonation velocity. Initially the shape is that of a section of a truncated cone with curved front and rear surfaces. Further away from the initiation the length of the detonation head grows so that it is controlled from the side release waves which meet on the axis of the charge forming a cone. It has been

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found (X ray radiography) that the length of the cone when the detonation is fully developed is approximately equal to the diameter of the charge. The density inside the detonation head is constant and approximately equal to $4/3 \rho_1$ where ρ_1 is the initial density of the explosive. The distance from the initiator to the point where the full head is formed is approximately equal to $3 \frac{1}{2}$ charge diameters for unconfined charges. As the explosive enters the detonation head it reacts. If it is in a granular form (e.g ANFO prills) the reaction starts at the surface and proceeds radially towards the centre of the prill. As it was mentioned in the previous the energy liberated supports the detonation. If the reaction is not completed inside the head the energy liberated is less than the maximum available and the detonation velocity is less than the maximum. This is what is normally known as non-ideal detonation. It is worth mentioning that non ideal detonations can be stable; indeed a great number of commercial explosives used by the mining industry today detonate at non ideal velocities at the diameters at which they are used. The detonation velocity is the most important parameter of the detonating explosive. It is well known that the velocity of detonation is a constant characteristic of a particular explosive when the other parameters are kept constant. It was explained that the knowledge of the detonation velocity can lead to fairly accurate estimates of the detonation pressure which is of particular importance and cannot be measured directly. In the next chapter the parameters influencing the detonation velocity will be discussed.

2.5 REFERENCES

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Observer moves to right at wave velocity D
 The discontinuity is at rest

FIGURE 1: FLOW THROUGH DETONATION WAVE

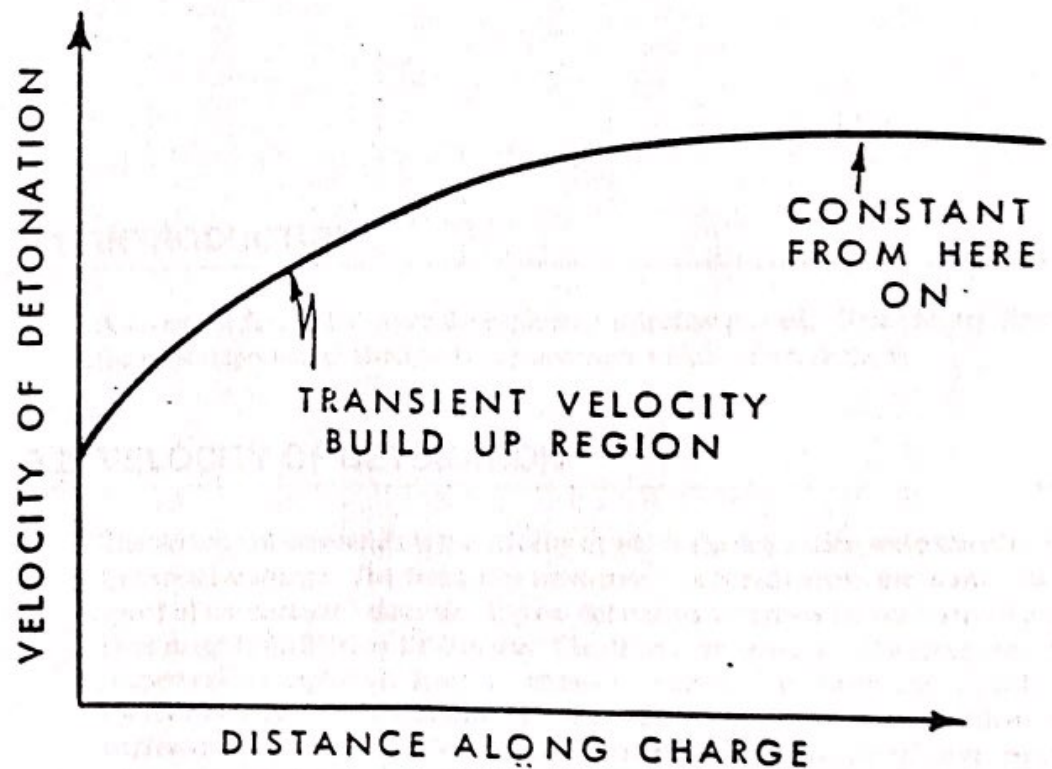
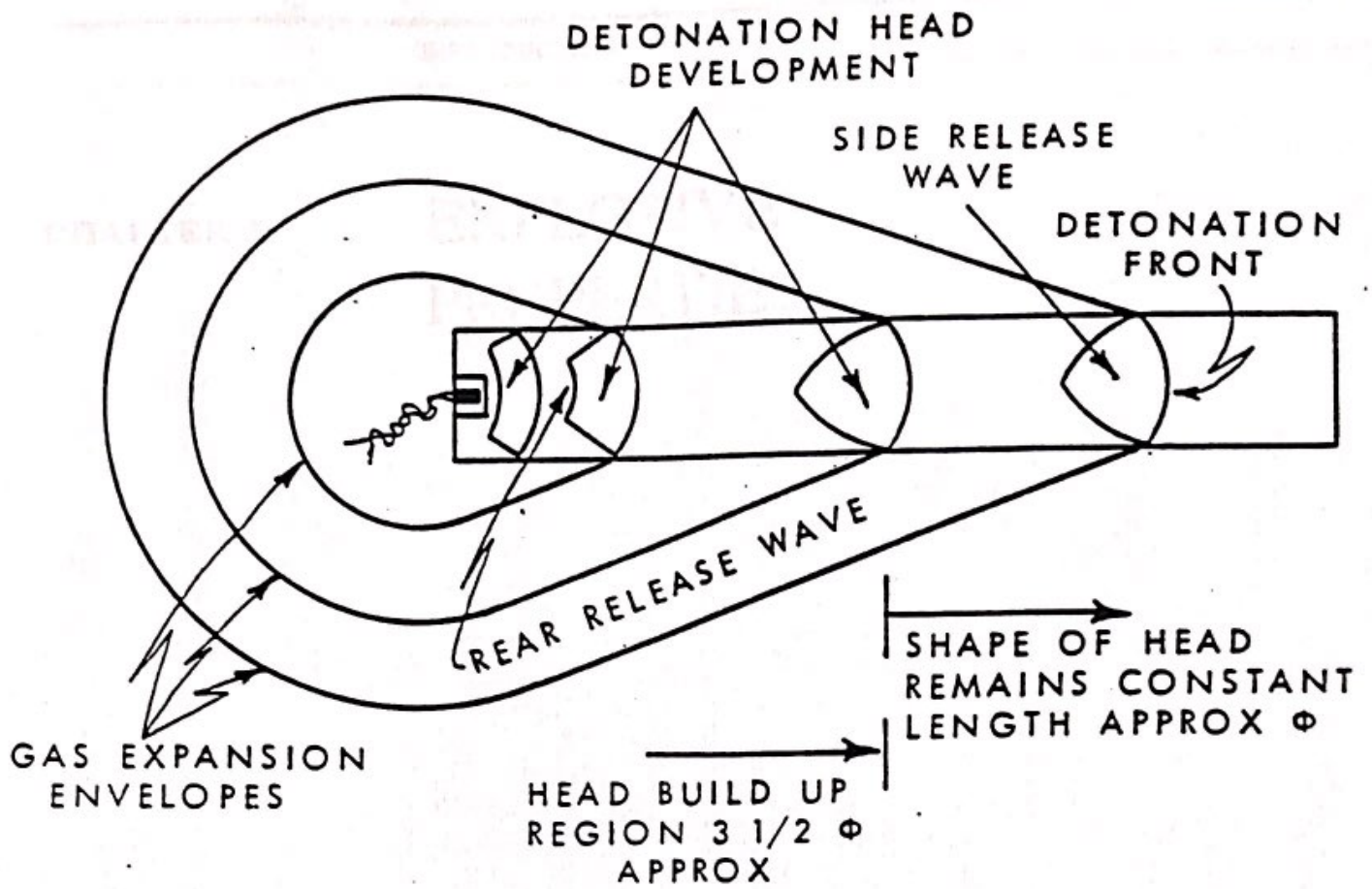


FIGURE 2: DETONATION HEAD FORMATION
(AFTER COOK AND BAUER)

CHAPTER 3**EXPLOSIVE
PROPERTIES**

3.1 INTRODUCTION

A variety of factors influence the explosives selection process. This chapter discusses the most important of them and the parameters which influence them.

3.2 VELOCITY OF DETONATION

The velocity of detonation is the velocity at which the detonation wave travels through an explosive charge. The detonation wave travels at speeds above the normal sound speed of the unreacted material. Typical detonation velocities for commercial explosives range from 2500 to 7000 m/sec. The detonation velocity is the most important property of the explosive. It can be measured easily and accurately and it can be used for the calculation of the detonation and borehole pressures which are of importance in explosive applications. The velocity of detonation of a particular explosive depends on factors such as charge diameter, confinement, density and particle size.

3.2.1 THE EFFECT OF CHARGE DIAMETER

Let us consider a typical velocity of detonation - diameter curve as shown in Figure 1⁽²⁾. If the diameter is too small the explosive fails to detonate. At some minimum diameter stable detonation occurs. This minimum diameter is called the critical diameter of the explosive.

As the charge diameter is increased the detonation velocity is increased as well. However when a certain diameter is reached, further increase in diameter does not result in an increase of the detonation velocity. At this point a maximum detonation velocity of the explosive is reached. This velocity is called the ideal detonation velocity of the explosive and is the value predicted by thermohydrodynamic codes.

The detonation head model as developed by Cook⁽¹⁾ can be useful in explaining the shape of the observed detonation velocity - diameter curves. Figure 1 illustrates the length of the established detonation heads in charges of various diameters and indicates what happens when a solid particle of explosive enters the detonation head. For the small diameters, the degree of reaction is small and the energy liberated is not enough to support a detonation. As the diameter is increased the detonation head length is increased and for the same size of particle the degree of reaction increases. At the critical diameter the degree of reaction is sufficient to support stable detonation. If the diameter is increased further a larger amount of explosive reacts in the detonation head. When the ideal detonation occurs, the full amount of explosive reacts in the detonation head.

3.2.2 EFFECT OF CONFINEMENT

The effect of confinement is to lower the rate of expansion of the gases off the side of the charge⁽²⁾. This in turn slows down the rate at which the lateral rarefaction travels into the reaction region. As a result it takes longer for the side release waves to meet on the charge axis. The length of the detonation head is thus increased. This is shown in Figure 2⁽¹⁾, where the development of the detonation head is outlined for both the confined and the unconfined cases. Therefore, if the explosive was not reacting fully at a particular charge diameter, the effect of confinement would be to increase the degree of reaction and consequently the detonation velocity at this diameter. Similarly, confinement will reduce the critical charge diameter (Figure 3)⁽²⁾.

Thus confinement will only affect the performance parameters in the case of a non ideal detonation. In the case of ideal detonation the shock velocity and pressure will remain unaffected.

However confinement cannot be quantified. Steel, glass, various kinds of rock and soil will produce a different effect. For this reason most of the tests are done with the explosive charge unconfined.

3.2.3 EFFECT OF PARTICLE SIZE

If the size of the explosive particles is reduced at a given charge diameter in the non ideal velocity region, the degree of reaction is enhanced because of the increase of the

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surface area. Furthermore since the grains are smaller, they are consumed faster in the detonation head. As a result the critical diameter is decreased and the explosive reaches ideal detonation at a smaller diameter (Figure 4)⁽²⁾.

3.2.4 EFFECT OF DENSITY

If the density is increased, the specific energy is increased; as a result the ideal detonation velocity is increased. It has been found that the detonation velocity and the density are related linearly. Figure 5⁽³⁾ shows the detonation velocity density relationship for various explosives.

However if the density is increased beyond a critical point, steady state detonation is not possible. The phenomenon is called dead packing and a qualitative explanation can be given by the fact that the volume of the entrained air is insufficient to provide enough hot spots for the reaction to proceed⁽⁸⁾. Dead packing is a problem for air bubble sensitized explosives when they are subjected to hydrostatic heads inside boreholes since their density can increase drastically. Typical velocity diameter curves for air bubble sensitized slurries when they are subjected to hydrostatic pressures are shown in Figures 6 and 7. Curves for a microballoon sensitized emulsion are shown in Figure 8. The fact that the emulsion was not affected by the overpressure is explained by the fact that its density did not change under the hydrostatic pressure.

The relationship between critical diameter and density is shown in Figure 9⁽⁵⁾. This is typical for any explosive. It is obvious that apart from the density in which the material is dead packed there is a critical density below which the explosive will not shoot.

3.2.5 EFFECT OF TEMPERATURE

The initial temperature of the explosive has a small influence on the velocity of detonation at diameters well above the critical. However the critical diameter is dependant on the initial temperature. Figure 10 shows the effect of the temperature on the critical diameter powdered TNT⁽⁸⁾. The effect is not very significant and it is typical of the case of solid explosives in which no phase changes are observed.

In the case of commercial liquid-phase explosives the effect is more pronounced. Figure 11 shows the effect of low temperatures on the critical diameter of a typical small diameter slurry explosive⁽⁵⁾. The effect on a small diameter emulsion explosive is shown in Figure 11a⁽⁵⁾. Obviously critical diameters are increased when temperatures drop but the effect cannot be quantified. As a general rule, changes should be expected once phases change. Slurries change phases quite easily because the external phase is the aqueous solution. In emulsions the aqueous supersaturated phase is protected by the continuous oil/wax phase and phase changes are not observed easily when the temperatures drop moderately. However at extremely low temperatures crystallization may occur which is an irrecoverable process indicating a product break-down.

3.2.6 EFFECT OF WATER

Generally slurries emulsions and gelatin dynamites are not affected by the presence of water inside boreholes. Ammonium nitrate mixed with fuel oil has no water resistance. The product absorbs water and soon becomes desensitized. Generally performance drops drastically as the weight of water in the composition is increased. This is shown in Figure 12 where the performance of ANFO at 4" diameter charges with various water contents is shown.

Heavy ANFO can provide good water resistance if the concentration of emulsion is sufficient. Generally, this concentration is about 55% by weight.

3.3 DETONATION PRESSURE

The detonation pressure is a very important parameter. It is an indicator of the ability of the explosive to produce the desired fragmentation in the rock. However, due to its high magnitude the detonation pressure cannot be measured directly. For this reason the experimental determination is difficult. The detonation pressure is related to the square of the detonation velocity. Parameters which influence the detonation velocity have a very significant effect on the detonation pressure.

3.4 DETONATION TEMPERATURE

The detonation temperature is the parameter about which the least amount of information is available⁽⁶⁾. The detonation temperature is measured from the brightness of the detonation front as it is observed by a sensor. However it is not known how much radiation is absorbed from the partially decomposed material between the sensor and the front. Furthermore, any gas bubbles in the material will flash brightly when they are impacted by the detonation wave. This, obviously, will affect the measurement.

3.5 FUMES

It must be assumed that in all cases explosive fumes are to some degree toxic. Excess oxygen causes the formation of nitrogen oxides while oxygen deficiency causes the formation of carbon monoxide.

In the United States the fumes of any explosive are classified after detonating the explosive in a Bichel bomb and analyzing its fumes. The following classes exist⁽⁷⁾:

A. Permitted explosives (USBM)

Fume class	Toxic Gas	Toxic Gas
	ft /lb	l/kg
A	< 1.25	< 78
B	1.25 - 2.50	78 - 156
C	2.50 - 3.75	156 - 234

B. Rock blasting explosives

Fume class	Toxic Gas	Toxic Gas
	ft /lb	l/kg
1	< 0.16	10
2	0.16 - 0.33	10 - 21
3	0.33 - 0.67	21 - 42

It is worth mentioning here that the relative toxicity of the fumes is important and this is not shown in the above tables. NO is much more toxic than CO (about 6 times as much)⁽³⁾. It has been found that the fumes depend on :

1. The oxygen balance
2. Marginal priming
3. Water attack
4. Critical diameter
5. Gaps in loading
6. Deflagrations.

The effect of oxygen balance on the production of CO and NO_x by AN/FO charges is shown in Figure 13⁽¹²⁾. The effect of priming on the fumes produced by charges of crushed ANFO is shown in Figure 14⁽¹³⁾.

3.6 ENERGY OF EXPLOSIVES

Explosives are substances that rapidly liberate their chemical energy as heat to form gaseous and solid decomposition products at high temperature and pressure. The hot

and dense detonation products produce shock waves in the surrounding medium and upon expansion impart kinetic energy to the surrounding medium. The energy released in the detonation process is given by the following formula:

$$Q = \Delta H_f(\text{products}) - \Delta H_f(\text{reactants}) \quad (\text{EQ 12})$$

where ΔH is the heat of formation.

The energy per unit weight is called the weight strength of the explosive.

The energy per unit volume is called the bulk strength of the explosive.

Sometimes it is useful to express the weight and the bulk strengths as relative values obtained by dividing the strength (weight or bulk) to the corresponding strength of a standard explosive. The commercial industry normally uses AN/FO as the standard explosive.

3.7 SHELF LIFE

The shelf life of an explosive determines the maximum time period the explosive can be in storage. Various explosives age and their use is unsafe or they cannot be detonated reliably.

3.8 PRESSURE DESENSITIZATION

Commercial explosives can be susceptible to hydrostatic heads. Hydrostatic heads can compress the explosive to high densities and "dead packing" can result.

3.9 MEASUREMENT OF THE DETONATION PROPERTIES

3.9.1 DETONATION VELOCITY

There are various methods of measuring detonation velocities. These are outlined in the following:

I. The continuous probe method.

The system consists of the explosive charge, along the central axis of which a uniform resistance probe is inserted, a constant current source, a triggering source and an oscilloscope.

The resistance probe consists of a resistance wire inserted into a small diameter brass tube. The resistance wire is a nichrome wire having an accurately known linear resistance.

The oscilloscope is connected in parallel to both the current source and the probe (Figure 15)⁽⁵⁾. At detonation the wire resistance probe is consumed. However the circuit remains closed due to the fact that the detonation wave is sufficiently ionized. The circuit follows Ohm's law. Therefore, since current is constant, the voltage change with time shown on the oscilloscope, is proportional to the resistance. Knowing the full voltage drop across the probe and the length of the probe, the voltage drop can be converted to distance along the charge. Therefore the velocity of detonation can be calculated by interpreting the voltage drop - time record provided by the oscilloscope.

II. SLIFER system

The SLIFER system was originally developed by Sandia National Laboratories to measure the propagation of shock waves from nuclear explosions. SLIFER stands for Shorted Location Indication by Frequency of Electrical Resonance. The system can however be used in blasting. The system utilizes the fact that a shorted length of coaxial cable, less than $1/4$ wavelength long is at the resonant frequency inductive⁽¹⁴⁾. The cable becomes part of an oscillator circuit the frequency of which depends on the length of the cable. As the cable is crushed by the shock wave the frequency increases. Frequency versus time provide the position of the shock front at different times. The system has been applied to VOD measurements by BHP⁽¹⁵⁾, BLASTECH and ICI. A schematic representation of the system is given in Figure 16. For field applications the shorted end of a coaxial cable is attached to the primer which is loaded in the hole. The system is triggered by the detonation of the explosive. A typical trace taken from Moxon et al⁽¹⁵⁾ is shown in Figure 17. The diameter of the hole was 190 mm. From the trace, the VOD as well as the crush velocity of the stemming can be obtained.

III. CORRTX system

The CORRTX system was originally developed by Los Alamos National Laboratories for the measurement of nuclear yield. CORRTX stands for Continuous Reflectometry for Radius versus Time Experiments. This system is also suitable for blasting. The technology on which it is based (Time Domain Reflectometry or TDR for short) is well known and used in a variety of fields. What is unique with CORRTX is that the system pulses at a high rate (200000 pulses per second for the commercial VOD monitor). The concept involved in the operation is similar to that of a radar in which a pulse of radio waves is sent out and a reflected

wave is returned to provide ranging information. The system uses a coaxial cable to carry a fast rise time electrical pulse⁽¹⁶⁾. The pulse will be reflected at the point where the cable is crushed by a shock wave. The time between the sending of the pulse and its

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return is accurately measured, so the length of the cable in time is known. The system is commercially available through BAI and is known as VODR. A schematic representation of the system is given in Figure 18. A typical example of a trace taken from Chiappetta⁽¹⁷⁾ is shown in Figure 19. Again as in the case of SLIFER both VOD and stemming crush velocities can be obtained.

iv. Start-stop method

Two probes are placed at a known distance apart in the explosive. Each probe consists of two wires placed in close proximity. When the detonation wave contacts each probe it shortens the circuit by bringing the two wires in contact. By measuring the signals obtained by either a counter or an oscilloscope one can measure the detonation velocity.

v. Ionization system (VODEX)

The VODEX system is an eight channel high speed timer that records time intervals between channels and converts them to Detonation Velocity. It relies on the ionized plasma generated inside the detonation front. This plasma sequentially short circuits a series of wire pairs terminating at known positions in the explosive charge. Normally ribbon cable is used for this purpose, with individual pairs cut back to the desired sensor positions⁽¹⁸⁾. The operating principle is shown in Figure 20⁽¹⁸⁾.

vi. Fiber optic system

The fiber optic systems use synchronous timers which measure the time intervals between the illumination of successive optical probes. Figure 21⁽¹⁹⁾ shows the principal of operation of the explomet-to system made by Kontinitro.

vii. Streak camera method

The method is shown in Figure 22⁽⁹⁾. The streak camera uses a mirror which rotates at the centre of the drum. The film is placed on the drum. The field of view of the camera lens is masked except for a narrow slit. The charge is aligned so that its axis is parallel to the slit of the camera. The light generated by the detonation front enters through the slit and after being reflected on the rotating mirror, leaves a mark on the film. Thus the streak camera trace is essentially a time distance record. The slope of the trace made by the luminous wave provides the velocity of detonation. A typical streak camera record is shown in Figure 23.

viii. D'Autriche Method.

This is the least sophisticated method. It is outlined in Figure 24⁽⁹⁾. The method uses a detonating cord both ends of which are inserted in the explosive at a known distance apart. A metal witness plate is placed close to the middle of the detonating cord. The detonation wave in the charge initiates the detonating cord at both ends. When the detonation waves travelling in opposite directions in the detonating cord collide, they leave a dent in the witness plate. This helps to find the position in the detonating cord at which the collision took place. Thus, the distance, and therefore the time, each wave travelled in the detonating cord can be found. The difference in the times the two waves travelled

MEASUREMENT OF THE DETONATION PROPERTIES

In the cord provides the time it took the detonation wave in the test charge to travel the distance L .

3.9.2 DETONATION PRESSURE

The measurement of the detonation pressure is normally based on photographic techniques. These techniques require a streak camera and accurate experiments (aquarium technique). In the aquarium technique, a transparent liquid serves as a pressure gauge for measuring transient pressures. The transparent liquid has to be selected in such a way that the reflected wave at the gauge-liquid interface is either a weak shock or a very weak rarefaction. The technique, as described by Cook⁽⁸⁾ consists of the following two stages:

I. Initially the Hugoniot of the liquid which serves as a gauge is determined. The experimental set up is shown in Figure 25. The method consists of the simultaneous measurement of the shock velocity at the free surface and the free surface velocity as the shock emerges from the transparent medium. Observations of the shock velocity and the free surface velocity are made by using a streak camera. By changing the height (h) of the liquid inside the container, one changes the shock velocity and the free surface velocity. By assuming that the particle velocity of the liquid at the interface is half of the free surface velocity the relationship between shock velocity and the particle velocity in the liquid (Hugoniot) is obtained.

II. The experimental set up for the second part of the technique is shown in Figure 26. In this experiment, the velocity of detonation in the explosive charge and the initial transmitted shock velocity in the liquid are measured. From the transmitted shock velocity in the liquid and the known Hugoniot of the liquid, the initial pressure in the liquid can be calculated. The corresponding pressure in the detonation head is calculated by using the following relationship:

$$P_d = \frac{(P_{il}(\rho U_s)_{il} + \rho_{le} U_{se})}{2(\rho U_s)_{il}} \quad (\text{EQ 13})$$

where

P_d is the detonation pressure

ρ_{le} is the initial density of the explosive

U_s is the detonation velocity

$(\rho U_s)_{il}$ is the initial impedance of the liquid and

P_{il} is the initial pressure in the liquid.

The initial pressure in the liquid is calculated by the well known relationship

$$P_{il} = \rho_l U_{sl} U_{pl} \quad (\text{EQ 14})$$

where P_{il} is the pressure in the liquid
 U_{sl} is the shock velocity
 U_{pl} is the particle velocity and
 ρ_l is the initial density of the liquid.

Because of the difficulty in measuring detonation pressures it is often necessary to calculate the detonation pressure from the detonation velocity by using the approximate formula:

$$P = \frac{(\rho D^2)}{4} \quad (\text{EQ 15})$$

where P is the detonation pressure
 ρ is the initial density of the explosive and
 D is the measured detonation velocity.

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**FIGURE 1: DETONATION VELOCITY - CHARGE DIAMETER
FOR A GRANULAR EXPLOSIVE
(After Bauer)**

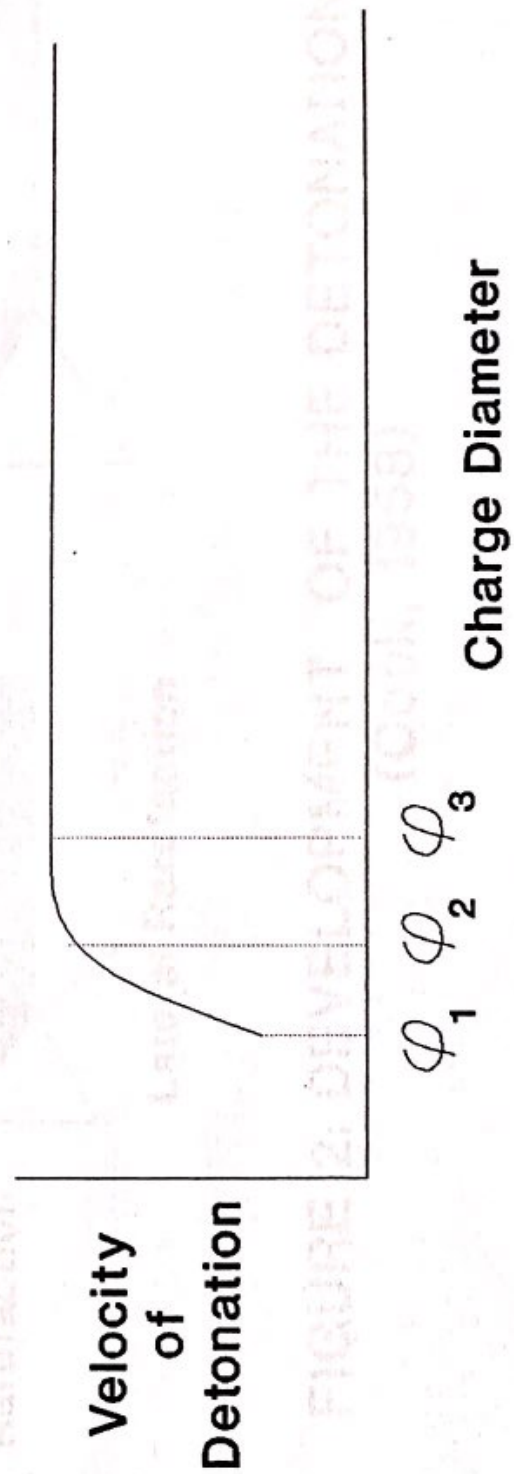
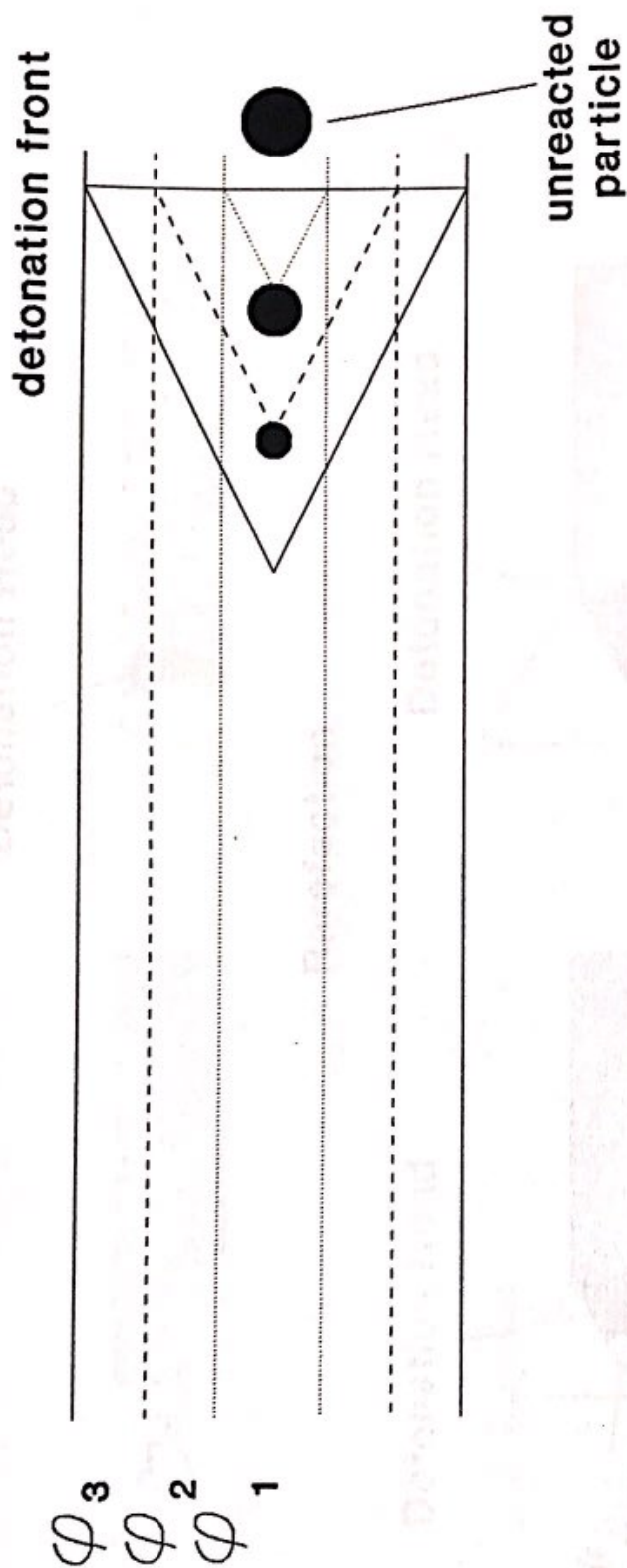
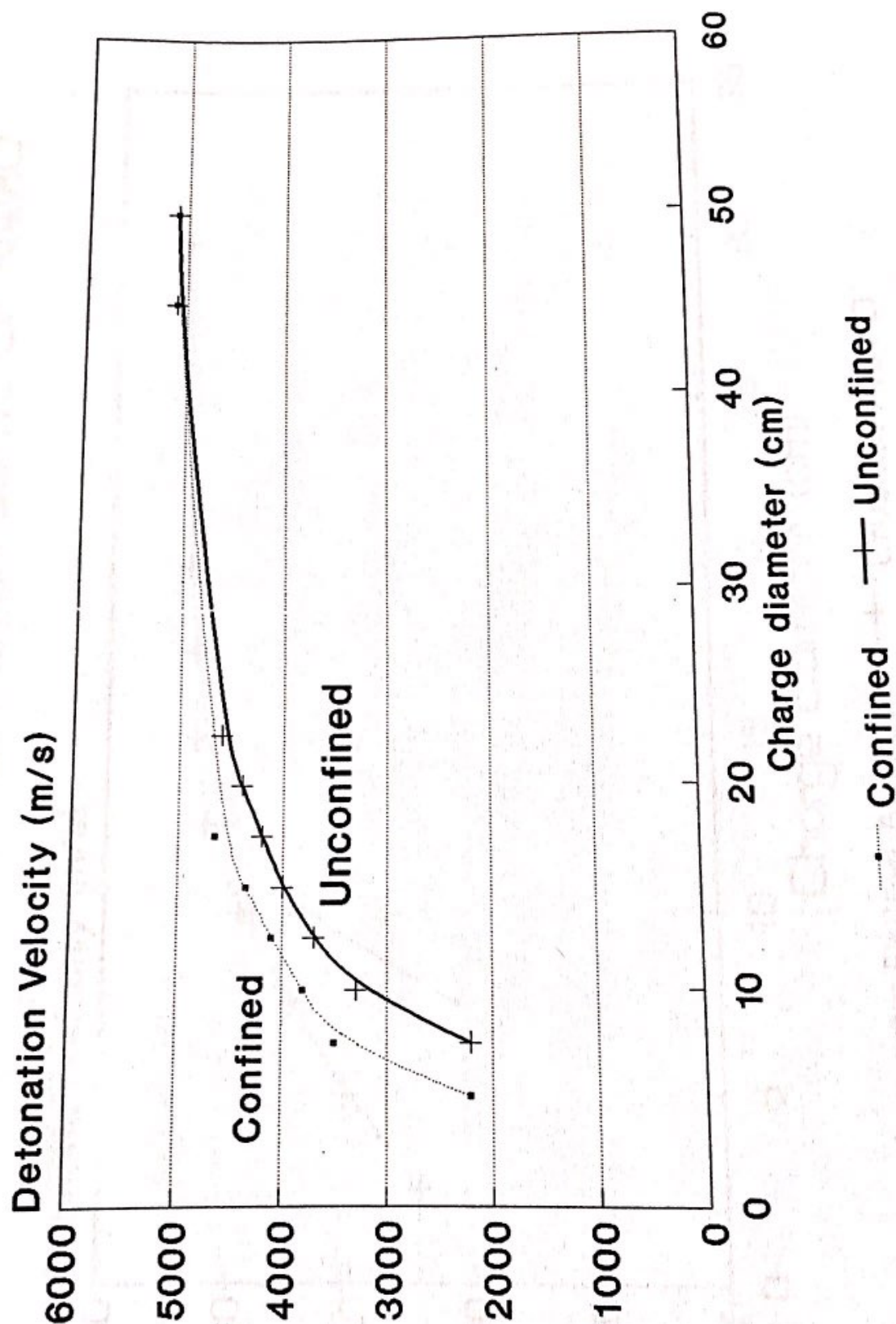
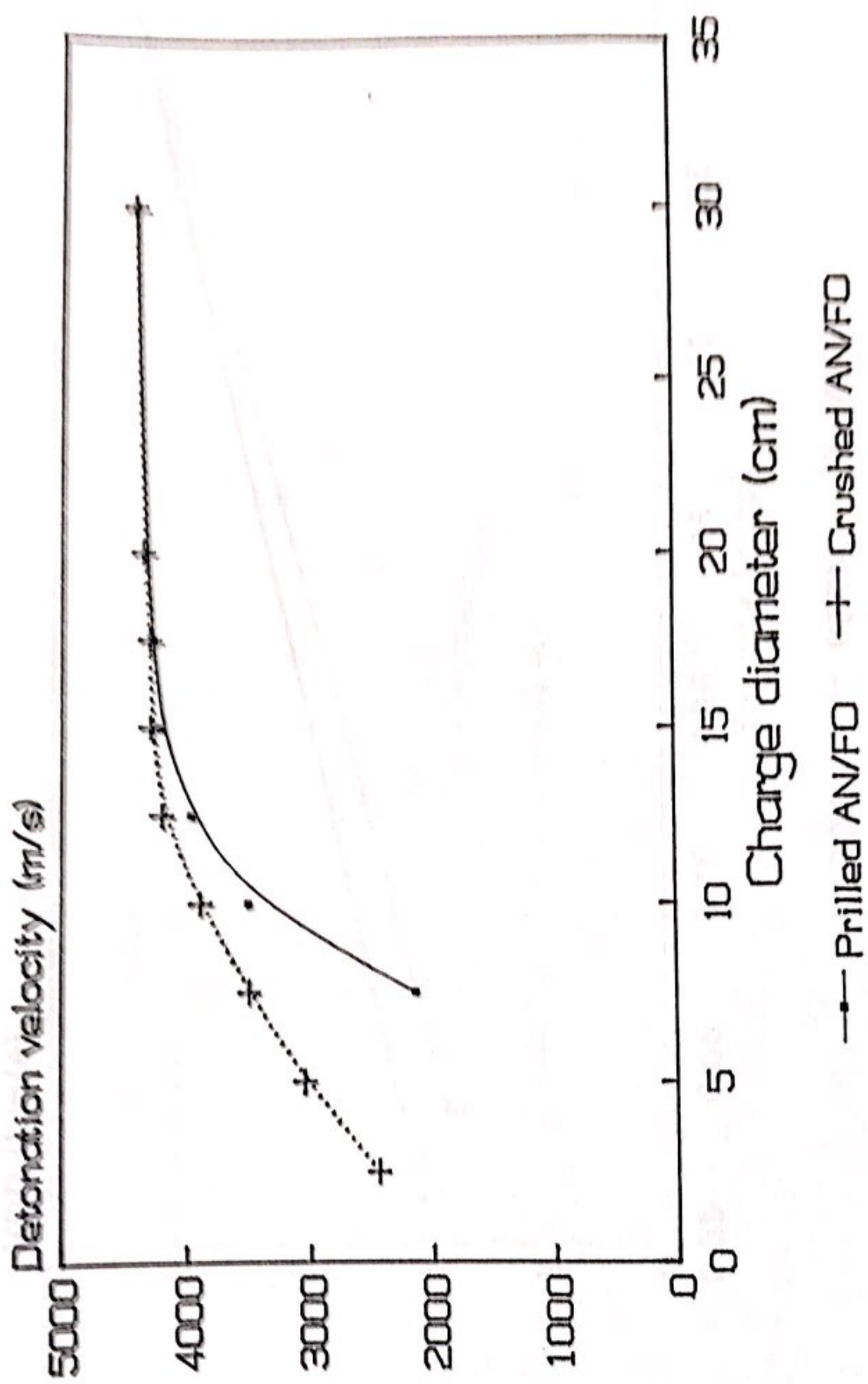


