U. S. Army Ordnance
Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland
Approved Proposal No. 3175
Authorization No. 4086

EXPLOSIVES RESEARCH CENTER

STRESS WAVES IN BOUNDED MEDIA

Quarterly Report
December 1, 1964 to February 28, 1965

BUREAU OF MINES, PITTSBURGH, PA.

UNITED STATES
DEPARTMENT OF
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per Dr. Glass

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Prepared for:

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STRESS WAVES IN BOUNDED MEDIA

Introduction

This is the first quarterly report of research conducted under a program entitled "Stress Waves in Bounded Media". The program is supported by the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland. The purpose of this program will be to explore in detail, from a fundamental aspect, phenomena associated with the interaction of intense stress waves at the free boundaries of simple media or at the interfaces between different media. Stresses generated by detonating explosives or from impact by high-velocity objects are of prime interest. The development of new methods and techniques for the solution of these problems will be an integral part of the program.

Techniques

Installation and Calibration

The experimental phases of the program outlined above require precise velocity-measuring techniques. In anticipation of this need, a high-speed streak camera has been installed in the firing chamber assigned to this program. The camera is a rotating mirror type with a mirror speed that is variable over the range of 50 to 700 rps to provide writing periods of 2029 to 145 μsec at respective writing rates of 0.38 to 5.25 mm/μsec. In addition to the camera installation, high-voltage discharge circuits to be used for exploding wire background lighting have been constructed; the use of argon bombs as background light sources has also been explored.

In order to estimate the error involved in applying this system to a specific measurement, a series of detonation-rate measurements were carried out using nitromethane (NM) (Commercial Solvents Corporation, 99% grade) as a standard. NM was chosen for this purpose because highly precise rate measurements, using an electronic technique, are available for this explosive[1/]. In these trials the NM was confined in glass tubes having an inside diameter of 2.57 inches and a length of 8.0 inches; the wall thickness of the tubing was 3/16 inch. The charges were initiated by a 1-5/8-inch diameter x 1.0-inch long tetryl donor. In view of the known dependence of the detonation rate on temperature[2/], the temperature of the liquid was maintained at 12°C throughout the experiment. A careful analysis of the streak records of four test firings produced individual rates of 6315, 6317, 6345, and 6332 m/sec. The average rate was 6327 ± 15 m/sec indicating a shot-to-shot reproducibility of approximately 1/2 percent. For the same test arrangement, Campbell, et al[3/] reported values of 6346, 6348, and 6349 m/sec or an average rate of 6348 ± 2 m/sec. While the reproducibility of the streak camera results is not as good as that obtained with the electronic technique, the average value obtained agrees to within 1/4 percent of the Los Alamos data.

1/ Campbell, A. W., M. E. Malin, T. J. Boyd, Jr., and J. A. Hull. Precision Measurement of Detonation Velocities in Liquid and Solid Explosives. Rev. Sci. Instr., Vol. 27, No. 8, 567-574, August 1956.

2/ Campbell, A. W., M. E. Malin, and T. E. Holland. Temperature Effects in the Liquid Explosive, Nitromethane. J. Appl. Phys., 27, 963 (1956).

3/ See work cited in reference 1.

Penetration Mechanics

Penetration Studies in Water and Glycerin

In a recent paper[4/], steady-state penetration velocities calculated from both incompressible and compressible flow theory were compared for several projectile-target combinations. For the most extreme case treated, that of the supersonic penetration of aluminum in water, a difference of only 5% was found between the penetration velocity computed by the two methods. The calculated velocities were in good agreement with framing camera measurements of the velocity of the detached shock wave ahead of the stagnation point. While demonstrating the adequacy of theory for predicting the steady-state penetration velocity, these measurements permitted only rough estimates of the time required to establish the steady-state regime. In addition, since the pre-impact lengths of the projectiles were not known a comparison could not be made between the observed and calculated values of hydrodynamic penetration depth. Since these questions are especially pertinent to the problem of predicting target damage produced by the rod-like projectiles having relatively small L/D ratios, some additional experiments have been carried out in this area.

