ACOUSTICAL AND VISUAL ATTENUATION THROUGH DYNAMIC REGULATION OF MUZZLE GAS FLOW

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INTRODUCTION

The occurrence of muzzle flash and noise while firing military weapons has been an annoying, as well as a discriminating characteristic throughout the history of firearms. From the standpoint of the gunner, flash obscures vision because of its blinding brightness while noise creates damage in the unprotected ear (1); therefore, both reduce the gunner's efficiency. From another aspect, noise and flash reveal to the enemy both the presence and the location of the weapon, thus inviting defensive action.

The most recent events to create renewed activity toward the reduction of flash and sound were, first, the complaint of excessive flash while using the M73 machine gun in the M60 tank installation and, secondly, a project for a silent weapon system to support guerrilla activity.

Weapon muzzle devices developed in the past have been flash suppressors, muzzle brakes, compensators and silencers and all these affect the muzzle gas flow in some manner; however, the functional use of one can be detrimental to another. For example, a muzzle brake usually increases the sound pressure level at the shooter's ear. The development of flash suppressors and sound suppressors (silencers) can be complimentary; that is, the discoveries of one will aid the advancement of the other.

GENERATION OF FLASH AND SOUND

The study of ballistics has been divided into three regions: interior, exterior and terminal. Each division has been the subject of exhaustive studies. An area of even greater complexity is that region of transition between interior and exterior ballistics where projectiles and hot, high velocity gasses emerge into a relatively static atmosphere. In this locality, the gases undergo expansion, cooling, deceleration, mixing with air, and create shock fronts with possible additional burning. For purposes of definition, this region will be titled "transitional ballistics". A knowledge of interior ballistics is necessary to the extent that it determines the initial conditions upon which transitional ballistics can be based.

For supersonic velocities, the air in the gun barrel ahead of the projectile is compressed and accelerated and its muzzle exit causes a weak shock wave to form. Following muzzle exit of the projectile, the high pressure gun gases begin a rapid expansion to the atmosphere, causing a strong wave propagating at supersonic velocities for a short distance. This shock or overpressure condition decays rapidly and then continues to travel at sonic velocity as an impulse wave or sound wave. A schlieren photograph of this expanding shock wave is shown in Figure 1. A second important sound source is the shock wave created by a supersonic projectile. However, recent studies (2) indicate that it will not reveal weapon location; therefore, this study is concerned with muzzle gas sound only.

The generation of muzzle flash has been discussed rather exhaustively in the literature (3, 4). Most interior ballistics studies (5) show that propellant combustion terminates at about one-third of the barrel length; however, since none of the common propellants contain sufficient oxygen for complete combustion, the gases which emerge from the muzzle contain considerable amounts of CO and H_2, along with CO_2, N_2, H_2O and other minor constituents. These gases expand, cool, and mix with air and, if sufficient oxygen is added, it again becomes a combustible mixture. Ignition temperatures may be provided by an unburned powder particle, a hot barrel muzzle, a tracer round, or the temperature increase across a shock front. Muzzle flash can be divided into two segments; that caused by the gases at the muzzle with sufficient temperature to create visible radiation called "muzzle glow", and that caused by gases mixed with additional oxygen and reignited called "secondary flash". This secondary flash is objectionable because it is highly visible and it provides a second source of sound generation. A photograph of secondary flash is shown in Figure 2.

When studies were begun with the M73 weapon, it was believed that a large amount of gas accumulated at the muzzle because of automatic firing and was then ignited with a tracer round. Firing groups of ammunition in which no tracer rounds were used failed to reduce secondary flash. A second experiment performed was that of retaining the muzzle gases in a container until they had somewhat decelerated, cooled, and expanded before they were allowed to mix with the atmosphere. This was accomplished inexpensively by use of an existing metal shipping container eight inches in diameter and 10 inches deep. This unit was mounted on the M73 booster having a bullet exit hole 7/16 ~~inch in~~ diameter. Air entrainment within the container was prevented by flushing with carbon dioxide before firing. In theory, the CO_2 would be flushed out by repeated firing until only gun gas remained in the container and, if additional oxygen is required to support combustion, secondary flash should occur at the exit hole. No secondary flash was observed during either single or automatic fire using combat linked ammunition, that is, one tracer round to four ball rounds; therefore, the residual gas was not ignited by a tracer round. In addition, the sound level was drastically reduced. This sound level was not measured with instrumentation, but appeared similar to that of a .22 caliber rimfire cartridge. This sound reduction may be rationalized as follows: Using the published data on the NATO 7.62mm round, Corner's theory (5) for space mean pressure and assuming adiabatic expansion, the gas pressure in the can for one round is only 31.54 psia, assuming no flow out the exit hole. This results in a critical pressure ratio of .466; therefore, the gas exit velocity may be subsonic and the sound recorded is that created by the projectile.

