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MUZZLE BLAST PRESSURE LOADINGS
UPON AIRCRAFT SURFACES

Edward M. Schmidt

February 1984



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
 ABERDEEN PROVING GROUND, MARYLAND

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I. INTRODUCTION

While medium caliber (20-40 mm) cannon are widely employed on fixed wing aircraft, they have only recently been considered for installation on attack helicopters. Originally visualized for air-to-ground fire support, the use of cannon in the air-to-air mode is of increasing interest. The current doctrine for helicopter employment dictates engaging targets from behind cover. In turn, this requires the weapons to be fired at or near maximum elevation bringing the muzzle into close proximity with the aircraft surface. The increased possibility of damage to helicopter surfaces, structure, or avionics components has led to studies to examine muzzle blast overpressure loads. In the present paper, the complete firing signature including blast, flash, and recoil impulse of a 30 mm cannon is examined.

Loadings upon structures due to passage of the blast from the detonation of conventional and nuclear explosives have received considerable attention; however, relatively little information is available describing the blast from guns. Westine¹ uses measurements from firings of a number of different weapons to develop a set of universal contours of overpressure, time of arrival, and positive phase impulse which are scaled to characterize the blast from any weapon. In addition, he conducts experiments on the reflection of muzzle blast from flat surfaces aligned parallel to the line of fire. He notes that the reflection process is complex and that a whole family of shock interactions may be identified. Westine states that reflection coefficients are presented by Glasstone² and that these could be coupled to his description of the free field blast to model the impingement process. However, in his paper, he simply extends his scaling approach to specific surface geometries for which data are available.

Smith³ improves upon the graphical representation of Westine by proposing an analytic description of the blast wave using the initial rate of energy deposition from the weapon muzzle as an essential scaling parameter. He provides a treatment of the effects of altitude and aircraft speed upon the blast and notes the consequences of firing at supersonic velocities. Smith demonstrates the ability to describe the overpressure pulse from a 7.62 mm rifle; however, he does not claim that the relations are universally applicable. Rather, they must be experimentally established for each weapon considered.

-
1. P. S. Westine, "Structural Response of Helicopters to Muzzle and Breech Blast," FTR02-2029, Southwest Research Institute, San Antonio, TX, Nov 68. (AD 844287L).
 2. S. Glasstone and P. Dolan, The Effects of Nuclear Weapons, Government Printing Office, Washington, DC, 1977.
 3. F. Smith, "A Theoretical Model of the Blast from Stationary and Moving Guns," Memo 17/74, RARDE, Kent, UK, Dec 74 (AD B001816L).

Mabey and Capps⁴ conduct firings with a 7.62 mm rifle mounted in a tri-sonic wind tunnel and confirm the scaling relations of Smith. The data are limited to weak waves where the ratio of reflected to incident pressure level is two. Munt, Perry, and Moore⁵ have recently presented the results of a study, again using a 7.62 mm rifle, which examine the reflection of strong shock waves from a static, sea level surface. They find that the best fit to test data is obtained by centering the origin of the blast forward of the muzzle and using an angular correlation function which varies with distance from the muzzle. Surface interactions are treated by computing the regular reflection process using standard techniques and estimating the Mach stem region in an approximate fashion.

The energy rate dependent scaling approach of Smith³ is extended by Fansler and Schmidt⁶ to provide relations which are nominally applicable for all weapons. They present comparison with experiment which indicates good agreement in most cases. However, they note the approximate nature of the analysis and discuss difficulties in validating the relation for the positive phase duration.

In the present report, experiments are conducted on a 30 mm cannon which is to be installed on the Advanced Attack Helicopter (AAH). Data are taken on the weapon interior ballistics since these are essential input to any reasonable analysis of the blast field. The other measurements include determination of recoil impulse, muzzle blast- both free field and on a simulated aircraft surface, and muzzle flash. As reduction of weapon recoil is of interest, different muzzle brake configurations are tested to determine their influence on the firing process. The results of experiment are compared with the theory of Fansler and Schmidt⁶ which is extended to include surface reflections.

II. EXPERIMENTAL PROCEDURE

The weapon tested is the 30 mm, XM230 Chain Gun having a barrel length of 1.07 m, a chamber volume of 53.9cm³, and a twist of rifling of one turn in 27.3 calibers of projectile travel. The test projectile is the XM788, TP, weighing 0.233 kg. The propellant is 0.051 kg of WC855 which yields a muzzle

-
4. D. G. Mabey and D. S. Capps, "Blast from Moving Guns," *AIAA J. Aircraft*, Vol 14, Oct 77, pp. 687-692.
 5. R. M. Munt, A. J. Perry, and S. A. Moore, "Gunfire Blast Pressure Predictions," *AGARD, Symposium on Dynamic Environmental Qualification Techniques*, Noordwijkerhout, Netherlands, Sep 1981.
 6. K. S. Fansler and E. M. Schmidt, "The Prediction of Gun Muzzle Blast Utilizing Scaling," *US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, ARBRL-TR-02504, July 1983 (AD B075859L)*.

velocity of 780 m/s. The weapon exit properties at the time of shot ejection were measured using an acoustic thermometry procedure.⁷ To obtain best results, firings are performed for a range of launch velocities. Therefore, data are taken by downloading the propellant in the cartridge case. The measured exit conditions are presented in Table 1. Also included in the table are the computed sonic exit properties which are the initial conditions used in blast and flash analyses.

TABLE 1. PROPELLANT GAS PROPERTIES AT THE MUZZLE AT THE TIME OF SHOT EJECTION

m_c (g)	v (m/s)	a_e (m/s)	p_e/p_∞	M_e	u^* (m/s)	T^* (K)	p^*/p_∞
13.6	310	805	59	0.39	752	1303	29.2
18.2	390	825	95	0.47	777	1391	51.1
22.7	462	840	135	0.55	799	1471	80.5
29.4	496	850	156	0.58	811	1515	96.0
34.1	570	870	202	0.66	838	1618	137.0
38.9	657	890	257	0.74	864	1720	189.0
50.6	780	920	330	0.85	904	1883	275.0

At each of the above launch conditions, the free field blast for bare muzzle firings is measured using an array of six static or side-on pressure transducers placed on an arc 0.9 m from the muzzle of the gun. The transducers are Kistler 201B5 Piezotrons mounted in sharp-edged circular plastic discs having a diameter of 0.07 m. The discs are aligned such that the plane of their surfaces would, if extended, pass through the axis of the gun tube. Output of the pressure transducers is recorded on Physical Data, Inc., Model 515A Transient Wave Recorders and processed through a Hewlett-Packard 9845B desk-top computer.

Overpressure levels on a simulated aircraft surface are measured for the condition of maximum elevation, forward fire, where the muzzle of the 30 mm cannon is in close proximity to the AAH (Figure 1). The helicopter surface is simulated using a 0.9 m x 0.9 m x 0.02 m Aluminum plate. The plate is instrumented with a linear array of ten piezoelectric pressure transducers, Kistler Model 201B5. The plate is aligned at angles of zero and minus five degrees relative to the line of fire, with separations from the muzzle of 0.26 m and 0.228 m, respectively. The blast field forward, behind, and normal to the weapon muzzle is surveyed by moving the plate. Sufficient overlap of gauge positions is maintained to insure compatibility of the various sets of

7. E. M. Schmidt, E. J. Gion, and D. D. Shear, "Acoustic Thermometric Measurements of Propellant Gas Temperatures in Guns," *AIAA J*, Vol 15, Feb 77, pp. 222-226.

data. Since recoil and blast loadings on the airframe are of concern, a variety of muzzle devices have been proposed (Figure 2). Measurements of surface pressure distribution were acquired on a total of nine different muzzle configurations; although, only three will be discussed in the present report.