FIGURE 3: VOD - CHARGE DIAMETER CURVES
FOR CONFINED AND UNCONFINED AN/FO



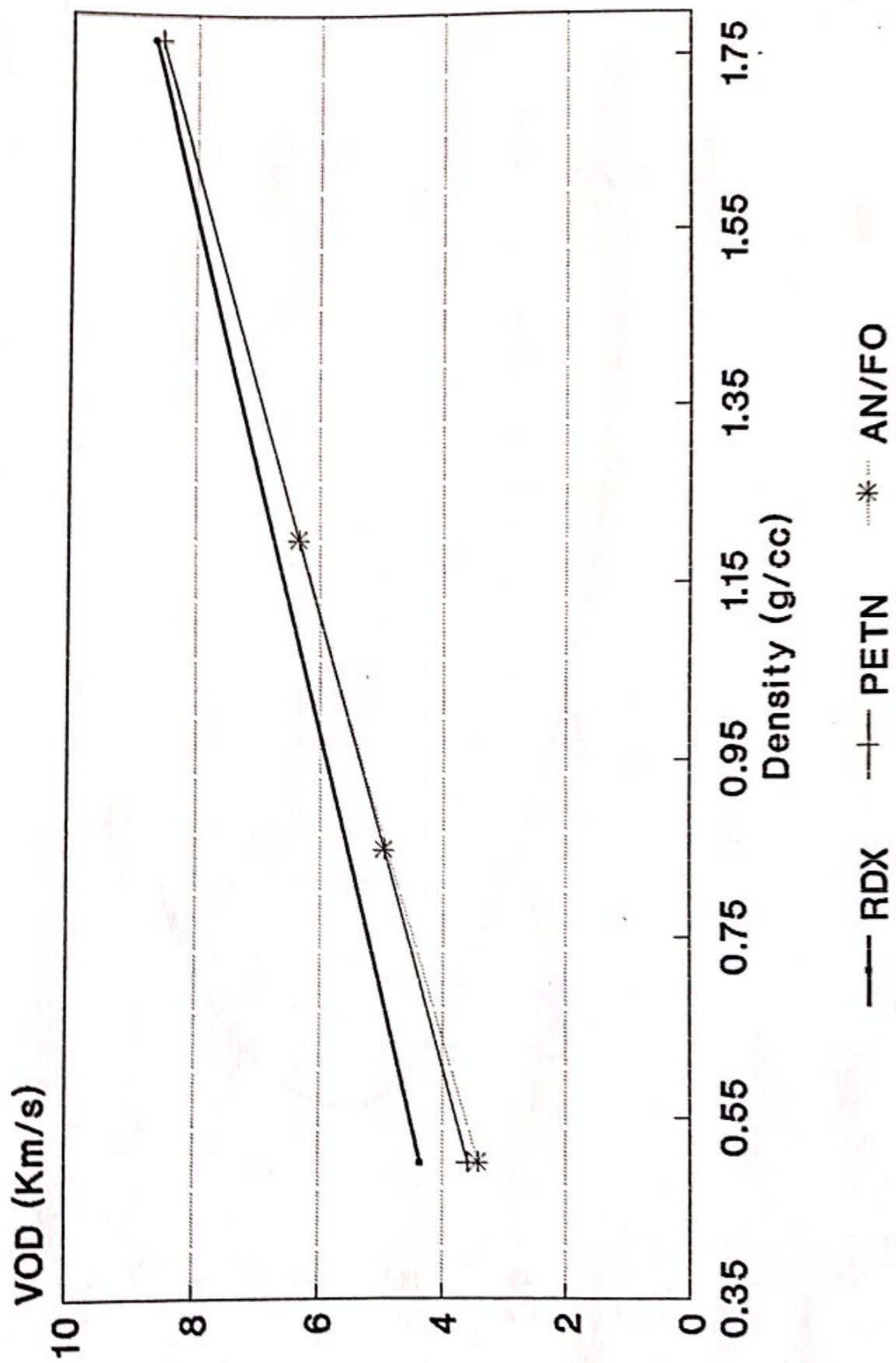
density = 0.85 g/cc

FIGURE 4: EFFECT OF THE PARTICLE SIZE ON THE VELOCITY - DIAMETER CURVE OF AN/FO



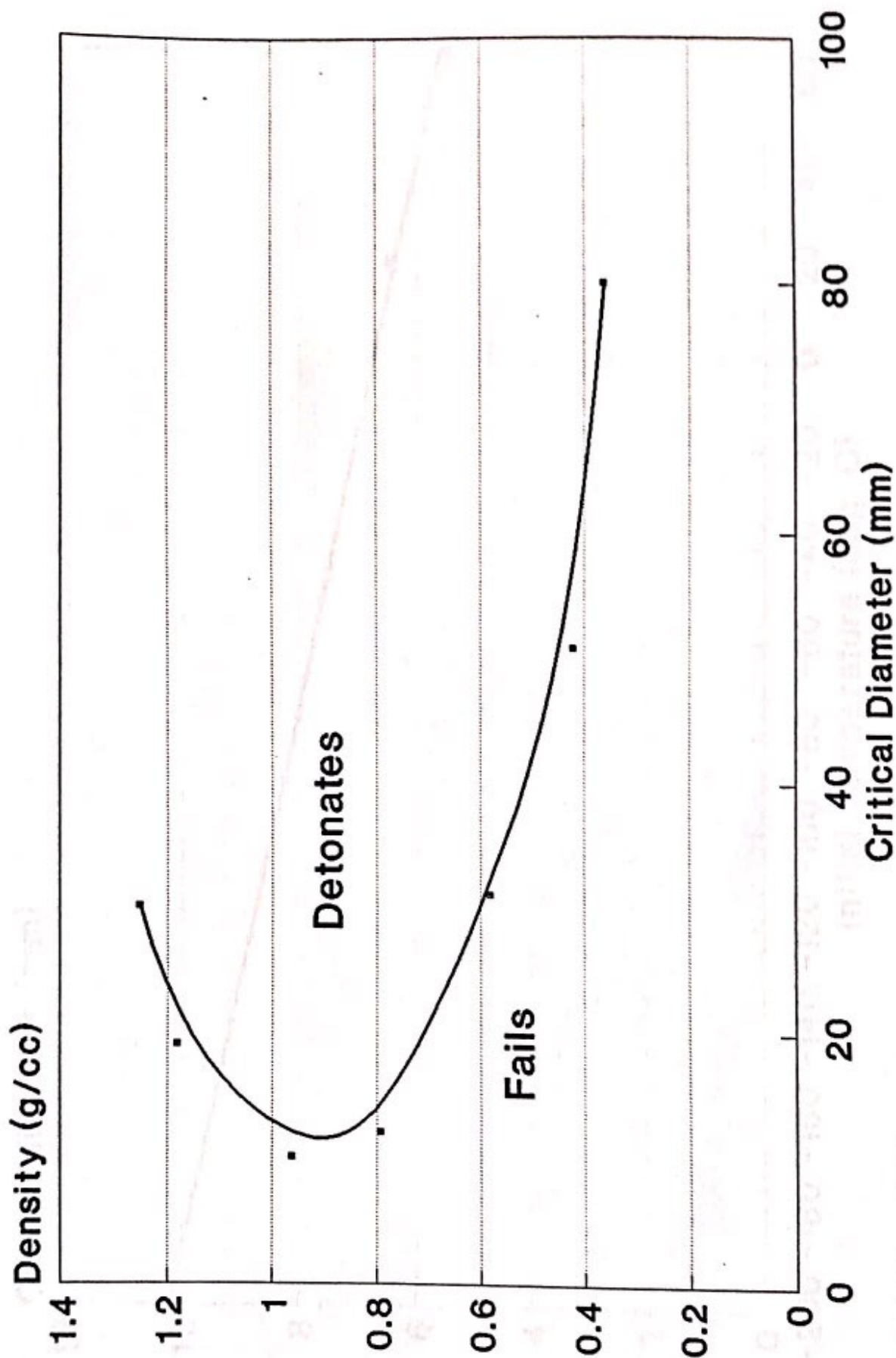
density = 0.85g/cc

FIGURE 5: VELOCITY OF DETONATION AS
A FUNCTION OF DENSITY



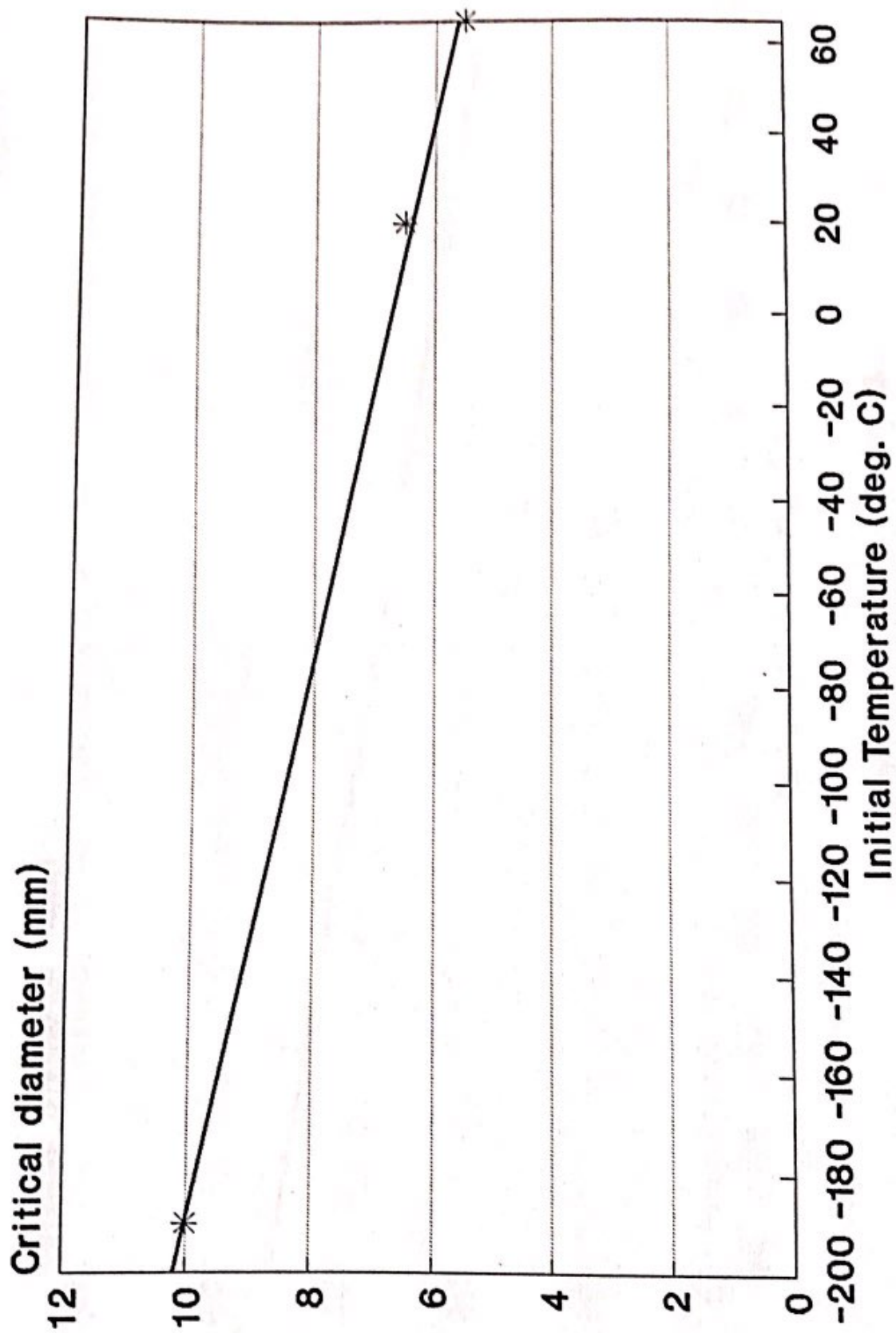
Theoretical Values

FIGURE 6: CRITICAL DIAMETER VERSUS DENSITY FOR A TYPICAL EMULSION



Unconfined tests

**FIGURE 7: CRITICAL DIAMETER OF POWDERED
TNT AS A FUNCTION OF INITIAL TEMPERATURE**



After Belyaev, 1968
density = 1.0 g/cc

**FIGURE 8: EFFECT OF TEMPERATURE ON THE
CRITICAL DIAMETER OF SLURRIES**

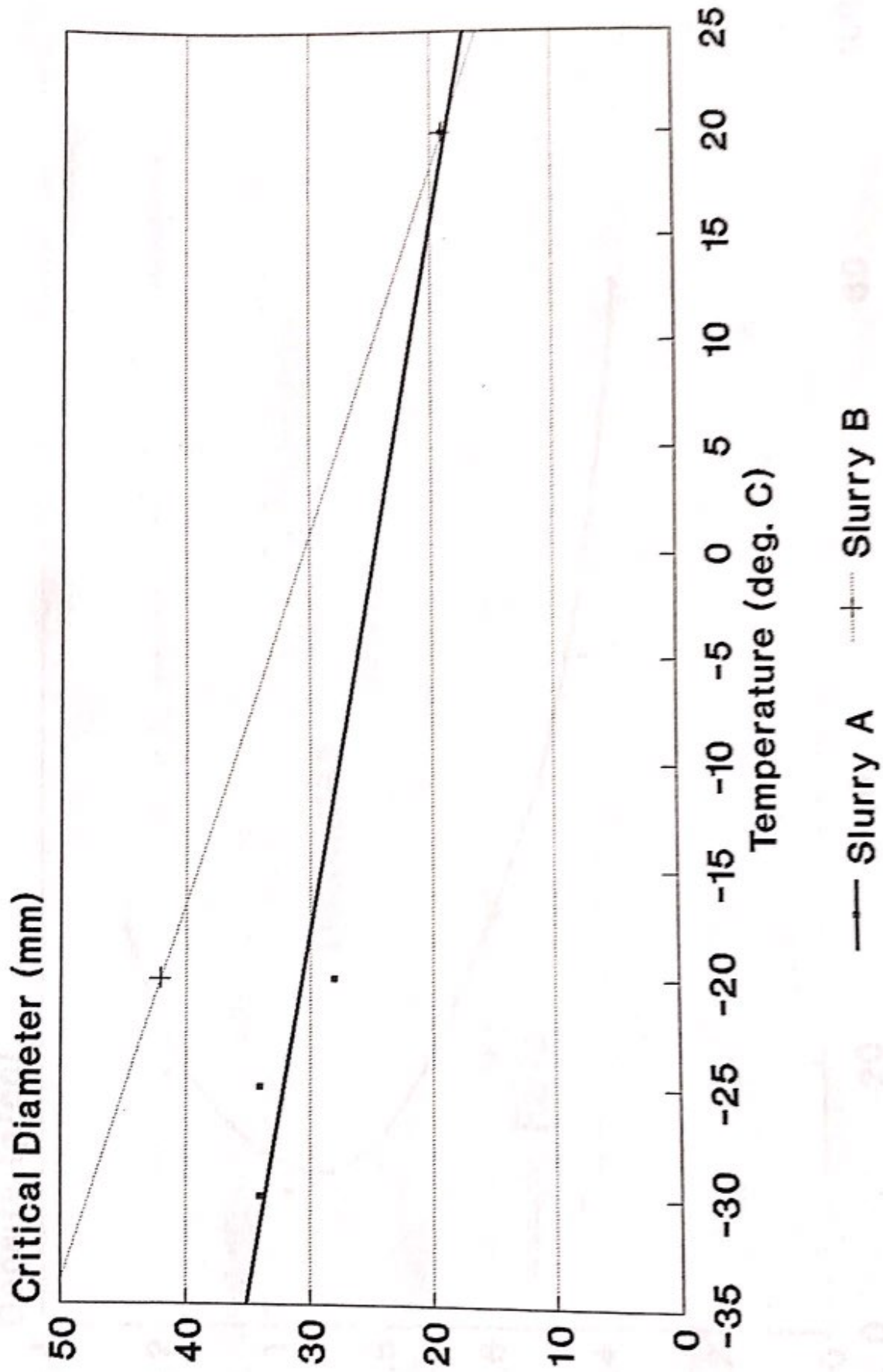
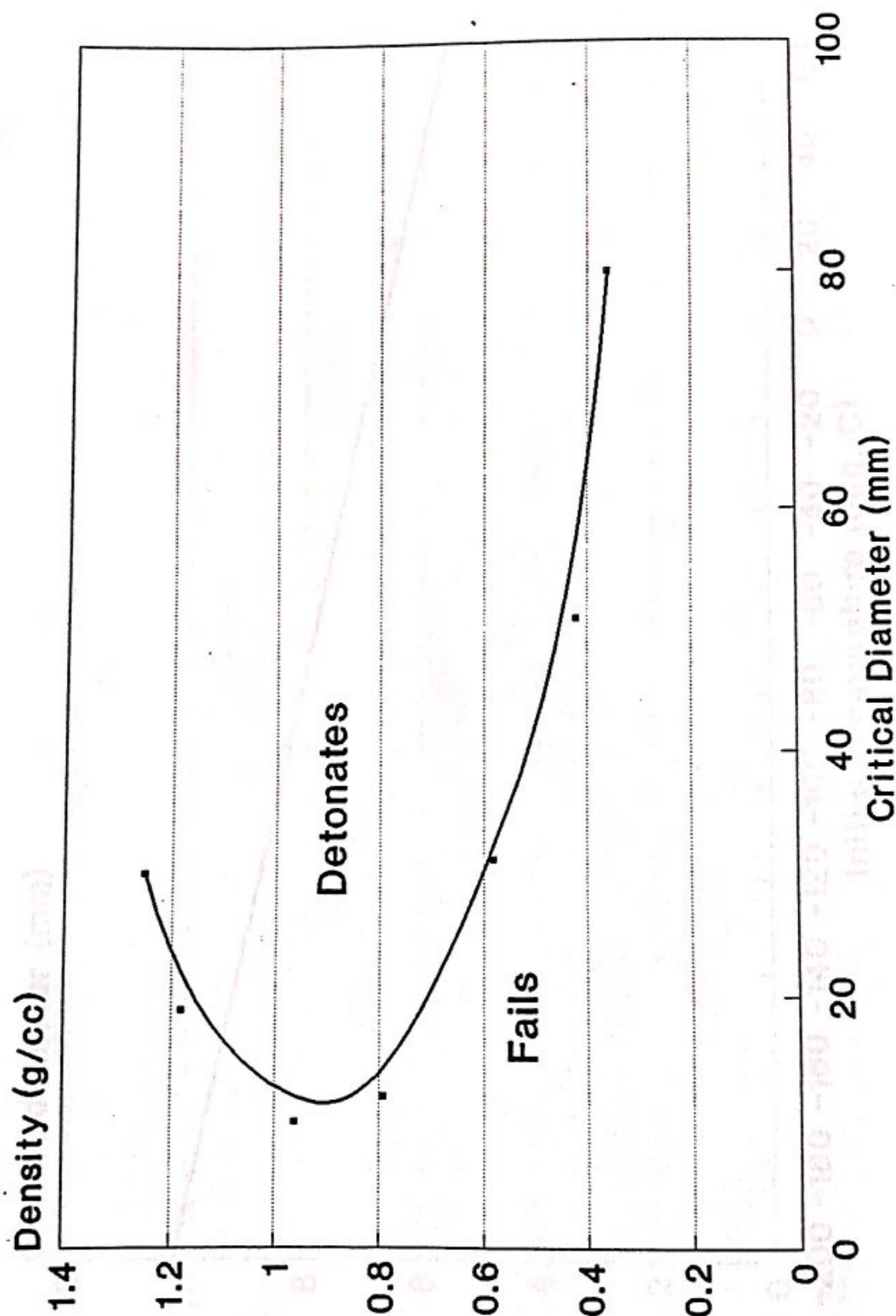
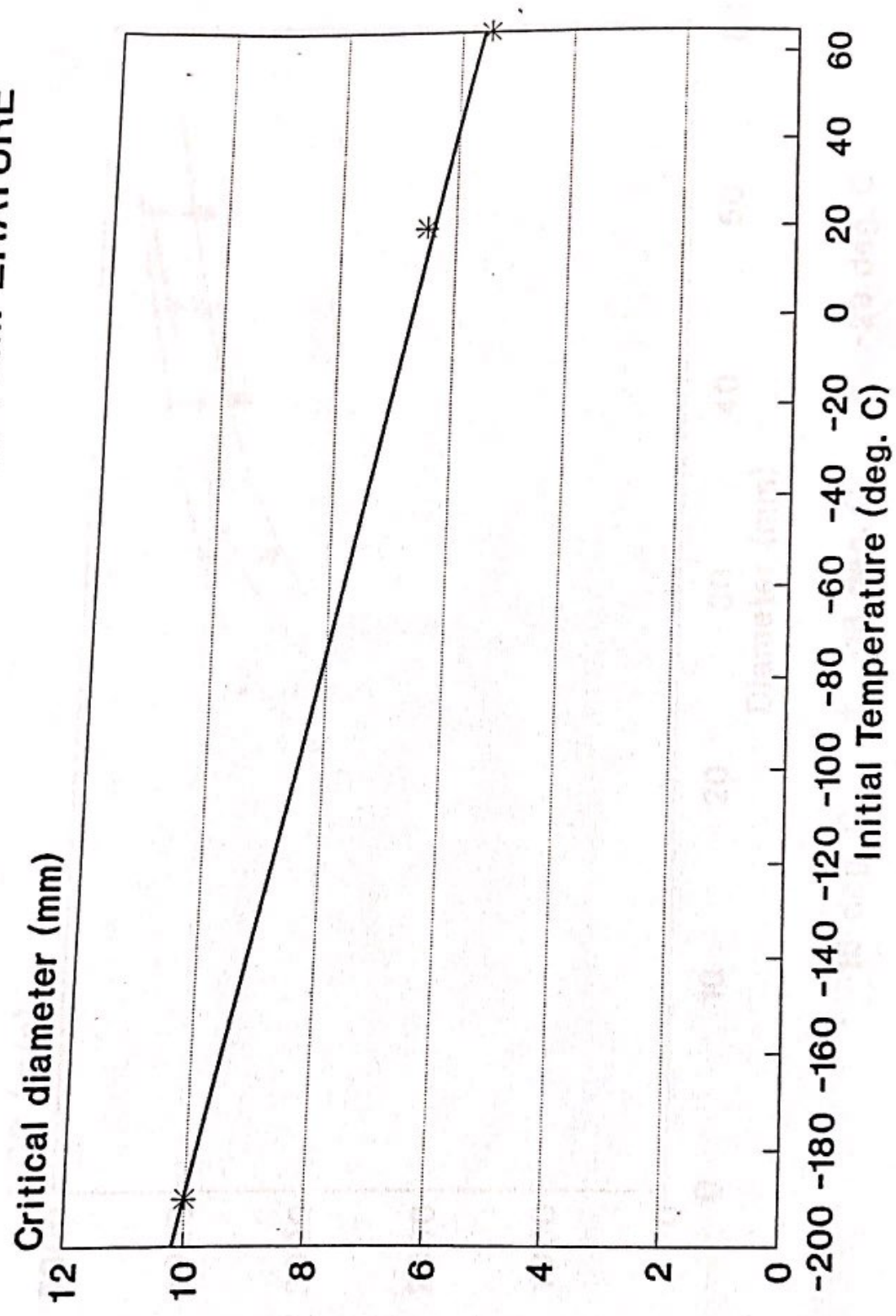


FIGURE 9: CRITICAL DIAMETER VERSUS DENSITY FOR A TYPICAL EMULSION



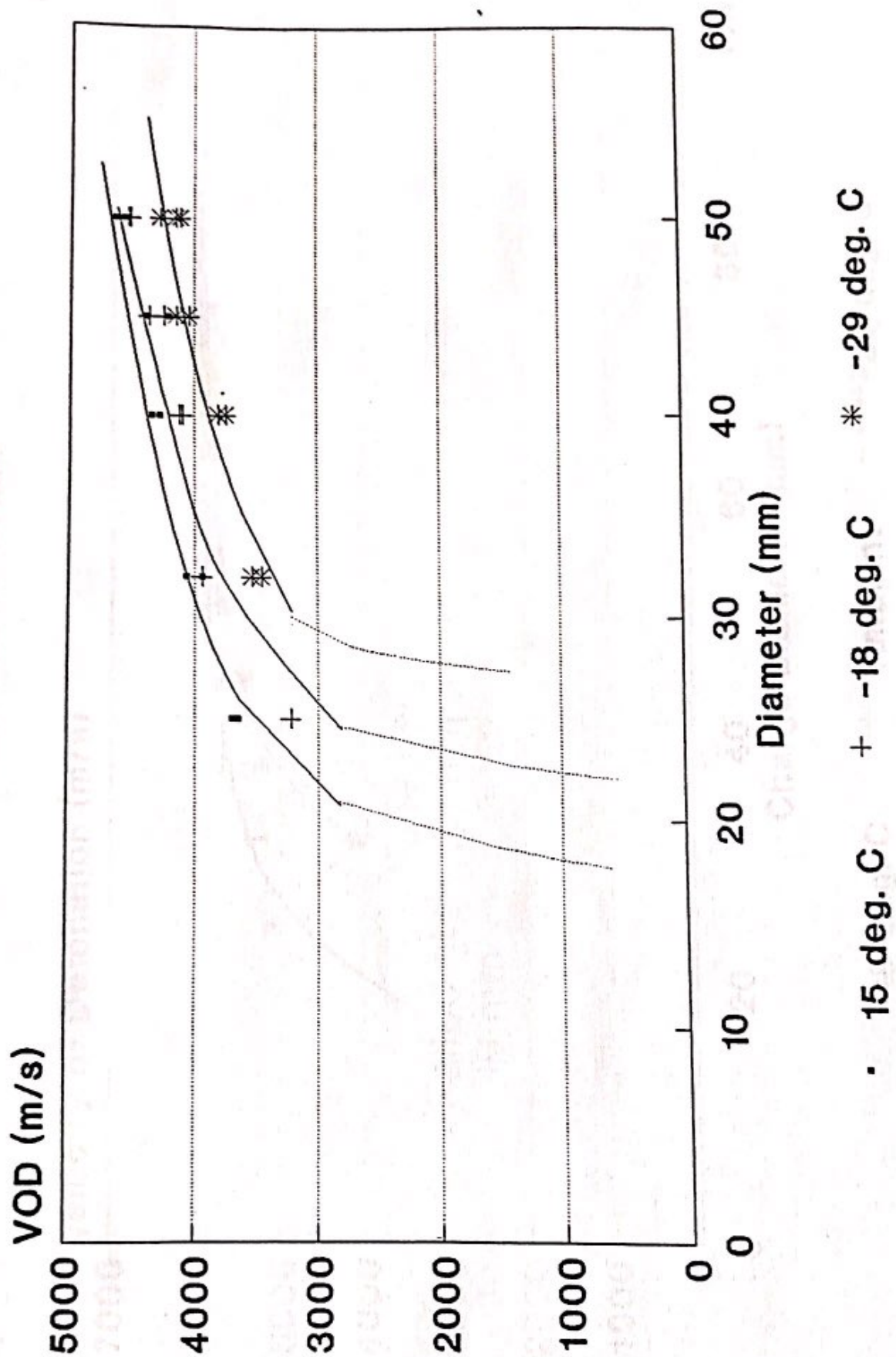
Unconfined tests

FIGURE 10: CRITICAL DIAMETER OF POWDERED TNT AS A FUNCTION OF INITIAL TEMPERATURE



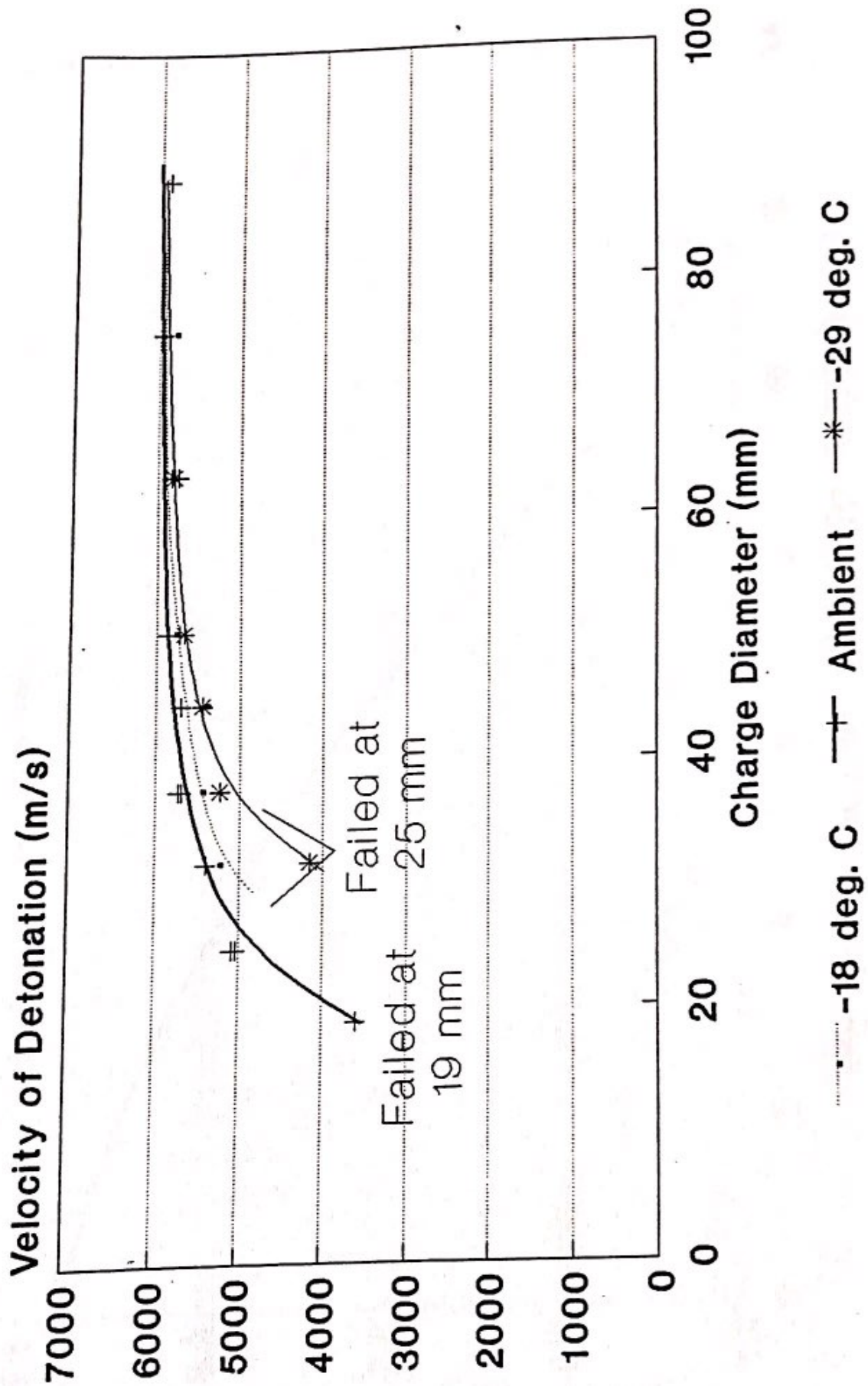
After Belyaev, 1968
density = 1.0 g/cc

**FIGURE 11: VOD VERSUS TEMPERATURE
A SMALL DIAMETER SLURRY**

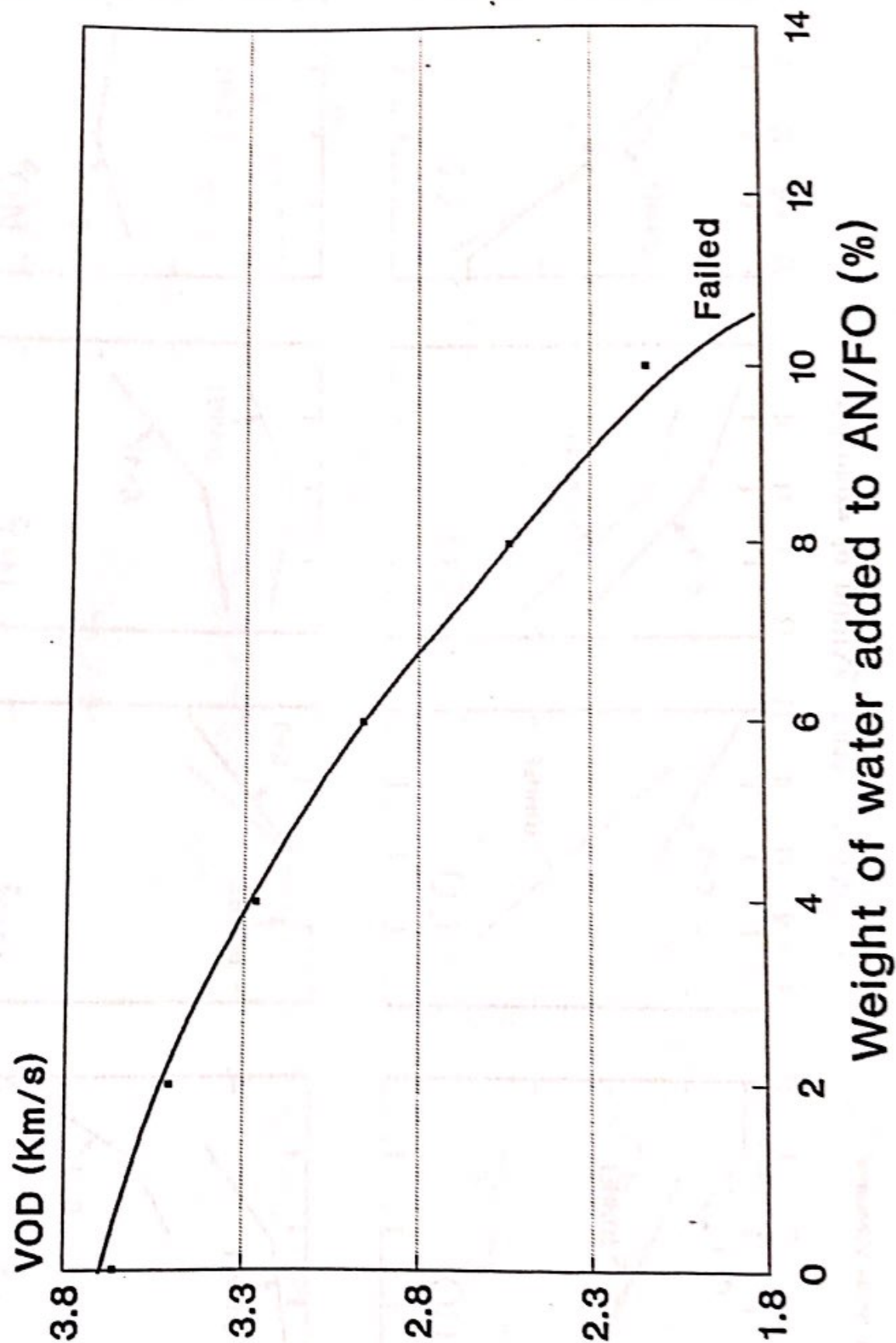


density = 1.18 g/cc

**FIGURE 11a:VOD - CHARGE DIAMETER FOR A
SMALL DIAMETER EMULSION AT VARIOUS
TEMPERATURES**



**FIGURE 12: EFFECT OF WATER ADDITION
TO THE VOD OF AN/FO**



Charge in 10.1 cm diameter plastic
pipe

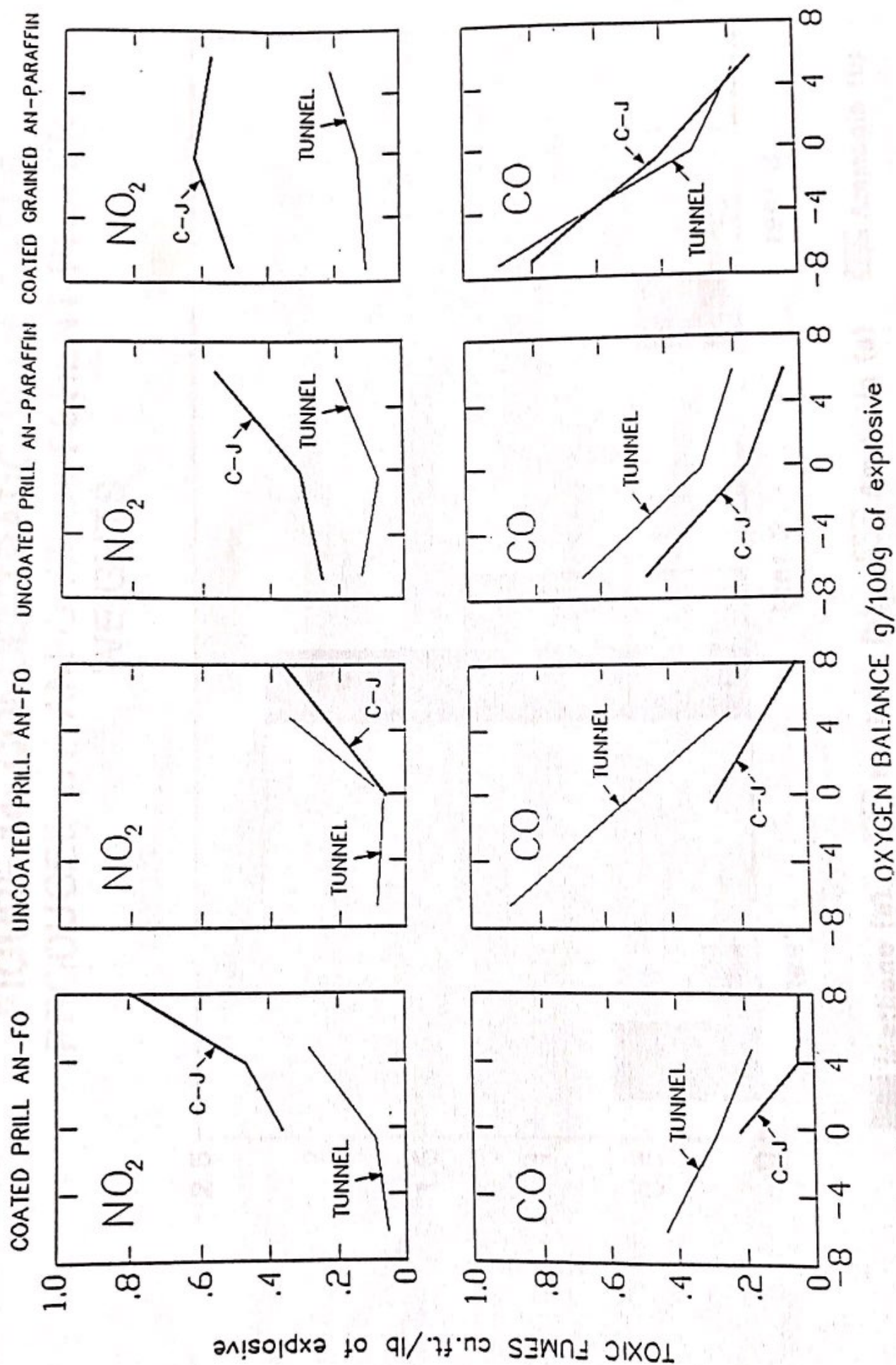
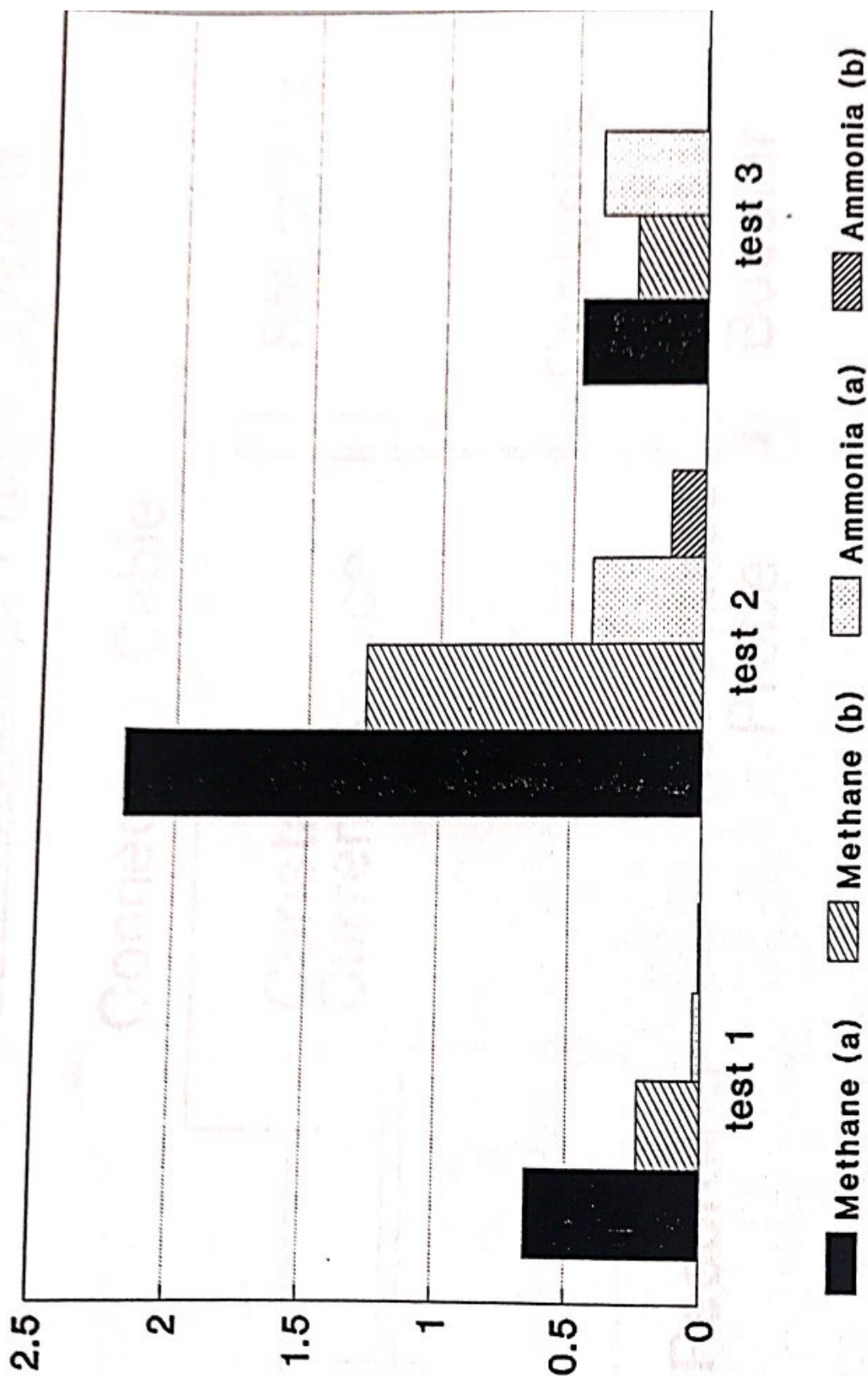


