

## Studies on Shock Attenuation in Plastic Materials and Applications in Detonation Wave Shaping

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## Studies on Shock Attenuation in Plastic Materials and Applications in Detonation Wave Shaping

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**Abstract.** Pressure in plastic materials attenuates due to change of impedance, phase change in the medium and plastic deformation. A lot of theoretical and experimental efforts have been devoted to the attenuation of shock wave produced by the impact of explosive driven flyer plate. However comparatively less work has been done on the attenuation of shock waves due to contact explosive detonation. Present studies deal with the attenuation of explosive driven shock waves in various plastic materials and its applications in design of Hybrid Detonation Wave Generator. In present work shock attenuating properties of different polymers such as Perspex, Teflon, nylon, polypropylene and viton has been studied experimentally using rotating mirror streak camera and electrical position pins. High explosive RDX/TNT and OCTOL of diameter 75-100mm and thickness 20 to 50mm were detonated to induce shock wave in the test specimens. From experimental determined shock velocity at different locations the attenuation in shock pressure was calculated. The attenuation of shock velocity with thickness in the material indicates exponential decay according to relation  $U_S = U_0 \exp(-\alpha x)$ . In few of the experiments manganin gauge of resistance 50 ohms was used to record stress time profile across shock wave. The shock attenuation data of Viton has successfully been used in the design of hybrid detonation wave generator using Octol as high explosive. While selecting a material it was ensured that the attenuated shock remains strong enough to initiate an acceptor explosive. Theoretical calculation were supported by Autodyne 2D hydro-code simulation which were validated with the experiments conducted using high speed streak photography and electrical shock arrival pins. Shock attenuation data of Perspex was used to establishing card gap test and wedge test in which test items is subjected to known pressure pulse by selecting the thickness of the plastic material.

### 1. Introduction

The detonation of high explosives in contact with the solid materials produces interface pressure of the order of hundreds of Kbar depending upon the shock impedances of the two materials. The high dynamic pressure exerted by the detonating explosives results in the formation of a shock wave which travels with a velocity more than sound speed in that material. Because of the Taylor wave following the detonation front in plane unsupported detonation, the pressure time profile across the shock wave in solid is triangular in shape. Very high shock pressure excites different attenuation mechanisms such

as irreversible compression & heating, plastic deformation and phase changes. As a result of the interaction of Taylor wave and other attenuation mechanisms the shock wave generated in solids has a decreasing velocity till the shock wave becomes elastic wave.

Ideally a flat topped shock wave is necessary for the shock velocity to stay constant over the measuring distance. A flat topped shock wave is produced by the collision of two flat metal plates [1,2]. In this method an explosively accelerated thin plate impacts on a target of like material. Two shock waves are generated at the interface of impact, one travelling into the target and other travelling back into thin flyer plate. When the latter reaches the rear free surface of the flyer plate a rarefaction fan is generated which eventually overtakes and attenuates the shock wave in the target material. A square shock pulse is thus produced whose amplitude depends upon the flyer velocity and time duration depends upon the thickness of the flyer. A lot of theoretical and experimental efforts have been devoted to the attenuation of shock wave produced by the impact of explosive driven flyer plate. However, comparatively less work has been done on the attenuation of shock waves due to contact explosive detonation. Drummond [3] studied the attenuation of explosive driven shock waves in metals. He analyzed the propagation of plane shock waves in solids and developed a procedure for calculating the attenuation of the shock wave. He determined the equation of state of the burned explosive gas from shock attenuation characteristics of the metals. He also obtained, theoretically, the approximate solution for attenuation of plane shock wave in metals and compared the results with experimental values by adjusting the value of specific heat ratio for detonation products. Present studies deal with the attenuation of shock waves in various plastic material and applications in detonation wave shaping. There were two motives for the present studies. First; to select the materials with energy absorption capacity for protecting the equipments and materials in shock environment and second; to find out the shock attenuating characteristics of plastic materials for their use in design of hybrid detonation wave generators.