The experimental arrangement used in these studies is shown in figure 1. The streak camera described in the previous section of this report was used to measure the initial projectile velocity, the time (or distance into the target) required for the impact shock to decay to a steady-state level, and the steady-state penetration velocity. Additionally, the streak records permit a

4/ Watson, R. W., K. R. Becker, and F. C. Gibson. "Hypervelocity Penetration of Composite Targets". Seventh Hypervelocity Impact Symposium, Tampa, Florida, November 1964.

reasonable estimate of the point in the target at which the steady-state shock starts decaying (closely corresponding to the hydrodynamic penetration depth) as well as the shock pressure level in the target after the depletion of the projectile. The projectiles were obtained for a Scale I inhibited shaped charge of the type designed at BRL. In order to compare the estimated values of hydrodynamic penetration depth from the streak records with values predicted by theory, a flash radiograph was used to determine the pre-impact length of the projectile for each firing; the projectiles were fired through 4-inch thicknesses of Styrofoam to eliminate undesirable debris. The target materials investigated, water and glycerin, were contained in a transparent plastic container.

A typical streak camera record of a water trial is presented in figure 2 while the results of a similar shot into glycerin is presented in figure 3. Contact prints of the pre-impact radiographs of the projector are also included, as insets, in figures 2 and 3. Several features of these trials are of interest and will be discussed at some length. It was observed that the projectile velocities (V) are somewhat lower than the values of 9.3 km/sec previously established[5/] for the 1/2 scale version of this projectile system; this can probably be attributed to the difference in projector scale size. The second point of interest is that, in the case of the water trial, an apparent steady-state shock develops at a point approximately 1.2 cm below the point of impact on the liquid. The steady shock progressed at a rate of 5.75 mm/μsec which cor-

5/ Watson, R. W., K. R. Becker, and F. C. Gibson. Hypervelocity Impact Phenomena. Bureau of Mines Quarterly Report, U. S. Army Ordnance, Aberdeen Proving Ground, Md., September 1, 1963 to November 30, 1963.

responds to the steady-state penetration velocity (U). This value may be compared with a value of 5.67 mm/μsec calculated for incompressible flow theory or 5.35 mm/μsec when the effects of target compressibility and the shock wave ahead of the stagnation point are considered. In view of the high precision of the streak camera calibration trials, it is difficult to assign this discrepancy entirely to experimental error. The difference between the observed and computed values of penetration velocity may, in part, be due to projectile compression arising from the intense impact pressure which is estimated to be approximately 680 kilobars for a 9.0 km/sec aluminum-water impact.

Another interesting feature of the streak record of figure 2 deals with the observed depth at which the steady-state shock first starts to decay in the target. This corresponds to the point of hydrodynamic depletion of the projectile and was found to be 6.7 cm for the water trial. Substituting the value into the simple penetration formula derived from incompressible flow theory[6/] yields a value of 4.1 cm for the projectile length. This distance, labeled ℓ_p, is indicated in the pre-impact radiograph shown in figure 2; the computed value of projectile length compares very well with the observed value. On the basis of the results of this experiment, it can be concluded that the projectile formed by the inhibited jet projection system is near normal density. This observation should add confidence to quoted values of projectile mass which are ordinarily obtained from radiographic estimates of the projectile size and an assumed normal density.

6/ Birkhoff, G., D. P. MacDougall, E. M. Pugh, and Sir Geoffrey Taylor. Explosives with Lined Cavities. J. Appl. Phys., Vol. 19, No. 6, 563-582, June 1948.

The firing into glycerin produced results that are qualitatively similar to the water trial. The observed penetration velocity of 5.74 mm/μsec was higher than that predicted from theory--5.37 mm/μsec. The time required to establish steady-state conditions--distance into the target--was somewhat longer than that noted in the water trial. However, the observed hydrodynamic penetration depth was entirely consistent with the radiograph observations of the projectile length.

The shock pressure levels measured from the point of projectile depletion are presented for both water and glycerin in figure 4. The pressure values for water were deduced from the slopes of the shock trajectories obtained from the streak records together with equation-of-state data published by Rice[7/]. Corresponding values for glycerin were obtained from a normalized equation of state for liquids[8/] having the form

$$P' = Au' + Bu'^2 + C \qquad (1)$$

where A = 1.44161; B = 1.55120; C = 0.7196. The reduced pressure, $P' = \frac{P}{\rho_o c_o^2}$ and reduced particle velocity $u' = \frac{u}{c_o}$ where ρ_o is initial density of the fluid and c_o the normal sound velocity. For glycerin, $\rho_o = 1.26$ gm/cm^3 and $c_o = 1.986$ mm/μsec.