In addition to surface pressure, the recoil impulse and flow field characteristics are evaluated for cases with the muzzle devices installed. The weapon firing impulse is measured by firing from a free recoil mount. This device presents minimum resistance to rearward travel of the gun for a distance of 0.1 m. By measuring the velocity of the recoiling parts, the total impulse may be readily determined. The velocity is obtained from interruptions of a laser beam directed through a calibrated grating fixed to the moving parts. The flow field is examined using optical techniques. Spark shadowgraphs are taken of the near field to determine the shock structure during impingement. An open shutter camera loaded with color Polaroid film having an ASA rating of 75 is used to monitor secondary combustion in the exhaust flow.

III. TEST RESULTS

A. Free Field Blast

The free field blast is measured for the bare muzzle configuration in order to test the applicability of scaling analyses. A typical pressure-time history is shown in Figure 3a. The features of interest are the arrival of the weak precursor wave associated with expulsion of the tube air ahead of the projectile. This is followed by the stronger blast generated by the release of the propellant gases. The wave is characterized by a rapid rise to the peak pressure followed by a decay through atmospheric pressure, a negative phase, and recovery to ambient values. For purposes of presentation of blast duration as illustrated in Figure 3b. Westine¹ uses Friedlander equation to represent this behavior, where

$$p(t) = P [1 - (t - t_a)/\tau] e^{-(t - t_a)/\tau} \quad \text{for } t_a < t < (t_a + \tau) \quad (1)$$

with P = peak overpressure (in atmospheres)

t_a = time of arrival of wave

τ = positive phase duration

Fansler and Schmidt⁶ provide the following simple scaling relations to describe these wave parameters:

$$p = 2.4 / (r/l')^{-1.1} \quad (2)$$

$$t_a = (r/l') f(Z) - 9.24 - 0.94 \cos\theta \quad (3)$$

$$\tau = (l'/a_\infty) [1 + 0.13 (r/l')] \quad (4)$$

where $Z = (r/\ell')^{-1.1}$

$$f(Z) = 1 + 10 Z - (Z^2/1.2) + (Z^3/2.3) - (Z^4/3.4) + \dots$$

and

$$\ell'/\ell = 0.78 \cos\theta + (1 - 0.608 \sin^2\theta)^{1/2} \quad (5)$$

is the relationship providing the variation in blast properties with angle from the line of fire, and the basic scaling length is dependent upon the energy release rate

$$\ell/D = 0.1 [p_e v_p / ((\gamma-1)p_\infty a_\infty)] \quad (6)$$

The measured free field peak overpressure for each launch velocity is presented in Figure 4. In all cases, the overpressure is greatest forward of the muzzle and decays monotonically toward the rear of the weapon. As the launch velocity increases, the overpressure also increases. The measured trends in the peak overpressure are reasonably well predicted by the analysis of Fansler and Schmidt.⁶ A set of computed contours of wave parameters is presented in Figure 5. The overpressure contours show the strong directional dependence of the muzzle blast field. The time of arrival contours represent the shape of the blast wave at any instant of time. These are observed to rapidly assume a nearly spherical geometry with a center displaced somewhat forward of the muzzle. The positive phase duration contours indicate that forward of the muzzle, the wave length continually increases. Whereas, behind the gun, a nearly constant duration is obtained.

The analytical description of the blast may be readily extended to approximate interactions with surfaces. Since Equation (2) provides the shock strength at any point in the field and Equation (3) describes the shock shape, the interaction with a simple surface may be computed if the reflection process can be defined. Glasstone² presents a set of reflection coefficients based upon experiments involving spherical waves impinging on flat surfaces (Figure 6). In this plot, grazing incidence corresponds to alpha equal to 90 deg while normal incidence occurs at zero deg. It is interesting to observe that for weak waves, the peak reflected pressure is not for the case of normal reflection. Rather it occurs just at the point where there is transition from regular to Mach reflection.⁸ Up to this point, it is possible to determine the reflection coefficient using oblique shock theory;⁹ however, for greater incidence angles, the Mach stem must be treated in an approximate fashion. The approach taken here is to fit the coefficient to a third order polynomial in alpha between the point where the Mach stem forms and grazing incidence. This definition of the reflection coefficient coupled with the relations describing the blast wave permits a definition of the pressure distribution on any planar surface adjacent to the weapon muzzle. The predictions of this procedure will be compared with experiment in the

8. B. P. Bertrand, "Measurement of Pressure in Mach Reflection of Strong Shock Waves in a Shock Tube," U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, BRL Memorandum Report BRLMR-2196, June 1972 (AD 746613).

9. H. W. Liepmann, and A. Roshko, *Elements of Gasdynamics*, J. Wiley and Sons, New York, 1962.

following section.

B. Plate Surface Pressure

Three weapon configurations are considered: bare muzzle, a cowled double baffle brake, and an open single baffle brake. The latter being brakes number 3 and 5 in Figure 2, respectively. In examining the performance of muzzle brakes, an important parameter is their recoil attenuation efficiency, defined as

$$\beta = (I_{wo} - I_w) / (I_{wo} - m_p v_p) \quad (7)$$

where

I_w = measured impulse with device installed

I_{wo} = measured impulse for bare muzzle

$m_p v_p$ = impulse of projectile at muzzle

The numerator of Equation (7) is the change in recoil impulse due to addition of the muzzle brake, while the denominator is the total residual impulse available in the exhausting propellant gases. These properties are measured for the configurations tested and are presented in Table 2.

TABLE 2. MEASURED RECOIL PROPERTIES

	I (N-s)	β	Flash
30 mm Bare Muzzle	245	-	no
Muzzle Device #3	184	1.06	yes
Muzzle Device #5	177	1.13	no

Both devices are seen to have nearly identical efficiencies; however, the flash characteristics of the two devices differ. No secondary combustion is observed for the case of the bare muzzle or the single baffle design, No. 5. The double baffle brake, No. 3, produces strong secondary combustion throughout the exhaust plume. This behavior has been analyzed previously¹⁰ and interpreted as being caused by the shock processes internal to the device which produce significant elevation in the temperature of the propellant gas/air mixture in the external flow.

The pressure distribution about the two devices is also significantly different (Figure 7). This figure presents the surface pressure distribution along the line of fire for the case where the plate is aligned parallel to the

10. E. M. Schmidt, "Gun Muzzle Flash and Associated Pressure Disturbances," AIAA Paper 81-1109, AIAA, New York, NY, Jun 81.

gun and separated by a distance of 0.26 m. Forward of the muzzle, the peak overpressures measured for the bare muzzle firings are significantly greater than either of the muzzle brake cases. The reverse is true behind the weapon. Interestingly, even though their efficiencies are nearly equal, the single baffle brake shows a much higher pressure aft of the muzzle than does the double baffle brake. This result is important since it demonstrates that there is not a direct link between muzzle brake momentum recovery and the blast field alternations due to the presence of the device.