FIGURE 13: EFFECT OF OXYGEN BALANCE ON FUMES
PRODUCED BY AN/FO (Van Dolah, 1961)

**FIGURE 14: CONCENTRATIONS OF GASES
PRODUCED BY ANFO AT DIFFERENT PRIMER
WEIGHTS**



a: 2g of Detasheet b: 6g of Detasheet

FIGURE 15
Continuous Resistance Probe System

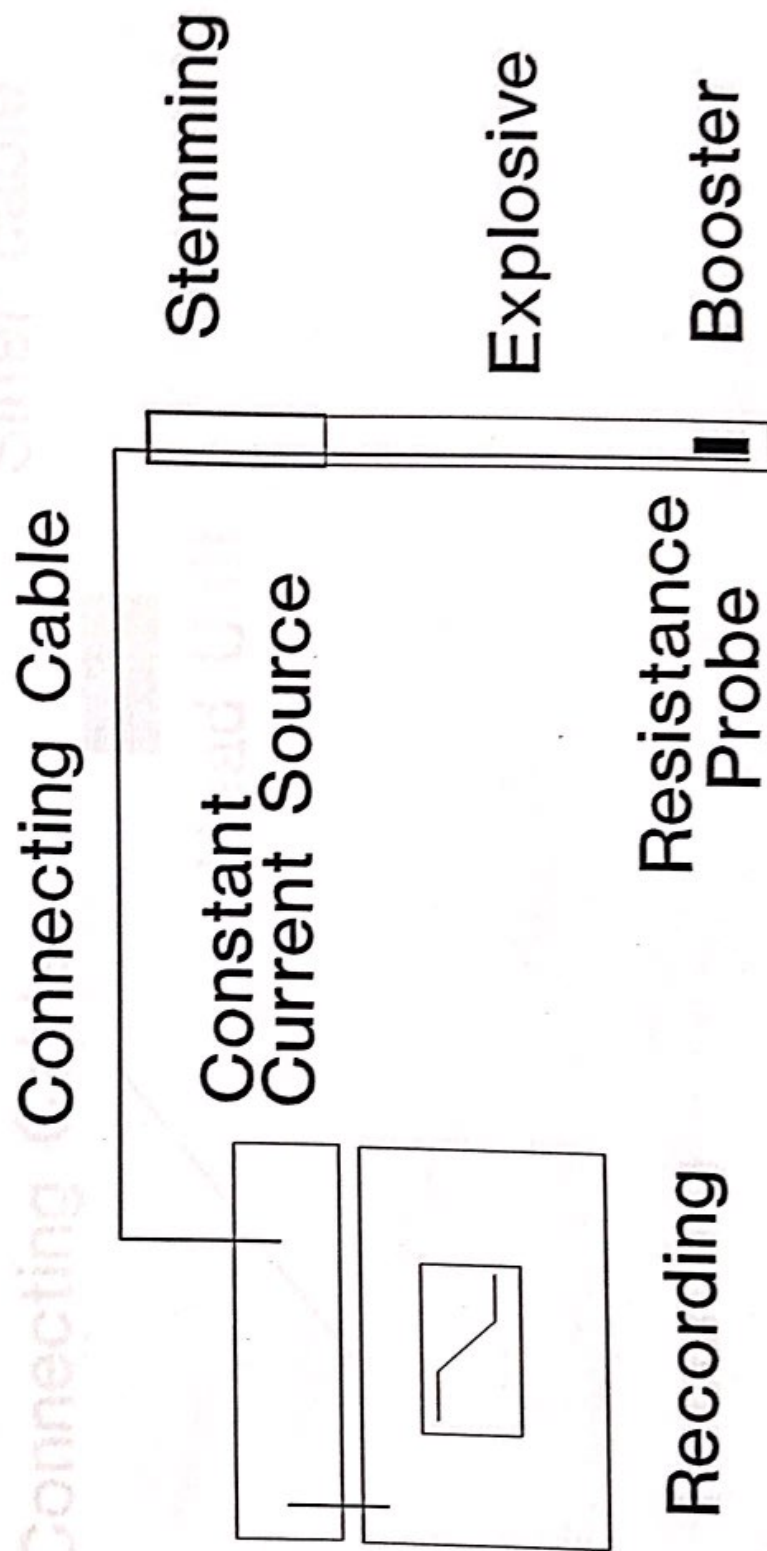
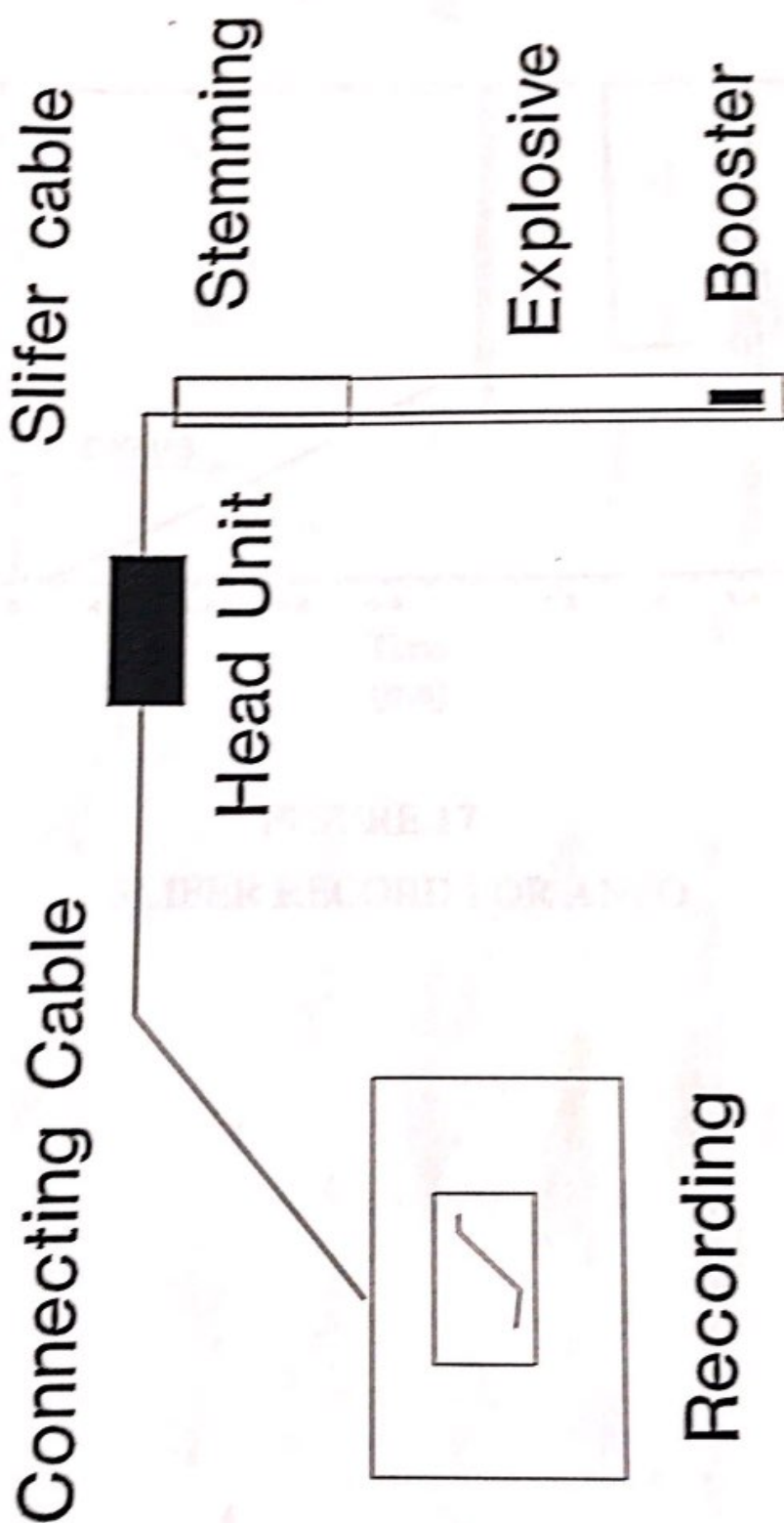


FIGURE 16

SLIFER SYSTEM



After Moxon, Hopkins and Danell (BHP)

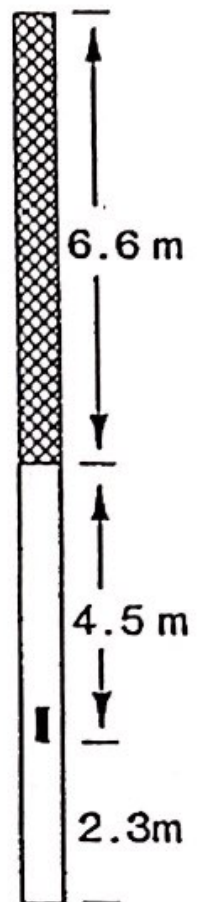
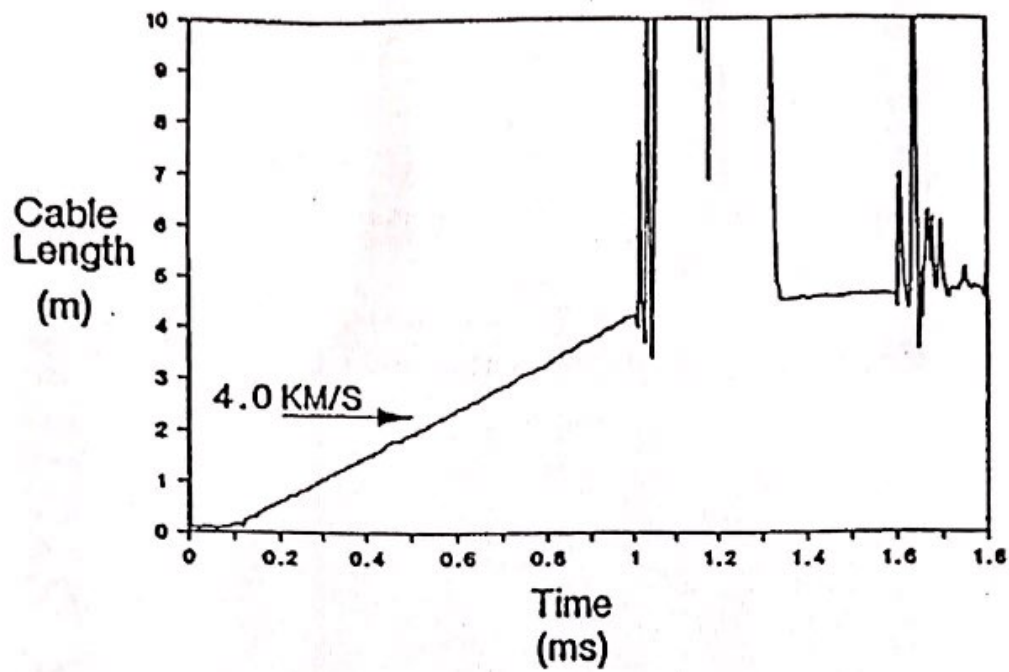
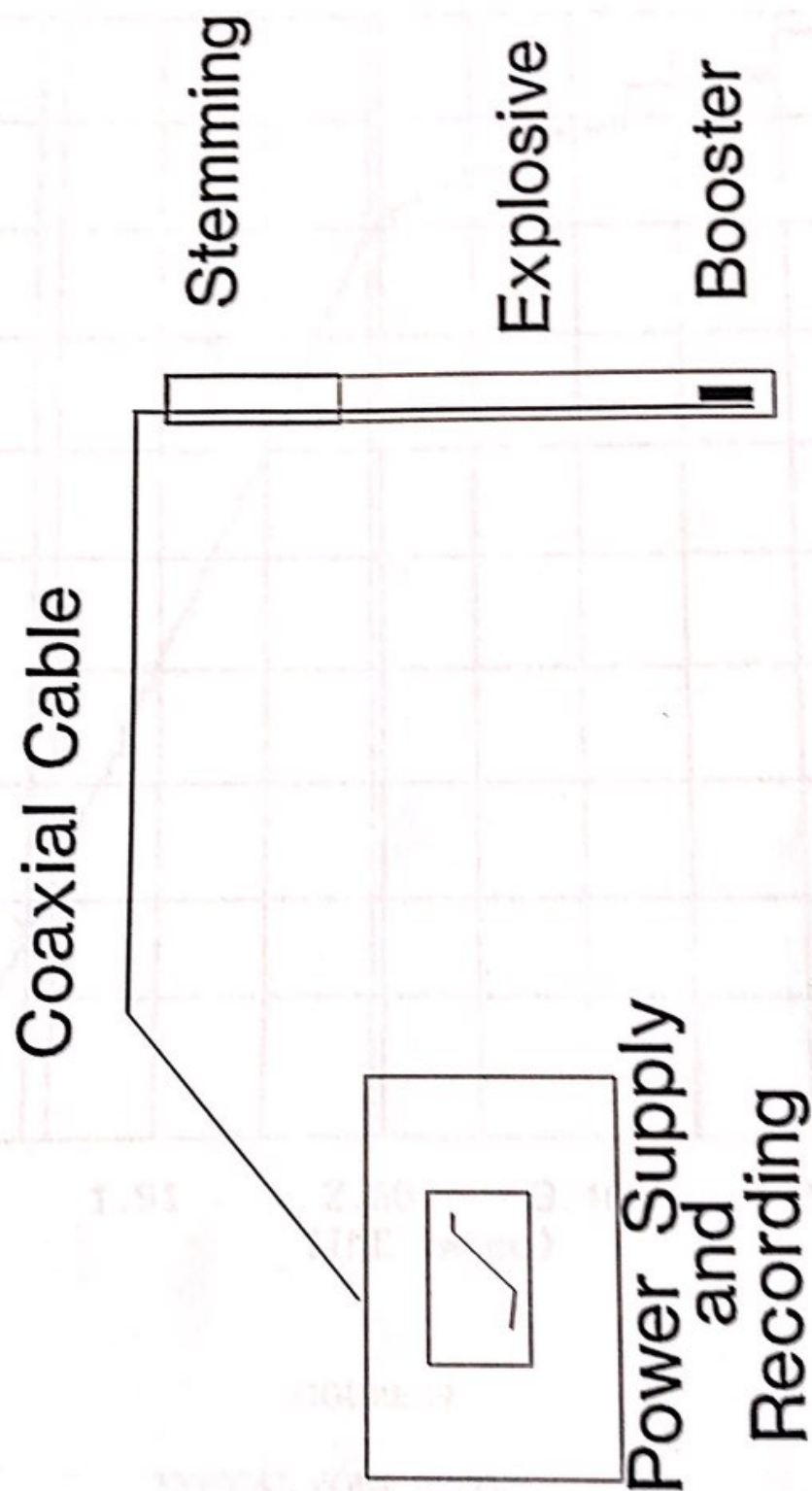


FIGURE 17
SLIFER RECORD FOR ANFO

FIGURE 18
CORRTEX SYSTEM



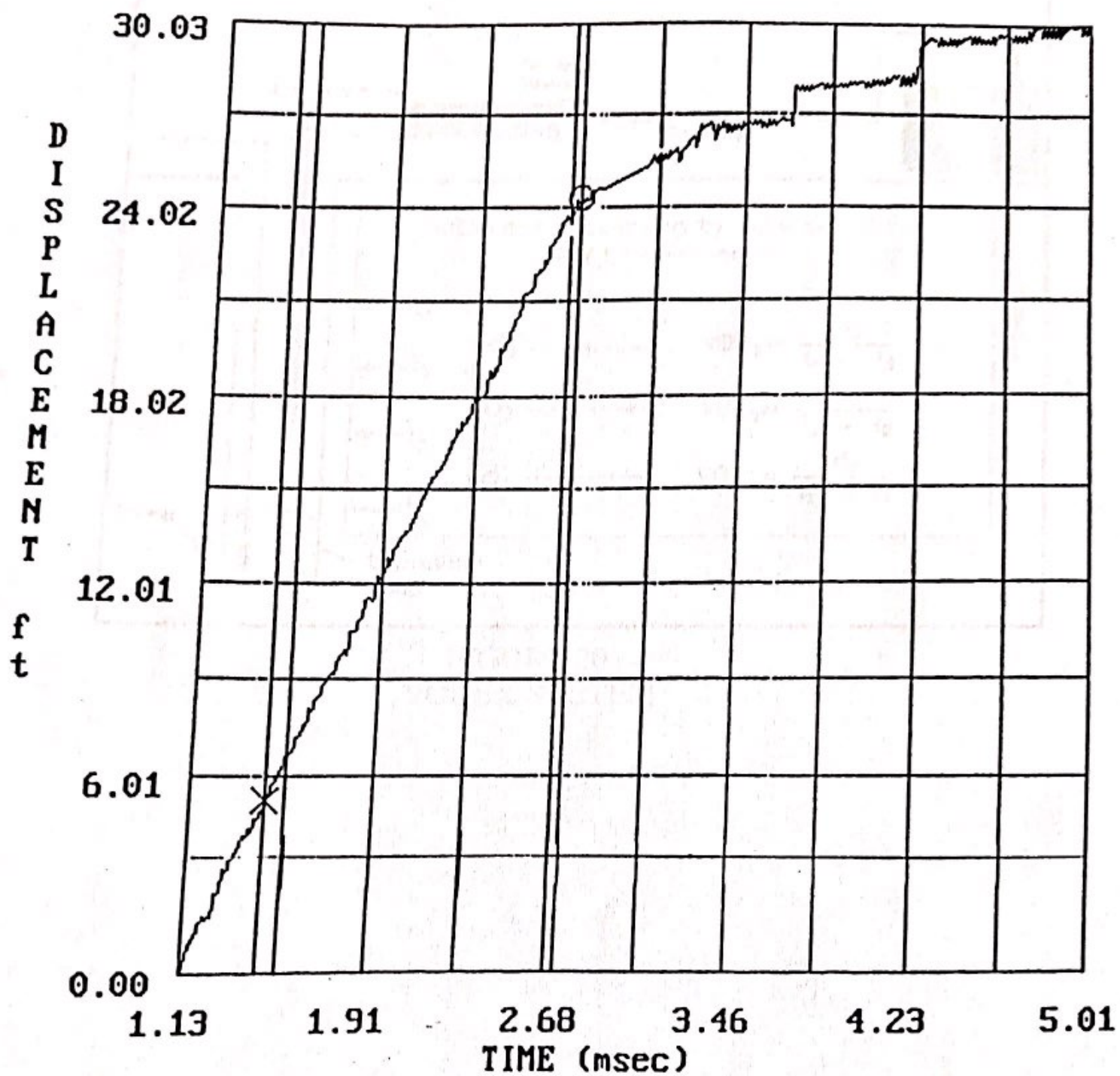


FIGURE 19

TYPICAL VODR RECORD

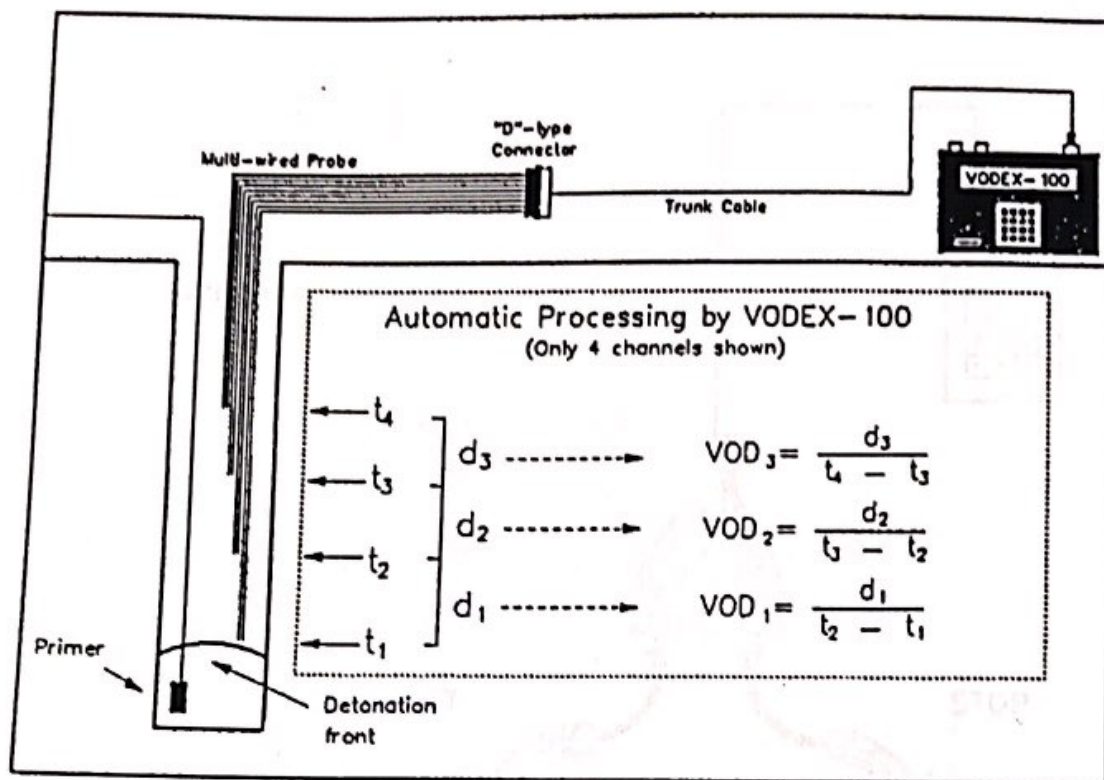


FIGURE 20
VODEX SYSTEM

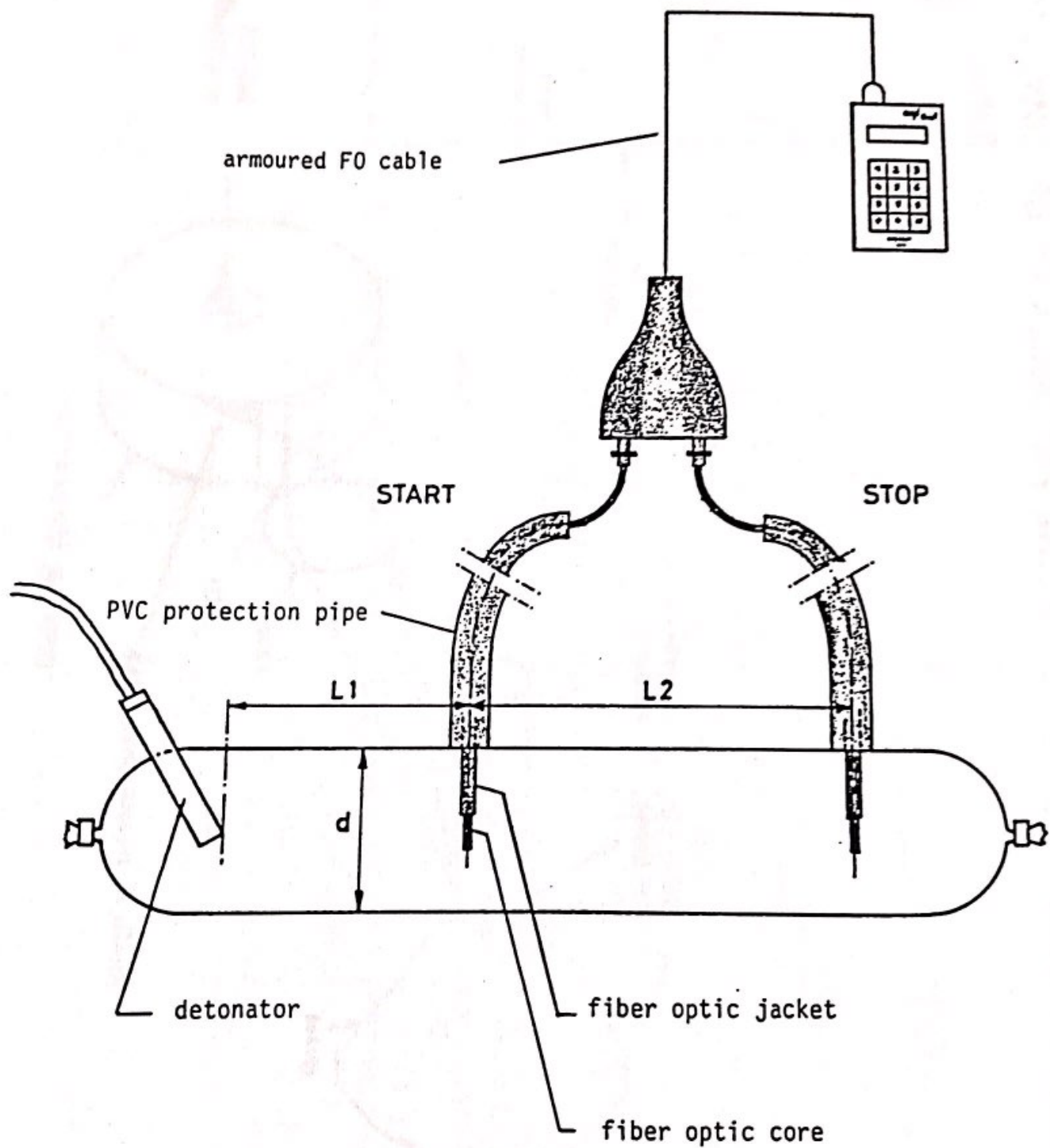


FIGURE 21
KONTINITRO FIBER OPTIC VOD SYSTEM

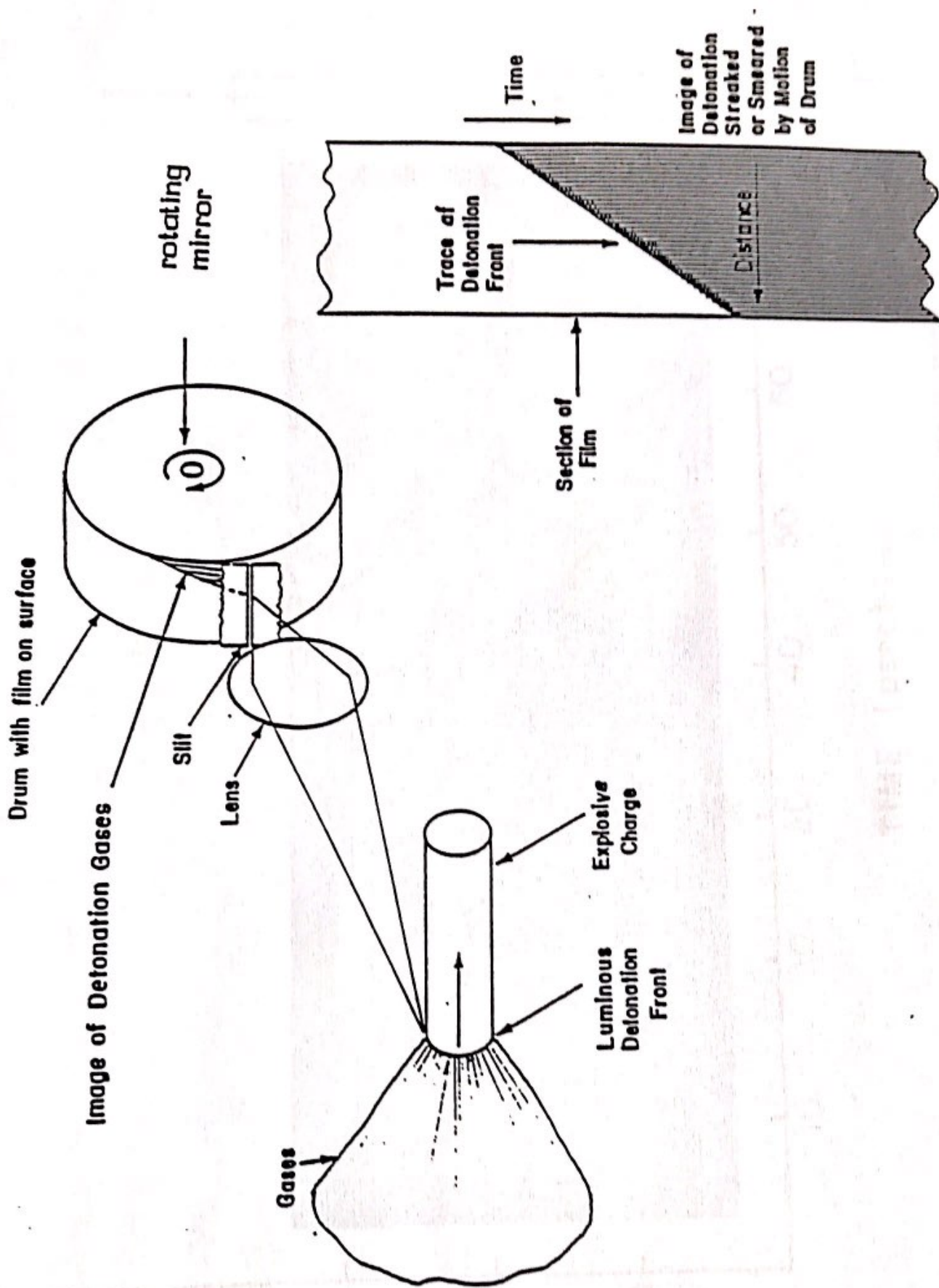


FIGURE 22: MEASUREMENT OF THE VELOCITY OF DETONATION USING A STREAK CAMERA (ref. 9)

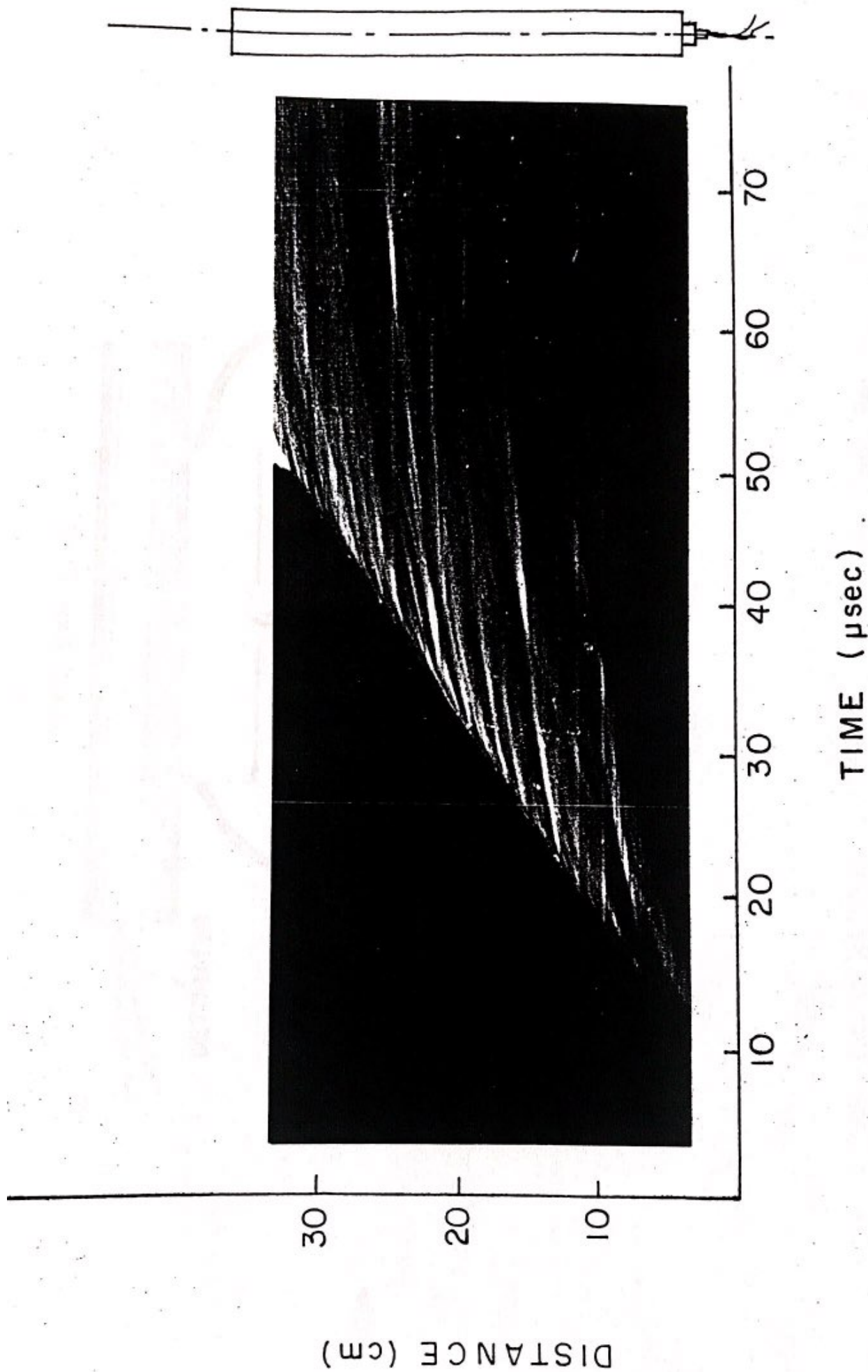


FIGURE 23: STREAK CAMERA RECORD FOR THE DETONATION
VELOCITY OF PENTOLITE

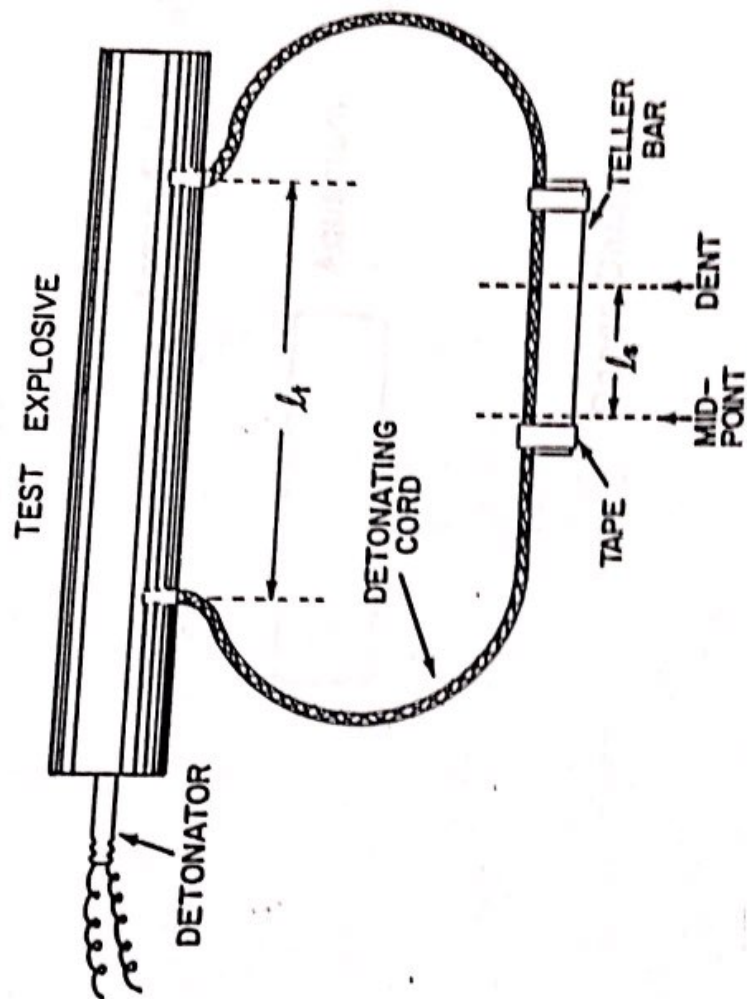


FIGURE 24: D'AUTRICHE METHOD FOR THE MEASUREMENT OF
DETONATION VELOCITY (Ref. 9)

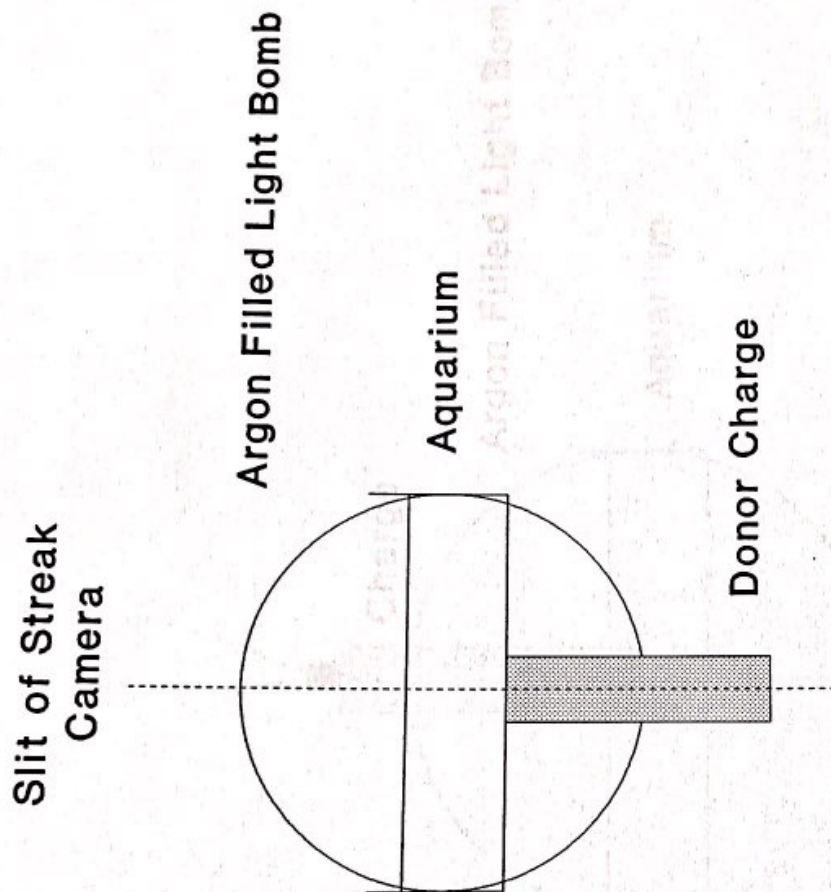


FIGURE 25

AQUARIUM TECHNIQUE - STEP 1

Measurement of free surface velocity to obtain the Hugoniot of the liquid in the aquarium

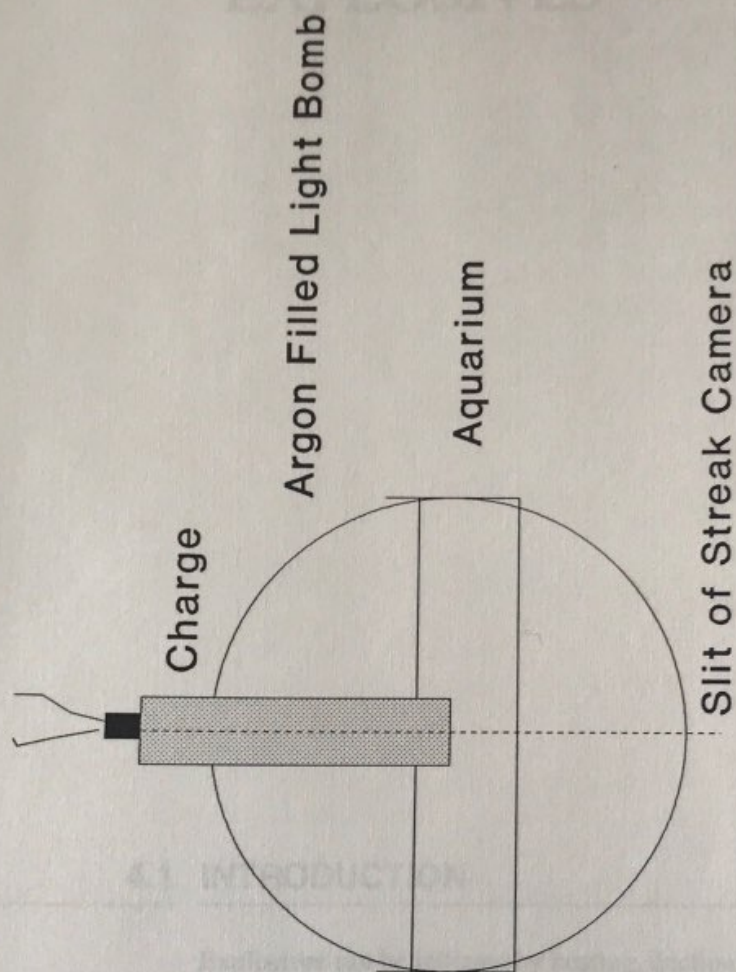


FIGURE 26

AQUARIUM TECHNIQUE - Step 2
Measurement of Detonation Velocity of Test Charge
and of the Initial Shock Velocity in the Liquid

CHAPTER 4

INITIATION OF EXPLOSIVES

4.1 INTRODUCTION

Explosives can be initiated by heating, friction, shock or burning. Thermal explosion is of particular importance in the storage of explosive materials. In the normal form of deliberate initiation, the shock initiation is the most important for secondary explosives. Secondary explosives are normally initiated by a shock which is created by a primary explosive. The primary explosive is initiated by a flame. However in accidental initiation the shock initiation is of particular importance since many accidents are associated with shocking the explosive and in any case the transition to detonation passes through a shock formation.

