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LOW AMPLITUDE SHOCK INITIATION OF COMMERCIAL EXPLOSIVES

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ABSTRACT

This paper describes a study into the low amplitude shock initiation of three explosives using experimental and theoretical techniques. Experimentally these explosives were tested using a modified gap test to determine the pressure threshold to initiation for each. This gap test is similar to the method used by Tasker and Kroh. The free surface velocity of the acceptor plate is recorded as a function of the thickness of the plexiglas attenuator. The results of these tests are used to determine the pressure threshold for the onset of shock to deflagration and deflagration to detonation transition.

In order to compare these test values, the pressure profile and particle velocity profile under the shock wave for the threshold of these explosives were calculated by Lagrangian Code. From the pressure profiles, the critical energies for the explosives were obtained by evaluating the integral of pressure profile of the shock wave in the acceptor and particle velocity profile [p(t)Up(t)dt]. To determine the performance of these explosives, Tiger Code calculations have been carried out for detonation pressure, detonation velocity and Gurney velocity.

The explosives used in this study consisted of pressed RDX/WAX (90/10) which was used as a standard, a slurry explosive and an emulsion explosive. These commercial products are typical small diameter mining explosives with both containing less than 5% aluminum.

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INTRODUCTION

The Canadian Explosives Research Laboratory regularly evaluates commercial explosives for authorization under the Canada Explosives Act. As part of the evaluation process safety characteristics such as impact sensitivity and shock sensitivity are evaluated. Low velocity impacts or low amplitude shock waves can be a cause of a violent event which can lead to a major catastrophy, for example, in a transportaation accident. For this purpose the sensitivity of commercial products to low amplitude shock waves was examined experimentally and theoretically. The effort was concentrated in establishing the low amplitude impact sensitivity of commercial explosives by using calibrated gap tests. In addition, knowledge of both the sensitivity and performance enables us to find commercial explosives with high performance and low sensitivity. Such explosives include slurry and emulsion explosives.

This paper describes theoretical and experimental investigations which were conducted on two types of commercial explosives to obtain shock sensitivity and performance data.

BACKGROUND

The process of shock impact can lead to a deflagration or detonation. The shock wave, if it is strong enough will shock initiate the explosive and deflagration to detonation transition can occur. In order to determine shock to detonation transition, projectile tests on slurry and emulsion explosives were conducted previously (1). A series of tests were conducted by varying projectile velocity and diameter. Aluminum projectiles were fired from a cannon towards targets of explosive. The projectile diameters used were 2.5 cm, 5.1 cm, 10.2 cm and 15.4 cm. The explosives were tested unconfined and confined in steel tubes. The projectile velocity was calculated by reading the time interval for passage of the projectile between two light sensors placed a known distance apart in front of the explosive target. The impact was observed by a high speed camera having a writing speed of 3000 frame per second. Thus the detonation or failure of the target was determined. The experimental set up is shown in Figure 1. The results of the tests are shown in Table 1. The results conclude that the slurry and emulsion explosives tested did not detonate from low velocity impact under unconfined conditions and that it was a case of shock to detonation transition.

PROPERTIES OF EXPLOSIVES

Three explosives were tested by the above technique to obtain the threshold to initiation. These explosives were pressed RDX (90% RDX, 10% WAX) and, a slurry at density of 1.15 g/cc and an emulsion at density of 1.15 g/cc. The waxed RDX was used as a standard because of the reproductibiity of the acceptor charges. The slurry and the emulsion products were typical cap sensitive commercial explosives. Both of

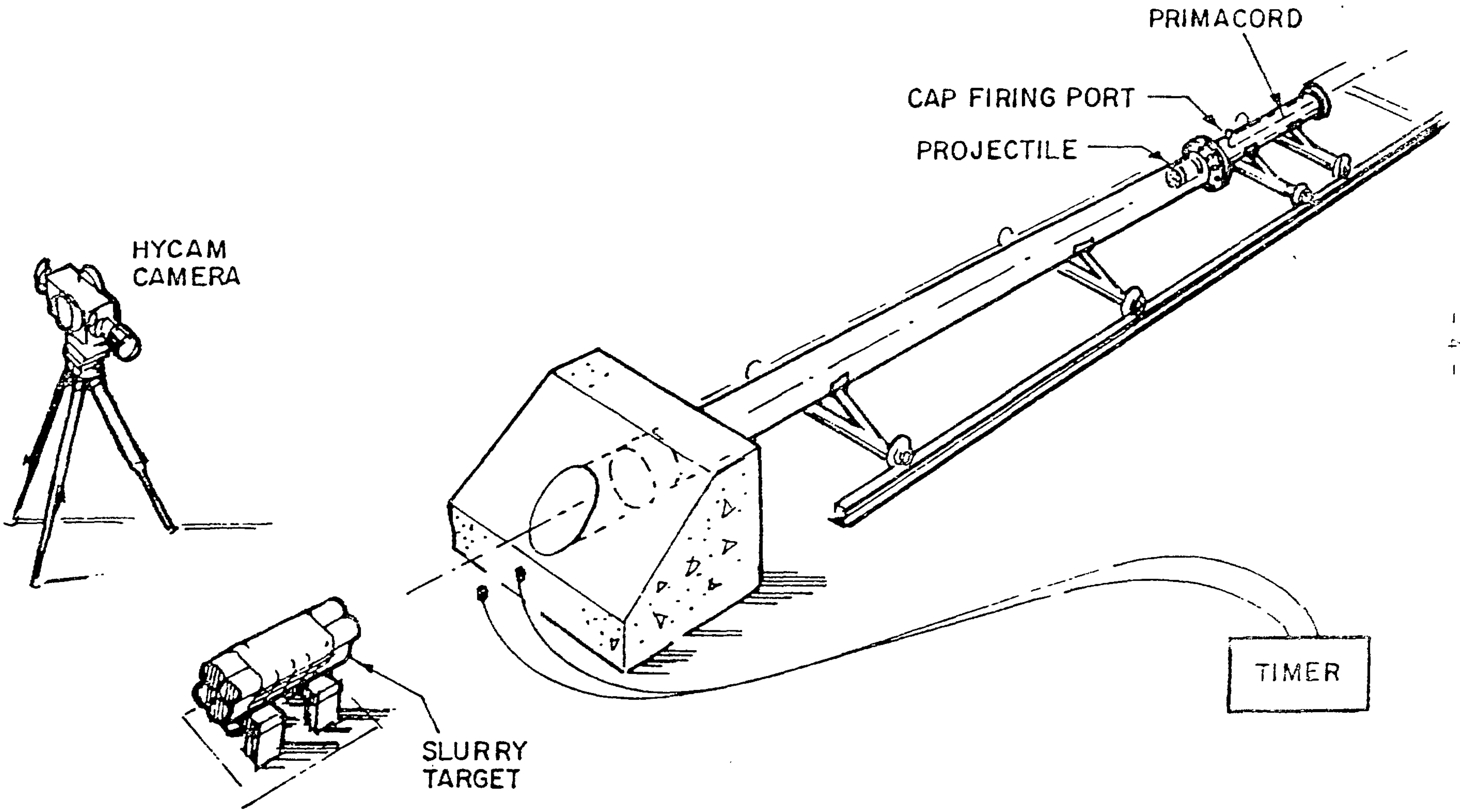

FIGURE 1 : EXPERIMENTAL ARRANGEMENT FOR THE PROJECTILE TESTS.

TABLE 1 : PROJECTILE IMPACT TEST RESULTS FOR SLURRY AND EMULSION EXPLOSIVES

Explosives	Slurry A					Slurry B			Emulsion
Projectile dia. (mm)	25	25*	50	100	152	25	50	152	25
Projectile Length (mm)	50	50	100	150	152	50	100	152	50
Projectile Velocity (m/s)									
33			F						
132					F				
219			F						
296	F								
315								F	
330		F		F					
337		D		F			F		F
342					F				F
344			F	F	D				
347	F		D/F						
350			D	D			F		
356		D							
358							D	F	
363		D			D				
369								D	
380									F
396									
410		D							
417									F
421	F	D							
444	D					F			
460						D			F
537	D								F

* CONFINED IN 50 mm STEEL PIPE

them are used in small diameter applications and they contain a small amount of aluminum (less than 5%). The major components of the slurry explosive used are ammonium nitrate, calcium nitrate, ethylene glycol, aluminum and water, the major components of the emulsion explosive used are ammonium nitrate, sodium nitrate, calicum nitrate, aluminum, water and oil.

The slurry uses air bubbles in order to achieve the desirable sensitivity. The air bubbles vary in size from a few microns to a few millimeters. The emulsion uses glass microballoons with an average size of 70 microns. The pressure of the gas inside the microballoons is normally below the atmospheric pressure.

Further differences in the two products are found in their physical characteristics. In the slurry, the discontinuous phase consists of fuels and oxidizer salt crystals and the continuous phase is the oxidizer solution.

In the emulsion, the continuous phase is the oils while the discontinuous phase consists of the oxidizer salt solution. There are no crystals in the emulsion and the mix is much more intimate than in the case of the slurry.

CALIBRATED GAP TESTS

From the projectile impact data, it is apparent that the results apply to a transition to detonation and not initiation to deflagration which may not result in detonation. For this reason a modified gap test was used to provide data for low amplitude shock initiation. The test is similar to the one implemented by Tasker [2], Liddiard [3] and Kroh [4].

The experimental set up is shown in Figure 2. The test consisted of a donor charge, an attenuator plate, an acceptor charge and an Argon filled light bomb. The free surface velocity of the acceptor plate is recorded as a function of the thickness of the plexiglas attenuator. The donor is made of three disks of pressed RDX (90% RDX, 10% Wax). Each disk has a diameter of 7.64 cm and a height of 2.54 cm. The density of the charge is 1.55 g/cc. The attenuator is made of square plates of plexiglas with dimensions of 17.8 cm X 17.8 cm. The block of plexiglas is normally polished so that it is transparent. The acceptor has the same diameter as the donor and a height of 2.54 cm and it is place in such a way that they have a common axis of symmetry. Donor, attenuator and acceptor are glued without air bubbles. The charge is placed exactly perpendicular to the slit of the streak camera.

