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Technical Memorandum 11-65

TRANSDUCER TECHNIQUES FOR MEASURING THE EFFECT OF SMALL-ARMS' NOISE ON HEARING

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July 1965
AMCMS Code 5011.11.84100

HUMAN ENGINEERING LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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TRANSDUCER TECHNIQUES FOR MEASURING THE EFFECT OF SMALL-ARMS' NOISE ON HEARING

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ABSTRACT

This study investigated several types of transducers which might be considered for use when evaluating the hearing hazard of pressure waves that small arms produce. In measuring the small arms' peak sound-pressure level, error was directly proportional to the measured rise time and inversely proportional to the positive pressure duration of the wave. The most accurate results were obtained by positioning the transducers vertically, with the pressure wave grazing the sensing surface at 90° incidence. Moreover, there was good agreement between measurements made with a wide-band piezoelectric transducer and those made with a wide-band condenser microphone. Finally, pistonphone calibrations at low levels (127 dB) compare favorably with shock-tube calibrations at high levels (170 to 180 dB).

CONTENTS

TABLES

TRANSDUCER TECHNIQUES FOR MEASURING THE EFFECT OF SMALL-ARMS' NOISE ON HEARING

INTRODUCTION

Recent years have seen the development of small arms that give the user greater range and firepower. But these improvements have raised the sound-pressure level (SPL) at the operator's ear until many firers show large hearing losses (2). The accuracy of the instrumentation is of primary importance when determining the possible hearing hazard of a weapon. This report deals with the characteristics of several transducers which might be considered for measuring impulse noise and with the way these transducers should be used.

This report is not intended to compare specific pressure transducers, but merely to indicate some of the problems of measuring the pressure-time histories that small arms produce. It aims to show the capabilities and limitations certain types of devices have, and to show the way they should be used for a specific application: determining how small-arms noise affects hearing. In addition, it compares calibrating a condenser microphone at low levels (127 dB* zero to peak) with a pistonphone and calibrating it at high levels (171 dB) with a shock tube.

The investigation had three parts. First, a shock-tube study determined the dynamic accuracy of the transducers. Second, the muzzle shock wave from an M14 rifle and the shock wave produced by its projectile in flight were measured to determine the most suitable microphone-incidence angle for measuring true incident pressure (i.e., the value that would be obtained if the transducer had negligible size and perfect response). Finally, the muzzle shock wave from an M14 rifle was measured at various distances from the weapon so the pressure-time histories of the transducers could be compared for various pressure levels.

We hope this report will help establish a uniform procedure for measuring small arms pressure waves accurately -- the primary requirement for evaluating how such weapons affect hearing.

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* In this report, the reference level is 0.0002 microbar.

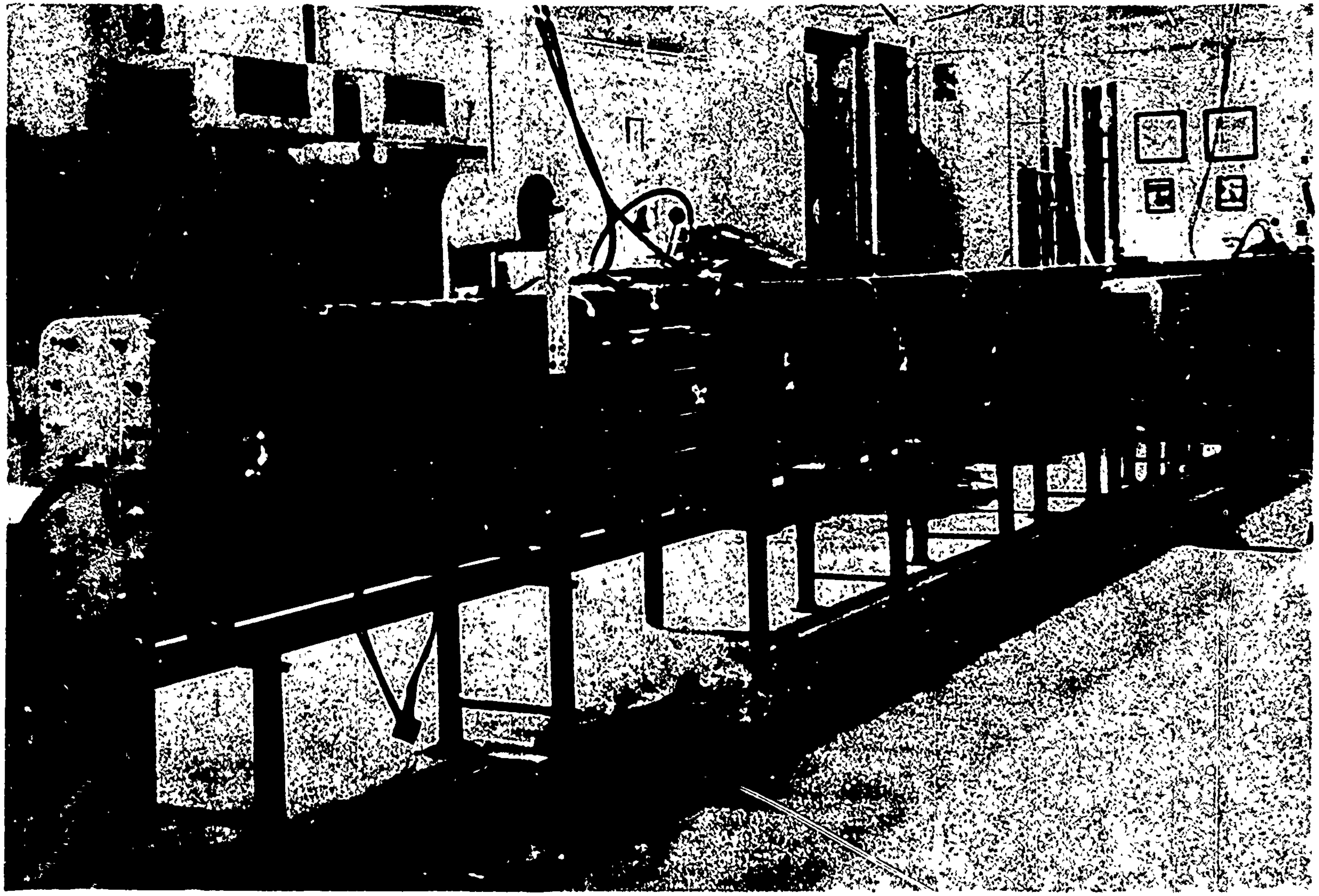


Fig. 1. SHOCK TUBE USED IN EVALUATING THE TRANSDUCERS

PART I: SHOCK-TUBE STUDY

METHOD

The shock-tube measurements were made with the Ballistic Research Laboratories (BRL) shock tube in Bldg. 1101-A, Aberdeen Proving Ground, Md. (Fig. 1).* The shock tube was 15 inches high, 4 inches wide, and 40 feet long, with a four-foot driver chamber. The pressure at the transducer was calculated to an accuracy of 1.5 percent from the Rankine-Hugoniot equation:

$$P_s = 7/6\, P_o\, (m^2 - 1) \tag{1}$$

where: P_s = shock-wave overpressure
P_o = ambient pressure
m = Mach number = v/c
v = speed of the shock wave
c = speed of sound

The sonic velocity, c, was calculated from the equation

$$c = 20.06\sqrt{T} \quad \text{meters/sec} \tag{2}$$

where T is the temperature of the air inside the shock tube, measured in degrees Kelvin. The ambient pressure, P_o, was measured with a Wallace & Tierman dial manometer gage; and the temperature, T, with a calibrated thermometer. The speed of the shock wave, v, was determined by measuring the time the pressure wave took to travel between two pressure gages that were 34 inches apart. This time interval was measured with a Transistor Specialties, Inc., counter-chronograph.

The shock tube nominally produces a shock wave which rises "instantaneously" to a preselected pressure, remains at that pressure for approximately six milliseconds, then gradually returns to ambient pressure. When a transducer measures this shock-tube pressure wave, the time-history oscillogram is an accurate index of the transducer's rise-time capability for a given pressure and a given angle of incidence. Moreover, the shock tube produces an accurate, preselected pressure, which is a useful reference for two purposes: validating the manufacturer's sensitivity specification, and verifying other calibrating methods, as from a pistonphone. The transducer's ringing and overshoot characteristics may also be evaluated.

* Invaluable assistance was rendered by Mr. Benjamin A. Granath in the operation and technology of the BRL shock tube.

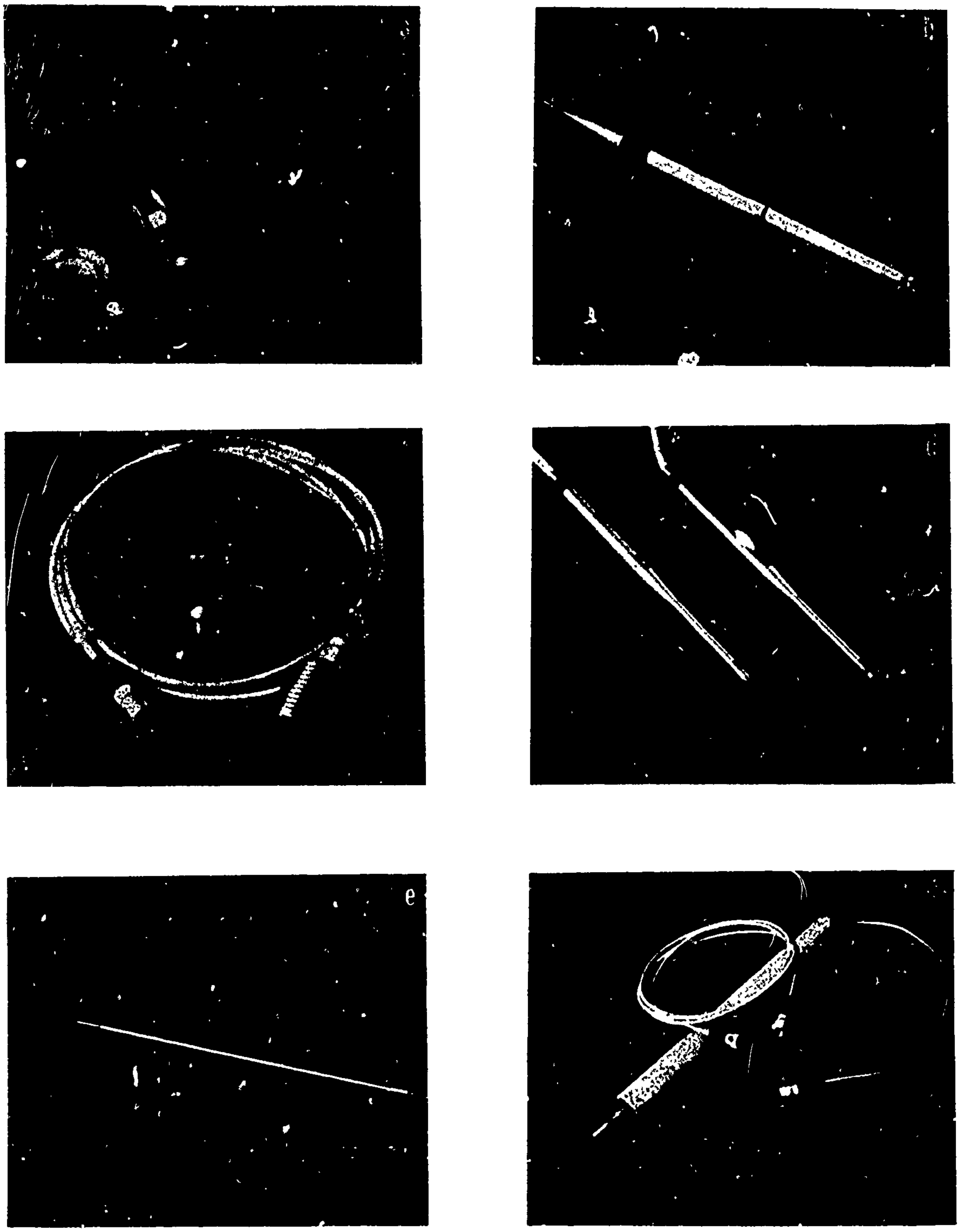


Fig. 2. TRANSDUCERS USED IN THE EVALUATION
(a. Altec Lansing 21-BR-180, b. Atlantic Research LC-33, c. Ballistic Research Laboratories BRL 250-kc, d. Bruel and Kjaer 4135 and 4136, e. Dickey HPO62L, and f. Kistler 601-A.)

The transducers investigated in this report (Fig. 2) and their associated instruments were:

a. Altec Lansing type 21-BR-180 one-half-inch condenser microphone, with a General Radio (GR) type 1551-P1-25 cathode follower. The polarization voltage was supplied by a GR type 1551-P1 power supply.

b. Atlantic Research model LC-33 lead zirconate pressure transducer, with a Kistler type 566 charge amplifier.

c. Ballistic Research Laboratories BRL 250-kc lead zirconate pressure transducer, with a Kistler type 566 charge amplifier.

d. Bruel & Kjaer (B&K) types 4135 and 4136 one-quarter-inch condenser microphones, with a B&K type 2615 cathode follower. The polarization voltage was supplied by a B&K type 2801 power supply.

e. Dickey HPO62L -- a one-sixteenth-inch lead zirconate pressure transducer, with a Kistler type 566 charge amplifier. This transducer was manufactured by Clyde W. Dickey, Pennsylvania State University.

f. Kistler model 601-A quartz pressure transducer, with a Kistler type 566 charge amplifier.

The output from all transducers was fed to a Tektronix type 502-A oscilloscope and photographed with a Tektronix type C-12 R camera. The oscilloscope sweep was set at 50 microseconds per centimeter for all transducers (except for the Altec-Lansing normal-incidence measurement). The B&K transducers were measured both with and without their protective grids.

Pressure levels as measured by each transducer in the shock tube were based on the information in Table 1.

TABLE 1

Method of Obtaining Transducer Sensitivities

Transducer	Source of Sensitivity Reference
Altec Lansing 21-BR-180	GR type 1552-B sound-level calibrator
Atlantic Research LC-33	Manufacturer's sensitivity rating (2480 pc/psi)[a]
BRL 250-kc	Manufacturer's sensitivity rating (24.0 pc/psi)
B&K 4135 and 4136	B&K type 4220 pistonphone
Dickey HPO62L	Manufacturer's sensitivity rating (13.2 pc/psi)
Kistler 601-A	Manufacturer's sensitivity rating (1.04 pc/psi)

[a]picocoulomb/pound per square inch

The transducers were oriented in two ways in the shock tube:

a. Grazing incidence (90°) -- for these measurements the transducers were inserted through a port in the side of the tube, and the shock wave travelled parallel to the sensing surface.

b. Normal incidence (0°) -- for these measurements the transducers were inserted through a port in the end of the tube, and the shock wave travelled perpendicular to the sensing surface. To keep reflections from the end of the shock tube from appearing on the oscillograms, the transducer's sensing surface was positioned about six inches from the end.

RESULTS

The results are shown in Figures 3 to 11. The voltage calibration of the oscillograms in Figure 11 (0° incidence) was slightly inaccurate; therefore, the measured overpressure was omitted. The oscilloscope records show that, at pressures below 170 dB, the time histories are quite irregular. This effect arises because the shock-tube diaphragm does not break instantaneously at low pressures. Irregularities at higher pressures are caused by transverse reflections in the shock tube.

DISCUSSION

Probably the most important attribute of a pressure transducer is its accuracy in measuring pressure (i.e., its absolute pressure accuracy). Figures 3 to 11 show that there was good agreement between the absolute pressure accuracy of a wide-band condenser microphone and that of a wide-band piezoelectric device.

In measuring small arms, the transducer's rise-time capability is also very important. Figure 7 shows that the B&K 4136, when used at 90° incidence without its protective grid, has a rise time of about 20 microseconds at 170.7 dB. This rise time is limited by the time the pressure wave takes to cross the transducer. Interestingly, however, replacing the protective grid reduces the rise time for the same pressure to about ten microseconds. Apparently, adding the cavity and grid in front of the diaphragm improves the microphone's rise-time capability beyond what conventional transit-time considerations would predict.

The transducer's rise-time capability depends on several factors, the most important of which are:

a. Frequency response of the transducer and the associated equipment. The rise-time capability is proportional to the reciprocal of the upper limiting frequency.

b. Transit time. The transducer's transit time is a function of its diameter, D, and the incidence angle, Θ, and is proportional to $D \sin \Theta$.

c. Peak pressure. The transducer's rise-time capability -- particularly for condenser microphones -- depends on the pressure being measured. For instance, Figure 3 shows a rise time of 70 microseconds at 165 dB; at 171 dB, the rise time is approximately 160 microseconds. In a later section we will discuss how rise time depends on peak SPL.

d. Damping. Rise time is also affected by the degree of damping in a transducer. In a condenser microphone, damping may be controlled both electrically and by the resistance the backplate provides.

The results show that a pistonphone calibration at low levels (127 dB, zero to peak) agrees with a shock-tube calibration at 170 dB to 180 dB within 0.7 dB. This suggests that condenser microphones have a high degree of linearity through their dynamic measuring range, so they may not require high-intensity-pistonphone calibration before measuring high-intensity impulse noise. Also, transducers should give comparable measurements whether calibrated in a shock tube or with a pistonphone.

The oscilloscope records show that there may be overshoot when the pressure wave strikes a transducer at 0° (Figs. 3 to 11). This overshoot is caused by the pressure the face of the transducer reflects, and it is affected by the amount of damping in the transducer. For example, the B&K 4135, which is overdamped, does not overshoot at 0° incidence; but the 4136, which is critically damped, overshoots by about 80 percent. The Kistler transducer, when positioned at 0° incidence (Fig. 11) shows both overshoot and a degree of ringing. In measuring weapons, it is important to minimize overshoot and ringing which may give rise to a false pressure-time history.