4.2 THERMAL EXPLOSION

Thermal explosion is concerned with the effects of uncontrolled internal heating of explosives. This heating can be a result of external sources or of spontaneous decomposition. Every explosive has a critical temperature above which it will

detonate. This critical temperature is characteristic for each explosive. It is worth mentioning that the critical temperature is also related to the diameter of the test charge. The maximum safe temperature not to be exceeded, is the point at which thermal energy from slow chemical decomposition is given off faster than it can be dissipated. It is called the self heating temperature and is dependent on the amount of explosive, its environment, and the time held at elevated temperature⁽⁴⁾.

Because of the hazard of thermal explosions, explosives should always be stored in ways that will provide for the maximum possible dissipation of heat. This means that large consolidated piles should be avoided⁽⁵⁾. It has been found that if rapid reaction starts at the surface of the explosive the explosive normally deflagrates. However if it starts in the interior of the explosive mass the reaction will be confined and will have a greater probability of building up to a detonation⁽⁵⁾. If the explosive mass is burning the size of the mass will determine the event. If the size is sufficient surface burning has a high probability of resulting in a detonation. Thus, in disposing of high explosives it is common to burn the material only after it is dispersed in small pieces on the ground and never in large consolidated masses⁽⁵⁾.

4.3 SHOCK INITIATION

With regard to the shock initiation process, explosives can be differentiated into two main categories, homogeneous and heterogeneous explosives. Homogeneous explosives are the explosives which do not contain any discontinuities in their mass. Heterogeneous explosives are the explosives in which discontinuities such as gas bubbles, grit, solid metallic or nonmetallic particles and air bubbles are present in their mass. The method of initiation is different between the two categories. According to Mader⁽⁶⁾ if one introduces gas bubbles or grit into a homogeneous explosive, the minimum shock pressure necessary for initiation of detonation is decreased by about one order of magnitude.

According to Campbell, Davis and Travis⁽⁷⁾, when a homogeneous explosive is shocked, the detonation starts at the interface between the donor and the acceptor charge. This is shown in Figure 1. The shock wave enters the acceptor explosive, compresses it and at the same time, heats it. The shock heated explosive finally detonates at the interface after a certain induction time⁽⁷⁾.

The same investigators have shown that, in heterogeneous explosives⁽⁸⁾, when a shock wave enters the explosive, it proceeds at a slowly increasing velocity for a distance which is a function of the shock pressure. Eventually the shock velocity increases to a value associated with the detonation velocity of the explosive. Of course this supposes that the initial shock wave is of sufficient strength. According to Mader⁽⁶⁾ this is explained by the interaction of the shock wave with density discontinuities which produce local concentrations of energy called "hot spots". The hot spots decompose and liberate energy, which strengthens the shock, so that when it interacts with additional inhomogeneities, higher temperature hot spots are formed. This results in a larger mass fraction of the explosive being decomposed in the shock. Thus, the shock wave grows

THE HOT SPOT CONCEPT

stronger and stronger, releasing more and more energy, until it becomes strong enough for detonation to occur. A typical distance from the impacted surface - time record for the case of heterogeneous explosives is shown in Figure 2.

Commercial explosives are heterogeneous explosives the sensitivity of which is based on air gaps (air or glass bubbles) or solid particles. For this purpose the shock initiation of heterogeneous explosives will be studied.

4.4 THE HOT SPOT CONCEPT

The formation of spots within the explosive having temperature greatly exceeding that of the rest of the explosive was originally proposed by Bowden and Yoffe⁽¹⁰⁾. According to them, when a solid explosive is subjected to impact or friction, the explosion which may result is thermal in origin. This means that the mechanical energy must first be degraded to heat and concentrated in small localized regions to form "hot spots". It was proposed⁽¹⁰⁾ that there are three classes of hot spots.

- a. Voids within the explosive (bubbles).
- b. Regions where the explosive is heated by viscous flow or plastic deformation when rapidly flowing explosive escapes from between impacting surfaces.
- c. Points of friction at the surface of the container walls, or grit particles or crystals of explosive.

In recent years, it has been found that the voids inside the explosive are of paramount importance to its sensitivity. The theory proposed initially was that the gas bubbles in the explosive heat adiabatically and rapid decomposition starts as a result of the high temperature obtained in the bubbles. However the heat transfer between the bubble and the explosive is relatively slow for the duration of interest⁽⁹⁾ (a few microseconds). For this reason several other theories have been proposed.

It has been shown that the compression of a spherical bubble in a medium which is shocked does not take place symmetrically⁽⁹⁾. For this reason it was proposed that a high velocity jet is created. The jet by hitting the opposite surface of the bubble creates spots of high pressure and temperature (hot spots).

Mader showed numerically that the shock wave interacts with density discontinuities (voids, particles etc.) and the resulting convergence of shocks creates spots of high pressure and temperature. These spots decompose, liberating energy which strengthens the shock until finally detonation occurs.

It follows that although there is a general acceptance of the hot spot concept, the precise function of the hot spot is not exactly understood. A combination of the above proposed mechanisms might be the reason of the generation of hot spots.

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4.5 REFERENCES

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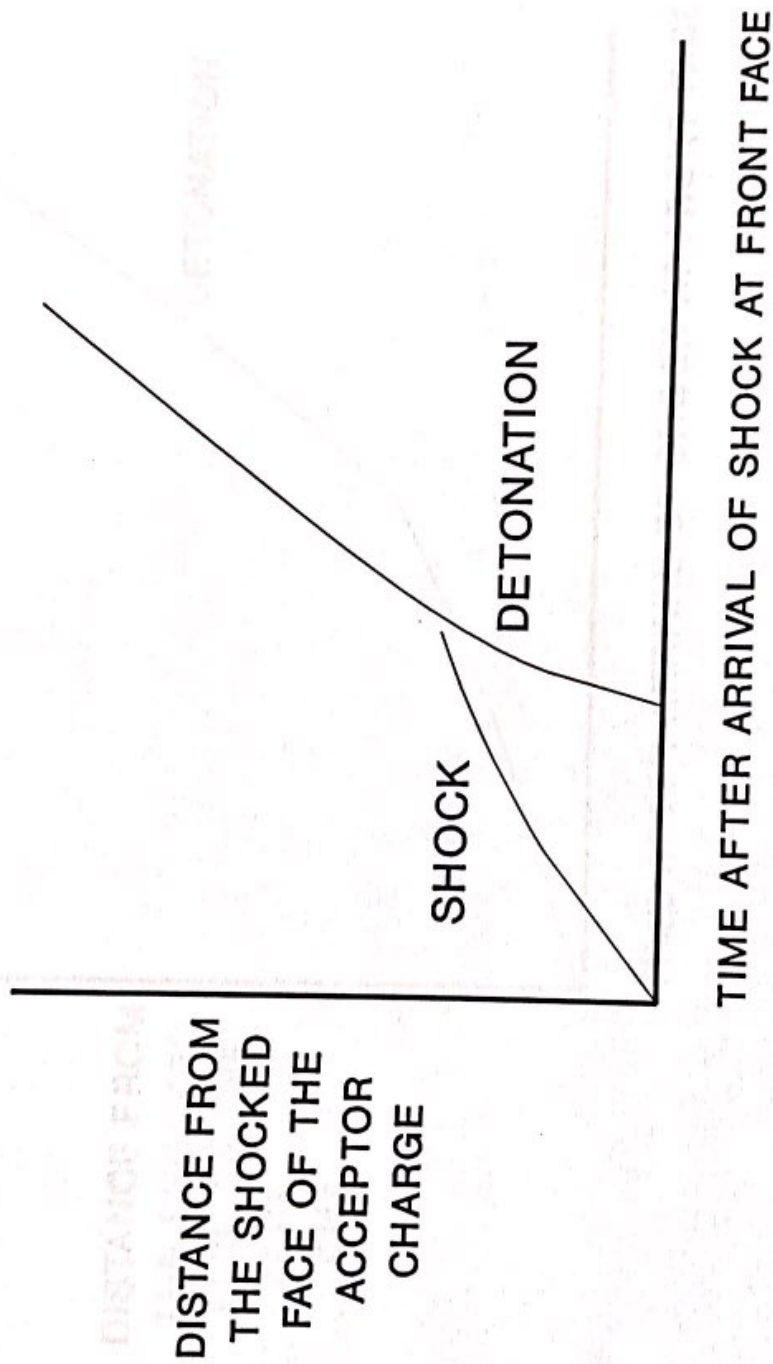


FIGURE 1

SHOCK TO DETONATION TRANSITION IN HOMOGENEOUS EXPLOSIVES (ref. 8)

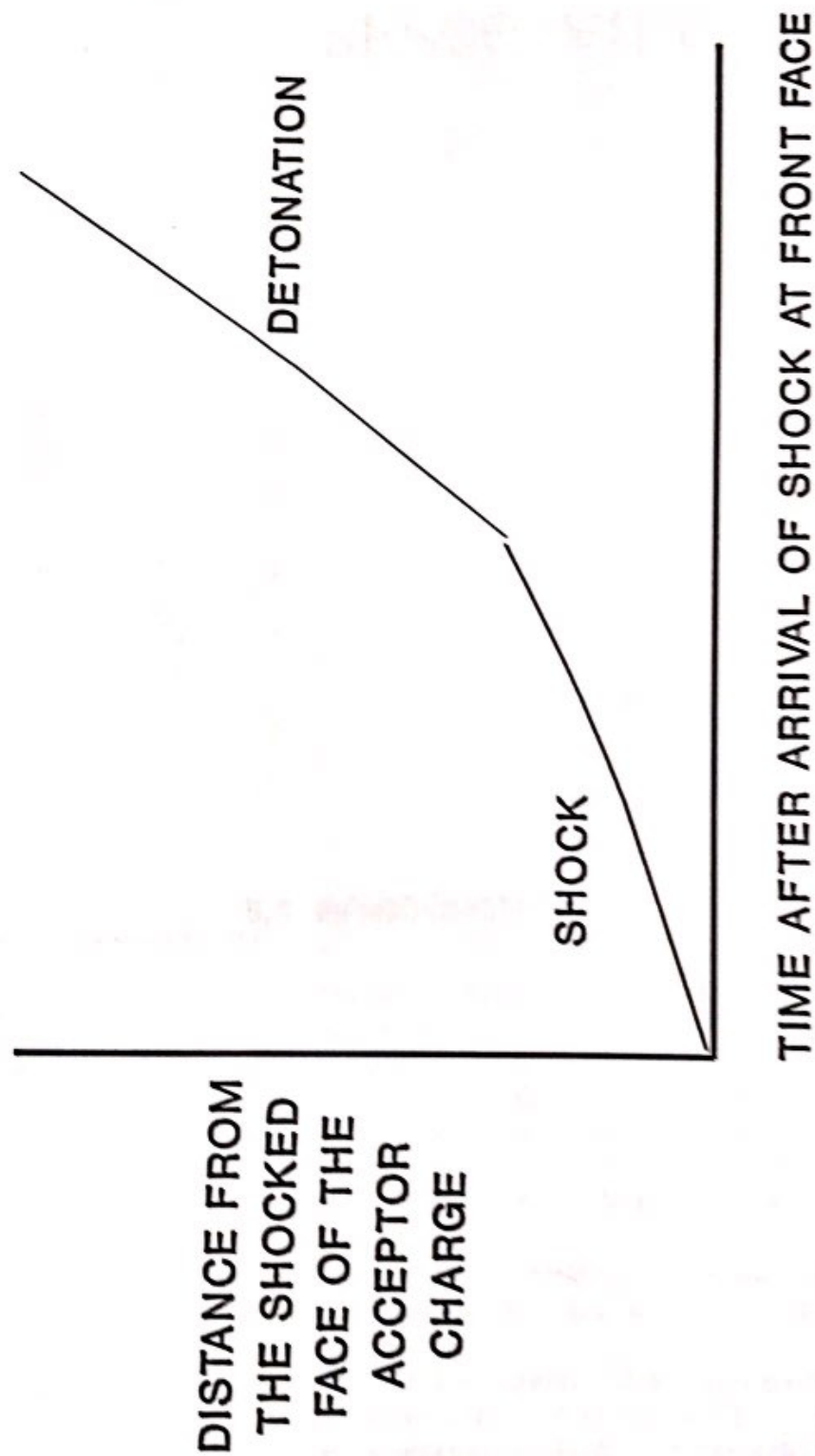


FIGURE 2
SHOCK TO DETONATION TRANSITION IN HETEROGENEOUS
EXPLOSIVES (ref. 8)

CHAPTER 9

AMMONIUM NITRATE - FUEL OIL EXPLOSIVES

9.3 PROPERTIES OF AMMONIUM NITRATE

It is well known that ammonium nitrate is a very popular nitrogen fertilizer. It is a white crystalline solid, highly soluble in water, and is stable under normal conditions. It is a powerful oxidizing agent and is used in a wide variety of applications, including explosives. The most common form of ammonium nitrate is the 34% solution, which is used in the fertilizer industry. The other common forms are the 20%, 25%, and 30% solutions. The 34% solution is the most popular because it is the most economical to produce and transport.

The properties of ammonium nitrate are well known and are listed in Table 9.1. It is a white crystalline solid, highly soluble in water, and is stable under normal conditions. It is a powerful oxidizing agent and is used in a wide variety of applications, including explosives. The most common form of ammonium nitrate is the 34% solution, which is used in the fertilizer industry. The other common forms are the 20%, 25%, and 30% solutions. The 34% solution is the most popular because it is the most economical to produce and transport.

9.1 INTRODUCTION

Ammonium nitrate - fuel oil or AN/FO is the cheapest explosive used in mining today. Although it had been known since long ago that ammonium nitrate crystals mixed with fuel oil could be detonated, the product was not used widely due to its large critical diameter and its poor shelf life.

The successful development and use of AN/FO came about by coincidence. According to G.B. Clark⁽¹⁾ before 1945, most of the manufacturers of fertilizer grade AN manufactured it in prilling towers in which molten Ammonium nitrate was sprayed down in a cooling tower. In 1945 the moisture content before prilling was raised. The small amount of water left was evaporated after the prill formation and as a result porous prills were formed. This permitted the intimate mixing of fuel oil with the ammonium nitrate and resulted in a commercial product.

9.2 MANUFACTURE OF AMMONIUM NITRATE

Ammonium nitrate solution is made from the neutralization of nitric acid and ammonia. Ammonia is made from nitrogen and hydrogen which combine together under high pressure in the presence of catalysts. Ammonia is then oxidized to nitric acid using air in the presence of platinum. Hot ammonium nitrate is then formed by neutralization of ammonia with nitric acid. The process is shown in Figure 1⁽²⁾. The concentrated AN solution can be turned in several forms or it can be used in slurries⁽²⁾.

9.3 PROPERTIES OF AMMONIUM NITRATE

It is well known that ammonium nitrate is a very popular oxygen carrier in explosive mixtures. It is also used in rocket propellants, since it is a totally gasifiable oxygen carrier. It is very soluble in water (saturated solution contains about 65% NH_4NO_3). Transitions in different crystal forms happen at 125, 84, 32 and -17 degrees Centigrade. The greatest problems associated with its use are its caking and hygroscopicity⁽³⁾.

Hygroscopicity of Ammonium Nitrate was considered to be the major cause of caking. In the last two decades the polymorphism of crystals has been recognized as the critical factor. It has been found that at 32 degrees Centigrade a phase transition occurs. It was found that hardening occurs during the process of cooling ammonium nitrate heated above 32 degrees. Furthermore it was found that some substances have a great influence on the change. If the ammonium nitrate is chemically pure and free of water a different transition (phase IV to phase II) happens at 50 degrees. This is not as undesirable as the transition from phase IV to phase III⁽⁴⁾.

The repeated transition between phases III and IV results in the generation of fine particles which cake readily through the absorption of moisture.

For this purpose anti caking substances are used. It has been found that surface active substances are very helpful as anti caking agents. However the effect of these substances on the thermal stability of ammonium nitrate is very important. Furthermore an organic substance increases the sensitivity of ammonium nitrate.

The hygroscopicity of ammonium nitrate is its other drawback. Ammonium nitrate can be protected against moisture by mixing it with substances such as calcium or zinc stearate, petroleum tar, asphalt, barium sulphate and guar gum powder⁽⁵⁾. Urbansky mentions that stearates are in powder form of 5-20mm in size while ammonium nitrate is of 70 - 120mm. Thus a small proportion of stearates is sufficient to cover ammonium nitrate.

9.4 CHEMICAL AND EXPLOSIVE PROPERTIES OF AMMONIUM NITRATE

Urbansky provides a comprehensive list of references with regard to chemical properties. Of importance to the subject of these notes is the fact that some organic substances lower the thermal stability of ammonium nitrate. A recent experience is the accident which happened in 1978 in Tunisia. According to Urbansky⁽⁵⁾ the floor of the storage house was covered with saw dust. The saw dust reacted with the ammonium nitrate causing a temperature rise and ignition. Finally detonation occurred (80 tons of ammonium nitrate).

7.5 FORMS OF AMMONIUM NITRATE

Ammonium nitrate is sold in the following forms:

1. **Grained Ammonium nitrate.** It looks like fine sugar, cakes and it is used only in dynamites.
2. **Porous prills.** Their size is -6-14 mesh. They flow freely with anticaking agents.
3. **High density prills.** They are hard prills made for agricultural purposes. Their size is similar to the previous prills.
4. **Stengel cubic form.**

Only the porous prills are suitable for use with fuel oil directly as a blasting agent. The anticaking agent used is Kieselguhr (2-3%) or some surface active agent (sulphonates) or combinations of the two.

9.5 AMMONIUM NITRATE - FUEL OIL EXPLOSIVES

The detonation ability of ammonium nitrate - fuel oil mixes depends on the reaction rate between the oxidizer and the reducer. In order to increase the reaction rate the particle size of the ammonium nitrate can be reduced. However, this method has a limit because ammonium nitrate and oily fuels repel each other⁽³⁾. For this reason the action of surfactants has been examined by Hino and Yokogawa⁽³⁾. It was found that anionic surfactants, such as sodium dinaphthylmethane disulfonate, sodium laurylsulphate and

sodium dodecylbenzene sulphonate improved the caking characteristics of the mix as well as its detonating ability.

Figure 2⁽³⁾ shows the effect of the surfactant to the critical diameter as well as the saturation effect of the surfactant.

9.5.1 Fuels Used In Ammonium Nitrate - Fuel Explosives

The most common fuel used in ammonium nitrate fuel explosives is regular #2 fuel oil. Fuel oil is not viscous and it can be mixed easily. The amount of fuel oil which has to be used is determined by the oxygen balance of the composition. For the oxygen balanced composition



Therefore 14g of fuel oil are mixed with 240g of ammonium nitrate. This results in a composition of ammonium nitrate 94.5% and fuel oil 5.5%. This is the normal AN/FO.

Other energetic fuels can be used instead of fuel oil. When examining the alternatives the areas of concern are: flash point, health hazard, composition variation, ability to mix and blend properly, cost, energy output, viscosity at low temperatures and ability of the prills to hold the necessary quantity of fuel.

In the past nitromethane was proposed to be used with ammonium nitrate. The oxygen balanced mixture is determined by the following equation:



This would result to a composition ammonium nitrate 67%, nitromethane 33%. It is considered impossible that ammonium nitrate prills can hold such a quantity of fuel. Furthermore nitromethane is highly volatile with hazardous fumes (ignitable by a spark and dangerous to health).

To oxygen balance it the composition should be ammonium nitrate 87, nitropropane 13%. This can be achieved. However nitropropane is volatile with fumes hazardous to health.

One promising alternative from a cost point of view is the use of used lubricating oil. Lubricating oils have flash points higher than fuel oil (150 - 200 deg. C versus 80 deg. C). Fuel retention tests have been satisfactory⁽⁶⁾. However the viscosity of these oils is much higher than fuel oil. As a result the mix is not as intimate as in the case of fuel oil. Furthermore the composition of the used oil is not exactly known.

In tests the compositions with used oil behaved in a very similar fashion as the compositions with fuel oil. A slight difference was noticed only in the critical diameters. In the case of AN/FO ($\rho=0.85\text{g/cc}$) the critical diameter is 7.5 cm (unconfined) while in the case of AN/used oil it was 10 cm⁽⁶⁾.

According to Bauer and Crosby⁽⁶⁾ blends of up to 50/50 new/used oil is satisfactory in low temperatures.

Other fuels which have been tried are coal dust, sawdust and bagasse. These pose a problem in mixing. However they can be a promising alternative to fuel oil where the economic conditions are favourable.

9.5.2 Sensitivity⁽⁷⁾

Various factors affect the sensitivity of ammonium nitrate - fuel mixes. The major parameters are particle size, porosity, intimacy of mixing and stoichiometry.

1. Effect of particle size. Figure 3 shows the relationship between ammonium nitrate particle size and the sensitivity of the AN/FO product expressed as the reciprocal of the weight of the minimum primer. Figure 4 shows the same relationship for a mix of AN/FO with a solid fuel.

2. Effect of porosity. As it was explained before the oxidizer and the fuel have to be mixed well in order to improve the reaction rate. Improving the porosity essentially reduces the particle size. Therefore a similar effect to that of reduced particle size can be obtained by increasing the porosity of the product. However, when dealing with solid fuels, the effect of porosity becomes less pronounced since these fuels cannot penetrate the porous prills but they can only contact external surfaces.

3. Intimacy of mixing. Table 1⁽⁷⁾ shows the results of sensitivity measurements of ammonium nitrate - fuel mixes prepared with liquid fuels of different viscosities. It follows that the least viscous fuels resulted in the most sensitive product. Table 2⁽⁷⁾ shows results obtained when ammonium nitrate is mixed with solid fuels of various particle size. The maximum sensitivity results were obtained for the most intimate mixture.

4. Stoichiometry. Figure 5⁽⁷⁾ shows the effect of the composition on the sensitivity of AN/FO in a prilled form. The most sensitive composition is the oxygen balanced one. This is not always the case. Grubb⁽⁷⁾ has reported maximum sensitivities when the product is overfueled or underfueled when various and/or various coatings of the ammonium nitrate prill are used.

5. Composition. Sometimes sodium nitrate is used with ammonium nitrate because of its low cost and its higher density. Figure 6⁽⁷⁾ shows the effect on sensitivity of the addition of sodium nitrate.

6. Density. Figure 7⁽⁸⁾ provides the relationship between sensitivity and density of AN/FO for various particle size distribution. For the very small sizes sensitivity is not affected markedly by changes in the bulk density between values 0.9 and 1.1 g/cc. The larger prills are affected more.

9.5.3 Detonation Properties

A typical velocity of detonation charge diameter curve for Ammonium Nitrate - Fuel oil is shown in Figure 8⁽¹⁾. The critical diameter of the prilled product ($\rho=0.8$ g/cc) is 7.5 cm when the product is unconfined. Confinement decreases the critical diameter to about 5 cm. The ideal detonation velocity of AN/FO at a density of 0.85 g/cc is 5200 m/sec. From the above curve it follows that AN/FO detonates non-ideally even at very large diameters. It has been found that ideal detonation of AN/FO can be achieved when using very strong confinement (Persson) or using confinement and a very large diameter (44 cm).

Factors which affect the AN/FO performance are the density, particle size, porosity and composition. The effect of density is shown in Figure 9⁽¹⁾. Although the so called ideal velocities in this figure represent the maximum velocities achieved in practical tests and not the theoretical velocities, the trend is correct. It is obvious that the maximum density at which AN/FO can be used is 1.2 g/cc. Above this density the product will be dead packed. It should be stated here that a density of 1.2 g/cc will not be achieved by using the prilled product. Such a density can result only in crushed and pressed AN/FO.

The effect of the particle size is shown in Figure 10⁽¹⁾. Smaller AN particle size results in smaller critical diameters.

The detonation parameters of AN/FO are seriously affected by water in the borehole. Water desensitizes AN/FO. Figure 11⁽¹⁾ provides a typical example of the effect of water in AN/FO.

The composition of AN/FO affects its detonation parameters. Table 3 lists detonation state velocities and pressures for AN/FO of various fuel oil contents as calculated by the TIGER code. Figure 12 shows the effect of the composition on the energy output. It is obvious that the best results are obtained at the oxygen balanced composition (94.5% AN, 5.5% FO).

9.5.4 Fumes

Since ammonium nitrate / fuel oil is used in underground mines, the fumes produced from the detonation are of particular importance. The lack of proper control over the preparation of the mixture can lead to serious problems. Marginal initiation, water in the boreholes and inadequate burdens can increase the amounts of deleterious gases produced. Van Dolah et al. have investigated experimentally the effect of oxygen balance on the production of toxic fumes (CO and NO_2). This is shown in Figure 13. It follows that the amount of carbon monoxide increases dramatically when the oxygen balance of the composition drops below zero. Also the production of NO_2 increases significantly when the composition is underfueled. The same investigators have examined the role of the primer in the production of toxic gases⁽¹⁰⁾. It was found that underpriming increases the production of nitrogen oxides (Figure 14).

9.6 QUALITY CONTROL

Since the quality of the ammonium nitrate prill is very important for the mixing of it with fuel oil, it is necessary to examine the following parameters⁽¹¹⁾:

i. Moisture. High moisture in the prill leads to caking which causes poor fuel mixing since it will inhibit the ability of the prill to absorb fuel oil. The manufacturer of Ammonium nitrate has to examine the moisture content carefully. The porosity of the prills depends on the amount of moisture which is included in the prill prior to the prilling process.

ii. Density. High density prills do not absorb fuel oil properly. Very low density prills break easily under normal application.

iii. Particle sizing. The ammonium nitrate prills should be free flowing. Typical particle sizes are given in the following⁽¹¹⁾:

+8 mesh	5 - 10%
+10	50 - 65%
+14	15 - 20%
+20	5 - 10%
-20	0 - 1%

iv. Oil absorbency. The prills should be able to absorb at least 6% fuel oil (by weight).

v. Friability. It determines if the material will break under normal handling.

vi. Clay content. Water insoluble materials are added to the Ammonium Nitrate as anti caking agents. These materials are also inert and therefore do not contribute to the detonation reactions.

vii. Fuel oil content in the final product. The oxygen balance determines the performance, the sensitivity and the fumes of the product when it detonates. Frequent test to determine the fuel oil content should be conducted. Samples must be taken on a random basis. The sample is washed with diethyl ether to extract the fuel oil (Figure 15). The weight of the sample before and after the extraction gives the weight of the fuel oil.

9.7 APPLICATION OF AN/FO

Dry mixes are used in underground and open pit operations.

9.7.1 Underground operations.

The underground application of AN/FO is influenced by the following factors:

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9.7 APPLICATION OF AN/FO

Dry mixes are used in underground and open pit operations.

9.7.1 Underground operations.

The underground application of AN/FO is influenced by the following factors:

- The diameter of the boreholes. Prilled AN/FO has a large critical diameter. Underground operations utilize boreholes ranging from 25mm (1") to 153mm (6"). It is obvious that if small diameters are used crushed AN/FO must be used. Crushed AN/FO has a smaller critical diameter than prilled AN/FO. Pneumatic loaders are normally used for loading the boreholes. A typical diagram of a pneumatic loader is shown in Figure 16. It should be noted that a variety of pneumatic loaders exists. Some of these loaders will crush the AN/FO prill in the blasthole by moving it at a relatively high velocity. Thus they achieve high loading densities and good sensitivity of the product (since small particle AN/FO is more sensitive). However pneumatic loading results in static electricity build ups unless proper procedures are followed. Static electricity can interfere with the electric blasting caps and cause premature detonations. According to Atlas powder company the following are the principal mechanisms to minimize the static electricity hazard⁽¹²⁾:

1. Ground the pneumatic loader.
2. Use a conductive loading hose.
3. Ground the operator.
4. Ambient relative humidity should be more than 50%.

9.7.1.1 Wet holes

AN/FO is affected by water. The problem is overcome by using proper liners. If static electricity is a problem the liners should be conductive (by semiconductive ground straps). The procedure of loading the borehole is shown in Figure 17⁽¹³⁾. First the water is blown out from the hole by using the loading hose. Then the liner is attached to the pipe, inserted in the borehole and loading continues as usual.

9.7.1.2 Fumes.

Explosives used underground should not produce large amounts of toxic gases. The minimum amounts of carbon monoxide and nitrogen oxides are produced when the composition is oxygen balanced. Furthermore the composition must be primed by a strong primer. In addition to that the blasting sequence must be designed properly so that very small burdens are eliminated.

9.7.2 Open Pit Operations

AN/FO is the most popular explosive because of its low cost. In large open pit operations AN/FO and aluminized AN/FO are handled by special bulk mix trucks. A schematic representation of such a truck is shown in Figure 18. The truck consists of hoppers for the ammonium nitrate, augers, valves to stop air bleeding back into the system and an air stream or augers to convey the mixed product in the borehole. Care should be exercised to establish correct mixing. A schematic of the mixing arrangement is shown in Figure 19.

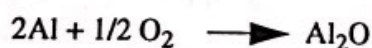
A significant problem in the use of AN/FO is its use in wet holes. For this purpose special dewatering equipment has been manufactured to dewater the boreholes before loading. The loading of the holes is then done by using dryliners. These consist of polythene tubing sealed at the bottom. Dryliners can be bought or they can be manufactured on site. The dryliners should be waterproof, free of pinholes and should be strong enough to withstand normal handling.

Today fast AN/FO loaders have been developed which can be used in open pits and quarries. These loaders compact the material in the blasthole, increasing the density and reducing the particle size of the powder. As a result the economics are improved from the increase of the bulk strength while the explosive detonates with higher velocity of detonation.

9.8 ADDITION OF ALUMINUM⁽⁶⁾

Aluminum is being used in explosives to increase their energy output. Aluminum, when reacting in the detonation process, produces aluminum oxides. The reactions are very exothermic and the energy output of the explosive is improved. Figure 20 shows the effect of Aluminum in the energy of AN/FO. It is obvious that energy can be increased. However the rate of increase falls off beyond the 13%-15% Al point. This is probably the upper limit for economic reasons as well. Furthermore at higher percentages the energy output falls off. It should be noted here that solid Al_2O_3 results as a product of reaction. This has energy trapped in it. From blasting studies it is estimated that only 1/2 of the energy which is associated with the solids is available for useful work. Furthermore a large percentage of Al desensitizes the product.

Another disadvantage of the aluminized mixes is the production of Hydrogen. Hydrogen mixed with oxygen from the atmospheric air is an explosive mix which can result in secondary explosions. This happens through the following reactions in the detonation products⁽¹⁴⁾:



The size of the aluminum grain must be small enough so that reaction can be completed in the detonation head. However there is a limit to the size which is imposed by safety considerations. Aluminum dust can be explosive and the particle size is the most significant factor controlling the explosibility of the dust. This is shown in Figure 21. It follows that the minimum size of the Aluminum grain should not be smaller than 150 mesh.

Particle sizes larger than 20 mesh do not react properly since the surface area they provide is small. Thus the largest particles should not be larger than 20 mesh.

9.9 WATER RESISTANT AN/FO

Recently products called "water resistant AN/FO" have appeared in the market. In spite of their name these products should be used after dewatering of the holes. "Water resistant AN/FO" contains guar gum which coats the AN/FO prills. The gum when it comes in contact with water turns into a gel. This can reduce small water inflows to the blast-hole after the loading of the product. However the gel normally does not react in the detonation wave. Thus the effective diameter of the product is reduced at the point where the gel has formed.

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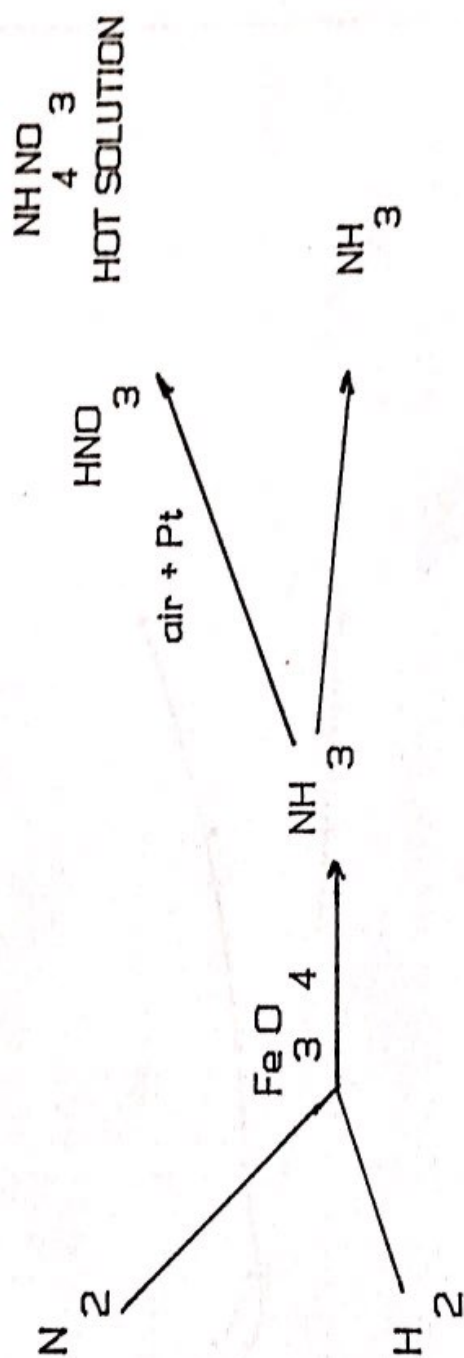
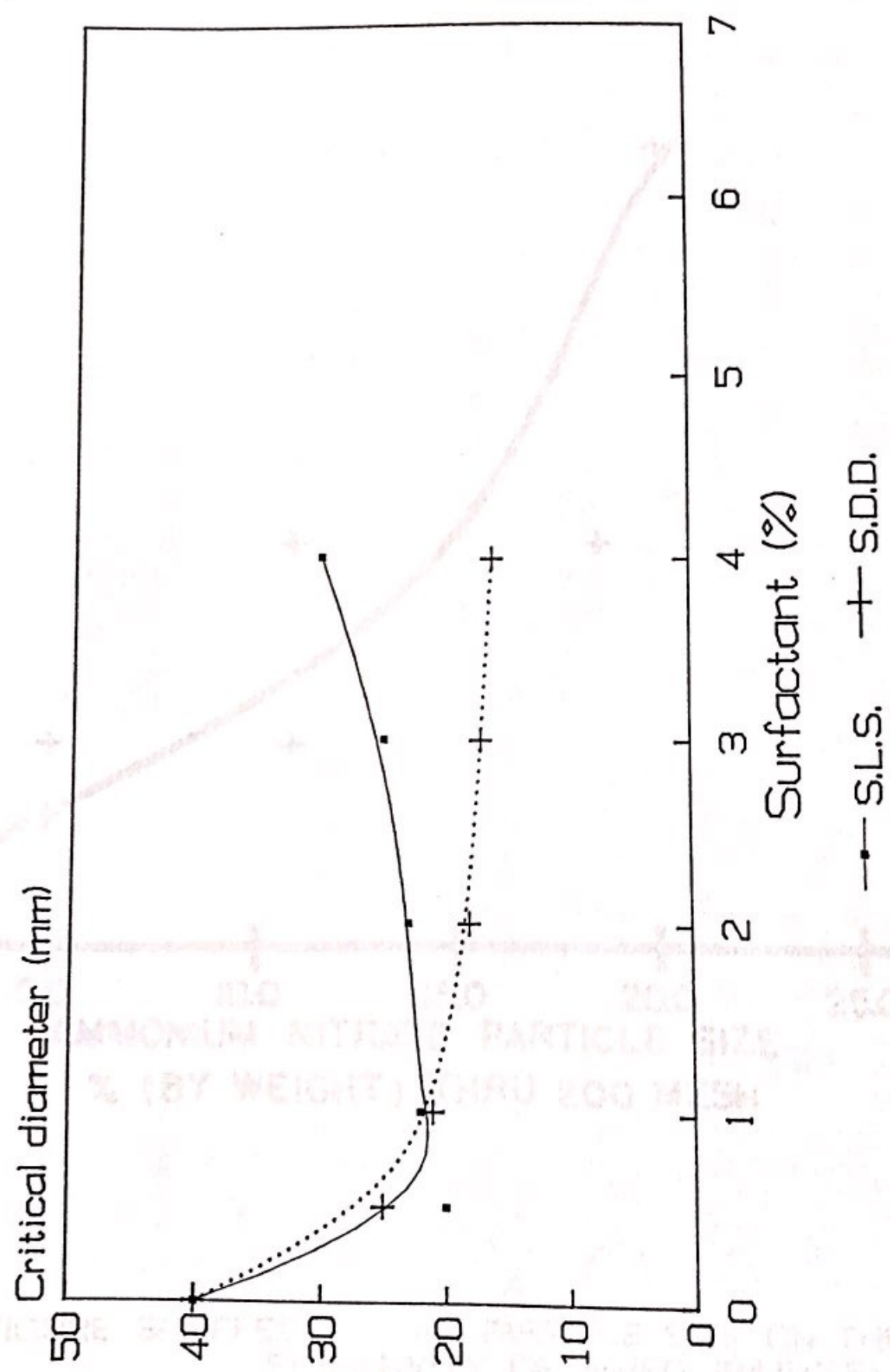