The donor is initiated by a 10 g PETN primer and the event is recorded by using a streak camera. The slit of the camera is placed at the centre of the charge, parallel to the axis of symmentry of the charge. At a specific time the light bomb is detonated to produce the back light necessary for the shadowgraphic streak camera techniques. From the cutoff of this light, as the shock wave passes through the plexiglas,

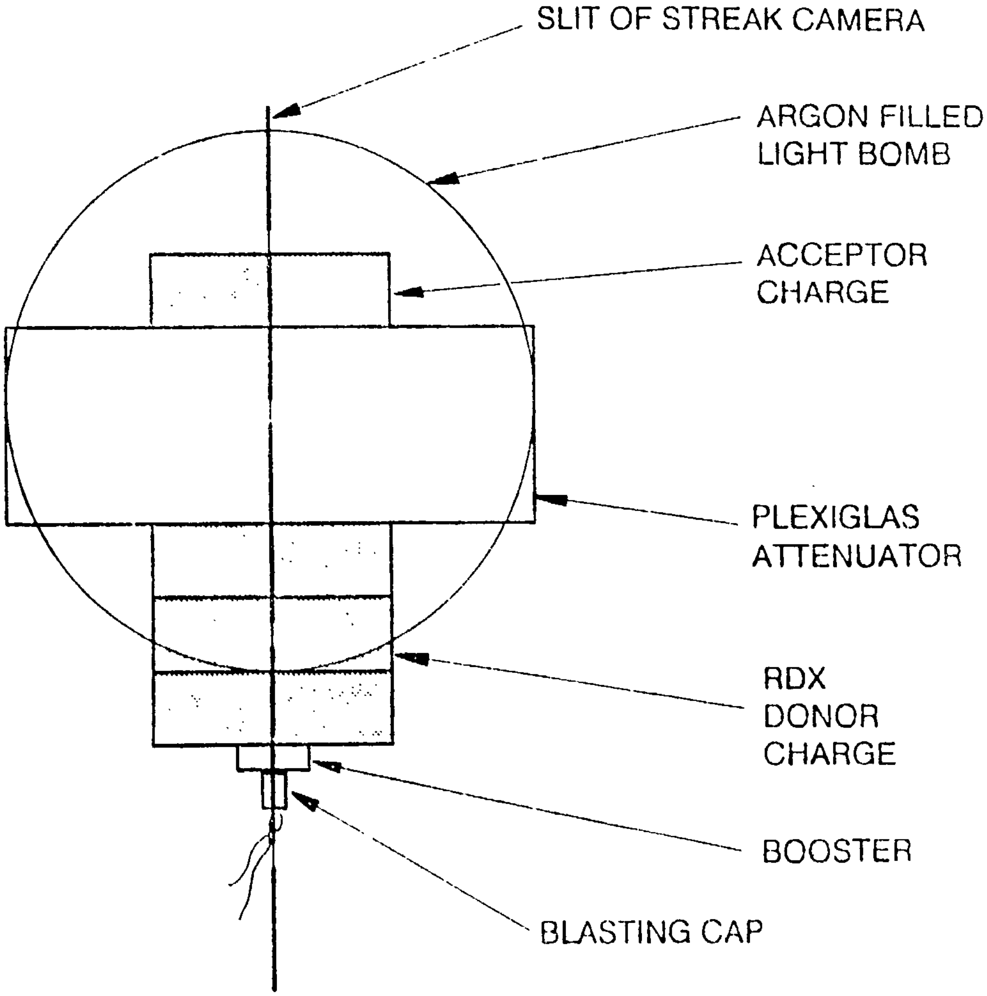

FIGURE 2 : EXPERIMENTAL ARRANGEMENT OF THE CALIBRATED GAP TESTS.

it is possible to obtain the shock velocity in the plexiglas attenuator as a function of thickness of the plate. Furthermore when the shock wave reaches the free surface of the acceptor, it moves it, producing a cutoff of light. From the slope of this line, the free surface velocity can be measured. If the acceptor detonates, a bright flash is normally seen in the streak camera record. Streak camera records of a calibrated gap test for RDX/WAX, Slurry A and Emulsion A are shown in Figures 3, 4 and 5 respectively.

INTERPRETATION OF EXPERIMENTAL RESULTS

The results of the calibrated gap test are reported as free surface velocity vs impact pressure curves which indicate the thresholds to deflagration and detonation. In order to obtain these curves it is necessary to calculate the pressure in the plexiglas attenuator as a function of the thickness of the attenuator for the case of the shock provided by the standard donor. The calculation steps are as follows:

a) From the streak camera records, the shock velocity in the plexiglas can be obtained at various points of the attenuator. The relationship between shock velocity and thickness is shown in Figure 6.

b) From the shock velocity and the Hugoniot of the plexiglas ($Us=2430+1.5785xUp$), the particle velocity can be calculated.

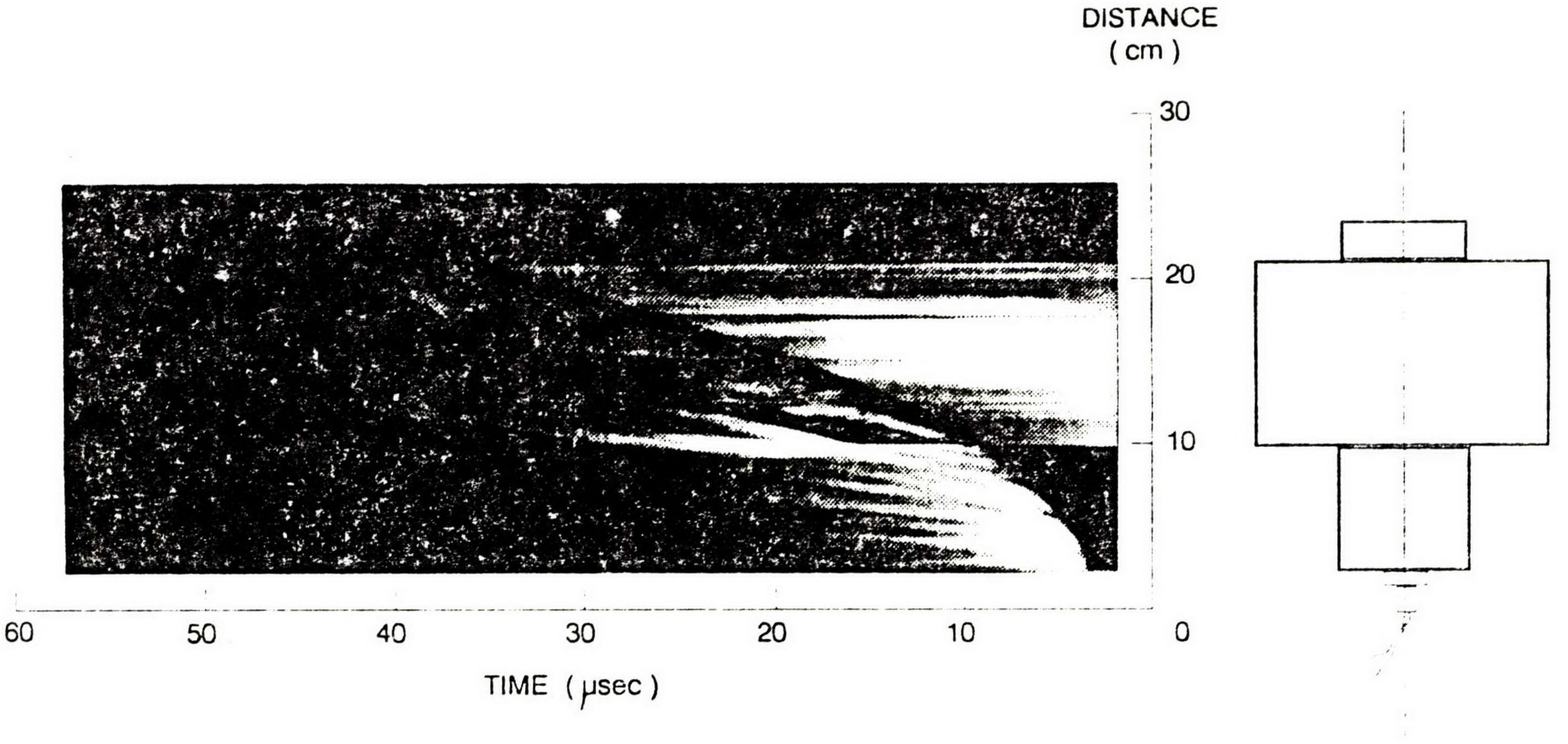

FIGURE 3 : STREAK CAMERA RECORD OF A CALIBRATED GAP TEST FOR WAXED RDX.

