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INVESTIGATION INTO CUTTING BY WATER JET

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To His Majesty King Hussein Bin Talal

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ABSTRACT

Jet cutting is gaining importance in recent years due to the fact that it is applied to industrial processes where other available technologies fail.

There are different parameters affecting jet cutting performance, such as stand-off distance, aspect ratio, jet type, jet size,...etc.

This work is devoted to investigate the effect of these parameters on the depth of penetration in different metallic and non-metallic target materials using different orifice diameters, namely 1.0, 1.5, and 2.0 mms. Drinking water was used as the cutting jet.

Results showed that cutting performance did not only depend on jet speed but also on the aspect ratio l/D, where l and D are the jet length and diameter, respectively, at which depth of cut is maximum for the most stable jets. 'Plasticine' and tin targets showed the two extremes in the cutting depth due to their, relatively, weak and strong mechanical strength, respectively.

The cavity formed in the target was cylindrical in shape. The diameter of the cavity was found to vary from the diameter of the jet to three or four times the diameter which attributed to the shear in the radial direction of the jet, therefore, the effect of some chemical additives in ppm including arabic gum and polyethylene glycol were added to the jet in order to reduce the shear effect.

" القطع باستخدام النفاثة المائية "

الملخص

لقد اكتسبت عمليات القطع باستخدام النفاثة المائية أهمية كبرى في الآونه الاخيرة وذلك لامكانية تطبيقها في العمليات الصناعية التي تعجز عن القيام بها التقنيات الاخرى المتوفرة .

وتتأثر عملية القطع باستخدام النفاثة المائية بعدة عوامل تؤثر على أدائها كالمسافة بين الفتحة والهدف ، نسبة طول النفاث الى قطره ، نوع مادة النفاث ، ... الخ .

وعليه ، فقد اهتم هذا البحث في دراسة هذه العوامل وتأثيرها على عمق التجويف المقطوع في اهداف معدنية وغير معدنية مختلفة المواد باستخدام فتحات (Orifices) بأقطار ٠ر١ ، ١ر٥ ، ٢ر٠ ملم ، وقد استخدم ماء الشرب كمادة النفاث القاطع .

وقد أشارت النتائج بأن اداء القطع لا يتأثر بسرعة النفاث فحسب ، بل بنسبة طول النفاث الى قطره ايضا (Aspect ratio) ، بحيث ان اكبر عمق قطع يمكن الحصول عليه في حالة استخدام اكثر النفاثات ثباتا واستقرارا .

كما ودلت النتائج على ان اكبر واصغر عمق تجويف يمكن الحصول عليه في حالة استخدام الصلصال والقصدير كمواد للاهداف المقطوعة ، على الترتيب ، ويعزى ذلك للتفاوت النسبي بين قوتهما الميكانيكية .

ومن النتائج الهامة التي ظهرت في هذه الدراسة هو الشكل الاسطواني للتجويف المقطوع ، وقطر التجويف الذي وجد بأنه يتغير من ثلاثة الى اربعة أضعاف قطر النفاث القاطع ، مما يساهم في زيادة اجهادات القص (Shear Stresses) في الاتجاه النصف قطري للنفاث ، وبذلك ، فأن تأثير بعض الاضافات الكيمائية الذائبة في الماء بالجزء بالمليون (ppm) كالصمغ العربي وال (بولي ايثيلين جلايكول) قد بحث للتقليل من تأثير هذه الاجهادات .

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NOMENCLATURE

C,	Acoustic speed (m/s);
d,	Penetration (mm);
D,	Orifice diameter (jet's diameter) (mm);
E,	Young's modulus of elasticity (N/mm^2);
l,	Jet's length (mm);
S,	Stand-off distance (mm);
T,	Temperature $(^{\circ}C)$;
V,	Velocity (m/s);

GreekSymbols

ρ,	Density (Kg/m^3);
σ,	Stress (N/mm^2);
$\dot{\epsilon}$,	Strain rate $(1/s)$;

Subscripts

j,	Jet;
p,	Piston;
t,	Target;
w,	Water;

Abbreviations

ppm,	Part per million;
TDS,	Total dissolved salts;
TH,	Total hardness.

Chapter 1

INTRODUCTION AND LITERATURE SURVEY

1.1 Introduction

When a liquid mass strikes a solid surface, compressible behaviour, a sharp peak pressure, may occur in the initial stages of the impact. The duration of the peak depends on the dimensions and impact velocity of the liquid mass, and also on the compression wave velocity of the liquid. There are similarities between this type of loading and that produced by the detonation of small quantities of explosive, since both give intense pressure peaks of only few microseconds duration which leads to a high rate of strain.

In recent years, a large number of studies have been made on the behaviour of solids at high rates of strain. Many of these experiments have been of a kind involving the high-speed impact between two solids (Taylor [1], Rhinehart and Pearson [2]). Less attention has been given to the equally interesting care of the high-speed impact between a liquid and a solid, possibly because it is less commonly met with in everyday life. The studies which have been concerned with liquid/solid impact have been closely related to cases of practical importance; much of the early work, for example, was concerned with studying the factors affecting the erosion of steam- turbine blades by collision with water droplets suspended in the steam. Hongger [3], Gardner [4], and de Haller [5], using an apparatus which simulated conditions inside a turbine. Erosion of metal specimens was caused by whirling them at velocities up to $336 m/s$ through streams of water. They showed that at these velocities it was possible for the water to cut through even the hardest of the metal specimens. Their works have also shown that the damage increased rapidly at higher velocities, but no general relationship could be given. Gardner [4] found that the hardness of the metal was the main property for determining the resistance to erosion. Hongger [3], on the other hand, did not find a correlation between hardness and erosion resistance.

More recently, the erosion of aircraft and rockets moving at high speeds through rain has attracted attention and renewed the interest in the liquid impact problems.

Unlike the usual impact firing methods, Jenkins [6] has fired solid specimens at velocities up to $244 m/s$ through stationary liquid drops. Engel [7] has considered the mechanism of rain erosion and related the deformation produced by liquid drops striking a solid surface at a high velocity to that of a soft metal sphere striking the solid at much lower velocity. On the other hand, Zaid et al.[8] has considered the impact of non-deformable flat-ended cylindrical projectiles on mild steel plates for impact velocities up to $300 m/s$.

1.2 Water-Jet as a Cutting Tool

High-pressure water jets have been recognised as cutting tools in a wide variety of industries. Most metals and non-metals can be cut rapidly and efficiently with a water-jet. The advantages offered by water-jet cutting include [9]:

- Minimal or no dust,
- High cutting speed,
- Multidirectional cutting capacity,
- No dulling of the cutting tool (the jet),
- No thermal stresses,
- No fire hazards associated with the cutting process.

1.2.1 Methods of Producing High Speed Jets

Different methods are used to produce high speed jets,

- If a hollow high explosive charge, lined with sheet metal, is detonated in contact with a block of metal, then the pressure on the sheet metal liner due to the explosive is very large, such that the yield strength of both the liner and the target material may be neglected and the system can be treated hydrodynamically assuming the metal to flow as a non- viscous fluid, this is not to say that the metal is in a fluid state. The pressure and high speed of the collapsing liner will penetrate the block, target plate, and cause a crater.

- Applying a high pressure loading to a water contained in a packet and forcing it through a nozzle or an orifice with high speed.

A schematic representation of the last stages in a typical high speed liquid-jet generating device is shown in figure 1.1.

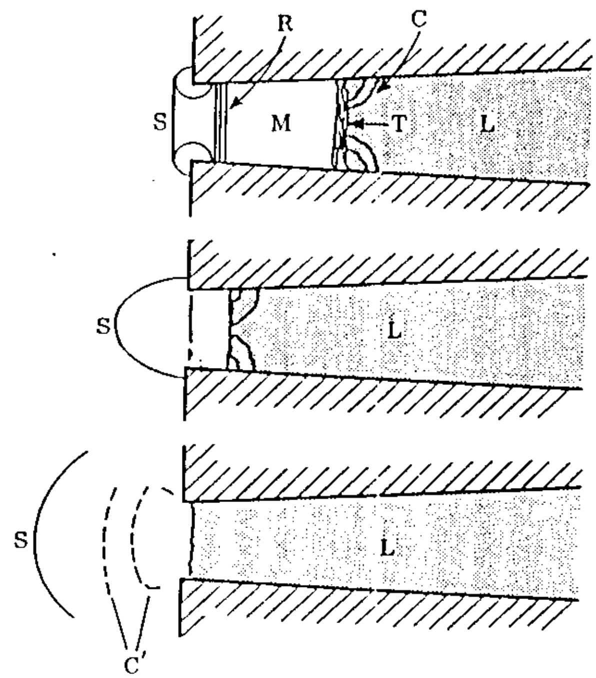

Fig.1.1 A typical high speed liquid jet generating device, L is high- velocity liquid in the final stages of a converging nozzle. It is acted on by corner compression signals, C. T, A frontal compression zone; M, a region of compressed air and droplets; R, air relief waves; S, the shock; C', compression waves [10].

A package of liquid is impacted by a projectile forcing the fluid into a long slowly converging nozzle. The result is that a small segment of the initial water packet reaches the orifice of the generator with both large velocity and a density in excess of the liquid's equilibrium density under normal atmospheric conditions. If the generating device is immersed in a gaseous environment, such as the atmosphere, the accelerating fluid will be preceeded by a gas shock, with a relatively high pressure region between the shock and the fluid front. Also the compression of the liquid will lead to large internal pressures in the front region of the accelerating packet.

1.2.2 Parameters Affecting Jet Cutting

Examination of the available literature, reveals that there are several parameters distinctly affecting the jet cutting process, these are:

- Impact velocity.
- Stand-off distance (spacing between the nozzle and the target).
- Stability of the jet.
- Multi-plate targets (lamination).
- Targets and jet materials.

Bowden and Brunton [11] have studied the deformation of solids at high rates of strain, produced by the impact of a small cylinder or jet of liquid on the surface of the solid, at velocities up to $1200m/s$.The subsequent deformation of the solid under impact and the behaviour of the liquid was observed using high speed photography.

The mode of deformation of the solid has been investigated for plastic ,elastic and brittle materials.There was evidence that the liquid jet, on impact , behaves initially in a compressible manner.Part of the deformation is due to these compressible effects and part to the shearing action of the liquid flowing at very high speeds across the surface.

If the head of the jet has an appropriate shape, the velocity of the flow across the surface may be much greater than the velocity of approach. It was found that there were five general types of deformation produced in the solid. These were, 1- circumferential surface fracture, 2- sub- surface flow and fractures, 3- large-scale plastic deformation, 4- shear deformation around the periphery of the impact zone, and 5- fracture due to the reflection and interference of stress waves.The predominating mode of deformation depends primarily on the mechanical properties of the solid and on the velocity of impact.

Field [12] investigated the fracture and deformation of glasses, hard polymers, single crystal and ceramic materials by liquid impact at velocities up to $1000 m/s$ and briefly compared the obtained results with those produced by solid/solid impact and explosive loading. The detailed development of fracture had been followed by high speed photography.In brittle solids the main characteristics of damage on the front surface is a ring fracture surrounded by a largely undamaged area.The ring fracture forms at the edge of the loaded area were high tensile forces develop during impact.Outside this main ring of fracture, short circumferential cracks occur. More complex fracture patterns appeared on the front surface of the plate due to the reinforcement of the surface wave with the components of stress reflected from the back surface. Thin plate specimens often exhibit 'scabbing' fracture at the rear surface; in brittle materials of low attenuation this form of damage can be of prime importance.

Experiments were reported on limestone, and sandstone by pulsating water jets with jet velocities up to $1450 m/s$ and piston impact energies up to $65,000 Joules$.

Data on the specific energy for single pulse spall craters in the face of $30 cm$ cubic rock samples was plotted against the specific pressure (the ratio of jet stagnation pressure to rock compression strength). The results showed that the specific energy decreases rapidly as the jet pressure is increased from 1.45 to 3.95 times the compressive strength.

A specific energy of $500J/cm^3$ was observed for Barre granite [13]. The relatively low values of specific energy were attributed to the high jet pressure in combination with a relatively short length-to-diameter ratio of the water slug. This produces efficient shear fracture without wasting the energy by eroding an excessively deep hole.

A determination of the feasibility of water jet cutting of surfaces with asperity sized geometry which match to form discontinuities was investigated by Dowding et al.[14].

The preheating of hard-rock before mechanical or hydraulic impact had been proposed by Orlo McNary [15] as a method of enhancing rock disintegration. The efficiency of surface heating as a function of time led to the conclusion that the heating time must be short for an economical process. A simple formula was given which allowed judgments to be easily made regarding the duration of the heating time, and that a critical heating time exists where the total specific fragmentation energy is a minimum. The total specific fragmentation energy was increased for heating times other than the critical time and surface heating does not lower the energy requirements in all situations, that is, the critical heating time may be zero in some cases. This study yields useful guidelines for defining the conditions under which supplemental heat addition can increase the rate of excavation.

Measurements of wall-pressure in the impact-chamber of an impulsive water-cannon were carried out by Edwards et al.[16]. The results indicated that the radial oscillations of the piston caused fluctuations in the axial velocity at the piston/water interface. Also the effect of the axial wave motion in the impacted piston had been examined experimentally by varying the time of travel of longitudinal pressure waves along the piston, using pistons of different lengths and materials of different acoustic velocities. It was found that such variations in the piston characteristics had no discernible difference in the pressure histories in the impact chamber. Similarly, radial oscillations of the walls of the impact chamber had been examined theoretically and found to exert only a marginal effect on the pressure in the impact chamber.

As expected, varying pistons's material and dimensions affects the performance of the process. Edwards et al.[17] selected different piston's length and materials. Computer calculations and laboratory experiments were described in which the influence of the geometry and acoustic properties of the piston on the maximum jet velocity produced by a water-cannon were assessed. Design recommendations concerning the selection of both piston length and material were included. Both computer computations and laboratory measurements confirm that maximum jet velocity for a given piston impact velocity is a function of the length of the piston in addition to its acoustic impedance [17].

The influence of nozzle geometry on the performance of pulsed water cannons was studied by Edney [19]. Four nozzles, two of an exponential shape and two of a hyperbolic shape had been tested both in air and vacuum.The quantities measured include the peak jet velocity as a function of piston impact velocity and the time between piston impact and the appearance of the jet. The experimental results obtained showed that at low velocities (<1500 m/s), the experimental results are in reasonable agreement with the incompressible flow theory. At higher jet velocities it is necessary to include in the calculations both compressibility effects in the water as well as the effects of air ahead of the jet in order to explain the experimental results [19].

An important advantage of high speed liquid jets over the more conventional mechanical cutter for rock-cutting and drilling lies in the appreciably greater rates of energy input provided by the former especially in the case of pulsed operation.Various types of nozzle shape have been used to produce high-speed jet pulses of short time duration.Edwards et al. [18] tried to choose a certain design in order to maximize the velocity of the head of the jet. The main findings in their work were [18]:

Short nozzles produce rapid velocity decay and produce the highest initial jet velocity, but they gave rise to the greatest pressure within the nozzle. The useful stagnation impulse provided by an exponential nozzle depends in part on the overall length and also on the strength of the target material.

Increasing the overall area ratio also improved the maximum jet velocity and the stagnation impulse, but only at the expense of generating greater pressure in order to increase the initial packet velocity.

Overall result of their work is that adjusting the length ratio and initial velocity would appear to be a more attractive means of optimizing nozzle performance than using high area ratios [18].

Cutting with water jets alone has the limitations in cutting hard materials such as metals, ceramics and high strength composites and for such materials jets of higher power levels are required for acceptable cutting rates.

To increase the capabilities of water jet cutting, abrasives were introduced to produce abrasive water jet system.The addition of abrasives greatly increased the cutting capability and the performance of the process . Abrasive water jet cutting was studied by Harris [20]. The results of his investigation indicate that abrasive water jet cutting technique can be effectively used to cut most materials including metals, composites and ceramics in a wide range of thicknesses and is suitable for a range of material removal applications including weld toe dressing, gouging, weld edge preparation.

As a result of momentum transfer between water and abrasives, a focused, high velocity stream of abrasives out of the exits of the accelerator nozzles performs the cutting action. Cutting or controlled depth penetration of the target material occurs as a result of erosion, shearing failure under rapidly changing localized stress fields or micromachining effects, depending upon the specific properties of the material being cut. The cutting rate can be controlled by adjusting the feed rate, the stand-off distance, the water jet pressure, or the abrasive parameters [9].

1.3 Stability of the Jet

An intensive study of water jets discharging into air is being made in order to develop improved fire-fighting equipment for U.S. Navy ships and shore installations. As part of the research, a detailed study of the mechanism of jet formation, and resultant air entrainment were presented (Hoyt et al. [22]). Through reduction of spray formation and air entrainment it is believed that more compact, coherent, and longer-range fire-fighting streams will result.

The laminar-turbulent transition and initial turbulent formation on the surface of the jet is followed by amplified disturbances which result in spray detachment. A very large modification to this process is observed when polymers are added to the water [22].

Laboratory experiments had been carried out by Edwards et al.[21] to assess the progressive loss of potential cutting effectiveness of impulsive water jets with increasing stand-off distance from nozzle to target, both in air and vacuum, and the separation of droplets from the jet boundary all over the stand-off distance. The impulsive high speed water jets produced in and travelling through atmospheric air lack coherence even at short distance from the nozzle exit [21]. Similar jets produced in, and traversing a vacuum show a much greater coherence even at relatively large stand-off distance and offer appreciably greater potential for jet cutting.

1.4 Impact of Solid-Jet, Penetration, and Perforation

Penetration may be defined as the entrance of a projectile into a target without completing its passage through, whereas, perforation implies the complete piercing of the target by the projectile [23].

The penetration of projectiles (solid-jet) into metallic and non- metallic targets has long been of interest to ordance engineers; however, because of its military connection, little published material is available on this topic. More recently. interest in this field has arisen due to the need for information concerning [23],

1. The dynamic properties of materials at high rates of strain (of the order of $10^3/s$ during penetration process);
2. The containment of fragments resulting from the failure of high speed rotating machinery (e.g. turbine blades); and
3. The meteroidal damage of space vehicles.

Perforation of a plate by a flat-ended punch has similarities with the blanking operation [8], in that both define the punching of a hole in a sheet and the production of a blank, of the same profile as the punch; perforation could be considered as an extreme, but very importable, case of blanking in which the punch/die clearance is such that the die is entirely beyond the plastically affected region, so that it no longer takes any part in the operation.