From the test results and observations made with suppressors thus far, some requirements for such devices to be effective can be listed:

1. It should cool the gun gases which would either quench the burning gases or prevent reignition,
2. It should provide gradual mixing with air to prevent external oxygen from supporting combustion,
3. It should decelerate the gases to prevent shock-front formation, and/or
4. It should retain the gases until they have expanded to provide cooling and prevent shock-front temperature increases.

To be successful, any one or a combination of the above features must be incorporated in a suppressor. Cooling may be accomplished by retaining the gases near a heat sink to enhance heat transfer by convection and conduction or by adiabatic expansion in a changing area flow passage. Gradual mixing may take place by progressive venting downstream. Deceleration and retention may be accomplished by changing the cross-sectional area of flow passage.

THEORETICAL GAS DYNAMICS

Methods of high velocity gas control are numerous (6); however, the peculiarity of a weapon is the necessity of providing a through passage for the projectile to travel its course unhindered while followed directly, or even preceded by hot, high velocity gases. The investigator at once envisions a contrivance which will effect gas flow and still allow a cylindrical clearance throughout its length. A study of fluid flow phenomena reveals some new lines of investigation. It is noted that a common flash hider has been a cone or divergent section on the end of a barrel. By definition, a nozzle is a device to increase velocity while a diffuser is a device to decrease velocity. Preliminary investigation by Bernoulli's theorem would indicate that a divergent section is always a diffuser. However, Bernoulli's equation is determined by integration of Euler's equation in which density is constant; consequently, it is applicable for steady flow of an incompressible, nonviscous (ideal) fluid. This assumption, which is fundamental to classical hydrodynamics, will give only an approximation for compressible (real) fluids and then only at moderate velocities.

The effect of area variation of a flow passage on compressible flow is derived from the combinations of the differential equations of momentum and continuity, which is further simplified by expression in terms of Mach number. This rather complex mathematical combination (7) results in either of the two following forms and is directly applicable to the problems in a suppressor:

$$\frac{dA}{A} = \frac{dP}{\rho V^2}\left(1 - N_M^2\right) \qquad (1)$$

or

$$\frac{dA}{A} = \left(N_M^2 - 1\right)\frac{dV}{V} \qquad (2)$$

where: A = area of flow passage
P = fluid pressure
ρ = gas density
V = velocity
N_M = Mach number

From examination of equations 1 and 2, it is possible to formulate some conclusions of practical significance which indicate the radical difference between subsonic and supersonic flow. These are summarized schematically in Figure 3. The effects of area variation on compressible flow are seen to be exactly opposite for subsonic and supersonic flows. For the compressible flow to accelerate at supersonic velocity (nozzle), the flow passage must diverge. This divergence is necessary because, in supersonic flow of compressible (real) fluid, the decrease in fluid density is greater than the increase in flow velocity and the area of the flow passage must increase in order for the mass flow ($G = \rho VA$) to remain constant.

A constant mass flow is not a necessity in a weapon muzzle attachment since the work performed by the gas of accelerating the projectile is essentially complete. An interesting feature of compressible fluid flow in a convergent-divergent section is the phenomena of restricted or choked flow and is a function of the ratio of downstream pressure to upstream pressure. This pressure ratio, where the flow per unit area is a maximum, is called the critical pressure ratio and has a value for real gases of approximately 0.5. Figure 4 illustrates the flow phenomena in such a passage.