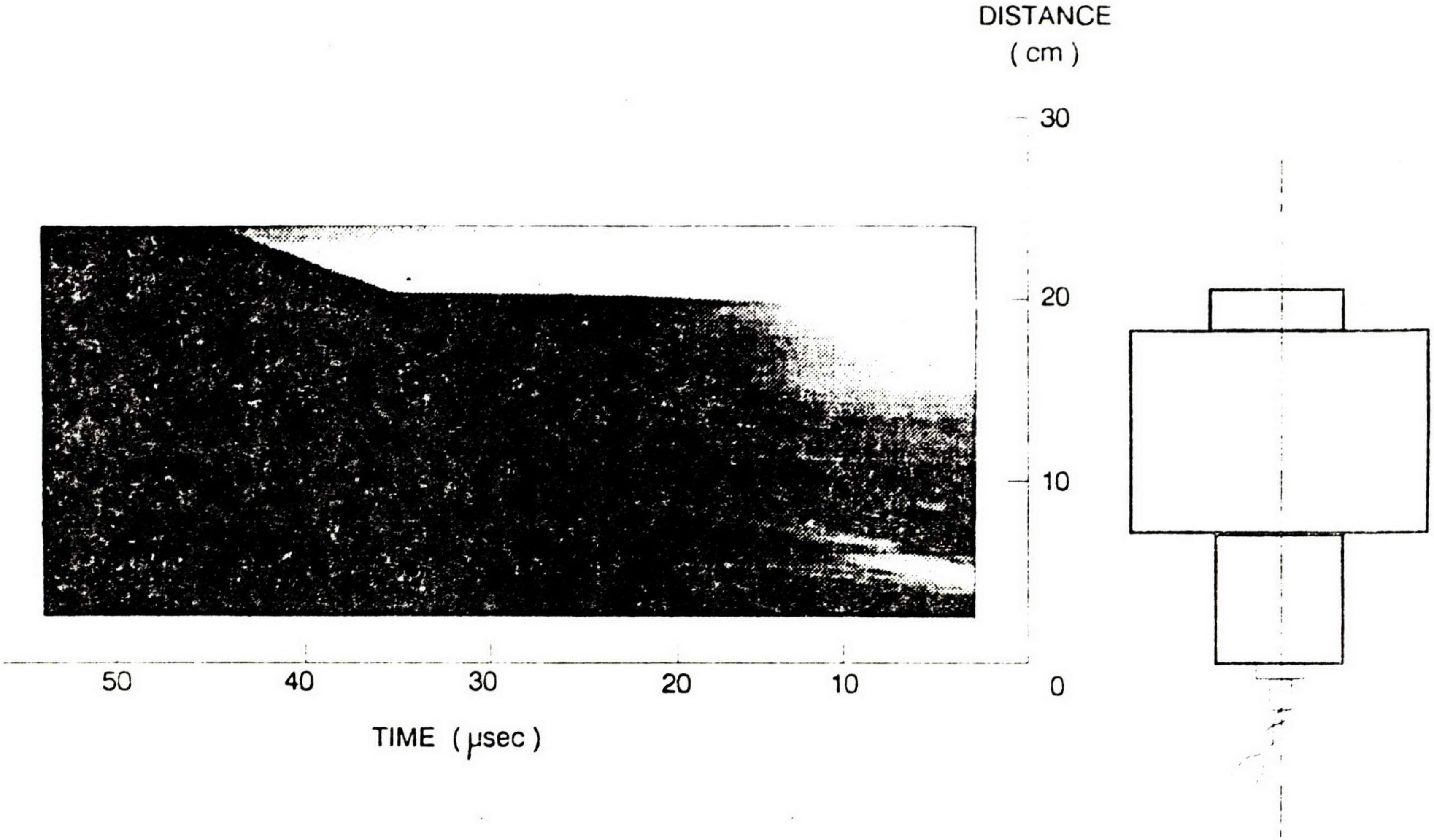

FIGURE 4 : STREAK CAMERA RECORD OF A CALIBRATED GAP TEST FOR SLURRY A.

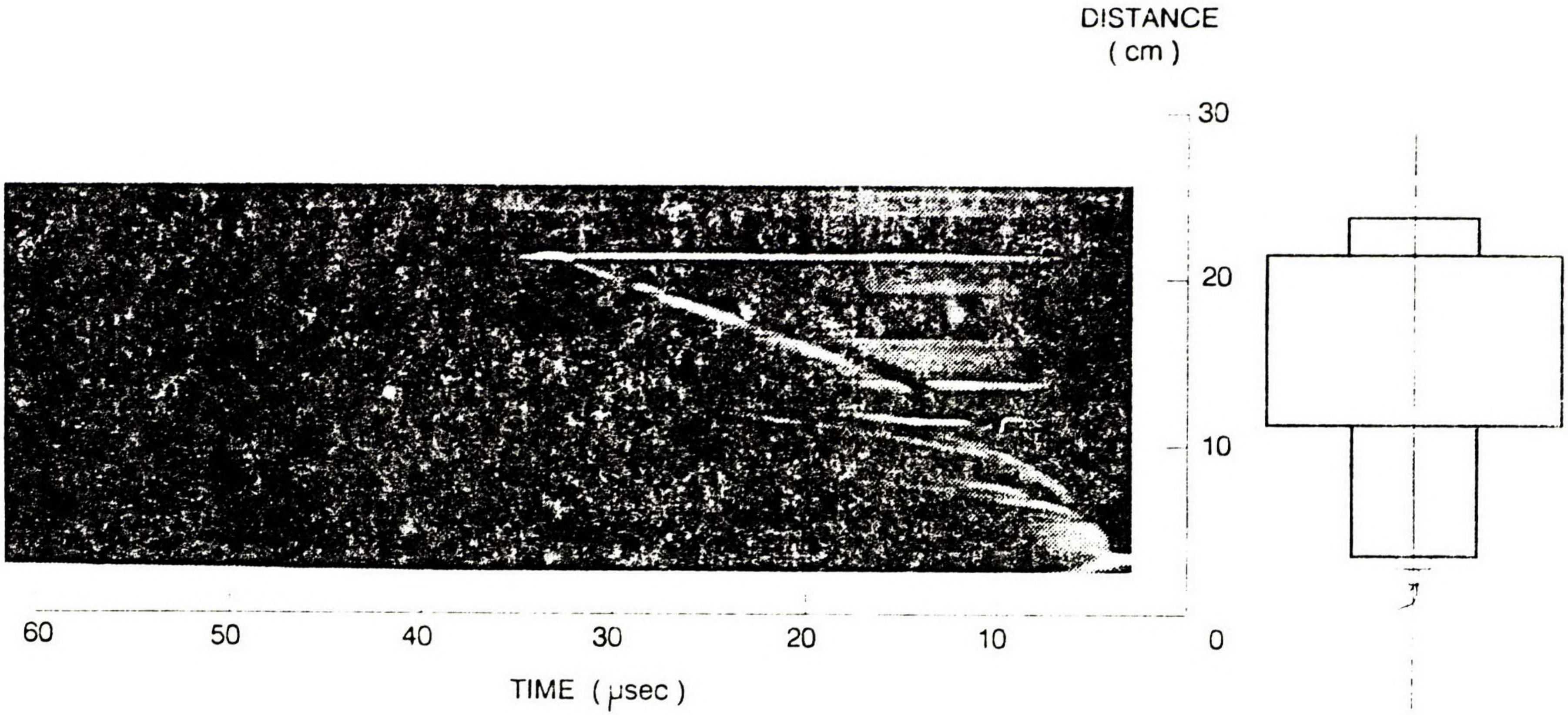

FIGURE 5 : STREAK CAMERA RECORD OF A CALIBRATED GAP TEST FOR EMULSION A.

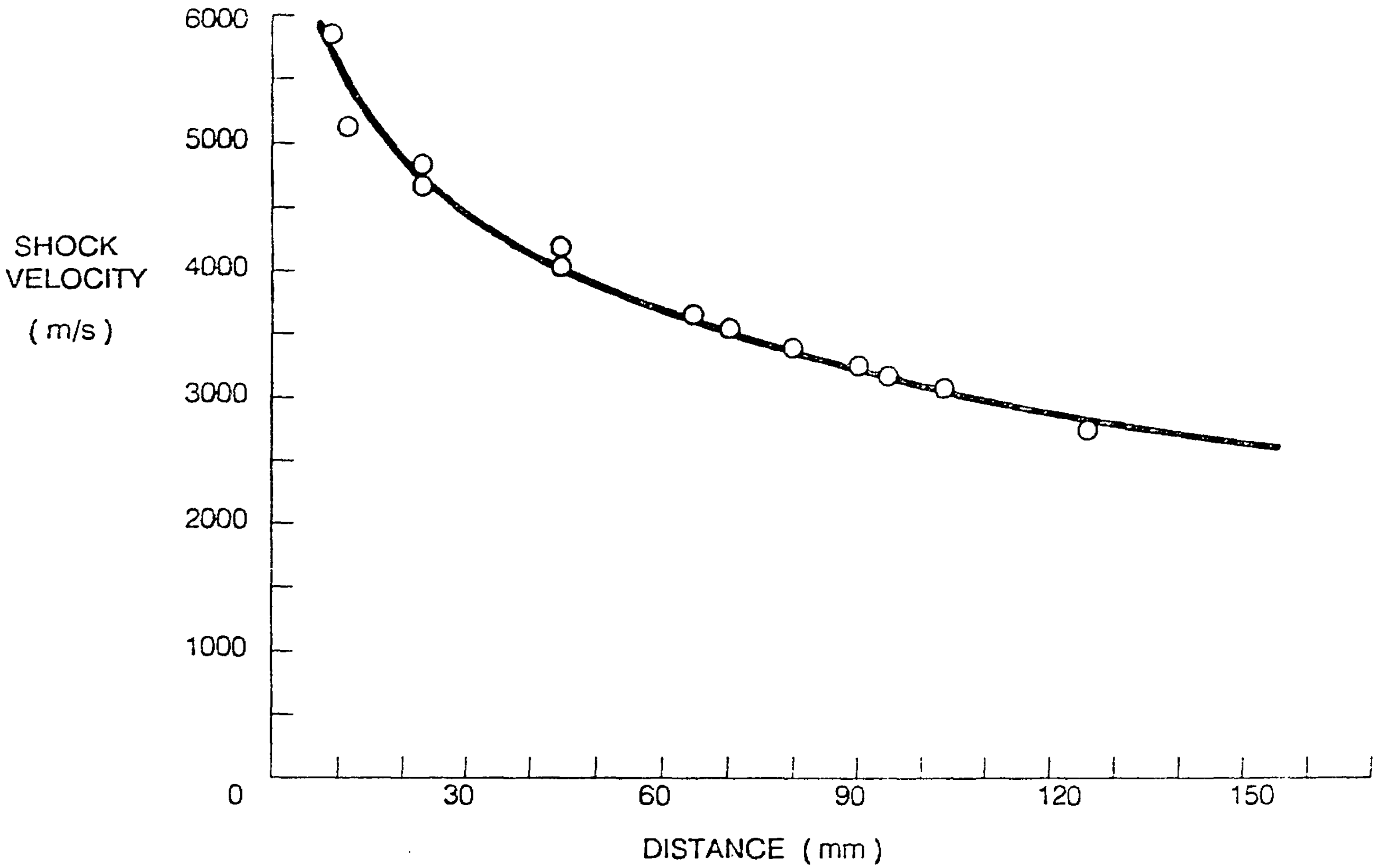

FIGURE 6 : SHOCK VELOCITY VERSUS PLEXIGLAS THICKNESS FOR THE CALIBRATED GAP TEST.

c) The pressure in the plexiglas can be calculated from the density, shock velocity and particle velocity, ($P = \rho UpUs$).

