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DESIGN OF FLUIDIC DEVICES FOR SMALL ARMS STABILIZATION.(U)
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DESIGN OF FLUIDIC DEVICES FOR SMALL ARMS STABILIZATION

by

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HARRY DIAMOND LABORATORIES

WASHINGTON, D.C. 20438

ABSTRACT

The feasibility of stabilizing small arms in full automatic fire by use of fluidics was investigated. The man-gun interaction was studied to define the role of the fluidic system components. A system consisting of angular rate sensors, signal amplifiers, a fluid-to-mechanical converter, and a controllable muzzle device was postulated. A hydraulic analog of muzzle gas flow was developed to aid in design of the controllable muzzle device. This analog expands the gas-flow time scale by a factor of one thousand. Thus, designs are easily modeled, and the resulting flow interaction with the model is readily observable in the laboratory. The proposed system appears to be feasible, and the design techniques for further development are available.

FOREWORD

This report summarizes work performed under USASASA Project No. A543 for USA Small Arms Systems Agency under the cognizance of J. L. Baer.

CONTENTS

1. INTRODUCTION

The increasing deflection of the line of fire of consecutive rounds resulting from firing a conventional automatic weapon without a bipod severely limits the probability of hitting a target beyond point blank range with any but the first round (ref 1). The Harry Diamond Laboratories has been directed by the U. S. Army Small Arms Systems Agency to investigate a means of using fluidics to either eliminate the instability or reduce it to a tolerable level.

The study began with an investigation of the man-gun interaction during automatic fire. This was done to define the role of the stabilizing device. The M-16 rifle was used as a basis for the study. The man-gun interaction investigation included mathematical modeling and motion studies of various shooters firing from the offhand and hip positions.

These studies indicate a large variation in man-gun interaction due to differences in firing position, body structure, response time of reflexes, and the firer's conscious attempt at stabilizing the rifle. This led to the conclusion that stabilizing an automatic rifle would require an adaptive or automatically controlled system as opposed to one which is fixed or preset. The system approach that has been selected is to sense the rifle deflection during automatic fire and use sensor output signals, through appropriate signal processing, to operate a deflection control element.

The use of fluidic devices requires a power supply. Rather than penalize the system by adding fuel or reservoirs, the available sources of power would be used; these were muzzle gas flow and recoil. Because muzzle gas flow is the larger source of power, an analysis of the flow was performed. From the resulting analytic description, it was concluded that a water table, which is useful in observing supersonic flow, should be used to simulate the muzzle gas flow phenomenon. The hydraulic analog that evolved closely resembles shadowgraph pictures of actual rifle-muzzle gas flow. The analog has permitted the experimental modeling of muzzle devices. Among the devices modeled is the rifle stabilization control element that uses the gas exhausting from the muzzle to provide a corrective thrust, thereby reducing the rate of deflection of the weapon.

2. MAN-GUN INTERACTION

Analysis of the man-gun interaction was undertaken to define the role of the system required for automatic rifle stabilization. The initial model was a four-bar linkage consisting of (1) rifle, (2) shoulders, (3) arm, and (4) forearm. The force equations were developed with eight degrees of freedom in a three-vector space with a resulting set of 24 simultaneous differential equations. La Grange's equation for nonconservative systems was applied to this system of forces. This led to a simplification of coordinates plus direct use of external spring and dashpot forces without the need for breaking them into components. It was then discovered that the U. S. Army Weapons Command had initiated a man-rifle interaction analysis program. To avoid duplication of effort, we gave them the results of our work and directed our efforts to other aspects of the task.

An experimental approach to understanding the function to be performed by a fluidic stabilizing device was then taken to provide the basis for system concept and component development prior to completion of the mathematical analysis. To accomplish this, high speed motion pictures were taken of six persons firing the M-16 rifle in the automatic mode. The shooters all fired from both the hip and the shoulder in a standing position. There was a wide variation in height, weight, body structure, and physical condition among the shooters. A preliminary analysis of the high-speed motion pictures indicated a large variation in man-gun interaction. Some causes for this wide variation can be identified as differences in each person's firing position, physique, reflex action, response time, and conscious effort at stabilizing the rifle. A typical frame of the motion pictures of one shooter is shown in figure 1. Rifle deflection vertically, horizontally, and rearward was determined using six-inch grids located behind and below the shooter as well as a mirror mounted above the shooter at a 45-deg angle.

Measurements of the rifle deflection are given for two shooters as a function of round numbers for the bursts fired. These indicate the variation in response. One shooter (C) used the conventional hip firing-position with the rifle supported using a long sling over the right shoulder. The rifle was supported primarily by the arms with the side of the butt against the hip. The other shooter (S) used a modified hip firing-position. He stood with his right foot forward with the butt of the rifle on the right hip bone. He also used a long sling over the right shoulder and held the rifle with both hands. Both shooters fired right-handed. The muzzle deflection as a function of round number for both firers is given in figure 2. It is broken down into the following components: x (horizontal, positive displacement to the right), y (vertical, positive displacement upward), and z (line of aim, positive displacement rearward).

Firer C consciously attempted to correct for muzzle deflection while firer S relied on his firing position to stabilize the weapon. Firer C was able to correct the deflection by the 5th round in all three directions. The muzzle of S drops and then rises due to the rearward impulse imparted to the hip which causes the shoulders to slump forward so that deflection in only this one direction was corrected. The reflex act of straightening the body causes the shoulders to rise thus causing the sling which rides on the right shoulder to raise the muzzle.

Figure 1. Shooter firing in the offhand position.