The measured values of peak overpressure, time of arrival, and positive phase duration for each configuration are presented in Figures 8-10. Again, the data are along the line of fire for the parallel plate tests. The positive phase duration is measured at the half peak height. This is necessary since the zero crossing is difficult to measure in a consistent fashion. In part, the problem is associated with instrumentation noise; however, the flow field near the muzzle of a gun is quite complex and the blast waves are not as yet well formed (Figure 11). If the overpressure pulse is assumed to be represented by a Friedlander waveform, the positive phase duration and half-peak width are simply related by

$$\tau = 3.17 \tau_{\frac{1}{2}}$$

For the bare muzzle case (Figure 8), the measurements are compared with the predictions of the analysis described above. The peak overpressure distributions are in good agreement. The time of arrival results are estimated quite well by the analysis. As seen, the positive phase duration is over-predicted and is a problem area identified in the original report⁶ which has as yet not been resolved. Extension of the scaling relations to the treatment of blast from weapons equipped with muzzle devices is difficult as indicated by the difference in blast overpressure measured for brakes having nearly identical efficiencies (Figure 7).

From the measured pressures on the plate surface, it is possible to obtain the force and impulse transmitted to the plate. Since data are acquired in a limited region, this integration is performed only over a one-centimeter wide strip along the line of fire (Figure 12). The force due to the bare muzzle firing is greater than that produced with either of the brakes in place. For the cases with the brakes mounted, the peak forces are roughly equal; however, the duration of the loading with the single baffle is greater than that with the double baffle brake. The impulse transmitted to the plate is obtained by integrating these profiles and is listed below:

$$I(\text{bare muzzle}) = 0.36 \text{ N-s}$$

$$I(\text{double, \#3}) = 0.23 \text{ N-s}$$

$$I(\text{Single, \#5}) = 0.29 \text{ N-s}$$

IV. SUMMARY AND CONCLUSIONS

An experimental program is conducted to measure the blast from a 30 mm cannon mounted on a helicopter. The weapon in-bore, muzzle blast, and muzzle flash properties are determined for a variety of test conditions. The impingement of the blast wave upon the aircraft surface is examined by obtaining measurements on a large plate positioned near the cannon. The experiments indicate that the free field blast is reasonably well predicted using existing scaling analyses. Further, it is shown that these analyses can be extended to treat the problem of shock impingement and reflection from surfaces. The presence of muzzle brakes has a significant influence on the overpressure distribution. The effect of these devices is not simply related to a gross characteristic such as recoil attenuation efficiency. Additionally, the details of the brake design is demonstrated to have a strong impact on potential for the occurrence of secondary combustion in the plume.