The relationship between pressure in the plexiglas and the plexiglas thickness is shown in Figure 7.

The initial pressure in the explosive can be caluculated if the Hugoniot of the unreacted explosive is known. It is assumed that the pressure and particle velocity are the same on both sides of the attenuator - explosive interface. Since the shock pressure and the particle velocity in the attenuator are known, the pressure P and the particle velocity Up in the explosive are found by reflecting the attenuator Hugoniot along the line Up = constant, and finding the intersection of this curve and the line provided by the Hugoniot of the explosive . The process is illustrated in Figure 8.

Hugoniots of explosives were estimated based on values from previous work (5), (6). The particle velocity of the unreacted explosive is half of the free surface velocity of the acceptor. The pressure of the unreacted explosive can be estimated from the Hugoniot for the explosive and the momentum conservation equation. $P_i = \rho\,(CUp + SU^2p.)$

RESULTS

The experimental results for waxed RDX are shown in Figure 9. Figure 10 shows the relationship between the

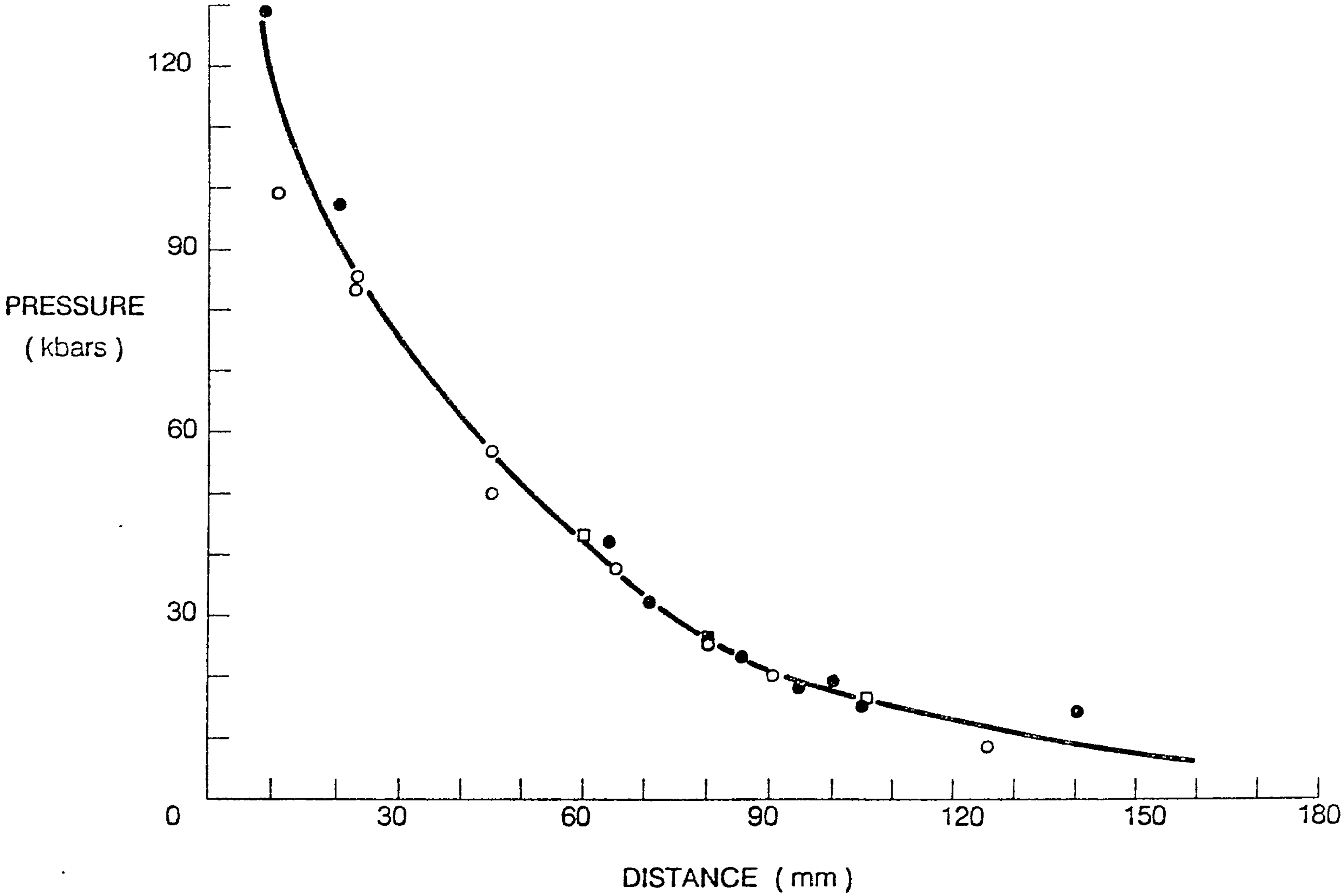

FIGURE 7 : ATTENUATION OF THE SHOCK WAVE PRODUCED BY THE DONOR IN THE CALIBRATED GAP TEST.

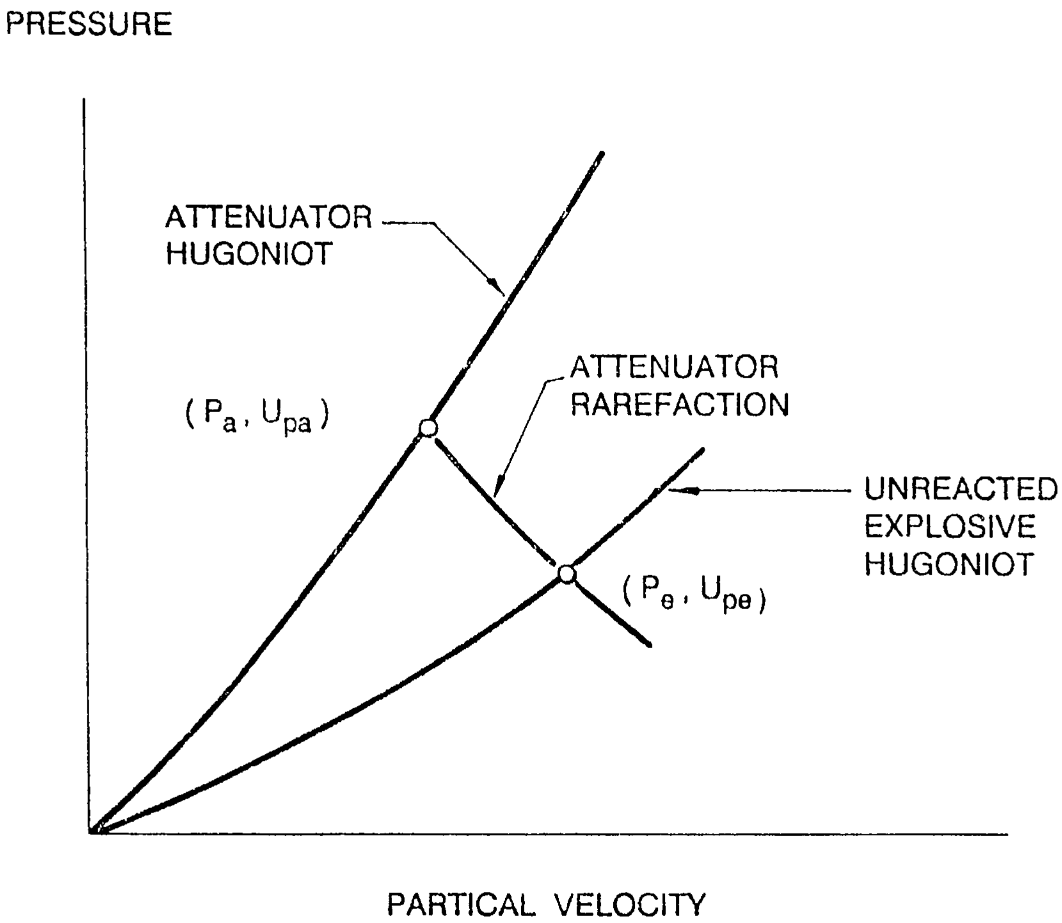

FIGURE 8 : GRAPHICAL METHOD OF OBTAINING SHOCK PRESSURE AND PARTICAL VELOCITY IN UNDER-INITIATED EXPLOSIVE.