## 2. Shock Propagation in Solid Materials

Consider an explosively generated shock wave in an inert specimen. Since the mass of the explosive is finite, the pressure behind the shock front falls off rapidly due to rarefaction waves. The peak pressure decays as the wave propagate outward because the energy distributed over the constantly increasing area and also is due to finite dissipation of energy in the transition through shock front. Figure1(a) shows a test set up for loading the shock waves in solids by contact explosive detonation and Figure1(b) shows progressive attenuation of the peak shock pressure with distance travelled in the solid specimen. The peak pressure and the shock velocity decreases till the shock wave becomes an elastic wave. Since the sound velocity is increasing function of pressure the shock pulse becomes broader with distance traveled in solid specimen.

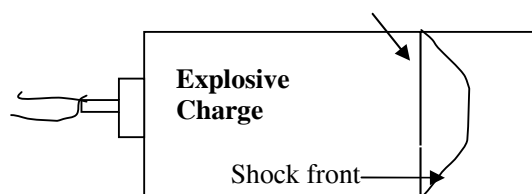


Figure 1(a). Test set up for shock loading of solids by contact explosive shock front

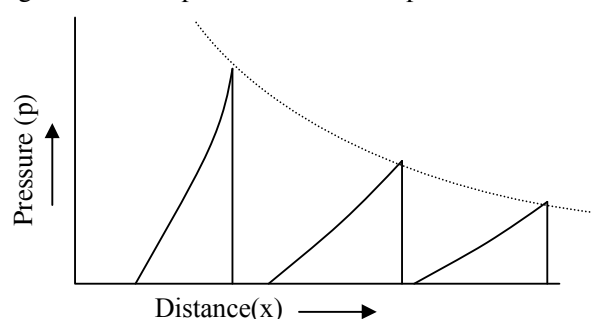


Figure 1(b). Attenuation of peak pressure  $p$  with the distance traveled in the solid specimen

The decrease of pressure of shock wave in travelling a unit distance in the solids is dependent on the pressure gradient in non uniform wave profile behind the shock front and the ratio of velocities of

rarefaction wave and the shock wave in the specimen. If  $U_s$  is the velocity of the shock front then pressure can be calculated from shock jump condition

$$P = \rho_0 U_s u_p \quad (1)$$

Where  $u_p$  is the particle velocity. Shock velocity and particle velocity are related by a linear equation

$$U_s = c_0 + b u_p \quad (2)$$

Where  $c_0$  is the bulk sound speed in the media.  $b$  constant

The pressure attenuation with distance is written as

$$\frac{dP}{dx} = \left( \frac{u_p + c}{U_s} - 1 \right) \frac{dP}{ds} \quad (3)$$

where  $c$  is sound velocity in compressed solid,  $dP$  is change in pressure over a distance  $dx$  in solids and  $dP/ds$  is pressure gradient behind the shock front. The pressure gradient  $dP/ds$  is a function of the length of explosive.

In the near region of shock loading the shock velocity attenuates according to an exponential law

$$U_s = U_{s0} \exp(-\alpha x) \quad (4)$$

where  $U_{s0}$  is the amplitude of transmitted shock velocity at the explosive solid interface and  $\alpha$  is attenuation constant. A more general law of attenuation in form of mach number is described by equation

$$M_s = (M_{s0} - 1) \exp(-\alpha x) + 1 \quad (5)$$

where  $M_s = U_s/c_0$ , is the ratio of shock velocity to the sound velocity at normal pressure. At explosive solid interface,  $x = 0$  and  $M_s = M_{s0}$  and at  $x = \infty$ ,  $M_s = 1$ , which means the shock wave degenerate into an elastic wave at very large distance. The attenuation coefficient  $\alpha$  in equation (2) depends on the material, incident shock velocity and shape of the shock front.