The observed steady-state shock velocities of 5.74 mm/μsec for glycerin and 5.75 mm/μsec for water correspond to pressures at the shock front of 142 and 140 kilobars respectively. These

7/ Rice, M. H. and J. M. Walsh. Equation of State of Water to 250 Kilobars. J. Chem. Phys., Vol. 26, No. 4, April 1957.

8/ Bureau of Mines Quarterly Progress Report, "Sensitivity of Propellant Systems", Bureau of Naval Weapons, Order No. 19-65-8023-WEPS, October 1 to December 31, 1964.

pressures persist until the projectiles are depleted. After depletion of the projectile the pressure is observed to decay rapidly, reaching a level of approximately 55 kilobars for glycerin and 35 kilobars for water at a point 2 cm beyond the depletion point. These pressure levels are still adequate to cause appreciable flow in low-strength target materials. As a consequence, the total depth of penetration can be appreciably higher than that predicted from hydrodynamic theory for the penetration by short rods.

Current Research

Current research includes the following items:

(1) The development and calibration of a source for the generation of spherical shock waves has been partially completed. The interaction of these waves at the plane boundary between two different media will then be explored.

(2) Signature techniques applicable to shock waves are being explored. The 131-kilobar phase transition in Armco iron is being investigated as a possible method of mapping the shock pressures in studies involving the reflection of spherical waves.

(3) A study of the interaction of detonation waves with high precision metallic liners has been initiated. Detonation rate and wave-front curvatures are currently being measured as a function of charge diameter for Composition B, TNT, 50-50 nitroglycerin-ethylene glycol dinitrate, and nitromethane.

(4) Theoretical methods for predicting certain aspects of the reflection of a spherical wave from a plane boundary between two different media are being explored. As a first step in this program, the oblique impact between two dissimilar materials is

being investigated using the technique outlined by Walsh, et al[9/]. The functional dependence of the critical impact angle on plate velocity is being computed for aluminum and beryllium using experimental equation-of-state data for these two materials. Preliminary calculations for aluminum indicate that there may be some discrepancy between these calculations and the original calculations by Walsh which were based on an equation of state estimated from hydrostatic data and the Fermi-Thomas model[10/].

9/ Walsh, J. M., R. G. Shreffler, and F. J. Willig. Limiting Conditions for Jet Formation in High Velocity Collisions. J. Appl. Phys., Vol. 24, No. 3, March 1953.

10/ Feynman, Metropolis, and Teller. Phys. Rev. 75, 1561 (1949).