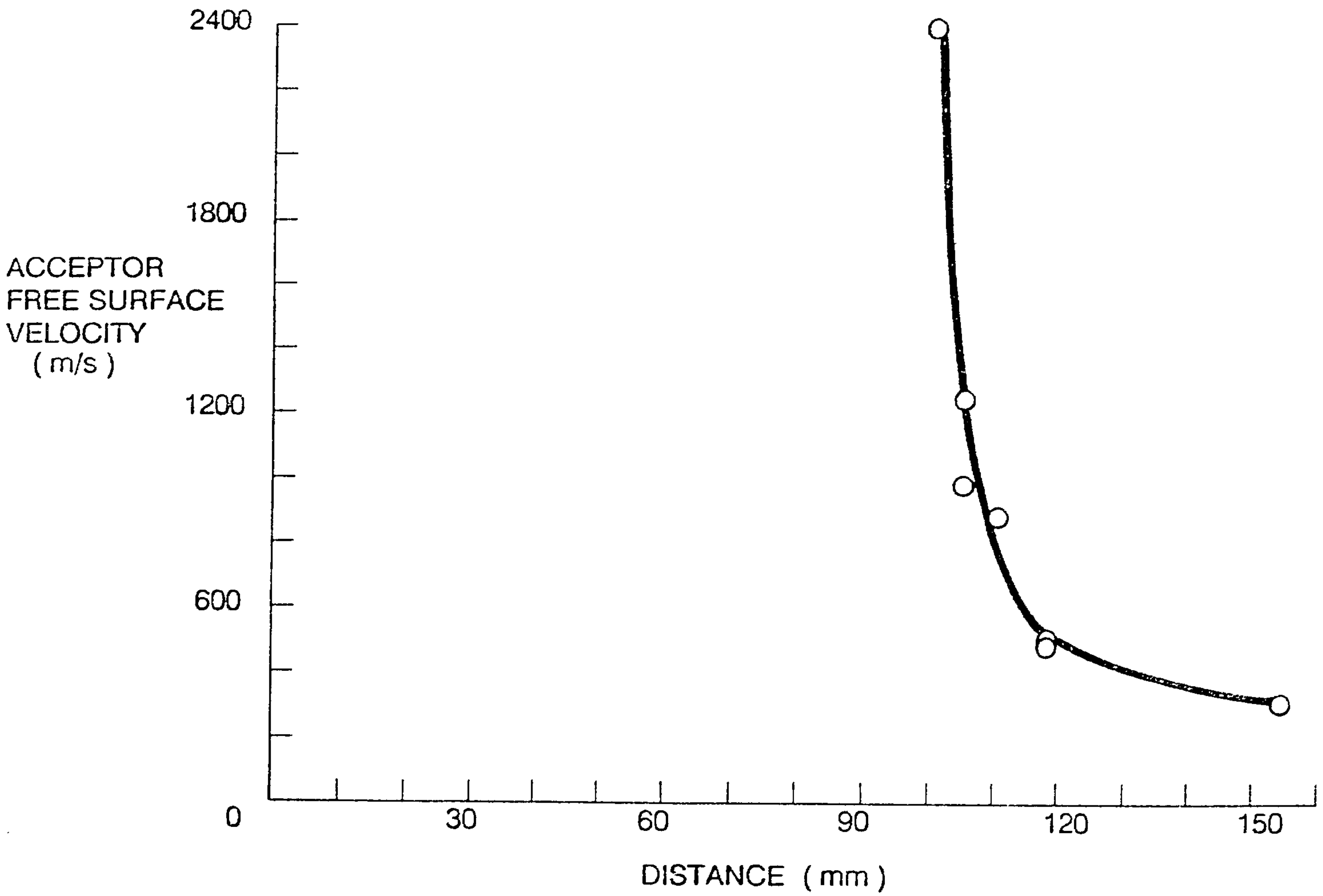

FIGURE 9 : ACCEPTOR FREE SURFACE VELOCITY VERSUS PLEXIGLAS THICKNESS FOR WAXED AND PRESSED RDX.

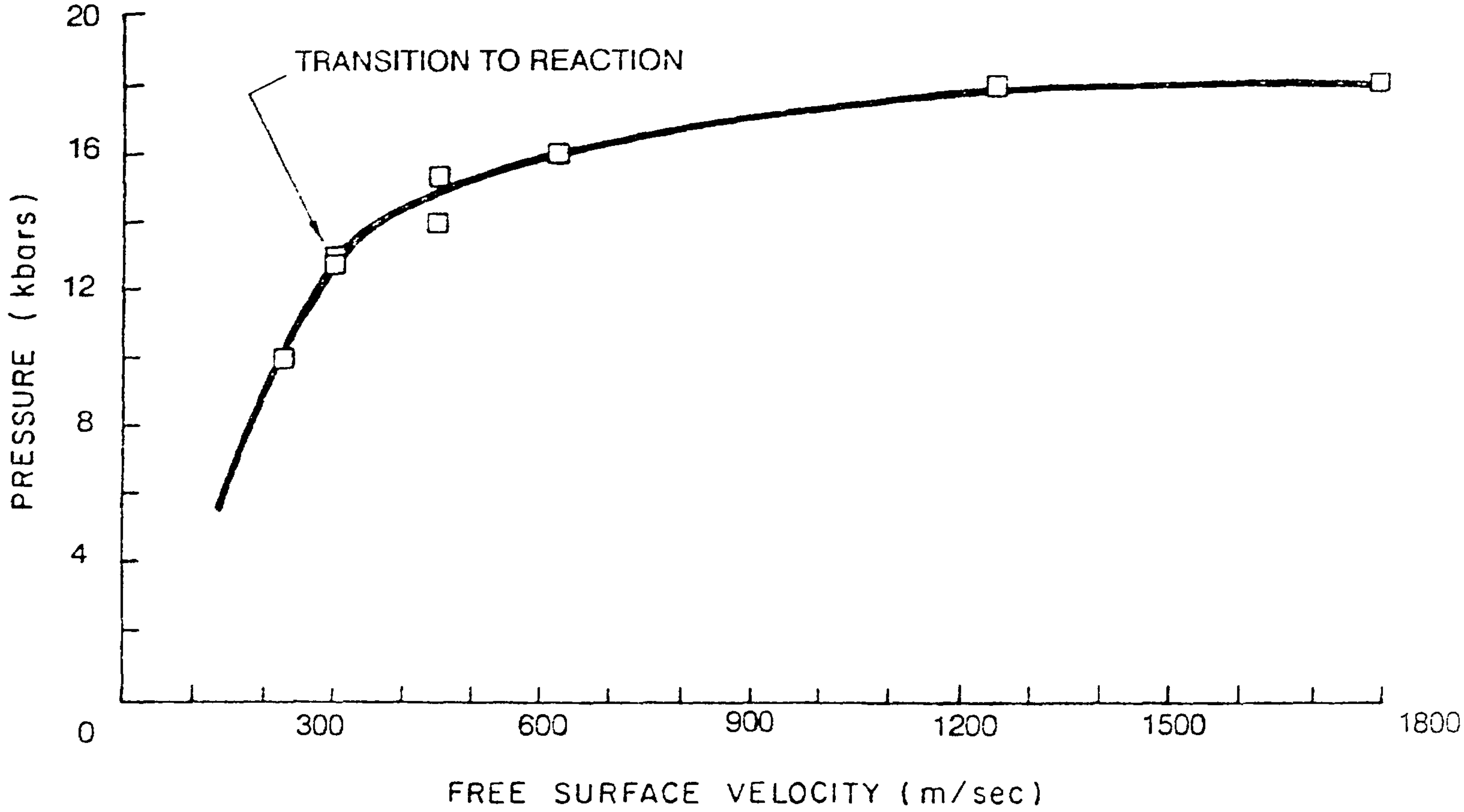

FIGURE 10 : PRESSURE VERSUS FREE SURFACE VELOCITY FOR WAXED RDX

plexiglas shock pressure and acceptor free surface velocity for waxed RDX. It follows that the trigger initiation threshold is at a plexiglas thicknesss of 115 - 125 mm or at a shock pressure in the plexiglas of between 11 and 13 kbars.

The experimental results for Slurry A are shown in Figure 11. Figure 12 illustrates the relationship between plexiglas shock pressure and acceptor free surface velocity. The trigger initiation threshold is at a thickness of 135 - 145 mm or a shock pressure in the plexiglass of between 10 and 15 kbars.

The experimental results for the emulsion explosive are plotted as plexiglas thickness - acceptor free surface velocity and plexiglas shock pressure - acceptor free surface velocity curves in Figures 13 and 14 respectively. The trigger initiation threshold is at a thickness of 105-115 mm or at shock pressure in the plexiglas of 13-15 kbars. The experimental work shows that a threshold to initiation could be found in all three explosives tested. These results are summarized in Table 2.

TABLE 2 : RESULTS OF MODIFIED GAP TESTS

Explosive	Density g/cm^3	Trigger Initiation Threshold (kbar)	Detonation Threshold (kbar)
Slurry A	1.15	10.2	30.33
Emulsion A	1.15	13.15	23.25
Waxed RDX	1.55	11.13	18.20

CRITICAL ENERGY CALCULATION

The gap test values of the critical pressure for initiation are dependent not only on the chemical composition and the physical properties of the acceptor charge, but also on the dimensions of the tests. A donor of different dimensions will produce different impulses and an acceptor of a different diameter will also change the pressure-time profile inside the acceptor charge. Obviously, the threshold values given represent only the test described previously. As such the test is good only for comparative purposes. In order to obtain values which are not dependent on the geometry, the pressure profile has to be considered. This can be performed by calculating the critical energy for initiation and detonation (7), (8), (9), (10).

In order to evaluate the computer code calculations, the calculated results were compared to available experimental data. Hence, the relationship between plexiglas pressure and plexiglas thickness for the standard donor was used. Figure 15 illustrates both the experimental and the calculated curves. The agreement is good. Figure 16 shows pressure histories for various points along the axis of symmetry of the experiment. The critical energy in calculated as $Ecr = \int PU_p dt$ where p is the pressure, Up is particle velocity, t is the time duration. This is the time until the particle velocity vector has a direction opposite to the direction of the propagation of the initial shock wave created by the impact.