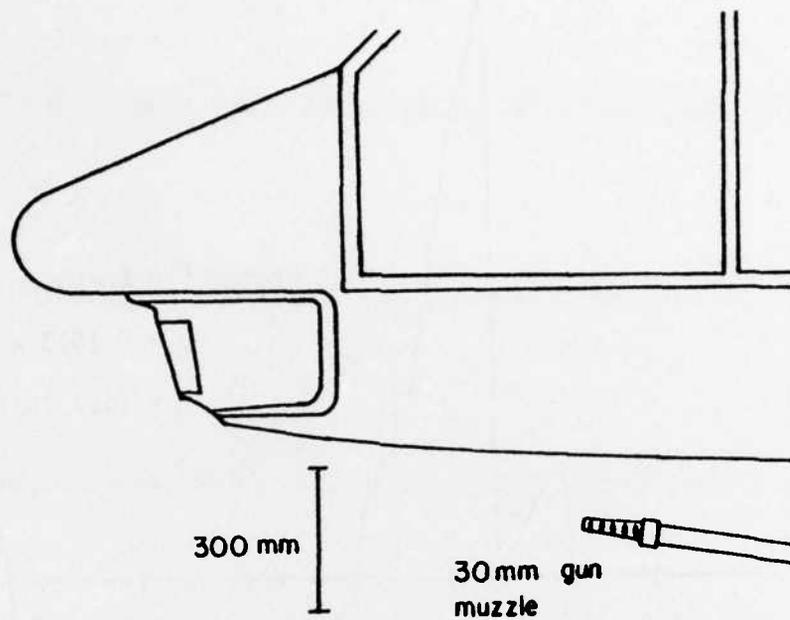


Figure 1. Schematic of 30 mm Cannon Mounted on the AAH

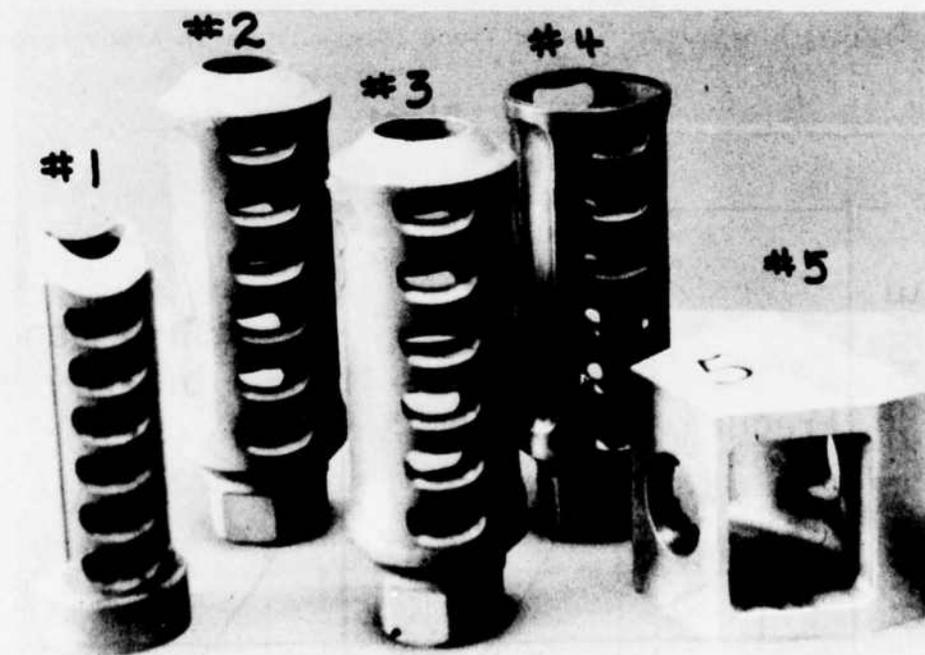


Figure 2. Sample Muzzle Devices Included in the Test Series

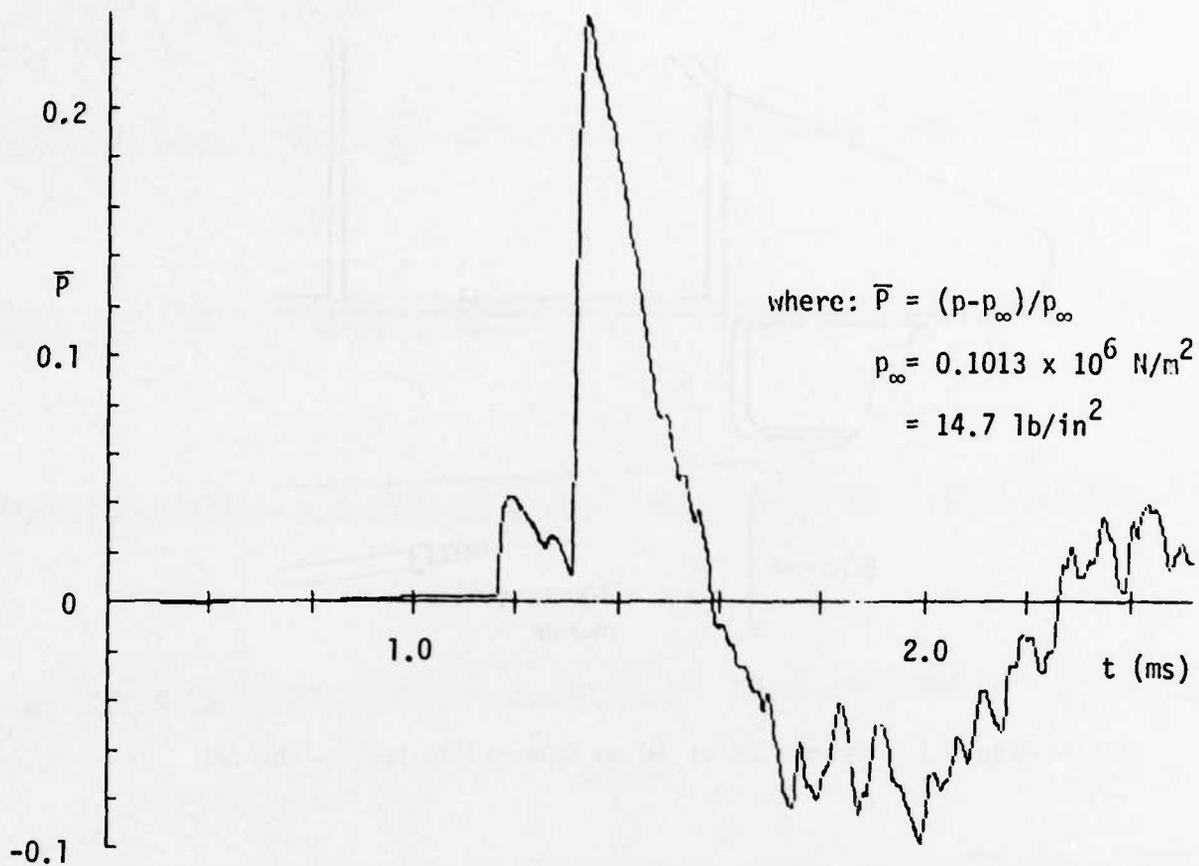


Figure 3a. Typical Blast Overpressure Trace (Pressure is in Atmospheres)