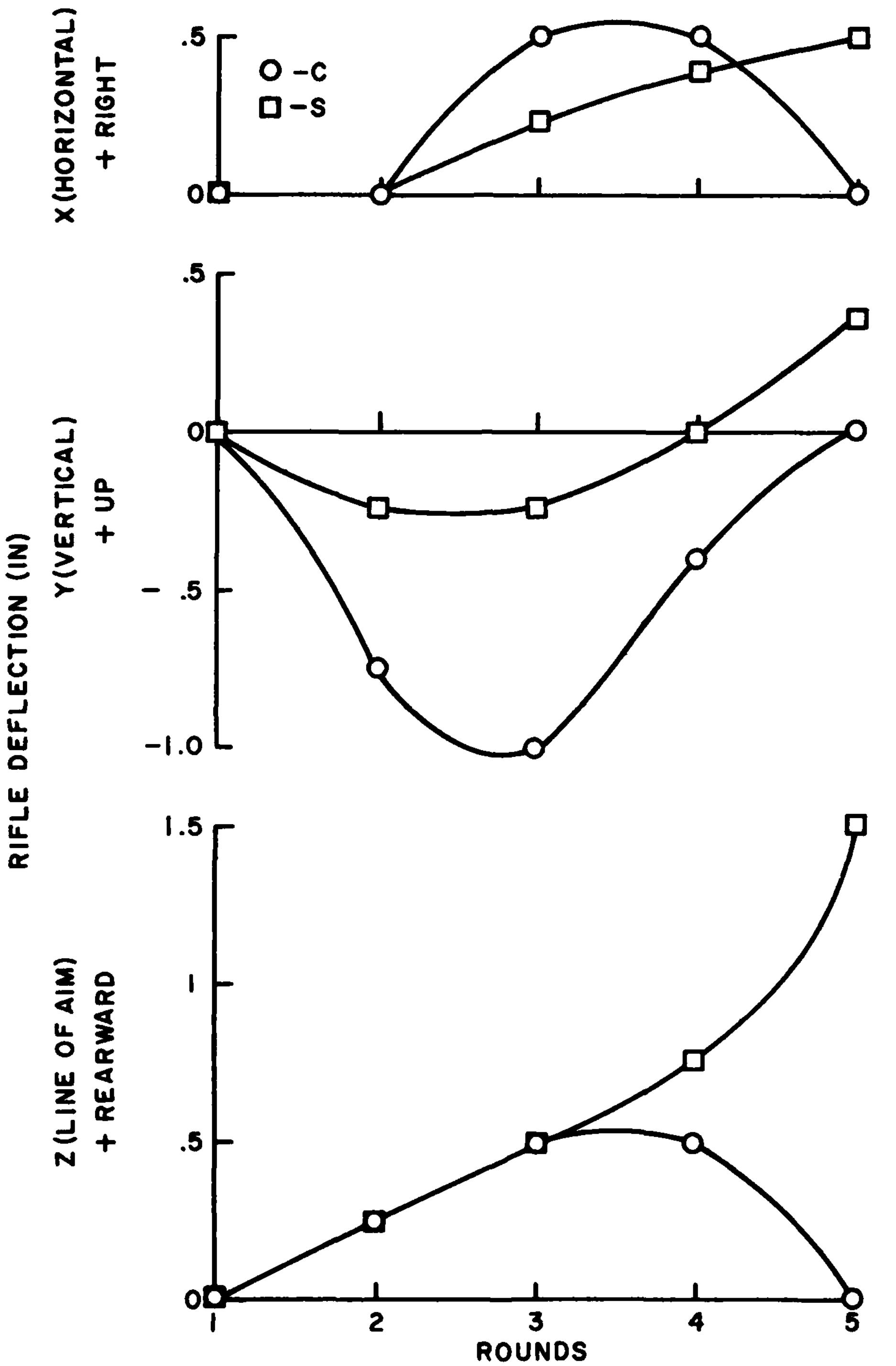

Figure 2. Muzzle displacement for two shooters firing from the hip.

Figure 3 gives deflection components of the muzzle for the case of the same two shooters firing from the offhand position. In case S_1, the shooter fires while relaxed and erect. In case S_2, the same shooter is rigid while leaning toward the target. Shooter C is rigid and leans toward the target as well; however, as was the case when firing from the hip and unlike shooter S, he consciously attempts to correct for muzzle deflections.

These data indicate the extent of the muzzle deflection as well as the difference in muzzle deflection for different shooters and firing positions. This information is given as an indication of the shooter-to-shooter difference in man-gun interaction.

To maintain a given line of fire the gun must maintain a constant angular position. Since the shooter's firing position is varied by recoil, and angular deflections of the gun result, maintaining the line of fire requires application of a force at the muzzle of the gun normal to the line of fire. This force cannot be preset, but must be adjusted from shot to shot depending on the particular angle of deflection. This would aid the shooter in maintaining the gun on the line of fire. Additionally, recoil and noise reduction would decrease the error-inducing forces on the shooter and would be desirable. Translation errors are not considered because they cannot be corrected without separating the butt of the gun from the shooter.

Films of two persons of different physiques, firing from the hip and in the offhand position were sent to U. S. Army Weapons Command (Lt. Gary Fisher, AMSWE-ST) for analysis. The WECOM work on man-gun interaction in FY 70 included a more thorough analysis of these films.

3. MUZZLE GAS FLOW

As the projectile leaves the muzzle of a gun, it is followed by rapidly expanding propellent gas. The gas expansion and mixing process follows a definite sequence of events (ref 2). Initially, a normal shock forms at the forward area of flow with an oblique shock of revolution connecting the outer edge of the normal shock and the muzzle (figure 4). The volume enclosed by these shocks is referred to as the shock bottle of the flow. Principal expansion and cooling of the propellent gases occur within the shock bottle.

Surrounding the shock bottle is a turbulent area in which mixing of propellent gases with ambient air occurs. The shock bottle expands in size until it reaches a maximum volume state (figure 4). The shock bottle shape then changes to form a quasi-stationary normal shock and oblique shock wave of revolution as shown in figure 5. As propellent gas further emerges from the muzzle, there is a steady shrinking of the bottle without apparent change in shape. With further reduction of pressure, the bottle collapses and the remaining flow becomes subsonic

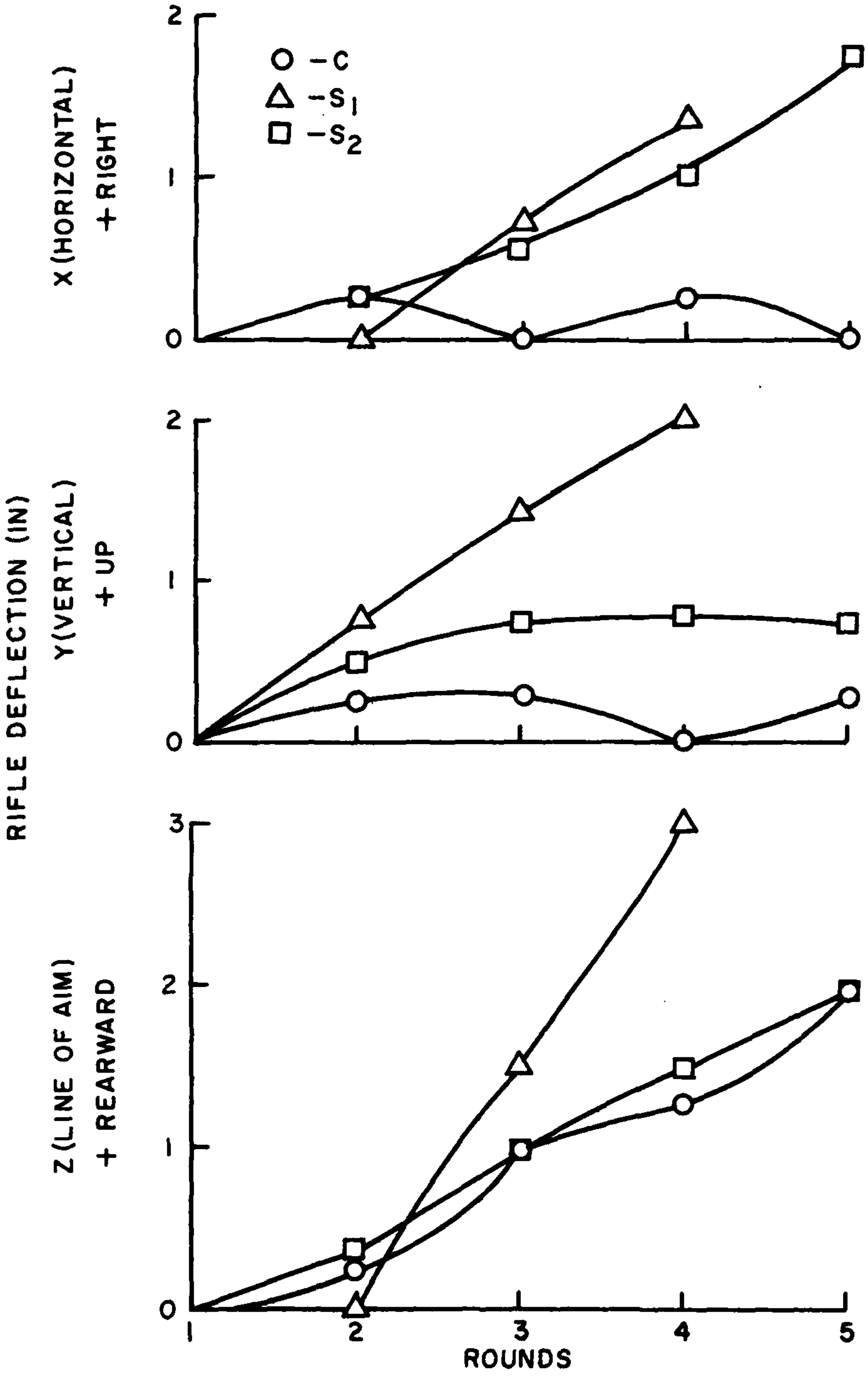

Figure 3. Muzzle displacement for two shooters firing from the shoulder (right-handed).