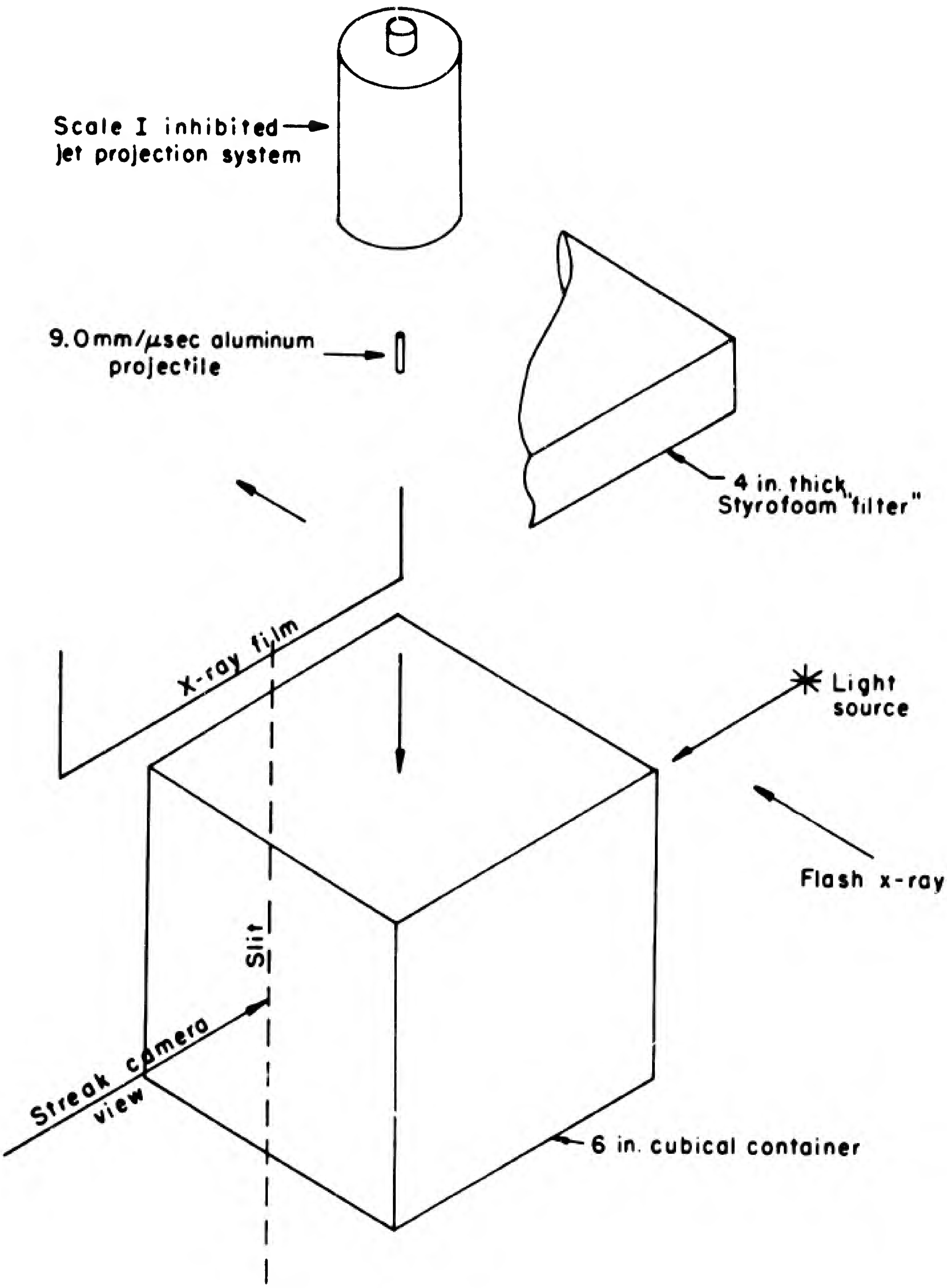
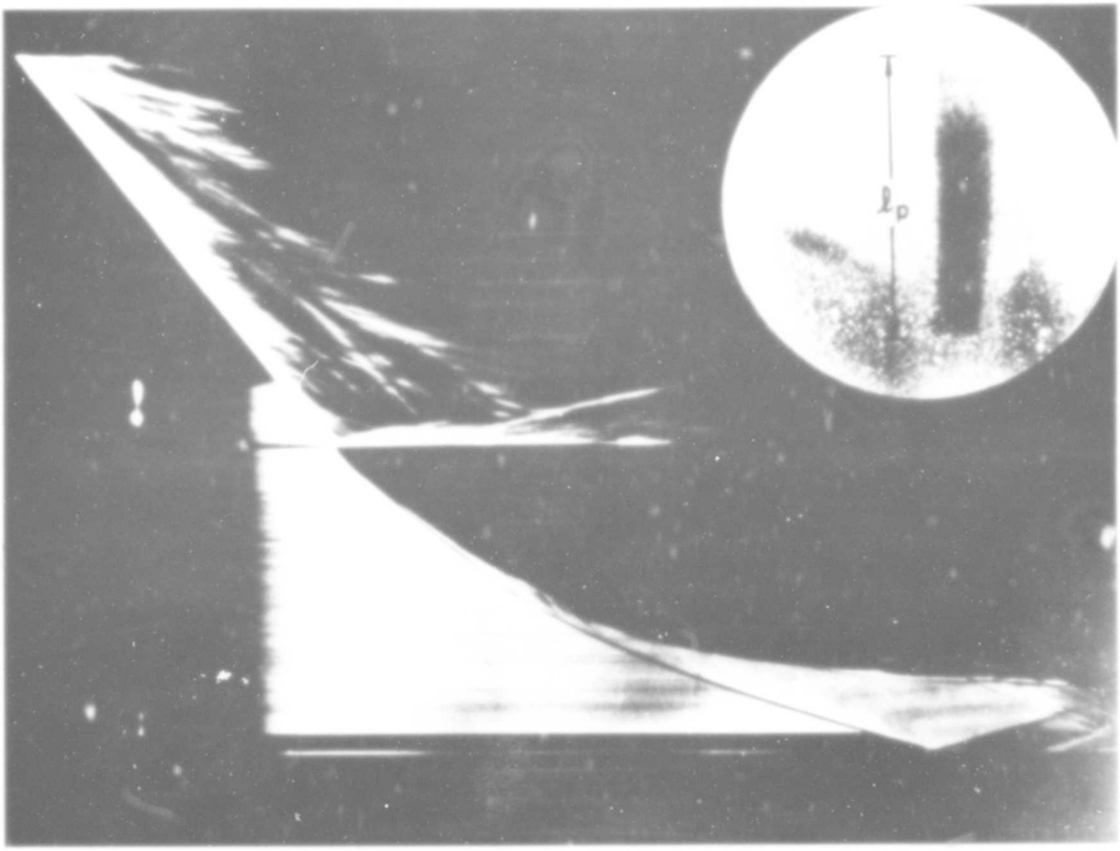