CONCLUSIONS

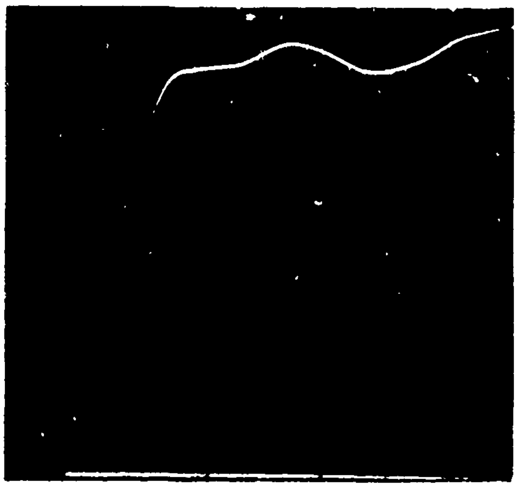
The shock-tube measurements suggest these conclusions:

a. A wide-band piezoelectric transducer and a wide-band condenser microphone with adequate rise-time capability measure the absolute pressure with equal accuracy.

b. The transducer's rise-time capability must be considered carefully when measuring small arms, since some transducers have rise-time capabilities which are longer than the pressure transient to be measured.

c. Calibrating a condenser microphone at low SPL (127 dB) with a pistonphone agrees within 0.7 dB with a shock-tube calibration at high SPL (171 dB).

d. When measurements will be used to evaluate whether small arms pose a hearing hazard, zero-degree incidence measurements produce misleading time histories: the record will include reflected pressure, as well as overshoot inherent in the transducer. Overdamped transducers, such as the B&K 4135, will not show this contamination; however, overdamping reduces rise-time capability.

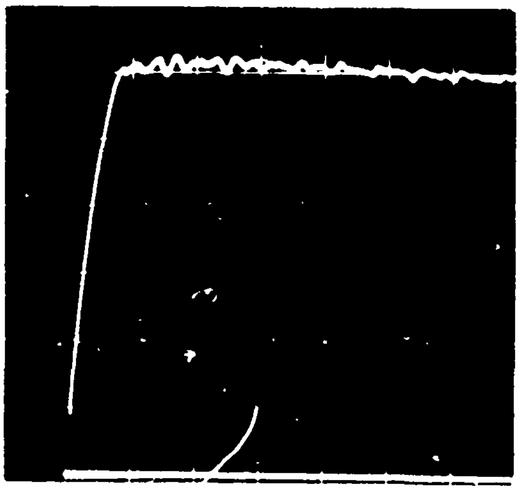


Transducer Altec Lansing 21-BR-180 S.N. 942, 90° incidence

Horizontal 50 microseconds/major div.
Vertical 2.16 volts/major div.
Measured Overpressure 166.3 dB
Actual Overpressure 164.9 dB

Transducer Altec Lansing 21-BR-180 S.N. 942, 90° incidence

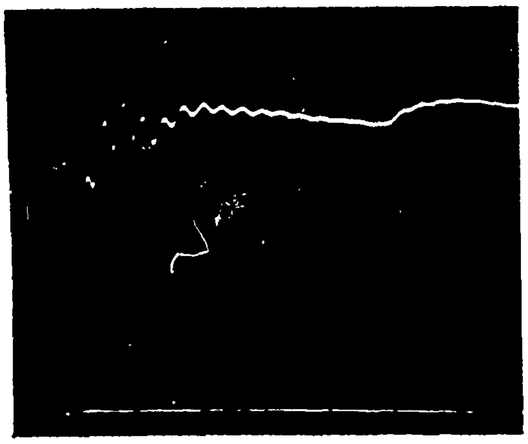
Horizontal 50 microseconds/major div.
Vertical 5.08 volts/major div.
Measured Overpressure 172.4 dB
Actual Overpressure 170.8 dB



Transducer Altec Lansing 21-BR-180 S.N. 942, 0° incidence

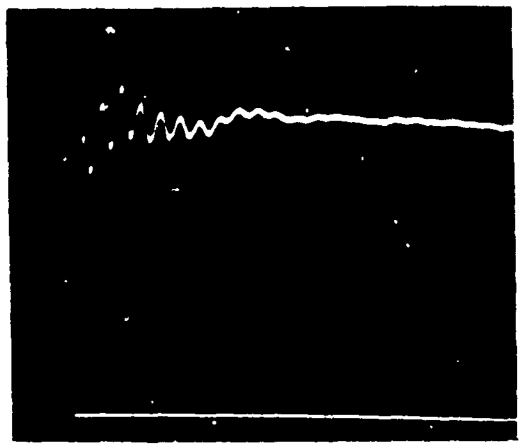
Horizontal 1.0 milliseconds/major div.
Vertical 4.92 volts/major div.
Measured Overpressure 173.7 dB
Actual Overpressure 170.7 dB

Fig. 3. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH AN ALTEC LANSING 21-BR-180 AT 0° AND 90° INCIDENCE



Transducer Atlantic Model LC-33
S.N. 351

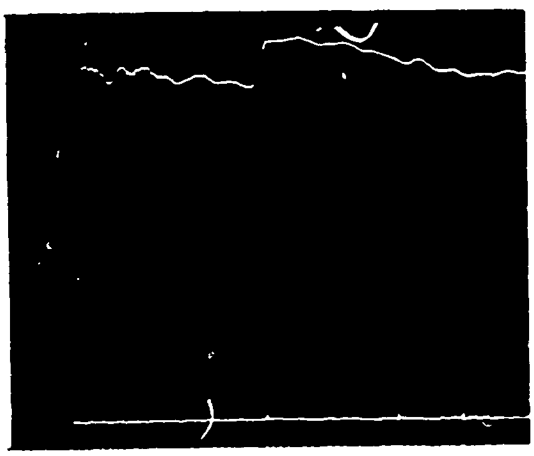
Horizontal 50 microseconds/major div.
Vertical 302 picocoulombs/major div.
Measured Overpressure 164.8 dB
Actual Overpressure 163.5 dB



Transducer Atlantic Model LC-33
S.N. 351

Horizontal 50 microseconds/major div.
Vertical 593 picocoulombs/major div.
Measured Overpressure 171.0 dB
Actual Overpressure 170.9 dB

Fig. 4. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH AN ATLANTIC RESEARCH LC-33
(Nominal pressure is 164 and 171 dB.)



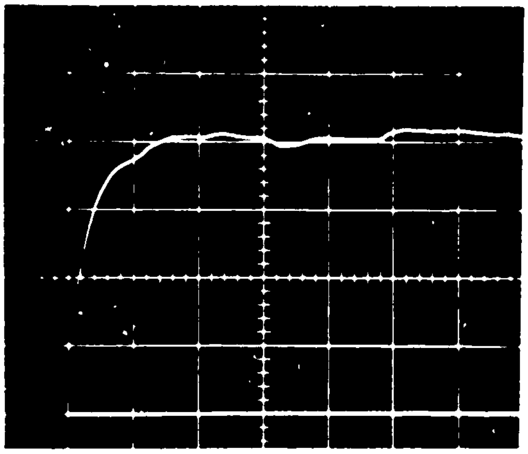
Transducer BRL 250-kc
90° incidence

Horizontal 50 microseconds/major div.
Vertical 2.33 picocoulombs/major div.
Measured Overpressure 164.8 dB
Actual Overpressure 164.9 dB

Transducer BRL 250-kc
90° incidence

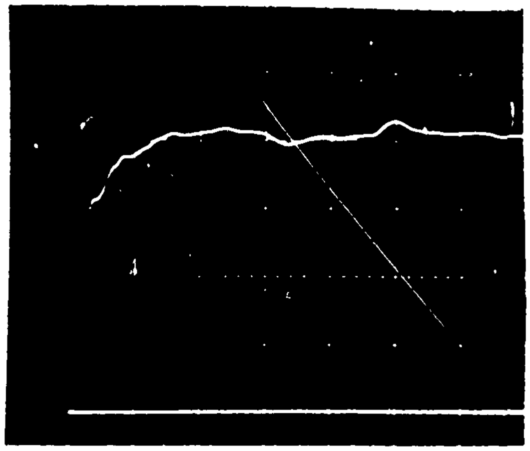
Horizontal 50 microseconds/major div.
Vertical 4.71 picocoulombs/major div.
Measured Overpressure 170.7 dB
Actual Overpressure 170.9 dB

Fig. 5. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED
WITH A BRL 250-kc TRANSDUCER AT 90° INCIDENCE
(Nominal pressure is 165 and 171 dB.)



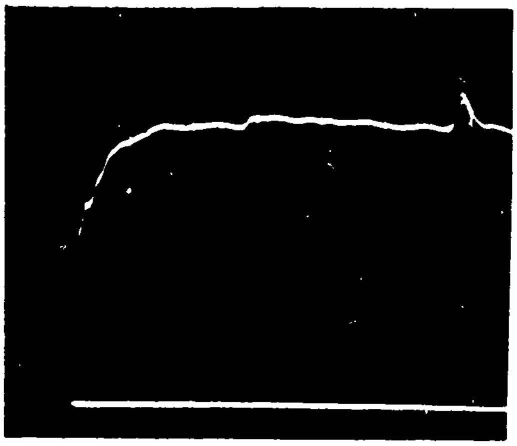
Transducer B&K Type 4135 S.N. 77227, 90° incidence without protective grid.

Horizontal 50 microseconds/major div.
Vertical 5.07 volts/major div.
Measured Overpressure 171.8 dB
Actual Overpressure 170.5 dB



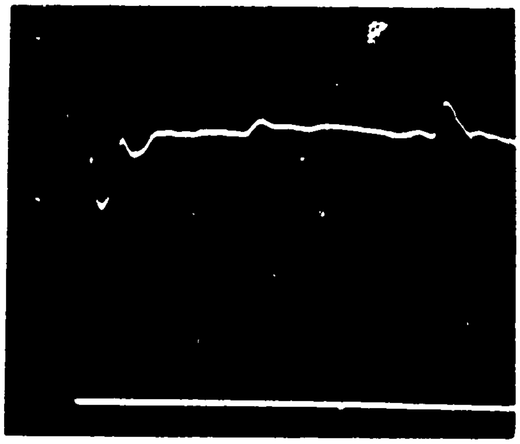
Transducer B&K Type 4135 S.N. 77227 90° incidence with protective grid.

Horizontal 50 microseconds/major div.
Vertical 5.07 volts/major div.
Measured Overpressure 171.8 dB
Actual Overpressure 170.7 dB



Transducer B&K Type 4135 S.N. 77227, 0° incidence without protective grid.

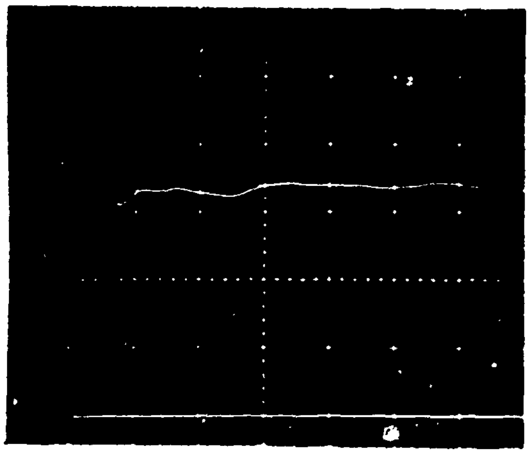
Horizontal 50 microseconds/major div.
Vertical 5.07 volts/major div.
Measured Overpressure 172.0 dB
Actual Overpressure 170.5 dB



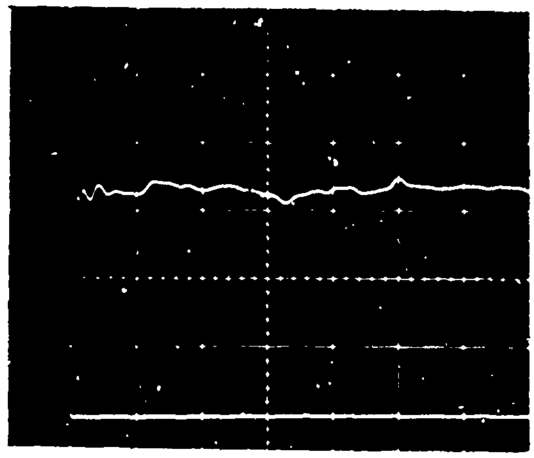
Transducer B&K Type 4135 S.N. 77227, 0° incidence with protective grid.

Horizontal 50 microseconds/major div.
Vertical 5.07 volts/major div.
Measured Overpressure 171.8 dB
Actual Overpressure 170.6 dB

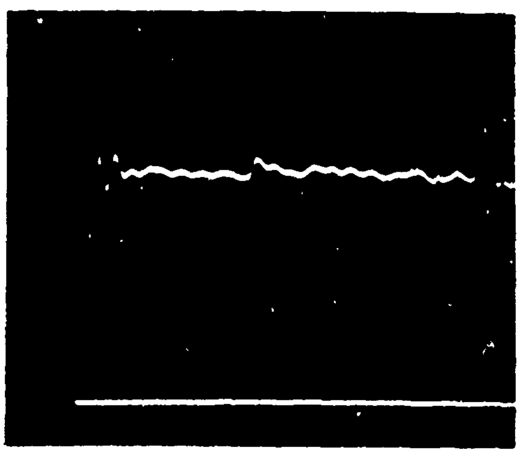
Fig. 6. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH A B&K 4135 WITH AND WITHOUT PROTECTIVE GRID AT 0° AND 90° INCIDENCE
(Nominal pressure is 171 dB.)



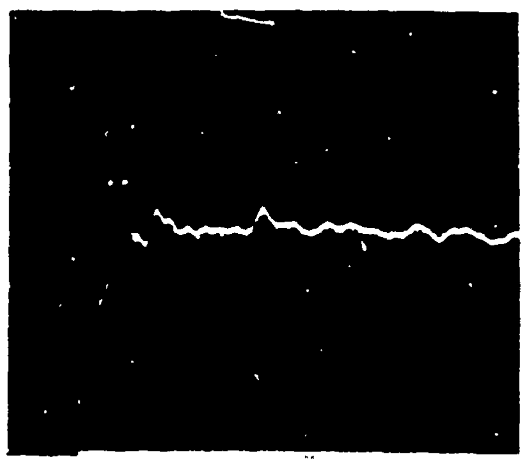
Transducer B&K Type 4136 S.N. 81227, 90° incidence without protective grid.
Horizontal 50 microseconds/major div.
Vertical 2.01 volts/major div.
Measured Overpressure 171.2 dB
Actual Overpressure 170.7 dB



Transducer B&K Type 4136 S.N. 81227, 90° incidence with protective grid.
Horizontal 50 microseconds/major div.
Vertical 2.01 volts/major div.
Measured Overpressure 171.2 dB
Actual Overpressure 170.7 dB

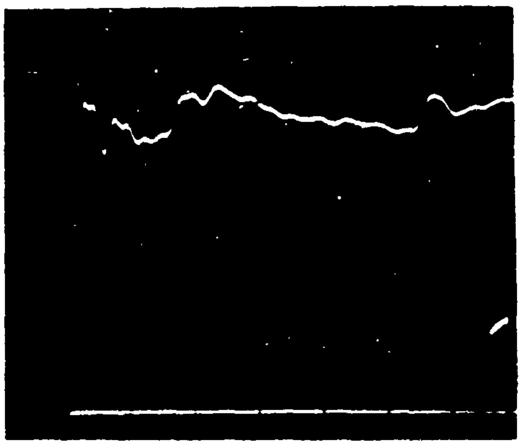


Transducer B&K Type 4136 S.N. 81227, 0° incidence without protective grid.
Horizontal 50 microseconds/major div.
Vertical 2.05 volts/major div.
Measured Overpressure 171.6 dB
Actual Overpressure 170 7 dB



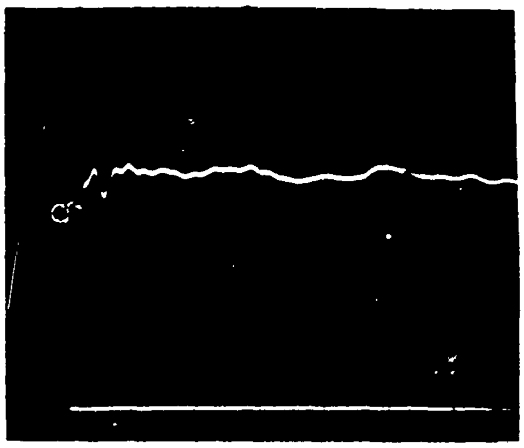
Transducer B&K Type 4136 S.N. 81227, 0° incidence with protective grid.
Horizontal 50 microseconds/major div.
Vertical 2.05 volts/major div.
Measured Overpressure 171.4 dB
Actual Overpressure 170.5 dB

Fig. 7. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH A B&K 4136 WITH AND WITHOUT PROTECTIVE GRID AT 0° AND 90° INCIDENCE
(Nominal pressure is 171 dB.)



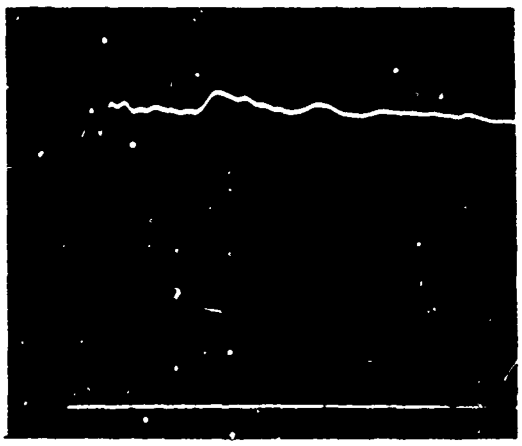
Transducer B&K Type 4136 S.N. 07123, 90° incidence with protective grid.