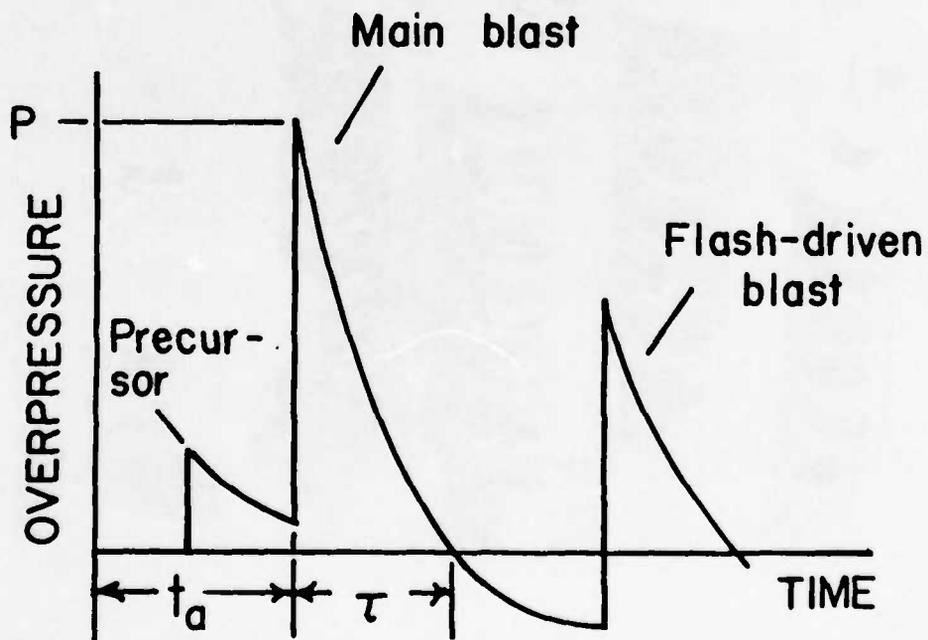


Figure 3b. Schematic of Overpressure Pulse Showing Features of Interest

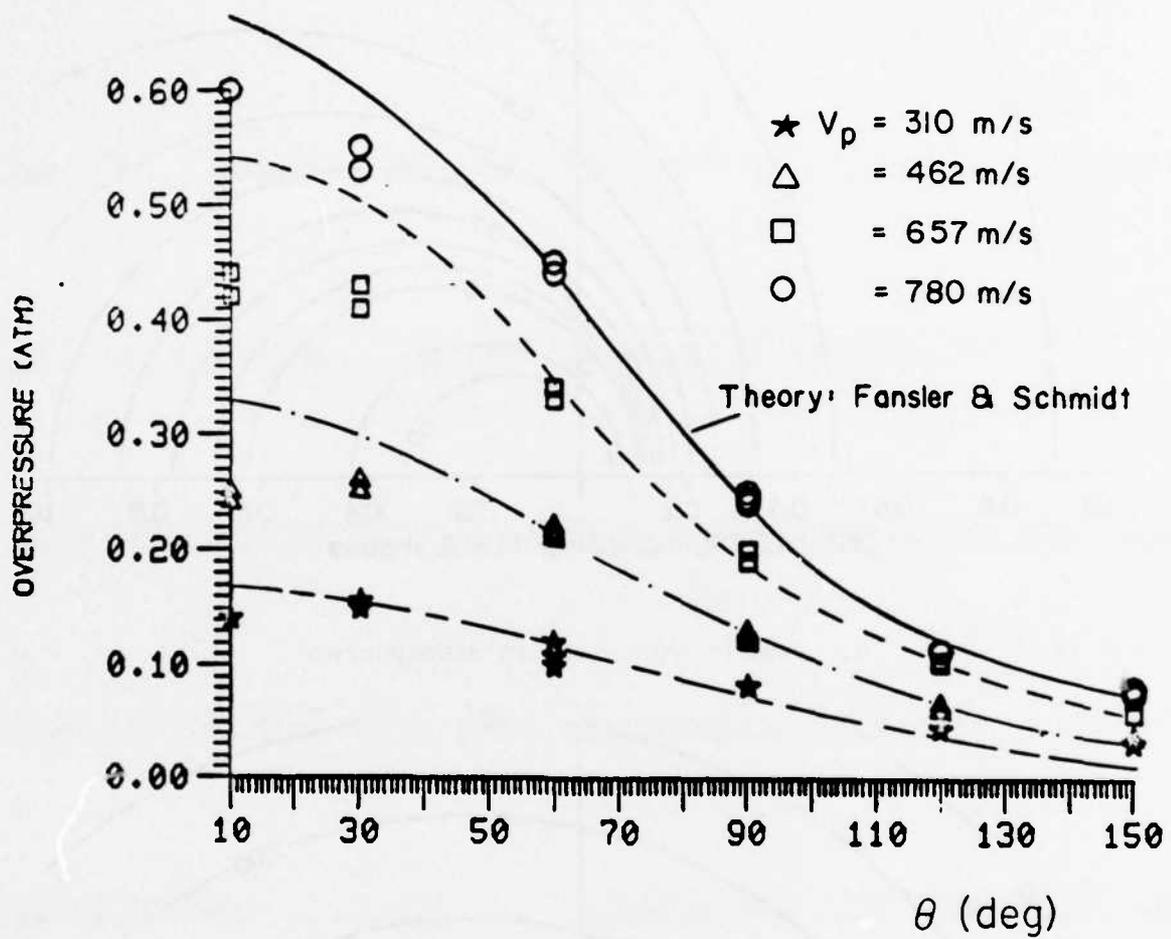
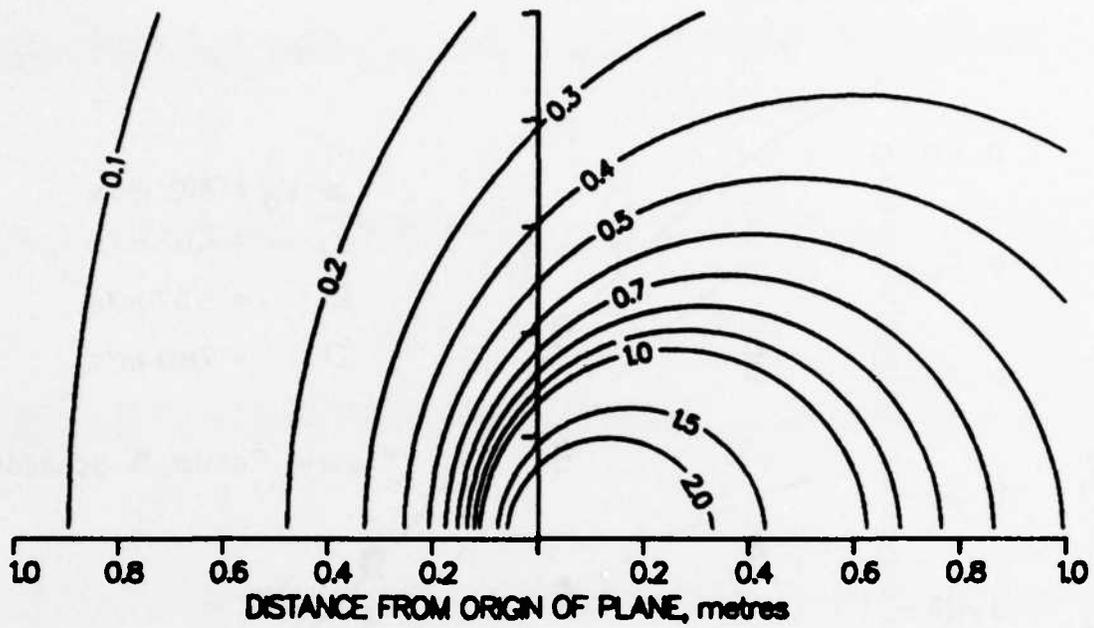
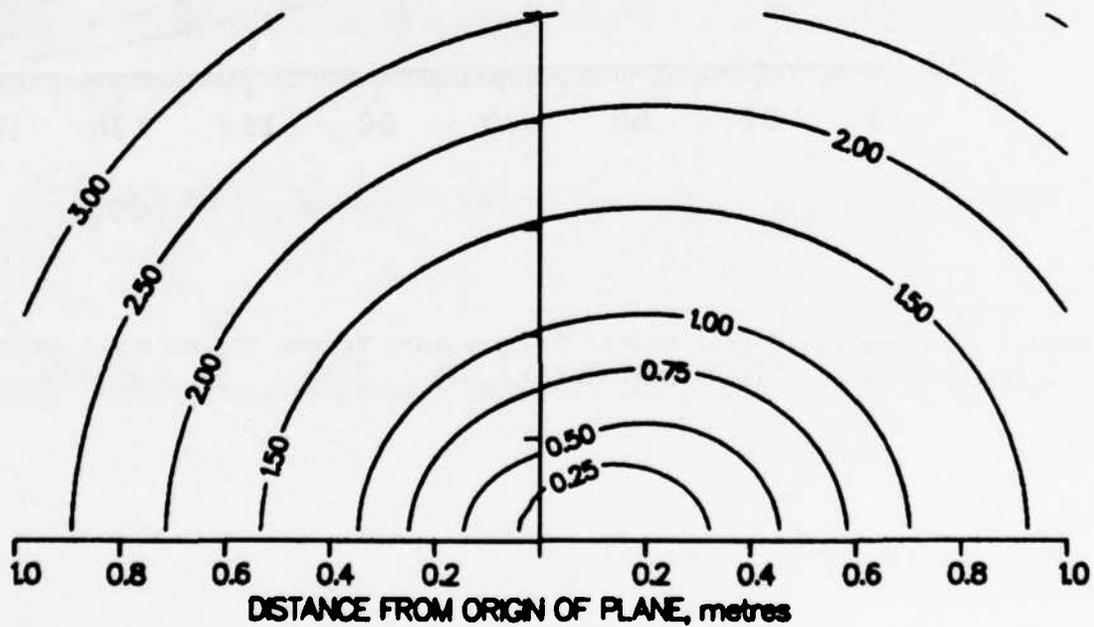


Figure 4. Free Field Peak Static Overpressure Versus Angle From Line of Fire at Fixed Radius ($r/D = 30$)