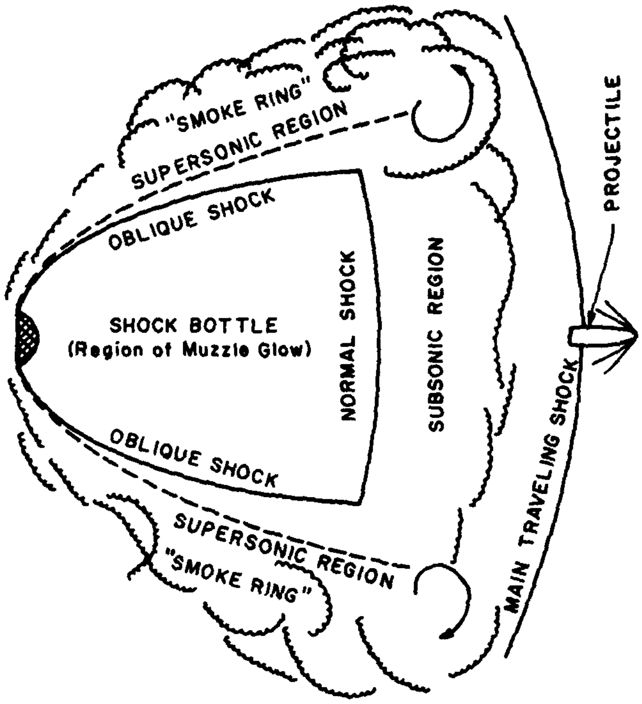

Figure 4. Maximum volume stage of shock bottle (ref 2).

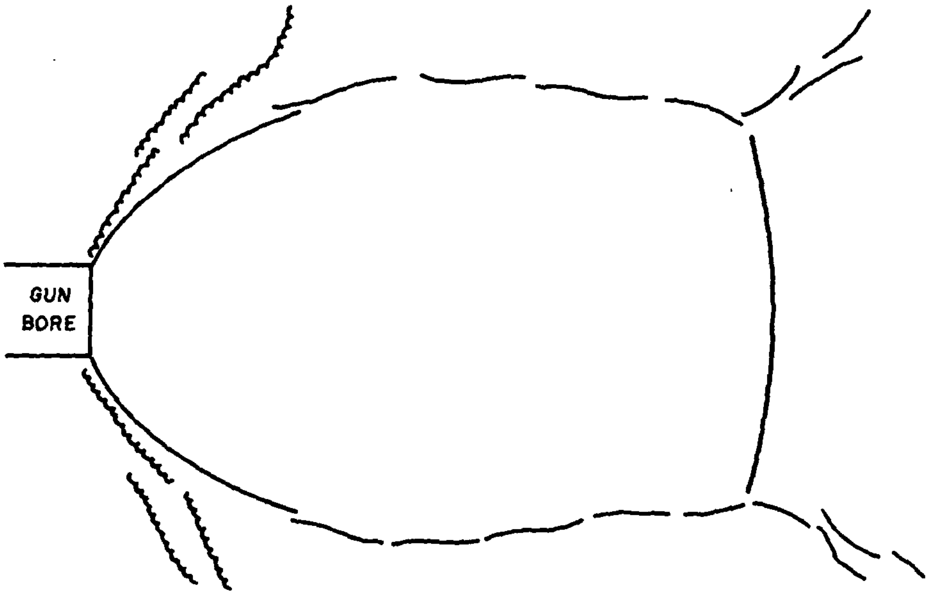

Figure 5. Steady state shape of shock bottle (ref 2).

A quantitative analysis of the muzzle gas flow from the M-16 rifle was conducted utilizing expressions obtained from reference 2 and M-16 ballistic data from reference 3. The pressure within the muzzle at the instant of shot ejection (p_o) is given by the following expression:

$$p_o = \frac{12\ RT_o}{g\left(\frac{V_t}{w_c} - \eta\right)} \left(1.0 + \frac{w_c}{6w_p}\right)$$

where
R = gas constant
T_o = propellent gas temperature at shot ejection
A = bore area
V_t = volume of bore and tubing leading to bolt
g = acceleration of gravity
w_c = weight of powder charge
w_p = weight of projectile
η = covolume term $P(V - \eta) = RT$ of the Abel equation of state

RT_o the specific impulse of the propellent shot ejection is determined from the energy equation of interior ballistics:

$$\frac{w_c}{\gamma - 1} (RT - RT_o) = 1/2\ w_p V_o^2 (1 + \delta) + 1/6\ w_c V_o^2$$

where
T = propellent adiabatic flame temperature
γ = isentropic constant
RT = specific impulse of propellant
V_o = muzzle velocity
δ = fractional heat loss to gun tube as function of [illegible] energy

Substituting values for the constants into the energy equation yields

$$RT_o = 6.75 \times 10^6 ft^2/sec^2$$

Using this value, p_o was found to be 12,182 psi. This value is in good agreement with experimental value of 11,669 psi (ref 3).

The flow rate Q of the propellent gas as a function of time t after shot ejection can be determined using a modified version of the Hugoniot's gas flow theory (ref 2) in which time after shot ejection is taken as negative.

$$Q = 12 \frac{w_c A}{V_t} \left(1.0 + \frac{w_c}{6\gamma w_p}\right)\left(1.0 + \frac{t}{\theta}\right)^{\frac{1+\gamma}{1-\gamma}}$$

$$x = \sqrt{\gamma \, RT_o \left[1.0 + \frac{(\gamma - 1)w_c}{6\gamma w_p}\right] \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

$$\text{where } \theta = \frac{V_t}{6A(\gamma - 1)} \sqrt{\frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}}{\gamma RT_o \left[\frac{1.0 + (\gamma-1)w_c}{6\gamma w_p}\right]}}$$

Substitution of appropriate values yields

$$\theta = 0.0108 \text{ sec}$$

Substituting the value for θ into the equation for Q and computing Q as a function of t yields:

$$Q = 3.29 \left(1 + \frac{t}{.0108}\right) \quad 9.33 \text{ lb/sec}$$

A plot of Q versus t is given in figure 6. Flow is completely exhausted when $t = -\theta$ or $-.0108$ sec.

The rate of change of momentum, $\dot{M}$, is given by the following expression:

$$\dot{M} = \frac{12 \, ART_o w_c}{gV_t} \left(1.0 + \frac{w_c}{6w_p}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \left(1.0 + \frac{t}{\theta}\right)^{\frac{2\gamma}{1-\gamma}}$$

Substituting values $\dot{M}$ as a function of t becomes

$$\dot{M} = 264 \left(1 + \frac{t}{.0108}\right)^{10.33} \frac{\text{lb-sec}}{\text{sec}}$$

$\dot{M}$ versus t is given in figure 7. The integral of this curve is the recoil impulse caused by the exhausting gases following shot ejection. It was found to be 0.245 lb/sec, which is in fair agreement with the empirical value of .27 lb/sec (ref 4).