FIGURE 1: MANUFACTURE OF AMMONIUM NITRATE

FIGURE 2: EFFECT OF SURFACTANT ON THE CRITICAL DIAMETER OF AN ANFO MIX



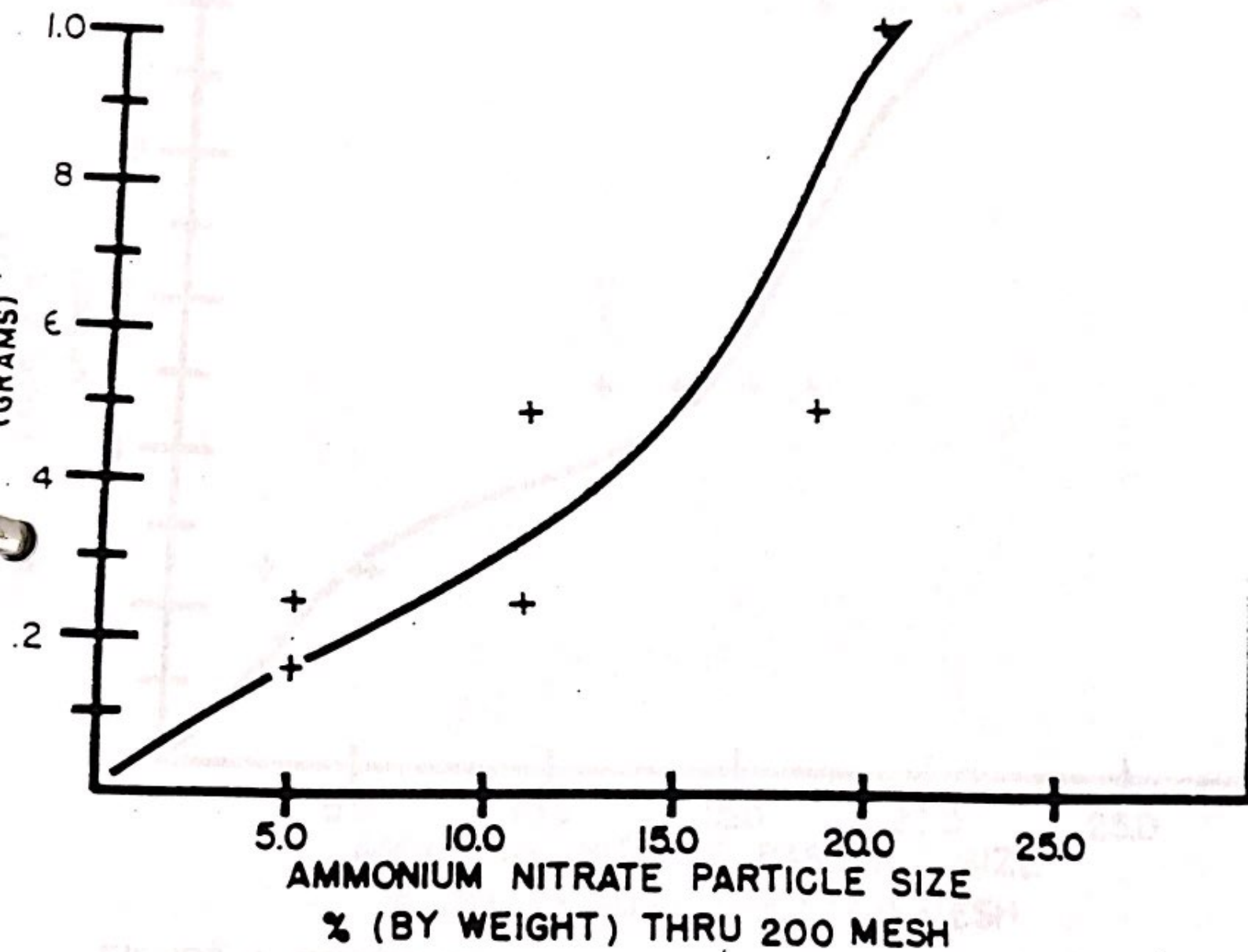


FIGURE 3: EFFECT OF AN PARTICLE SIZE ON THE SENSITIVITY OF AN/FO (94.5/5.5)

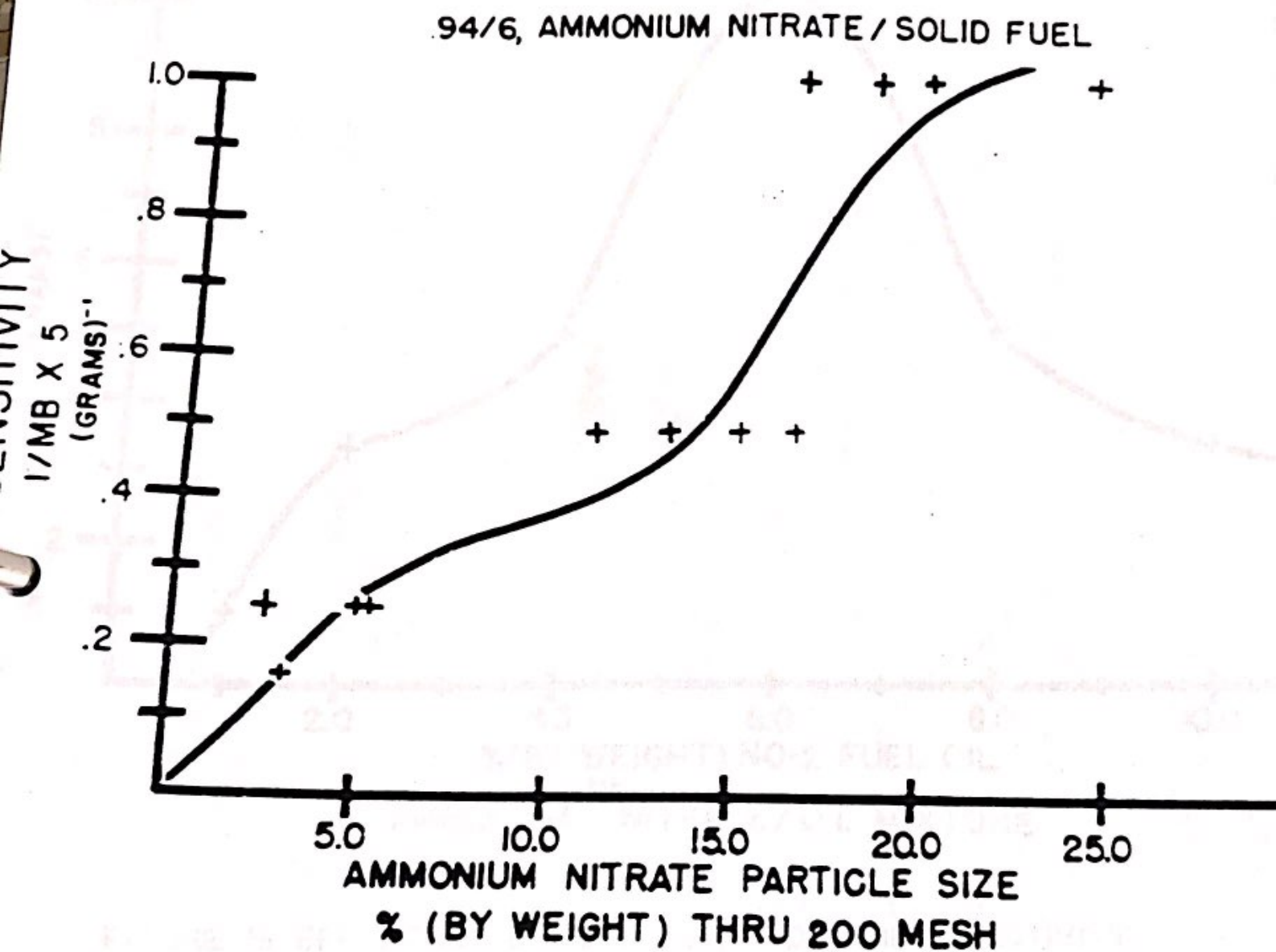


FIGURE 4: EFFECT OF AMMONIUM NITRATE PARTICLE SIZE ON THE SENSITIVITY OF AN MIXED WITH SOLID FUELS

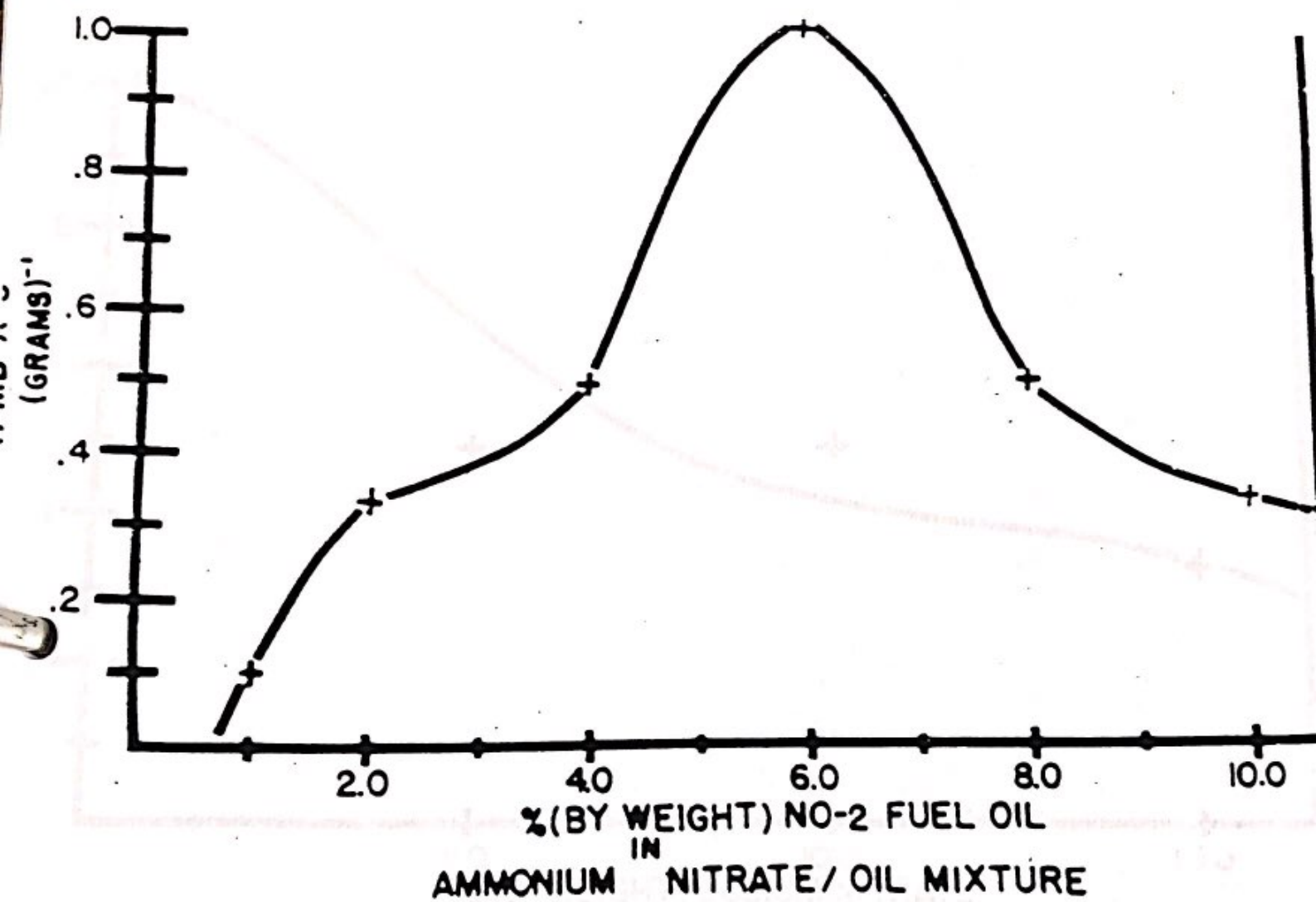


FIGURE 5: EFFECT OF STOICHIOMETRY ON THE SENSITIVITY OF AN/FO

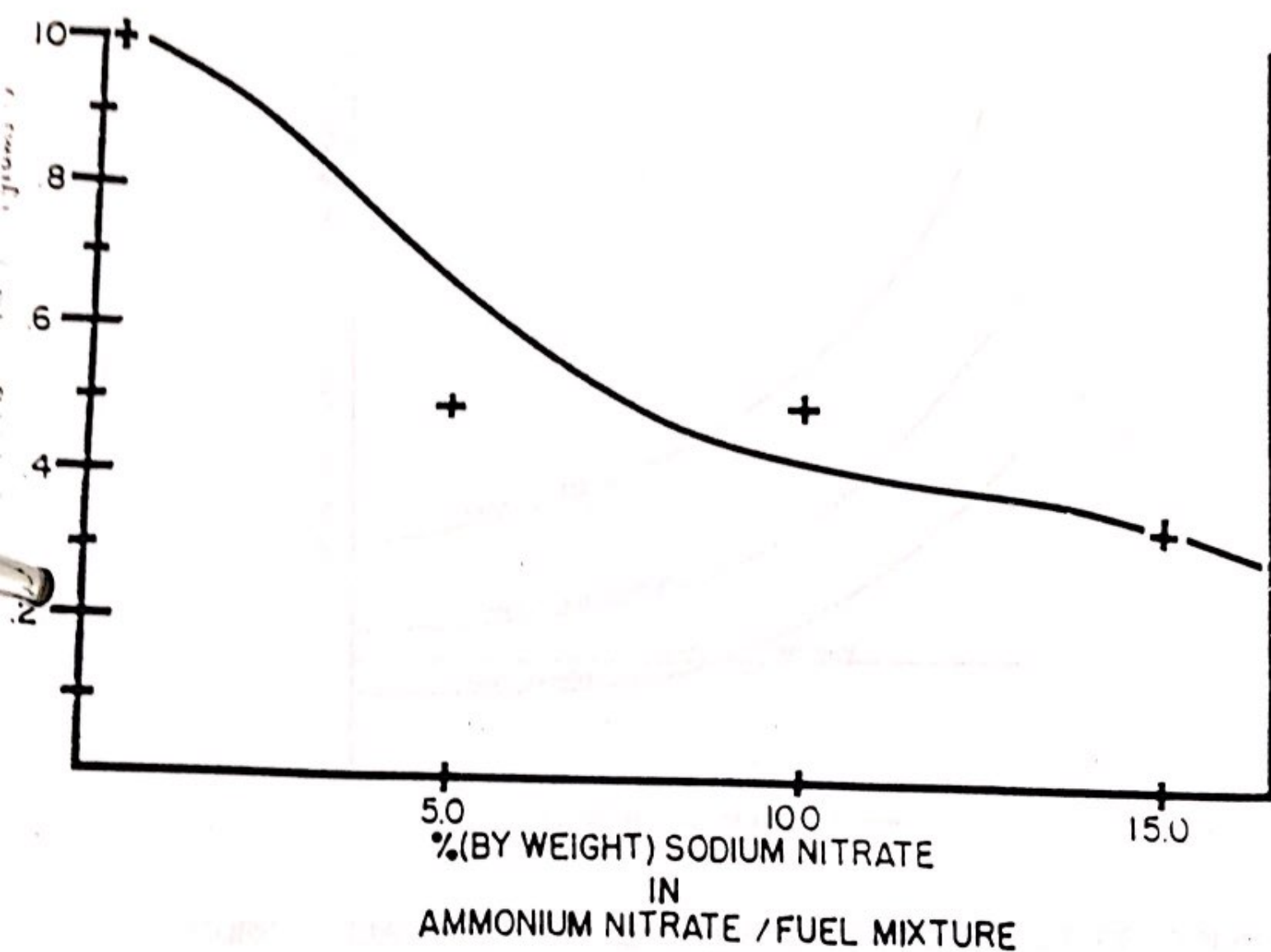


FIGURE 6: EFFECT OF SODIUM NITRATE ON THE SENSITIVITY OF AN/FO

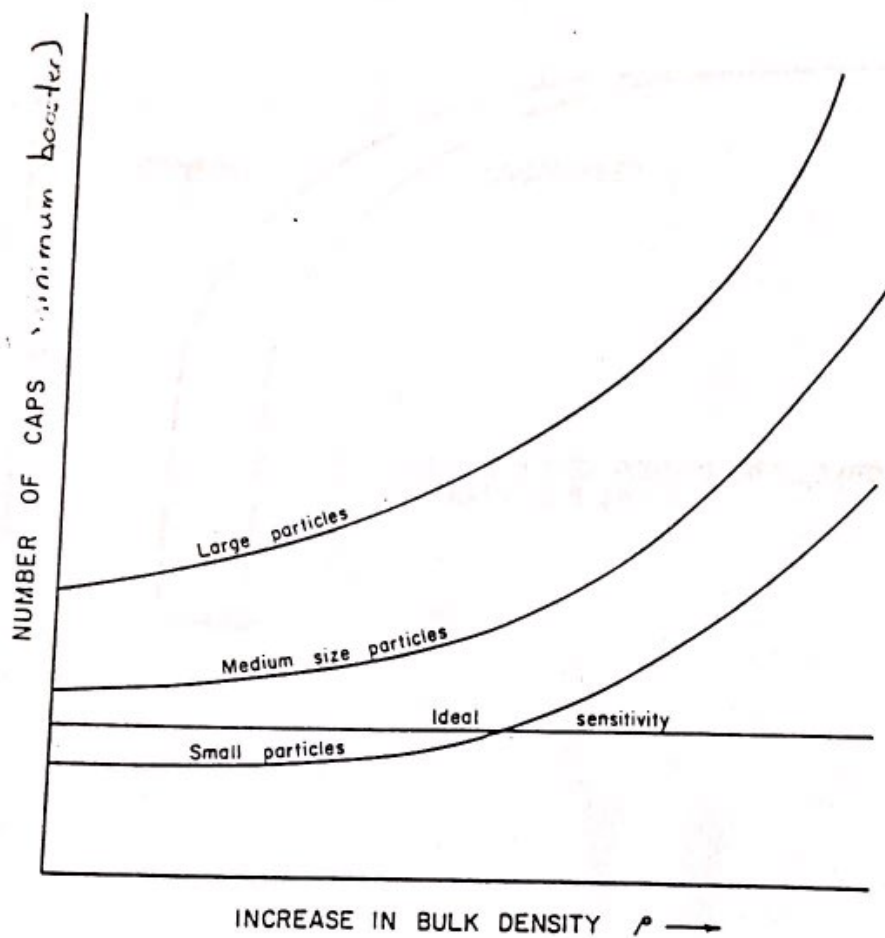


FIGURE 7: DIAGRAMATIC SKETCH SHOWING THE EFFECT OF DENSITY ON THE SENSITIVITY OF AN/FO.

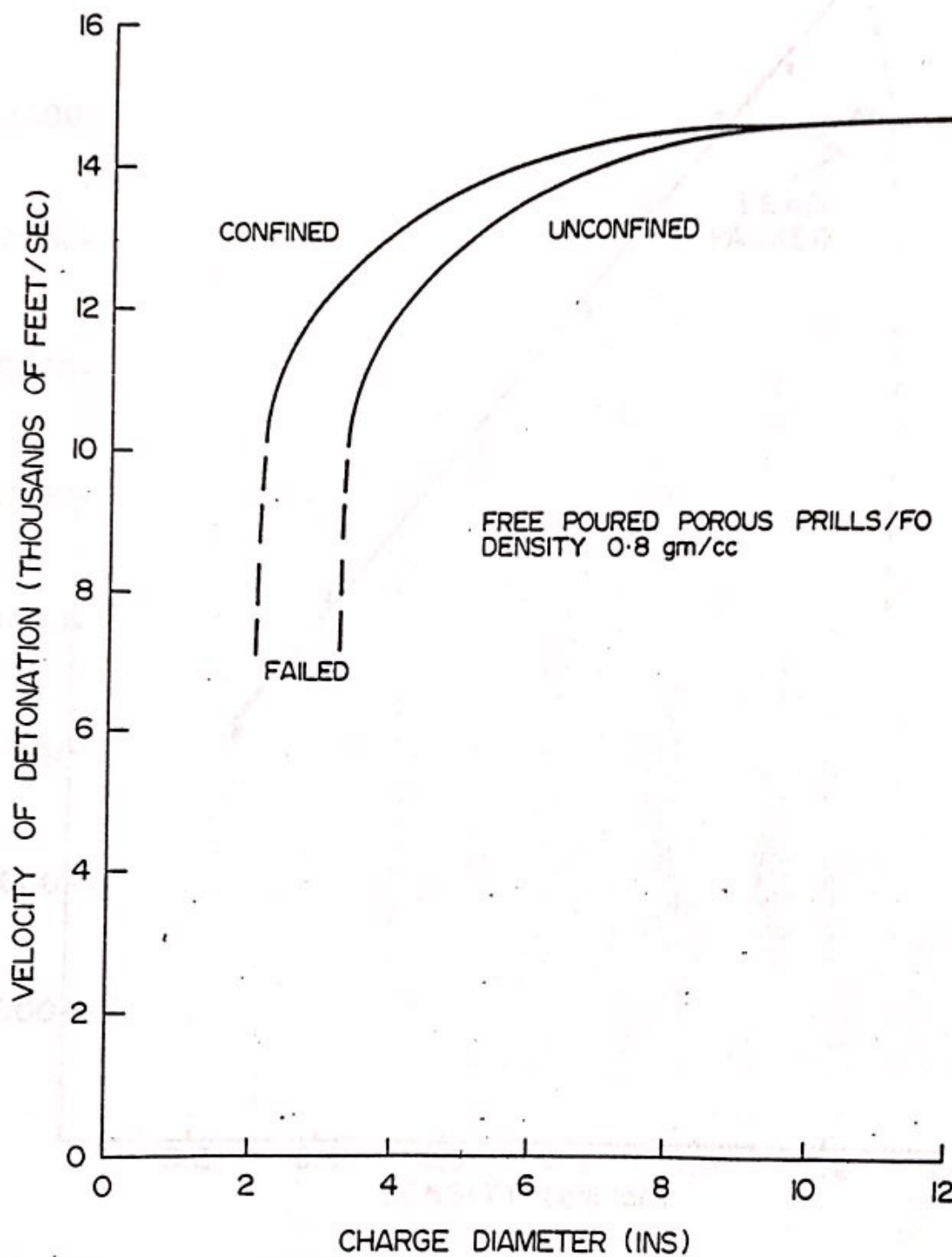


FIGURE 8: VELOCITY OF DETONATION CHARGE DIAMETER CURVES FOR CONFINED AND UNCONFINED AN/FO.

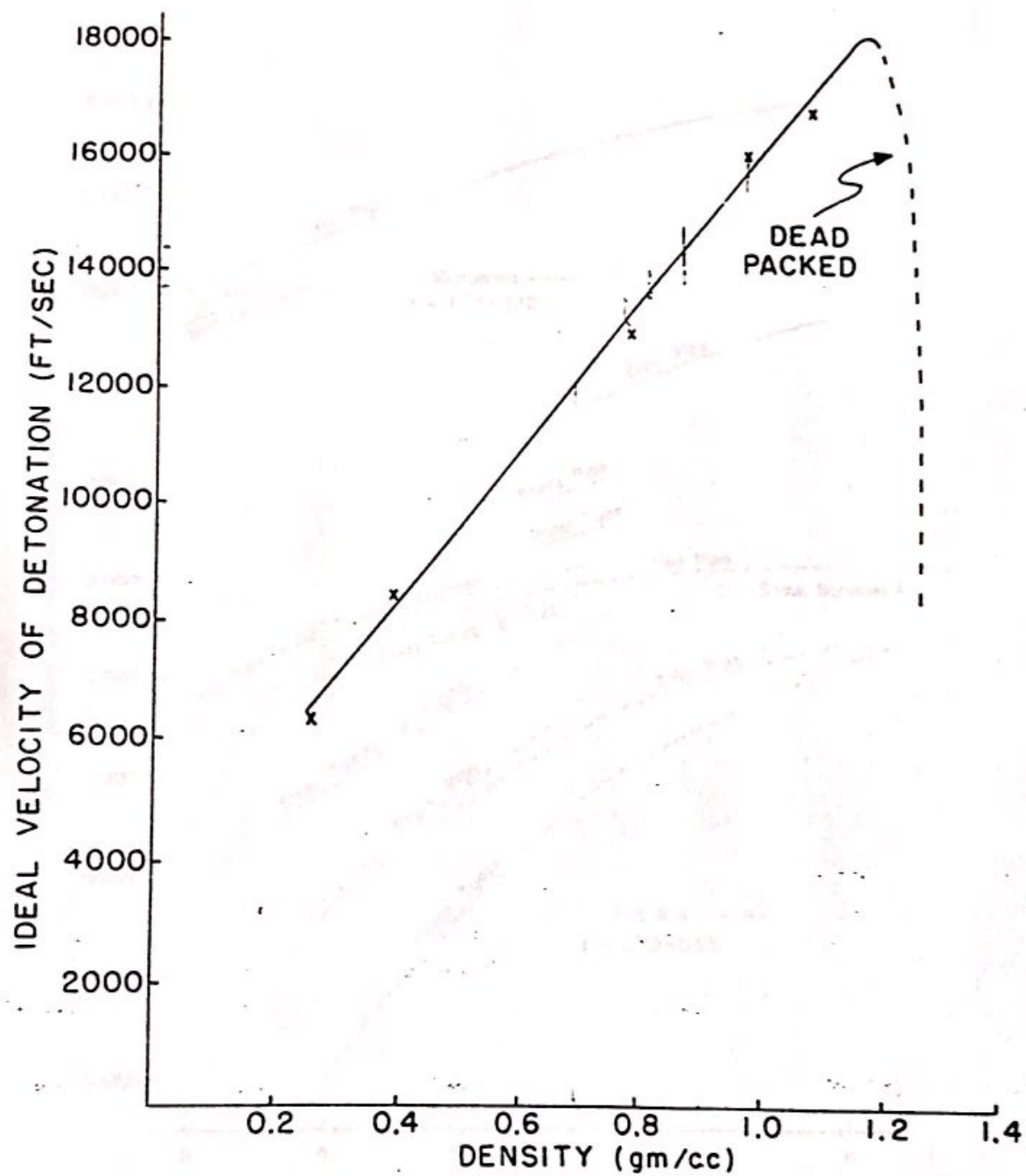


FIGURE 9: VELOCITY OF DETONATION - DENSITY RELATIONSHIP FOR AN/FO.

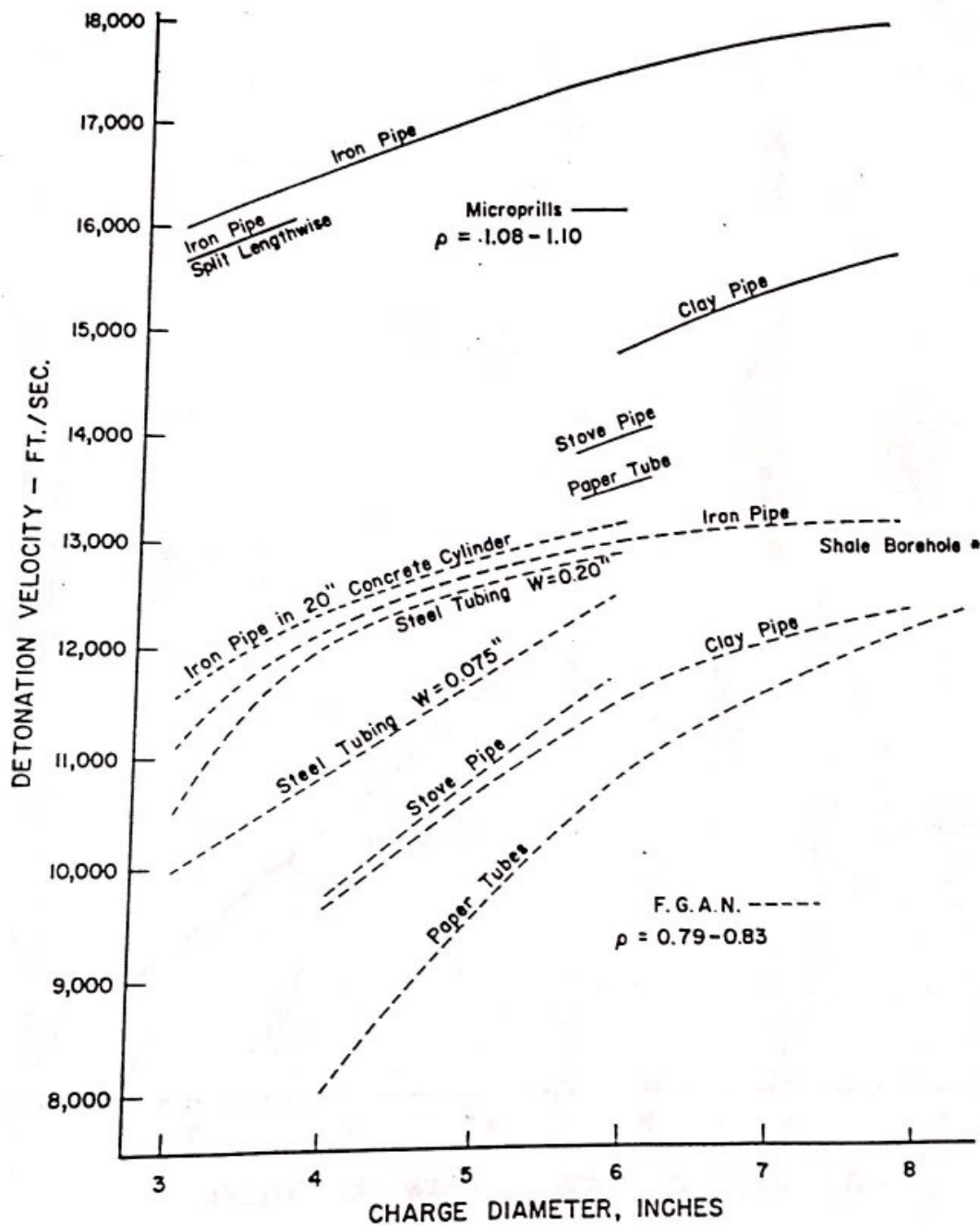


FIGURE 10: EFFECT OF PARTICLE SIZE ON THE DETONATION VELOCITY OF ANFO (F.G.A.N = fertilizer grade ammonium nitrate)

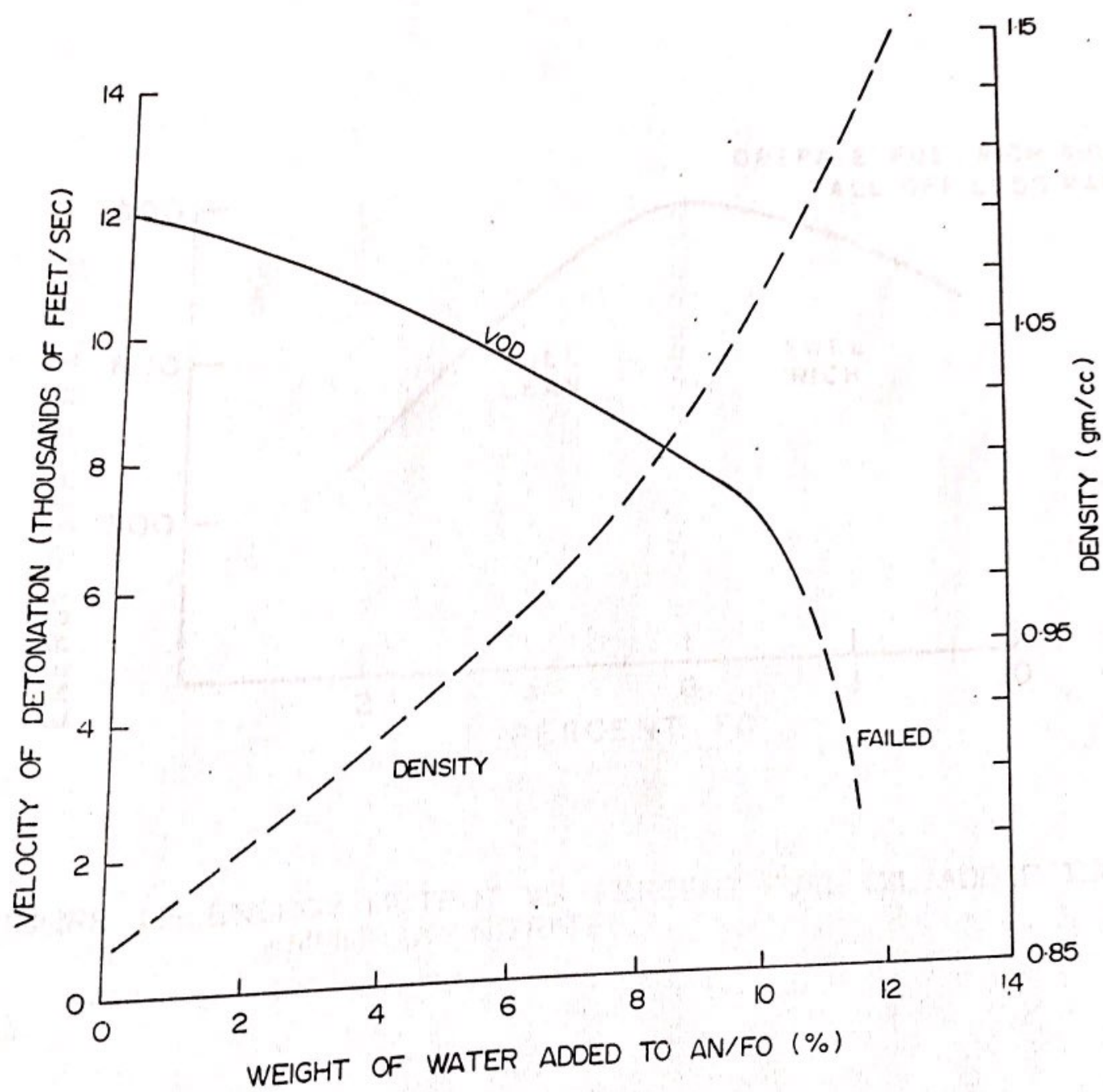


FIGURE 11: THE EFFECT OF WATER ADDITION TO AN/FO FIRED WITHIN 5 HOURS OF MIXING IN 4" DIAMETER PLASTIC PIPES USING 1# PROCORE PRIMERS.

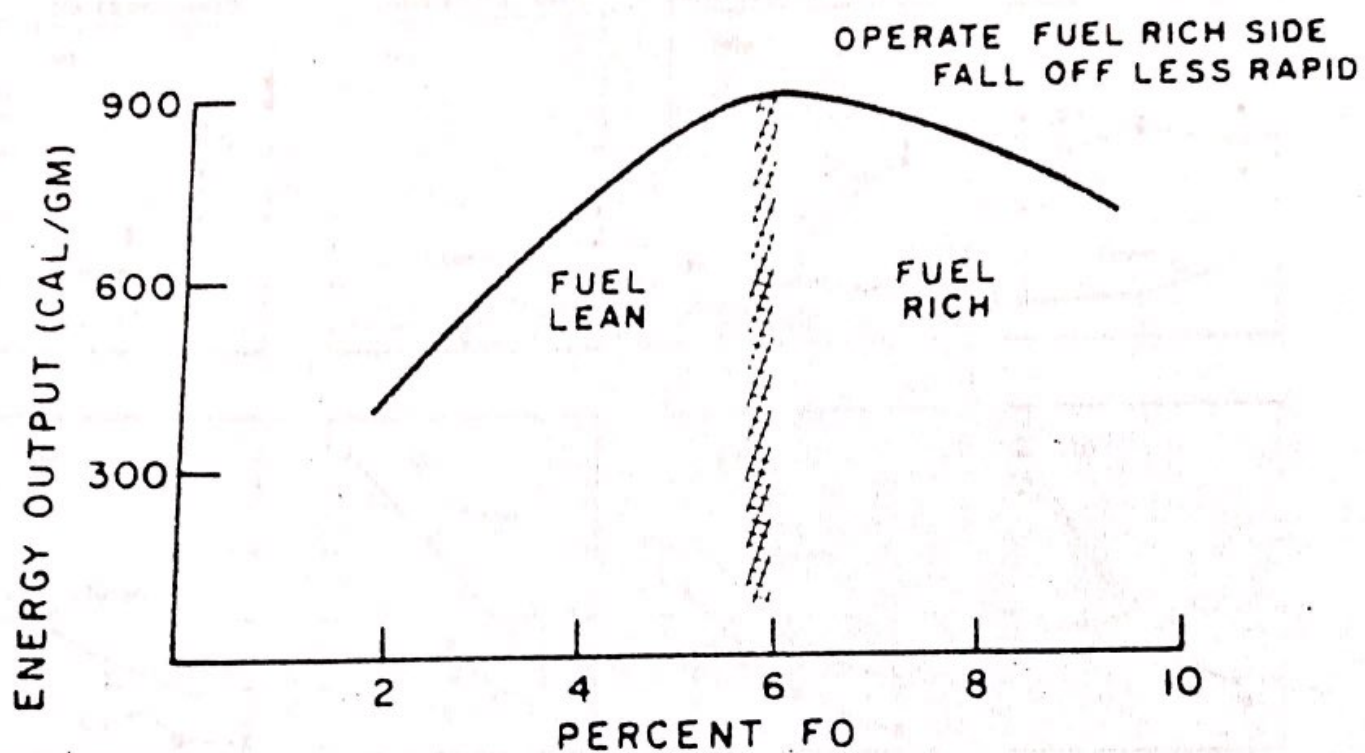


FIGURE 12: ENERGY OUTPUT VS. PERCENT FUEL OIL ADDED TO AMMONIUM NITRATE.

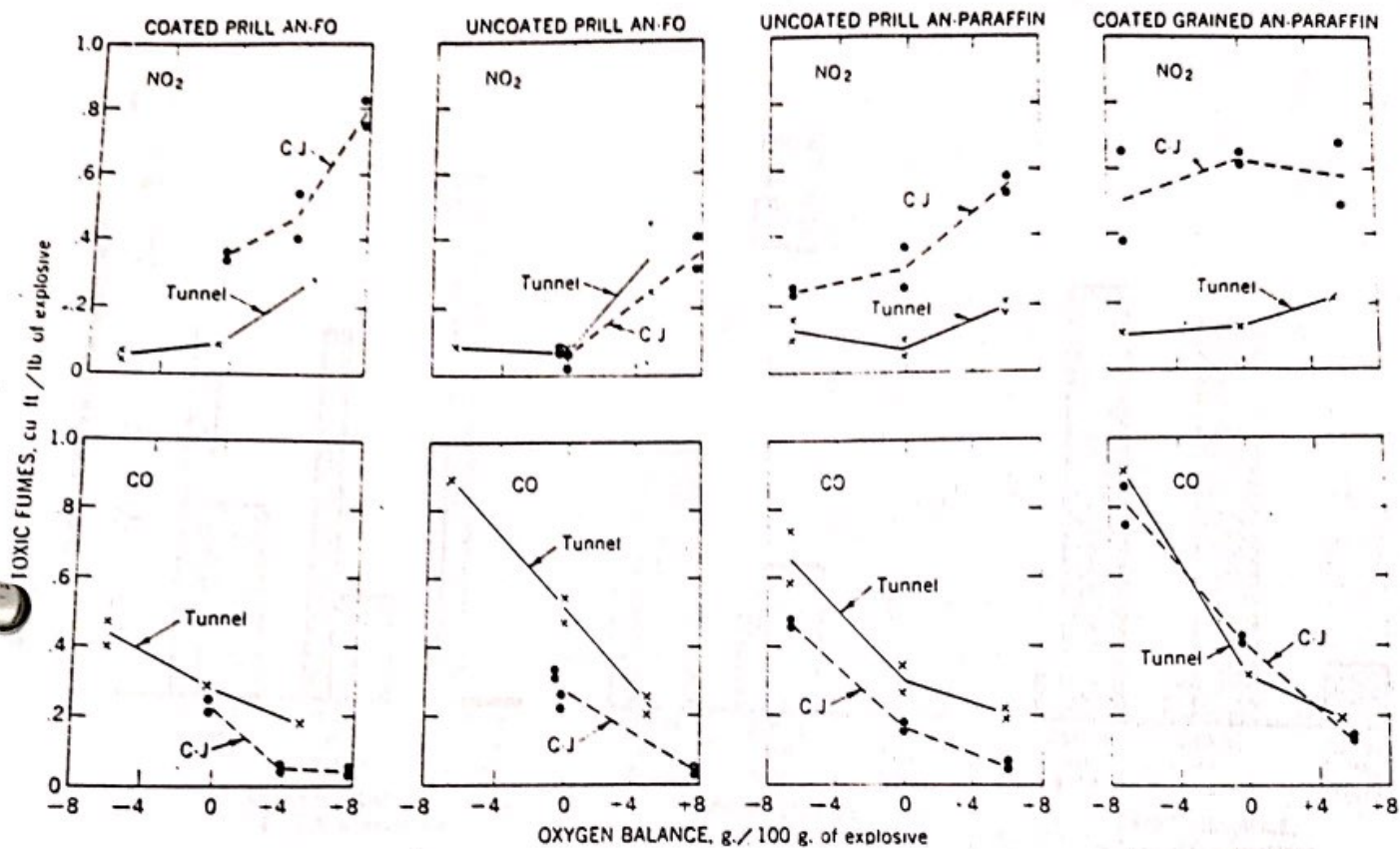


FIGURE 13: EFFECT OF OXYGEN BALANCE ON THE FUMES OF AN/FO.