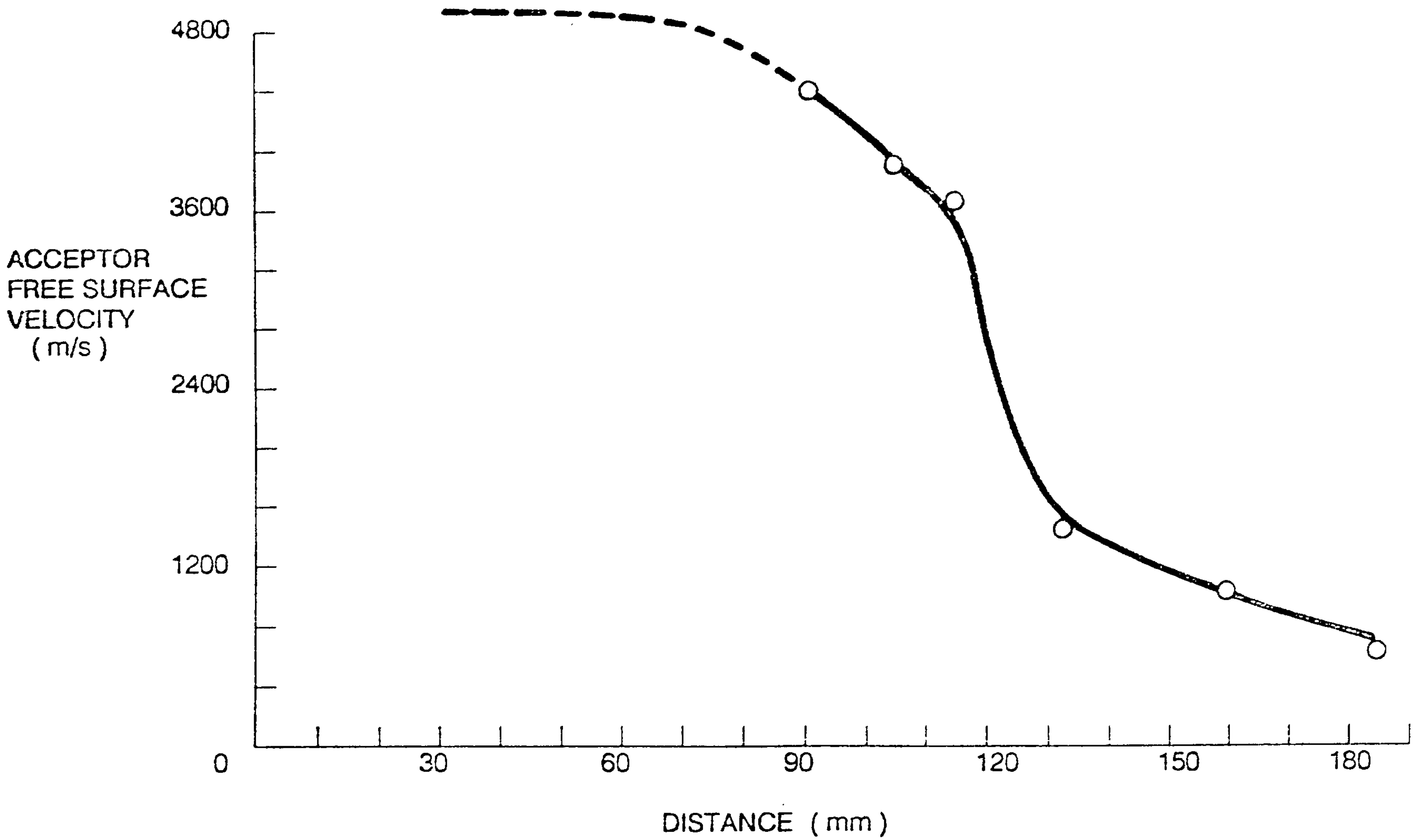

FIGURE 11 : ACCEPTOR FREE SURFACE VELOCITY VERSUS PLEXIGLAS THICKNESS FOR SLURRY A.

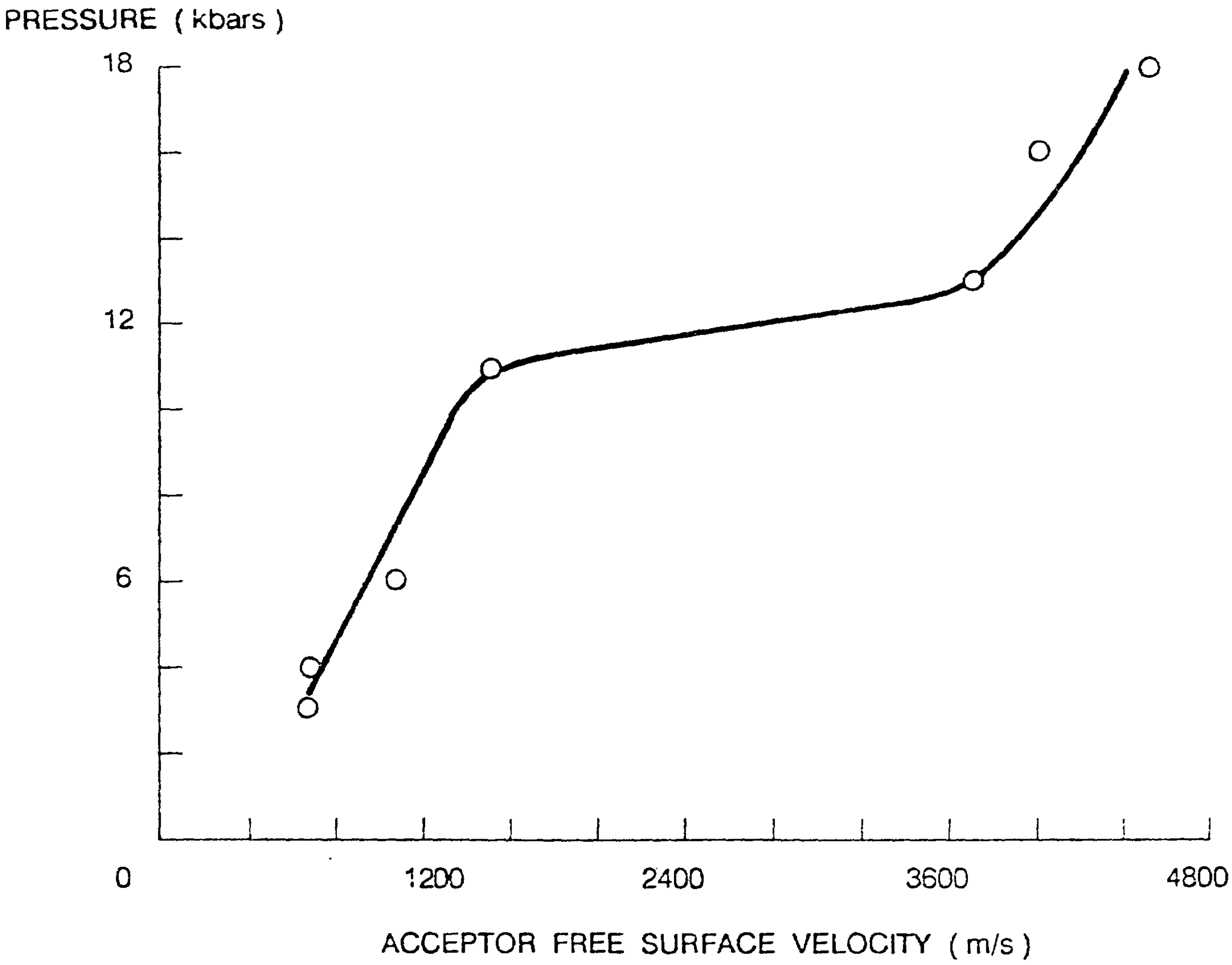

FIGURE 12 : PRESSURE VERSUS FREE SURFACE VELOCITY FOR SLURRY A.

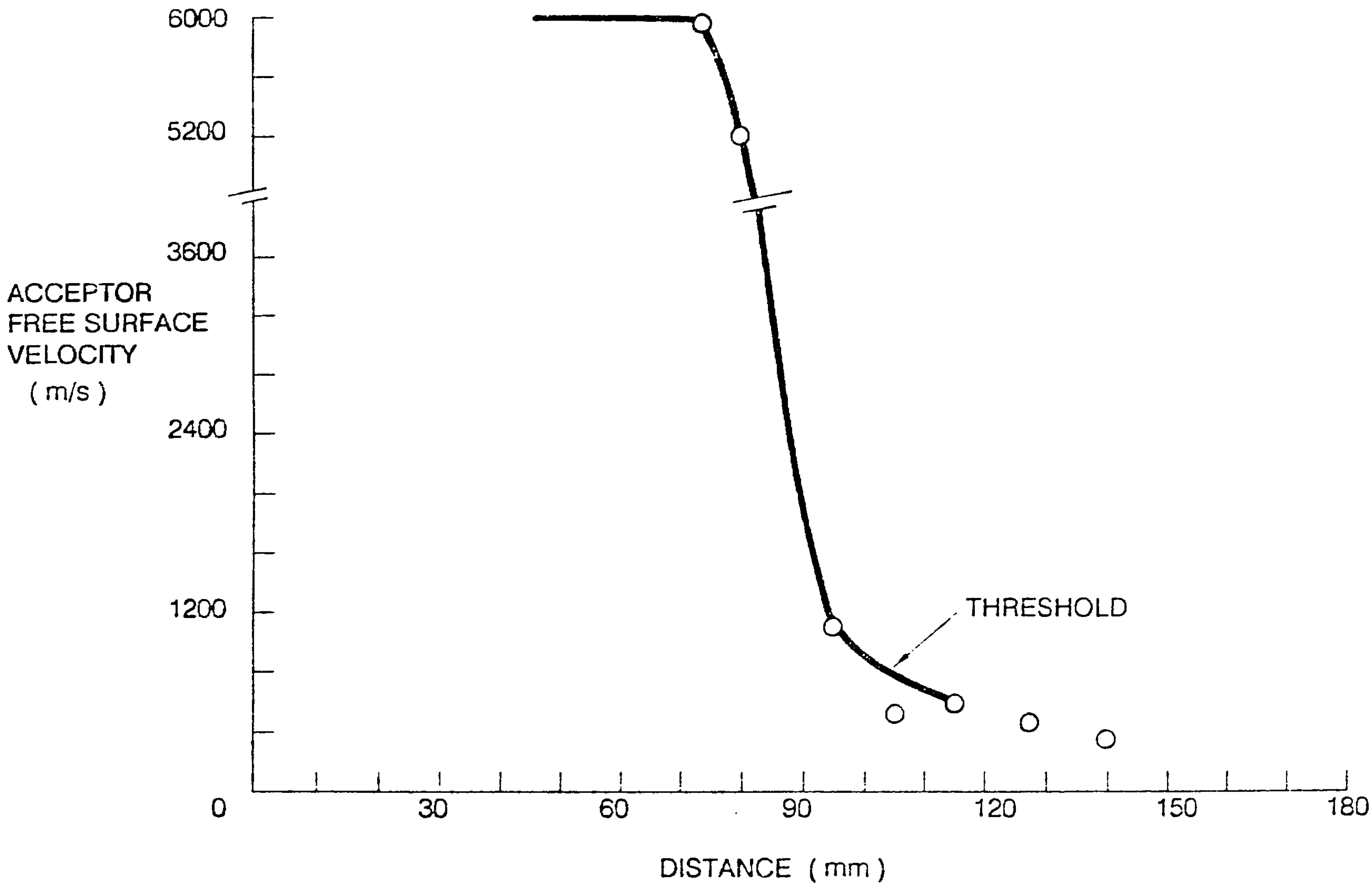

FIGURE 13 : ACCEPTOR FREE SURFACE VELOCITY VERSUS PLEXIGLAS THICKNESS FOR EMULSION A.