### 3. Experimental procedure

Cylindrical test specimen of nylon, Perspex, teflon & polypropylene of dia 75-100mm were machined out of the rod. High explosive RDX/TNT (60:40) of dia 75-100mm and thickness 20 to 50mm were detonated to induce shock wave in the test specimen shown in figure 2. High explosives were center initiated to induce a spherically diverging shock wave in the test specimen. A flat bottomed hole of diameter 8mm were drilled in the test specimen terminating at a depth of 5mm from explosive solid interface. Perspex pallets of thickness 5-6mm were inserted into the hole leaving 0.25mm air gap in between the two pallets. The sequential light flashes generated by the shock ionization of successive air gap were recorded on a streak camera through an optical fibre. Rotating mirror streak camera with maximum writing rate of 10mm/microsecond was used to record the shock arrival at different locations inside the test specimen. Cylindrical test specimen of nylon, teflon & polypropylene of dia 75-100mm were machined out of the rod. High explosive RDX/TNT (60:40) of dia 75-100mm and thickness 20 to 50mm were detonated to induce shock wave in the test specimen shown in figure 2(a). High explosives were center initiated to induce a spherically diverging shock wave in the test specimen. A flat bottomed hole of diameter 8mm were drilled in the test specimen terminating at a depth of 5mm from explosive solid interface. Perspex pallets of thickness 5-6mm were inserted into the hole leaving 0.25mm air gap in between the two pallets. The sequential light flashes generated by the shock ionization of successive air gap were recorded on a streak camera through an optical fibre as shown in Figure 2(b). Rotating mirror streak camera with maximum writing rate of 10mm/microsecond was used to record the shock arrival at different locations inside the test specimen.

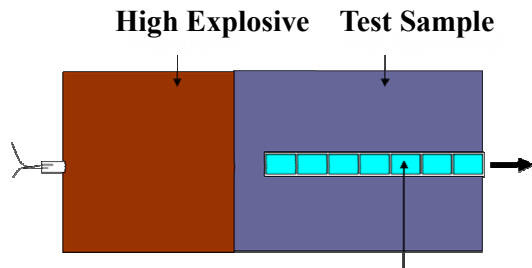


Figure 2(a). Sketch of experimental assembly used for shock attenuation

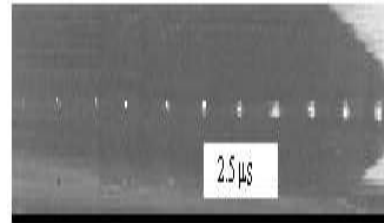
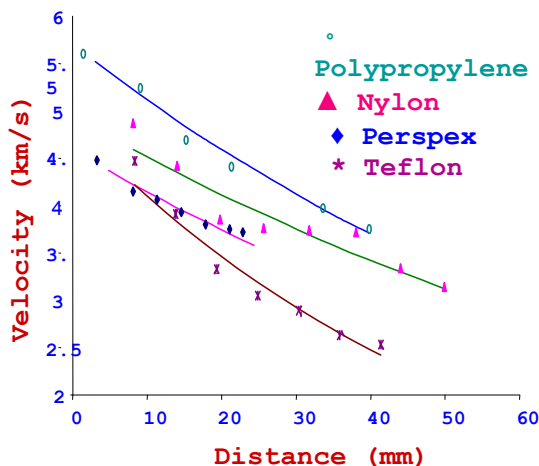


Figure 2(b) Streak camera record of shock attenuation in plastic materials

The shock velocity has been found to attenuate exponentially following the relation

$$U_s = U_o \exp(-\alpha x) \quad (1)$$

where  $U_o$  is the initial shock velocity at explosive plastic interface,  $\alpha$  is attenuation constant and  $x$  is thickness in plastic material.



Shock Attenuation relations  
 Polypropylene ( $\rho = 0.93\text{g/cc}$ )  
 $U_s = 5.70 \exp(-0.01x)$   
 Nylon ( $\rho = 1.14\text{g/cc}$ )  
 $U_s = 5.42 \exp(-0.0008x)$   
 Perspex ( $\rho = 1.18\text{g/cc}$ )  
 $U_s = 4.59 \exp(-0.0102x)$   
 Teflon ( $\rho = 2.14\text{g/cc}$ )  
 $U_s = 5.06 \exp(-0.0177x)$

Figure 3. Experimental data on shock attenuation in different plastic materials  
 Experimentally found out shock attenuation data of different materials is plotted in Fig 3.