If the pressures at the inlet section and the discharge section are the same, the ratio is one and there is no flow as indicated by curve A. As the ratio decreases, either by P_1 increasing or P_2 decreasing, flow accelerates as shown by curve B. Curve C depicts flow when this pressure ratio is critical, and the flow is a maximum at the throat. Further reduction in the pressure ratio creates new flow conditions in the divergent section but the throat pressure ratio remains critical. Curves D, E, and F show the formation of a normal shock in the divergent section with an abrupt change to subsonic flow. Flow across the shock is nonisentopic with a finite pressure difference, and this type of condition is desirable for flow in the weapon muzzle device. Correct design of the divergent section will produce curve G in which flow continues to accelerate. The divergent section will then be a supersonic nozzle as described earlier but will be undesirable as a weapon muzzle attachment.

A rigorous mathematical analysis of the described flows becomes highly complex within the velocity and temperature ranges at a weapon muzzle. The discussion on gas flow presented here is predicated on a steady state flow condition which is far from that at the weapon muzzle where gas flow accelerates and decreases to zero within a few milliseconds. Added to this is boundary layer, heat transfer, and projectile effects; thus, conditions may be so chaotic as to defy precise theoretical analysis. The above considerations do supply some fundamental background upon which to base an intuitive approach to some empirical studies on flash and sound suppression explained in the following sections.

FLASH SUPPRESSOR EXPERIMENTS

As mentioned previously, renewed activity in flash suppressor development was created by excessive flash with several new lots of ammunition used in the M73 machine gun installed in the M60 tank. The M60 installation imposes a restriction in that any device longer than four inches attached to the weapon muzzle protrudes beyond the outer end of the mantlet tube, making it vulnerable to external damage. This factor influenced and somewhat hampered experiments because attempts were made to remain within a minimum envelope size.

Four lots of ammunition which produced excessive flash in tank tests at Aberdeen Proving Ground were test fired at the Springfield Armory using the M73 machine gun equipped with the current production flash hider (part #7792390). These lots were combat linked, that is, four ball rounds and one tracer round. Of the lots tested, lot number FAL 79085 produced the greatest flash frequency and was selected as the control ammunition to be used for further testing to help eliminate the many variables.

A problem which became evident early in testing was the one of flash evaluation. Much has been published (4, 8) concerning light intensity, duration, visible distance, and so forth. In the past, flash has been evaluated by photographing 1-, 10-, and 20- round bursts in a single picture. A one- round picture is satisfactory provided that the one round produces flash; however, 10- and 20-round burst pictures taken with the camera shutter open show a composite of all flashes with no frequency defintion. Movie cameras also present problems such as setup and development time. The scientific method is to measure, with photometric apparatus, the luminous intensity versus time providing total light energy in one or more flashes; however, this procedure requires additional exotic equipment. As a result, physical photometry is considered entirely satisfactory for the following reasons:

The objectionable secondary flash is a brilliant white flash which appears about six to 12 inches from the muzzle, and is approximately three feet long and 12 inches in diameter. Thus far, the occurrence or frequency of secondary flash has been completely random in nature. A weapon firing schedule was established at 150 rounds per minute. The normal gun rate of fire is approximately 600 rounds per minute; the gun is fired for four seconds and cooled for 11 seconds. In this four-second period, from 35 to 40 rounds are fired. The incidence of secondary flashing may be from none to several, but usually at a low enough rate to be counted visually. Since the secondary flash has been reasonably consistent in size with its characteristic brightness, a flash can be called a "flash" with no further definition. With this in mind, it is now possible to establish an "index of performance" for the suppressor tested. This is accomplished by dividing the number of rounds fired by the number of flashes observed, indicating the number of rounds per flash in any given test. A low index number indicates poor performance and a high index number indicates better flash suppression. Each test consisted of 300 rounds of ammunition. The first example of this index number is the cone type flash hider (part #7792390) used to select the control ammunition and is pictured in Figure 5. Its index number of 1.4 denotes that for the 300 rounds fired, there were 214 secondary flashes.

The bar or prong-type flash suppressor as first developed by the Franklin Institute (4) has been acclaimed successful on some weapons; consequently, it was decided to design and fabricate one with the recommended design criteria such as bar width, slot width and bore diameter. Its length was somewhat restricted because of the M60 tank installation limits but its slots were all outside the mantlet tube. It provided a marked improvement with an index of 5.4 (Figure 5).