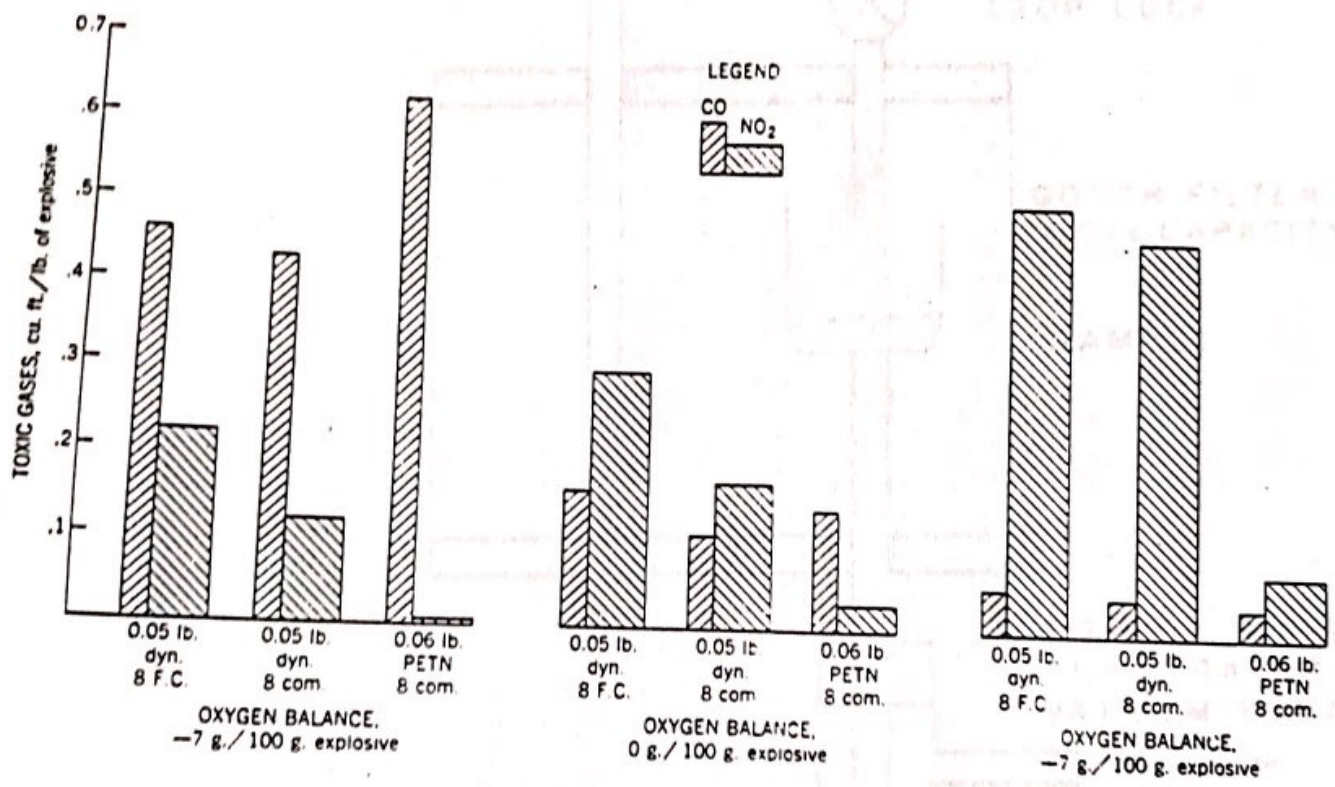


FIGURE 14: EFFECT OF PRIMER WEIGHT ON THE FUMES OF ANFO.

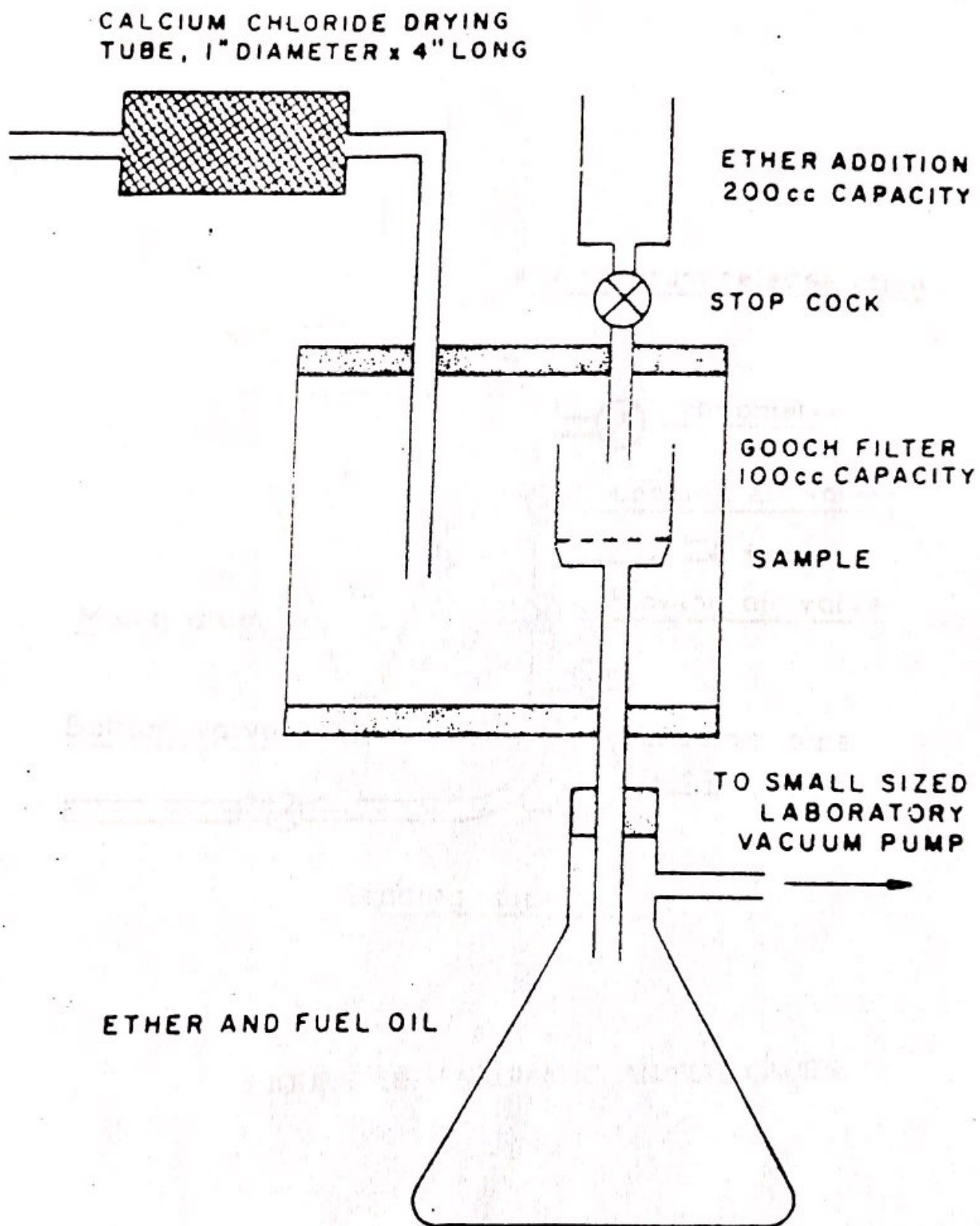


FIGURE 15: EXPERIMENTAL APPARATUS FOR THE MEASUREMENT OF FUEL OIL CONTENT.

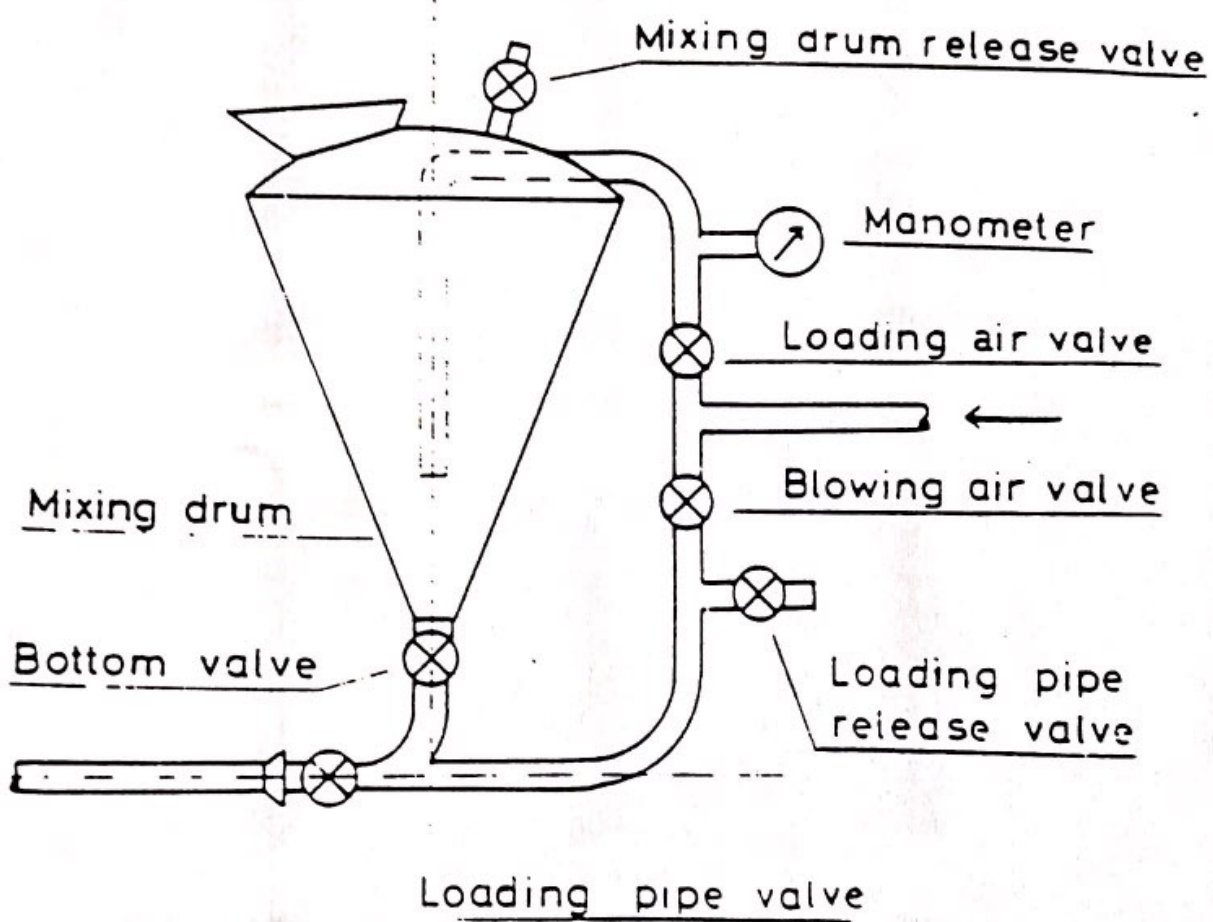


FIGURE 16: PNEUMATIC AN/FO LOADER.

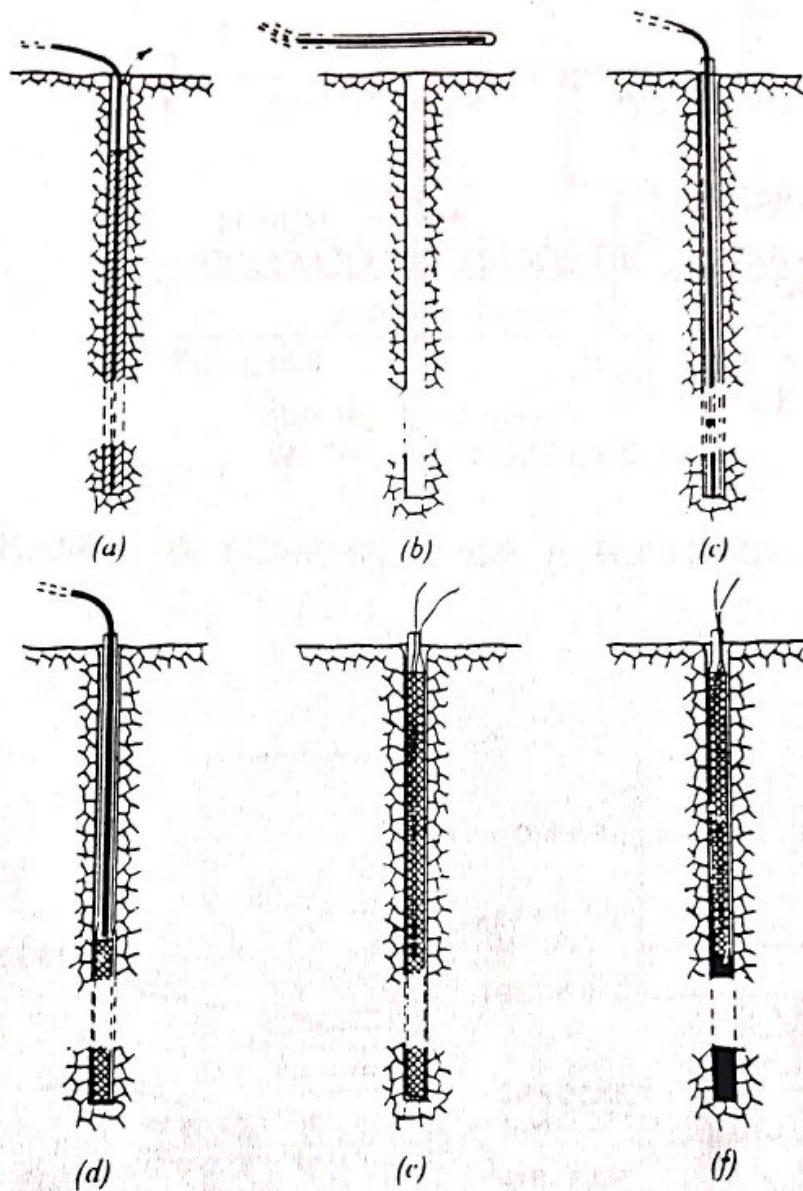


FIGURE 17: USE OF DRYLINERS IN UNDERGROUND WET HOLES.

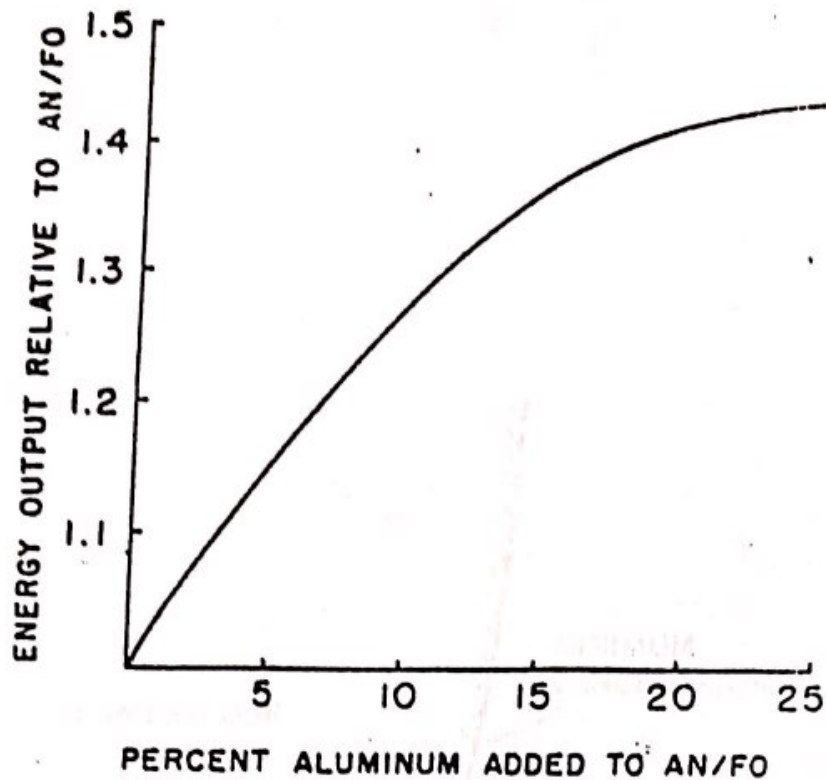


FIGURE 20: EFFECT OF ALUMINUM ON THE ENERGY OUTPUT OF AN/FO.

SIZE 100% -20 + 150 MESH Maximum 1 1/2% - 150 mes

PURITY 94% PLUS ALUMINUM
Mg CONTENT NOT CRITICAL AS FOR
WET MIXES

DUST SHOULD BE DUST FREE FOR BULK
MIXING OPERATION

DENSITY SHOULD BE CONSISTENT FOR A
BULK MIXING OPERATION SO
THAT CALIBRATION IS NOT BEING
CHANGED CONTINUALLY

FLOW SHOULD BE FREE FLOWING FOR
A BULK TRUCK APPLICATION

SPECIFICATIONS FOR ALUMINUM
GRANULES FOR DRY MIXES.

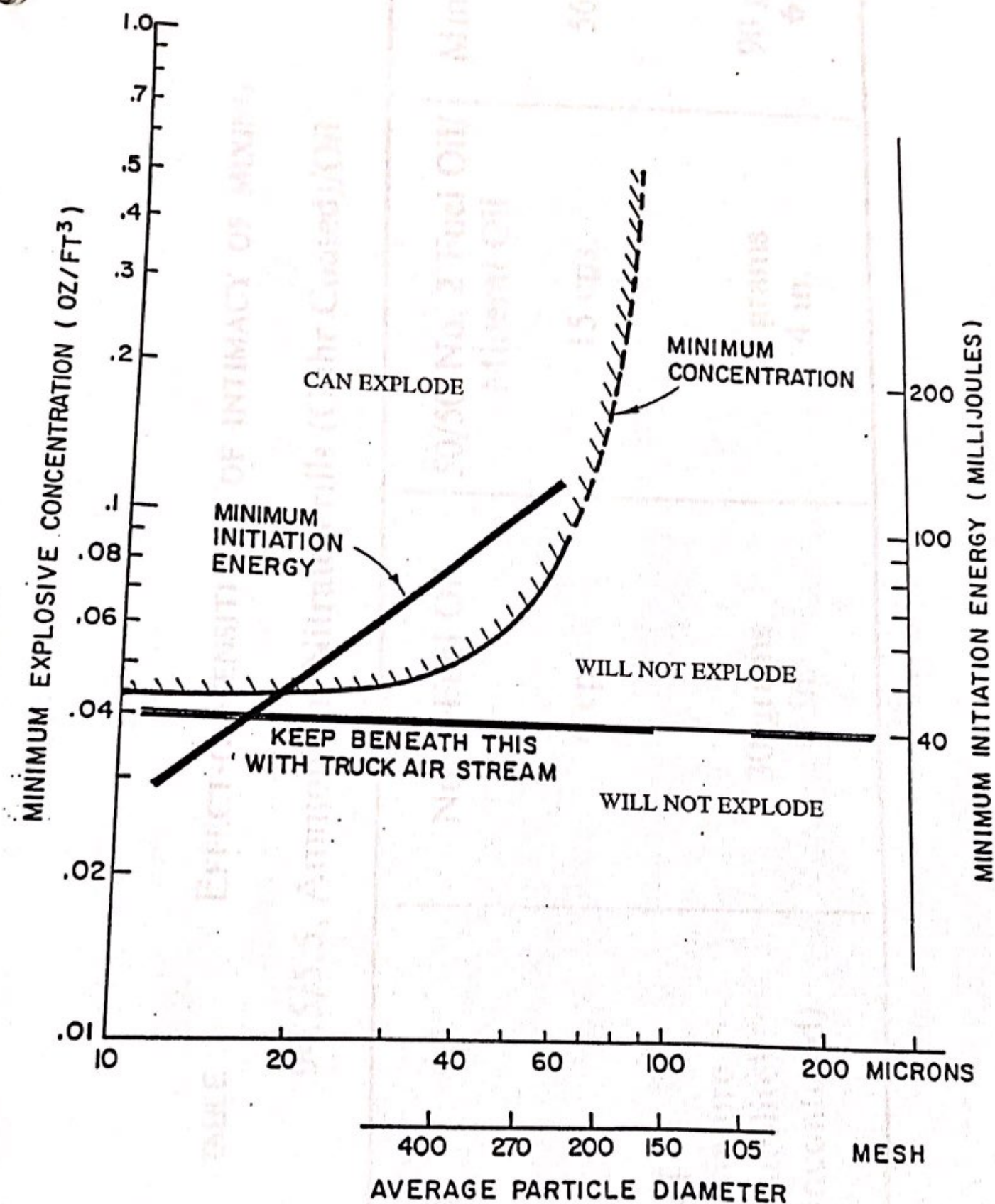


FIGURE 21: EXPLOSIBILITY CURVE FOR ALUMINUM DUST.

TABLE 1: EFFECT-ON-SENSITIVITY OF INTIMACY OF MIXING

94.5/5.5, Ammonium Nitrate Prills (Guhr Coated)/Oil

Type of Oil	No. 2 Fuel Oil	50/50 No. 2 Fuel Oil/ Mineral Oil	Mineral Oil
Viscosity	4 cps	15 cps	560 cps
Sensitivity of AMN/Oil Mixture MB (Pentolite) CD (Unconfined)	30 grams 4 in.	80 grams 4 in.	90 grams 6 in.

TABLE 2: EFFECT-ON-SENSITIVITY OF INTIMACY OF MIXING

94/6, Ammonium Nitrate/Solid Fuel

Type of Fuel	Coarse	Medium	Fine
Fineness Thru 200	0%	8%	17%
Sensitivity of AMN/Fuel Mixture MB (Pentolite) CD (Unconfined)	60 grams 7 in.	30 grams 5 in.	5 grams 3 in.

TABLE 3
EFFECT OF OXYGEN BALANCE ON PERFORMANCE

	COMPOSITION (AN/FO)			
	98/2	96/4	94/6	90/10
VELOCITY OF DETONATION (m/s)	4800	5000	5220	5160
DETONATION PRESSURE (kbar)	52	60	65	63

CHAPTER 10

SLURRY EXPLOSIVES

10.2 ADVANTAGES OF SLURRY EXPLOSIVES

The advantages of the slurry explosives are as follows:

1. High density, water transport, transportation less cost compared with rock charges.
2. Thick paste providing a good seal and not through which the gas diffusion occurs.
3. Water resistant, not for the risk of explosion and storage, transport and handling.
4. Water is added to the mixture to make it more explosive by taking part in the reaction under the condition of explosion, especially if the product is water.
5. Water resistant product is the result of high viscosity and the presence of water in the product.

10.1 INTRODUCTION

AN/FO products suffer from poor water resistance and low bulk strengths because of their low density. For this purpose slurry explosives were developed in the late 50's⁽¹⁾.

The fundamental concept of slurry explosives is to dissolve Ammonium nitrate in water and mix the solution with fuels so that the product detonates at a high detonation rate when it is properly ignited. The term "fuel" here can include an oxygen deficient explosive (e.g. TNT), or non explosive fuels such as hydrocarbons, carbonaceous and cellulosic materials and heat producing metals such as Aluminum^(2,3). Slurry explosives are made water resistant by means of guar gum which thickens the products, increases the viscosity and prevents flow or retards diffusion of the water into and out of the product⁽³⁾.

The first slurries were developed by Cook and Farnan and tested in Labrador, Canada (IOC)⁽³⁾. Two systems were developed. One was based on TNT as the sensitizer and the other on Aluminum powder. The Aluminized slurry however did not find immediate application because of the problems associated to its storage⁽³⁾. The TNT slurry was however successful in many open pit operations. The initial TNT slurry had the following composition: 25% coarse TNT, 55% NH_4NO_3 or NH_4NO_3 (35-45%) and NaNO_3 (10-20%) 20% water with guar gum as a thickening agent. The purpose of the guar gum was to prevent the segregation of the ingredients.

Later, control of the slow Al-water reaction in storage led to the development of slurry explosives with Al as the sensitizer. Al increases the weight strength of even very oxygen deficient explosives due to the creation of aluminum oxides. Furthermore it can substitute TNT which is a high explosive.

10.2 ADVANTAGES OF SLURRY EXPLOSIVES

The advantages of the slurry explosives are the following⁽²⁾:

1. By dissolution, water brings the ingredients into close contact with each other.
2. The solution provides a continuous medium through which the detonation wave passes.
3. Water desensitizes the explosive against fire, sparks, impact and friction thereby decreasing hazards associated with storage and handling.
4. Water is believed to increase the energy of the explosive by taking part in the reaction at the time of explosion especially if Al is present.
5. Water affects the products of detonation and suppresses the formation of toxic gases: carbon monoxide and oxides of nitrogen.
6. Water acts as a coolant and offers a perspective of using water-gel explosives in underground gassy coal mines. Some slurries have been accepted as permissible explosives to replace dynamites.

A disadvantage with regard to composition is that low percentages of water present a problem in storage. The explosive becomes hard and grainy due to the crystallization of inorganic oxidizer salts. On the contrary a higher percentage of water decreases the sensitivity as well as the strength. Urbansky suggests a percentage of water in the range of 8-20%⁽²⁾.

10.3 SLURRY FORMULATIONS

A slurry is a continuous liquid containing suspended solid particles. The liquid phase consists of a saturated aqueous solution of Ammonium nitrate (65% AN in 20 deg. C). In the liquid phase one finds amounts of undissolved nitrates in suspension, and fuels which react with the oxidizers during the detonation process. The commercial slurry explosives are normally thickened and crosslinked.

In the early formulations it was found that the guar gum thickened slurry was not very viscous. As a result the solid particles and the air bubbles would migrate and a deterio

DENSITY CONTROL

ration in performance was observed after storage of some days. The viscosity of the guar gum was significantly increased by incorporating cross-linking agents. Cross linking agents which are used are⁽²⁾; borax or other boron compounds, antimony compounds and semisynthetic and synthetic polymers (carboxyl cellulose or polycyclamide).

Typical oxidizers used are ammonium nitrate and sodium nitrate. In addition calcium nitrate can be used especially in cold conditions^(1,2,3). Another popular oxidizer is ammonium perchlorate. However ammonium perchlorate has the disadvantages of producing chlorine gas as a product of detonation and it can yield to unstable and very sensitive products.

A variety of fuels can be used in slurries. Reactive fuels such as TNT are used with success. Non reactive fuels are however popular since they are cheap and the use of high explosive is eliminated. Al in the form of flakes or granules is used with success. However in order to avoid deterioration the aluminum has to be properly coated with stearic or palmitic or oleic acid⁽²⁾.

In the last years liquid sensitizers have been introduced in the formulations of slurries. It has been found that alkylamine nitrates (e.g methylamine nitrate) increase the sensitivity and reduce the critical diameters. Another sensitizer used today is ethylene glycol mononitrate. It should be mentioned that these liquids are not classified as explosives. However they can be dangerous as a recent experience (1975) has indicated. As glycol mononitrate was considered safe to handle no special precautions were taken. A detonation which destroyed a factory in Canada and killed eight people was probably due to friction in the pumping operations of glycol mononitrate.

Figure 1⁽¹⁾ shows the various classes of slurry explosives available today.

Typical slurry formulations are shown in Tables 1 and 2⁽¹⁾.

10.4 DENSITY CONTROL

In order to have a detonable product with reasonable sensitivity the density of the product has to be within limits. Furthermore density control can be used to limit the loading density of the top of the hole where less explosive is required than in the bottom.

The density can be controlled by using porous solids or by using chemical gassing of the aqueous phase of the slurry. In the first method air is locked within the solid grains or is held on the surface of the grains by using naturally or artificially hydrophobic surfaces. Furthermore glass microballoons can be used for density control. Microballoons are not compressible and therefore they maintain the sensitivity of the slurries under hydrostatic heads. Of course the same can be noted for the case in which the solids of the slurry contain the air bubbles in their mass (e.g solid AN prills with about 12% internal free space or porous Al which can have up to 20% internal free space).

Another method of controlling the density of the slurry is by mechanical aeration. There is a tendency for natural aeration in all gelled slurries. According to Cook this natural aeration can be used to lower the density by as much as 10-15%. The density can be decreased further another 15-20% by artificial mechanical aeration. Further reduction of the density is achieved by chemical gassing. This can be done by the acetic acid decomposition of CaCO_3 or by slow NaNO_2 decomposition. In the first case the gas is CO_2 and in the second N_2 . The solubility of CO_2 changes with pressure and PH and for this reason N_2 gassing is preferred⁽³⁾.

The density - pressure curves of aerated or gassed slurries are calculated from the measured density at atmospheric pressure and the density at a very high pressure. In the second case this is going to be the maximum density of the explosive. The density at different pressures can be calculated by applying Boyle's law⁽³⁾:

$$\rho_1^{-1}(P) = P(0) \frac{(\rho_1^{-1}(0) - \rho^{-1})}{P} + \rho^{-1} \quad (\text{EQ 32})$$

where P is the pressure

$\rho(p)$ is the density at pressure P

ρ is the maximum density

10.5 PERFORMANCE OF SLURRY EXPLOSIVES

The performance of slurry explosives depends on many parameters, such as high explosive content, water content, density, temperature and pressure. In the following these parameters will be analyzed.

I. Effect of water. Figure 1 shows the effect of water content and aluminum content on the energy output of TNT slurries and Al slurry blasting agents. It follows that water reduces the energy output significantly.

II. Effect of high explosive content. Figure 2 shows the effect of the TNT content on the critical diameter of a TNT based slurry. It follows that in order to achieve small critical diameters large quantities of TNT would have to be used. This is not recommended because of the high cost of TNT. For this purpose small diameter slurries are based on liquid non explosive sensitizers and significant amounts of aeration in order to have adequate sensitivity and detonate in small diameters.

III. Effect of Temperature. Figure 3 shows the effect of temperature on the velocity of detonation - diameter curves of a typical TNT sensitized slurry and a typical NCN slurry. It is obvious that the low temperature increases the critical diameter significantly. The effect is more dramatic in the case of the NCN slurry. The same effect is shown in Figure 4 where the effect of low temperatures on the critical diameter of a small diameter cap sensitive slurry is shown. The phenomenon has not been explained quantitatively. A qualitative explanation results from the fact that the low temperatures

affect the physical state of the products. Crystallization occurs since the solubility of AN in water is dependant upon temperature. This changes the nature and the distribution of the density discontinuities which are responsible for the creation of hot spots. As a result desensitization occurs.

iv. Effect of Hydrostatic Pressure. The effect of hydrostatic pressures on the critical diameter of an NCN slurry and a TNT slurry is shown in Figures 5 and 6 respectively. It is obvious that the critical diameter increases and at some point the product fails to detonate. This happens because of the increase of the density of the aerated slurry in the borehole due to the hydrostatic head. This reduces the effectiveness of the air bubbles as reaction centres because of precompression and because of the change in their geometry. From the comparison of the previous figures it is obvious that the high explosive sensitized slurry is affected less by the hydrostatic head. This is due to the air which is included inside the TNT prills in this case plus the discontinuity provided by the TNT prill which is not affected by the pressure. Furthermore TNT as a solid high explosive is not affected by hydrostatic pressures significantly. The increase of the ideal detonation velocity which can be noticed in the curves of the figures is due to the increase in the density of the products.

To avoid exceeding the dead packed density at the bottom of the borehole the slurry is gassed down to a very low initial density. This is not a problem in dry boreholes. However in wet holes the amount of gassing is limited by the ability of the slurry to float.

Each gassed slurry composition has a set of characteristic curves indicating density as a function of depth which were calculated as in equation (1). These curves represent different levels of gas addition. Figure 6 is an example for an aluminized slurry. The critical diameter is also related to density. Figure 7 is typical of this relationship. By knowing the critical diameter at each particular density one can calculate the amount of gassing required to achieve proper detonation under a particular hydrostatic head. If water is present the ambient density has to be greater than 1.0 g/cc. An alternative to that is to use programmed gassing of the slurry in the borehole so that the density is controlled in the column of the explosive.

v. Composition. Apart from the obvious relationship between composition and performance and apart from the previously mentioned relationship between composition and effect of temperatures and pressures, the shelf life is strongly dependent on the composition. It has been found that basic air bubble sensitized slurries which do not contain any explosive sensitizers have shorter shelf lives. This is due to the migration of their ingredients and the coalescence of the bubbles on which their sensitivity is based.

10.6 LOADING

Small diameter boreholes are normally loaded with cartridge products. In large diameter boreholes this is not economical and it is time consuming. Therefore bulk trucks have been developed.

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10.7 REFERENCES

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TABLE 1: TYPICAL SLURRY COMPOSITIONS

TNT SLURRY		NCN SLURRY	
INGREDIENT	WEIGHT %	INGREDIENT	WEIGHT %
AN	54	AN	55
SN	10	SN	15
WATER	15	WATER	17
TNT	20	FUEL OIL	2
AL	-	AL	9
GUM+	1	GUM+	1
CROSS		CROSS	
LINKER		LINKER	
		GASSING AGENT	1
			0.7
density (g/cc)		1.3 1.37	

Large diameter products

TABLE 2: TYPICAL SLURRY COMPOSITION

NCN SLURRY	
INGREDIENT	WEIGHT %
AN	60.0
SN	16.5
WATER	17.0
FO	4.8
GUM+CROSS LINKER	1.0
GASSING AGENT	0.7
density (g/cc)	1.15

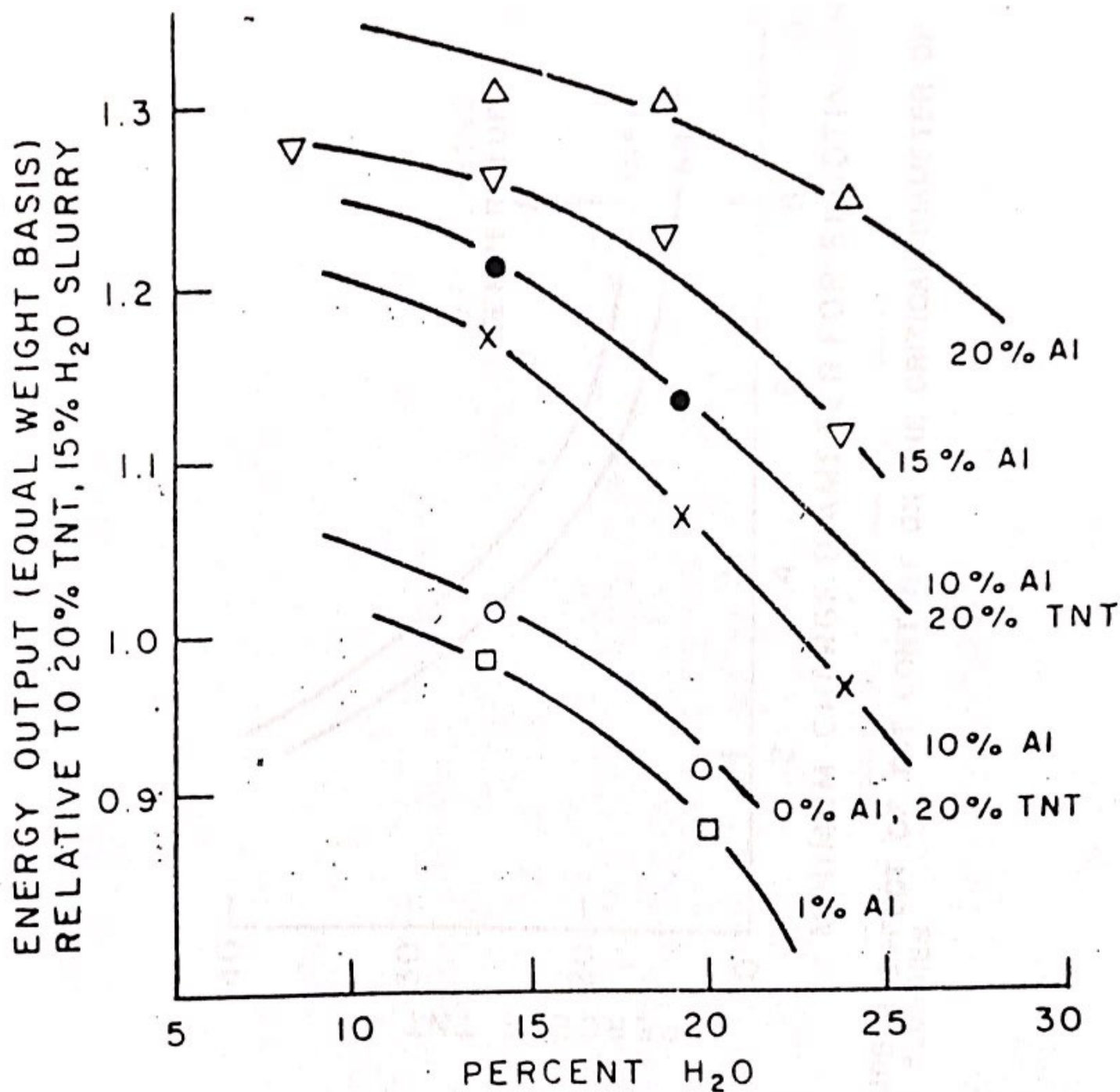


FIGURE 1: EFFECT OF WATER CONTENT ON THE ENERGY OUTPUT OF SLURRIES (BAUER, 1981)