For a critical and historical review of perforation by projectiles, the reader is referred to Zaid et al., work [24].

Results of experiments on the high speed perforation of different thicknesses of mild steel plate were presented and discussed by Zaid et al.[8]. Plate profiles, thinning of perforated plugs and energy requirements for perforation were presented and discussed.

It was found that the bulging of the target plate is greatest when the projectile is just contained, and that the bulging at containment increases with plate thickness over the early stages of the thickness range, after which it decreases with increasing plate thickness.This is contrary to the static case, in which the bulging continually increases. Metallurgical examination of the material at the plug-plate interface indicated that thermo-plastic instability occurs as a result of the adiabatic heating when perforating thicker plates at high speed.

Flat-ended cylindrical projectiles, of varying length were projected normally at high speed against a thin mild steel plate to examine the impact conditions relevant to their containment, Zaid et al. [23], and the mechanism of deformation was provided. The energy of the projectile is consumed in the bulging of the target and shearing the plug, and the amount of bulging is found to be drastically reduced by increasing the impact velocity beyond the containment limit, it is concluded that less energy will be consumed by the target when perforated by the projectile, than when the projectile is contained [23].

A comparison of single and multi-plate shields subjected to impact by a high speed projectile was also studied by Zaid et al.[24].The study included the spacing of the plates, their relative thicknesses and materials, the level of impact velocity involved and the presence of fillers between plates.

A mild steel single plate shields, and multi-plate shields of equivalent total thickness were subjected to normal impact by cylindrical flat ended hardened steel projectile at velocities up to $500m/s$.They concluded that, a thin laminated shield is less effective than a thin single plate shield of the same total thickness, in resisting penetration by a high speed flat-ended cylindrical projectile. As a shield thickness is increased, the laminated shield becomes relatively more effective, and this is shown to be associated with an increasingly greater amount of energy being absorbed in bulging the second plate.After penetrating the first plate, the projectile is capped by the plug from the first plate and therefore becomes deformable and ogival ended, and thus loses the ability to penetrate the second plate cleanly, so that the latter suffers significant bulging before eventual shearing of the plug terminates the penetration process.

The ratio of the shield total thickness to the projectile diameter was the major parameter in determining the bulging of the second plate, and the relative effectiveness of the laminated shield [24].

A recent topic is of a high importance investigated by Salem et al. [25]. A short high speed water jet is used for spot welding metallic combinations of different thicknesses and materials. The jet, which is extruded from a specially constructed portable water jet gun, is made to impinge on a thin flyer plate, causing it to deform locally forming a dimple (bulge) which advances with a high speed. The impact of the dimple on the parent plate, which is separated from the flyer plate by a suitable gap, gives rise to a condition of oblique collision similar to that encountered in explosive welding, causing the flyer plate to be welded to the parent plate.

with a 15 mm inside diameter hollow stainless steel cylinder of 2 mm thickness and fitted inside the gun's jacket, and extended from the explosion chamber to the outlet of the gun, and a 5 mm width groove was drilled over its length to allow the gases resulting from explosion to expand out of the gun barrel to stop the acceleration of the flying piston. Second, a 15 mm diameter and 22 mm length steel piston was used with a reduction of 1 mm in its diameter over 2/3 of its length to form a step in order to treat the effects of the reflected waves from the plane of discontinuity between the piston and water, i.e. the piston water interface.

2.2.2 The Extension Barrel and the Velocity Measuring Unit

An extension barrel, made of high strength steel, was machined to 38 mm outside diameter and 15 mm inside diameter and 140 mm length. One of its ends was screwed to the gun barrel and the other end to the water packet.

Four holes were drilled along the barrel two on each diameter and at 20 mm axial distance to accommodate the velocity measuring unit.

The velocity measuring unit, figure 2.1, consists of four high conductivity copper discs of 5 mm diameter and 7 mm thickness with four holes each 1 mm in diameter drilled through their centers to receive the two pencil leads which worked as conductors. The copper discs were covered by teflon to provide electrical insulation between the copper discs and the extension barrel. The copper discs were inserted and fixed by aroldite.

The flying piston passes over the first conductor, it breaks and an electrical circuit receives a starting pulse transferring it to a digital oscilloscope causing it to trigger, while the break up of the second conductor stops the start-signal of the oscilloscope and gives the time interval of the start-stop signals, figure 2.2.

2.2.3 The Water Packet

A hard carbon steel hollow cylinder , designated C60 (40655), supplied by the Jordanian cement factory, which has the following chemical analysis by weight

0.6 % carbon,

0.26 % silicon,

0.72 % manganese,

0.016 % phosphorous,

and 0.035 % sulphur.

was used with 15 mm inside diameter 10 mm wall thickness was machined to form a water packet which is connected to the extension barrel and receives the firing piston that impinges on the water surfaces and forces it through the orifice drilled at the lower end of the packet.

Three packets, with three different orifices machined at their lower ends were used. The orifices were 1.0, 1.5, and 2.0 mm's in diameter.

2.2.4 Protection Shield and the Base Plate

A shield was necessary in order to protect the worker from the flying water droplets or any other fragments from the target plate.

A hollow steel cylinder of 110 mm inside diameter, 11 mm thickness and 600 mm height with two thick flanges as a base and a holder to the gun assembly and extension barrel were used for this purpose.

A gate was opened in the shield to facilitate the replacement of target plates.

2.3 Procedure

The following procedure was followed in each test:

- Preparing the firing gun by cleaning the barrel of the gun itself, the explosion chamber, the extension barrel, and the water packet by a steel brush. Finally, it was made sure that the orifice is well opened.

- The flying piston was fitted in position in the explosion chamber checking that friction was minimized during the piston travel. A small piece of 'plasticine' was used to support the piston from dropping due to its weight.

- Ten gramms of drinking water was poured in the packet with a small piece of a sullo-tape on the orifice hole to prevent water from leaving the packet due to gravity.

- All parts are now connected in place: the firing gun, the water packet, the target plate at the desired stand-off distance, and the gate in the protection shield is closed, the velocity measuring unit is to be connected by passing carefully the two conductors (pencil leads) through the holes in the velocity measuring unit and the electrical circuit is connected to the oscilloscope which is now in triggering position.

- The cartridges are now fixed in their place,(for safety, the cartridges should be in the last step). Finally, the gun is fired.

- After firing, the cartridges are pulled out of the gun and the gate is opened, and the target plate is taken out to make the necessary measurements.

- The gun, water packet, the broken conductor pieces and piston are then removed and cleaned, ready for another test.

2.4 Experimental Observations

Some difficulties and observations were noted during the manufacture of the test rig, these are:

- A good alignment between the gun, the extension barrel, and the water packet must be achieved to facilitate a free flight to the piston without any obstacles, and frictional losses within the path of the piston.

- The wave reflection at the piston/water interface is a very important point that one must take care of. To treat this real problem, 5 mm brass and steel discs were used behind the flying piston to form a second plane of stress discontinuity in order to transmit the reflected wave and to stop the piston from reflecting back and jam in the explosion chamber, but this was not the ideal solution for this problem, since a fracture took place in these discs, i.e. scabbing.

  Another effective way of treating this problem was by reducing the diameter of the flying piston 1 mm over 2/3 of its length which stopped the piston from impinging back due to wave reflection at the interface due to impedance mismatch.

- A hard material should be used for the extension barrel and the water packet with enough thickness to prevent fracture due to high pressure.

- A heat treatment may be necessary for the flying piston to increase its hardness.

- Solid jet impact was observed to behave like fluid jet. An experiment was made in order to prove this behaviour, such that, four 5 mm thickness 'plasticine' discs with different colors, namely red, green, brown, and yellow, were sequently assembled to form a 20 mm thickness 'plasticine' bullet which was fired against a white 'plasticine' target. After impingement, the color sequence became, yellow, brown, green, and red, i.e. opposite to the color sequence before impact.

Chapter 3

THEORETICAL CONSIDERATIONS

The connected electrical circuit (the oscilloscope) to the velocity measuring unit was employed to measure piston's speed only.

The speed of the water contained in the packet was obtained as follows ,

Consider the original dynamic stress of the piston, σ_p, is fully transferred to the water in the packet, neglecting friction,

$$\sigma_p = \rho_p C_p V_p = \rho_w C_w V_w = \sigma_w \tag{3.1}$$

where, ρ_p is the density of the piston material, C_p is the piston's acoustic speed, V_p is the piston's speed before it impinges on the water surface, ρ_w is the the water's density, C_w is the water's acoustic speed, and V_w is the water's speed.

$$V_w = V_p - K \tag{3.2}$$

where,

$$K = \frac{\sigma_p}{\rho_p C_p}$$

Substitution of the value of σ_p from equation (3.1) into equation (3.2) yields,

$$V_w = V_p - \frac{\rho_w C_w V_w}{\rho_p C_p} \tag{3.3}$$

Thus,

$$V_w = \frac{\rho_p C_p}{\rho_p C_p + \rho_w C_w} V_p \tag{3.4}$$

Substitution for ρ_p, C_p, ρ_w, and C_w in equation (3.4) gives the result that

$$V_w = 0.97 V_p$$

this result is used to get the water speed at the water piston interface prior to the ejection from the orifice. V_p is obtained by dividing the fixed distance between the two conductors (pencil leads), which is needed by the piston to travel and break the two pencil leads, over the time interval measured by the oscilloscope in each firing.

Chapter 4

RESULTS

4.1 Introduction

This chapter is devoted to represent the results obtained during this research. The effect of the stand-off distance, orifice diameter, type of jet , jet speed and target materials on the penetration process are presented and shown in separate sections.

4.2 Penetration Results as a Function of Stand-off Distance

4.2.1 Paraffin Wax Targets

As previously discussed, stand-off distance is an important parameter that affects the process. Figures 4.1 through 4.3 inclusive show the depth of penetration as a function of stand-off distance for three different diameter orifices 1.0, 1.5, 2.0 mm's, respectively; at three piston speeds 800, 1000, 1670 m/s and indicated by symbols o, $\triangle$, and $\square$ respectively, using 40 mm thickness paraffin wax targets.

4.2.2 Lead Targets

Results concerning penetration of 20 mm thickness lead targets using the same conditions as those of paraffin wax mentioned previously are shown in figures 4.4 through

4.6 inclusive.

4.2.3 Tin Targets

Results using tin as target material at the same penetration conditions as those of paraffin wax and lead mentioned previously are shown in figures 4.7 through 4.9 inclusive.

4.2.4 'Plasticine' Targets

Results of penetrating 70 mm thick 'plasticine' targets are also shown in figures 4.10 through 4.12 inclusive at the same previously mentioned conditions.

4.3 Penetration with Orifice Diameters Results

Figures 4.13 through 4.16 are concluded from the previous figures which indicate the depth of penetration at a specified stand- off distance of 10 mm with orifice diameters for paraffin wax, lead, tin, and 'plasticine' targets, respectively. Figures are illustrated for the three speeds used in cutting the targets, namely 800, 1000, 1670 m/s indicated by symbols $*$, $+$, and $\Box$, respectively.

Figures 4.17 through 4.20 inclusive are concluded from figures 4.1 through 4.12 give the variation of maximum penetration with orifice diameter at any stand-off distance for penetrating paraffin wax, lead, tin, and 'plasticine', respectively.

4.4 Penetration with Different Additives to the Water Jet

Figures 4.21 through 4.23 inclusive represent the effect of stand-off distance on the depth of penetration for 2.0 mm orifice in paraffin wax targets, at piston speeds of 800, 1000, and 1670 m/s, respectively, for both water jets and water jets with Arabic gum as an additive indicated on each figure by symbols * and +, respectively.

Figure 4.24 is the same as figure 4.22 at the same conditions except using polyethylene glycol as an additive of 1000 ppm.

4.5 Variation of Depth of Penetration with Impact Speed

Figures 4.25 through 4.28 inclusive show the effect of piston speed on the depth of penetration, using paraffin wax, lead, tin, and 'plasticine' as target materials, respectively for three orifices, 1.0, 1.5, and 2.0 mm's indicated by symbols *, +, and □, respectively at a specified stand-off distance.

4.6 Ice Penetration

Figure 4.29 shows the variation of the depth of penetration with stand-off distance for 2.0 mm orifice diameter at 800 m/s piston speed, in an ice target.

Chapter 5

DISCUSSION

5.1 Introduction

As previously mentioned, water-jet cutting process is affected by different parameters, mainly, stand-off distance, impact speed, fluid type,...etc, that lead investigators for the optimization of these variables in order to enhance the process performance. This Chapter is devoted to discuss the results obtained in this work.

5.2 Effect of Stand-off Distance

The water-jet, used in cutting, consists of three regions [22], laminar, transient laminar-turbulent, and turbulent, respectively in the axial direction from the slug to the tip of the jet.

Thus by increasing the stand-off distance, the jet is transferred from laminar into turbulent flow which leads to scattering of the jet and the appearance of a water-droplets cloud which reduces the momentum of flow in the axial direction, hence reduces cutting performance.

Figures 4.1 through 4.12 inclusive represent the results of penetration at different stand-off distances (equivalent to 0D, 5D, 7.5D, 10D, 15D, and 20D where D is the jet mechanical strength and low melting point as shown in figures 4.10 through 4.12 inclusive.

In some cases, the maximum penetration is at zero stand-off distance, while in others it is minimum according to the impact speed used.

Figure 4.11 shows a common stand-off distance of 10.0 mm for two peaks at speeds 1000 and 1670 m/s and at 15.0 mm stand-off distance for 800 and 1670 m/s as shown in figure 4.12.

From the general look to the figures illustrated, it could be seen that 'plasticine' and tin form the penetration extremes in a way that the maximum is in the former and the minimum is in the latter.

5.3 Effect of the Orifice Diameter

5.3.1 For Constant Stand-off Distance

Figures 4.13 through 4.16 inclusive show penetration as a function of orifice diameters (jet diameters) for paraffin wax, lead, tin, and 'plasticine' targets ,respectively at constant stand-off distance, namely 10.0 mm. Those figures were concluded from figures 4.1 through 4.12.

Maximum penetration for paraffin wax and 'plasticine' targets was obtained when using 1.5 mm orifice diameter in an ordered increasing speed sequence as shown in figures 4.13 and 4.16, respectively, while it is minimum for tin targets at 1000 and 1670 m/s impact speeds, and it is maximum at 2.0 mm orifice diameter and 800 m/s speed as in figure 4.15.

Figure 4.14 clarifies the agreement of paraffin wax and 'plasticine' results at 1000 m/s impact speed to that obtained using lead targets, while penetration continuously increases with orifice diameters in the case of other speeds, namely 800 and 1670 m/s.

5.3.2 Maximum Penetration at any Stand-off Distance

Similar results were concluded for paraffin wax and 'plasticine' targets as discussed in section 5.3.1 and figures 4.17 and 4.20, while penetration is continuously increasing with orifice diameter for lead targets in an ordered impact speed sequence as in figure 4.18.

Figure 4.19 shows the maximum penetration with orifice diameter for tin targets. A reduction of the maximum penetration is observed when using 1.5 mm orifice diameter.

5.4 Effect of Additives to Jet

5.4.1 Arabic Gum - Drinking Water Jet

Penetration increases with increasing jet cohesion and the elimination of the water-droplets cloud formed as the jet progresses. Addition of some soluble additives to the jet may improve its capability on penetration. In this work, 1000 ppm arabic gum concentration was added to the water to study its effect on the jet capability for penetration.

Results are presented in figures 4.21 through 4.23 inclusive for impact speeds 800, 1000, 1670 m/s, respectively when paraffin wax targets and 2.0 mm orifice diameter were used. As it can be seen from these figures , at 800 m/s speed, penetration was reduced all over the stand-off distance range, whilst it was increased for 1000 and 1670 m/s speeds at zero stand-off distance after which it started to decrease.

5.4.2 Polyethylene Glycol - Drinking Water Jet

Figure 4.24 represents a comparison of penetration between water and 1000 ppm polyethylene glycol/water jet. A reduction of penetration all over the stand-off distance range was observed, however, at a 15.0 mm stand-off distance, the jet recovered its stability and penetrated the same depth of penetration as that of drinking water jet.

5.5 Effect of Impact Speed

Figures 4.25 through 4.28 inclusive show the effect of impact speed on depth of penetration for paraffin wax, lead, tin , and 'plasticine' targets, respectively.

Generally, as it can be seen from these figures, penetration increases with jet momentum, whilst for some points penetration is maximum at lower speeds as shown in figure 4.25 for 1.5 mm orifice diameter, paraffin wax targets, and 5D stand-off distance. This reflects the effect of other interdependent variables, e.g. aspect ratio and other parameters in the process.

5.6 Shape of the Penetrated Cavity

Penetration, as stated by Field et al. [10], is a function of the jet and target densities and the length of the jet (i.e. $d = l\sqrt{\rho_j/\rho_t}$, where d is the depth of penetration, l is the length of the jet, and ρ_j and ρ_t are the densities of the jet and the target, respectively).

Examination of this relationship indicates that penetration, d, increases as the target density decreases for the same jet fluid. Results obtained in this work are in full agreement with this relation, when comparing lead and tin targets with paraffin wax and 'plasticine' targets, while it is in full disagreement when comparing the penetration of tin with that of lead targets and penetration of paraffin wax with that of 'plasticine' targets.

The previous observations indicate that penetration process is more complicated to be treated and represented by the hydrodynamic model suggested by Field et al.[10] and previously by Taylor et al.[27] and other parameters such as mechanical strength, wave propagation,...etc affect the cutting performance.

It was also observed that the width of the penetrated cavity was tripled or even four times the jet diameter for some targets, which indicates that the effect of shear forces acting on the surface of the target plate cause this enlargement of the penetrated cavity. For these conditions addition of chemicals to the drinking water as jet will enhance the penetration capability of the jet.

The shape of the cavity was observed to be cylindrical all over its depth, which indicates an equal jets strength during penetration and melting occurance, unlike that caused from lined cavity metallic jets in the explosive shaped charge where the shape of the cavity was found to be conical.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Jet cutting technology is one of the topics that is of high concern due to its wide applications and advantages over the other machining processes.

This work was devoted to test some of the parameters which affect the process and in this section the conclusions made are given under each of these parameters.