A combination of the cone-type and bar-type flash suppressor was fabricated next by welding five bars in a cone section and extending the bars into the throat of the cone section as far as practical. Apparently this was a step in the wrong direction because the index dropped to 1.6 (Figure 5). A second model of this cone and bar type was made with a greater internal volume and the standard 300 round test proved the index to be 5.0 which was nearly identical to the bar type. Further experimentation with inserts at the base of the bars with different hole sizes to change entry conditions resulted in no improvement as the index varied from 2.3 to 3.1.

It became apparent during the preceding tests that no real progress was being made toward improving flash suppression on the M73 machine gun. A review of the literature and a study of gas flows described previously suggested a host of ideas and theories to be tried; however, the fabrication of individual items for experimentation would prove extremely costly and time consuming. A test fixture was devised which consists of a slotted sleeve to accommodate several inserts. These inserts can be changed, rearranged, and turned around to provide a wide variety of configurations similar to a "tinker toy" principle. Two M73 boosters (parts A and B), the sleeve (part C), and the many inserts are pictured in Figure 6. A total of 27 different configurations was used, firing 300 rounds for each test. A chronology of theories and tests follows.

Configurations A through D, Figure 7, were arranged to determine the effects of gradual lateral venting of the gun gases out the side of the fixture. If the gases are distributed over a larger area and mixed gradually with air, perhaps flash would be reduced; nevertheless, instead of one secondary flash down-range, there were four - one out each slot. Total light intensity of each flash was not reduced and their frequency is shown by the index numbers in Figure 7. A small amount of flash extended out the end of arrangements B and D and appeared to have very little forward velocity, indicating that the convergent section may be acting as a diffuser.

On the premise that a convergent section may act as a diffuser, configurations E through H were tested. Attempts were made to change the entry conditions with sleeves and baffles as shown in Figure 8. No improvement was noted, however, unit H provided some interesting data. Apparently the open section at the entry to the convergent section provided an air supply to support additional combustion because the unit created an exceptionally large flash on every round - an indication of what not to do. Configurations J through M, as shown in Figure 9, were assembled to test the effects of straight baffles and to provide greater internal volume for expansion and cooling before exit to the atmosphere. As a group they do show a great improvement in index number.

Configurations N through Q, as shown in Figure 10, comprised the next group tested to determine the results of a divergent section at the outer end. Note that these resemble the old cone-type hider but with various flow sections between the barrel exit and the outer divergent section. The results were very impressive with index numbers ranging from 25 to 100. If the entry conditions to this divergent section are correct, it can truly act as a diffuser. Configurations R and S were used to change these entry conditions to the terminal divergent cone and are shown in Figure 11. Unit S was outstanding with an index of 300, and unit T was assembled merely to show the contrast in performance. Unit U was tested to determine the effects of an interruption in the throat of the convergent-divergent section; however, performance was degraded far below that of unit S.

These tests indicate that the best configuration for mechanical flash suppression for the M73 weapon is one similar to configuration S. In reality, starting from the barrel exit, configuration S is a divergent-convergent-divergent flow passage which also performs the booster function. It is reasonably certain that entry conditions starting from the end of the barrel are supersonic since photographs taken during firing of a plain barrel show gases emerging with the projectile and actually preceding it for a short distance in flight, and this velocity has been estimated to be as high as 5,000 feet per second. With the available knowledge of fluid dynamics in both supersonic and subsonic regimes, together with an assumption of certain entry conditions to each change in flow passage, it is possible to prognosticate the gas behavior through the fixture. Curves showing hypothetical velocity and pressure distribution along the axis of configuration S are shown in Figure 12. The fixture is depicted as a diffuser throughout its length and the most speculative area is that between the barrel exit and point A. A series of normal shock fronts (nonisentropic flow) could cause the solid velocity line, or isentropic flow could cause the dotted velocity line. Of greatest importance is the transition from supersonic to subsonic flow at point B caused by the critical pressure ratio so that the outer divergent section is truly a subsonic diffuser. If this is reasonably correct, this type of flash suppressor will possess two of the desirable characteristics; namely, that of reducing gas velocity and reducing gas pressure.

SOUND SUPPRESSOR EXPERIMENTS

The desirable features of both flash and sound suppressors were discussed previously and experimental work conducted resulted in an improved method of flash suppression. A question now is: Will the same technique provide sound suppression?