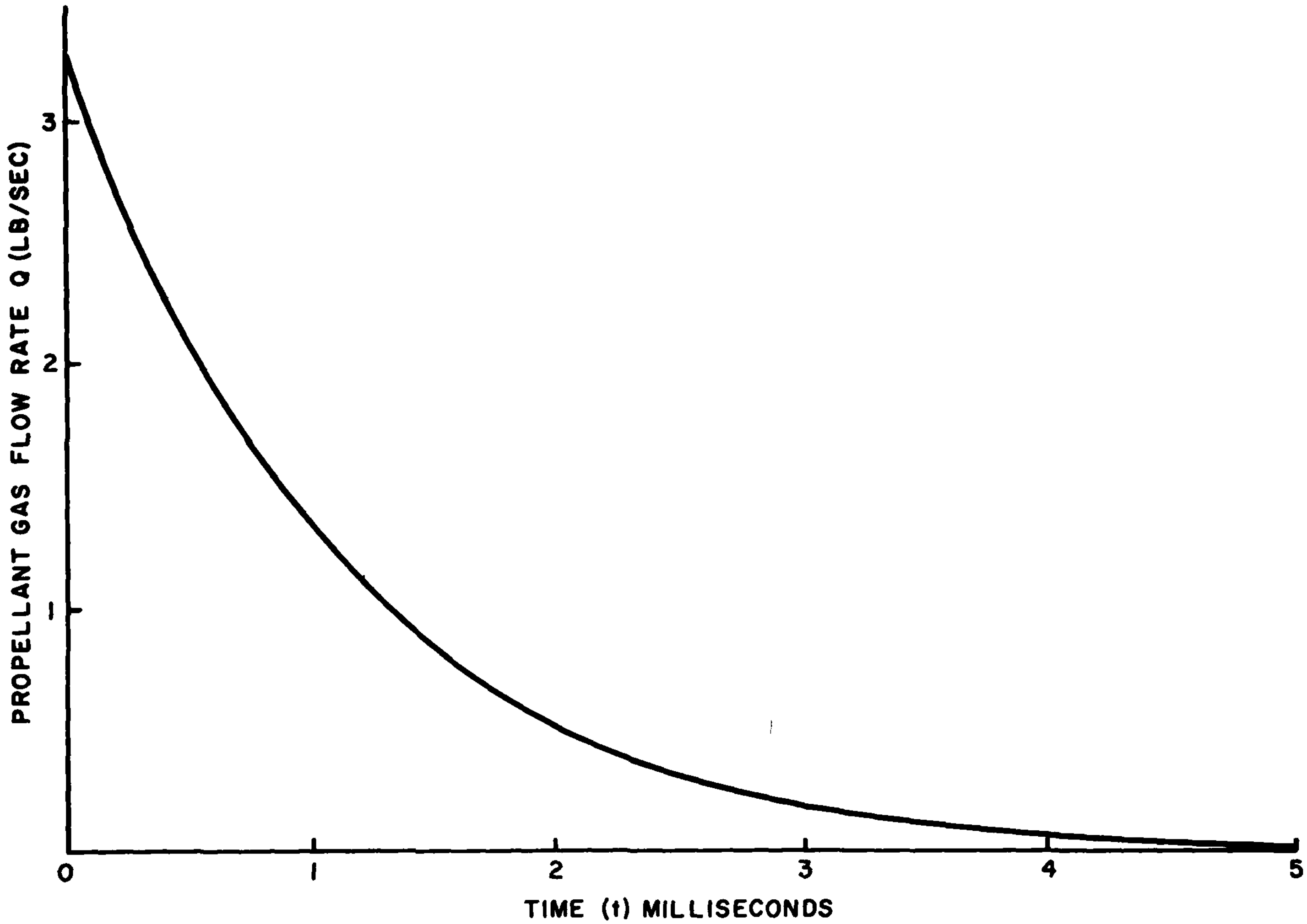

Figure 6. Propellant flow rate versus time.

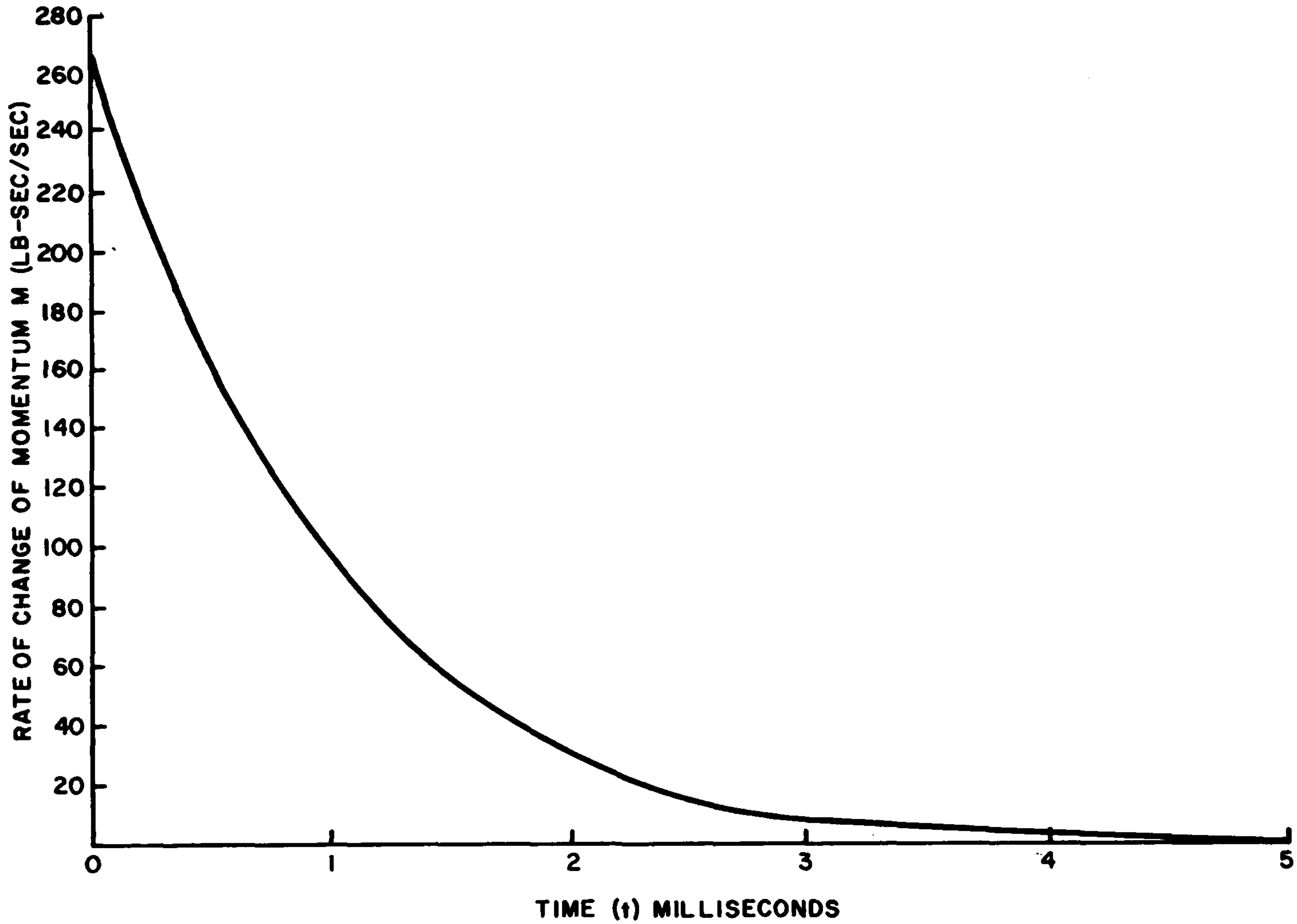

Figure 7. Rate of change of momentum versus time.

Due to the complexity, transient nature, and rapidity of the muzzle gas flow and blast phenomenon, it was decided that the hydraulic analogy to supersonic compressible fluid flow should be utilized as a simulation tool. The analogy between a steady two-dimensional, compressible, isentropic, perfect gas flow and incompressible water on a level plane with a free surface is given by Barclay, Bowers, and Morehead (ref 5). Using the analogy, a model was constructed to enable simulation of muzzle gas flow and blast from the muzzle of a gun. Assuming ideal two-dimensional flow of propellent gas from a muzzle imposes certain limitations on the analogy. However, in spite of the limitations, it was considered that the hydraulic analogy would be useful for modeling of muzzle devices. It was considered that use of the analogy would allow for generation of qualitative appraisals, design comparisons, and new muzzle device concepts.

The analogy derived in reference 5 is summarized below:

Liquid Flow Analog	Gas Flow
Water depth ratio, d/d_o	Temperature ratio, T/T_o
Water depth ratio, d/d_o	Density ratio, ρ/ρ_o
Water depth ratio squared $(d/d_o)^2$	Pressure ratio, p/p_o
Mach number $\sqrt{\frac{2d_o - d}{d}}$	Mach number, V/a

Conceptually, the model to be used to simulate propellent gas from the muzzle of a rifle was a reservoir of fixed volume which could be discharged rapidly through a nozzle as high as the reservoir height. The ratio of the depth of water in the reservoir to that on the table was determined from the similarity expression relating water depth and gas pressure,

$$\left(\frac{d}{d_o}\right)^2 = \frac{p}{p_o}$$

where p_o is the total pressure at the muzzle of an M-16 rifle at shot ejection (11,669 psi) and p is the ambient pressure at sea level (14.7 psi). Substituting these values in the above expression results in d/d_o = .0355.