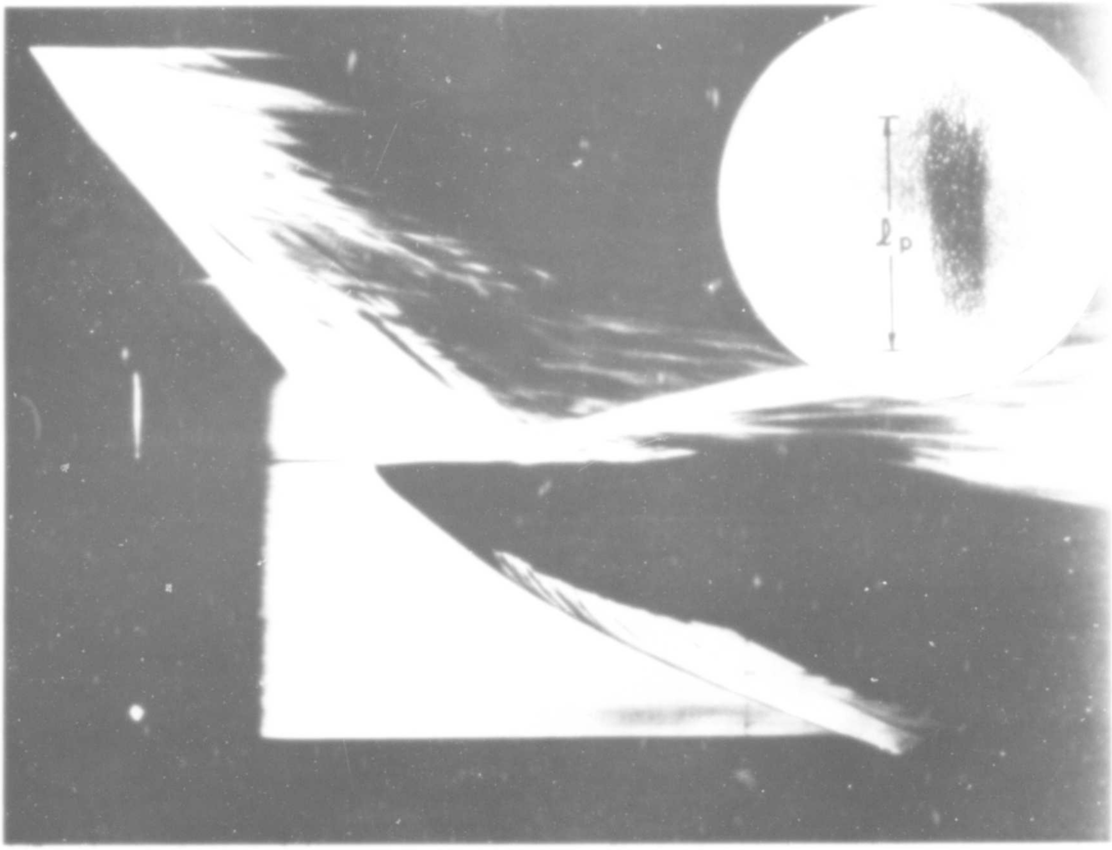
FIGURE 1. - Experimental arrangement used in penetration studies in liquids.



STREAK RECORD # 36: ALUMINUM IN WATER

$V = 9.06$ mm/μsec
$U = 5.75$ mm/μsec (5.62, 5.35)
$P_H = 6.74$ cm
$d = 1.16$ cm
ℓ_p(cal.) = 4.10 cm

FIGURE 2. - Records from a penetration test in water.