Horizontal 50 microseconds/major div.
Vertical 1.03 volts/major div.
Measured Overpressure 164.8 dB
Actual Overpressure 165.8 dB



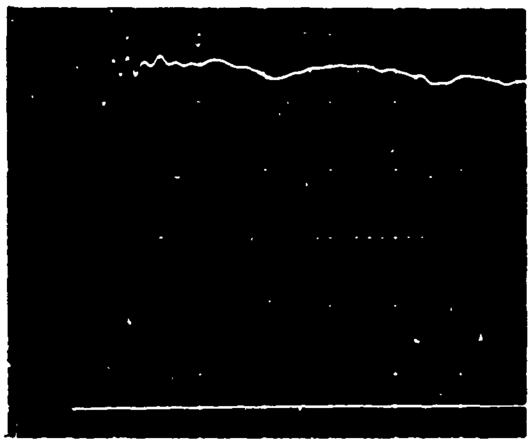
Transducer B&K Type 4136 S.N. 07123, 90° incidence with protective grid.

Horizontal 50 microseconds/major div.
Vertical 4.07 volts/major div.
Measured Overpressure 175.5 dB
Actual Overpressure 174.8 dB



Transducer B&K Type 4136 S.N. 07123, 90° incidence with protective grid

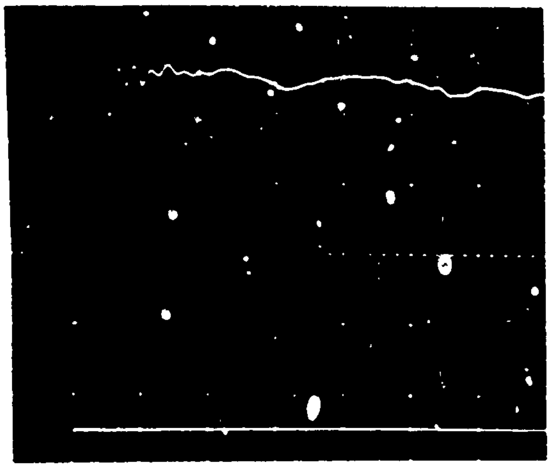
Horizontal 50 microseconds/major div.
Vertical 4.10 volts/major div.
Measured Overpressure 177.4 dB
Actual Overpressure 176.5 dB



Transducer B&K Type 4136 S.N. 81227, 90° incidence with protective grid.

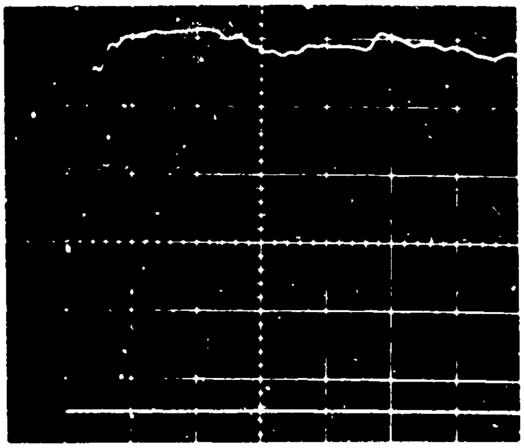
Horizontal 50 microseconds/major div.
Vertical 5.11 volts/major div.
Measured Overpressure 182.9 dB
Actual Overpressure 182.4 dB

Fig. 8. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH A B&K 4136 WITH PROTECTIVE GRID AT 90° INCIDENCE AT FOUR DIFFERENT PRESSURE LEVELS



Transducer B&K Type 4136 S.N. 81227, 90° incidence with protective grid.

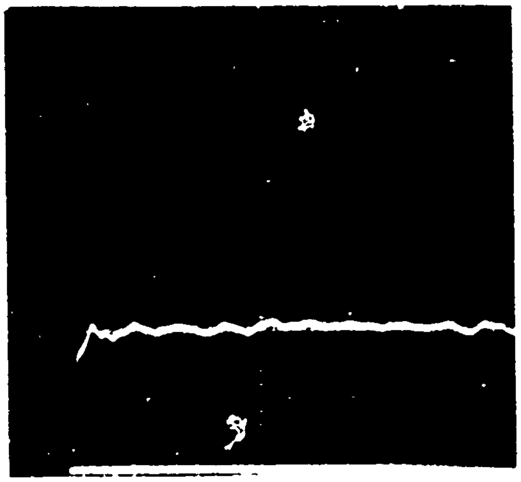
Horizontal 50 microseconds/major div.
Vertical 5.11 volts/major div.
Measured Overpressure 182.9 dB
Actual Overpressure 182.4 dB



Transducer B&K Type 4136 S.N. 81227, 90° incidence without protective grid.

Horizontal 50 microseconds/major div.
Vertical 5.09 volts/major div.
Measured Overpressure 183.6 dB
Actual Overpressure 183.0 dB

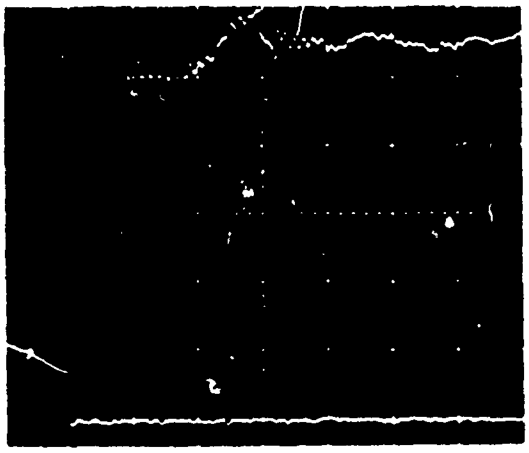
Fig. 9. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH A B&K 4136 WITH AND WITHOUT PROTECTIVE GRID AT 90° INCIDENCE
(Nominal pressure is 183 dB.)

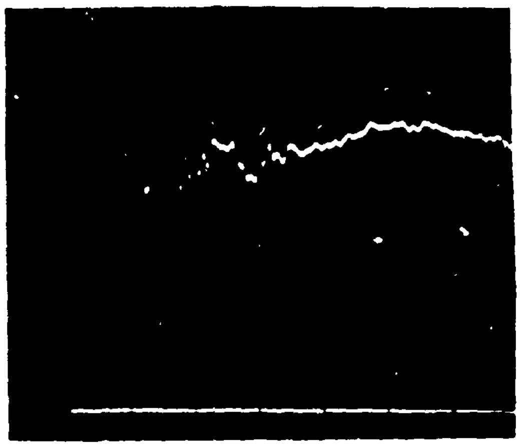


Transducer Dickey
S.N. 558 0° incidence

Horizontal 50 microseconds/major div.
Vertical 6.3 picocoulombs/major div.
Measured Overpressure 168.8 dB
Actual Overpressure 170.7 dB

Fig. 10. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH A DICKEY TRANSDUCER AT 0° INCIDENCE





Transducer Kistler Model 601-A, 90° incidence

Horizontal 50 microseconds/major div.
Vertical 0.206 picocoulombs/major div.
Measured Overpressure 170.6 dB
Actual Overpressure 170.6 dB

Transducer Kistler Model 601-A 0° incidence

Horizontal 50 microseconds/major div.
Vertical
Measured Overpressure
Actual Overpressure 170.9 dB

Fig. 11. SHOCK-TUBE PRESSURE vs. TIME HISTORY MEASURED WITH A KISTLER 601-A AT 90° AND 0° INCIDENCE (Nominal pressure is 171 dB.)

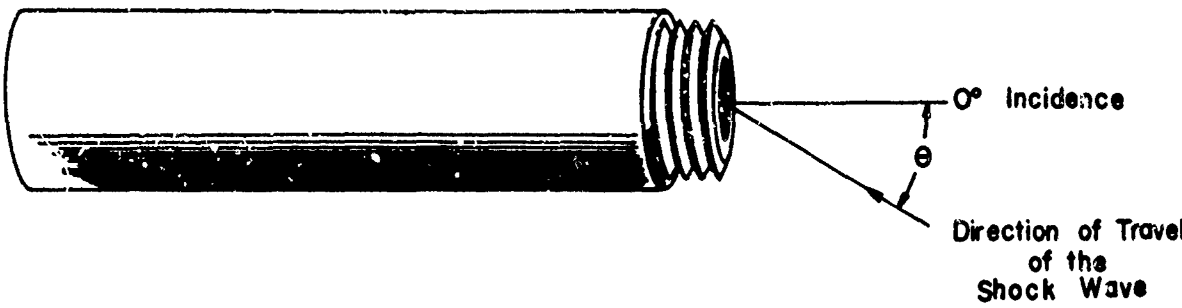


Fig. 12. INCIDENCE ANGLE θ, SHOWN AS THE ANGLE BETWEEN THE DIRECTION OF TRAVEL OF THE PRESSURE WAVE AND THE LONGITUDINAL AXIS OF THE TRANSDUCER

Fig. 13. TRANSDUCER LOCATIONS USED FOR THE BULLET-SHOCK-WAVE MEASUREMENTS (The transducer on the left is the BRL 250-kc, on the right is the B&K 4136, and the microphone near the center is for oscilloscope triggering. The path of the bullet was midway between the two measuring transducers.)

PART II: MICROPHONE ORIENTATION INVESTIGATION

METHOD

The first part of this report dealt with how incidence angles (0^{o} and 90^{o}) affected measurements with various transducers. This second part will examine how intermediate incidence angles affect measured pressure-time histories of small arms. For the purpose of this report, incidence is the angle between the shock-wave's direction of travel and the transducer's longitudinal axis (Fig. 12). Also, microphone locations will be given in polar coordinates, with the barrel's muzzle end at the center of the polar coordinate system, the line of fire at zero degrees, and angles measured in a clockwise direction (Fig. 19).

Small arms peak-pressure and pressure-time-history measurements are known to vary with the transducer incidence angle. This variation comes from pressure reflected by the transducer and from its overshoot characteristics. We decided, therefore, to do a two-part experiment to determine how varying transducer-incidence angles affect the time histories that two different impulse wave shapes produce.

The wave shapes chosen were the shock wave of a 7.62mm bullet in flight, which produces the classic "N" wave, and the shock wave of the expanding gases near the muzzle of a 7.62mm rifle. These wave shapes were measured with two transducers: (a) BRL 250-kc, and (b) B&K type 4136 (with protective grid). The B&K microphone was calibrated with a pistonphone, and the manufacturer's rated sensitivity was accepted for the BRL transducer.

Bullet-Shock-Wave Measurements

Measurements of the 7.62mm bullet's shock wave were made with transducers located as shown in Figure 13. Each transducer's output was fed to an oscilloscope, and both outputs were recorded simultaneously.

To orient the microphone properly with reference to the shock front, it is important to determine the acute angle between the bow wave and the line of fire. This angle, Θ, is given by:

$$\Theta = \sin^{-1}(c/v) \qquad (3)$$

where: c = speed of sound
v = velocity of the bullet

The M14 rifle has a nominal muzzle velocity of 2870 ft/sec, so Θ equals 23°. This angle may also be approximated from Figure 14 by direct measurement. The transducers were positioned at a 0° incidence angle (Fig. 15). Each transducer's output was fed to a separate Tektronix type 565 oscilloscope and both traces were recorded simultaneously. To assure that the two transducers were the same distance from the bullet's path, a single microphone triggered both oscilloscopes simultaneously. Pressure-time histories were recorded at incidence angles varying from 0° to 90° in 30° increments, with the transducer's sensitive surface as the pivot point. The results are shown in Figures 16 and 17.

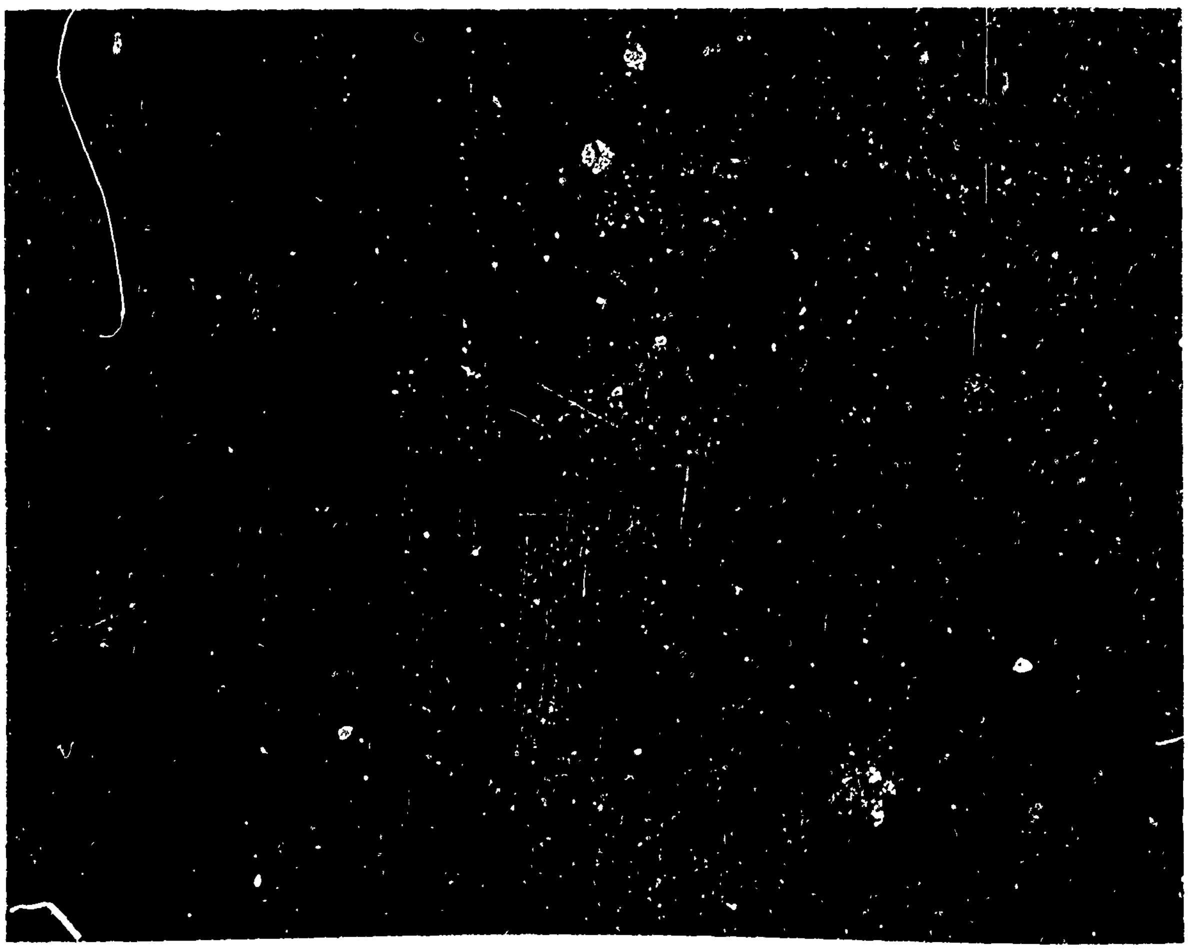


Fig. 14. SHOCK WAVE OF A 7.62mm BULLET IN FLIGHT AT A NOMINAL VELOCITY OF 2870 FEET PER SECOND

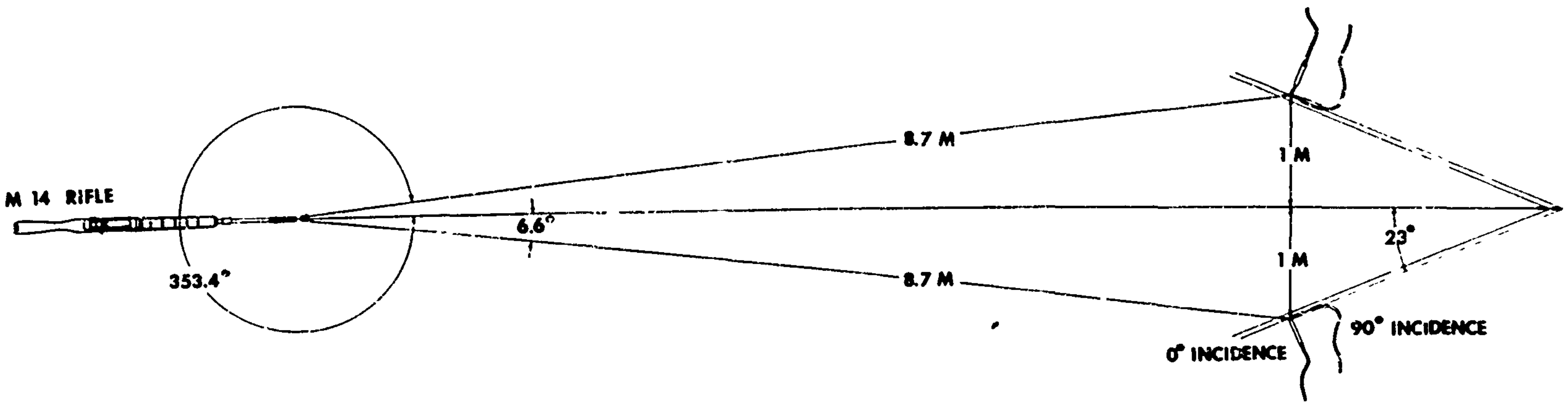
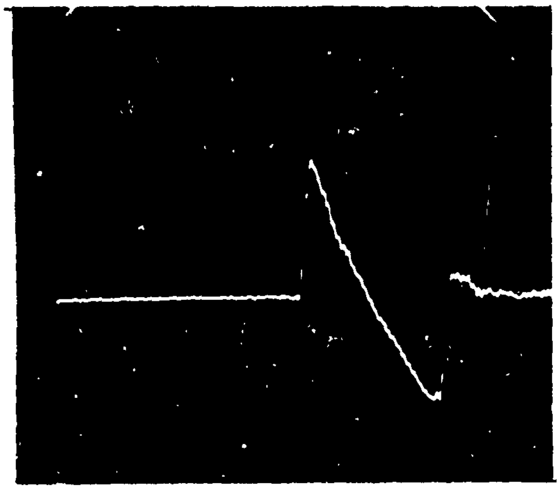
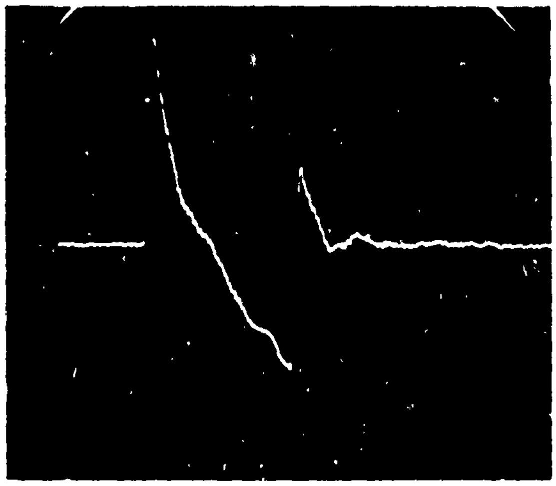