From a literature and hardware survey, existing weapon silencers can be generally categorized into two types. One type is attached to the weapon muzzle, using essentially the same barrel dimensions as the original weapon configuration. This is shown as type A in Figure 13. This type is subdivided into a model with baffles, such as A_1, and one with absorbent materials, such as metal screens or glass wool, like A_2. A second type of silencer requires alteration of the existing barrel of a weapon. It is designed to use standard ammunition and to reduce the projectile velocity to, or below, sonic speed, thereby reducing both the muzzle gas-expansion noise and the projectile shock-wave sound. This is accomplished by bleeding off the gases before normal acceleration is complete and usually before propellant combustion is complete. This provided a greater sound reduction; however, exterior ballistic performance is sacrificed. Examples of this type are shown as B_1 and B_2 in Figure 13.

To investigate the feasibility of sound attenuation using the convergent-divergent flow passage, inserts were machined for use in the same tube used for Model A_2. These are shown as models C_1 and C_2 in Figure 13. In an effort to omit the sound created by a supersonic projectile, the .45 caliber M1911 cartridge was used in a special single-shot firing fixture for these tests. Testing was conducted on an outdoor range using a General Radio type 1151-C sound level meter at 10 meters to the right of the muzzle. A comparison of results is listed below. Sound pressure level of the unaltered weapon was 141 decibels (Db).

A_1	A_2	B_1	B_2	C_1	C_2
124 Db	119 Db	116 Db	114 Db	136 Db	132 Db

The above comparison indicates that the convergent-divergent passage will provide sound suppression without altering exterior ballistics but not as effectively as the absorbent material in unit A-2. To make another method of comparison, the sound pressure level may be converted to energy level (9) and will show that unit C_2 in attenuating from 141 Db to 132 Db produces an 87 per cent reduction in energy level. It is recognized that the above tests are rather brief; however, they do provide justification for additional investigation. Future work is planned to produce optimum volumes and cone angles and also to combine absorbent materials with the convergent-divergent feature.

CONCLUSION

This paper has presented the fundamental concepts of fluid flow on which to base theoretical and empirical studies in the use of weapon muzzle attachments used for flash and sound suppression. It presents the development of an improved flash suppressor for a given weapon and provides a chapter of experimental data to be added to the theoretical data published in the references. When research was initiated on this project, the paucity of published test data left the researcher with something to be desired, that is, the link between theory and reality. The paper further serves to illustrate the fact that here is a fertile field for future research in the field of fluid dynamics. As in most problem solutions, the most difficult portion is the definition of the problem itself. As discoveries continue along the theory of submerged jet flow, heat transfer, thermodynamic properties of propellants, and equations of state of gun gases, the many assumptions now being made during theoretical analysis will be replaced with fact and the area of transitional ballistics will become thoroughly defined. This will reduce the art of muzzle device development to a practical engineering science.