#### 4. Shock Attenuation of Viton

Shock attenuation characteristics of Viton has been found out experimentally where Viton in the form of discs of diameter 100mm and 10mm thickness were processed. High speed streak photography and electrical shock arrival pins were deployed to monitor shock velocity at different locations inside the sample material. High explosive Octol (70:30) of diameter 100mm and thickness 30 to 40mm were detonated to induce shock wave in the test specimen. High explosives were center initiated to induce a spherically diverging shock wave in the test specimen. Half cut view of explosive assembly and layout of pins inside the test specimen is shown in Fig 4(a). Electrical shock arrival pins were used to record shock velocity at each interface of Viton discs. All the pins were used in a circular layout of radius 20mm as shown in Fig 4(b). A typical oscilloscope record is shown in Fig 5(a). A number of experiments were conducted and the experimental data has been found to fit into an exponential relation

$$U_s = 5.788 \exp(-0.01x)$$

where 5.788 is the initial shock velocity in Km/s, 0.01 is attenuation constant and  $x$  is the distance travelled in Viton.

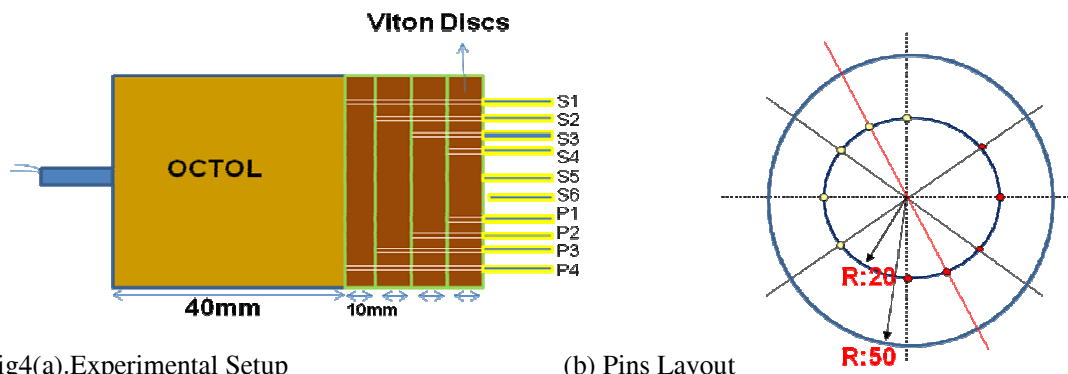


Fig4(a).Experimental Setup

(b) Pins Layout

The experimental data is plotted in Figure 5(b).