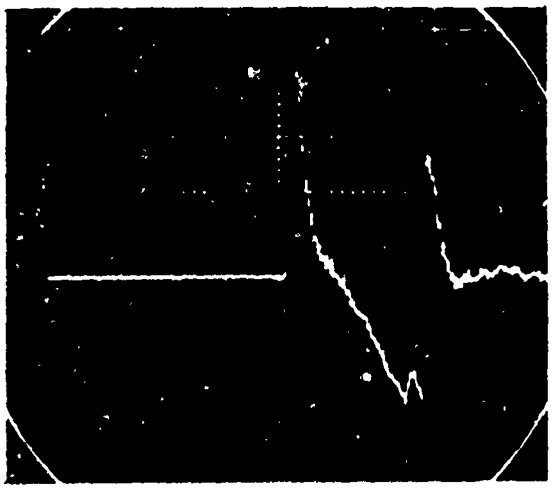
Fig. 15. TRANSDUCER LOCATIONS FOR THE MEASUREMENTS OF THE BULLET SHOCK WAVE AT ONE METER



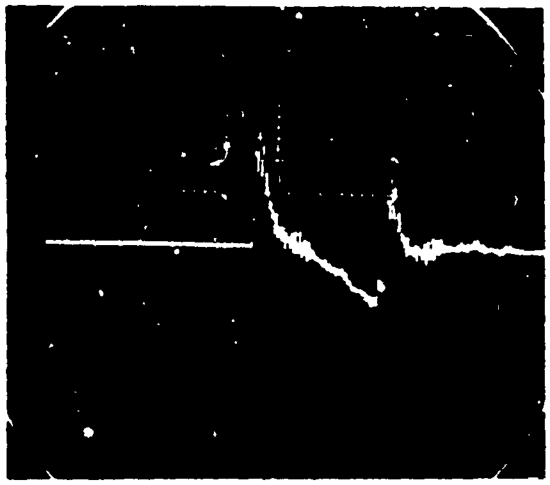
Source 7.62mm Bullet Shock Wave
Transducer BRL 250-kc at 8.7 meters from the muzzle and 6.6° azimuth. Incidence angle 90°
Horizontal 50 microseconds/major div.
Vertical 0.02 volts/major div.
Measured Overpressure 157.0 dB



Source 7.62mm Bullet Shock Wave
Transducer BRL 250-kc at 8.7 meters from the muzzle and 6.6° azimuth. Incidence angle 60°
Horizontal 50 microseconds/major div.
Vertical 0.02 volts/major div.
Measured Overpressure 160.3 dB

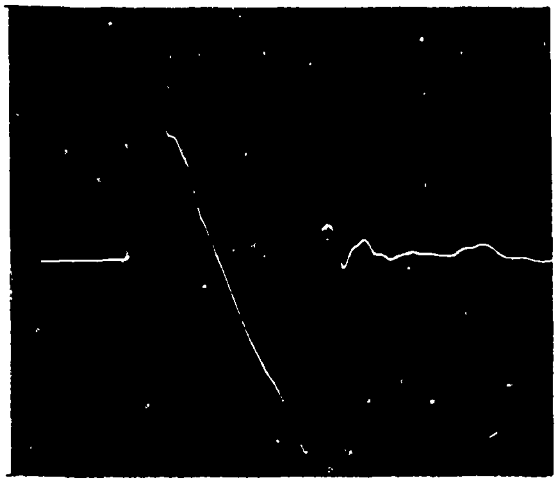


Source 7.62mm Bullet Shock Wave
Transducer BRL 250-kc at 8.7 meters from the muzzle and 6.6° azimuth. Incidence angle 30°
Horizontal 50 microseconds/major div.
Vertical 0.02 volts/major div.
Measured Overpressure 162.0 dB

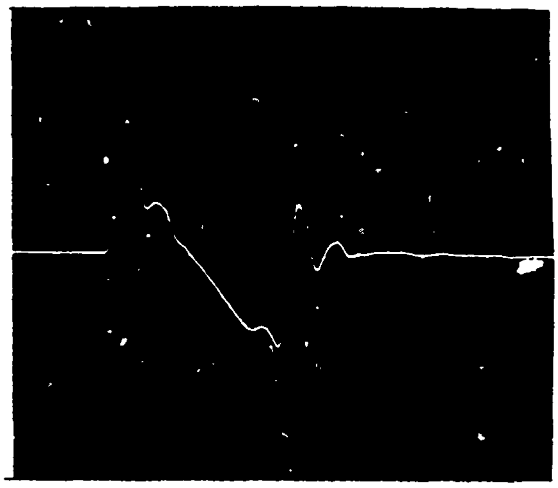


Source 7.62mm Bullet Shock Wave
Transducer BRL 250-kc at 8.7 meters from the muzzle and 6.6° azimuth. Incidence angle 0°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 166.0 dB

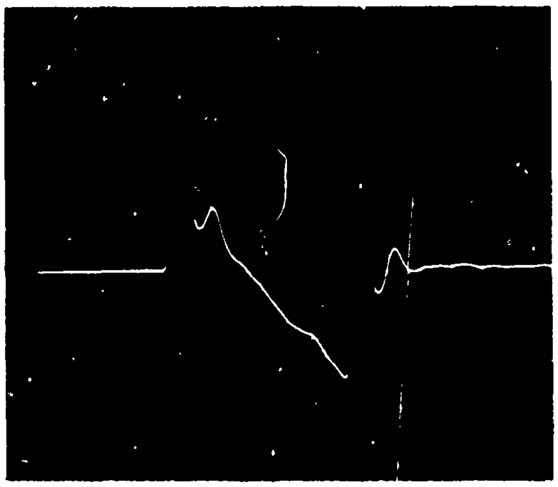
Fig. 16. PRESSURE vs. TIME HISTORY PRODUCED BY THE SHOCK WAVE OF A 7.62mm BULLET IN FLIGHT
(Measurements are made with the BRL 250-kc transducer at 90°, 60°, 30°, and 0° incidence angles.)



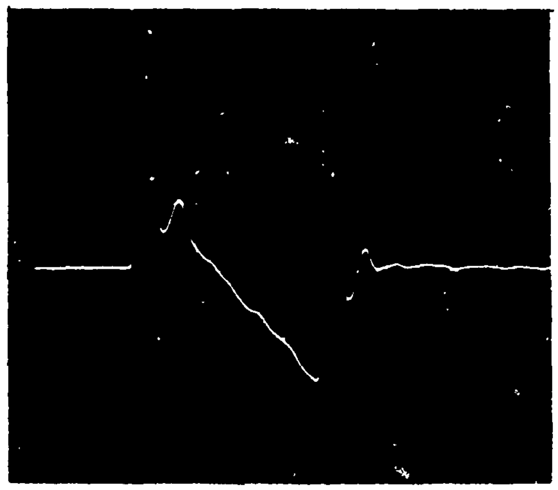
Source 7.62mm Bullet Shock Wave
Transducer B&K Type 4136 S.N. 107123 w/grid at 8.7 meters from the muzzle & 353.4° azimuth. Incidence angle 90°
Horizontal 50 microseconds/major div.
Vertical 0.5 volts/major div.
Measured Overpressure 156.7 dB



Source 7.62mm Bullet Shock Wave
Transducer B&K Type 4136 S.N. 107123 w/grid at 8.7 meters from the muzzle & 353.4° azimuth. Incidence angle 60°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 157.8 dB



Source 7.62mm Bullet Shock Wave
Transducer B&K Type 4136 S.N. 107123 w/grid at 8.7 meters from the muzzle & 353.4° azimuth. Incidence angle 30°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 160.3 dB



Source 7.62mm Bullet Shock Wave
Transducer B&K Type 4136 S.N. 107123 w/grid at 8.7 meters from the muzzle & 353.4° azimuth. Incidence angle 0°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 160.3 dB

Fig. 17. PRESSURE vs. TIME HISTORY PRODUCED BY THE SHOCK WAVE OF A 7.62mm BULLET IN FLIGHT (Measurements are made with the B&K 4136 transducer with grid, at 90°, 60°, 30°, and 0° incidence angles.)

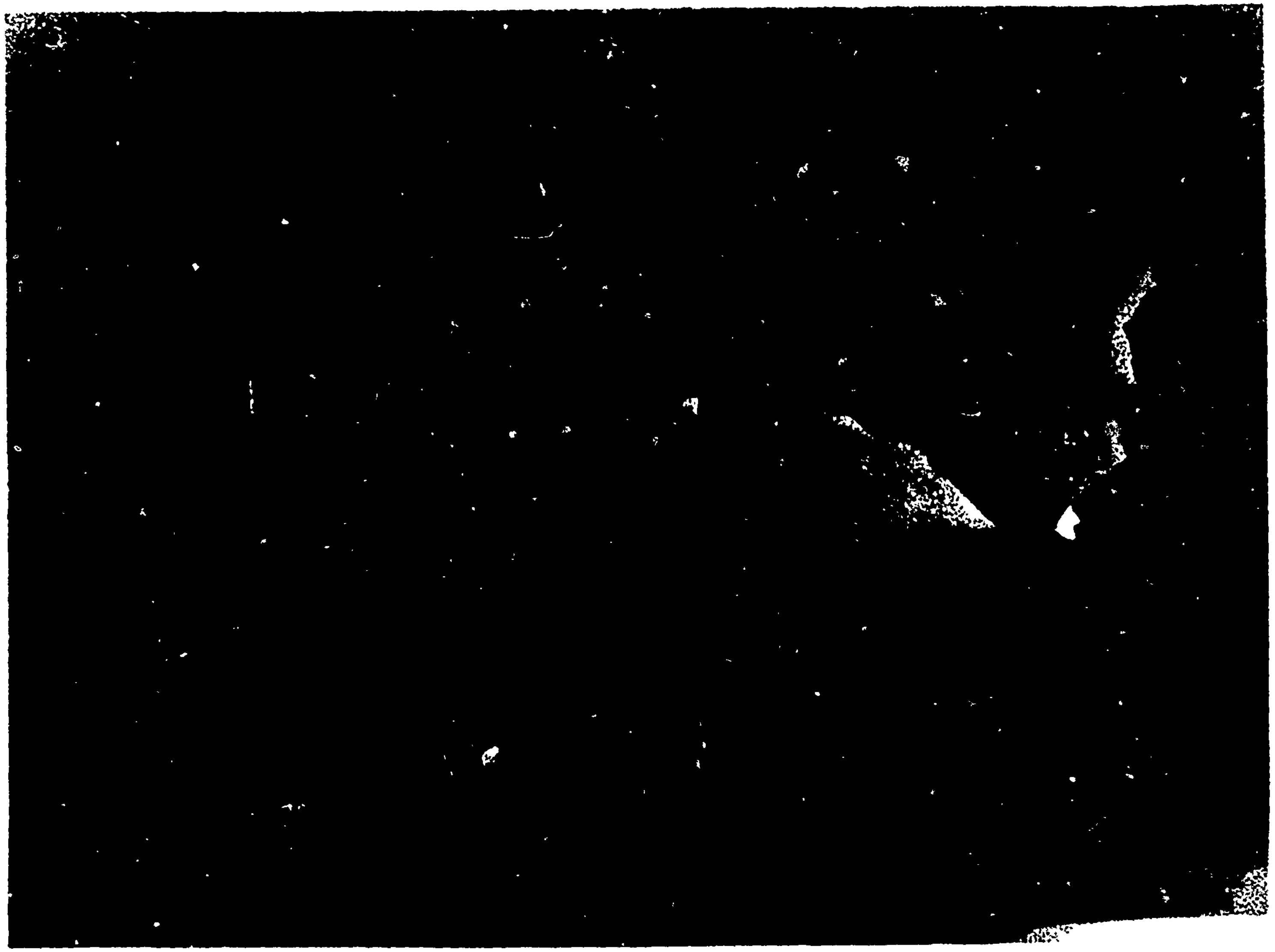


Fig. 18. SHOCK WAVE PRODUCED BY THE RAPIDLY EXPANDING GASES NEAR THE MUZZLE OF AN M14 RIFLE

Muzzle-Shock-Wave Measurements

The quasi-spherical shock wave (Fig. 18) produced by rapidly expanding gases from the muzzle of a 7.62mm rifle firing standard ball ammunition was measured at the side of the muzzle. The transducers were positioned as shown in Figures 19 and 20. Again, to assure that the shock wave reached both transducers at the same time, a single microphone triggered both oscilloscopes. Pressure-time histories were then recorded with microphone incidence angles varying from 0^{o} to 90^{o} in 15^{o} increments. The results are shown in Figure 21.