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GRAPHIC NOT REPRODUCIBLE

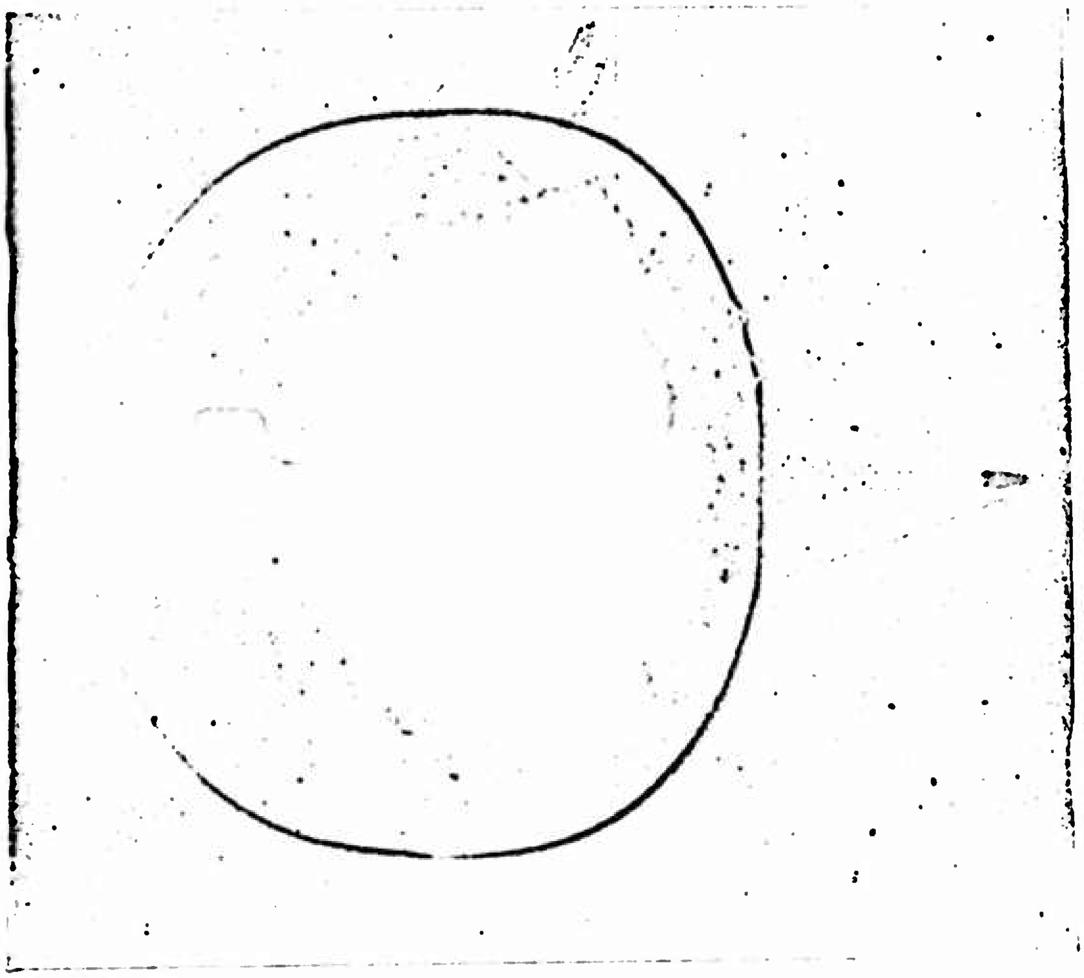

Figure 1. SCHLIEREN PHOTOGRAPH OF SHOCK WAVE