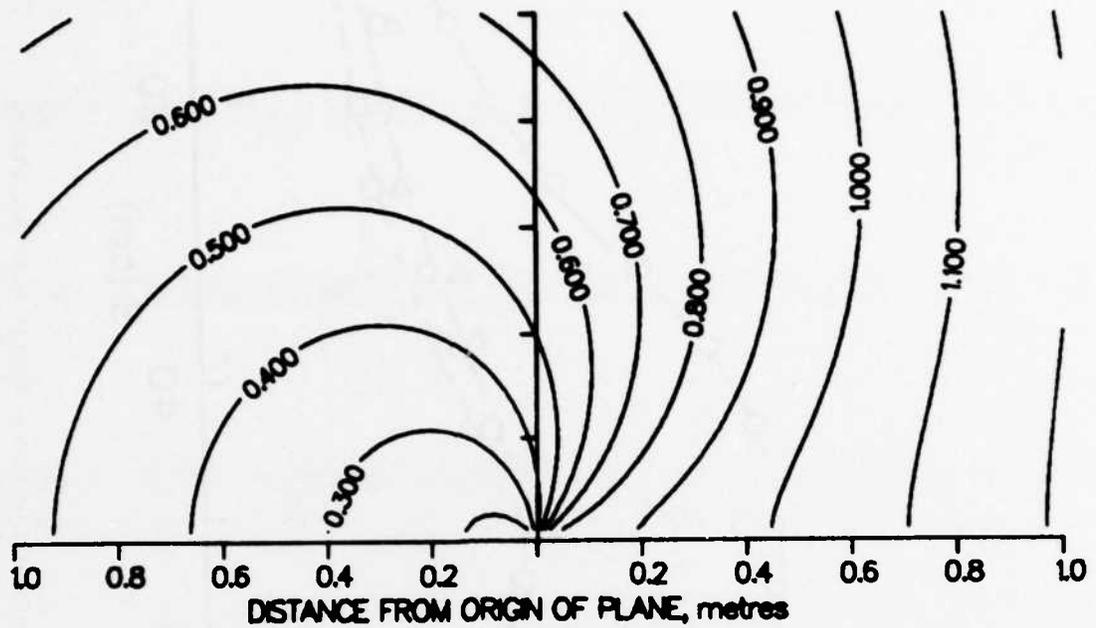


a. Peak Overpressure in atmospheres



b. Time of Arrival in milliseconds

Figure 5. Computed Contours of Free Field Blast for Bare Muzzle Case



c. Positive Phase Duration in Milliseconds

Figure 5. Computed Contours of Free Field Blast for Bare Muzzle Case

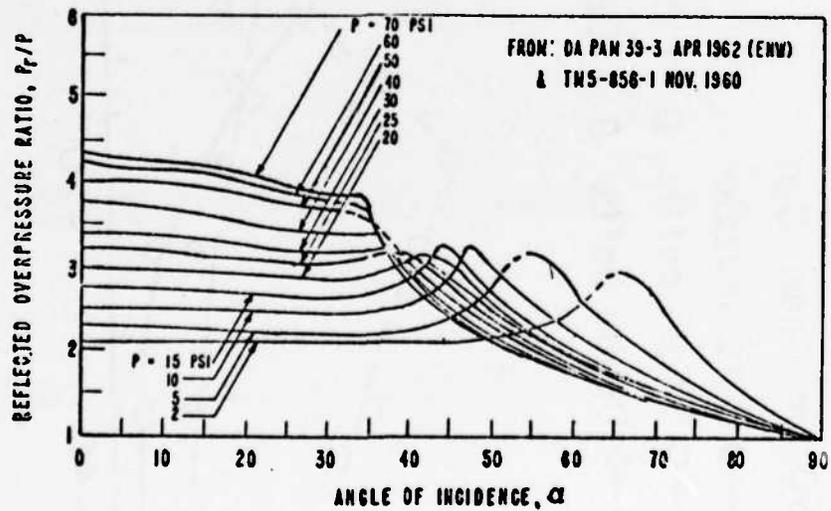


Figure 6. Shock Reflection Coefficients of Glasstone, et al

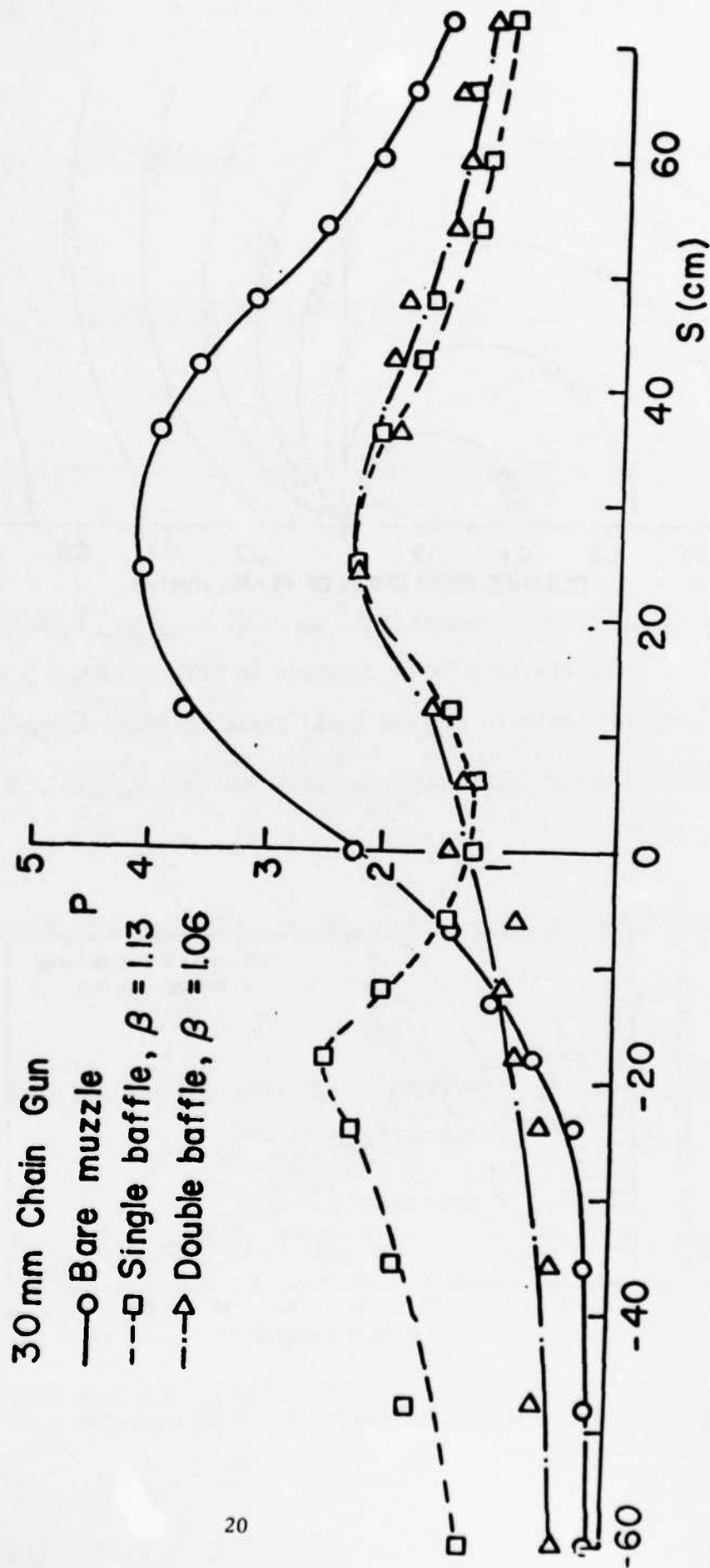
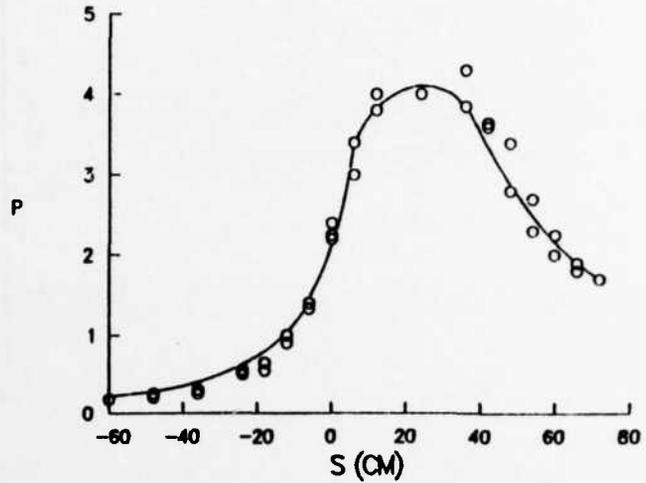
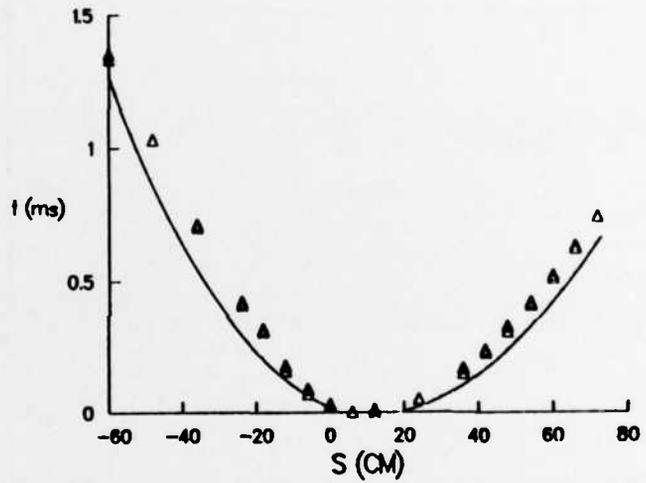