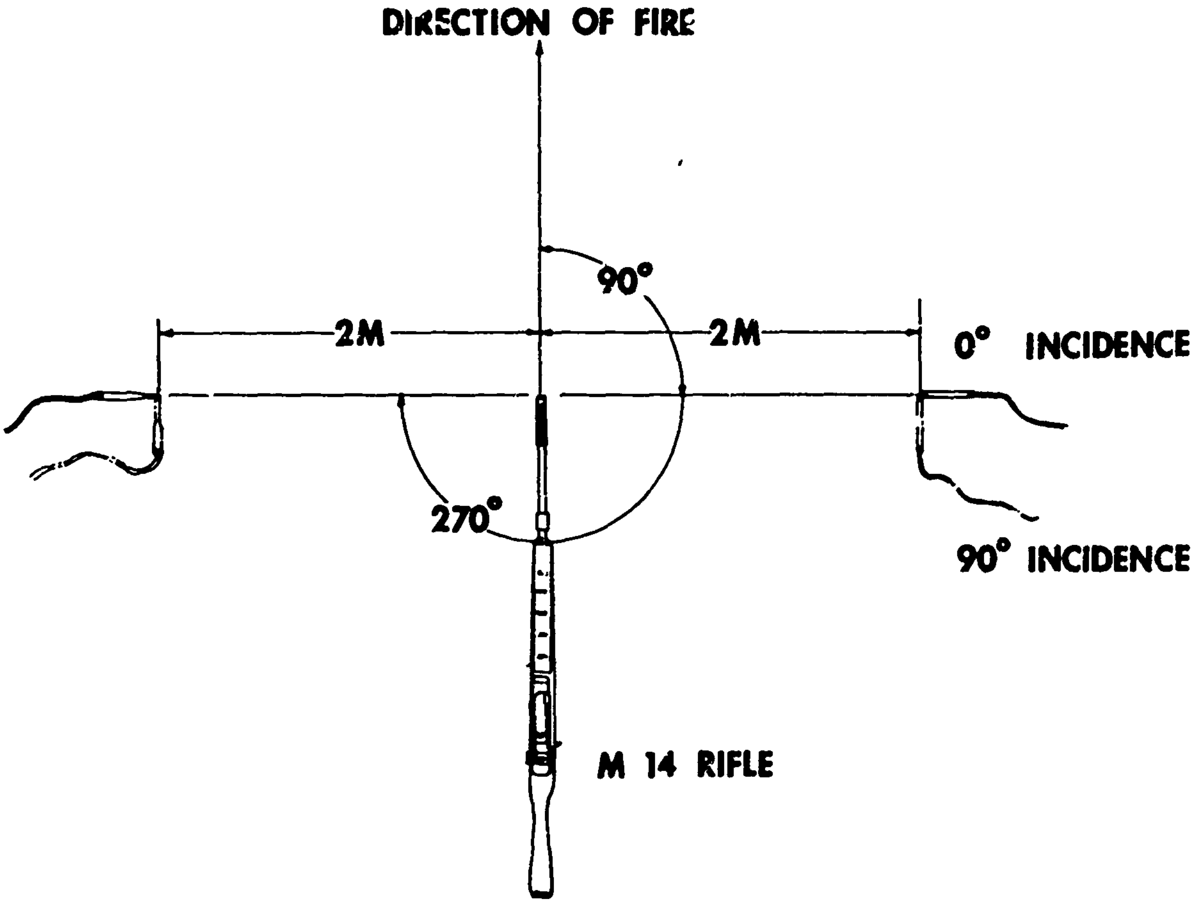


Fig. 19. TRANSDUCER LOCATIONS FOR THE MEASUREMENT OF THE MUZZLE SHOCK WAVE AT TWO METERS

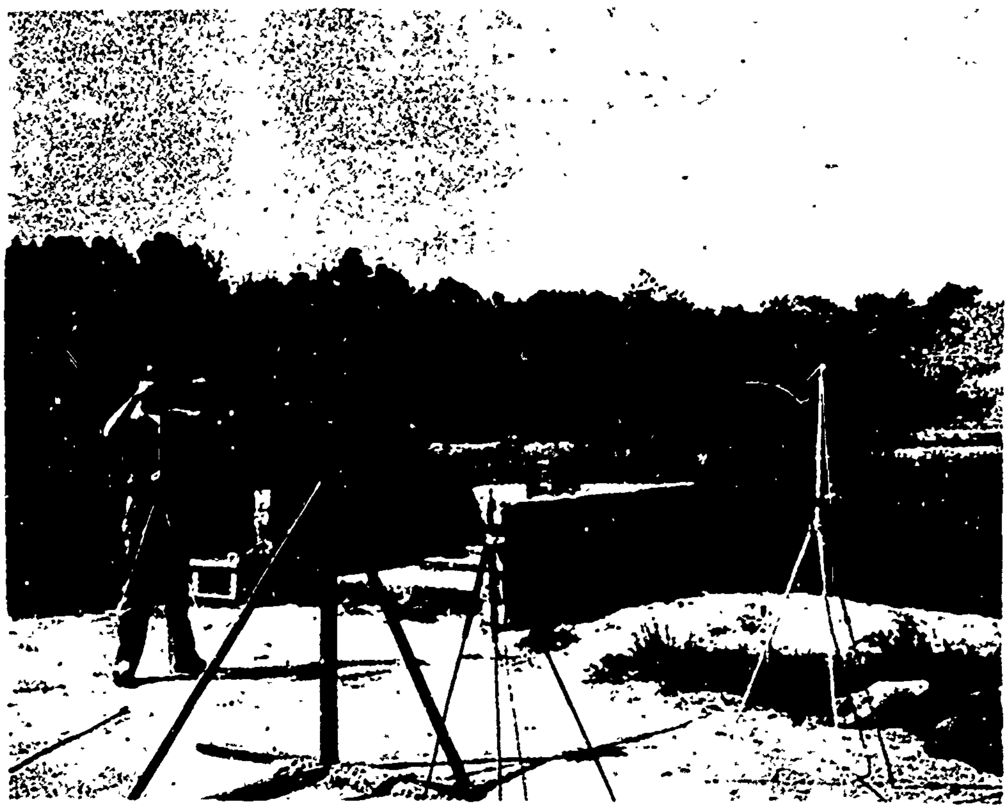
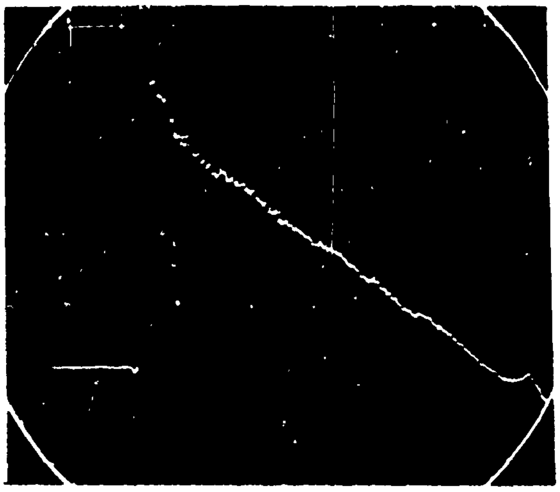
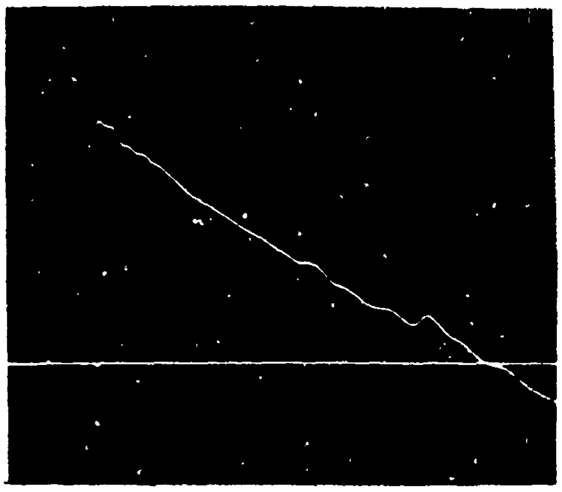


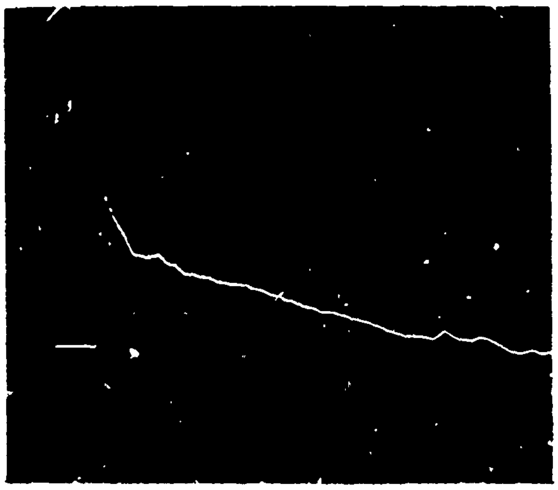
Fig. 20. TRANSDUCER LOCATION USED FOR THE MUZZLE SHOCK-WAVE MEASUREMENTS (The transducer on the left is the B&K 4136, on the right is the BRL 250-kc, and the microphone near the center is for oscilloscope triggering.)



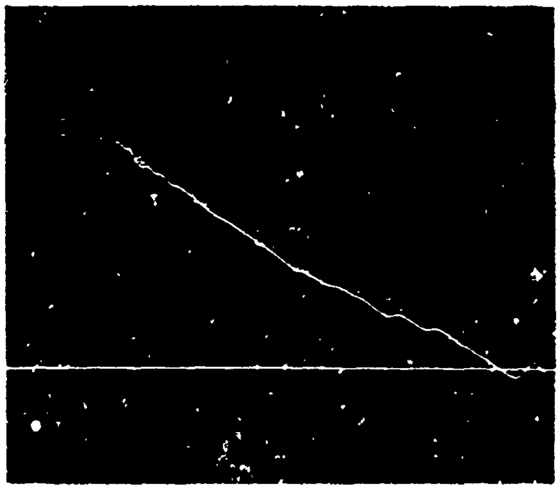
Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 90°
Horizontal 50 microseconds/major div.
Vertical 0.02 volts/major div.
Measured Overpressure 163.5 dB



Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 90°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 164.0 dB



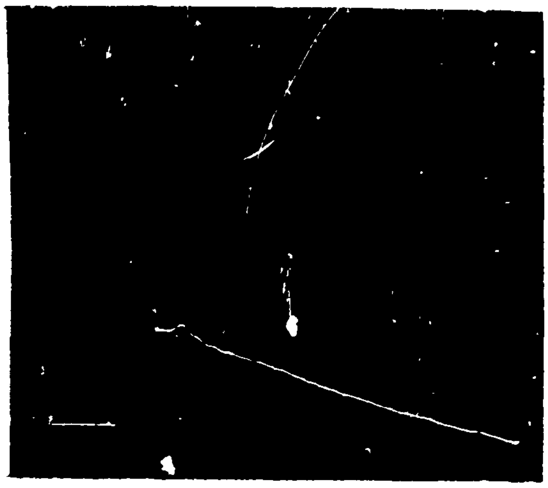
Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 75°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 166.0 dB



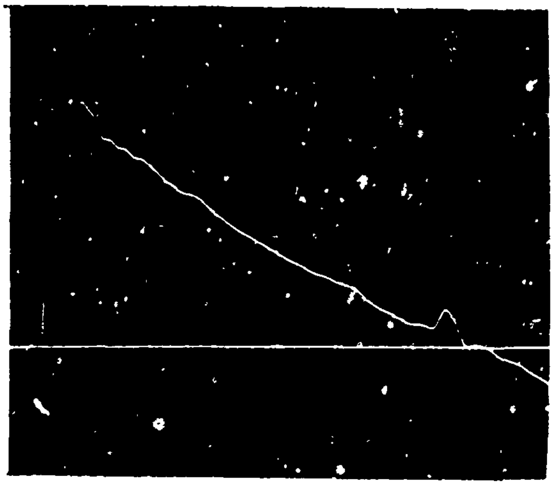
Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 75°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 164.0 dB

Note: *dB re. 0.0002 microbar*

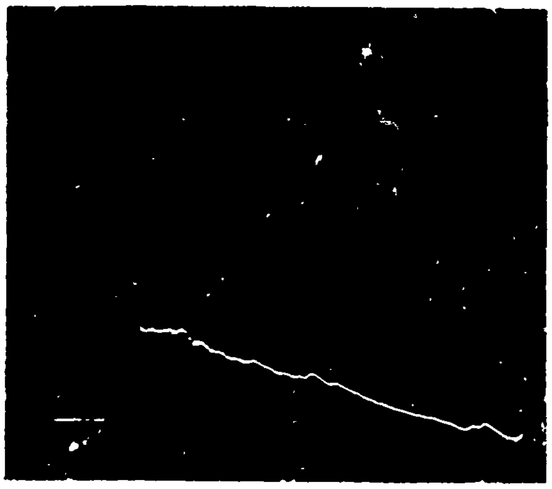
Fig. 21. PRESSURE vs. TIME HISTORY OF THE SHOCK WAVE PRODUCED BY THE EXPANDING GASES AT TWO METERS AND 90° FROM THE MUZZLE OF AN M14 RIFLE (Measurements are made with the BRL 250-kc and B&K 4136 transducers at 90°, 75°, 60°, 45°, 30°, 15°, and 0° incidence.)



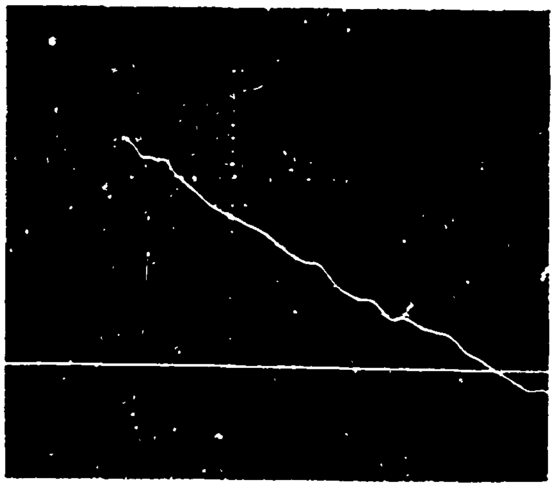
Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 60°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 167.8 dB



Source M-14 Muzzle Blast
Transducer B&K Type 4136 S. N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 60°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 164.5 dB

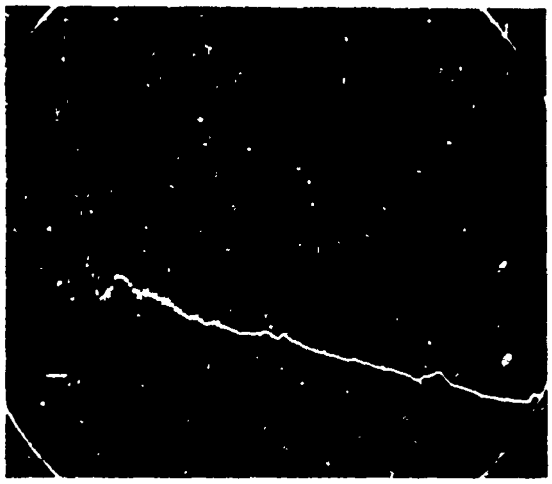


Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 45°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 168.8 dB

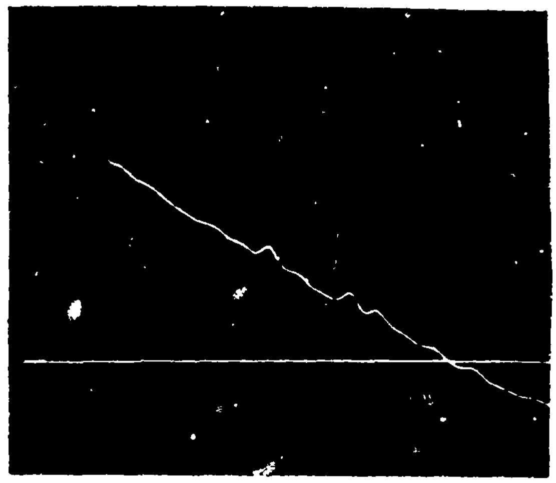


Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 45°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 165.0 dB

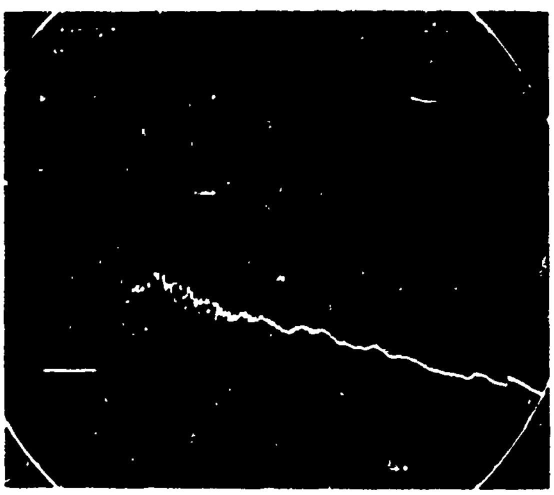
Fig. 21- Cont'd.



Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 30°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 169.0 dB



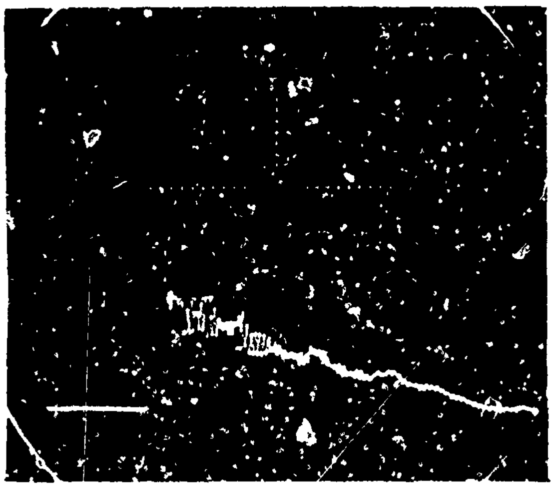
Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 30°
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 165.5 dB



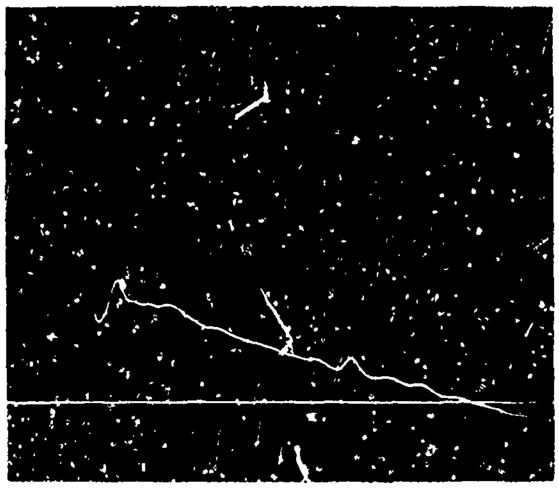
Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 15°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 171.8 dB

Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 15°
Horizontal 50 microseconds/major div.
Vertical 2.0 volts/major div.
Measured Overpressure 166.3 dB

Fig. 21 - Cont'd.



Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and 90° azimuth. Incidence angle 0°
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 173.3 dB



Source M-14 Muzzle Blast
Transducer B&K Type 4126 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 270°. Incidence angle 0°
Horizontal 50 microseconds/major div.
Vertical 2.0 volts/major div.
Measured Overpressure 166.5 dB

Fig. 21 - Cont'd.

DISCUSSION

The pressure profile produced by the shock wave of a bullet in flight will resemble an almost perfect "N" if the measurements are made at a distance which is great in comparison to the bullet's length. The "bow-wave" is an instantaneous pressure increase to some positive amplitude, p_1. The pressure then decreases linearly until it reaches a negative value, p_2, where ($|p_1| \approx |p_2|$), and then the "stern-wave" instantaneously returns the pressure to ambient. The important point here is that the pressure decrease from positive to negative pressure (p_1 to p_2) should approach a straight line, and with no overshoot in returning to ambient. The time histories of the bullet shock waves, shown in Figures 16 and 17, have peak pressures that agree within 0.3 dB when both transducers are at 90° incidence; the "N" wave's duration is the same (150 microseconds). Also wave shapes from the two transducers are very similar, and both produced the required straight line between p_1 and p_2. The BRL transducer's higher frequency-response capability is reflected in the time the wave takes to reach maximum pressure and in the higher-frequency minor deviations during the pressure decay. The B&K transducer averaged these variations into a smoother decay curve.

As the transducers are rotated from an incidence angle of 90° to 60°, several changes occur. The peak-pressure measurements are higher than at 90° incidence. The higher peak is caused by the pressure reflected off the transducer's face. This reflected pressure may be seen clearly in Figure 22, which shows a projectile's shock wave striking an object. A small spherical shock wave is generated, expanding until it reaches the corner of the object, and then dissipating, since there is no surface to support this reflected pressure. The time when this spherical wave expands over the transducer's sensing surface is the "relief time." In general, it has been found that the relief time is about twice the time it takes for the reflected wave to expand over the entire face of the transducer (4).