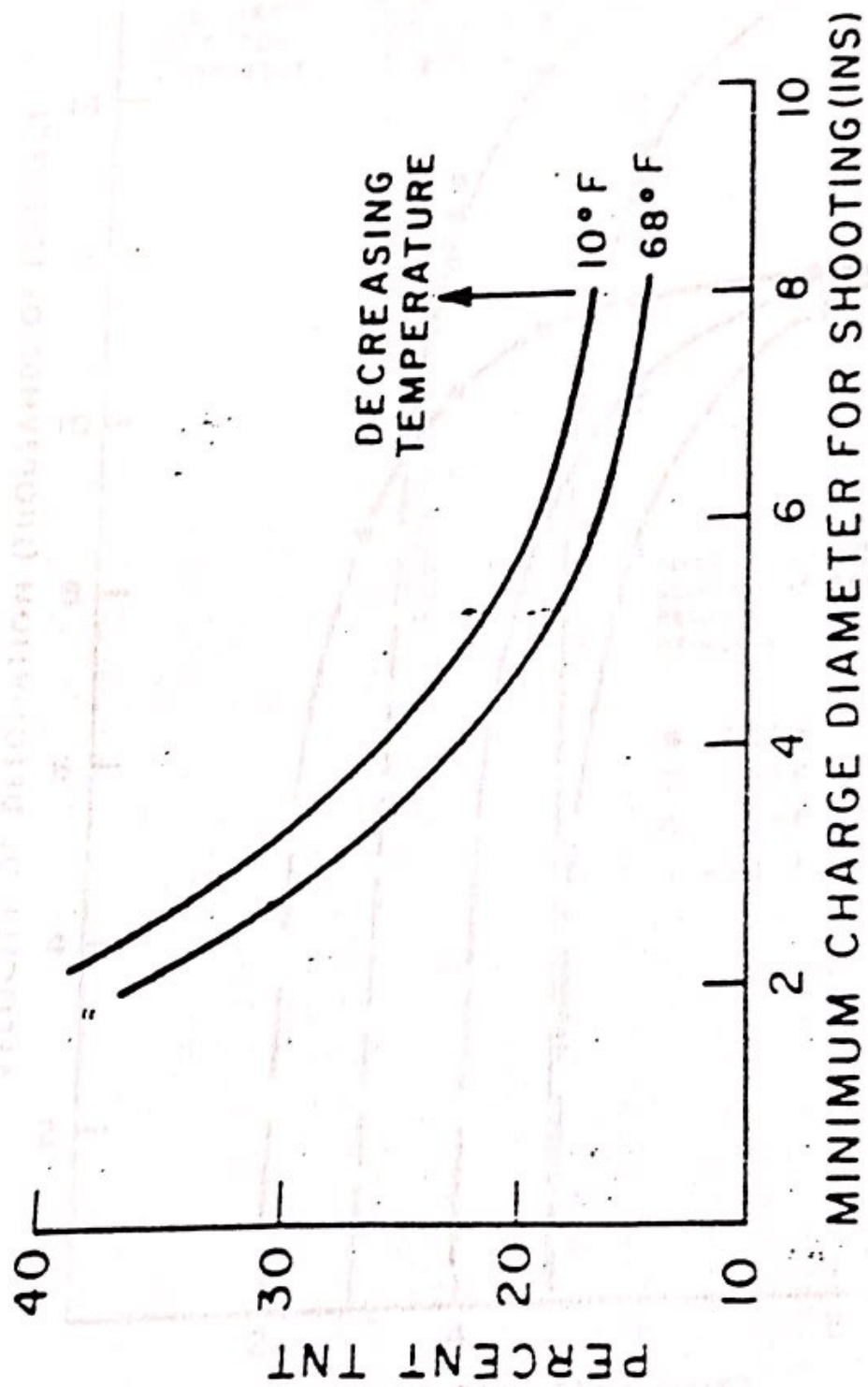


FIGURE 2: EFFECT OF TNT CONTENT ON THE CRITICAL DIAMETER OF TNT SLURRIES

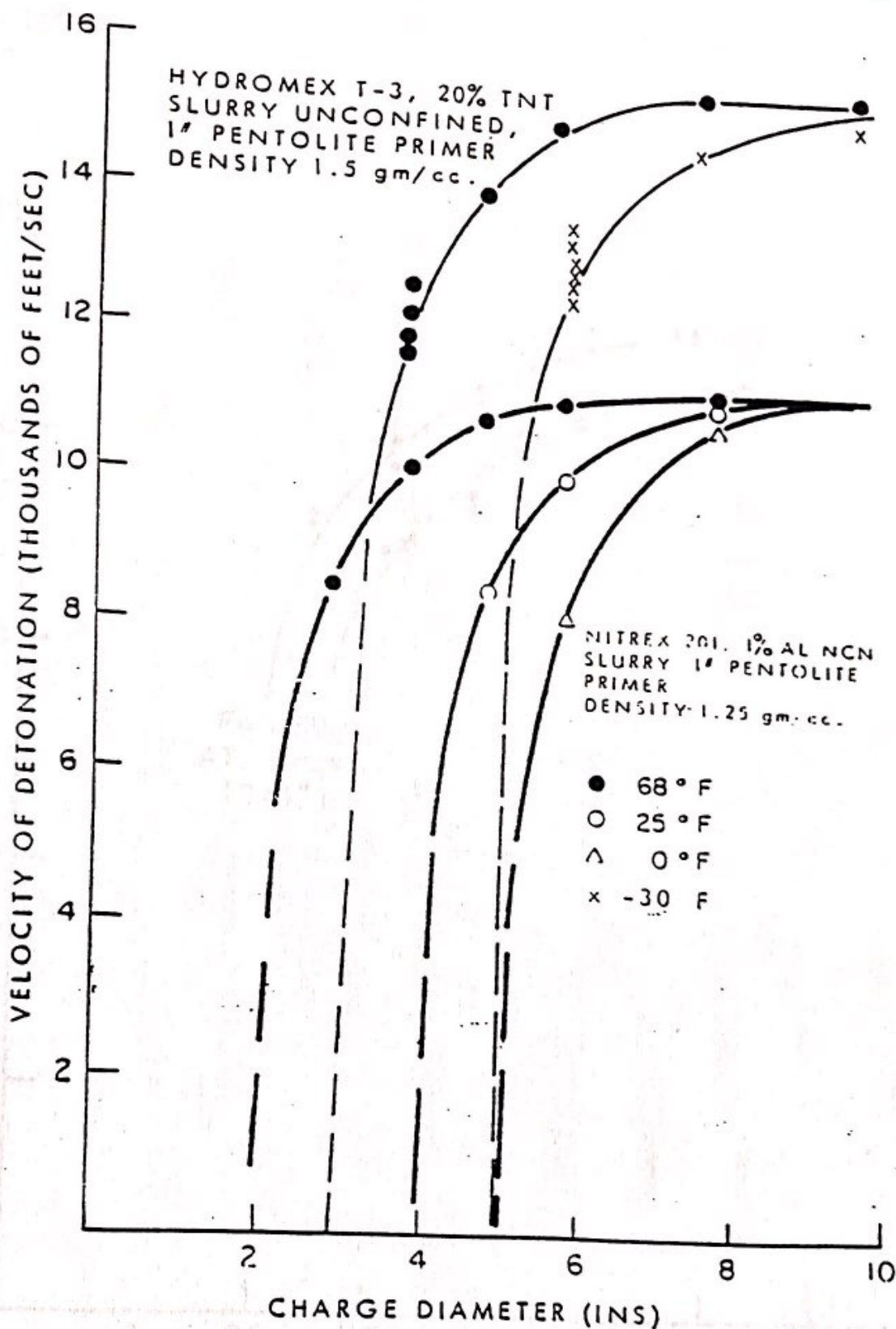


FIGURE 3: EFFECT OF TEMPERATURE ON THE VELOCITY OF DETONATION CHARGE DIAMETER CURVES OF TNT SLURRIES AND NCN LARGE DIAMETER SLURRIES (BAUER, 1981)

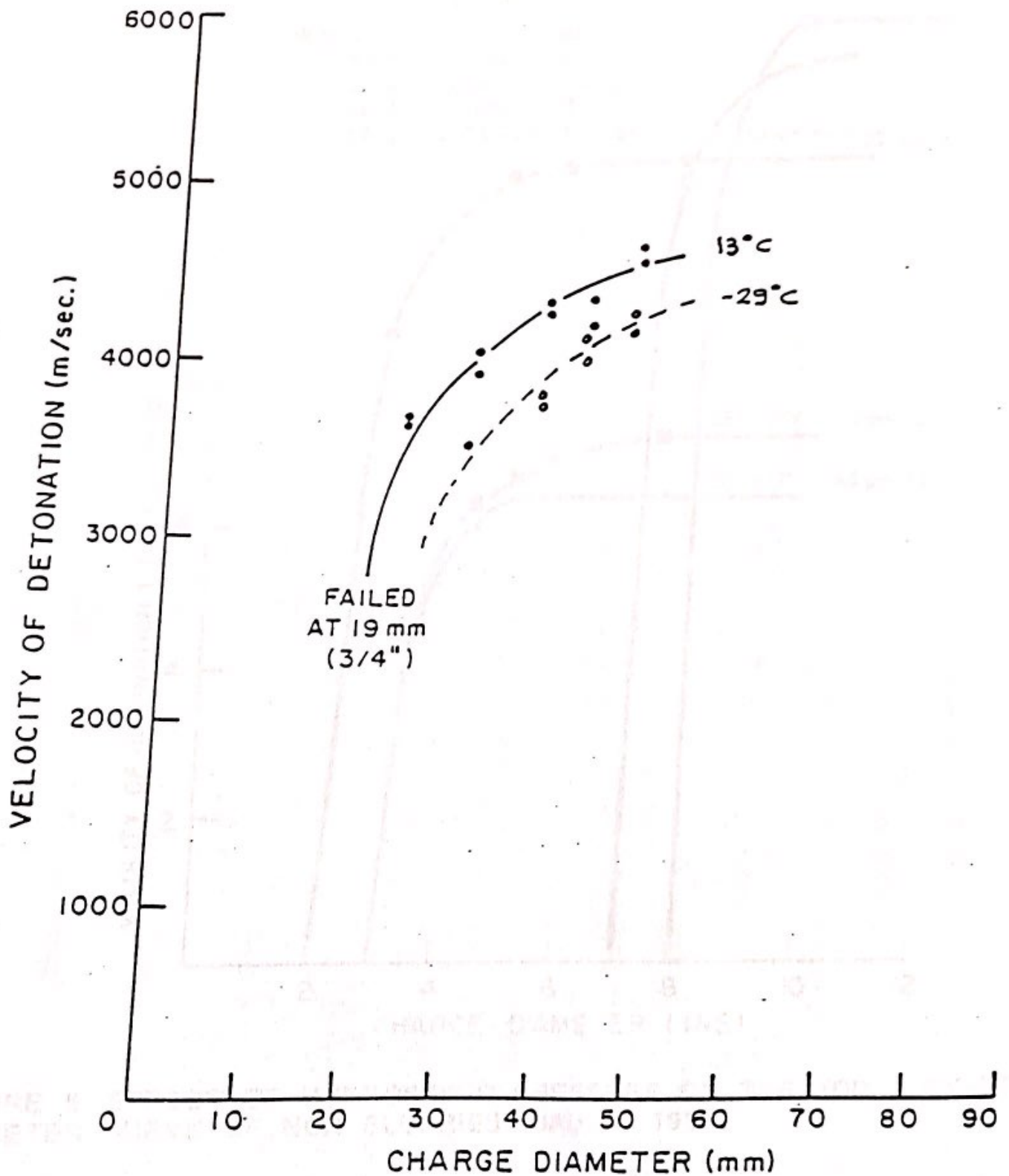


FIGURE 4: EFFECT OF TEMPERATURE ON THE VELOCITY OF DETONATION CHARGE DIAMETER CURVE OF A SMALL DIAMETER NCN SLURRY.

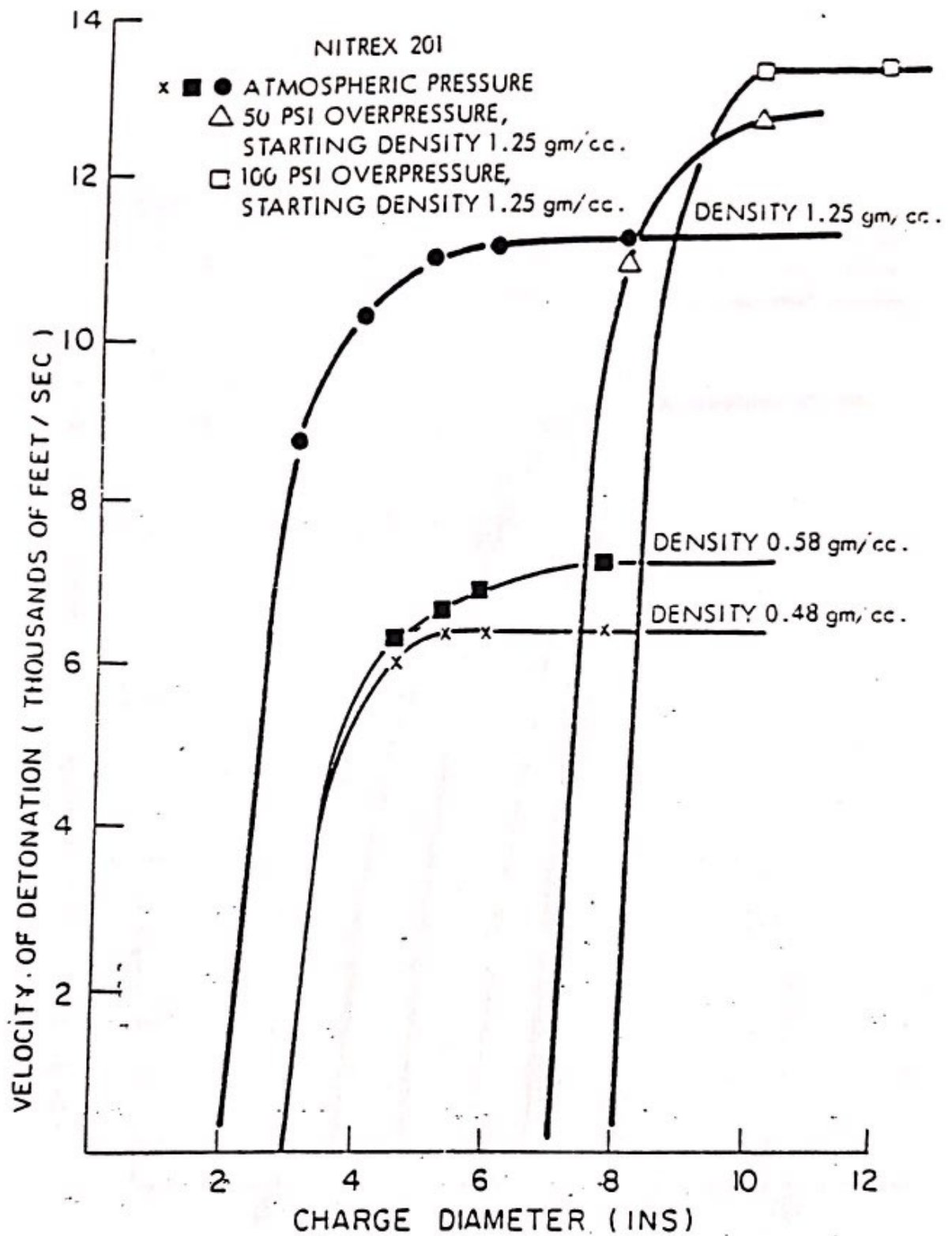


FIGURE 5: EFFECT OF HYDROSTATIC PRESSURE ON THE VOD - CHARGE DIAMETER CURVE OF NCN SLURRIES (BAUER, 1981)

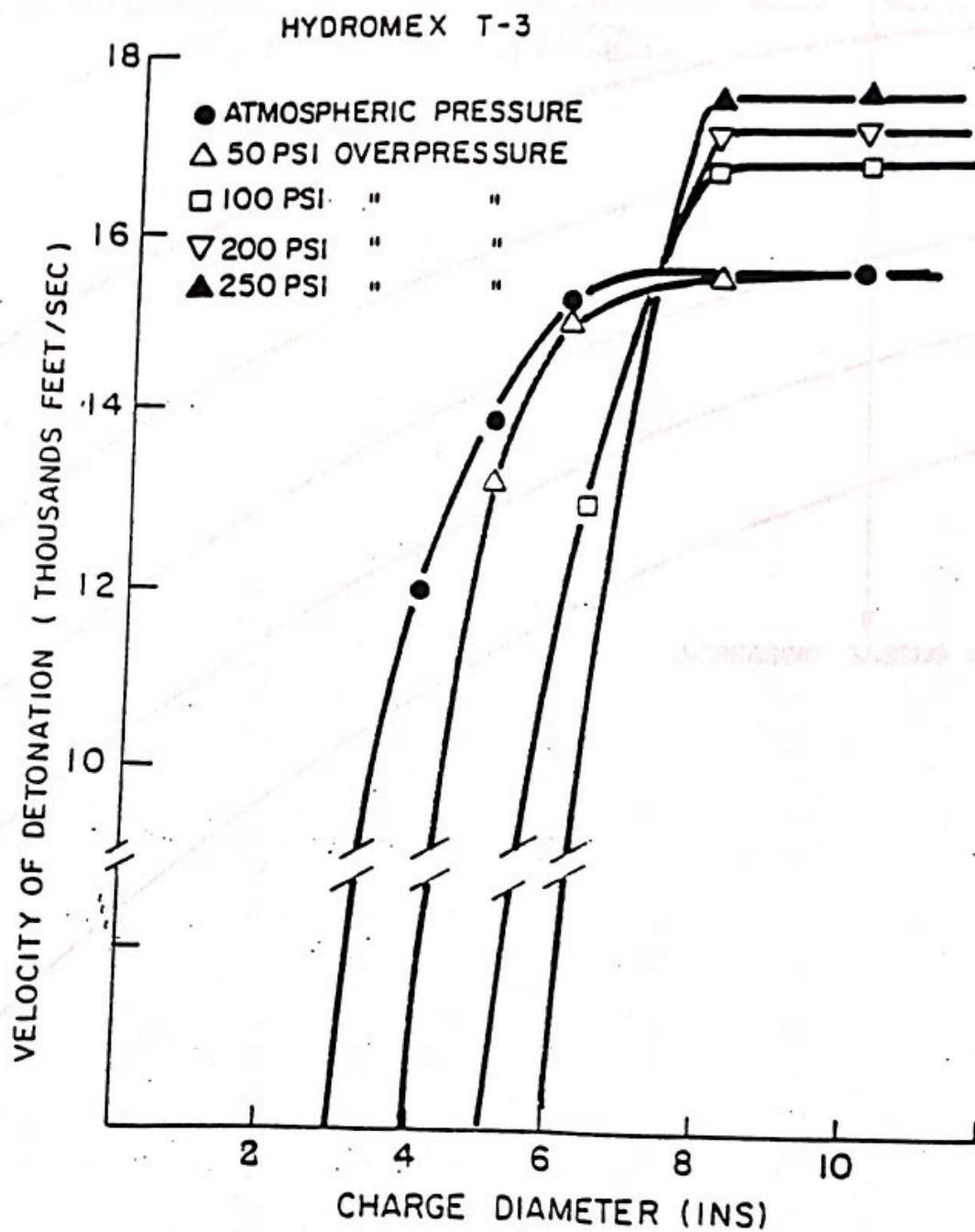


FIGURE 6: EFFECT OF HYDROSTATIC PRESSURE ON THE VOD - CHARGE DIAMETER CURVE OF A TNT SLURRY (BAUER, 1981)

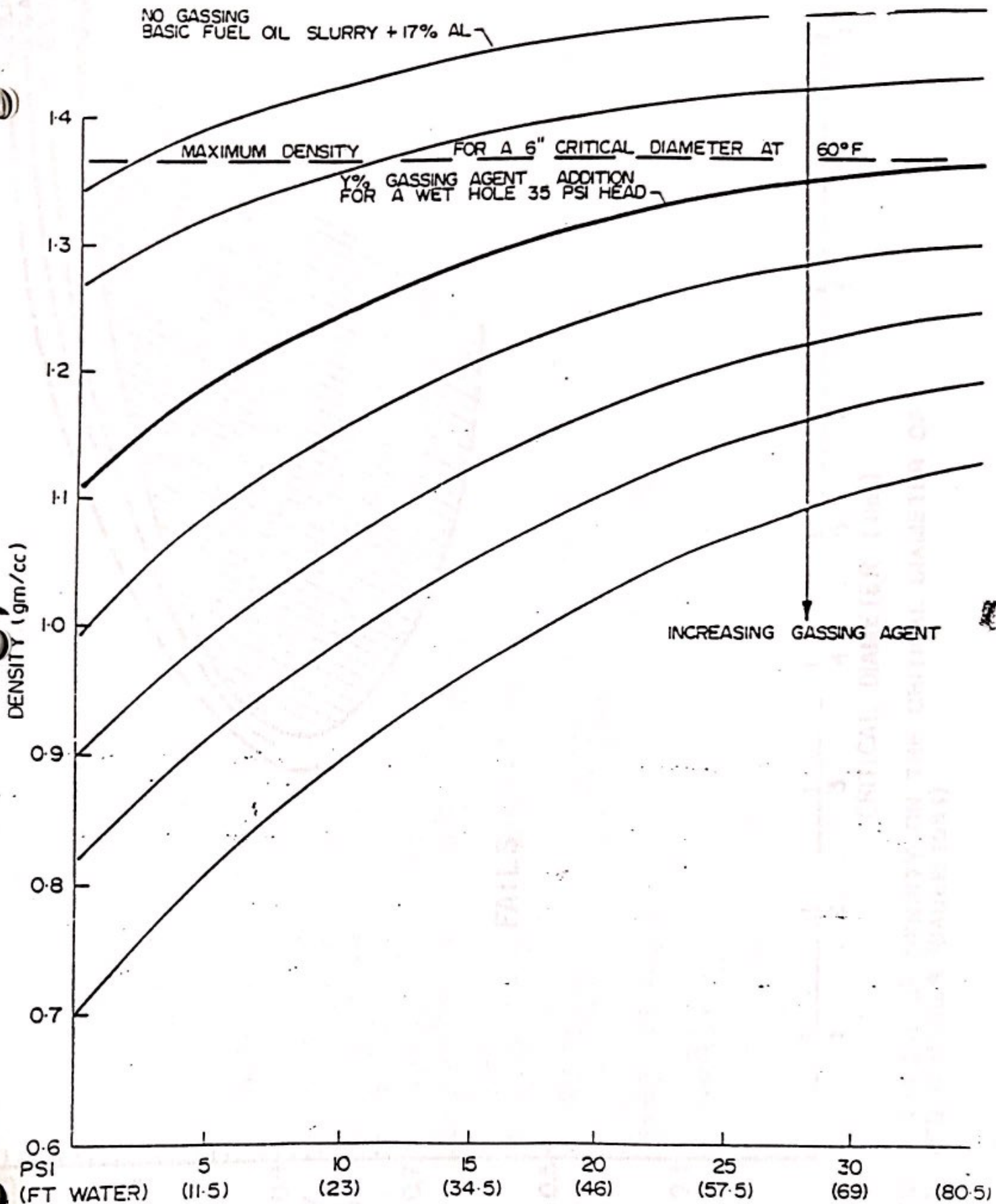


FIGURE 7: EFFECT OF THE HYDROSTATIC PRESSURE AND GASSING AGENT ADDITION ON THE DENSITY OF AN ALUMINIZED SLURRY (BAUER, 1981)

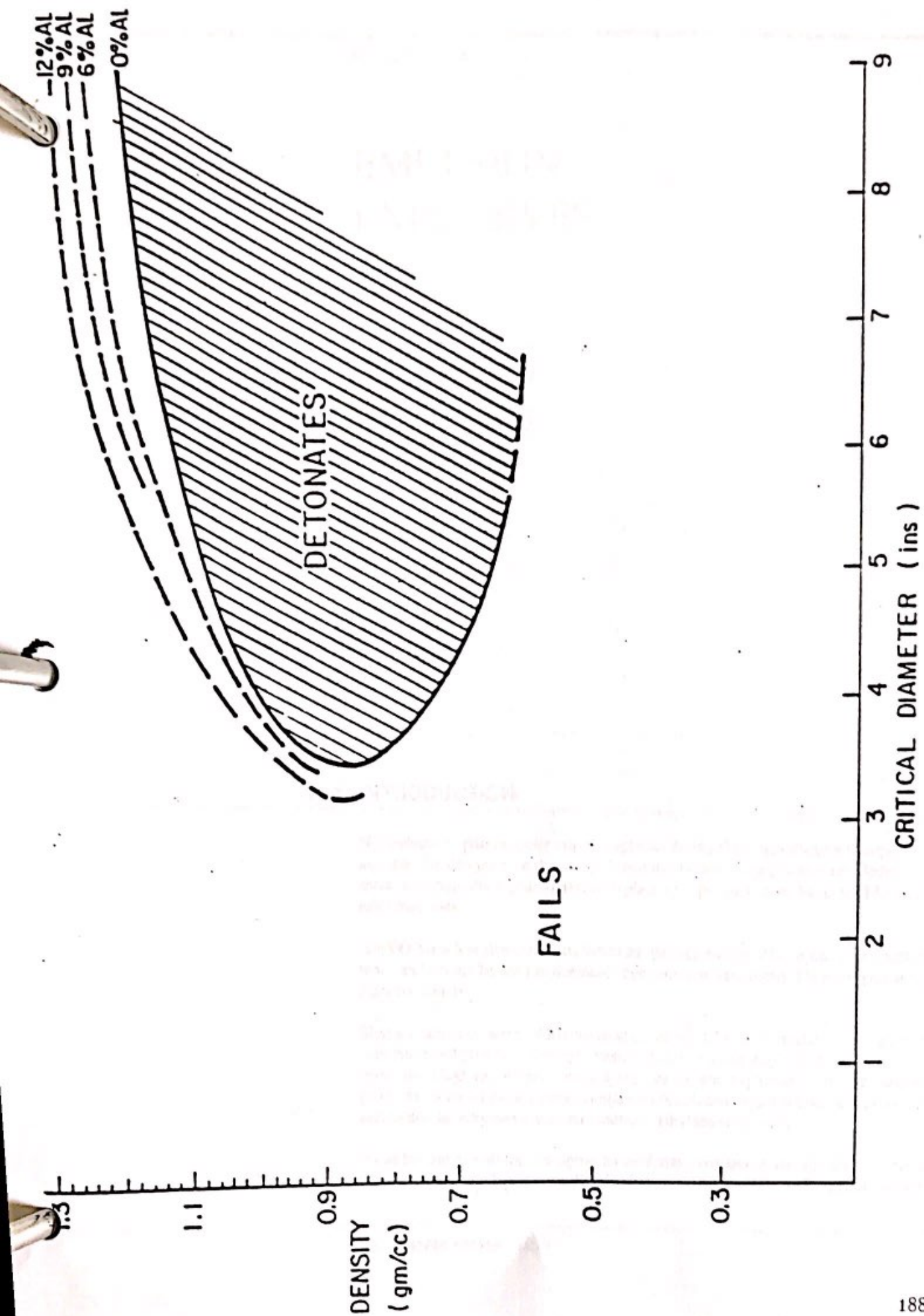


FIGURE 8: EFFECT OF DENSITY ON THE CRITICAL DIAMETER OF ALUMINIZED SLURRIES (BAUER, 1981)

CHAPTER 11

EMULSION EXPLOSIVES

11.1 INTRODUCTION

NG dynamites possess poor safety properties during their manufacture transportation and use. For this purpose the use of dynamites is diminishing with time. Safer explosives are gradually replacing them. Replacement products have been AN/FO, slurries and emulsions.

AN/FO has a low density which limits its blasting energy. Also it has poor water resistance and cannot be used in boreholes containing water, unless it is packaged in water tight containers.

Slurries came out in the 1950's because of the need for an explosive having good water resistance and high bulk strength. Various kinds of slurry explosives have been developed, from high explosive sensitized slurries to non-explosive, non-metal sensitized products. Some of these slurries contain non-explosive liquid sensitizers (monomethyl amine nitrate, ethylene glycol mononitrate, ethylamine nitrate).

It can be said that slurries comprise an oxidizing component, mainly ammonium nitrate, a fuel component dispersed or dissolved in an aqueous continuous medium, which is

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INTRODUCTION

thickened, usually by guar gum, and, where premium performance is required, contain sensitizers. A typical composition of an NCN slurry is given in the following:

Continuous phase

Water	15-20 %
Inorganic salt	65-80 %
Gum + cross linking agent	1-2 %

Discontinuous phase

Fuel oil	2-5 %
Gassing agent	0.2 %

Slurries are used widely in open-pit blasting operations. They can be applied as bottom loads where high pulling capability is desirable or in boreholes containing water. High loading densities, resulting in high bulk strengths permit lower drilling costs, higher blasting efficiencies and better rock fragmentation.

However slurries are not devoid of deficiencies. It becomes increasingly difficult to detonate them as their density is increased. Usually gassing is used, in order to make them sufficiently sensitive for detonation by small primers. Furthermore when they have to be used in deep boreholes, the hydrostatic head imposed on the lower part of the column increases the specific density of the explosive. Therefore unexploded charges can be left in areas where mining or excavation operations must be continued, resulting in hazardous working conditions necessitating costly remedial measures.

At low temperatures their critical diameters increase significantly and failures can occur. Moreover air bubbles can migrate and coalesce into larger ones. This has a pronounced desensitizing effect.

In order to tackle some of these problems many modifications have been proposed. Proportional gassing can result in controlled density inside the borehole and prevention of dead packing conditions. Cross-linking agents, gelling agents and thickeners prevent bubble migration and stabilize the small bubbles of air or gas, which are important for the propagation of the detonation wave.

Furthermore glass microballoons or similar closed cell void containing materials, such as perlite, are used to provide adequate sensitivity under hydrostatic pressures.

A serious disadvantage of the slurry explosives is the fact that they detonate non-ideally even in very large diameters. This is a result of the crudeness of their mix which makes the reaction process incomplete inside the detonation wave. To improve this and the other disadvantages of slurry explosives the next step in the development of commercial explosives was the invention of emulsion explosives.

11.2 CHEMICAL COMPOSITION OF EMULSION EXPLOSIVES

An emulsion type explosive comprises mainly inorganic oxidizing salts, water-insoluble organic fuels, an emulsifier and a bulking agent. The fuel oil phase is the external or the continuous one, while the oxidizer salt phase is discontinuous. This discontinuous phase comprising small supersaturated droplets is suspended in the continuous oil phase. The bulking agent is added for density control as a third phase dispersed in the basic emulsion. It can be either ultrafine air bubbles or artificial bubbles made of glass, resin, plastic etc. The emulsifying agent reduces the surface tension and the energy required to create new surfaces. Therefore it aids the process of subdivision and dispersion of the droplets in the continuous phase. The emulsification agent also reduces the rate of coalescence by coating the surface of droplets with a molecular layer of emulsifying agent⁽¹⁾.

A typical composition of an emulsion type explosive is given in the following⁽¹⁾:

Discontinuous aqueous phase

Water	10-22 %
Inorganic salt	65-85 %
Closed cell, void containing material	2.5-15 %

Continuous phase

Fuel	3.5- 8 %
Emulsifier	0.8-1.2 %

The carbonaceous fuel component of the continuous phase can include paraffinic, olefinic, naphthenic, aromatic, saturated or unsaturated hydrocarbons. In general, the carbonaceous fuel is a water immiscible emulsifiable fuel that is either liquid or liquefiable at a temperature of the order of 90 deg. C⁽¹⁾. However a certain percentage of the fuel component should be either a wax or oil, or a mixture of them. Waxes having a sufficiently high melting point can be used. Such waxes include microcrystalline waxes, paraffin waxes and mineral waxes. It has been found that more shelf stable emulsions can be obtained by using a blend of a microcrystalline wax and a paraffin wax⁽¹⁾.

Suitable oils used are the various petroleum oils. The viscosity of the oil is not so important for the emulsion explosives. The emulsion can contain auxiliary fuels such as aluminum, aluminum alloys, magnesium etc.

The emulsifiers used are water in oil emulsifiers, such as sodium oleate, sorbitanmonolaurate, sorbitan monostearate and sodium tristearate⁽¹⁾.

The discontinuous aqueous phase contains inorganic oxidizer salts dissolved in water. The inorganic oxidizer salt consists principally of ammonium nitrate. However another inorganic nitrate such as sodium nitrate, or an inorganic perchlorate such as ammonium

CHEMICAL COMPOSITION OF EMULSION EXPLOSIVES

perchlorate or a mixture of them can be used in the formulation⁽¹⁾. It is generally found that the presence of a material such as sodium nitrate permits greater quantity of oxidizer salt to be dissolved at a given temperature while influencing the final density of the emulsion⁽²⁾.

The gas forms a discontinuous phase in the emulsion. It may be in the form of gas bubbles, which are introduced by stirring, injection or chemical means, or in the form of a closed cell, void containing material such as plastic spheres, perlite spheres or hollow glass microspheres.

The function of the gas or the gas entrapping material is to reduce the density of the emulsion. Any gas can be used for that purpose. However, if a combustible gas or combustible gas entrapping material is used, it should be included in the calculation for the total fuel.

The usual size of glass microballoons is about 60-70 μ m. Their size distribution is between 40 and 100 μ m. Very small microballoons do not act as hot spots, during detonation, but as solid ingredients. Similarly thick walled microballoons are more difficult to collapse and are not as efficient as thin walled ones.

Plastic microballoons can be used in emulsion explosives but not in a continuous process. The reason for that is that a continuous process requires a blender with shearing action which destroys plastic microballoons⁽³⁾.

Recently, efforts were made to replace glass with perlite microballoons, which are cheaper⁽⁴⁾. However emulsion type explosives containing perlite microballoons proved to be less sensitive than those containing glass spheres. The reason for that is that perlite bubbles are not spheres, their voids are connected to each other and sometimes they do not provide a sealed cavity to act as a hot spot⁽³⁾.

Because of the type of mixture in emulsions, the aqueous oxidizer phase is protected by a continuous oil phase. Therefore evaporation of water during storage is prevented and the penetration of external standing water into the basic emulsion is inhibited. According to Wade⁽¹⁾ "the process is so effective that emulsions have excellent water resistance and do not depend upon a package for their ability to function in boreholes containing water".

Because of their structure the physical consistency of emulsions is related mainly to the properties of the continuous phase⁽¹⁾. The water immiscible fuels can be chosen in such a way that the emulsions can be manufactured in a variety of forms. Stiff putty-like compositions suitable for packaged products or almost fluid, pumpable ones, suitable for bulk loading, can be manufactured.

Emulsions have long shelf lives, high bulk strength and good safety properties. Therefore emulsion type explosives contain a flexibility that can permit application in open pit and underground operations under a wide range of conditions.

The system which has been described above is the simplest. During the last 12 years different modifications have been tried. The most important one is the development of an

emulsion-ANFO mix called heavy AN/FO. This system will be described in the next chapter.

11.3 METHOD OF MANUFACTURE⁽⁵⁾

In the process of manufacturing emulsion type explosives, two basic premixes are formed. The first comprises an aqueous solution of inorganic oxidizing salts, and the second, hydrocarbon fuel components, which provide the oil phase of the water-in-oil emulsion.

The aqueous solution of oxidizing salts is heated to a temperature above the crystallization point of the solution and is maintained at that temperature until the emulsion matrix is formed. To avoid crystallization when mixed with the aqueous solution, due to a temperature drop, the hydrocarbon fuel components are heated to approximately the same temperature. The emulsifier is added to the oil just before the mixing of the two premixes. The reason for that is that the emulsifier can be degraded, if it is subjected to high temperatures for long periods of time.

The emulsion matrix is formed in a mixer capable of subjecting the hydrocarbon fuel component, the aqueous solution of inorganic salts and the emulsifier, to emulsifying high shear rates.

The emulsion prepared in this manner is fed on a continuous basis to a blender where glass microballoons, and, if desired, auxiliary metal fuels are blended to form the final products. Figure 1 is a schematic representation of the above process.

11.4 PERFORMANCE OF EMULSION EXPLOSIVES

The detonation velocities of the emulsion explosives approach those obtain by thermohydrodynamic calculations even when the test charge is of a relatively small diameter. This indicates performance close to ideal even at small diameters. Figure 2 shows velocity of detonation charge diameter curves for a typical small diameter emulsion and typical small diameter slurries having similar compositions⁽⁶⁾. It is obvious that the non ideal region is extensive in the case of slurries and short in the case of emulsions. This is due to the intimacy of mix which is achieved by the emulsification process. This reduces the effective particle size of the product and the time to react in the detonation head. On the other hand slurries are a crude mix of an oxidizer solution phase, droplets of fuel and solid oxidizer and fuel components.

Since emulsions reach ideal performance in small diameters, they are ideal for use in secondary blasting, for blasting of hard rock formations and for use as primers.

AVAILABLE PRODUCTS

The effect of low temperature on small diameter emulsions and slurries is shown in Figure 3⁽⁶⁾. Low temperatures increase the critical diameters of both products. However the effect is more pronounced in the case of NCN slurries.

The effect of hydrostatic pressure on the performance of slurry and emulsion explosives is shown in Figure 4⁽⁶⁾. It is obvious that the emulsion was not affected significantly by hydrostatic pressures. Furthermore the difference in the performance of the various products can be explained by Figure 5 which shows the density as a function of the hydrostatic pressure. The density of the emulsion does not change significantly because it contains microballoons which are not compressible at moderate hydrostatic pressures. The small difference in the density is a result of the compression of bubbles which were included accidentally in the mass of the product during the manufacturing process. Slurry 2 contains some microballoons and air bubbles while slurry 1 contains only air bubbles. This is why the effect of pressure is more pronounced in this case.

A problem which has been found with microballoon sensitized products is the desensitization effect of detonating cord downlines or neighbouring holes detonating at a previous delay. Shock pressures (assumed to be of a strength lower than that required for direct initiation of the product) can rupture the microballoons or break the product down and cause desensitization⁽⁷⁾.

11.5 AVAILABLE PRODUCTS

A variety of emulsion products has been developed. These products are designed to meet the needs of the explosives consuming industries.

Small diameter cap sensitive products have been developed for use in underground operations or as primers. The density of these products is between 1.1 and 1.22 g/cc.

Large diameter products have been developed for open pit applications and large diameter underground blasting. These products require a primer for initiation. The density of these products is between 1.2 and 1.35 g/cc.

Small and large diameter products are made as cartridged products or as pumpable products for bulk handling. Bulk handling is more common in open pit large diameter applications. However pumpable emulsions have found application in underground mines.

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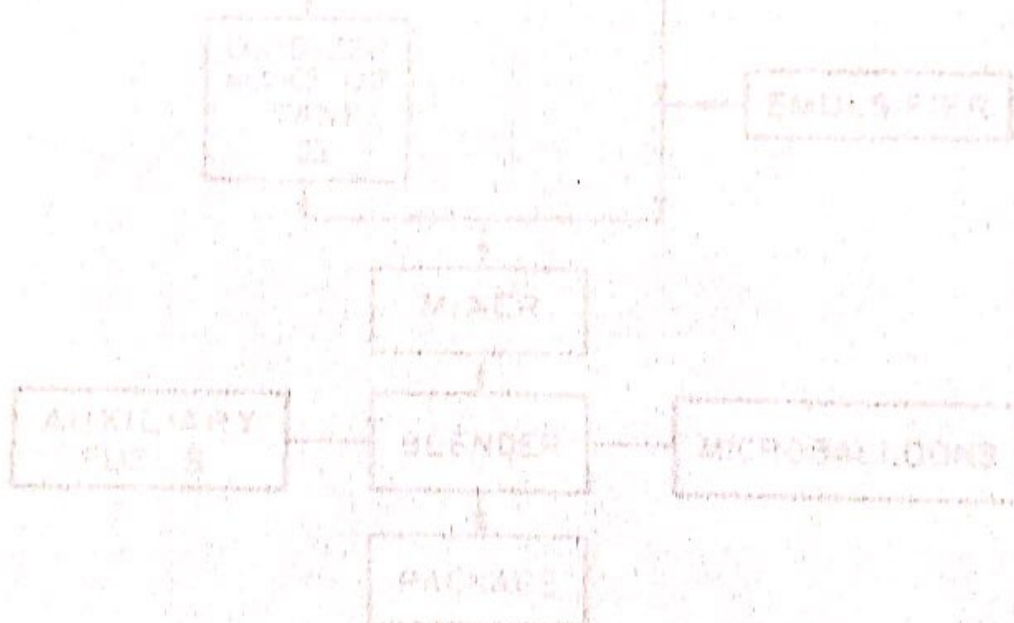


FIGURE 11 SCHEMATIC REPRESENTATION OF THE PRODUCTION

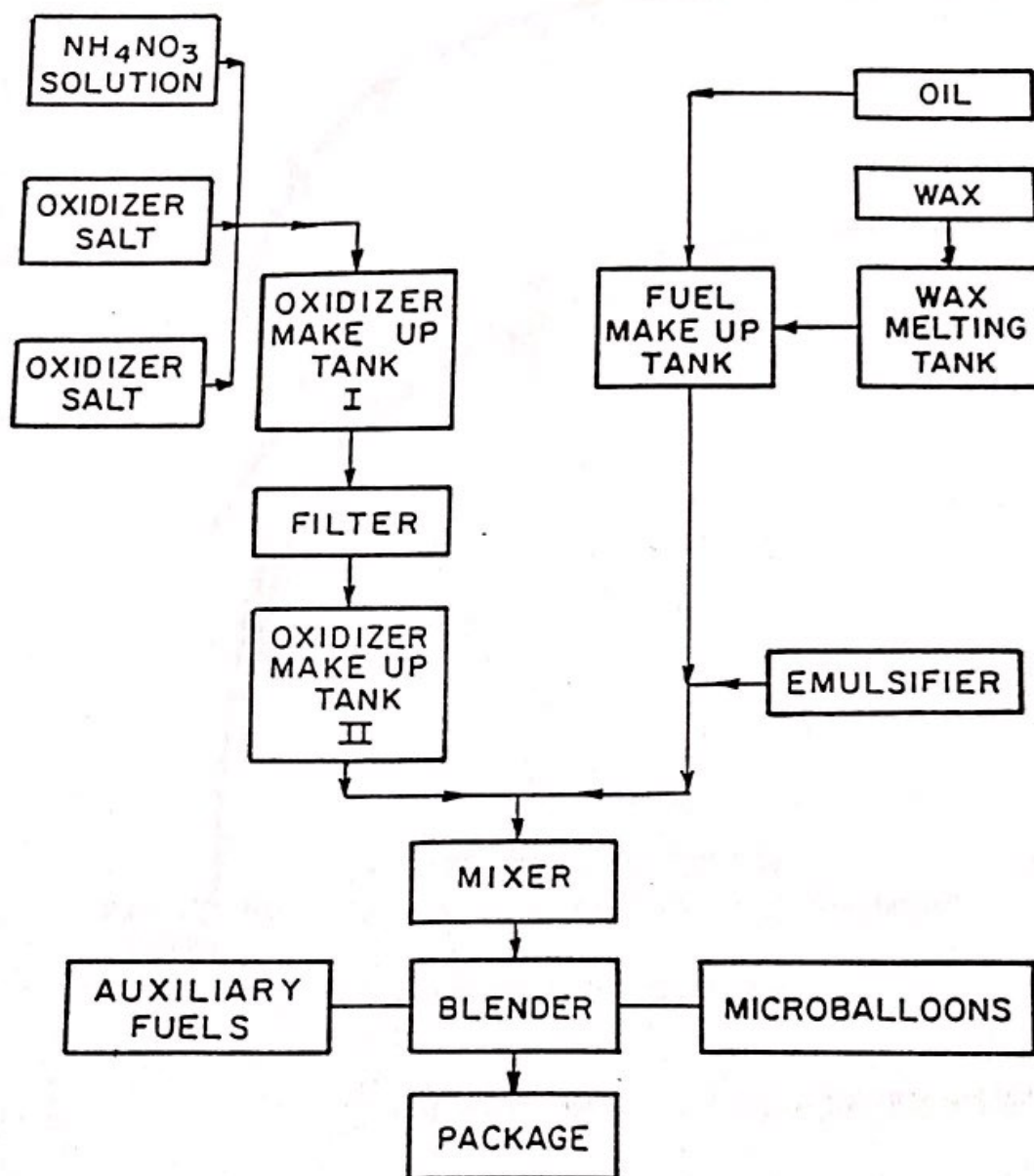


FIGURE 1: SCHEMATIC REPRESENTATION OF THE PROCESS OF MANUFACTURING EMULSION TYPE EXPLOSIVES.