6.1.1 Varying Stand-off Distance

Varying the stand-off distance while impact speed, orifice diameter , and jet type are kept fixed, the following conclusions can be drawn,

- Different target materials were used and the effect of stand-off distance on penetration, in general, was inversely proportional in all targets, due to the breakage of the jet as it progresses which reduces its stability and continuity.

- An important point, that one has to take into consideration, is the effect of aspect ratio,l/D, since penetration is not only a function of speed but also of this ratio (e.g. the optimum value of l/D for paraffin wax targets was found to be 5.0 for 2.0

mm orifice diameter and 1670 m/s impact speed, as shown in figure 4.3.

- In general, the maximum penetration was observed at zero stand-off distance (i.e. *l/D=0*) due to the cohesion capability of fluid particles in the laminar region when leaving the orifice depending upon the impact speed and the orifice diameter used. This is unlike the metallic jet resulting from a lined cavity shaped charge where certain stand-off distance is necessary to allow elongation of the jet before penetration [26].

  While the flow progresses, it will change its characteristics from the laminar into turbulent region through the transient laminar-turbulent which lead to the formation of water-droplets cloud that scatters the flow and reduces its momentum, and consequently, the ability to cut.

- The maximum and minimum penetration was observed in 'plasticine' and tin targets, respectively.

  'Plasticine' has the lowest mechanical strength and melting temperature among other used target materials hence needs the lowest dynamic loading for penetration.

6.1.2 Varying Orifice Diameter

Generally, in static loading, varying the impact speed leads to an increase in penetration or size of the cavity to be manufactured as in blanking process, while in dynamic loading ($\dot{\epsilon} \geq 10^3/s$, where ϵ is the strain rate) the rule is not general, since penetration depends upon both impact speed and the length of the jet indicated by the aspect ratio,l/D. So, for a suitable impact speed and jet's length characterized by high stability and continuity give the best cutting performance.

6.1.3 Jet Type

The bulk of the results in this work were obtained using drinking water. It was expected that using chemical materials that is soluble in water would increase the jet's stability and the ability to cut. Arabic gum and polyethylene glycol were used with a concentration of 1000 ppm. The results showed that penetration reduced for certain impact speeds, namely 800 m/s, and enhanced at the jet's laminar region (i.e. $l/D=0$) at 1000 and 1670 m/s piston speeds when using arabic gum as an additive.

6.1.4 Cavity Shape

Cavities obtained were cylindrical in shape which indicates an equality of the penetration strength over the cut path.

An enlargement of the cavity was observed in the radial direction due to the shear forces in the radial direction of the target that compensates a significant amount of the jet's momentum that causes the penetration in the longitudinal direction. Additives were used in these conditions to reduce this effect and enhance the depth of penetration by modifying the shear forces.

On the whole it can be concluded that 'plasticine' and tin as target materials represent the two extremes in the penetration process within the limitations of the testing made throughout this work.

Penetration, d, is inversely proportional to the target's density, consequently, tin targets penetration should be more than that of lead targets and it was in full disagreement with the results of this work. The same argument applies for paraffin wax and 'plasticine' targets.

This leads to think with other parameters affecting penetration other than the density of the target material and the length of the impact jet, as melting temperature, material's strength, wave propagation,...etc.

Accordingly, Taylor expression might need modification to include the strengths and melting points of the jet and target materials to be of the form [26],

$$d = l\sqrt{\frac{\rho_j}{\rho_t}} + [F(\sigma) * G(T)],$$

where $F(\sigma)$ and $G(T)$ are indications to the material's strength and melting process, respectively.

6.2 Recommendations

Jet cutting technology is a solution to many industrial applications that other cutting methods lack especially for processes where thermal stresses, fire hazards, and dust are to be avoided.

Concerning this work, extensions may be suggested for future investigations,

- Penetration of other materials that were not used in this work like ceramics, plastics, wood,...etc is recommended.
- The jet, in this work, was freely drawn out of the orifice, a swiral mechanism applied to the jet may increase its effectiveness, therefore it is suggested to be investigated.
- The target, in this work, was stationary, vibrating the target and applying a cross air jet over the surface of the target may affect penetration, and are worthwhile to be studied.

- Using polymers, with different concentrations, increase the stability of the jet [22], accordingly, these types of jets are suggested.

- Using different types of nozzles (e.g. exponential shape nozzles and others) and studying their performance numerically in order to optimize the system's nozzle design is suggested.

- Studying the effect of penetration on the microstructure of the target material and the mechanism of cavity formation and crack propagation needs to be further investigated.

- The effect of the target thickness and lamination is of prime importance on the penetration process, and requires investigation.

- Literature lacks data concerning the coefficient of discharge within orifices of different geometries at such high velocities of flow of water; therefore it is suggested that the coefficient of discharge should be determined and the data could be extended to include the effect of Mach number on penetration process.

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FIGURES

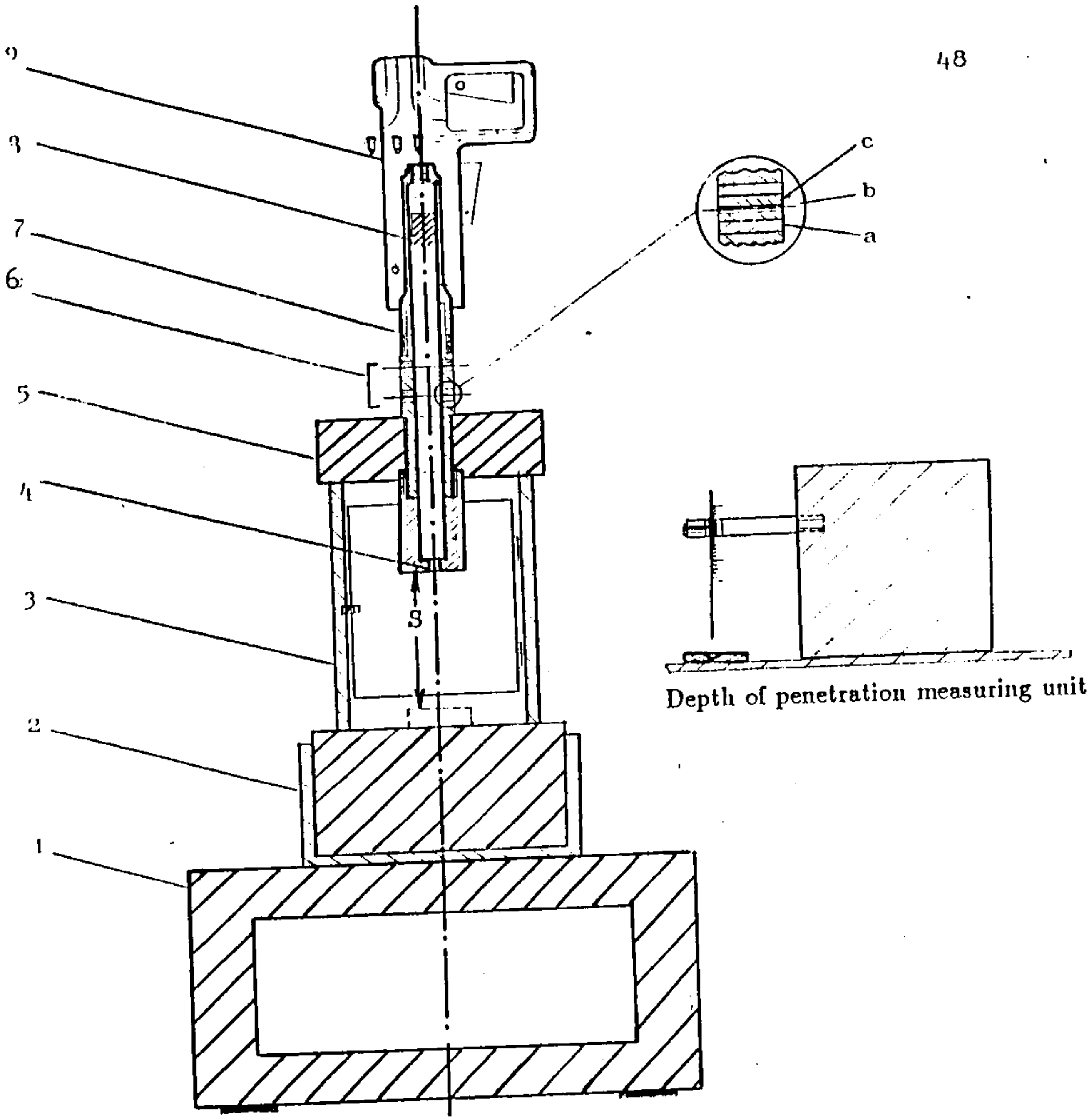

Fig.2.1. The test rig; 1- Base, 2- Base plate, 3- Protection shield, 4- Water packet with orifice, 5- Bush, 6- Velocity measuring unit, (a) Teflon, (b) Conductor, (c) Brass, 7- Extension barrel, 8- Piston, 9- Gun.

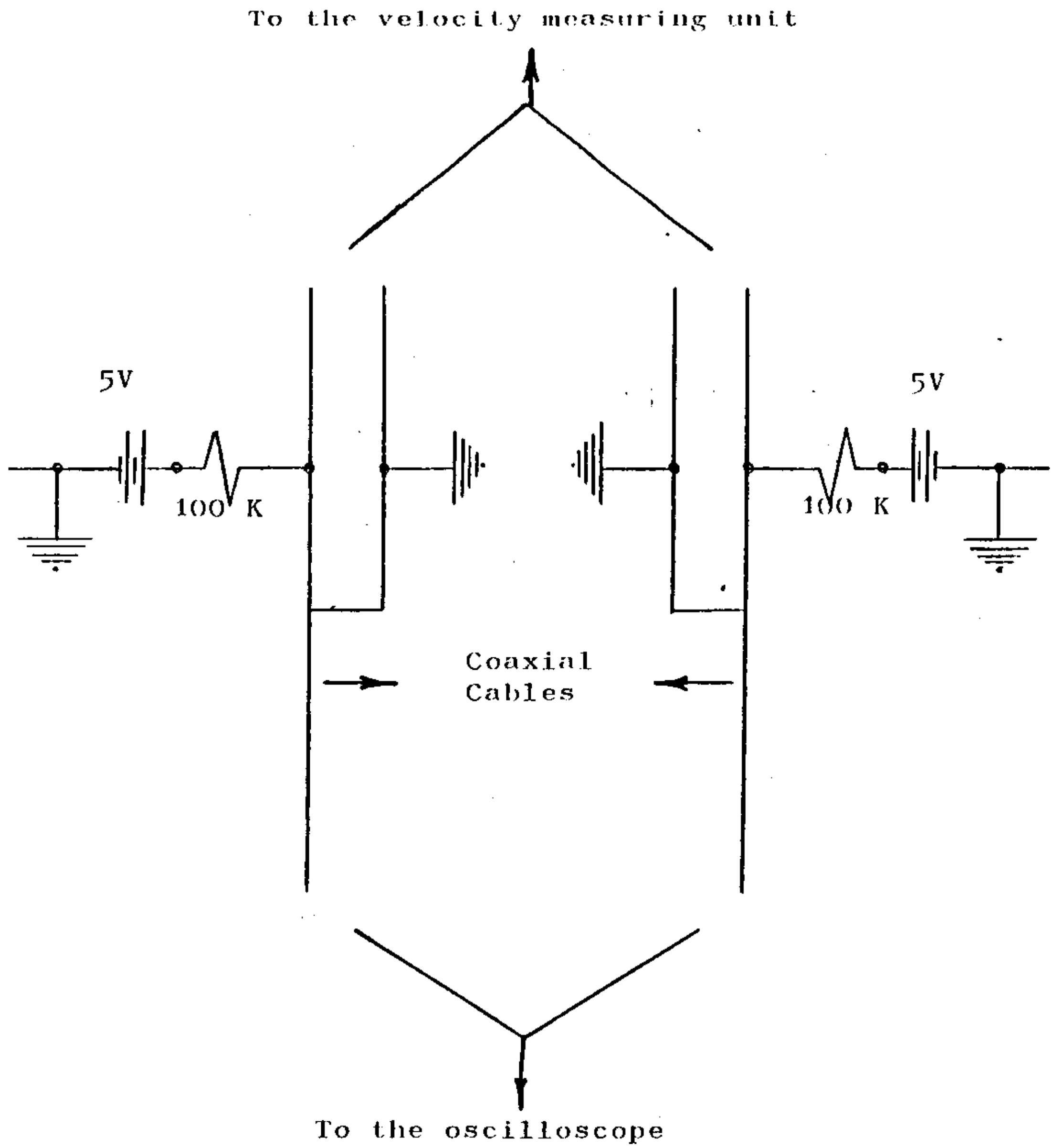

Fig.2.2. The electrical circuit connected to the velocity measuring unit.

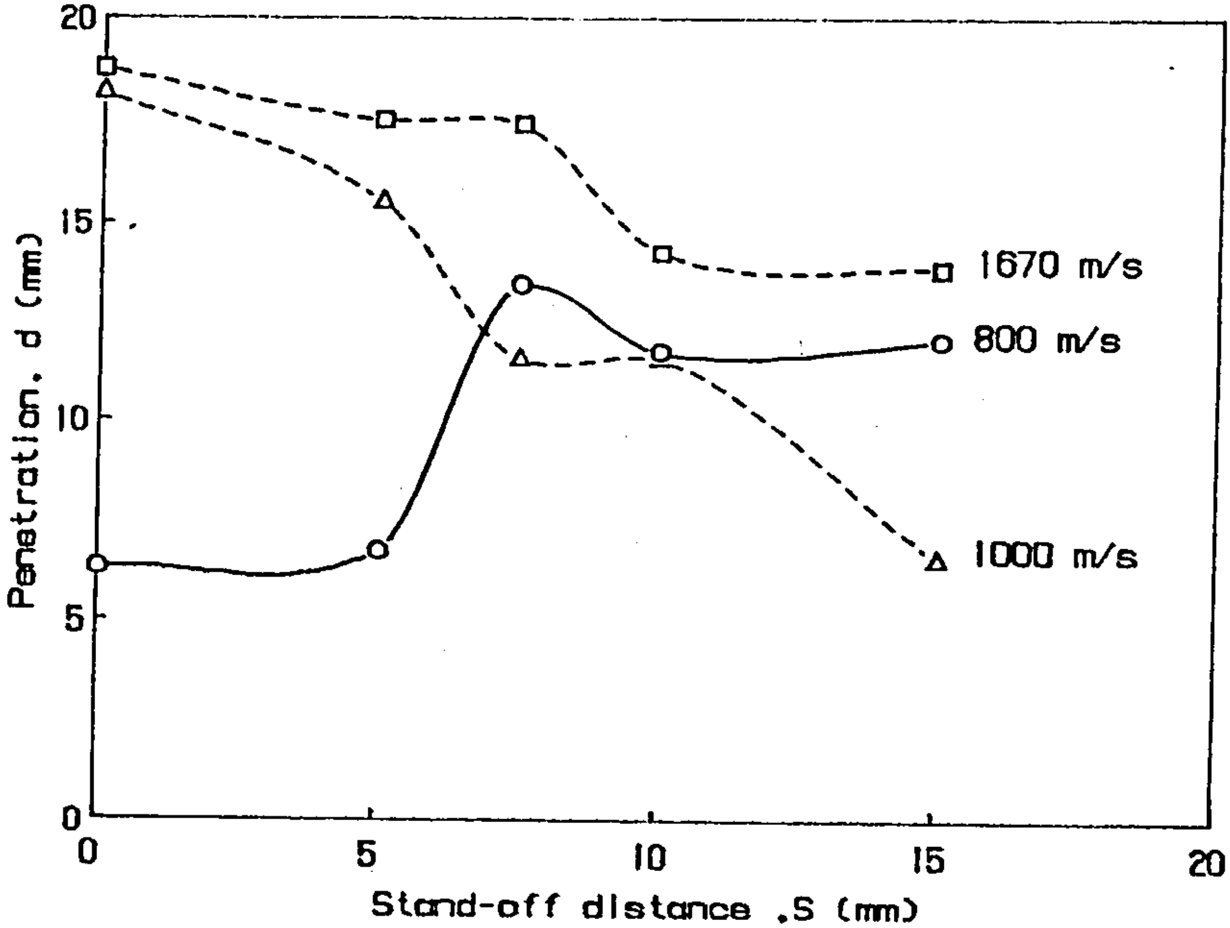

Fig.4.1. Variation of depth of penetration with stand-off distance at different piston speeds, for paraffin wax target and an orifice of 1.0 mm diameter.

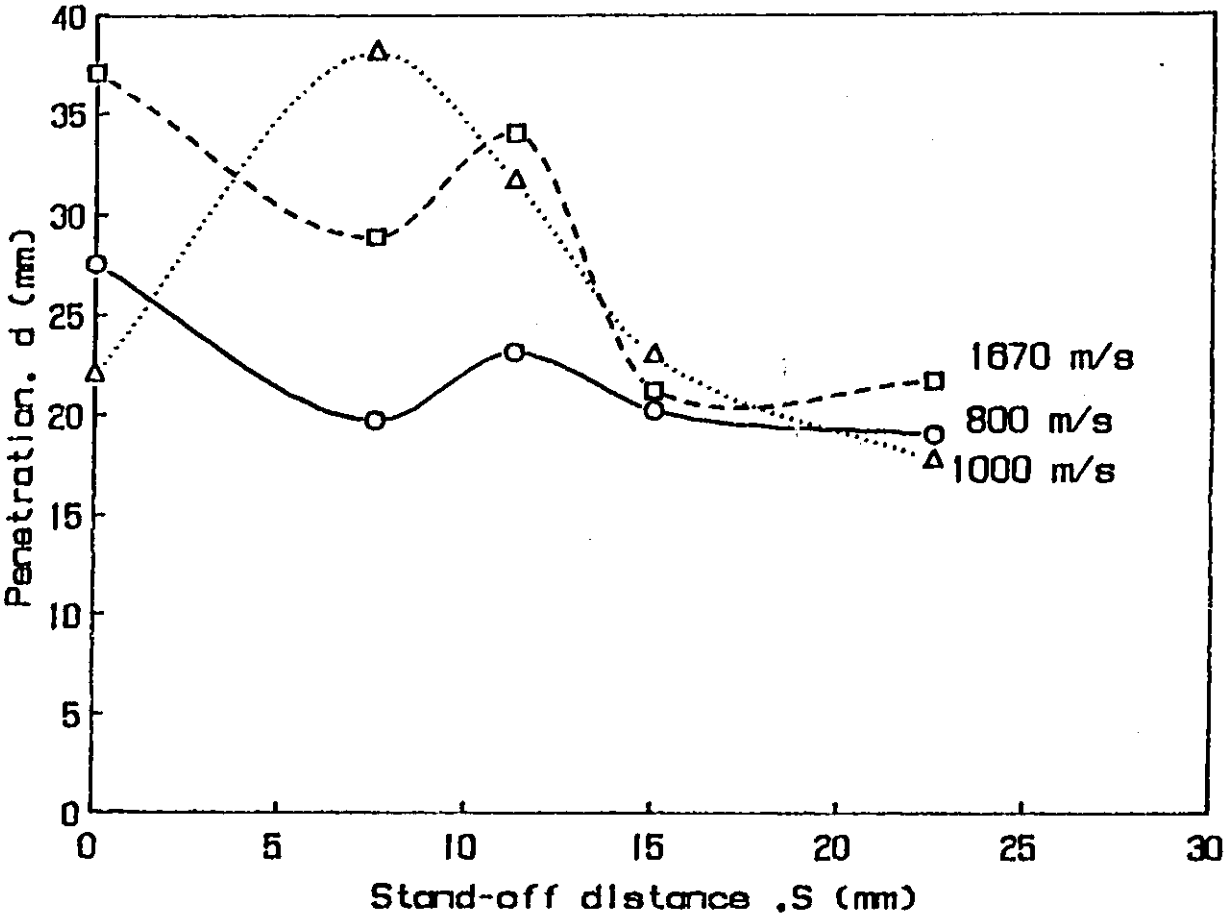

Fig.4.2. Variation of depth of penetration with stand-off distance at different piston speeds, for paraffin wax target and an orifice of 1.5 mm diameter.