In Figure 16, the smaller of the two positive peaks on the 60°-incidence oscillogram is due to reflection from the transducer's face as the stern wave passes, as well as slight transducer overshoot. The relief time is the time across the base of this small peak. This transducer's relief time at 60° is approximately 30 to 35 microseconds. The first positive peak is the sum of the incident pressure, reflected pressure, and overshoot. The amplitudes of both peaks increase as the transducer is rotated toward 0° incidence. On the 90°-incidence record, the small peak as the pressure returns from p_2 to ambient is probably caused by a slight inaccuracy in aligning the microphone with the shock wave's direction of travel.

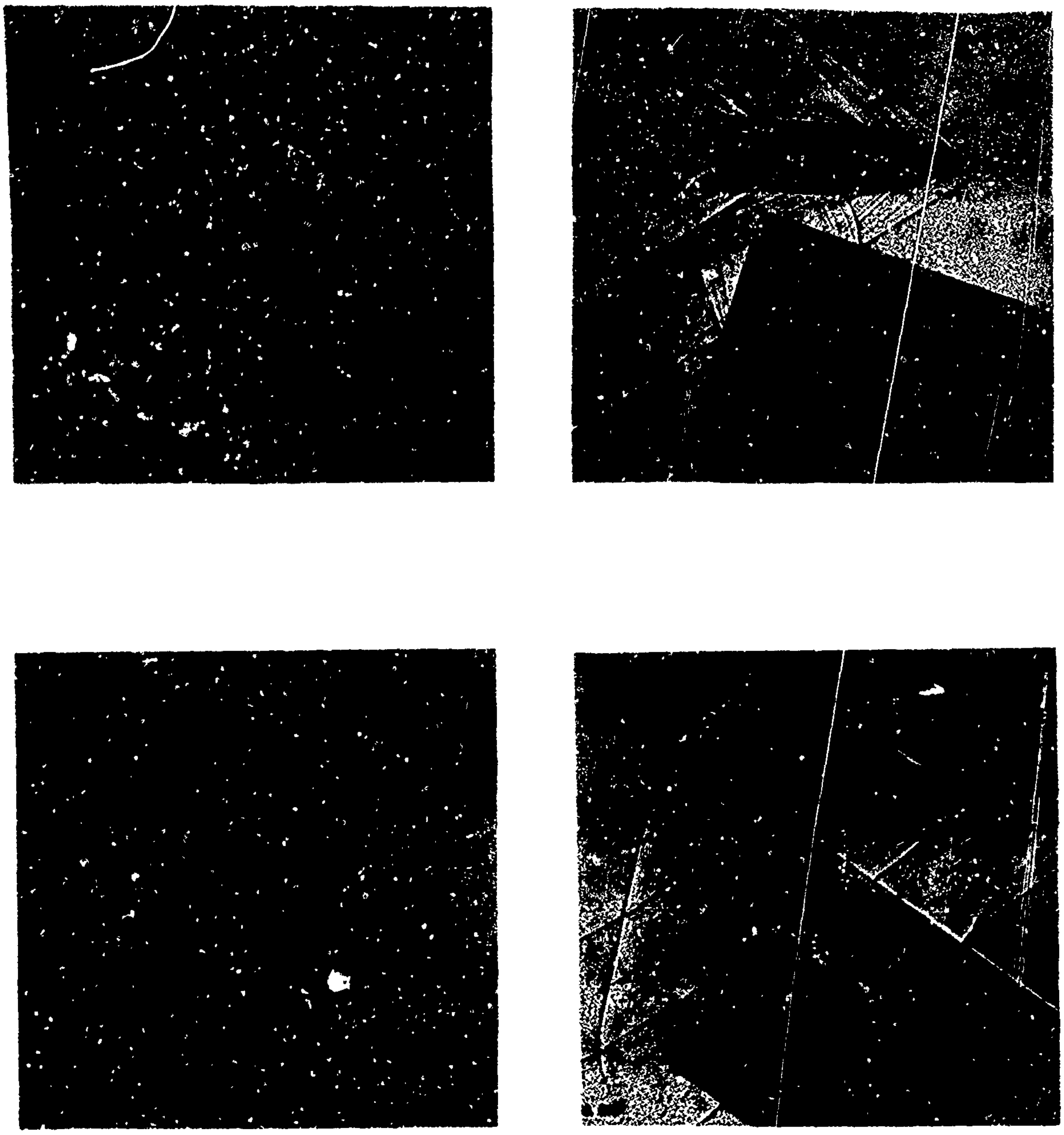


Fig. 22. SEQUENCE OF A PROJECTILE SHOCK WAVE STRIKING AN OBJECT AND THE DEVELOPMENT AND DISSIPATION OF THE REFLECTION PRODUCED BY THE "BOW WAVE"

Table 2 shows how peak SPL increases over the 90°-incidence record as the transducers are rotated from an incidence angle of 90° to 0°.

TABLE 2

Variation in Peak SPL at Different Incidence Angles for the BRL and B&K Transducers

Incidence Angle (Degrees)	Peak Pressure Deviation from 90° Incidence: Muzzle Shock B&K	Muzzle Shock BRL	Bullet Shock B&K	Bullet Shock BRL
90	--	--	--	--
75	0	2.5		
60	0.5	4.3	1.1	3.3
45	1.0	5.3		
30	1.5	5.5	3.6	5.0
15	2.3	8.3		
0	2.5	9.8	3.6	9.0

The oscilloscope records of the muzzle-shock-wave measurements show that the two transducers behave about as they do in measuring the bullet shock wave. At 90° incidence, both transducers indicate the same peak SPL, the same duration, and similar decay patterns. Again, as the transducers are rotated away from 90° incidence, the peak SPL increases until, at zero degrees, it is the sum of incident pressure, reflected pressure, and overshoot. The BRL transducer is damped so that, when measuring at 0° incidence, it has approximately 2.5 dB overshoot. Therefore at this incidence, the sum of the reflected pressure (6 dB) and overshoot (2.5 dB) agrees quite well with the measured data shown in Table 2. Figure 21 also shows that the BRL transducer has its best rise-time capability at 0° incidence: about 1 to 2 microseconds. But using the transducer at 0° incidences creates additional difficulties -- the measured peak SPL includes overshoot inherent in the design of the transducer, as well as reflected pressure. Moreover, the transducer's natural frequency is very easily excited at 0° incidence. The net result is a misleading incident pressure-time history.

The B&K transducer's record at 0^{o} (Fig. 21) indicates that its best rise time is about 10 microseconds, which agrees with the shock-tube measurements. Because of this poorer rise-time capability, reflected pressure and overshoot will not increase peak SPL at 0^{o} as much as with the BRL transducer.

CONCLUSIONS

Measurements of bullet and muzzle shock waves suggest the following conclusions about how transducers should be used when measuring small arms:

a. An incidence of 90^{o} should be used to minimize overshoot and to measure only incident pressure. This orientation gives a time history approaching that which would be expected if no transducer were present.

b. Both a crystal transducer and a condenser microphone yield essentially the same wave shape, although the crystal transducer's higher-frequency capability shows the pressure variations in more detail.

c. Although neither transducer had a rise time fast enough to follow the actual rise in pressure, which takes about 10^{-4} microseconds, most small arms have decay times long enough that measured peak SPL will be only slightly in error.

PART III: TRANSDUCER COMPARISON AT VARIOUS SPLs

METHOD

Thus far in evaluating transducer's abilities to accurately measure small-arms pressure waves, rise-time capability has been extremely important. Therefore, the following section investigates the rise-time capability various types of transducers have at different peak SPLs. Also, this section indicates the comparability to be expected when small-arm measurements are made with several different transducers under field conditions.

Measurments were made perpendicular to an M14 rifle's line of fire at points 0.25, 0.5, 1, 2, 4, and 8 meters from the muzzle. This investigation used the following transducers:

a. Altec Lansing 21-BR-180

b. BRL 250-kc

c. B&K 4135

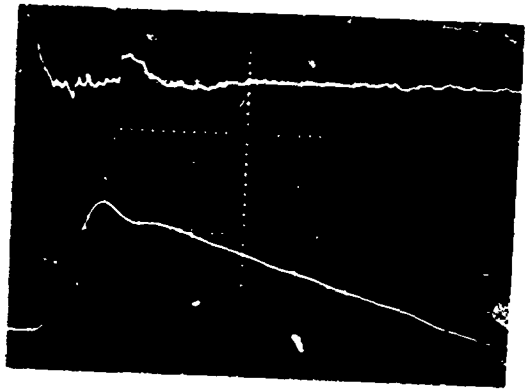
d. B&K 4136

e. Kistler 601-A

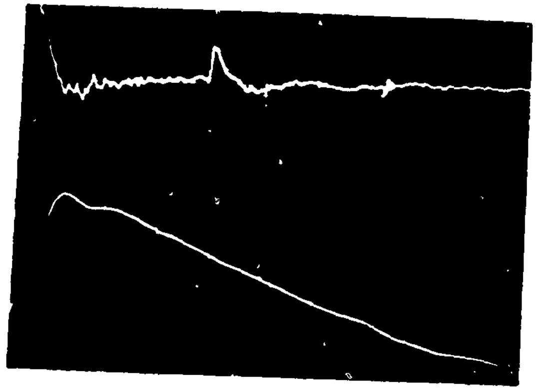
The barrel of the rifle and all of the transducers were 65 inches above the ground. All transducers were positioned at 90^{o} incidence (longitudinal axis of the transducers parallel to the line of fire, as in Figure 20), except the B&K 4135, which produced a more accurate time history at 0^{o} than at 90^{o} incidence (Fig. 6). The transducers were calibrated as described in Part I.

Then the transducers were tested individually, starting at 8 meters when possible. Successive placements of transducers were within $\pm$ 1 centimeter at distances of 1 meter or more and within $\pm$0.5 centimeter at the 0.25- and 0.5-meter distances. The Altec Lansing 21-BR-180 and the B&K 4135 were not tested closer than 0.5 meter because of possible damage. The crystal transducers were not tested at distances greater than 4 meters because of their low sensitivity. At least three rounds were fired for each condition. Variation of peak SPL between different rounds was found to be less than $\pm$0.5 dB.*

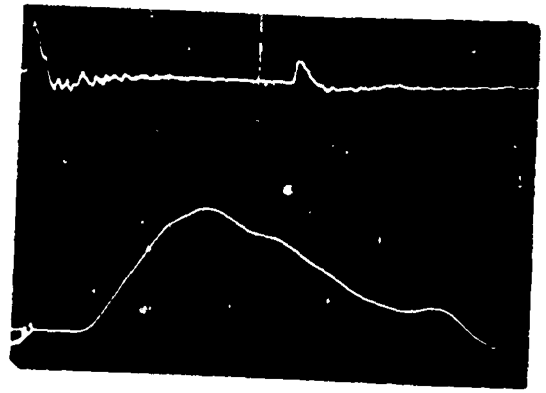
* Based upon unpublished HEL data, the standard deviation of the peak SPL produced by M14 ammunition at 8 feet, 90^{o}, is 0.68 dB with a sample of 624 rounds (1).



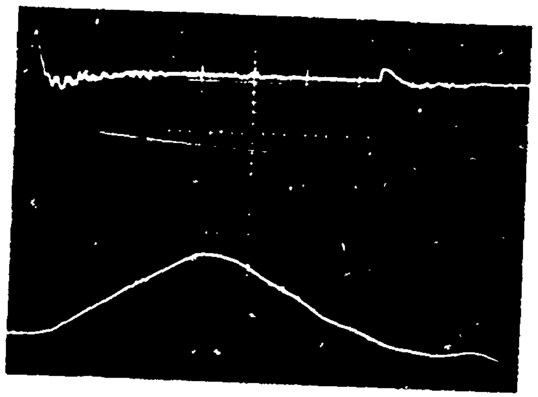
Source M-14 Muzzle Blast
Transducer Altec Lansing 21-BR-180 S.N. 175 at 8.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.5 volts/major div.
Measured Overpressure 148.0 dB



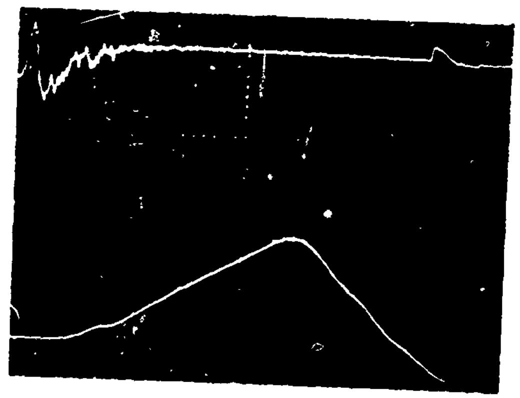
Source M-14 Muzzle Blast
Transducer Altec Lansing 21-BR-180 S.N. 175 at 4.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 154.9 dB



Source M-14 Muzzle Blast
Transducer Altec Lansing 21-BR-180 S.N. 175 at 2.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 2.0 volts/major div.
Measured Overpressure 160.1 dB



Source M-14 Muzzle Blast
Transducer Altec Lansing 21-BR-180 S.N. 175 at 1.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 5.0 volts/major div.
Measured Overpressure 164.7 dB



Source M-14 Muzzle Blast
Transducer Altec Lansing 21-BR-180 S.N. 175 at 0.5 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 5.0 volts/major div.
Measured Overpressure 167.0 dB

Fig. 23. PRESSURE vs. TIME HISTORY OF THE MUZZLE SHOCK WAVE OF AN M14 RIFLE AT 8, 4, 2, 1, AND 0.5 METERS USING THE ALTEC LANSING 21-BR-180 AT 90° INCIDENCE (The upper traces show the wave shape at one millisecond per major division and has an uncalibrated vertical scale.)

RESULTS

The time histories are shown in Figures 23 to 27. The smaller of the two peaks on the one millisecond/division portion of the records is the reflection from the ground.

The Kistler transducer showed a large amount of ringing (3 to 4 dB) at approximately 140 kc, which is the device's natural frequency. The shock-tube records showed this same ringing. The peak SPLs for each condition are compared in Table 3 and shown graphically in Figure 28.

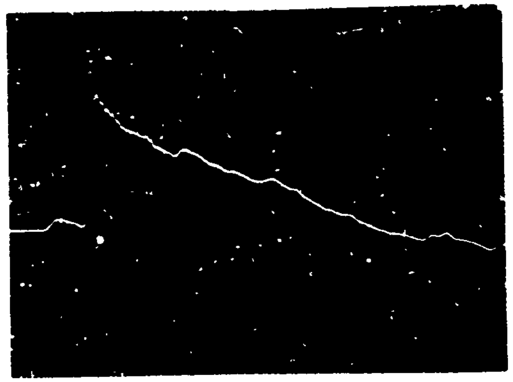
TABLE 3

Measured Peak SPL for Various Transducers at Different Distances from the M14 Muzzle

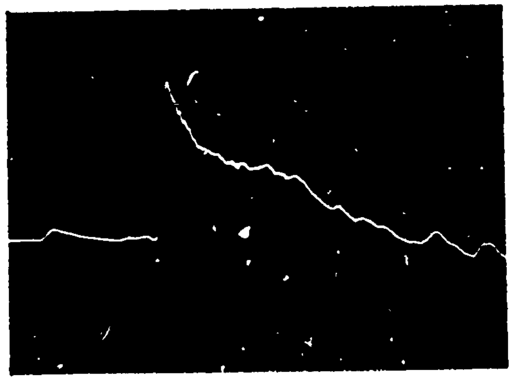
	Distance in Meters					
Transducer	0.25	0.5	1	2	4	8
BRL 250-kc	184.5	179.0	171.7	165.0	155.9	--
B&K 4136	179.9	175.6	170.0	163.5	156.0	150.1
B&K 4135	--	174.0	168.9	162.5	157.0	150.4
Altec 21-BR-180	--	167.0	164.7	160.1	154.9	148.0
Kistler 601-A	184.9	178.3	170.8	164.2	157.5	--

Source M-14 Muzzle Blast
Transducer BRL 250-kc at 4.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.02 volts/major div.
Measured Overpressure 155.9 dB

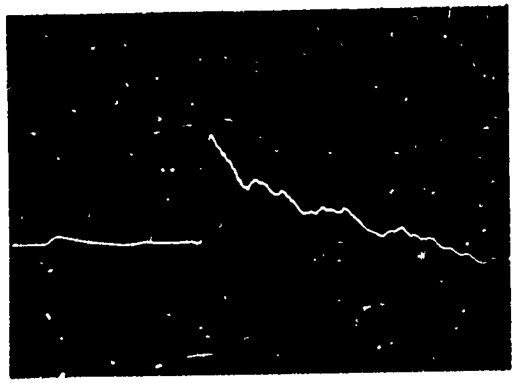
Source M-14 Muzzle Blast
Transducer BRL 250-kc at 2.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 165.0 dB



Source M-14 Muzzle Blast
Transducer BRL 250-kc at 1.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.1 volts/major div.
Measured Overpressure 171.7 dB

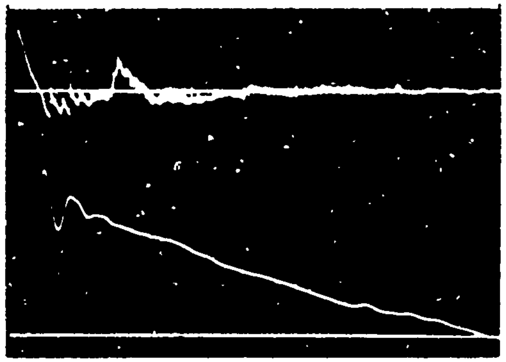


Source M-14 Muzzle Blast
Transducer BRL 250-kc at 0.5 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.2 volts/major div.
Measured Overpressure 179.0 dB