A reservoir height of 6 in. and a water table depth of 0.213 in. were established from the computed pressure ratio and found experimentally to produce shock bottle development closely resembling shadowgraph photographs of the M-16 shock bottle. This water table depth is close to the 0.20 in. depth usually chosen for simulating supersonic flow (ref 6). This is the depth that produces wave velocities substantially independent of wavelength (see figure 8). Based on this graph, it was decided that choice of a water depth of slightly greater than 0.2 in. should result in negligible increases in the dependence of wave velocity on wavelength.

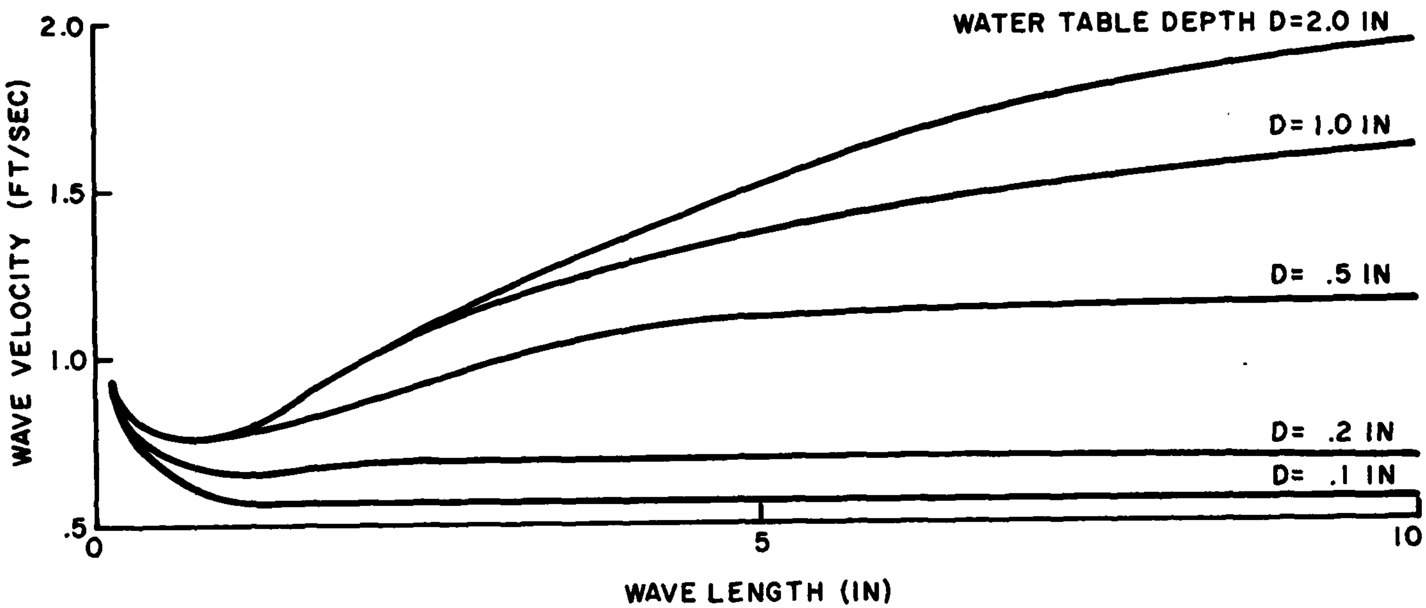

Figure 8. Propagation speed versus wavelength. (Data due to A. H. Shapiro).

A muzzle gas-flow simulation model was constructed with fixed dimensions as shown in figure 9. To induce jet spreading to simulate shadowgraph pictures of gas flow from a rifle more closely, a baffle was employed at the model nozzle. The baffle decreased the nozzle height and caused the flow behind it to be diverted in a downward direction, thus producing a jet with a more pronounced spreading angle.

The ratio of time of gas flow to time for analogous water flow on the water table is approximately 1 to 1000 (ref 5). Using this ratio, the time for reservoir discharge that corresponds to the time computed for propellent gas discharge is 10.8 sec. Fixing the height of water on the table at 0.213 in. and the reservoir water depth at 6 in., the reservoir volume was varied to yield a discharge time of approximately 10.8 sec. A sequence of still photographs of the exhaust flow during reservoir discharge are shown in figure 10. The flow patterns in these pictures display a striking similarity to the diagrams of the actual flow of propellent gas from a rifle shown in figures 4 and 5. The oblique and normal shock waves of propellent gas flow are hydraulic jumps on the water table. The growth and decay of the shock bottle of the hydraulic analog follows qualitatively the same well-defined series of stages as that of propellent gas discharge. A wave analogous to the main traveling shock wave or blast wave that is found after shot ejection may be observed also on the water table. A water depth gauge may be employed to obtain a trace of wave strength (height versus time)(fig.11). This trace is analogous to a recording of blast overpressure.

The effect of water table depth on shock bottle growth was ascertained by taking motion pictures of flow discharge for a range of table water depths, from .130 to .40 in. High-speed motion pictures (7,000 frames/sec) of the M-16 muzzle blast were also taken. The shock bottle growth on the water table for the different cases recorded was compared with 0.48-msec of shock bottle growth of the M-16. The M-16 shock bottle could not be detected on the film beyond this time, since direct photography was used instead of the preferred shadowgraph technique. Figures 12 and 13 give a comparison of shock bottle maximum width and normal shock displacement as a function of time for both the actual M-16 shock bottle and the hydraulic model with three different table water depths. The growth rate of the shock bottle width in the hydraulic model and that of the M-16 muzzle gas flow appear to be in good agreement. The displacement of the normal shock for the M-16 muzzle gas flow and the hydraulic analog are in good agreement up to the distance of 5 in. Beyond this displacement, the normal shock of the hydraulic analog progresses at a faster time-scaled rate than that of the M-16 muzzle gas flow. This is due to the fact that muzzle gas expands three dimensionally while the analogous flow on the water table is restricted to two dimensional flow. Despite this limitation, it was considered that the use of the hydraulic analog would permit generation of qualitative appraisals, design comparisons, and generation of new muzzle devices for small arms because such devices should be less than 5 in. in length.

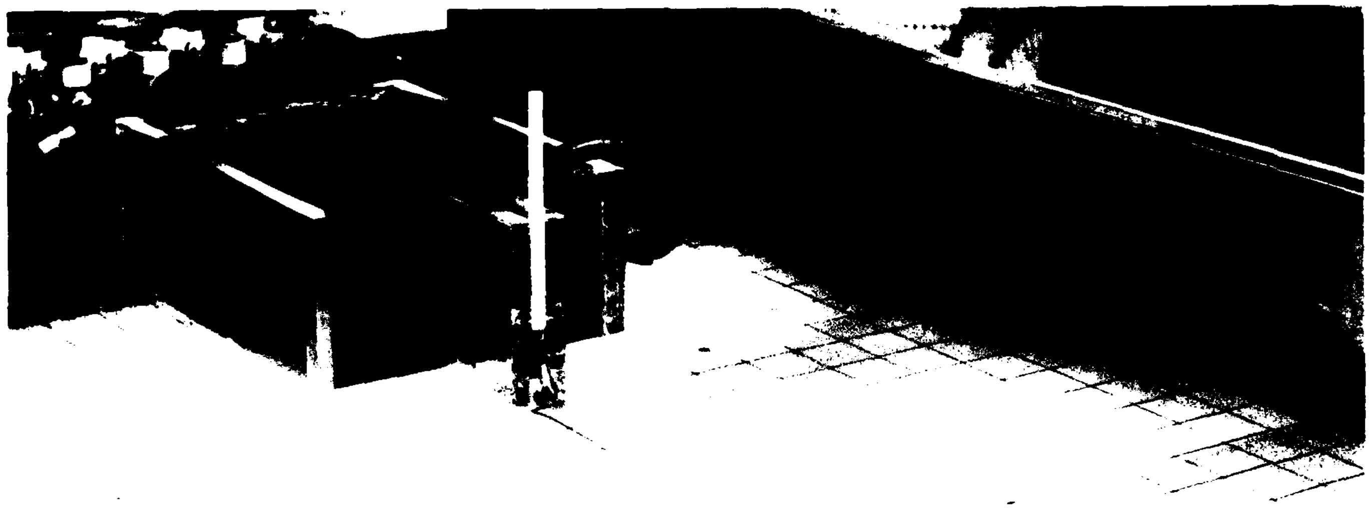

Figure 9. Model employed for muzzle gas flow simulation . Shock bottle shown in center foreground.