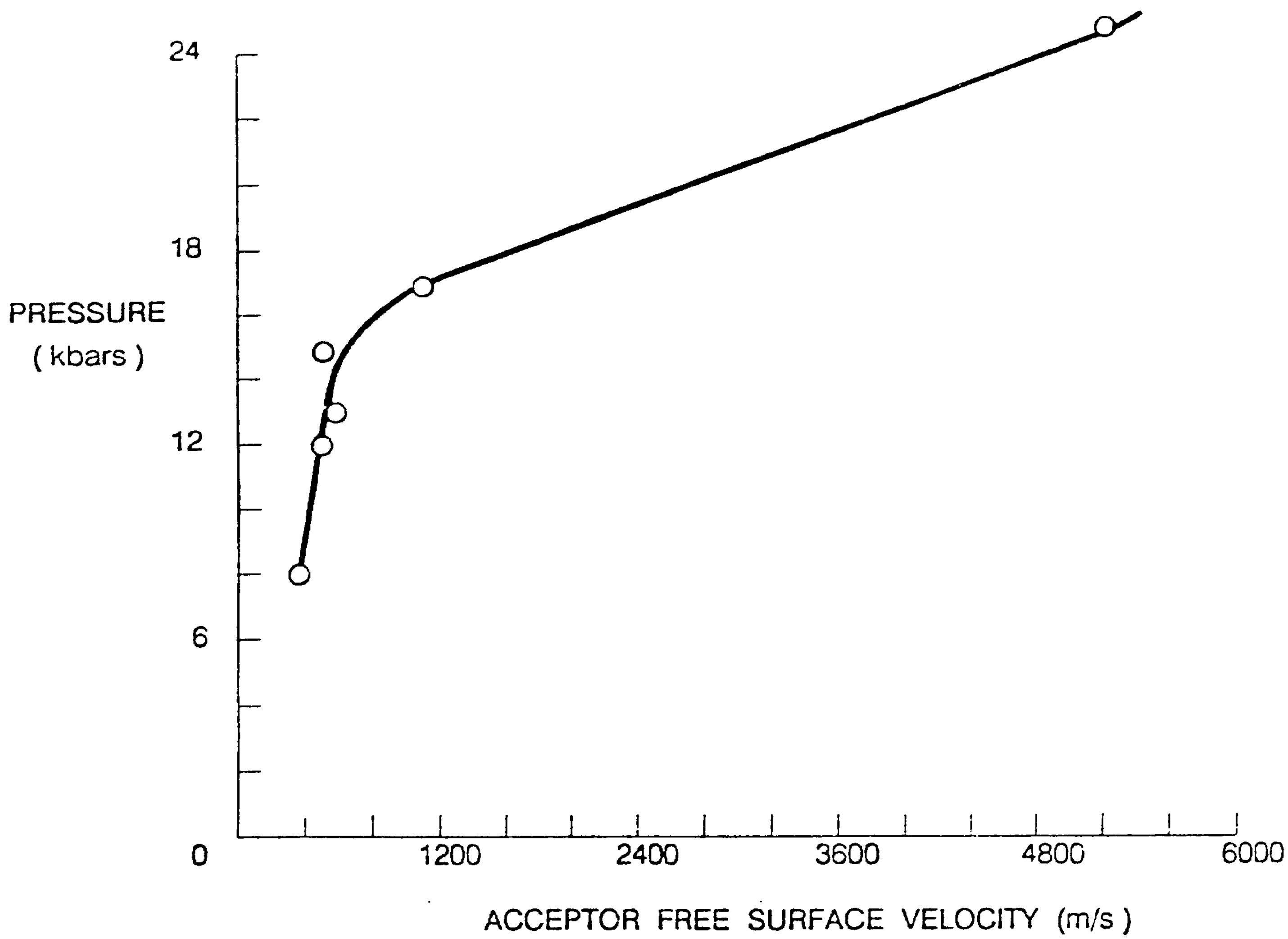

FIGURE 14 : PRESSURE VERSUS FREE SURFACE VELOCITY FOR EMULSION A.

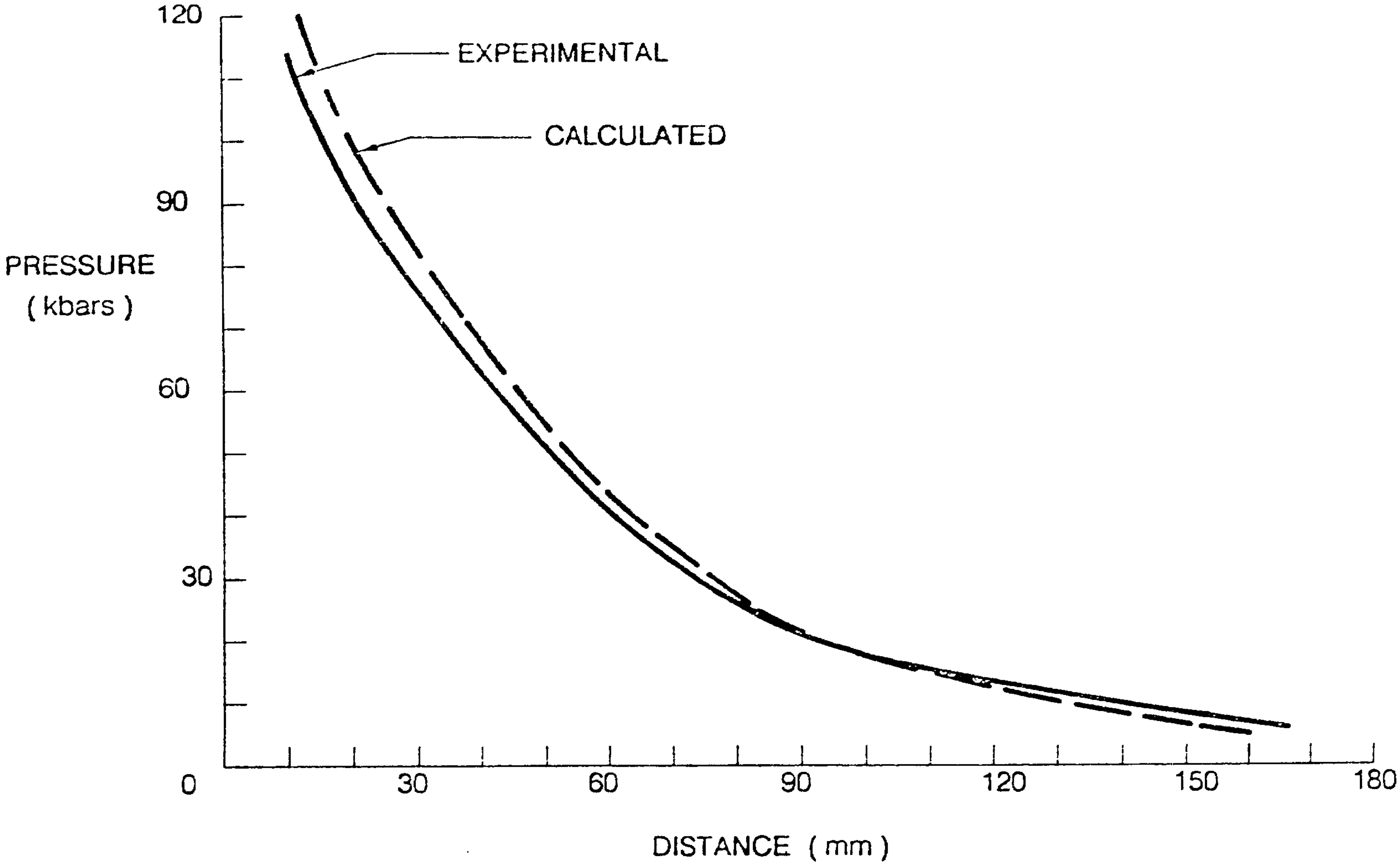

FIGURE 15 : EXPERIMENTAL AND CALCULATED CURVES SHOWING PLEXIGLAS PRESSURE AS A FUNCTION OF DISTANCE IN THE CALIBRATED GAP TEST.