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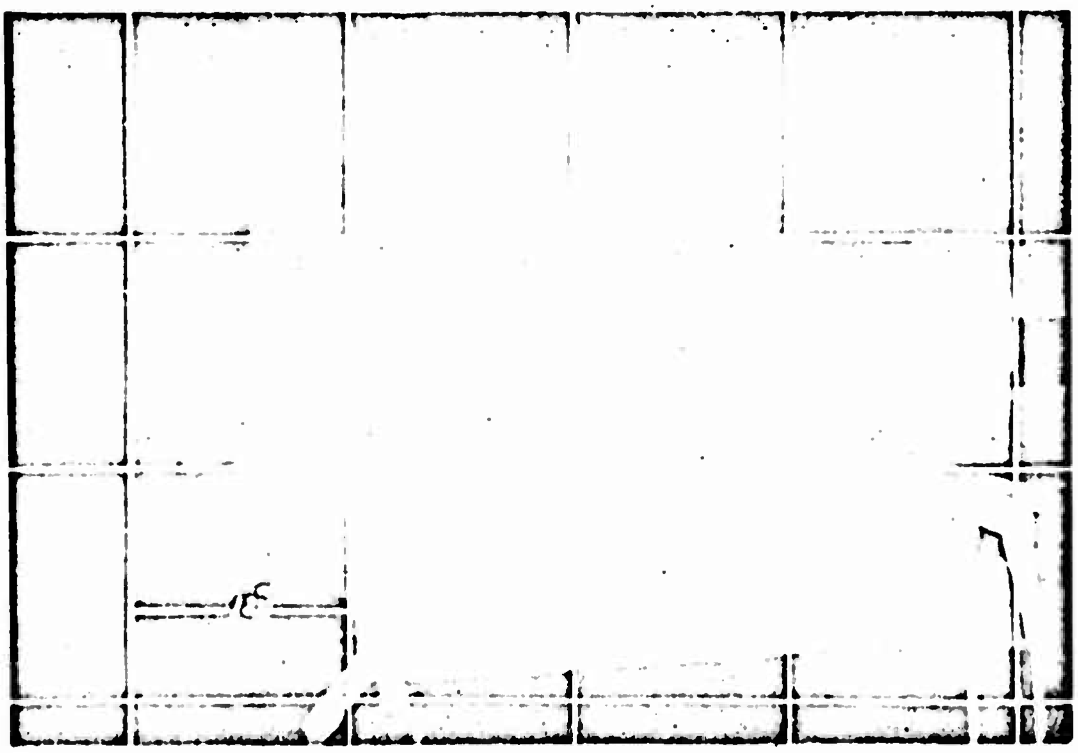
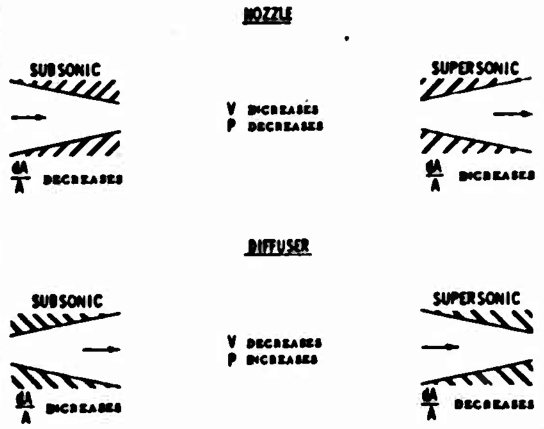
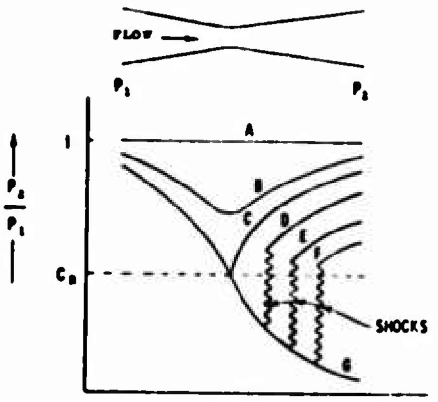