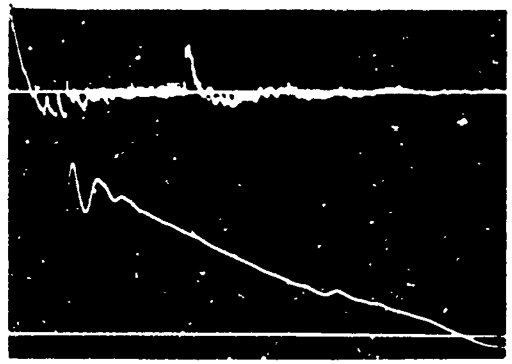


Source M-14 Muzzle Blast
Transducer BRL 250-kc at 0.25 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.5 volts/major div.
Measured Overpressure 184.5 dB

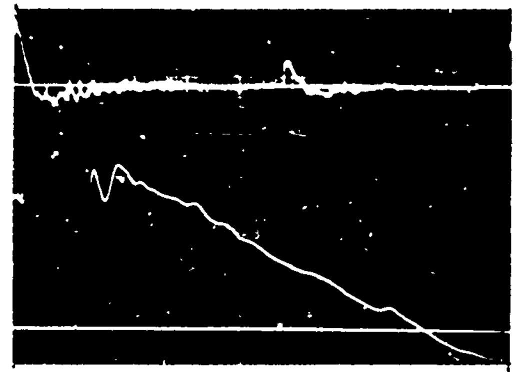
Fig. 24. PRESSURE vs. TIME HISTORY OF THE MUZZLE SHOCK WAVE OF AN M14 RIFLE AT 4, 2, 1, 0.5, AND 0.25 METERS USING THE BRL 250-kc AT 90° INCIDENCE



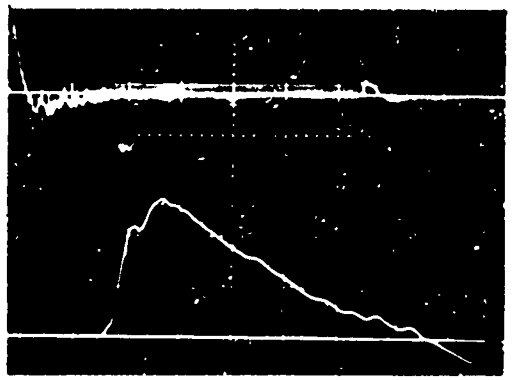
Source M-14 Muzzle Blast
Transducer B&K Type 4135 S.N. 101162 w/grid at 8.0 meters from the muzzle and azimuth 90°. Incidence angle 0°.
Horizontal 50 microseconds/major div.
Vertical 0.5 volts/major div.
Measured Overpressure 150.4 dB



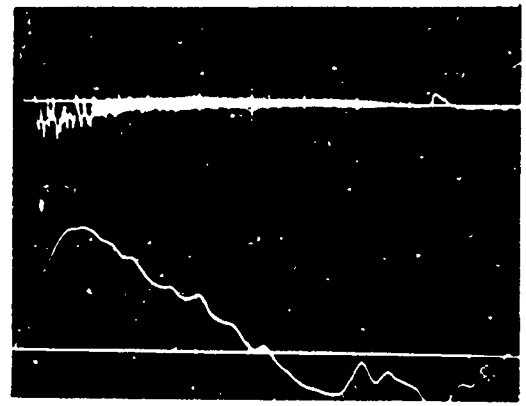
Source M-14 Muzzle Blast
Transducer B&K Type 4135 S.N. 101162 w/grid at 4.0 meters from the muzzle and azimuth 90°. Incidence angle 0°.
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 157.0 dB



Source M-14 Muzzle Blast
Transducer B&K Type 4135 S.N. 101162 w/grid at 2.0 meters from the muzzle and azimuth 90°. Incidence angle 0°.
Horizontal 50 microseconds/major div.
Vertical 2.0 volts/major div.
Measured Overpressure 162.5 dB

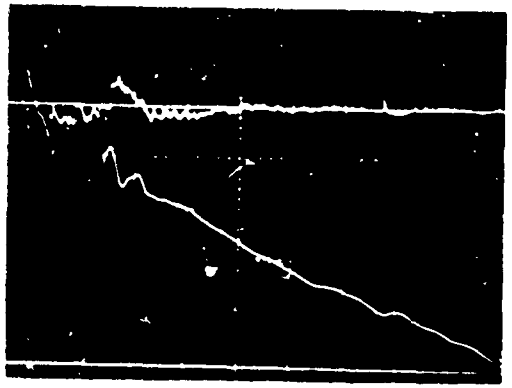


Source M-14 Muzzle Blast
Transducer B&K Type 4135 S.N. 101162 w/grid at 1.0 meters from the muzzle and azimuth 90°. Incidence angle 0°.
Horizontal 50 microseconds/major div.
Vertical 5.0 volts/major div.
Measured Overpressure 168.9 dB

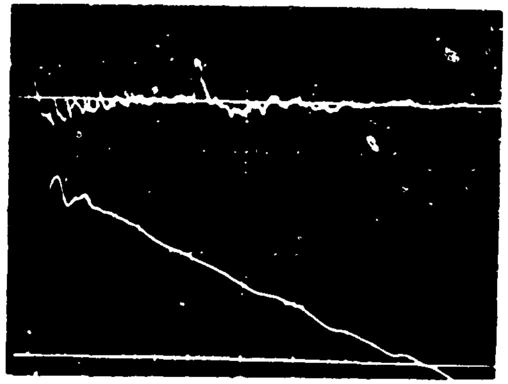


Source M-14 Muzzle Blast
Transducer B&K Type 4135 S.N. 101162 w/grid at 0.5 meters from the muzzle and azimuth 90°. Incidence angle 0°.
Horizontal 50 microseconds/major div.
Vertical 10.0 volts/major div.
Measured Overpressure 174.0 dB

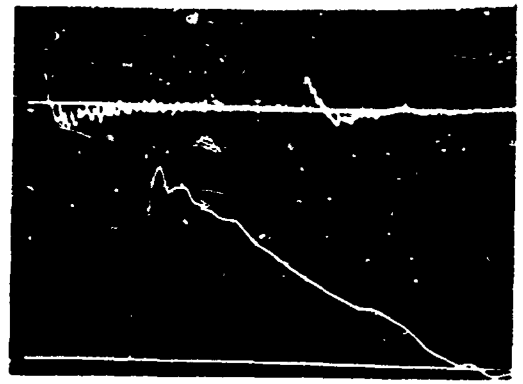
Fig. 25. PRESSURE vs. TIME HISTORY OF THE MUZZLE SHOCK WAVE OF AN M14 RIFLE AT 8, 4, 2, 1, AND 0.5 METERS USING THE B&K 4135 AT 0° INCIDENCE (The upper traces show the wave shape at one millisecond per major division and has an uncalibrated vertical scale.)



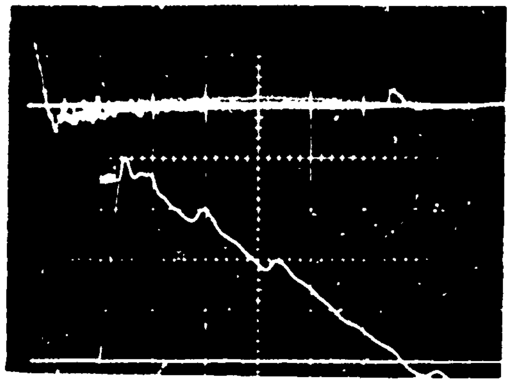
Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 8.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.2 volts/major div.
Measured Overpressure 150.1 dB



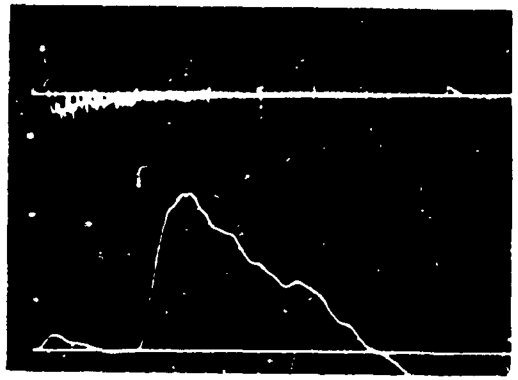
Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 4.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.5 volts/major div.
Measured Overpressure 156.0 dB



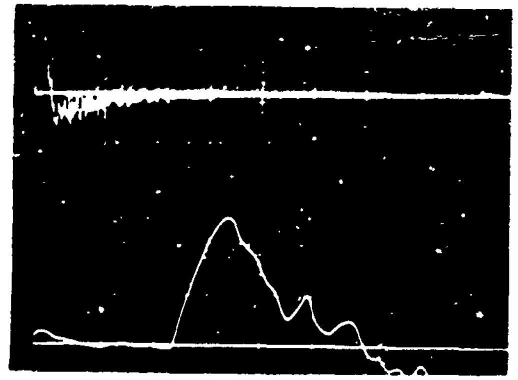
Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 2.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 1.0 volts/major div.
Measured Overpressure 163.5 dB



Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 1.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 2.0 volts/major div.
Measured Overpressure 170.0 dB

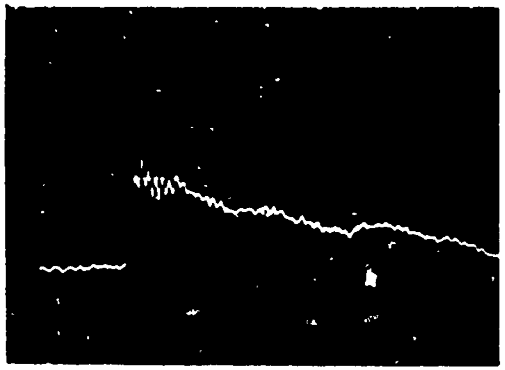


Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 0.5 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 5.0 volts/major div.
Measured Overpressure 175.6 dB

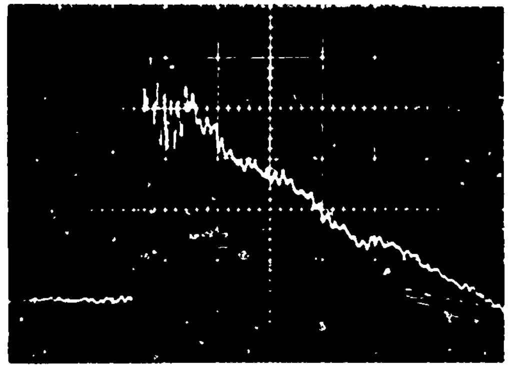


Source M-14 Muzzle Blast
Transducer B&K Type 4136 S.N. 107123 w/grid at 0.25 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 10.0 volts/major div.
Measured Overpressure 179.9 dB

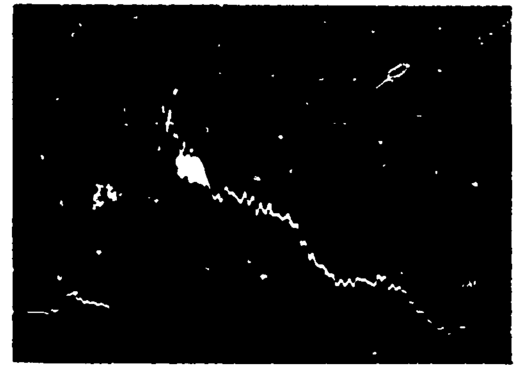
Fig. 26. PRESSURE vs. TIME HISTORY OF THE MUZZLE SHOCK WAVE OF AN M14 RIFLE AT 8, 4, 2, 1, 0.5, AND 0.25 METERS USING THE B&K 4136 AT 90° INCIDENCE
(The upper traces show the wave shape at one millisecond per major division and has an uncalibrated vertical scale.)



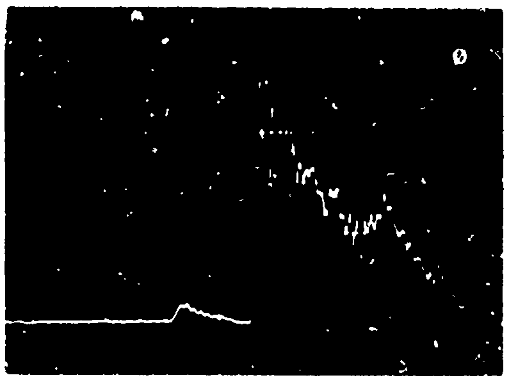
Source M-14 Muzzle Blast
Transducer Kistler Model 601-A at 4.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.01 volts/major div.
Measured Overpressure 157.5 dB



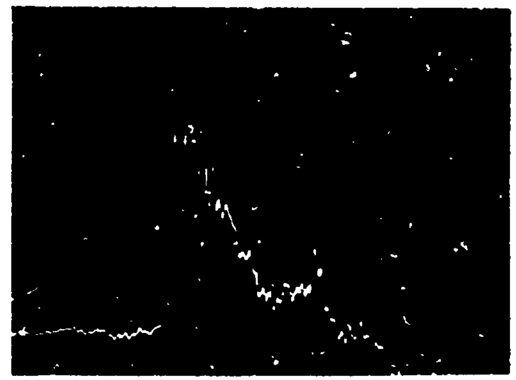
Source M-14 Muzzle Blast
Transducer Kistler Model 601-A at 2.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.01 volts/major div.
Measured Overpressure 164.2 dB



Source M-14 Muzzle Blast
Transducer Kistler Model 601-A at 1.0 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.02 volts/major div.
Measured Overpressure 170.8 dB



Source M-14 Muzzle Blast
Transducer Kistler Model 601-A at 0.5 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.05 volts/major div.
Measured Overpressure 173.3 dB



Source M-14 Muzzle Blast
Transducer Kistler Model 601-A at 0.25 meters from the muzzle and azimuth 90°. Incidence angle 90°.
Horizontal 50 microseconds/major div.
Vertical 0.1 volts/major div.
Measured Overpressure 184.9 dB

Fig. 27. PRESSURE vs. TIME HISTORY OF THE MUZZLE SHOCK WAVE OF AN M14 RIFLE AT 4, 2, 1, 0.5, AND 0.25 METERS USING THE KISTLER 601-A AT 90° INCIDENCE

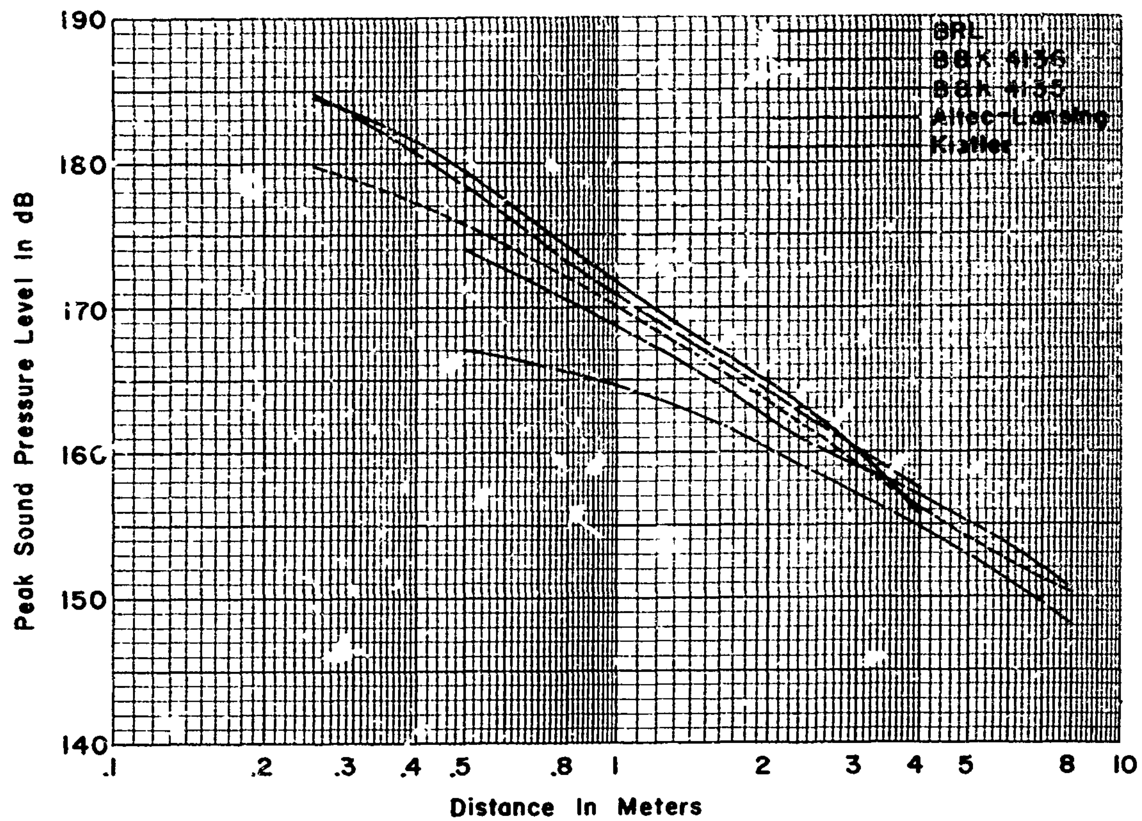


Fig. 28. MEASURED PEAK SOUND-PRESSURE LEVEL AT VARIOUS DISTANCES AT 90° AZIMUTH FROM THE MUZZLE OF AN M14 RIFLE USING FIVE DIFFERENT TRANSDUCERS

DISCUSSION

The design and operation of a condenser microphone are such that the output signal is proportional to diaphragm displacement when displacements are small. Measuring high pressures forces the diaphragm into relatively large displacements. Then the diaphragm does not move linearly and the rise-time capability deteriorates as shown in Figures 23, 25, and 26.

On the other hand, the two piezoelectric transducers (BRL 250-kc and Kistler 601-A) did not show this non-linearity and consequent rise-time deterioration; they rose to peak in less than 10 microseconds. In fact, Part I showed that the BRL 250-kc transducer achieves this fast rise time without overshoot.