Figure 7. Comparison of Peak Overpressures Measured in Plate Surface for Three Muzzle Configurations
(Plate Inclination Angle = 0 deg, Separation Distance = 0.26 m)

a. Peak reflected overpressure
in atmospheres



b. Time of arrival ($t = 0$)
set at time when blast
first impinges upon the
plate)



c. Half peak width

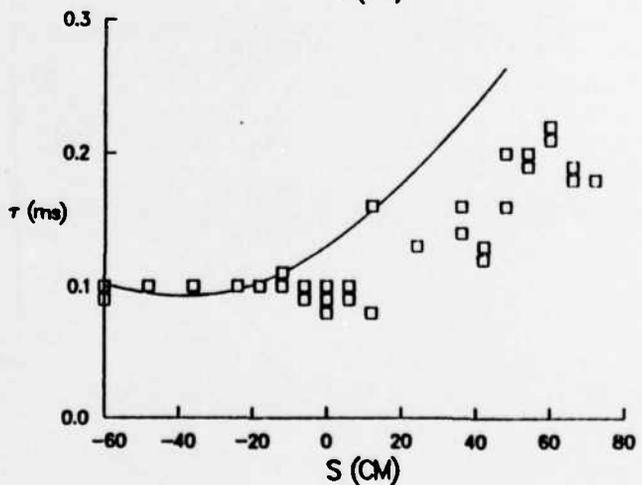
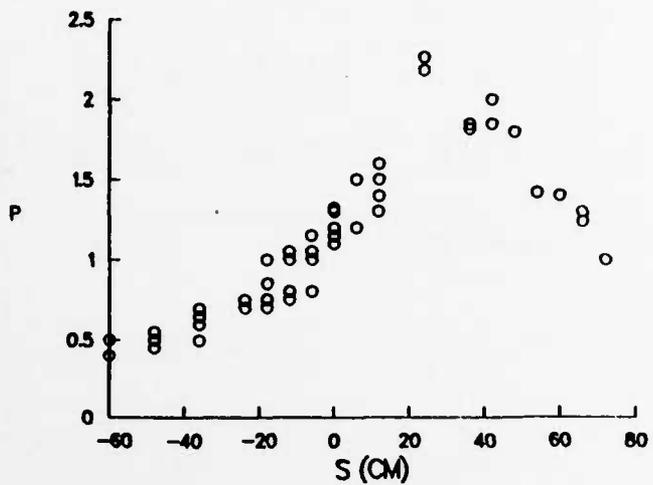
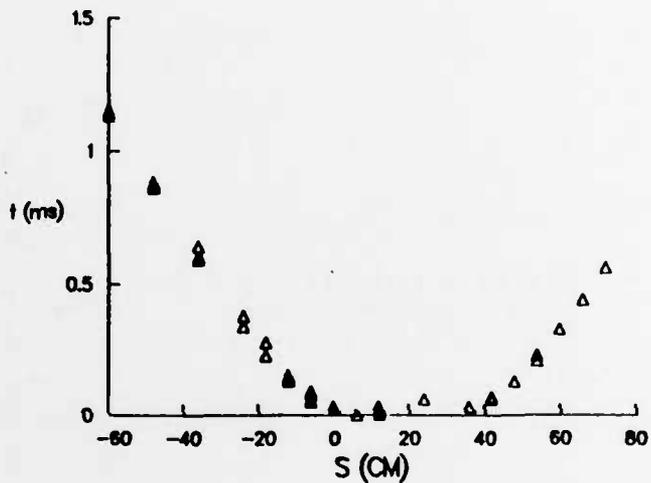


Figure 8. Properties of Pressure Pulse Measured on Surface of Plate and Comparison with Predictions of Analysis of Fansler and Schmidt. Bare Muzzle Case

a. Peak reflected overpressure



b. Time of arrival



c. Positive phase duration

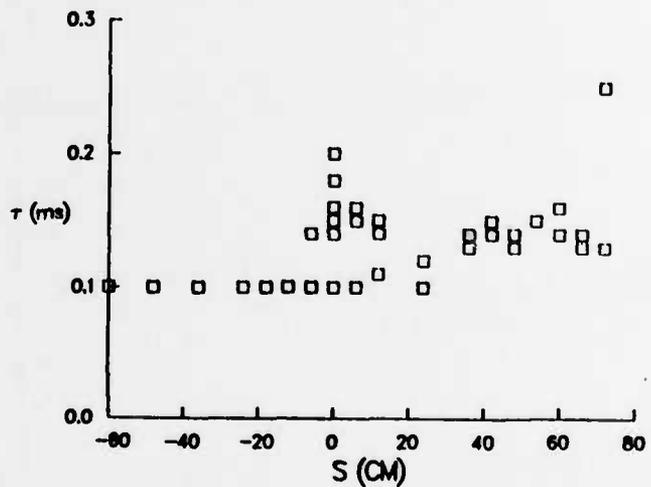
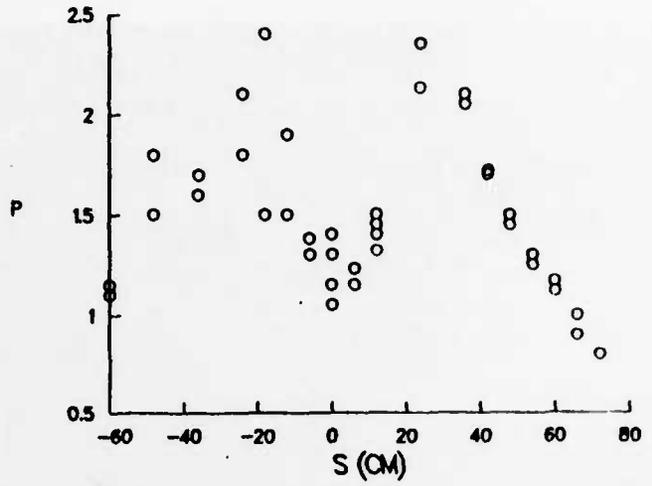
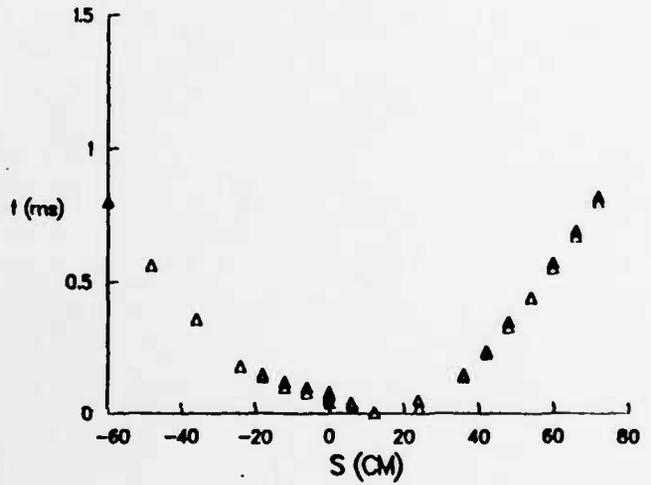