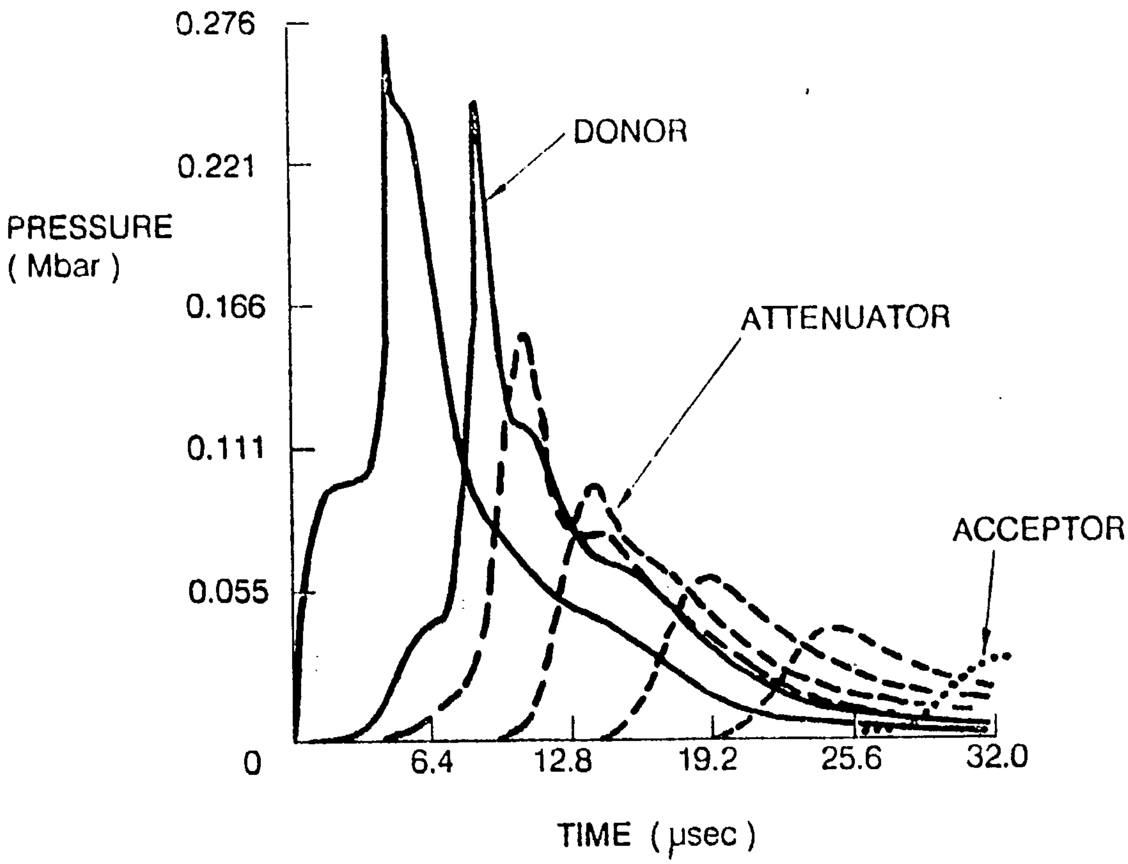

FIGURE 16 : TYPICAL PRESSURE HISTORIES FOR VARIOUS POINTS ALONG THE AXIS OF THE GAP TEST ARRANGEMENT.

According to the experiments and the pressure histories the critical energies for the studied explosives were obtained by evaluating the integal P(t)Up(t)dt. The results are listed in Table 3.

TABLE 3 : RESULTS OF CRITICAL ENERGY CALCULATIONS

Explosive	Density (g/cm^3)	Modified Gap (kJ/m^2)	Projectile Impact (kJ/m^2)
Slurry A	1.15	672	1202
Emulsion A	1.15	2430	4142
Waxed RDX	1.55	1382	1476

PERFORMANCE CALCULATIONS

The detonation pressure and velocity were calculated by Tiger Code (11) using the JCZ3 Equation of State. The Gurney velocity was estimated by Kamlet's formula (10). The calculation of detonation velocity is in a reason agreement with the experimental values. The results from the calculation are summarized in Table 4.

TABLE 4 : THE RESULTS OF PERFORMANCE CALCULATIONS

Explosive	Density (g/cc)	Tiger Code		Experiments Value (km/s)	Gurney Velocity (km/s)
		Detonation Velocity (km/s)	Detonation Pressure (kbar)		
Slurry A	1.13	4.4	72	4.1	1.712
Emulsion A	1.12	5.4	88	5.2	2.084
Waxed RDX	1.55	8.0	250	-	2.786

From Table 4, the emulsion explosive has higher performance than the slurry explosive, the value for the emulsion explosive is about 20% higher than for the slurry explosive. The calculated detonation velocities are in reasonable agreement with the experimental values measured using nichome resistance wire velocity probes.

DISCUSSION

The experimental results using the modified gap test show that a first threshold to deflagration before detonation occurred in all three type of explosives. On the contrary, projectile impact tests are a case of shock to detonation transition without indication of the first transition. The results of the projectile impact tests are reported as detonations or failures. Therefore, any initiation which did not propagate to a detonation is reported as a failure. There appears to be no general agreement on the exact role that the first transition plays in the shock initiation process determined from the modified gap tests. We call this transition point the trigger initiation transition. The energy required for this transition, we call trigger initiation energy.

The slurry explosive was shown to be more sensitive than the emulsion explosive or waxed RDX. It exhibited a large zone where buildup of reaction occurred. In addition to this, Figure 5 shows that a significant amount of burning takes place before detonation occurs as evidenced by the relatively long and flat transition area (Figure 12). In the case of the emulsion explosive and waxed RDX, a rapid build up to detonation is observed in Figures 3 and 4 when the shock pressure increased above the threshold for the initiation transition.

In a few cases, detonation was observed several microseconds after the arrival of the shock wave at the interface between plexiglas and acceptor. These events occurred in both the slurry and emulsion explosives. Figure 17 shows a streak camera record illustrating this. However, it was more common in the experiments conducted for the slurry explosive. This might be an indication of the role of air bubbles in slurry explosives or microballoons in emulsion explosives.

The emulsion explosive was somewhat more sensitive than the waxed RDX. This is due to the high density of the waxed RDX. One would expect waxed RDX to be more sensitive than the emulsion explosives at the same density.

The behaviour of an explosive subjected to impact is dependent on the test method and such variables duration of impact, deformation of sample and confinement. For example, Table 1 indicates the critical impact velocity for the slurry explosive is 447 m/s in non-confined test conditions and 337 m/s confined in 50 mm ID steel pipe. This is due to the arrival of rarefaction waves from the wall of the pipe and other effects.

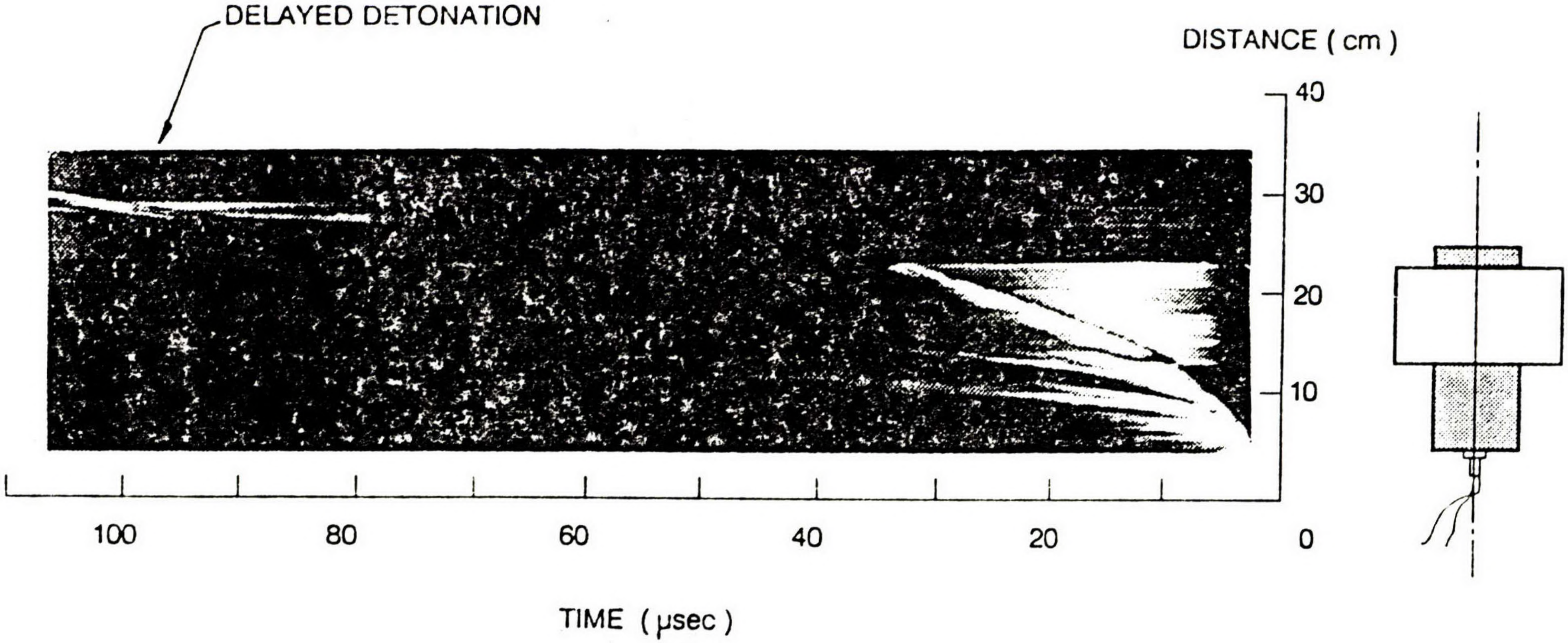

FIGURE 17 : **STREAK CAMERA RECORD FOR EMULSION A**

CONCLUSIONS

The experimental work shows that an initiation threshold to detonation could be formed in all three explosives tested. The slurry explosive was shown to be the most sensitive of the three. This agrees with the projectile test results for a detonation threshold.

From critical energy calculations, the slurry explosive exhibited considerable lower critical energy for initiation due to low amplitude shocks and for detonation due to high velocity projectile impact. Therefore, it is expected that the slurry explosive will be more susceptible to accidental initiation than the emulsion explosive tested.

Two thresholds, one for initiation and one for detonation, on the SDDT curve could be identified by modified gap tests, instead of one detonation threshold by projectile impact tests. The initiation and detonation thresholds from modified gap tests could be identified by interpreting the experimental shock pressure and particle velocity curves for the explosives.

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