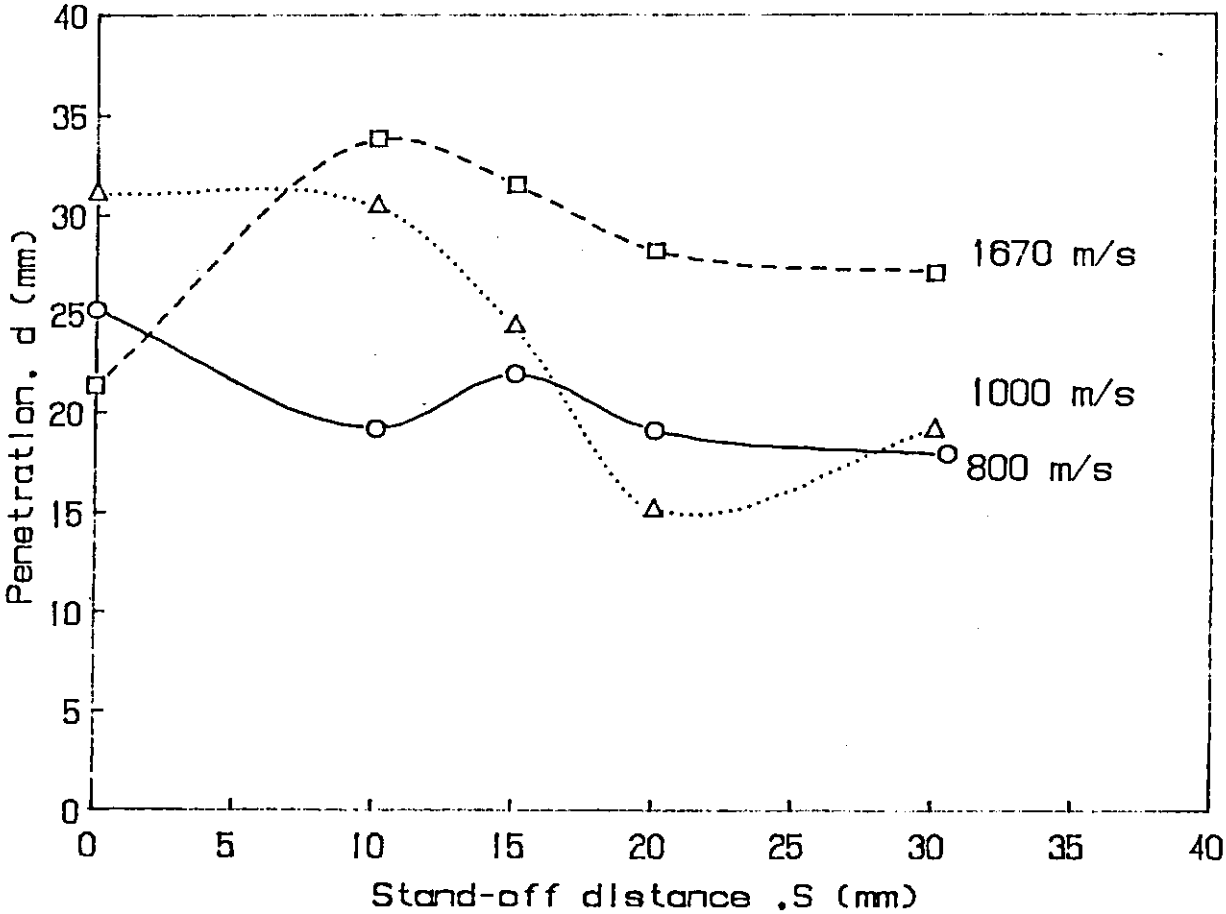

Fig.4.3. Variation of depth of penetration with stand-off distance at different piston speeds, for paraffin wax target and an orifice of 2.0 mm diameter.

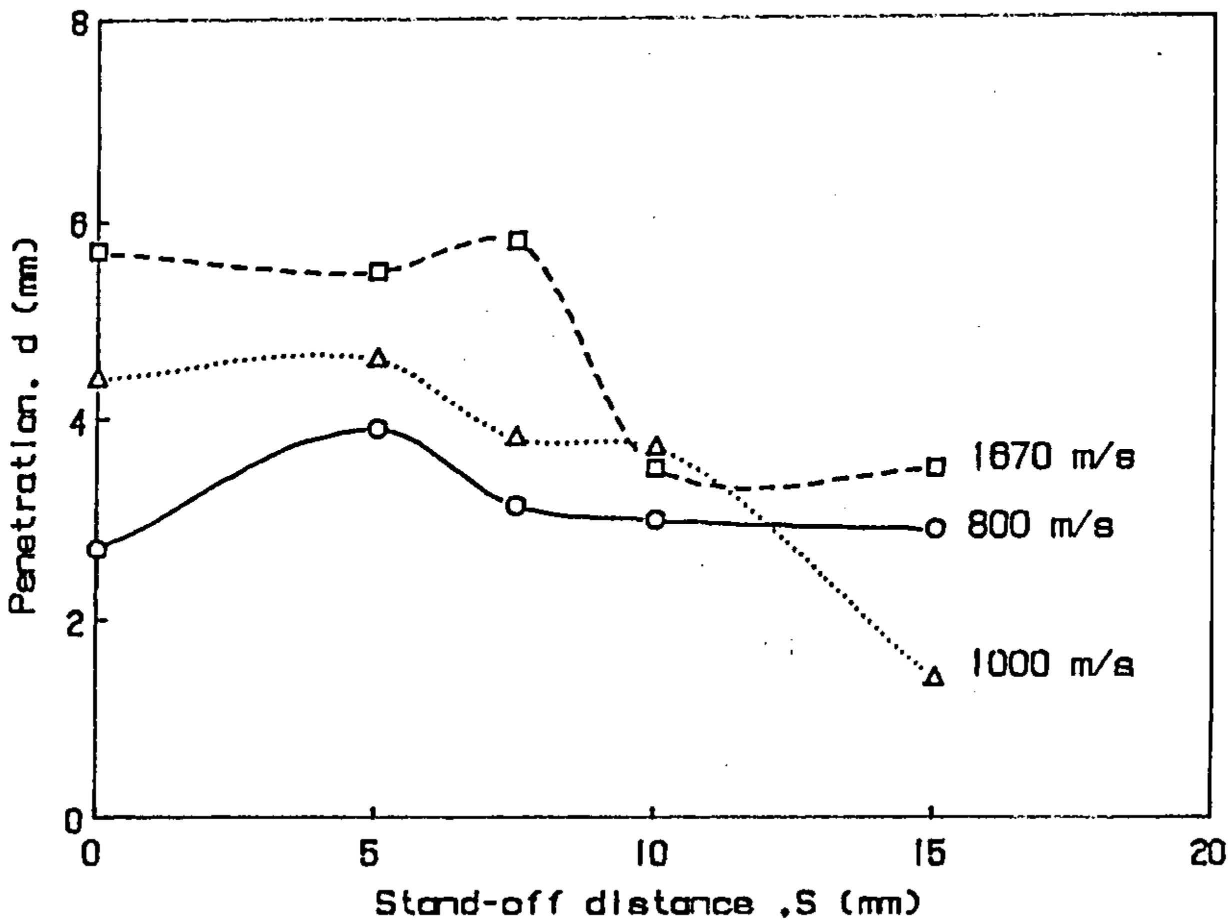

Fig.4.4. Variation of depth of penetration with stand-off distance at different piston speeds, for lead target and an orifice of 1.0 mm diameter.

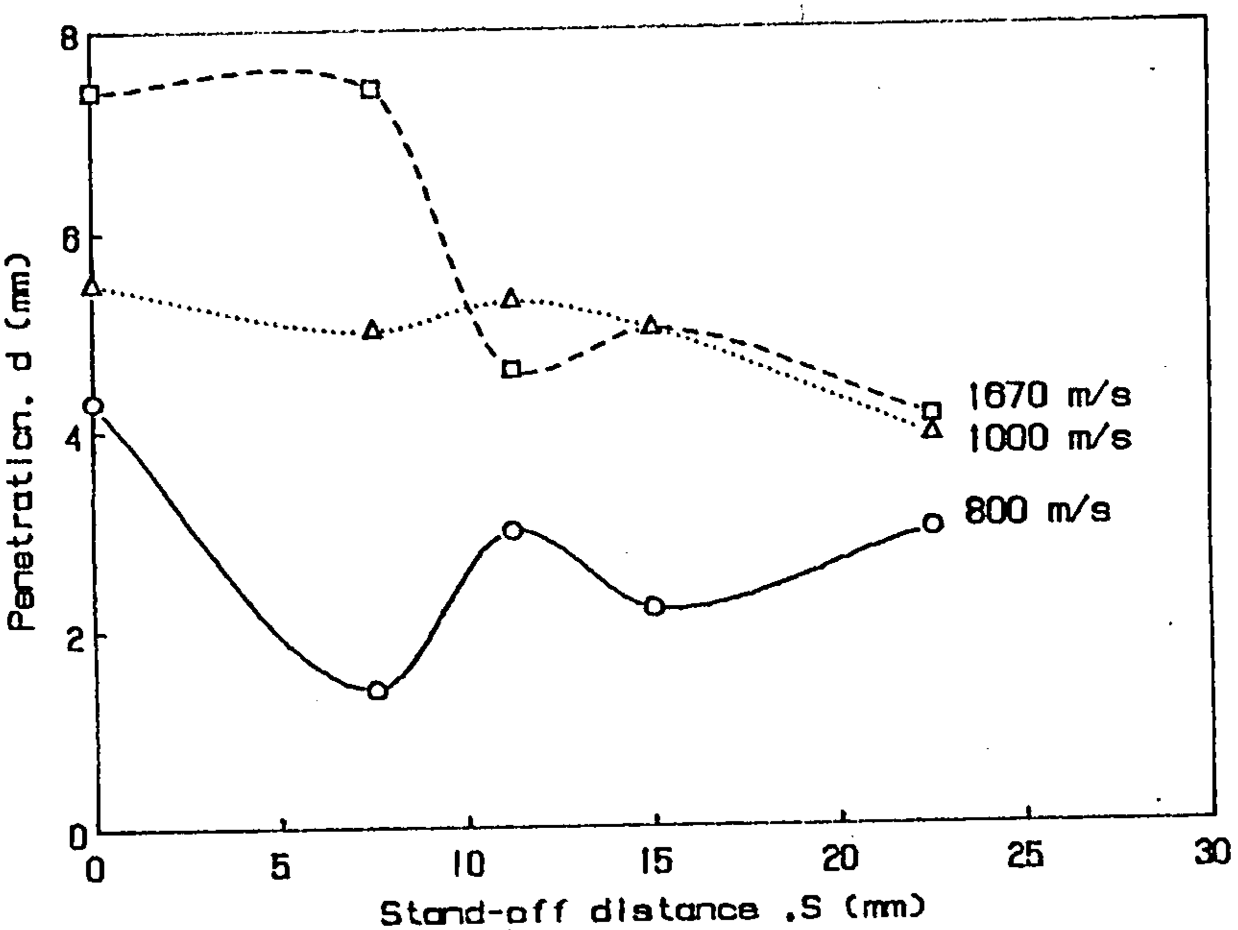

Fig.4.5. Variation of depth of penetration with stand-off distance at different piston speeds, for lead target and an orifice of 1.5 mm diameter.

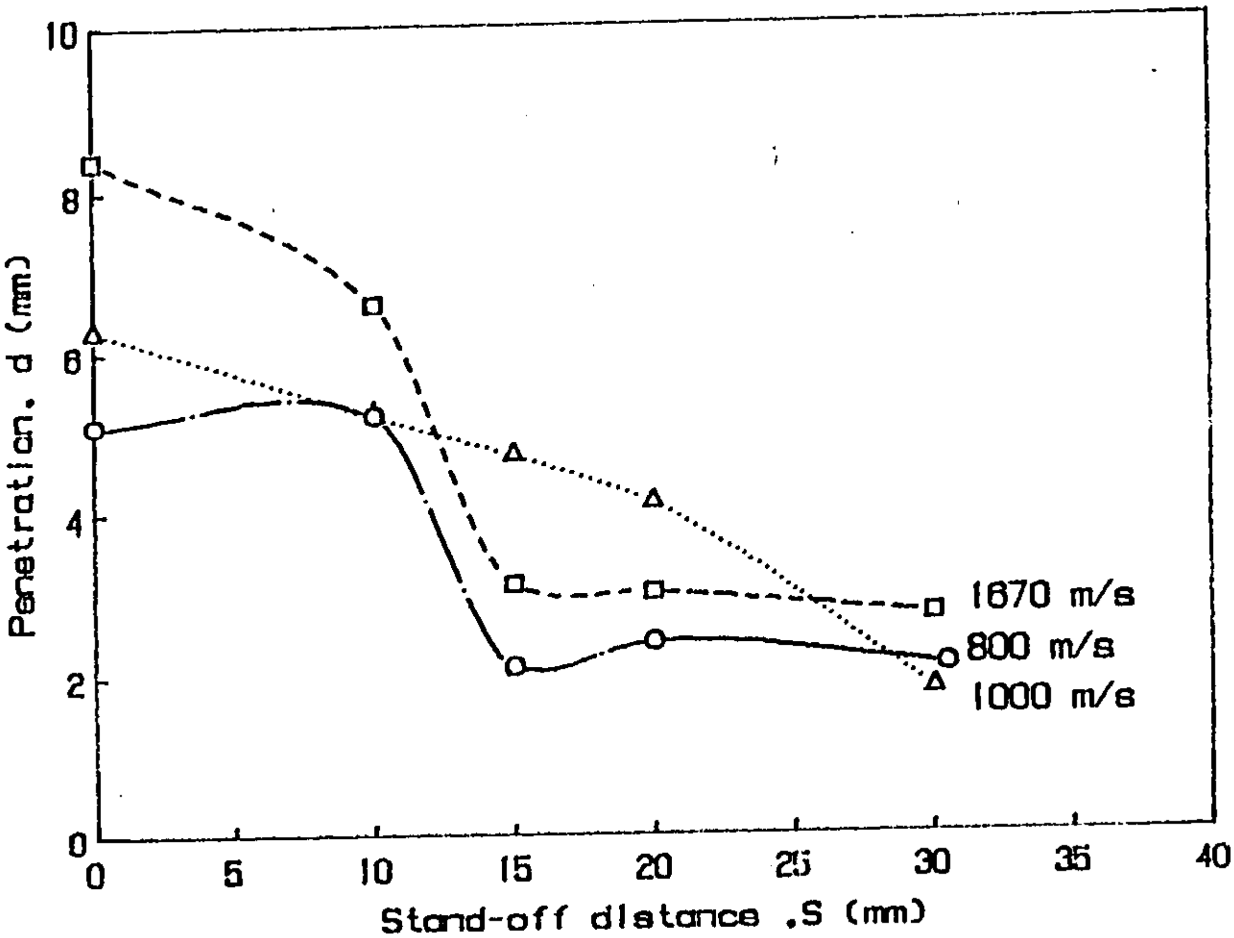

Fig.4.6. Variation of depth of penetration with stand-off distance at different piston speeds, for lead target and an orifice of 2.0 mm diameter.