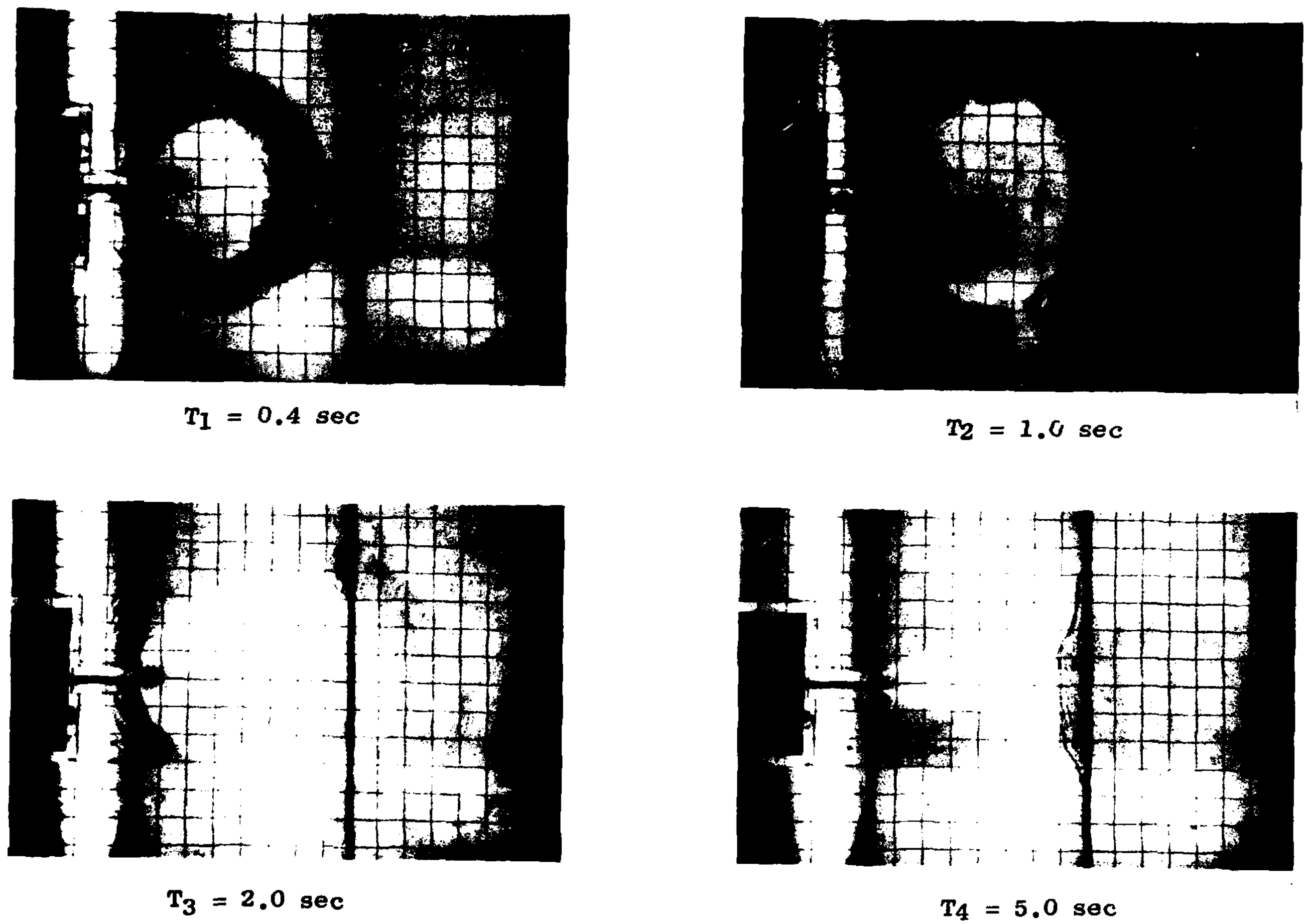

Figure 10. Shock bottle growth and decay as indicated in hydraulic analog of muzzle gas flow.

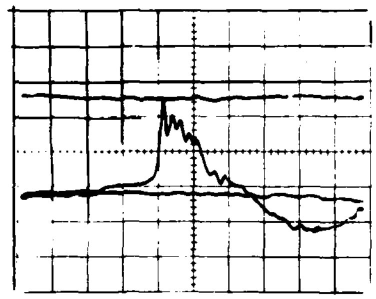

Figure 11. Hydraulic analog of muzzle blast overpressure wave. Sweep rate, 0.5 sec/cm).

4. MUZZLE DEVICES MODELED ON WATER TABLE

The water-table analog of gun muzzle flow was utilized to investigate various muzzle device configurations. Of the devices modeled, two configurations appear to have characteristics which make them worthy of further study as stabilization system components. Both are muzzle brakes.

One muzzle brake concept tends to reduce the intensity of the rearward moving shock wave (perceived as noise by the shooter) while reducing the forward momentum of the propellent gases. This device differs from the conventional muzzle brake in that it is an open structure and employs a conical baffle directly upstream of the principle flow deflectors (figure 14). The proper placement of the conical baffle reduces the intensity of the rearward moving shock that is increased when employing a typical muzzle brake. Movement of the conical baffle in the plane normal to the flow axis can make the flow asymmetric in order to obtain a corrective normal force along with noise and recoil reduction.

The other configuration that can be utilized to obtain normal displacement of the muzzle of a rifle and also reduce recoil is shown in figure 15. In this scheme a movable control deflector is located immediately downstream of the rifle muzzle and upstream of a right-angle