The transducer's rise-time capability becomes increasingly important with shorter-duration acoustical transients. For acoustical transients that have nearly a linear decay (Fig. 21, 90° incidence), there is a simple relationship between percent error and both duration of the transient and the rise time the transducer measures. Since the shock wave's rise time is negligible, the percent error can be written as:

$$\text{Percent error} = \frac{T_r}{T_d} \times 100 \qquad (4)$$

where: T_r = rise time measured by the transducer
T_d = duration of the transient

Figure 29 shows how this error manifests itself.

Since the transients' decay time was about 200 microseconds at 0.5 meter, the BRL 250-kc transducer's error due to its 10 microsecond rise-time limitation is, from equation 4, about 5 percent even at high pressures. A 5 percent error in measuring peak SPL of small arms is tolerable for most purposes, so the pressures measured by the BRL 250-kc transducer may be accepted as accurate and used as a standard for evaluating other devices. Such a comparison (based on the 0.5 data in Table 3) is given in Table 4, which shows the differences between peak SPL as measured by the BRL 250-kc transducer and the peak SPL as measured by the three condenser microphones. Table 4 also shows calculated differences between the peak SPL as measured by a device with inadequate rise time (i.e., the three condenser microphones when measuring high pressures) and the actual peak SPL from equation 4.

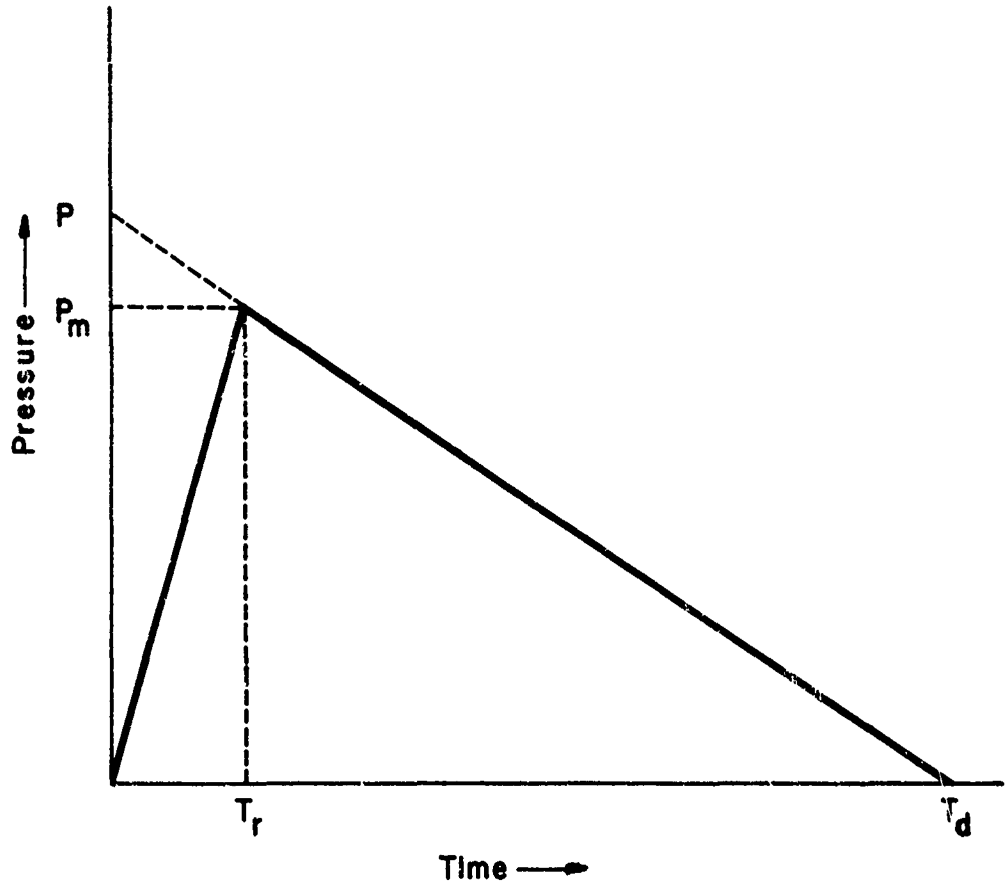


Fig. 29. DEVELOPMENT OF ERROR INTRODUCED AS A RESULT OF INADEQUATE RISE-TIME CAPABILITY WHEN MEASURING A SHORT ACOUSTICAL TRANSIENT OF "INSTANTANEOUS" RISE TIME

TABLE 4

Rise-Time Capability and Peak SPL Differences Between
the Three Capacitor Microphones and the BRL 250-kc Transducer at 0.5 Meter

Transducer	Rise Time	Measured SPL Difference	Calculated SPL Difference
Altec 21-BR-180	200 microseconds	12.0 dB	9.0 dB
B&K 4135	60 "	5.0 dB	2.4 dB
B&K 4136	35 "	3.4 dB	1.4 dB

At first glance, there seems to be a 2-3 dB difference between the measured and calculated SPL differences in Table 4. However, a closer look at Figure 24 shows the effect of reflected pressure. This reflected pressure arose because the transducer was not oriented exactly at 90° incidence to the center of the quasi-spherical shock wave. It becomes extremely difficult to orient transducers properly when they are close to the muzzle, because the acoustical center of the muzzle shock wave is in front of the muzzle (1). This difficulty could have been surmounted by positioning the transducer so its sensitive surface was parallel to the ground, as in Figure 30, rather than perpendicular to the ground, as in Figure 20. Figure 31 is a tracing of the oscillogram representing the 0.5-meter microphone position in Figure 24. Drawing a straight line along the decay curve after relief is completed gives an extrapolated pressure (point "B" in Figure 31) of 176.5 dB. This is the pressure which would have been obtained with exactly 90° incidence. When this correction is taken into account, the measured and calculated differences in Table 4 agree quite nicely.

As would be expected, the duration of the positive-pressure phase of the transient becomes longer as the distance from the muzzle increases, and the measured peak SPL decreases approximately 6 dB for each doubling of distance.

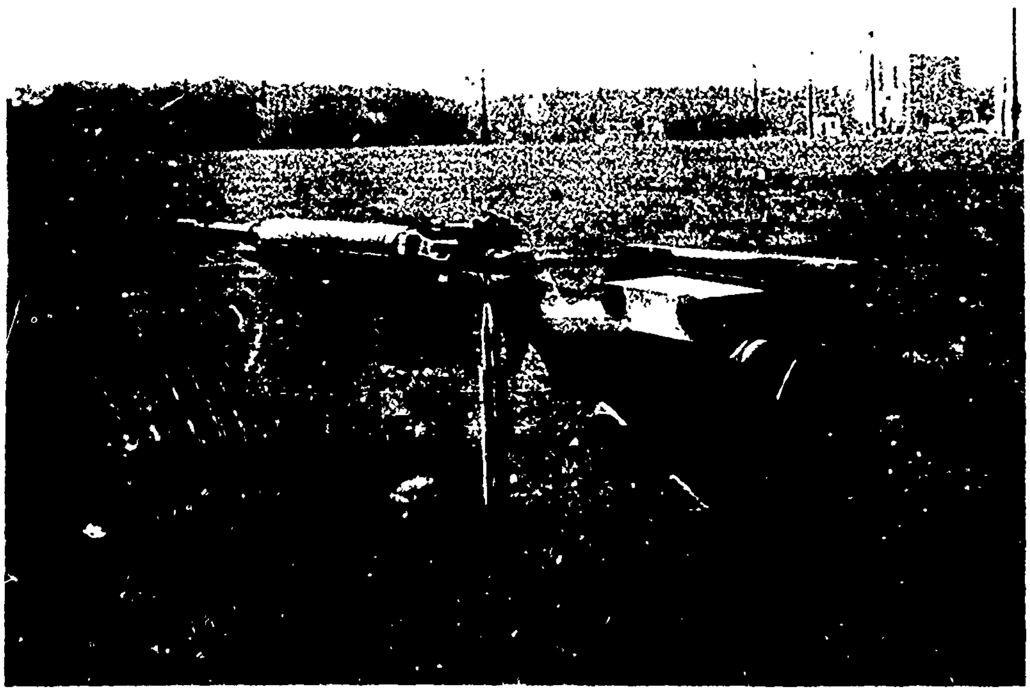


Fig. 30. RECOMMENDED MICROPHONE ORIENTATION FOR MEASUREMENTS MADE AT THE OPERATOR'S LEFT EAR POSITION

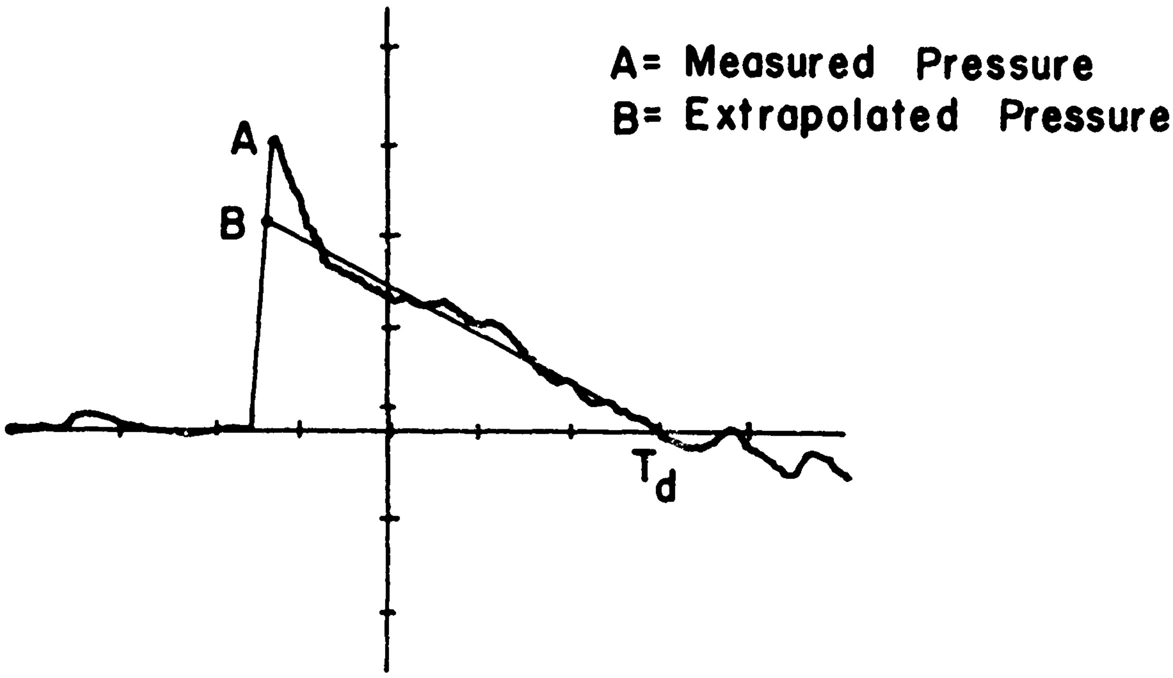


Fig. 31. EXTRAPOLATED PRESSURE FROM FIGURE 25 of BRL 250-kc TRANSDUCER (The transducer location is 0.5 meter from the muzzle.)

Fig. 32. EAR ORIENTATION OF THE FIRER WITH RESPECT TO M14 RIFLE MUZZLE

CONCLUSIONS

1. When selecting a transducer for small-arms measurements, one must be certain that the device (a) produces a linear output, (b) does not produce excessive ringing, and (c) has sufficient sensitivity to measure the pressure produced by the weapon being investigated.

2. The fact that a condenser microphone may have an adequate rise-time capability at low pressures does not necessarily mean its rise-time capability will be adequate at higher pressures. Its rise-time capability must be determined for the pressure to be measured.

3. Errors in measuring peak SPL will be small when the weapon being measured has a long duration and the transducer's rise-time capability is on the order of ten microseconds or less. In fact, from equation (4), rise and decay times of about ten and 250 microseconds respectively should produce errors of approximately 0.35 dB.

SUMMARY AND RECOMMENDATIONS

This investigation yielded several recommendations about types of devices and procedures that should be used to measure the operator hearing hazards produced by small arms. One of the transducer's most important characteristics is its rise-time capability. Although no present-day transducer can follow the pressure rise accurately, the device chosen must be able to reach a peak before significant pressure decay occurs. A rise-time capability of about ten microseconds will be adequate for measuring the shock waves produced by current small arms.

Part II of this report showed that, when measurements are made with different types of transducers at incidence angles other than 90°, peak SPL measurements will vary by more than 5 dB. On the other hand, measurements made at 90° incidence with wide-band condenser microphones and wide-band piezoelectric transducers, both having adequate rise-time capabilities, produce consistent results providing they were used in their regions of linearity. Part II also showed that the measured peak SPL may exceed the actual peak SPL by as much as 9 dB because of reflections and overshoot. Consequently, users must take care to measure only the incident pressure wave, i.e., the pressure that would be measured by a transducer with negligible size and perfect response. Orienting the transducer at 90° incidence approaches this condition.

It is interesting to note that recent HEL data (3) indicate temporary hearing loss is about 10-15 dB greater when the ear is positioned at 0° rather than 90° incidence to the pressure wave produced at the muzzle of a rifle. When a man fires a pistol or a shoulder rifle, his left ear is oriented at nearly 90° incidence (Fig. 32).* Therefore, to get an accurate representation of the pressure-time history and to estimate the noise characteristics which the firer's ear hears, the transducer should be positioned at 90° incidence.

Since the primary noise source of small arms is centered near the muzzle, it is logical to choose the ear closest to the muzzle (left ear for a right-handed firer) for the microphone location. HEL has found it convenient to measure the left-ear position with reference to the tip of the trigger. Also, the transducer should be oriented vertically (Fig. 30), rather than horizontally, to prevent as much as possible of the breech noise from "leaky" weapons from impinging on the sensitive surface of the transducer at 0° incidence.

* Measurements of several subjects show that the incidence angle between the muzzle and the rifle shooter's left ear is 80°.

In addition, the transducer's sensitivity and temperature stability become very important in measurements of low levels. Crystal transducers may raise this problem, and, since they produce relatively low-level signals which must be amplified greatly, the signal-to-noise ratio may be poor. Moreover, if the measurements are made outdoors, slight changes in the transducer's temperature may cause the oscilloscope trace to drift over a wide range.

Transducer calibrations will be in reasonable agreement, whether done with a shock tube at high levels or with a pistonphone at low levels. Consequently, a condenser microphone can be used to measure high pressures without being calibrated at high pressures, as long as the pressure to be measured does not produce nonlinear diaphragm motion.

In summary, our recommendations for measuring small-arms pressure waves are:

a. Use a transducer which has a rise-time capability of ten microseconds or less at the pressure being measured.

b. Transducer ringing and overshoot should be less than 1.5 dB at the pressure being measured.

c. The transducers used should have (a) enough sensitivity to allow a signal-to-noise ratio of 25 dB or greater, and (b) minimum drift caused by temperature instability.

d. In relation to the weapon, the transducer should be where the left ear of a right-handed firer would be. It should be oriented (a) at 90° incidence, and (b) with its sensitive surface approximately parallel to the ground.

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3. Hodge, D. C., Gates, H. W., Soderholm, R. B., Helm, C. P., & Blackmer, R. F. Preliminary studies of the impulse-noise effects on human hearing (Project HUMIN). Technical Memorandum 15-64, U. S. Army Human Engineering Laboratories, Aberdeen Proving Ground, Md., December 1964.

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APPENDIX

DESCRIPTIONS OF TRANSDUCER SYSTEMS AND CALIBRATION EQUIPMENT

TRANSDUCERS

SYSTEM 1

Altec-Lansing type 21-BR-180 one-half-inch condenser microphone (serial number 942), with a General Radio (GR) type 1551-P1-25 cathode follower (serial number 740). The polarization voltage was supplied by a GR type 1551-P1 power supply (serial number 728).

SYSTEM 2

Atlantic Research model LC-33 (serial number 351) lead zirconate pressure transducer, with a Kistler type 566 charge amplifier (serial number 1376).

SYSTEM 3

BRL 250-kc lead zirconate pressure transducer, with a Kistler type 566 charge amplifier (serial number 1376). This transducer was manufactured by the Ballistic Research Laboratories, Aberdeen Proving Ground, Md.

SYSTEM 4

Bruel and Kjaer (B&K) types 4135 (serial number 77227) and 4136 (serial number 81227) one-quarter-inch condenser microphones, with a B&K type 2615 cathode follower (serial number 106921). The polarization voltage was supplied by a B&K type 2801 power supply (serial number 111497).

SYSTEM 5

Dickey HPO62L one-sixteenth-inch lead zirconate pressure transducer, with a Kistler type 566 charge amplifier (serial number 1376). This transducer was manufactured by Clyde W. Dickey, Pennsylvania State University.

SYSTEM 6

Kistler model 601-A quartz pressure transducer (serial number 11756), with a Kistler type 566 charge amplifier (serial number 1376).

CALIBRATION SYSTEMS

1. B&K type 4220 Pistonphone (serial number 69721).

2. General Radio type 1552-B Sound-Level Calibrator (serial number 2622) and a General Radio type 1307-A Transistor Oscillator (serial number 2036).

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13. ABSTRACT

This study investigated several types of transducers which might be considered for use when evaluating the hearing hazard of pressure waves that small arms produce. In measuring the small arms' peak sound-pressure level, error was directly proportional to the measured rise time and inversely proportional to the positive pressure duration of the wave. The most accurate results were obtained by positioning the transducers vertically, with the pressure wave grazing the sensing surface at 90° incidence. Moreover, there was good agreement between measurements made with a wide-band piezoelectric transducer and those made with a wide-band condenser microphone. Finally, pistonphone calibrations at low levels (127 dB) compare favorably with shock-tube calibrations at high levels (170 to 180 dB).

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