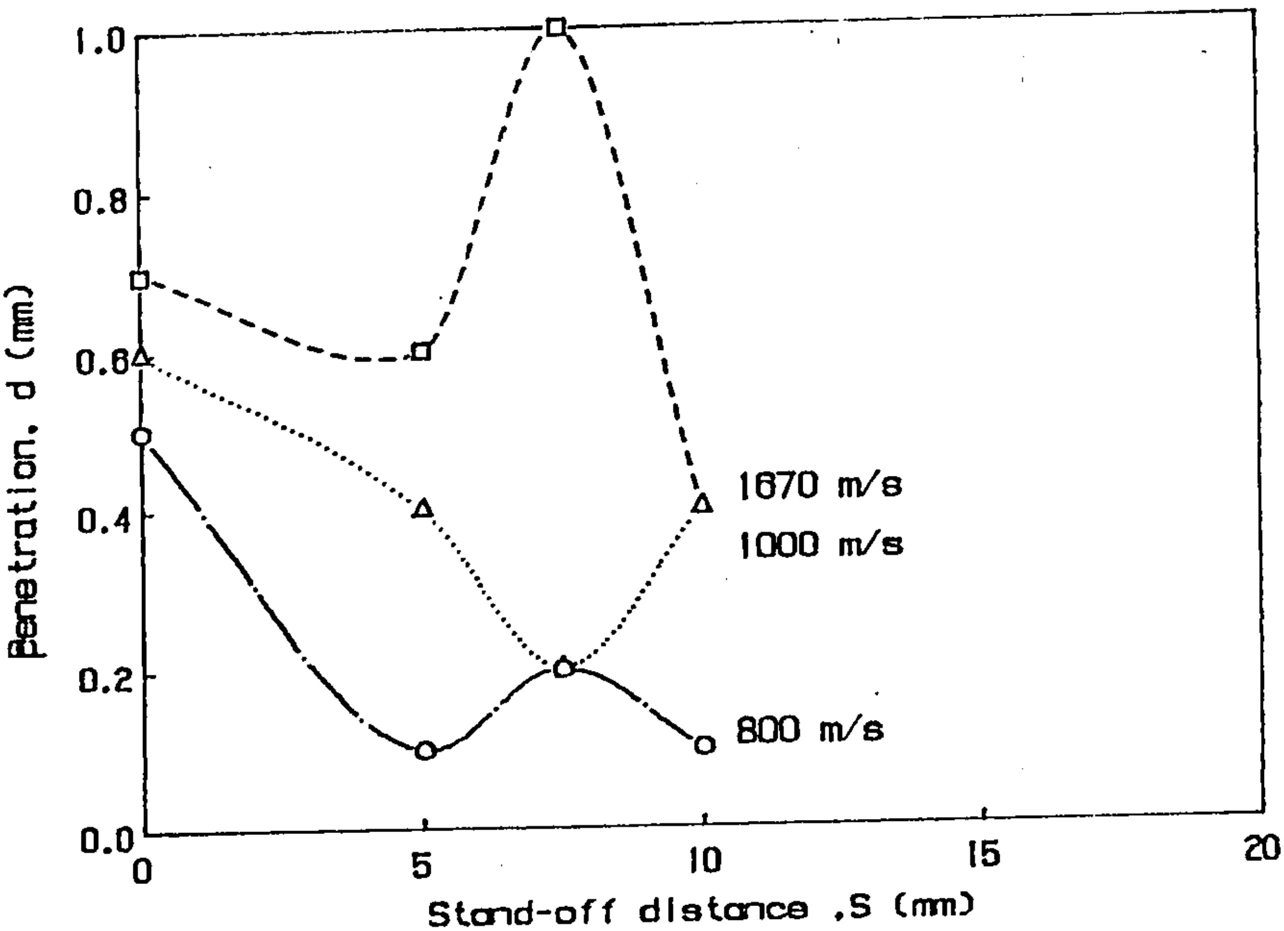

Fig.4.7. Variation of depth of penetration with stand-off distance at different piston speeds, for tin target and an orifice of 1.0 mm diameter.

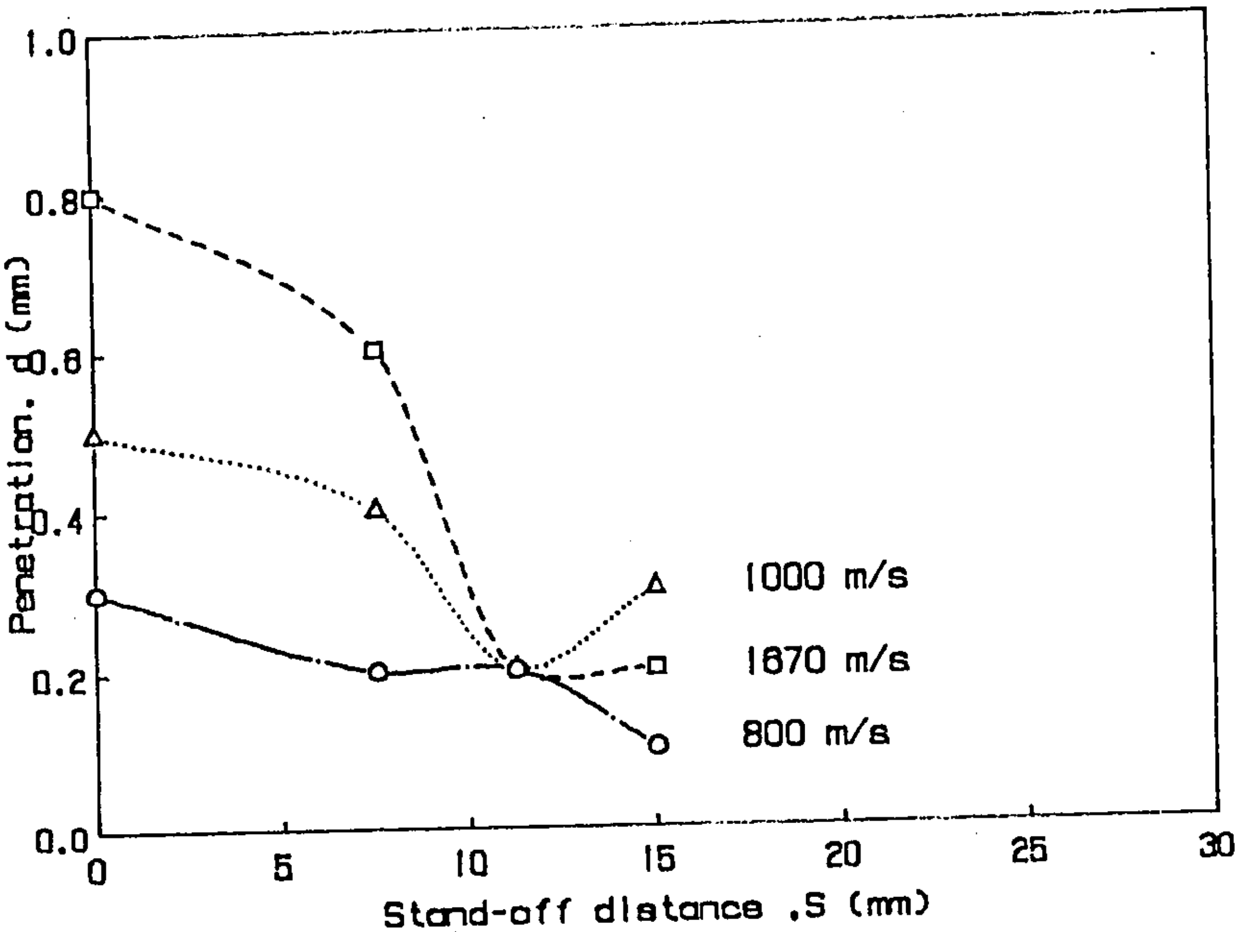

Fig.4.8. Variation of depth of penetration with stand-off distance at different piston speeds, for tin target and an orifice of 1.5 mm diameter.

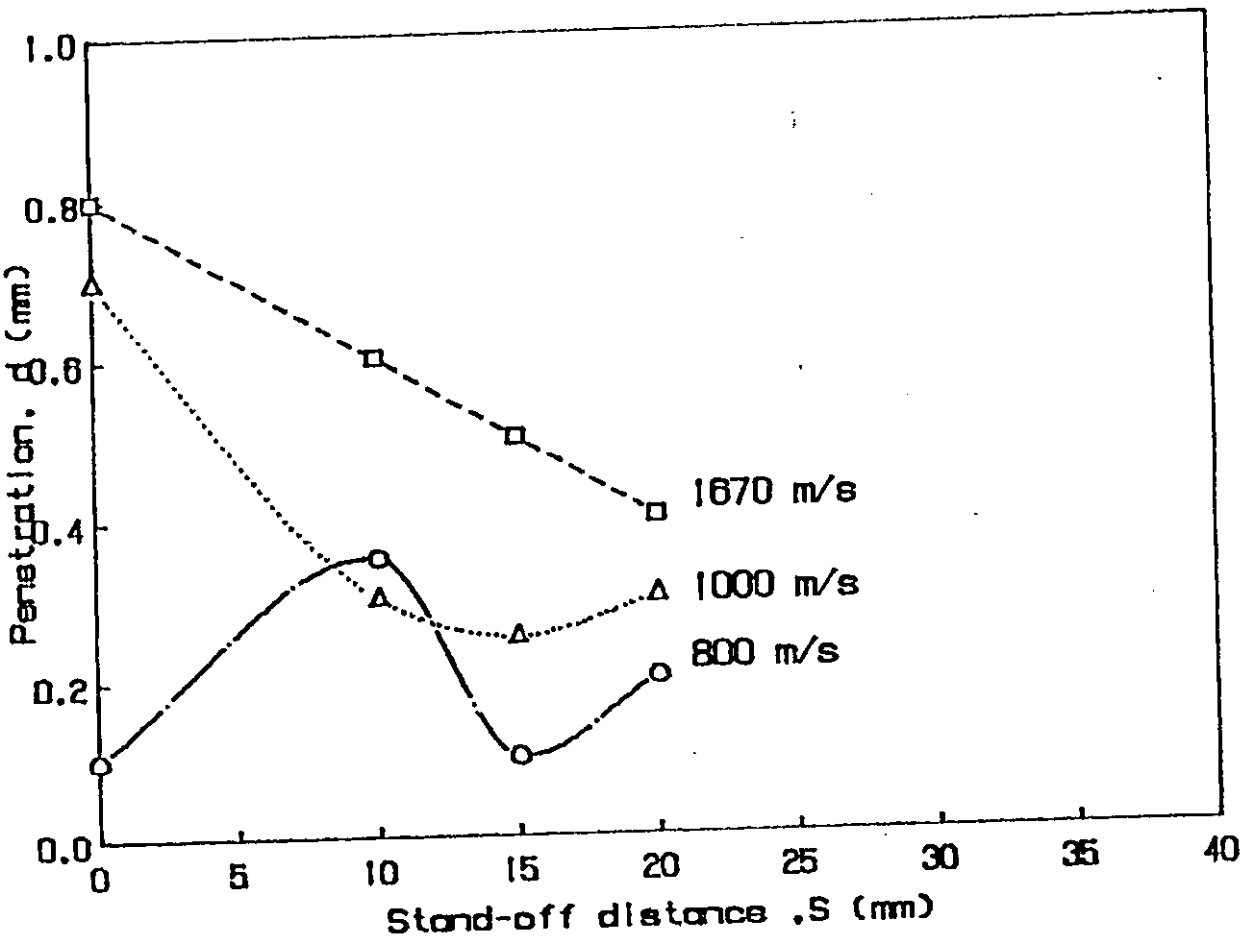

Fig.4.9. Variation of depth of penetration with stand-off distance at different piston speeds, for tin target and an orifice of 2.0 mm diameter.

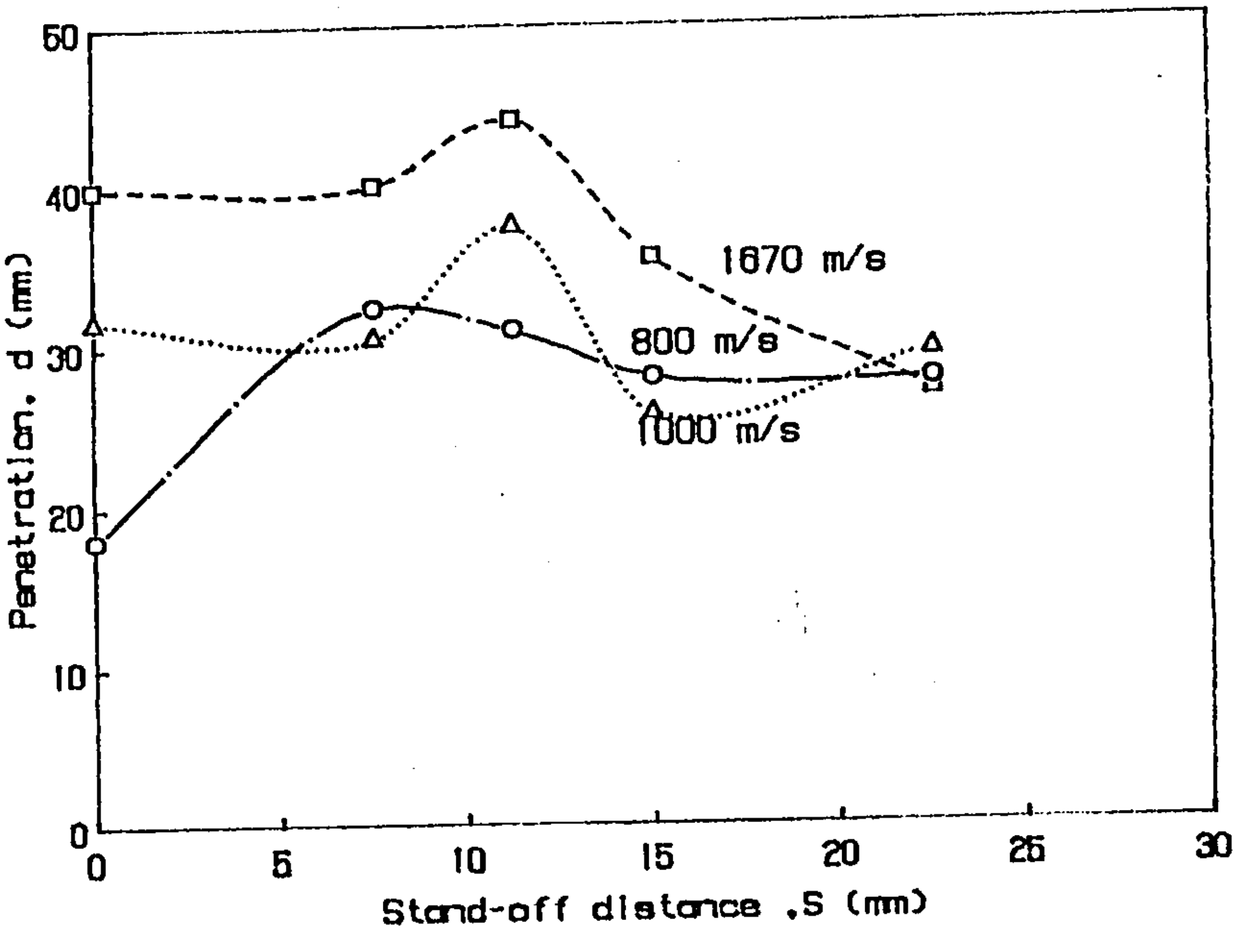

Fig.4.11. Variation of depth of penetration with stand-off distance at different piston speeds, for 'plasticine' target and an orifice of 1.5 mm diameter.

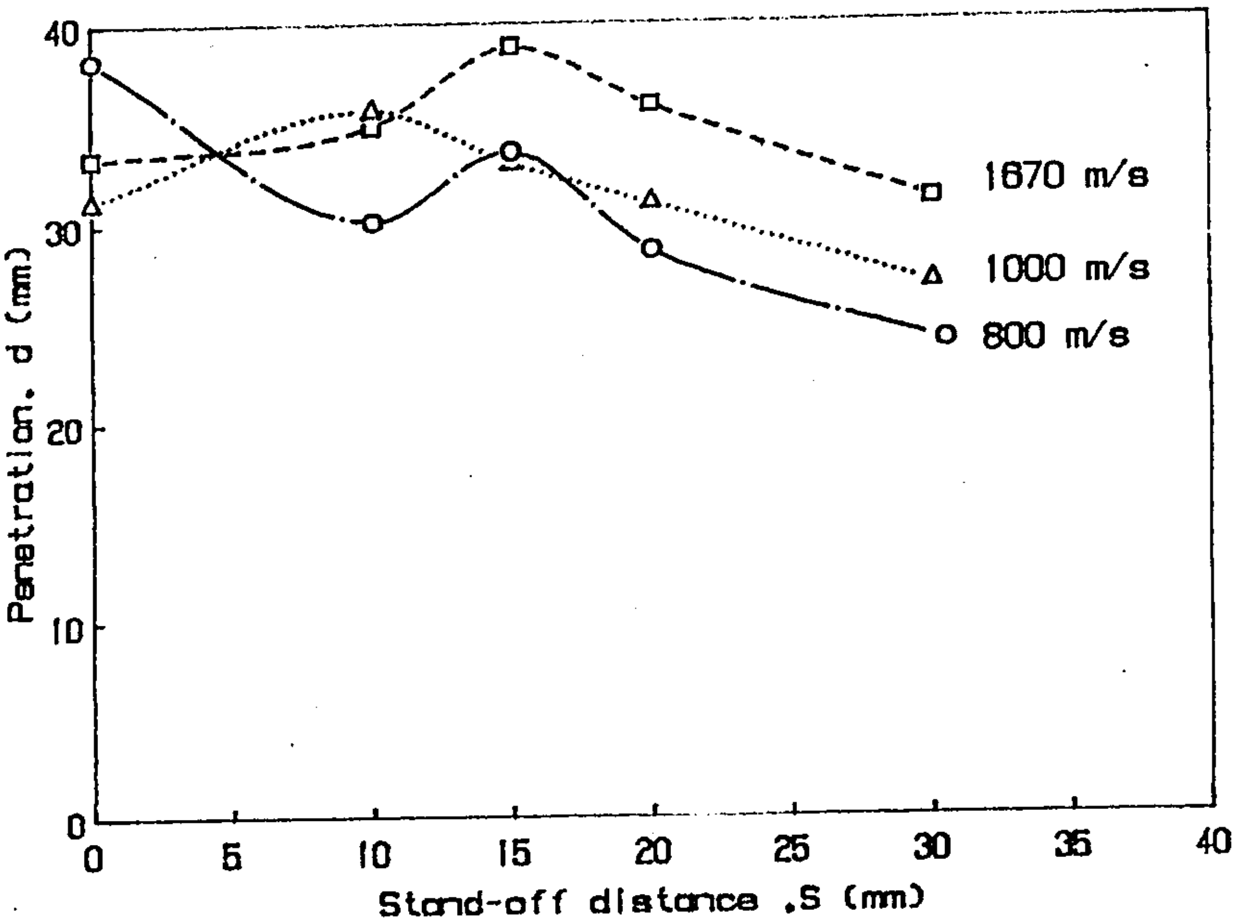

Fig.4.12 Variation of depth of penetration with stand-off distance at different piston speeds, for 'plasticine' target and an orifice of 2.0 mm diameter.