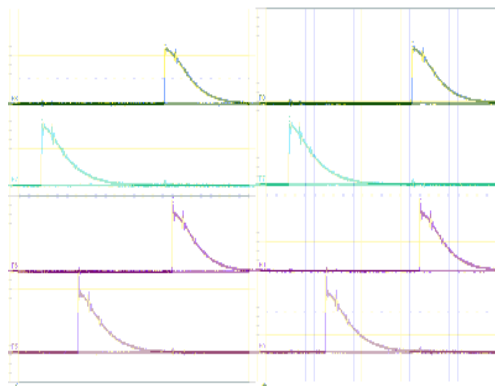


Figure5(a) Oscilloscope Record of shock arrival pins

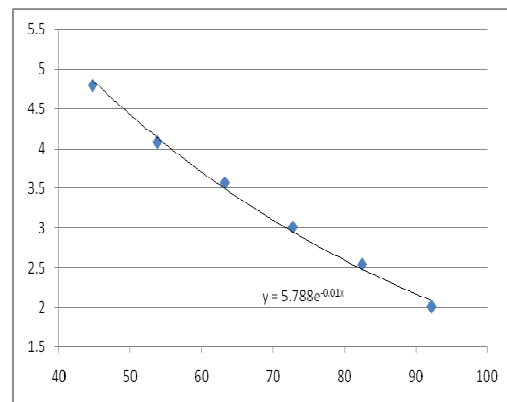


Figure 5(b) Experimental data of attenuation in Viton

### 5. Equation of State

Equation of state is important thermodynamic relation between P,V and T or E. Many EOS are available for solids but for the application under consideration shock EOS is more appropriate. Shock equation of state is a linear relation between shock velocity and particle velocity as given by  $U_s = a + bU_p$ . Shock velocity was found out experimentally at different distances from shock attenuation relations. The particle velocity was found from free surface velocity measurement. A total of four experiments were conducted with Viton material of varying thickness of 20, 30, 40, 50 & 60mm. Electrical shock arrival pins were deployed to monitor free surface velocity, one pin in contact with Viton disc and other 3mm raised. The results of four experiments has been plotted in the graph between shock velocity and particle velocity in Fig6.

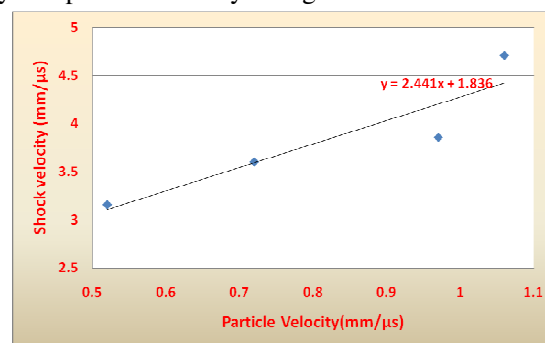


Figure6. Experimental data on particle velocity

So experimental data has been found to fit in the following linear relation  $U_s = 1.836 + 2.441U_p$

## 6. Applications in detonation wave shaping

### Design of Octol- Viton Spherical Explosive Lens

Based on shock attenuation data and equation of state found for viton a spherical wave lens has been designed by using combination of high VOD explosive Octol and viton an inert material[4]. Based on the calculations a preliminary design was made as shown in Fig 7.

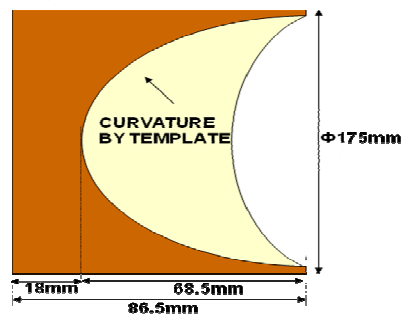


Figure7. Preliminary Design

## 7. Simulation Setup

Preliminary design was verified through numerical simulation using Autodyne2D hydrocode.

Simulation was done in 2D axial symmetry about x-axis. Eulerian space was created with uniform mesh density of 0.2mm square cell. JWL equation of state was used to represent explosive Octol having density of 1.82g/cc. Shock equation of state for Viton was used of density 1.91g/cc. Material models are shown in Appendix 'A'. Cycle 0 of simulation setup is shown in Fig8. Pressure time profile at exit surface of Viton vs time is shown in Fig 9(a) and snapshots of detonation/shock propagation in the designed lens are shown in Fig 9(b).