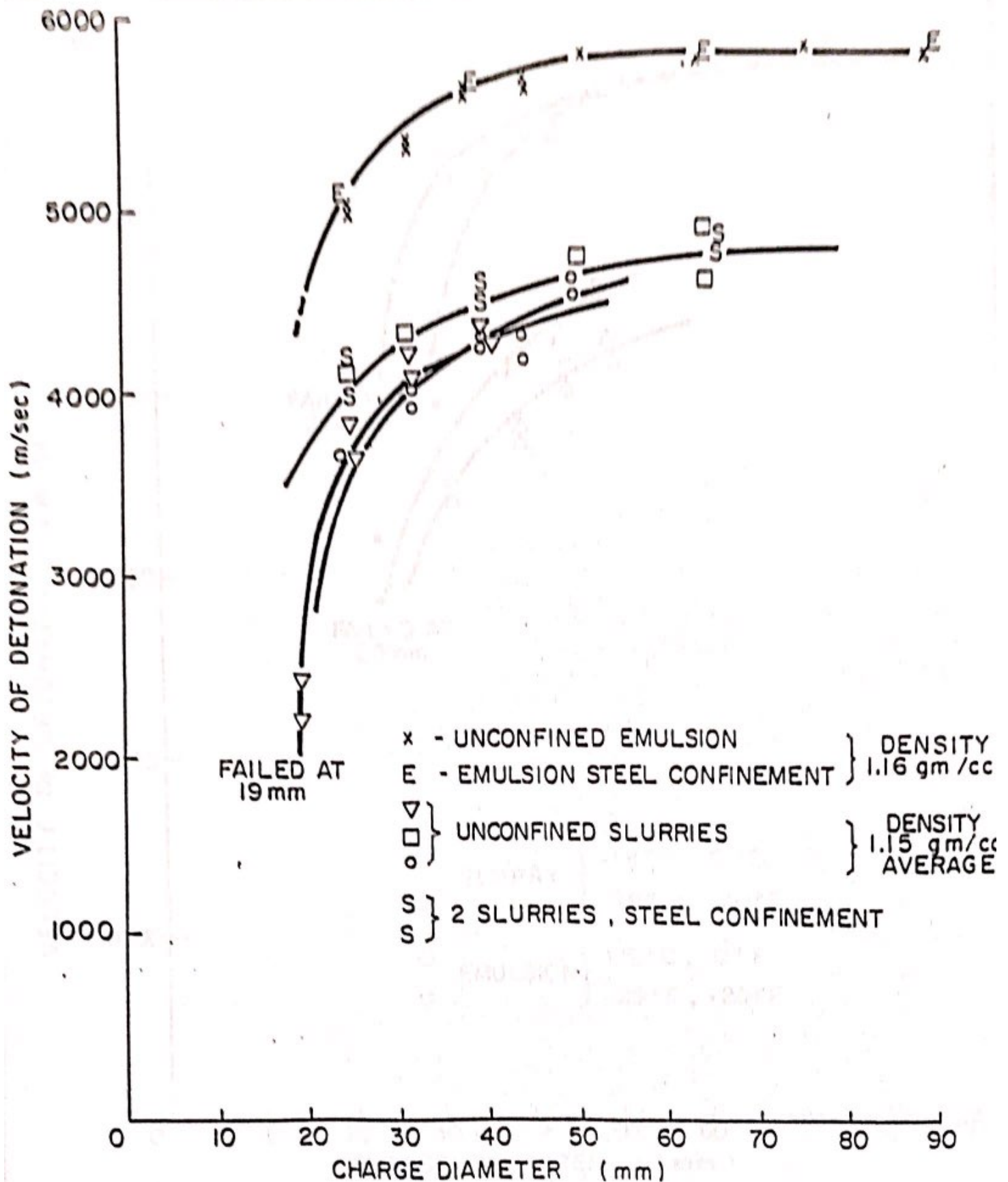


FIGURE 2: CONFINED AND UNCONFINED VELOCITIES OF DETONATION FOR SMALL DIAMETER COMMERCIAL EMULSION AND SLURRY EXPLOSIVES UNDER AMBIENT CONDITIONS (TEMPERATURE = 15 deg. C)

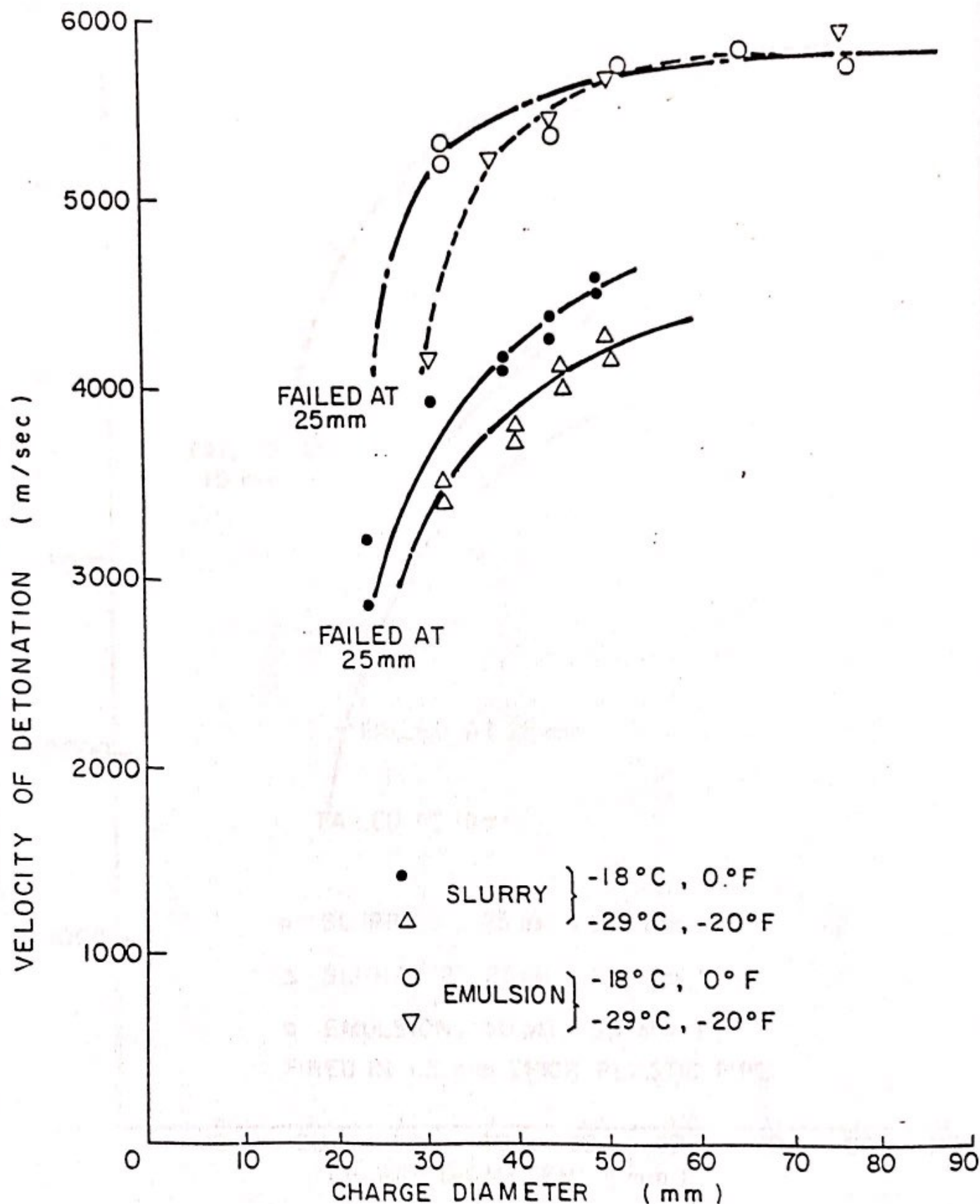


FIGURE 3: UNCONFINED VELOCITY OF DETONATION - CHARGE DIAMETER CURVES FOR SLURRY AND EMULSION EXPLOSIVES AT LOW TEMPERATURES.

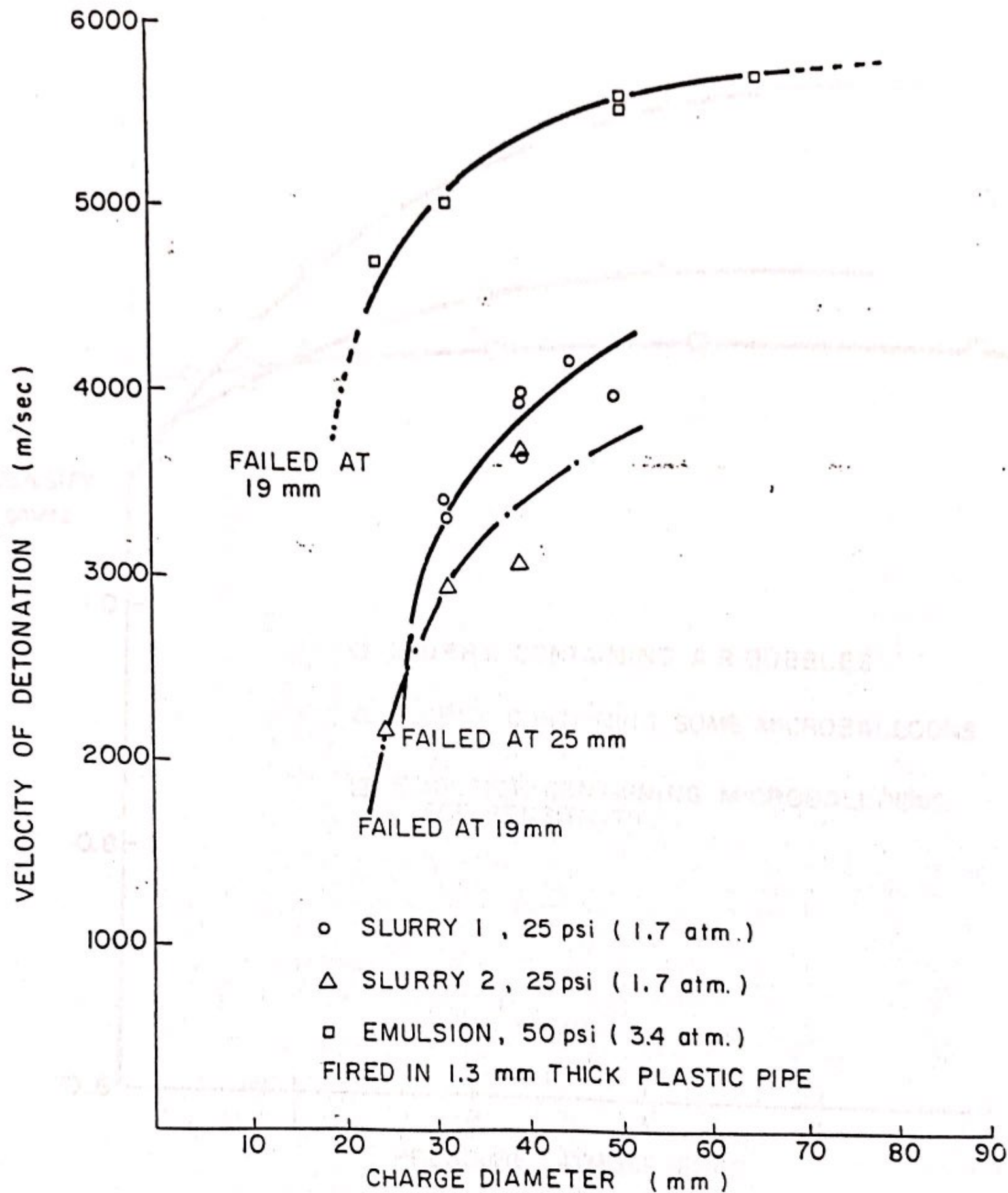


FIGURE 4: UNCONFINED VELOCITY OF DETONATION - CHARGE DIAMETER CURVES FOR SLURRY AND EMULSION EXPLOSIVES AT VARIOUS HYDROSTATIC PRESSURES.

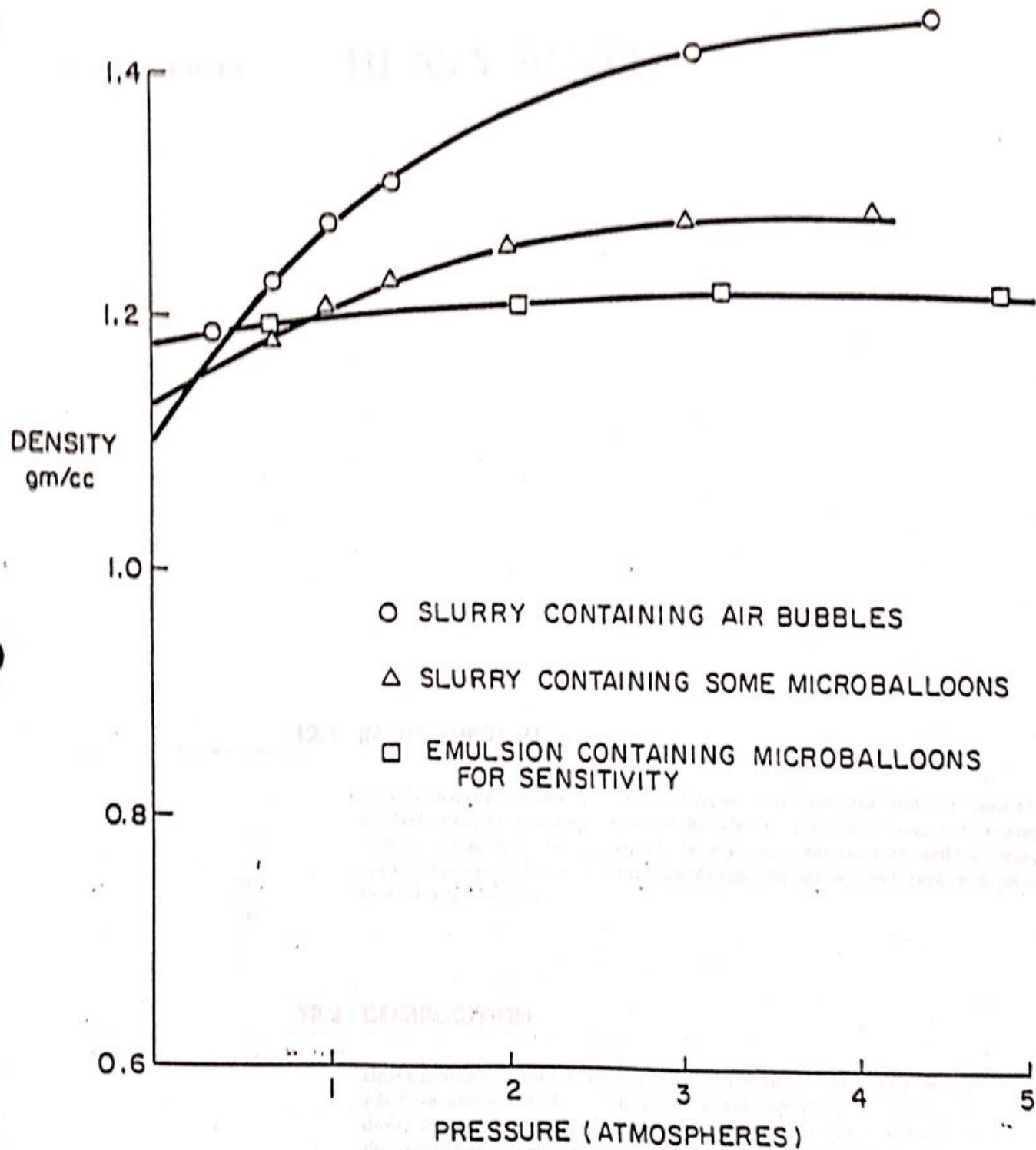


FIGURE 5: PRESSURE DENSITY RELATIONSHIPS FOR EMULSION AND SLURRY EXPLOSIVES.

CHAPTER 12

HEAVY ANFO

12.1 INTRODUCTION

It has been mentioned that dry AN/FO products suffer from poor water resistance and low bulk strengths. One way to increase the bulk strength of the product is by mixing it with various amounts of emulsion. If larger amounts of emulsion are used the product can become water resistant. It is customary to call the mix of ANFO prills with emulsion "Heavy ANFO".

12.2 COMPOSITION

Heavy ANFO products consist of a mix of an emulsion blasting agent with prills of ANFO or Ammonium Nitrate. The percentage of each ingredient varies according to the desirable result. For wet conditions a minimum of 50% emulsion is recommended. For dry applications the percentage of emulsion depends on the bulk strength requirements and on the economics of the operation.

A variety of grades of Ammonium Nitrate prills can be used. The emulsion should have the consistency of a fluid so that it can be mixed with the ANFO prills easily. The main

PERFORMANCE

Ingredients of the emulsion are ammonium nitrate, sodium nitrate, water, fuel oil and an emulsifier. Sometimes Calcium Nitrate is used replacing part of the Ammonium Nitrate and/or Sodium Nitrate. Calcium Nitrate requires a larger amount of Fuel oil than Ammonium Nitrate for the oxygen balanced reaction. This reaction is :



For the oxygen balance one has to use 12.5 % by weight of fuel oil. Emulsions containing calcium nitrate are more water resistant, since they contain more fuel. Furthermore the product becomes more fluid which is desirable for mixing it with ANFO.

Table 1⁽²⁾ shows the chemical composition of a typical Calcium Nitrate Emulsion and the compositions of various water resistant Heavy ANFO products.

It has been found⁽¹⁾ that in heavy ANFO compositions containing large quantities of emulsion, the emulsion must be sensitized by microballoons or air bubbles. Table 2⁽¹⁾ gives the results of a series of tests performed at Queen's. The first part of the table is for unsensitized emulsion added to ANFO and the second part shows the effect of the addition of microballoons to the emulsion. In the case of unsensitized emulsions the detonation velocities were found to be much lower than the theoretical ones. However the situation was greatly improved when sensitization was used. The results clearly demonstrate that sensitization of the emulsion is essential if the resulting product is to perform consistently well at emulsion concentrations higher than 25 %. Figure 1 is a plot of the maximum velocity of detonation versus density of ANFO to which various percentages of unsensitized emulsion have been added. This figure indicates that the maximum percentage of unsensitized emulsion which can be used is approximately 25 %. Beyond this, the decomposition is not completed inside the detonation head. It is obvious that since the detonation pressure is proportional to the square of the detonation velocity, the detonation pressures will be much lower in the case of unsensitized emulsion.

Sensitization of the emulsion can be achieved by using microballoons or by air bubbles which are included in the mass by mixing or by chemical agents. It should be noted that in the case of air bubble sensitization, the product will be susceptible to desensitization by hydrostatic heads due to the change in the density.

12.3 PERFORMANCE

Heavy ANFO compositions have a large bulk strength due to their density. Furthermore if superior performance is required, Aluminum can be added to the product. Table 3⁽²⁾ shows the performance of water resistant heavy ANFO compositions as calculated by the TIGER code by using the JCZ3 equation of state. The emulsion composition used is that of Table 1. The relative bulk strength is also reported in order to compare these formulations to ANFO. In the same manner Table 4 is compiled in order to show the effect of the emulsion content to the energy output of heavy ANFO compositions intended for dry hole applications. It is worth mentioning that the usual way of increasing the bulk strength of ANFO is by using Aluminum. Table 5⁽²⁾ shows the effect of the Aluminum

LOADING

content to the energy output of the composition (reported as bulk strength). It is obvious from the previous that the use of emulsion or Aluminum in ANFO results in an increase of the bulk strength. The economics of the operation will decide which method is preferable.

Today cap sensitive Heavy ANFO products are available for small diameter applications. Heavy ANFO is therefore a very versatile explosive system. By using various blends of ANFO and Emulsion, water resistance, bulk strength, degree of non ideal performance can be altered to suit a great number of blasting applications.

12.4 LOADING

Loading of the product in dry holes can be achieved by using an auger delivery system and drop the product inside the borehole. In wet holes this is not recommended. Tests at Queen's have indicated that the product breaks apart on impact with the water and also it entraps water in the composition. It is recommended that if this method is used the product should be passed through a dryliner which reaches the bottom of the hole where it is open ended. This way the product is loaded from the bottom up and water inclusions are avoided.

Another way of loading wet boreholes is by pumping the product. However in order to do this, the amount of solids has to be reduced to approximately 30 % in the system. This means that the emulsion will have to be sensitized by voids in order to obtain consistent performance.

The two systems of loading are shown in Figure 2⁽²⁾.

12.5 REFERENCES

1. Bauer, A., Heater R., Glynn G. and Katsabanis, P.: "A Laboratory Comparative Study of Slurry, Emulsion and Heavy ANFO Explosives", Proceedings of the Tenth Conference on Explosives and Blasting Technique, Society of Explosives Engineers, Orlando, Florida, 1984.
2. Bauer, A., Crosby, W. and Katsabanis, P.: "Explosives Technology Notes", Mining Resource Engineering Limited, 1986.

**TABLE 1: TYPICAL COMPOSITIONS OF HEAVY
ANFO PRODUCTS (BAUER 1986)**

TYPICAL EMULSION COMPOSITION	
INGREDIENT	WEIGHT %
Ammonium Nitrate	38.4
Calcium Nitrate	35.8
Water	13.0
Fuel Oil	10.8
Emulsifier	2.0

TYPICAL WATER RESISTANT HEAVY ANFO COMPOSITIONS	
INGREDIENT	WEIGHT %
Ammonium Nitrate	59.1
Calcium Nitrate	19.7
Water	7.2
Fuel Oil	5.9
Emulsifier	1.1
Aluminum	7.0
	61.1
	19.7
	7.2
	5.9
	1.1
	5.0
	64.1
	19.7
	7.2
	5.9
	1.1
	2.0
	66.1
	19.7
	7.2
	5.9
	1.1
	0.0

**TABLE 2: CONFINED VELOCITIES OF DETONATION FOR
HEAVY ANFO COMPOSITIONS WITH UNSENSITIZED AND
SENSITIZED EMULSION**

ANFO	WEIGHT % EMULSION	DENSITY (g/cc)	VELOCITY OF DETONATION (m/s)	THEORETICAL VOD (m/s)
100	0	0.83	5000	5100
80	20	1.01	4630	5470
70	30	1.10	4330	5700
60	40	1.23	4400	6300
50	50	1.30	4300	6460
WITH 1.6 % microballoons				
80	20	1.0	5730	5370
70	30	1.1	5640	5700
60	40	1.2	6340	6220
55	45	1.2	5700	6280
50	50	1.25	5670	6340

**TABLE 3: THEORETICAL PROPERTIES OF WATER RESISTANT
HEAVY ANFO COMPOSITIONS**

COMPOSITION	WEIGHT %			
Emulsion	55	55	55	55
AN	38	40	43	45
Al	7	5	2	0
density	1.40	1.40	1.40	1.40
VOD (m/s)	6920	6907	6880	6860
Relative				
Bulk Strength	1.65	1.57	1.45	1.37

TABLE 4: THEORETICAL PROPERTIES OF HEAVY ANFO COMPOSITIONS FOR DRY BOREHOLES

COMPOSITION	WEIGHT %		
Emulsion	15	20	30
AN	85	80	70
density	0.98	1.03	1.16
VOD (m/s)	5300	5440	5860
Relative Bulk Strength	1.11	1.14	1.24

Strengths relative to ANFO at a density of .83g/cc

TABLE 5: STRENGTHS OF AL/ANFO AND HEAVY ANFO PRODUCTS

EXPLOSIVE	DENSITY (g/cc)	RELATIVE WEIGHT STRENGTH	RELATIVE BULK STRENGTH
ANFO	0.83	1.0	1.0
5% Al/AN/FO	0.87	1.13	1.18
7% Al/AN/FO	0.88	1.18	1.25
10% Al/AN/FO	0.91	1.24	1.36
ANFO + 20% Emulsion	0.98	0.96	1.13
+ 30% Emulsion	1.10	0.92	1.22
+ 40% Emulsion	1.20	0.91	1.32

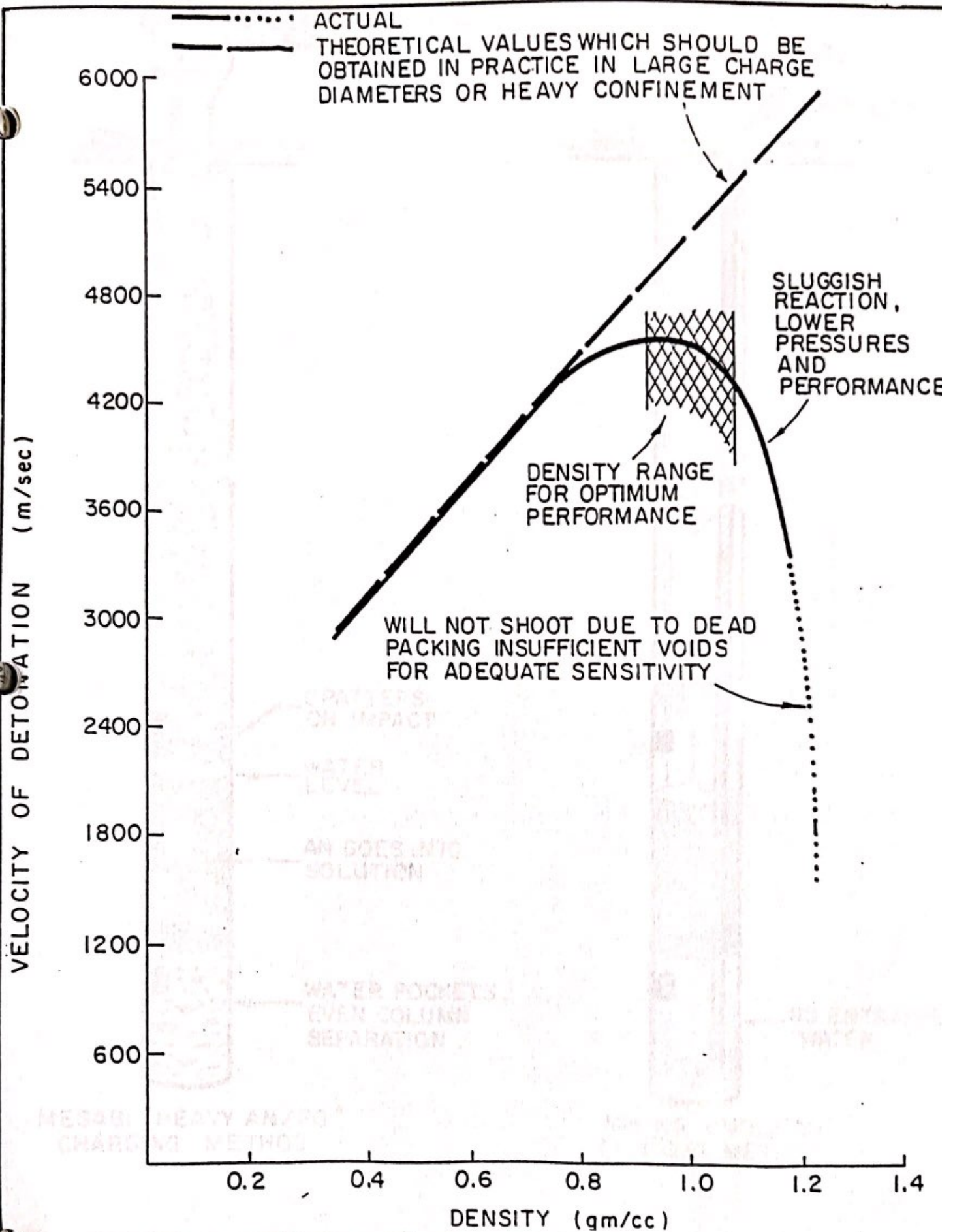


FIGURE 1: VELOCITY OF DETONATION AS A FUNCTION OF DENSITY FOR AN/FO AND AN/FO PLUS UNSENSITIZED EMULSION.

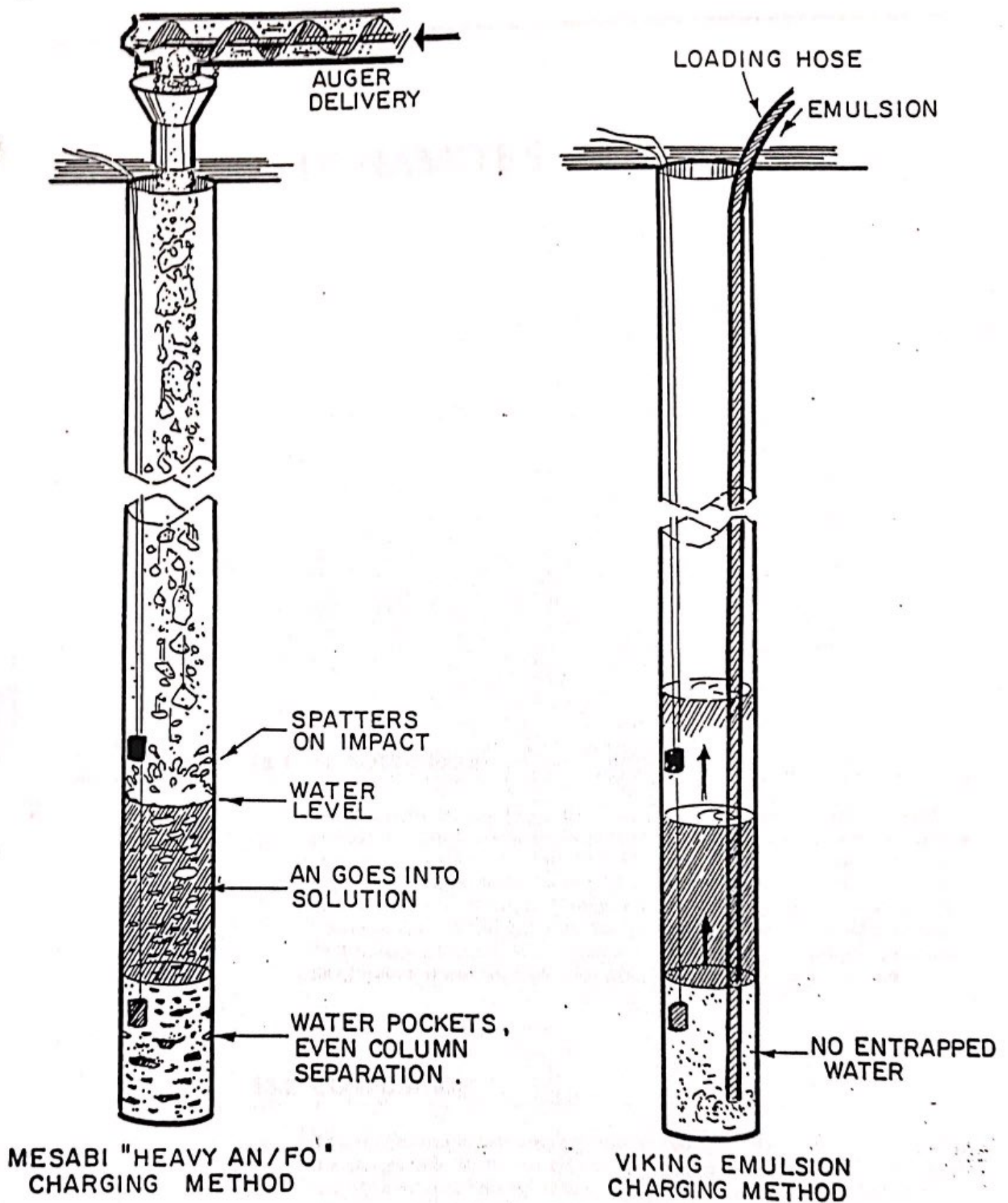


FIGURE 2: METHODS OF LOADING HEAVY AN/FO PRODUCTS (AFTER BAUER, 1986).

CHAPTER 13

DYNAMITES

13.1 STRAIGHT DYNAMITE

13.1 INTRODUCTION

The class of dynamites is the oldest class of commercial explosives. Although safer products are available, dynamites are still used, especially in underground coal mines as permitted explosives and in the construction industry. The main advantage of dynamites is their flexibility. Dynamites can be manufactured to possess high velocities of detonation, excellent water resistance, function under high hydrostatic pressures or under very low temperatures. The first dynamite was invented in 1844 by Alfred Nobel. It utilized 75 % Nitroglycerin and 25 % kieselguhr (diatomaceous earth). Kieselguhr (powdered SiO_2) is however inert and it was soon substituted by Sodium Nitrate and wood.

13.2 COMPOSITION

Today's dynamites include a large number of ingredients. The most important of them are nitroglycerin, nitroglycol, nitrocellulose, oxidizing salts and fuels. The liquid portion of the dynamites is a mix of nitroglycerin and nitroglycol. Both of them are referred to as NG. Normally nitroglycol is the largest part since it is cheaper, has a better heat stability and a lower freezing point.

The NG content of the dynamite varies from 5 % to 90 % of the composition. In addition to NG nitrocellulose and other ingredients are used.

Nitrocellulose serves as a gelling or thickening agent and gives water resistance to the product. In addition it binds the liquid ingredients and prevents exudation of nitroglycerin⁽¹⁾.

The rest of the ingredients are fuels and oxidizing salts which are included in a variety of percentages. Normally Ammonium Nitrate and Sodium Nitrate are used as oxidizers and starches, wood dusts, sulphur and vegetable gums are used as fuels. Salts are also used in permissible dynamites as it is indicated in Chapter 12.

By varying the various ingredients a large number of dynamites can be created. Figure 1⁽¹⁾ indicates how the various categories of dynamites are related.

13.3 STRAIGHT DYNAMITE

Straight dynamites come directly from Nobel's invention. They contain a large percentage of explosive oil (nitroglycerin and nitroglycol) and they are graded by the percentage of NG they contain. A typical 40 % straight dynamite has the following composition⁽²⁾:

weight %

Nitroglycerin + Nitroglycol	40 %
Sodium Nitrate	44 %
Antacid	2 %
Carbonaceous material	14 %

The role of the antacid is to stabilize the NG.

Straight dynamites normally have high densities high velocities of detonation, good water resistance and low detonation temperatures. However they have poor fume characteristics unless they are oxygen balanced. Also they are very sensitive to shock and friction. Because of their high cost their industrial use is declining.

13.4 AMMONIA DYNAMITES

Ammonia dynamites come from straight dynamites in which a large percentage of NG has been substituted by Ammonium Nitrate. A typical formulation of an Ammonia dynamite is shown in the following⁽²⁾:

BLASTING GELATIN

weight %

Nitroglycerin + Nitroglycol	14 %
Ammonium Nitrate	36 %
Sodium Nitrate	39 %
Antacid	1 %
Carbonaceous material	10 %

Ammonia dynamites are less sensitive than straight dynamites, they have lower densities and lower velocities of detonation. They have a good heaving action in blasting but they are desensitized by wet conditions due to the hygroscopicity of ammonium nitrate.

13.5 BLASTING GELATIN

Blasting gelatin is the strongest form of explosive used industrially. It consists of Nitroglycerin and Nitroglycol mixed with 7% Nitrocellulose to form a gel. The mix has excellent water resistance properties but poor fumes and poor safety characteristics.

13.6 GELATIN DYNAMITES

Gelatin dynamites or straight gelatins are similar to straight dynamites, except that the explosive oil (nitroglycerin and nitroglycol) has been colloided with nitrocellulose to form a gel⁽²⁾. A typical straight gelatin has the following composition⁽²⁾:

weight %

Nitroglycerin + Nitroglycol	40.0 %
Nitrocellulose	1.0 %
Sodium Nitrate	44.2 %
Sulphur	6.2 %
Calcium Carbonate	1.4 %
Carbonaceous material	7.2 %

The composition is varied to alter the density, energy output and oxygen balance. The product has excellent water resistance and it can have high velocities of detonation and pressures.

13.7 AMMONIA GELATIN

Ammonia gelatin dynamites are similar to the corresponding ammonia dynamites except for the addition of nitrocellulose to NG. A typical formulation is shown in the following:

weight %

Nitroglycerin + Nitroglycol	26.2 %
Nitrocellulose	0.4 %
Ammonium Nitrate	8.5 %
Sodium Nitrate	49.6 %
Fuel	8.9 %
Sulphur	5.6 %
Antacid	0.8 %

Ammonia dynamites have similar properties to the gelatin dynamites. Furthermore they are cheaper and have good fume characteristics. However they have somewhat lower velocities of detonation and detonation pressures and less resistance to water.

13.8 SEMIGELATIN DYNAMITE

The semigelatin dynamite is between the high density ammonia dynamites and the ammonia gelatins. They have a somewhat better performance than ammonia dynamites under wet conditions and they are less expensive than ammonia gelatins.

13.9 REFERENCES

1. Atlas Powder Company: "Explosives and Rock Blasting", Atlas Powder Company, Field Technical Operations, 1987.
2. Bauer, A.: "Explosives Technology Notes", Department of Mining Engineering, Queen's University, 1981.

FIGURE 1: DYNAMITES (ATLAS POWDER Co., 1987)