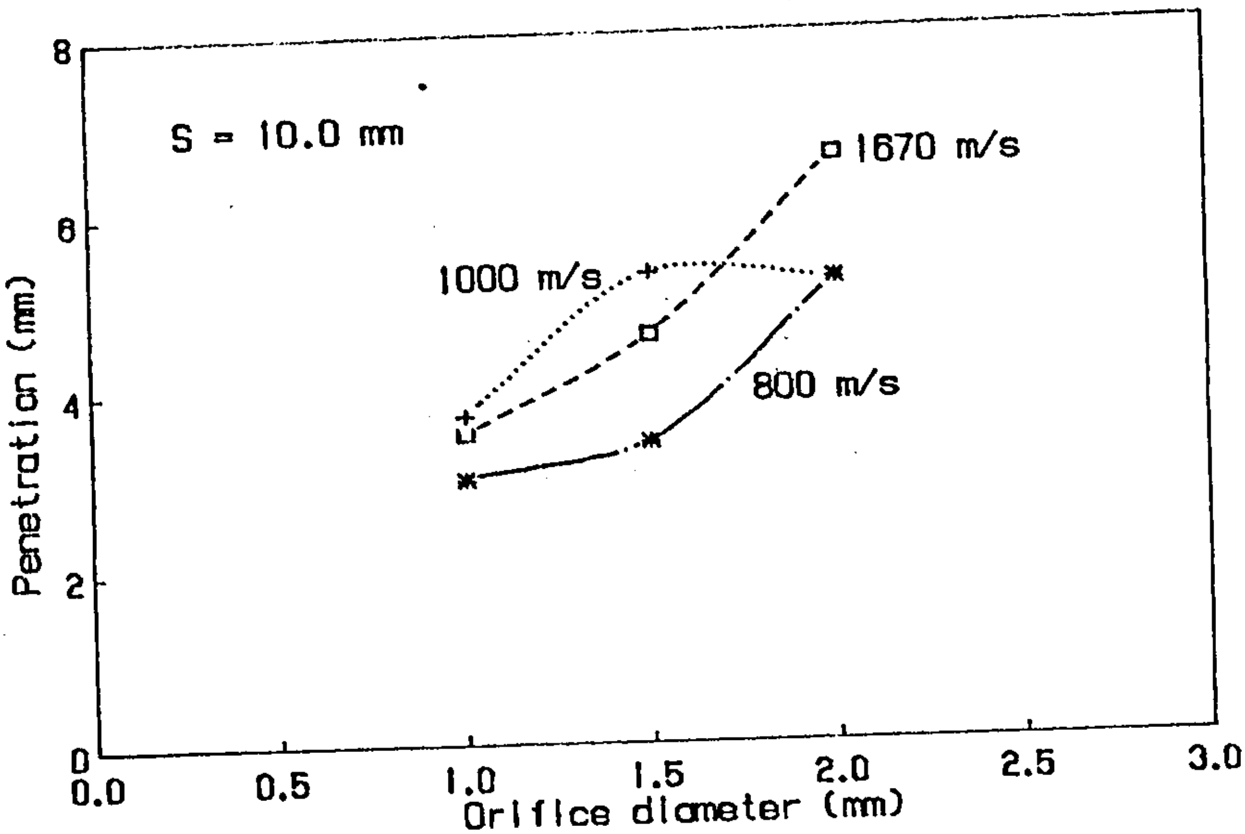

Fig.4.14. Penetration versus orifice diameter at 10 mm stand-off distance for lead target at different piston speeds

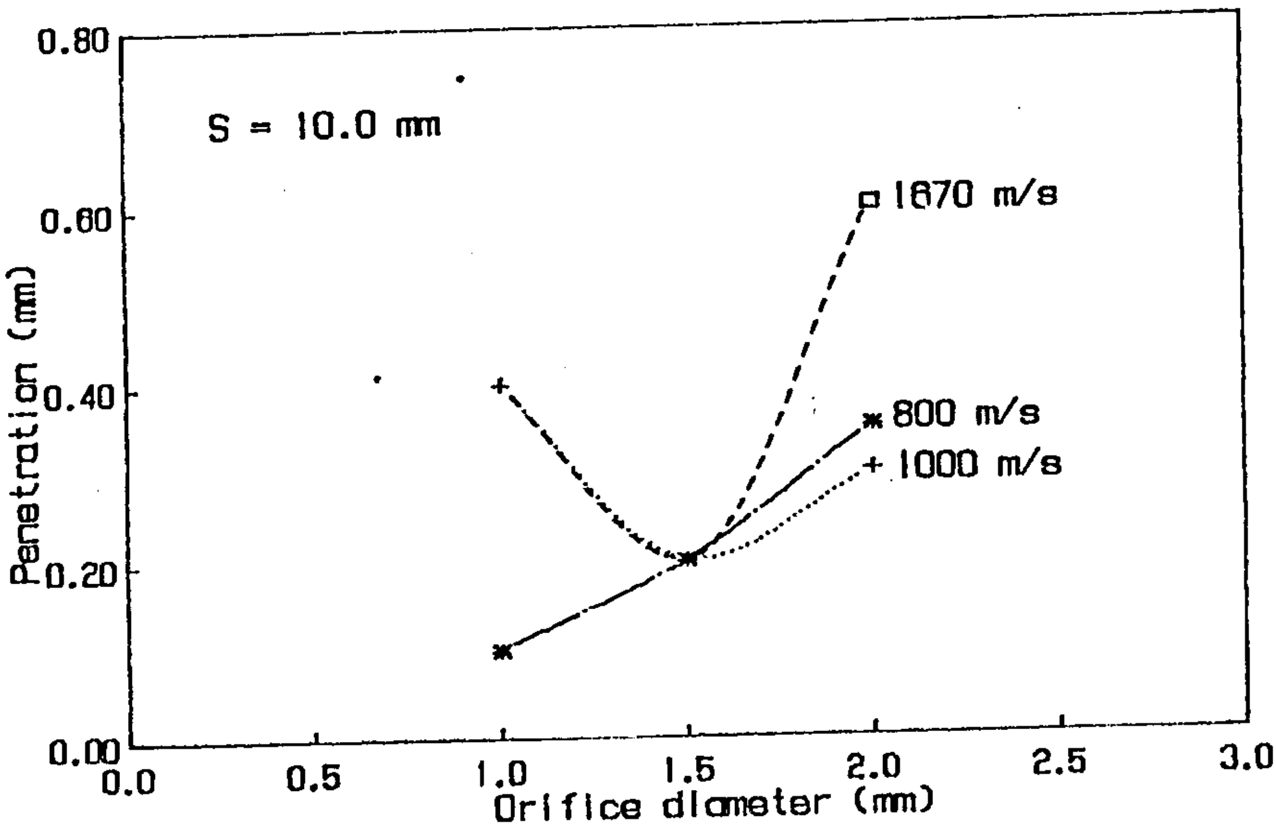

Fig.4.15. Penetration versus orifice diameter at 10 mm stand-off distance for tin target at different piston speeds

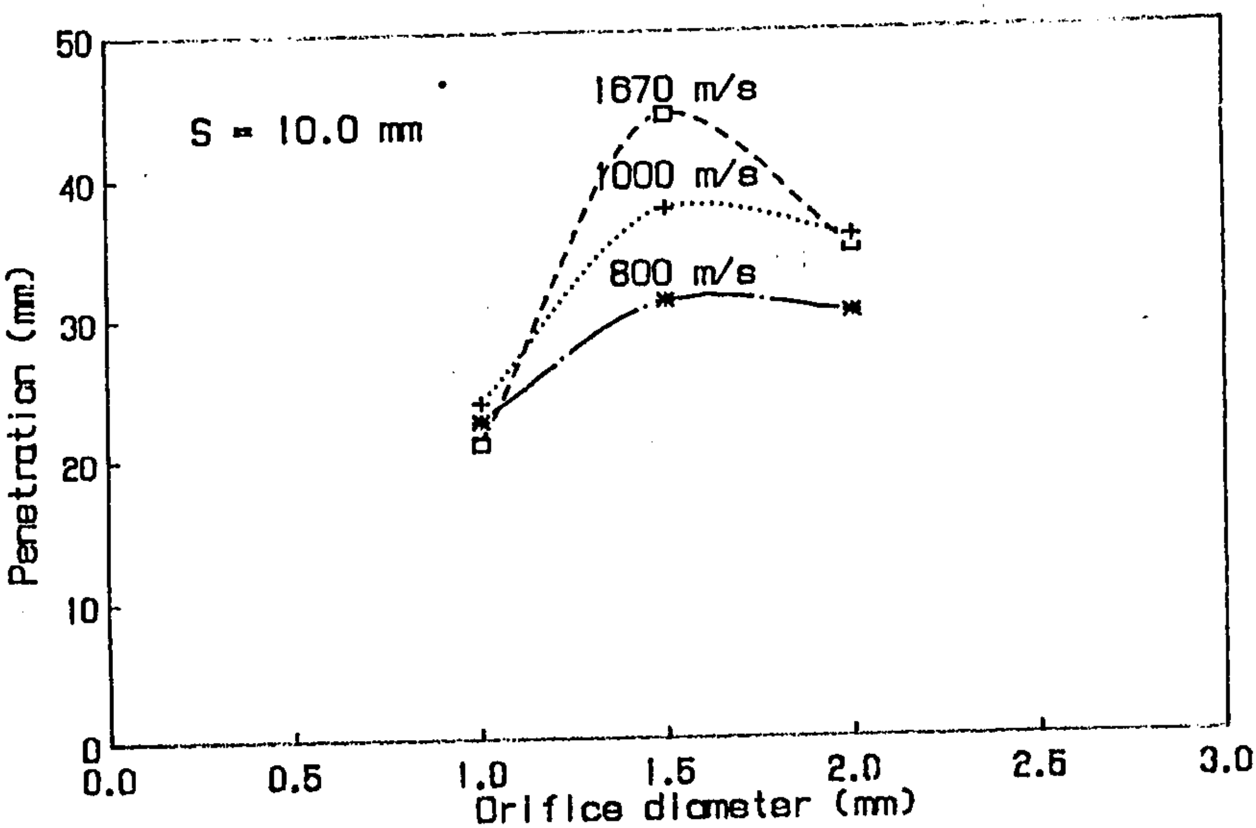

Fig.4.16. Penetration versus orifice diameter at 10 mm stand-off distance for 'plasticine' target at different piston speeds

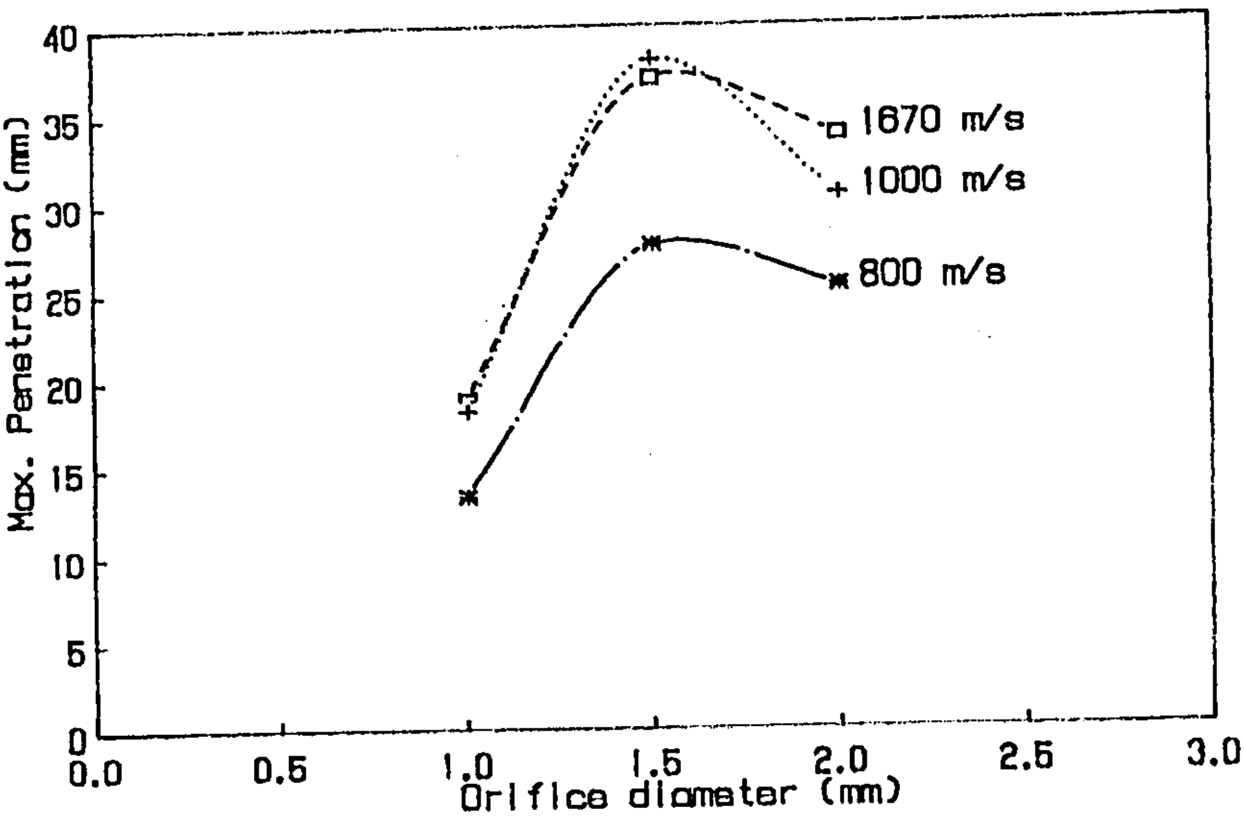

Fig.4.17. Maximum penetration versus orifice diameter at any stand-off distance for paraffin wax target at different piston speeds

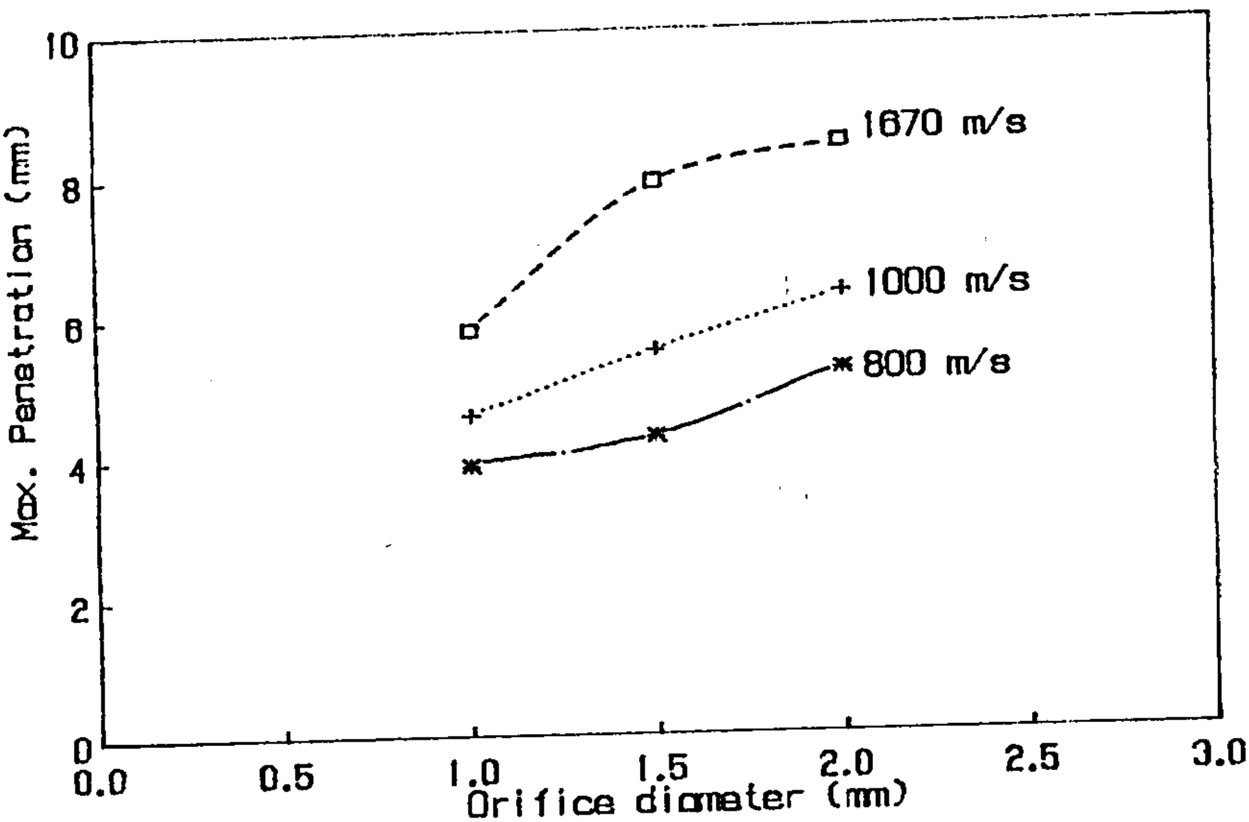

Fig.4.18. Maximum penetration versus orifice diameter at any stand-off distance for lead target at different piston speeds