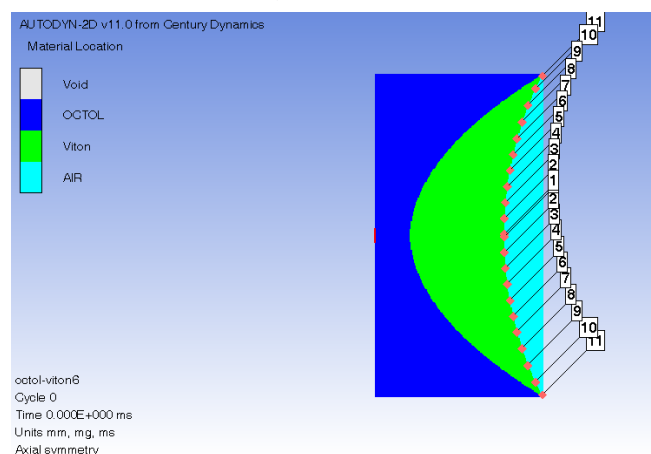


Figure8. Simulation setup for Octol/Viton

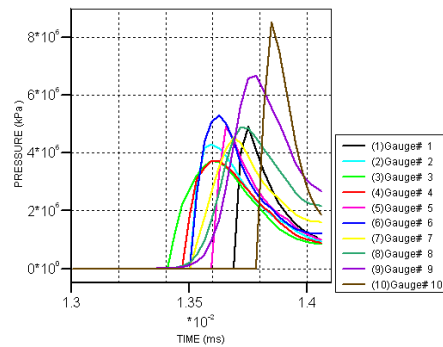


Figure 9(a). Pressure history at exit surface of Viton vs time

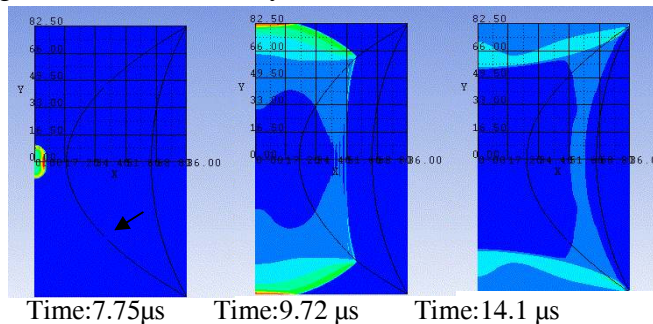


Figure 9(b). Simulation result showing shock wave arrival at front face of Viton

Simulation was used to verify the contour between the explosive and inert material so that the shock wave reaches the Viton surface simultaneously. On viton surface insitu casting of explosive was done. The design was then validated through experiments

## 8. Validation of Design through Experimental Evaluation

High speed streak photography and electrical ionization pins were deployed to monitor planarity of shock arrival at the front surface of Viton. Fig 10 shows the layout of electrical and piezoelectric pins to monitor simultaneity in shock wave arrival at front surface of Viton.



Figure 10. Experimental layout

Acceptor explosive in the form of strip was placed in contact with the viton to study the initiation of detonation. The simultaneity in detonation wave reaching the explosive free surface was recorded by a streak camera. The final photograph of the spherical explosive lens at the time of trial is shown in Fig 11.



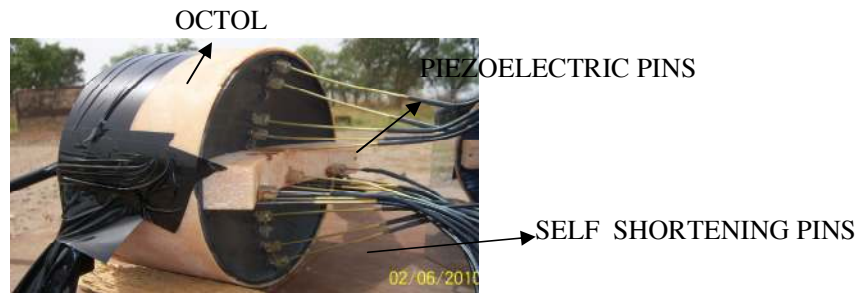


Figure 11. Trial Photographs

### 9. Results

Fig 12(a) shows the shock wave arrival at Viton free surface as recorded by the shock arrival pins and Fig 12(b) shows the shock arrival at Viton and detonation wave arrival at free surface of acceptor explosive.