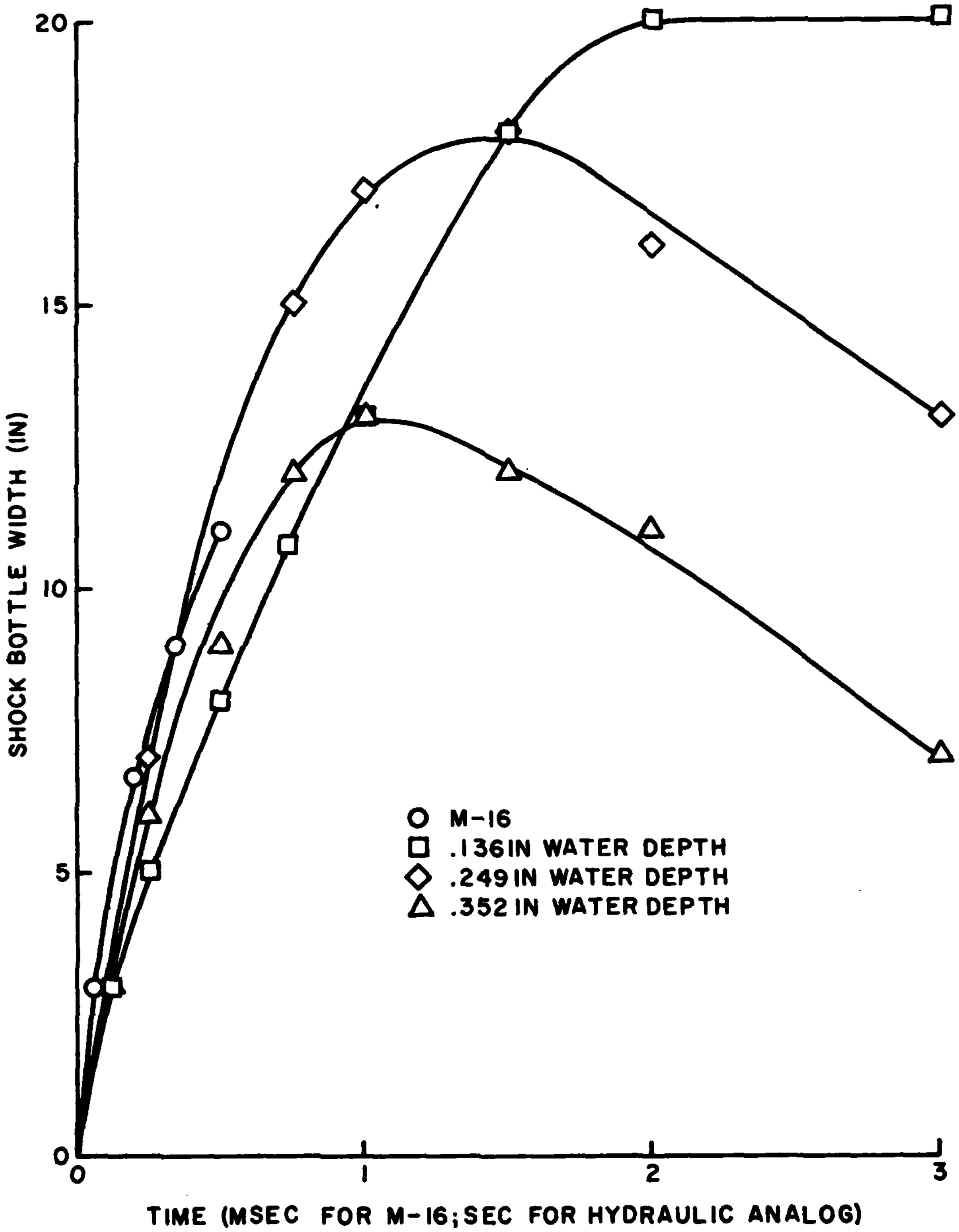

Figure 12. Shock bottle width versus time.

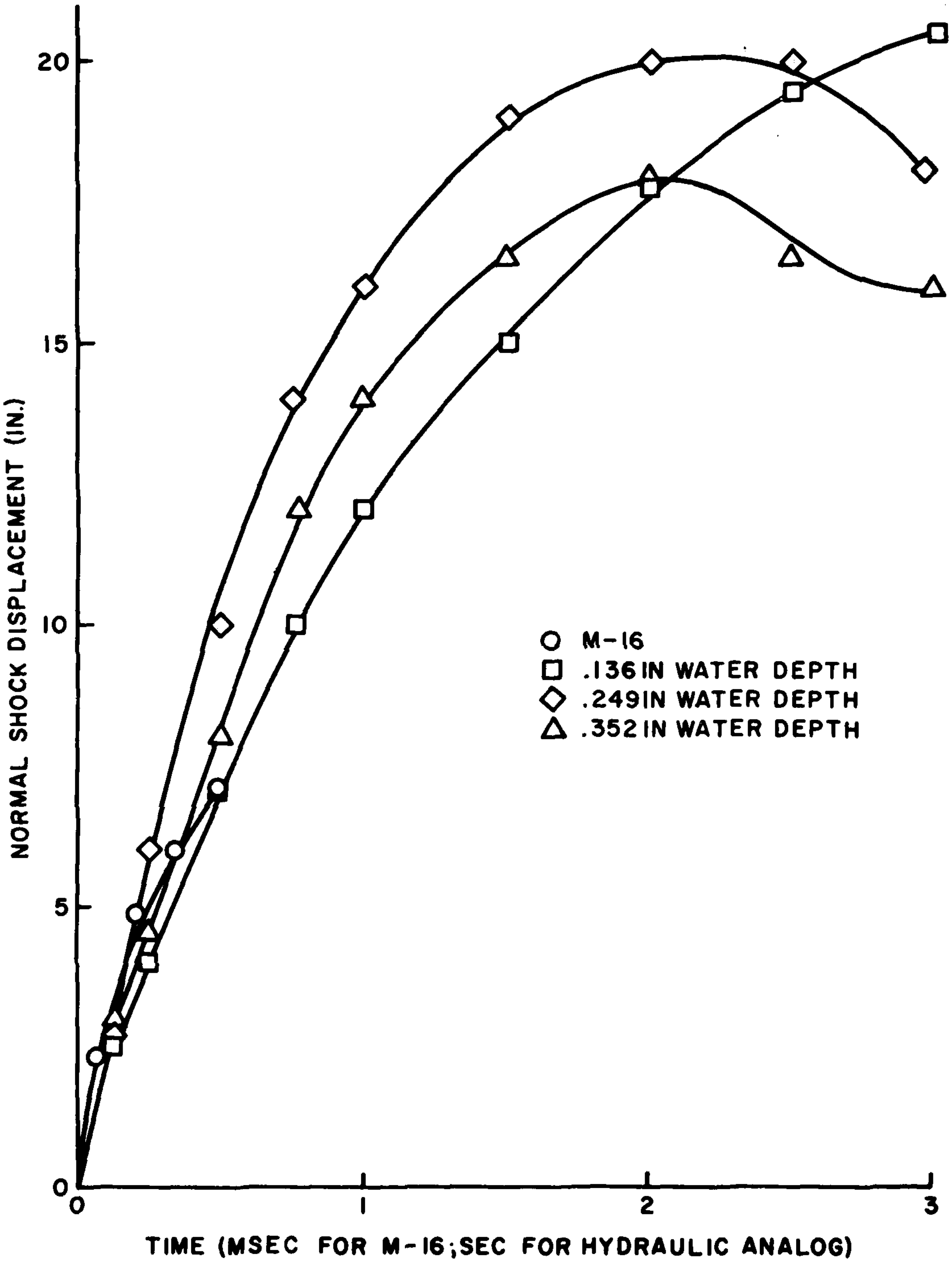

Figure 13. Normal shock displacement versus time.