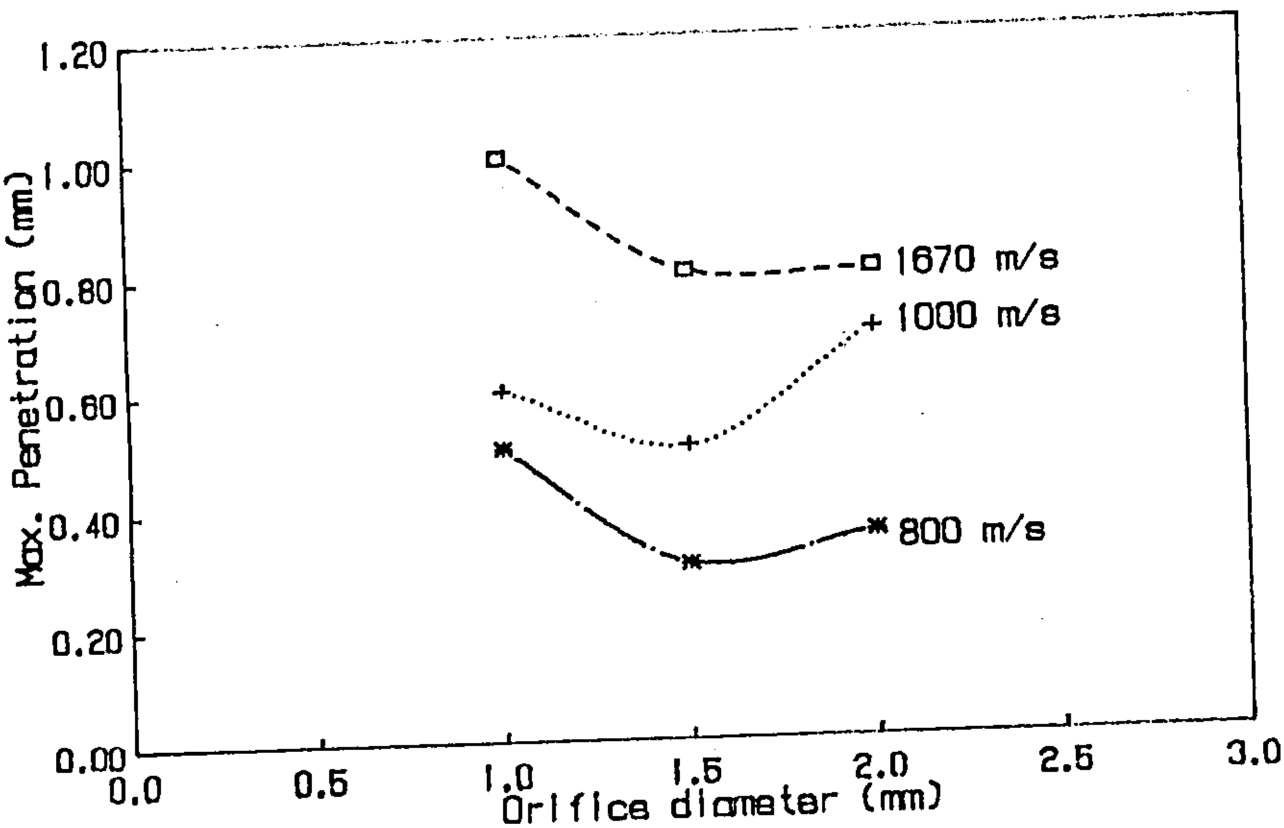

Fig.4.19. Maximum penetration versus orifice diameter at any stand-off distance for tin target at different piston speeds

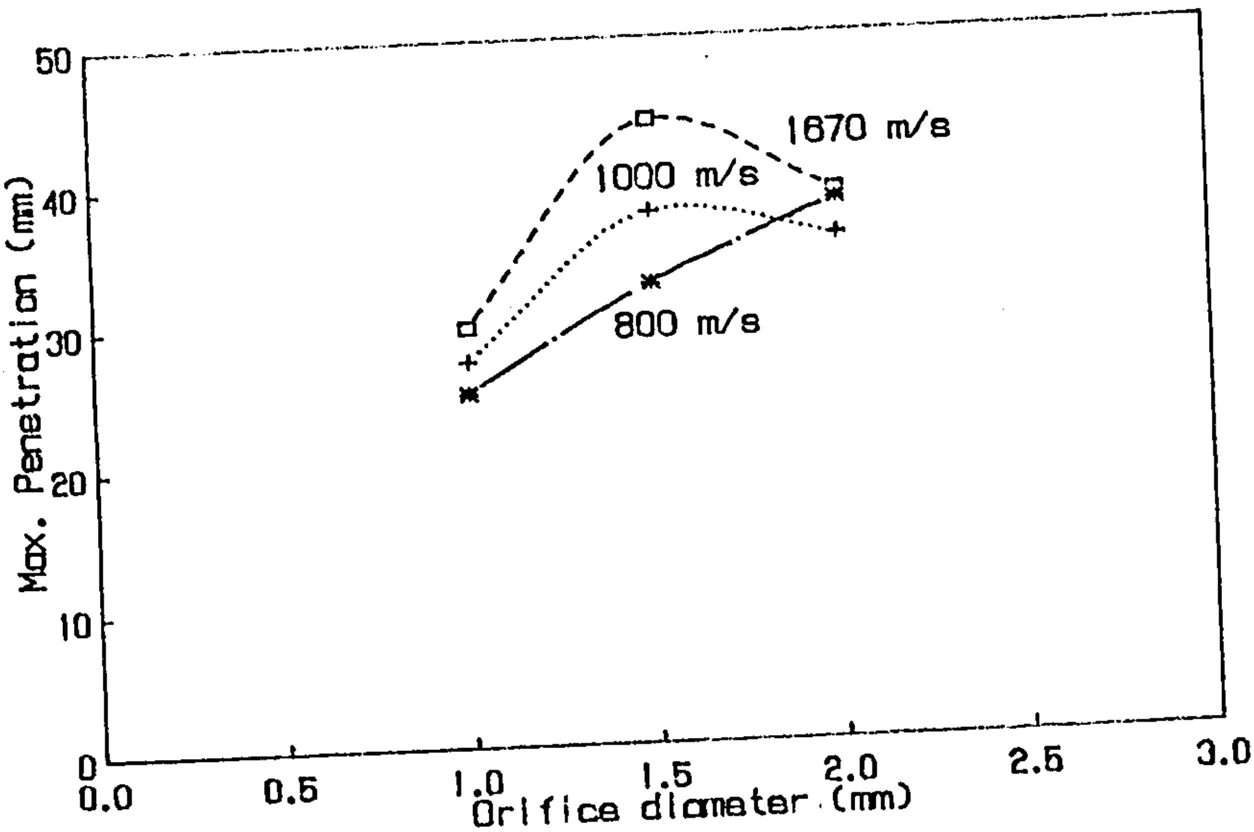

Fig.4.20. Maximum penetration versus orifice diameter at any stand-off distance for 'plasticine' target at different piston speeds

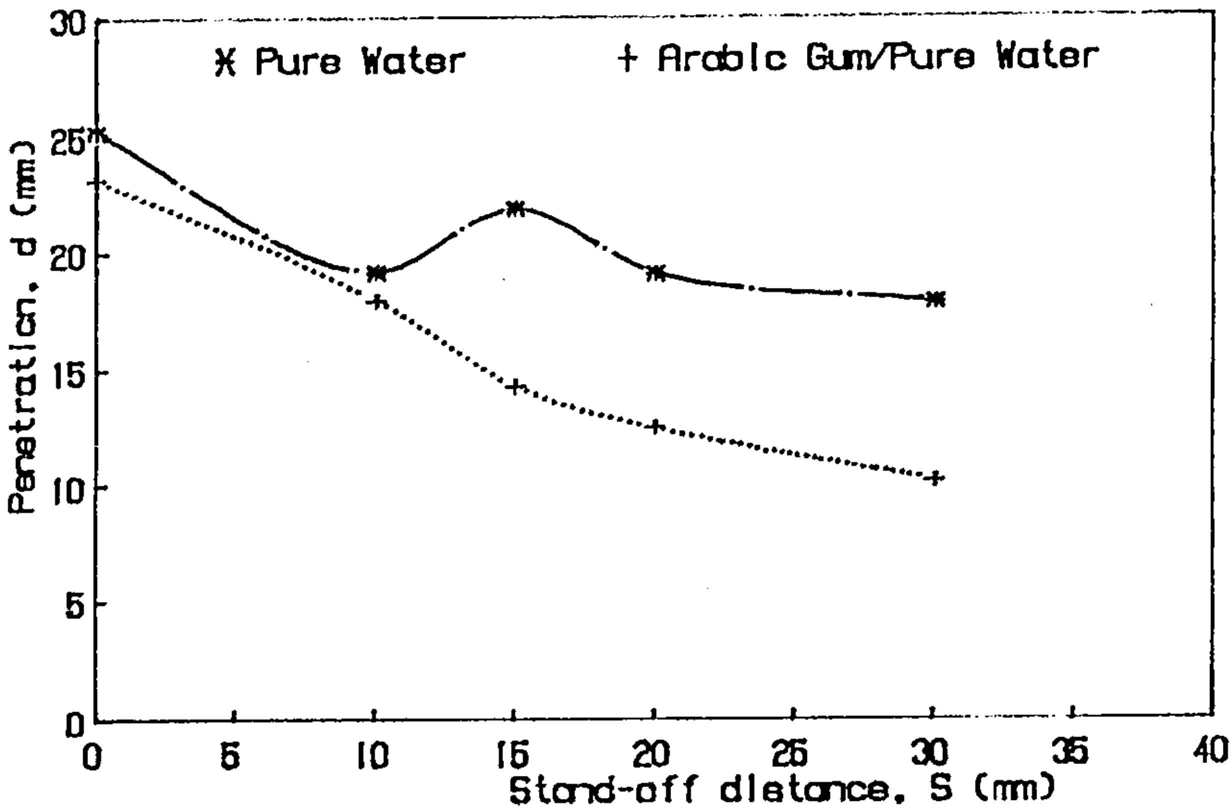

Fig.4.21. Variation of depth of penetration with stand-off distance for water and 1000 ppm Arabic gum-water jets in paraffin wax target at 800 m/s piston speed and an orifice of 2.0 mm diameter.

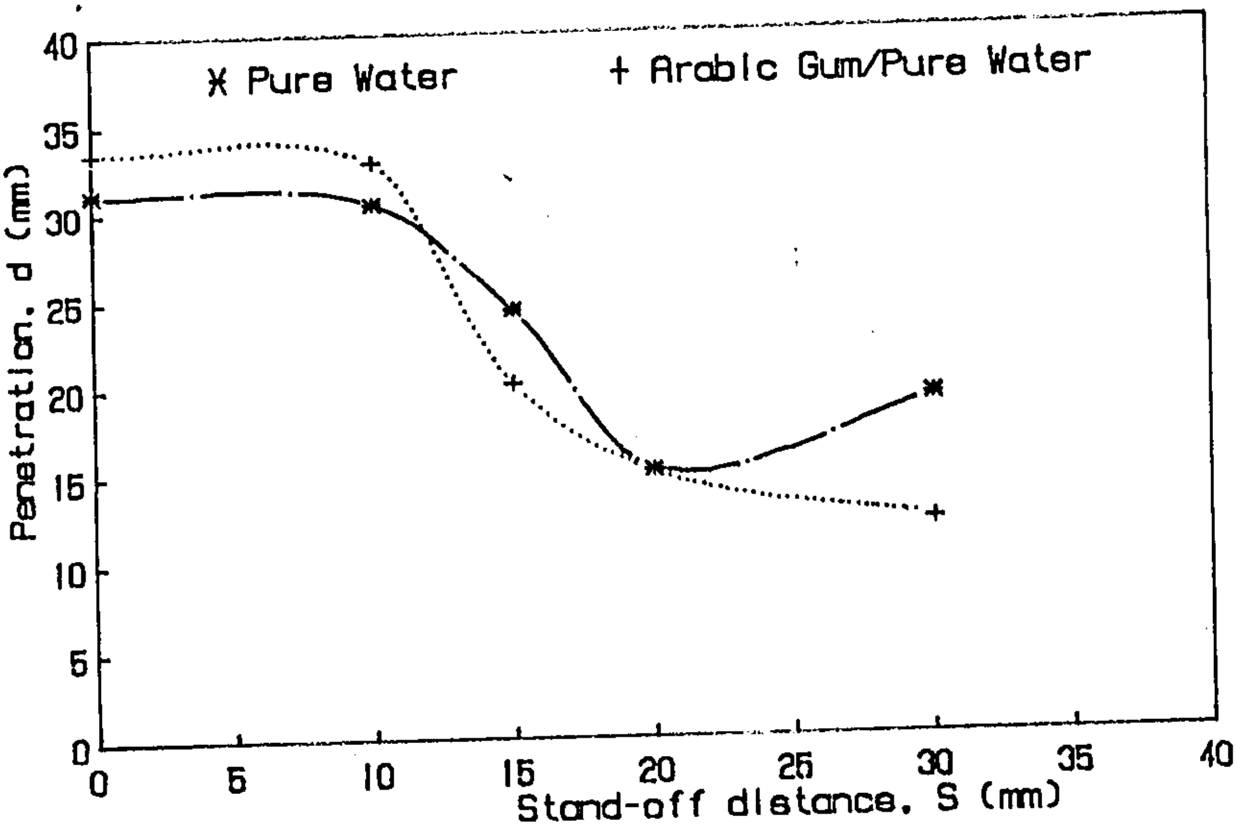

Fig.4.22. Variation of depth of penetration with stand-off distance for water and 1000 ppm Arabic gum-water jets in paraffin wax target at 1000 m/s piston speed and an orifice of 2.0 mm diameter.

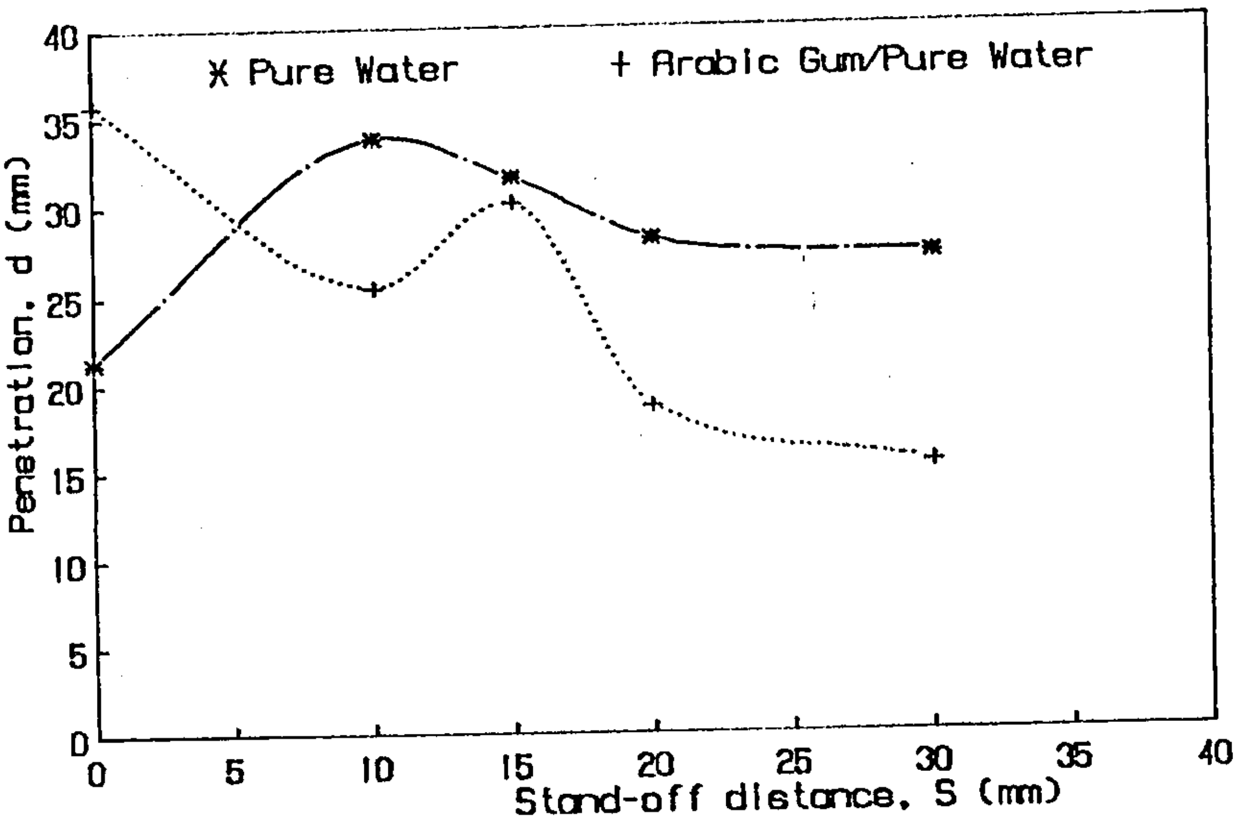

Fig.4.23. Variation of depth of penetration with stand-off distance for water and 1000 ppm Arabic gum-water jets in paraffin wax target at 1670 m/s piston speed and an orifice of 2.0 mm diameter.

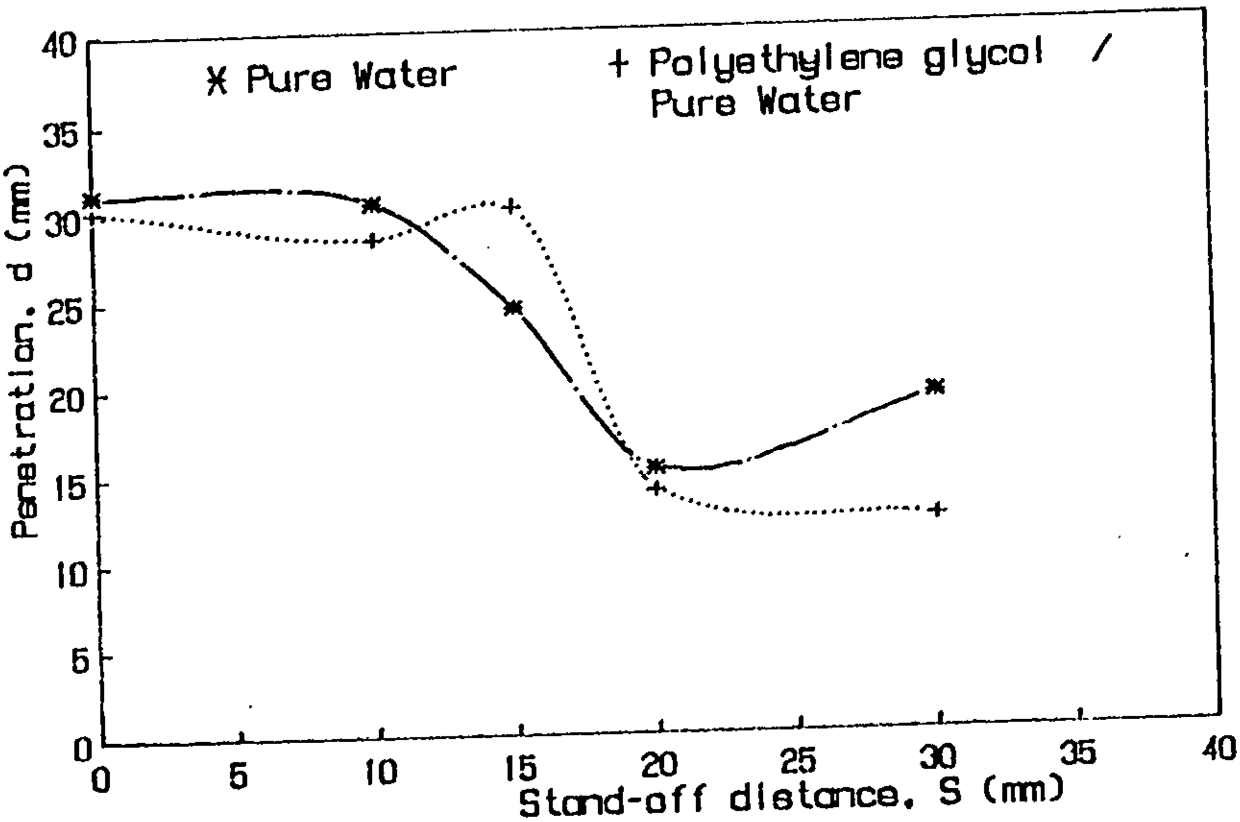

Fig.4.24. Variation of depth of penetration with stand-off distance for water and 1000 ppm polyethylene glycol-water jets in paraffin wax target at 1000 m/s piston speed and an orifice of 2.0 mm diameter.