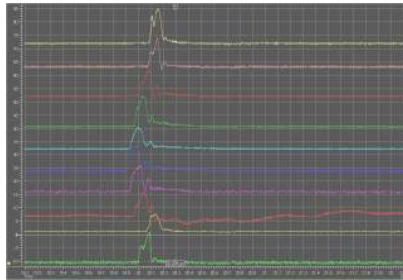


Figure 12(a) Oscilloscope record

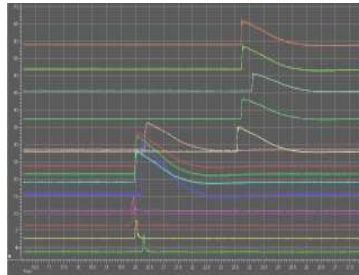


Figure 12(b) Oscilloscope record



Figure 13(c) Streak Camera Record

The measured simultaneity in shock wave arrival at Viton surface is  $0.18\mu\text{sec}$  which is acceptable. However the simultaneity in detonation wave arrival at explosive free surface was recorded by streak camera as shown in Fig 13(c) and the measured simultaneity is between  $0.13\mu\text{s}$  to  $0.18\mu\text{s}$  which is within the acceptable limit..

The shock attenuation data of Perspex was used in card gap test experiments. Perspex of density  $1.186\text{ g/cc}$  was used whose linear Hugoniot relation is given by

$$U_s = a + b U_p$$

where  $a = 2.561\text{ mm}/\mu\text{s}$  and  $b = 1.595$ .

In order to standardize the geometry, trials were conducted with the same experimental set up where Tetryl was used as the donor. Two pellets each of diameter 2 inch and length 1 inch were used followed by Perspex as the attenuator material[5]. The experiments were conducted using rotating mirror streak camera which is driven by compressed air and has a maximum writing rate of  $10\text{ mm}/\mu\text{s}$ .

Records were obtained by viewing the Perspex in velocity measurement mode where the event direction is parallel to the slit but perpendicular to the optical axis as shown in figure 14

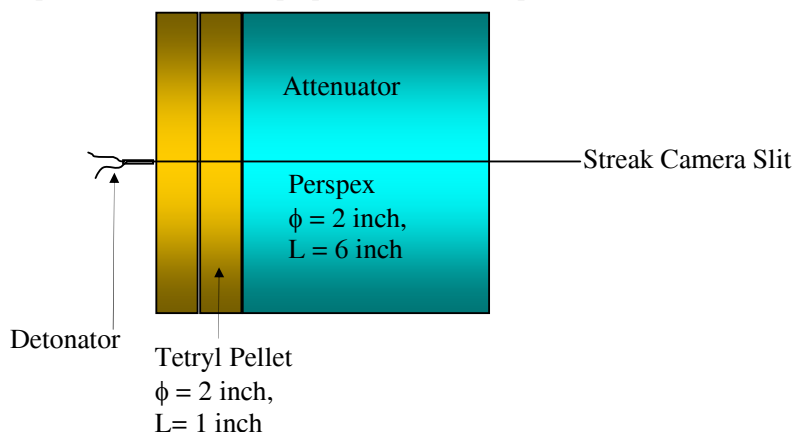


Figure 14. Trial Set-Up for Recording Shock Attenuation in Perspex

The results were analyzed on image analyzer and it was found that the shock wave attenuates with distance traveled in the Perspex. The shock pressure has been found to attenuate exponentially with the distance traveled in Perspex. The following relation was fitted after experiments

$$P = P_0 e^{-\alpha x}$$

$$P = 136 e^{-0.0358x}$$

where  $P$  is the pressure at a distance  $x$  in the Perspex and  $P_0$  is the initial pressure at interface,  $\alpha$  is the attenuation constant whose value in this case is 0.0358.

## 10. CONCLUSION

Shock attenuation relations for different polymers has been found out experimentally. Based on shock attenuation properties of polymers spherical wave lens of diameter 175mm have been designed. The developed DWG has been test fired and simultaneity of the order of 0.14μsec has been achieved. The shock attenuation of data of Perspex has been used to establish card gap test.

## 11. Acknowledgements

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