STREAK RECORD #39: ALUMINUM IN GLYCERIN

V = 9.06 mm/μsec
U = 5.74 mm/μsec (5.37, ——)
P_H = 4.95 cm
d = 1.69 cm
l_p (cal.) = 3.39 cm

FIGURE 3. - Records from a penetration test in glycerin.

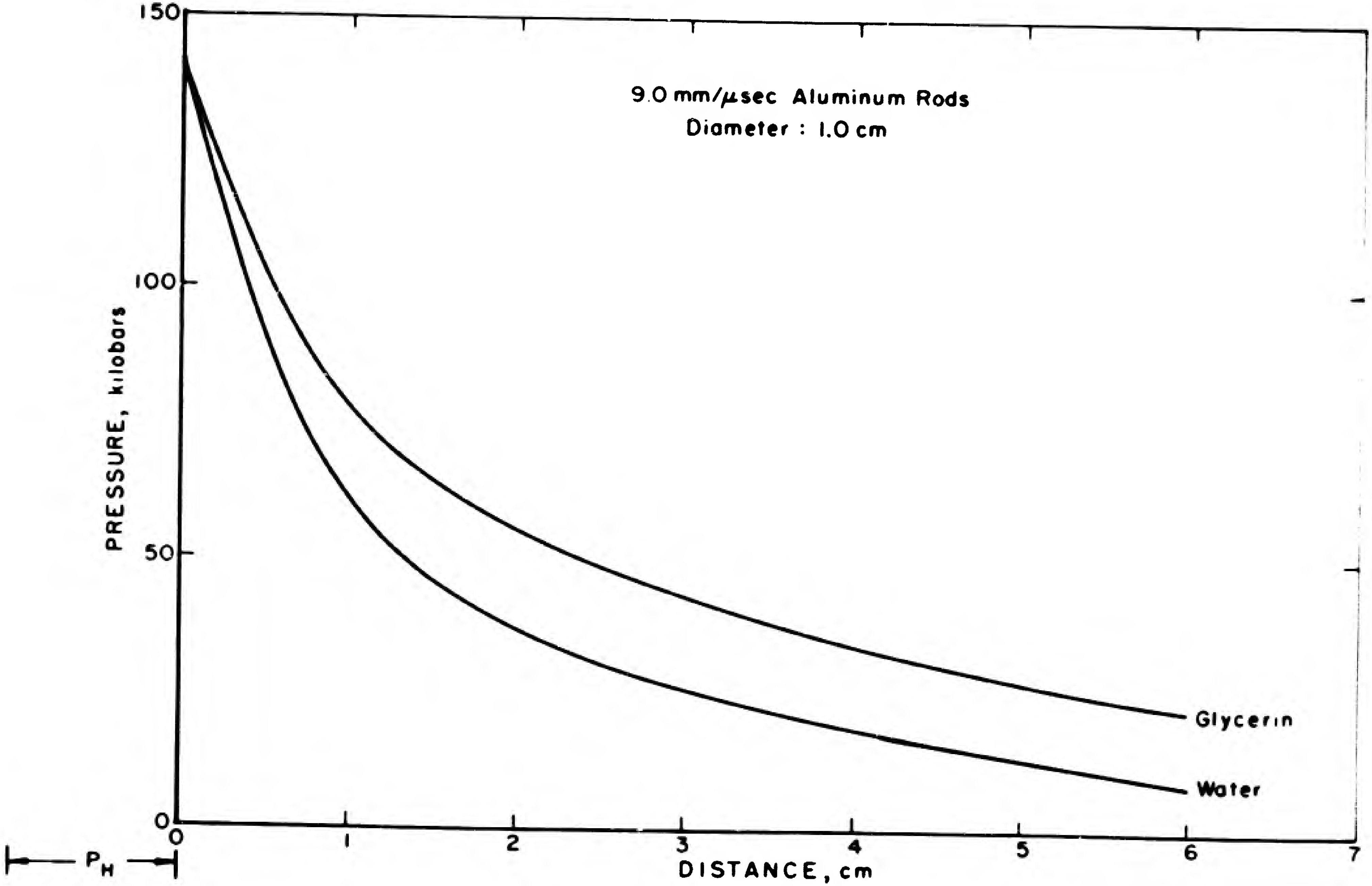


FIGURE 4. - Shock wave pressure versus distance measured from point of projectile depletion.