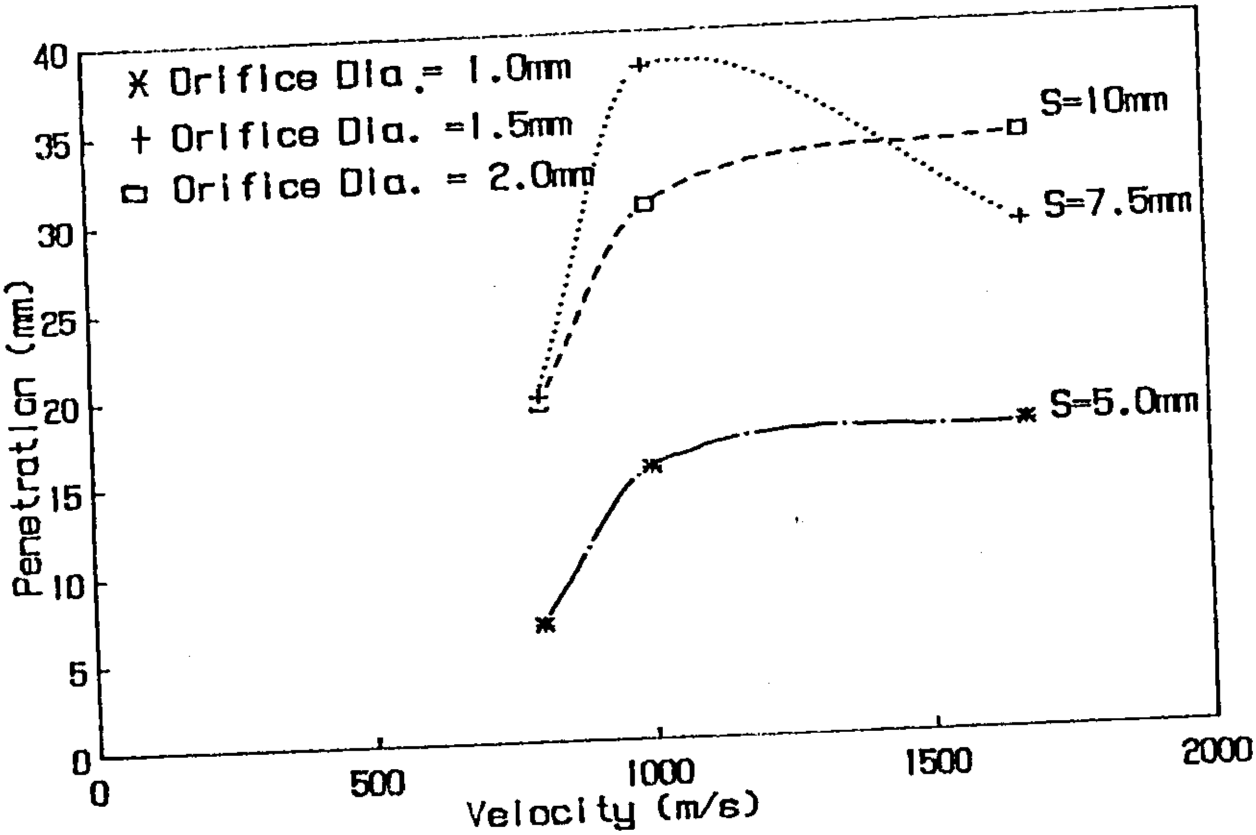

Fig.4.25. Penetration versus piston velocity at specific stand-off distances with different orifices in paraffin wax target

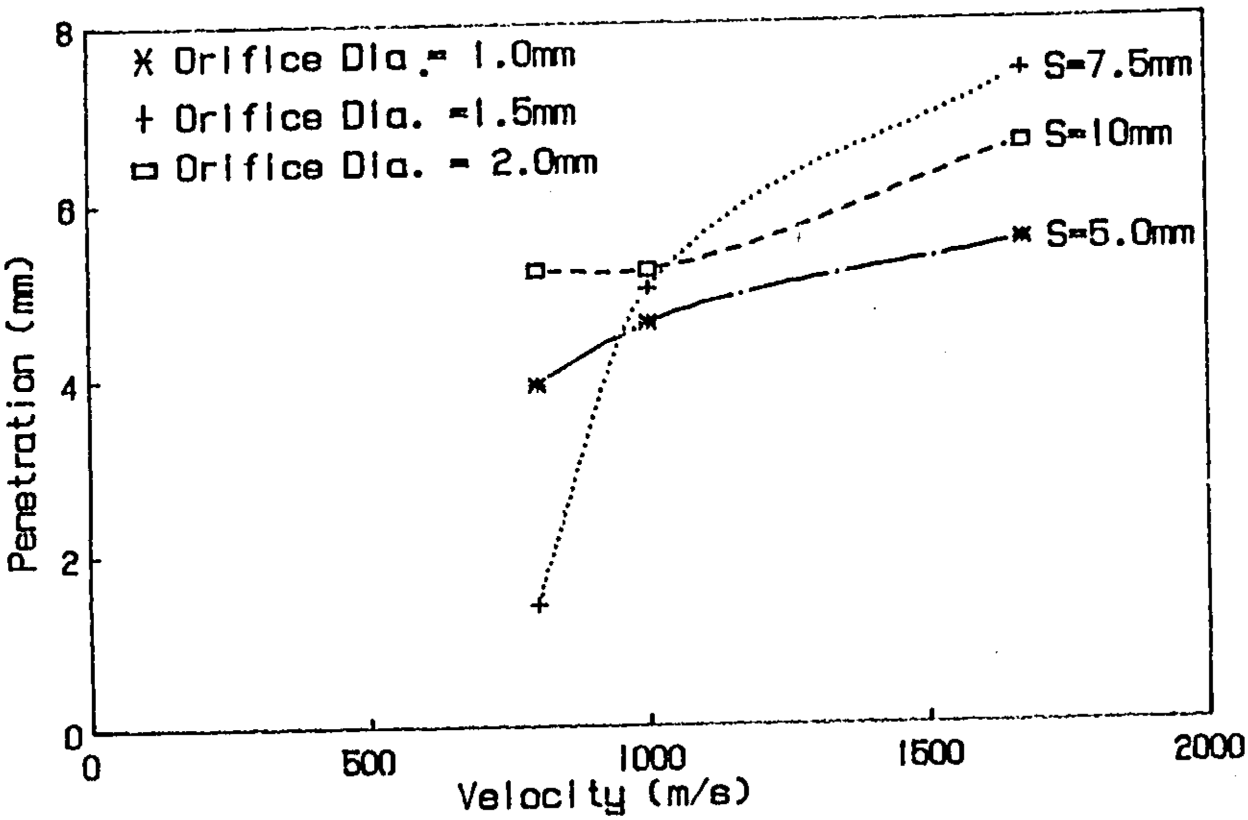

Fig.4.26. Penetration versus piston velocity at specific stand-off distances with different orifices in lead target

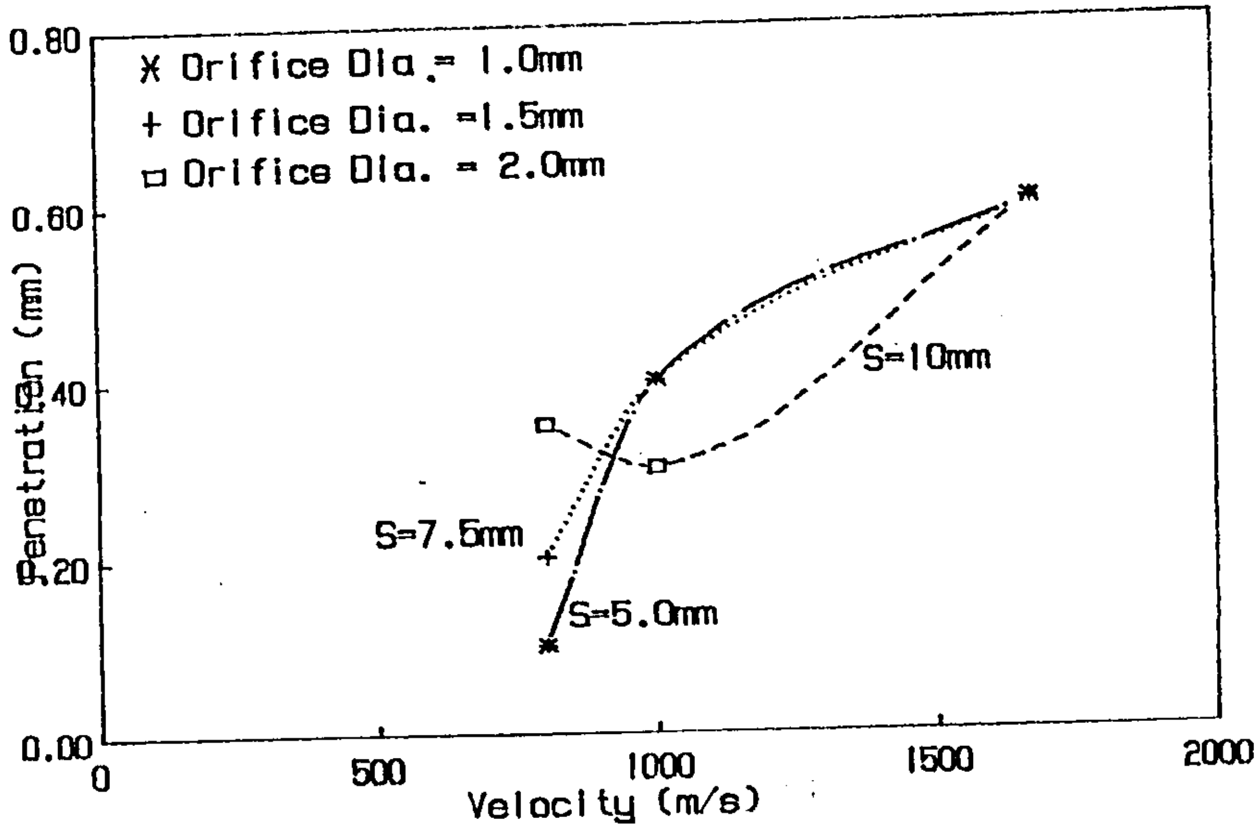

Fig.4.27. Penetration versus piston velocity at specific stand-off distances with different orifices in tin target

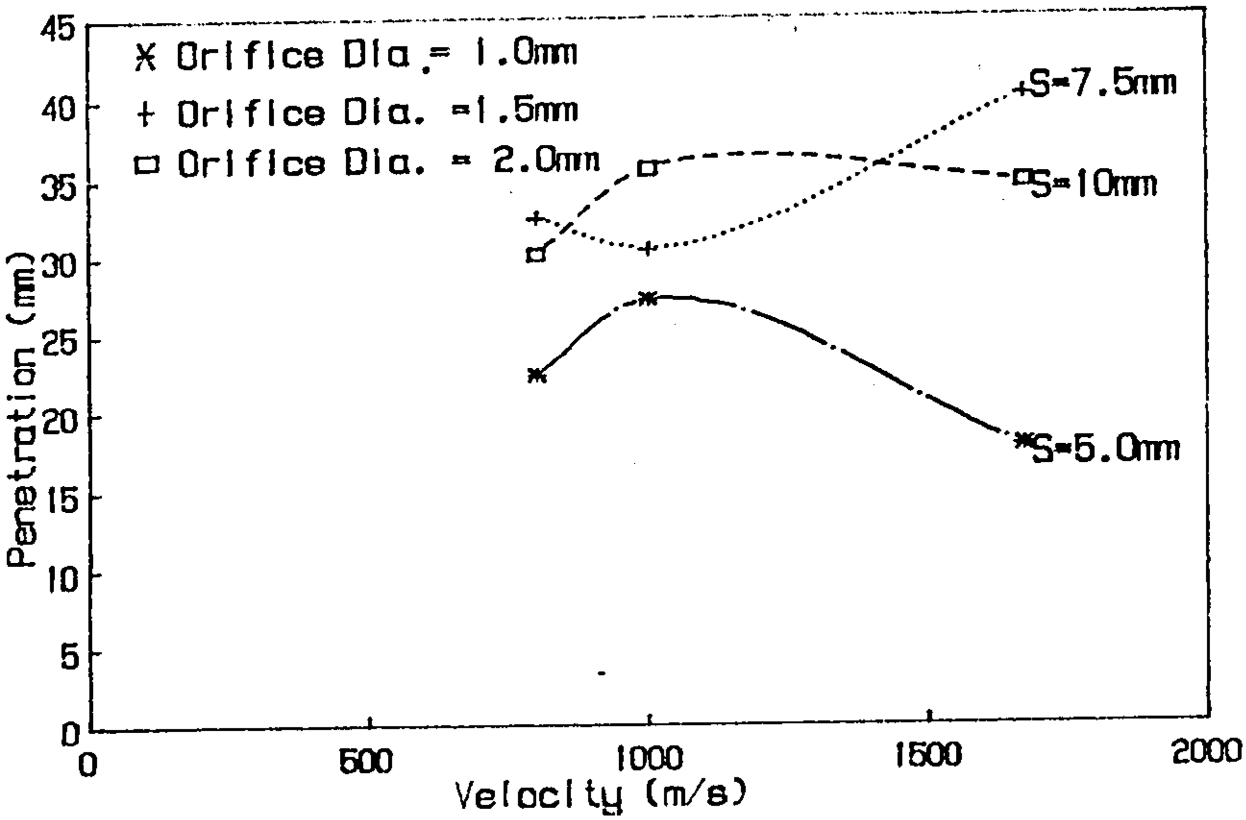

Fig.4.28. Penetration versus piston velocity at specific stand-off distances with different orifices in 'plasticine' target

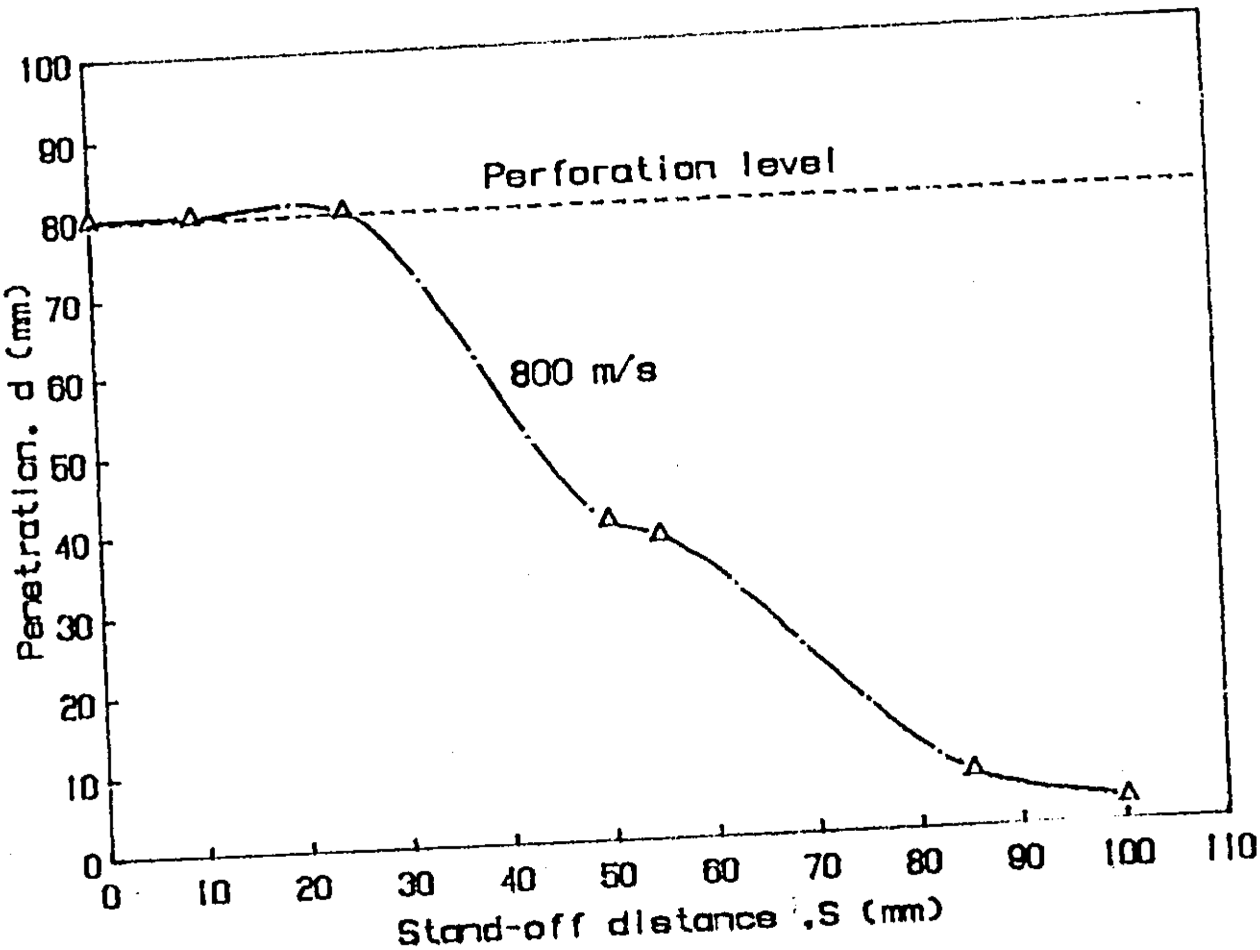

Fig.4.29. Variation of depth of penetration with stand-off distance at 800 m/s piston speed for ice target and an orifice of 2.0 mm diameter