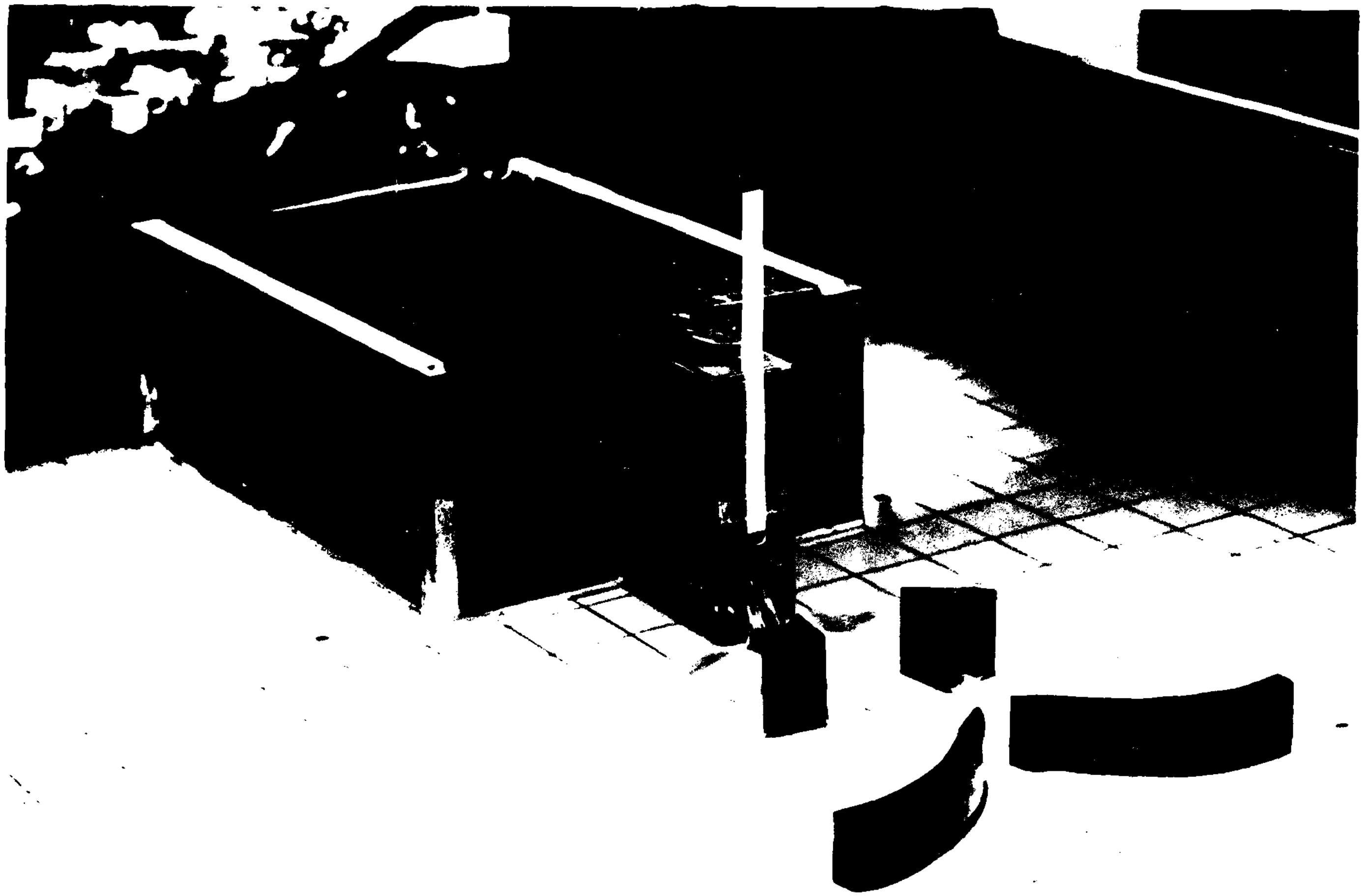

Figure 14. Muzzle brake modeled on the water table.

Figure 15. Asymmetric deflection of gas in a muzzle brake. The passage between the turning vanes is obscured by a holding weight.

flow turning vane. When the movable deflector is brought inside of the usual oblique shock wave of the shock bottle, the flow from the muzzle is turned away from the deflector. This results in an unbalanced flow to the right-angle turning vanes causing a resultant lateral force on the muzzle in the direction opposite to the diverted muzzle gas flow. Two pairs of controllable deflectors and turning vanes, one pair in the pitch plane and one pair in the yaw plane, in front of the muzzle would allow for generation of continuous horizontal and vertical control forces. This device is capable of greater control forces than the previously described muzzle brake because it can achieve nearly complete diversion of the flow.

5. CONSIDERATIONS OF STABILIZATION SYSTEM CONSTRAINTS

There are numerous constraints on the functioning and in designing a stabilization system. These necessarily define a feasible and desirable system.

The principal constraint on systems using diverted muzzle blast as a control force is the brief time that muzzle blast is available. The duration of high mass flow is effectively 3 to 5 msec.

The major constraint imposed by fluidic systems is the response and transport time for signal flow and fluid-to-mechanical outputs. Response times greatly below 1 msec are difficult to achieve, even without moving parts. Transport time is limited by the speed of sound, which requires about 1 msec per ft.

Let us assume a system in which the signal flows from a motion-sensing transducer through an impedance-matching amplifier, a signal-gain amplifier, and a power amplifier into the fluid-to-mechanical converter that manipulates the controllable muzzle device. Allowing only 0.5-msec response time for each fluid amplifier and the transducer gives a total fluidic response delay of 2 msec. The signal flow time and mechanical response time would then have to be added to this to obtain a minimum system response time. It appears impossible to compensate for the effects of recoil forces produced by any given shot through modulation of the muzzle blast from the same shot because of the system response time. Flow established by firing the first round could be utilized and the angular motion resulting from firing that round could be sensed to preset a muzzle device as soon as 40 msec later. Thus, a cumulative barrel deflection could be either reduced or eliminated. In a very real sense, that is the intent of small arms stabilization.

The loss of control forces on the first round of a burst not only is a negligible loss, but provides a particular advantage when the weapon is fired semi-automatically. The lack of intentional control force minimizes any variations of input to the man-gun system. This should prevent any loss of accuracy when firing semi-automatically.

The remaining constraints are effective system gain (corrective impulse per angular rate), maximum corrective impulse obtainable, and the degree to which intentional motion should be resisted. The effective system gain is definable as being within a range determined by the motion measurement, man-gun interaction, and fluid force output. The motion measurement would be performed by a fluidic angular-rate-of-rotation device that should become available during FY 71 through AMC sponsored research at Harry Diamond Laboratories. The man-gun interaction which determines the effective moment arm, is not yet completely defined, but probable limit cases can be identified. These limit cases would correspond to free support of the gun (infinite compliance in all degrees of freedom) and hinging the buttplate to a rigid body (zero compliance in recoil, finite but unequal compliance in pitch and yaw planes of rotation). These limit cases produce a moment arm varying between about 2 and 3 ft on an M-16.

The maximum corrective impulse obtainable would be determined by the transverse momentum imparted to the muzzle blast. This in turn is the product of mass of gas turned, sine of the net angular deflection, and exit velocity. These relate to the proportion of propellent gas deflected, the net angle of deflection for exit flow, and the energy losses involved in handling the muzzle blast flow. With the devices shown, it can be assumed that these limits are 100 percent of gas flow turned 90 degrees with not more than 50 percent energy loss (30 percent momentum loss). Therefore, a corrective torque impulse on the M-16 would be limited to gas momentum times moment arm which is approximately .27 lb-sec x .7 x 2.5 ft = 0.47 ft-lb-sec. This value would be equivalent to a steady pull of about 2 lb on the handguard in full automatic fire. This would, alternatively, balance out a recoil axis to support axis misalignment of about 0.4 ft.

It would seem that overcoming a force of 2 lb at the handguard would not be an excessive effort when intentional motion of the gun is desired as in delivery of a sweeping burst.

During FY 71 it is anticipated that a new angular rate sensor will have completed its research stage at HDL. This sensor should be capable of 0.5-deg-per-second threshold with greater than 100-Hz frequency response. This would mean that no correction would be made when an angular motion causing less than

$$0.5 \ \frac{\text{deg}}{\text{sec}} \times \frac{3.14}{180} \ \frac{\text{rad}}{\text{deg}} \times 0.1 \ \frac{\text{sec}}{\text{shot}} = 0.87 \ \frac{\text{mil}}{\text{shot}}$$

occurs. Corrective forces would be generated as defined by effective system gain for rates in excess of the threshold. This effective system gain would be defined by stability requirements and achieved by state-of-the-art fluid amplifiers and the muzzle device.

6. CONCLUSIONS

The design of an effective fluidic system for a small arms stabilization system appears to be feasible, although some components required are not yet available. The system would consist of an angular rate sensor that should be developed within a year, fluid amplifiers that now exist, and a muzzle device.

The development of a hydraulic analogy to muzzle flow, which was accomplished during this study, provides a powerful tool for analyzing muzzle flow phenomena. Of particular importance, this analog facilitates design of muzzle devices and generation of qualitative appraisals based upon observable fluid flow. The observation of fluid flow phenomena is greatly aided due to a 1000 to 1 lengthening of the time scale. Designs are easily modeled and resulting flow interaction with the test model is readily observable in the laboratory.

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13. ABSTRACT

The feasibility of stabilizing small arms in full automatic fire by use of fluidics was investigated. The man-gun interaction was studied to define the role of the fluidic system components. A system consisting of angular rate sensors, signal amplifiers, a fluid-to-mechanical converter, and a controllable muzzle device was postulated. A hydraulic analog of muzzle gas flow was developed to aid in design of the controllable muzzle device. This analog expands the gas-flow time scale by a factor of one thousand. Thus, designs are easily modeled, and the resulting flow interaction with the model is readily observable in the laboratory. The proposed system appears to be feasible, and the design techniques for further development are available.

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