Figure 9. Properties of Pressure Pulse Measured on Surface of Plate
Double Baffle Brake #3

a. Peak reflected overpressure



b. Time of arrival



c. Positive phase duration

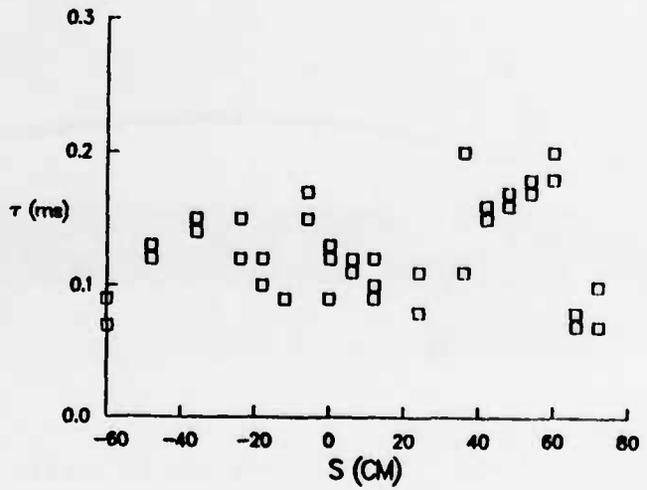


Figure 10. Properties of Pressure Pulse Measured on Surface of Plate
Single Baffle Brake #5

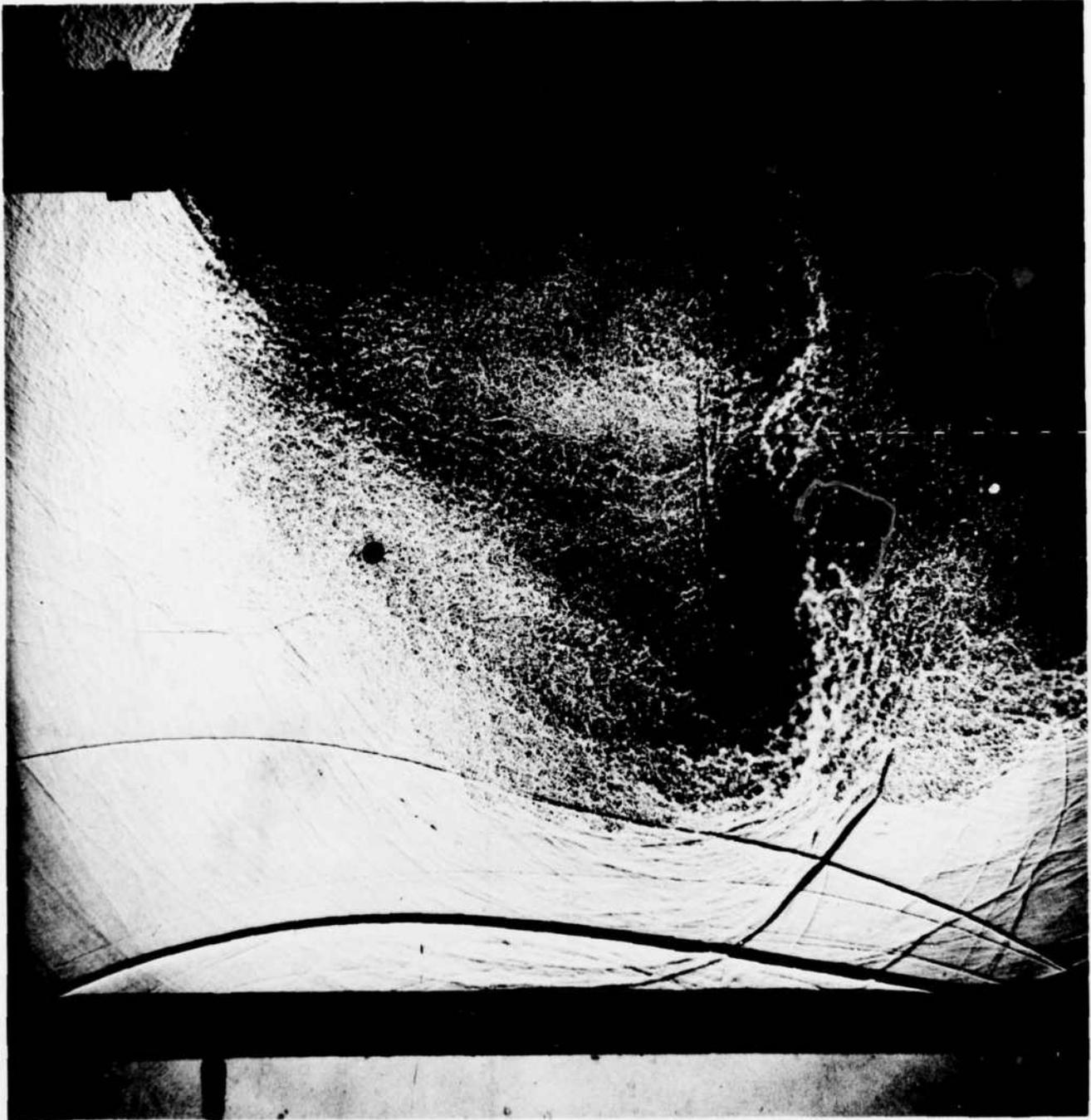


Figure 11. Spark Shadowgraph of Muzzle Blast Impinging Upon Plate Surface

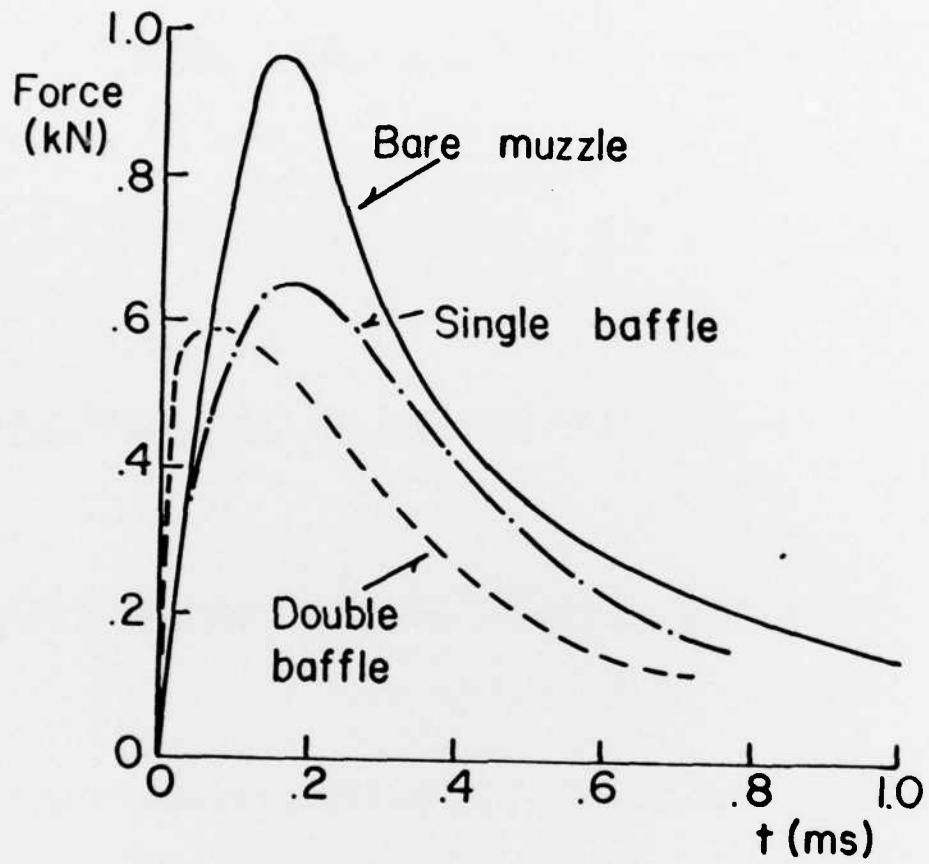


Figure 12. Force Exerted by Blast Wave on a 1.0 cm Wide Strip on Plate Parallel to the Line of Fire

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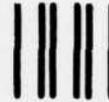
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