Figure 2. PHOTOGRAPH OF SECONDARY FLASH



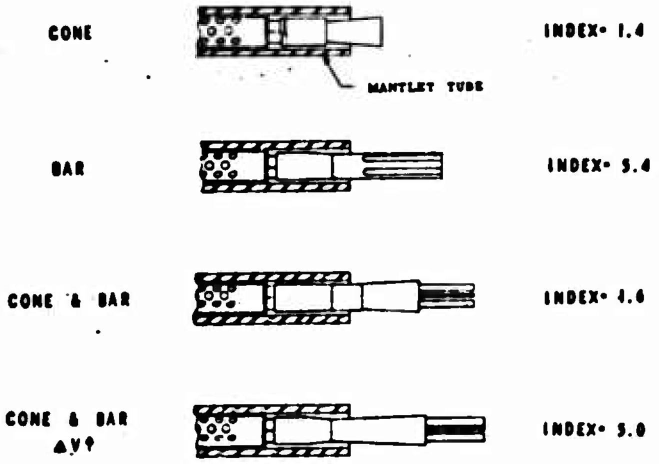
EFFECTS OF AREA VARIATION ON COMPRESSIBLE FLOW

Figure 3.



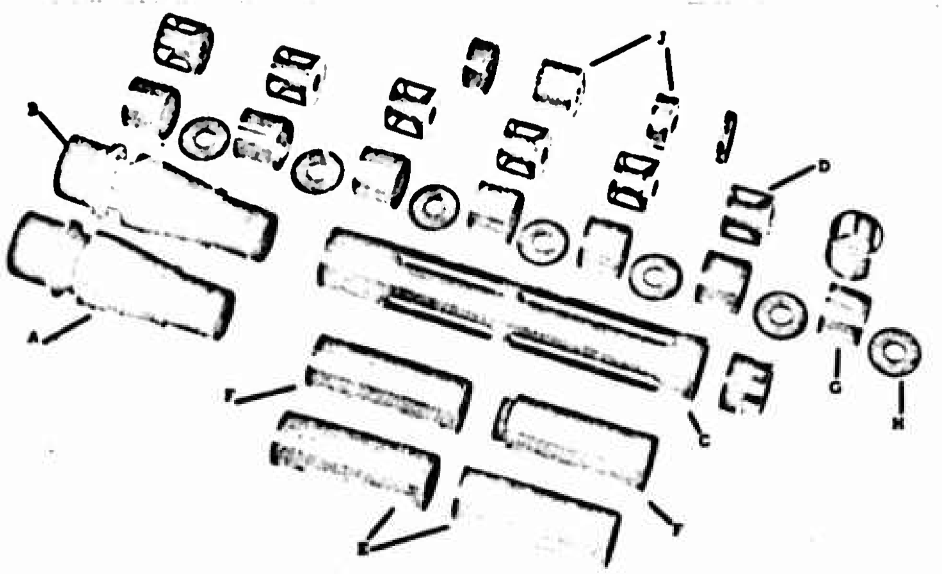
ONE-DIMENSIONAL COMPRESSIBLE FLOW IN A CONVERGENT-DIVERGENT PASSAGE

Figure 4.



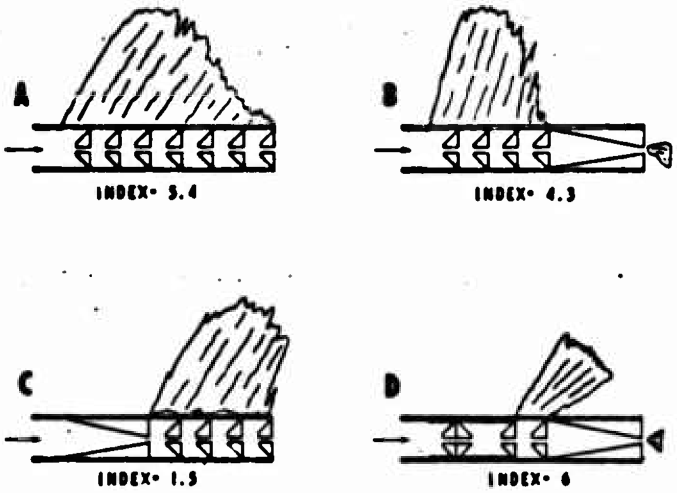
M 73 FLASH SUPPRESSORS — M 60 TANK

Figure 5.



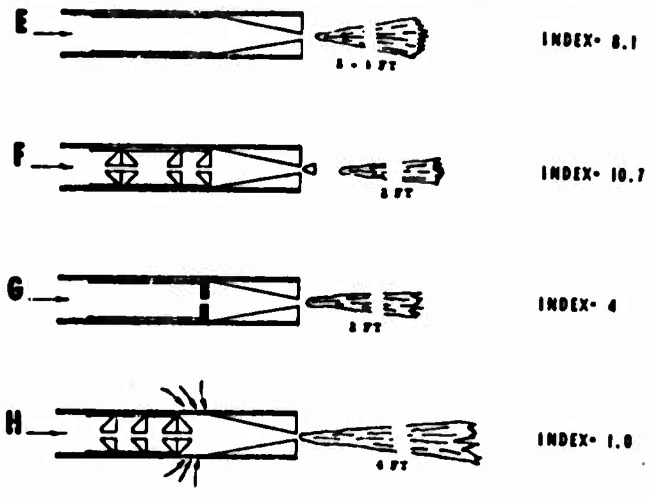
FLASH SUPPRESSOR TEST FIXTURE

Figure 6.



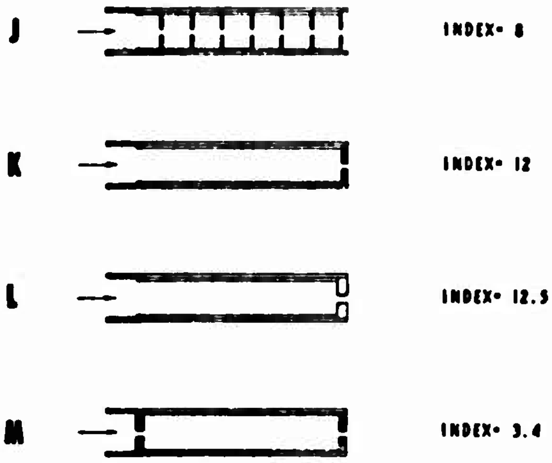
FLASH SUPPRESSOR TEST FIXTURE PROFILES

Figure 7.



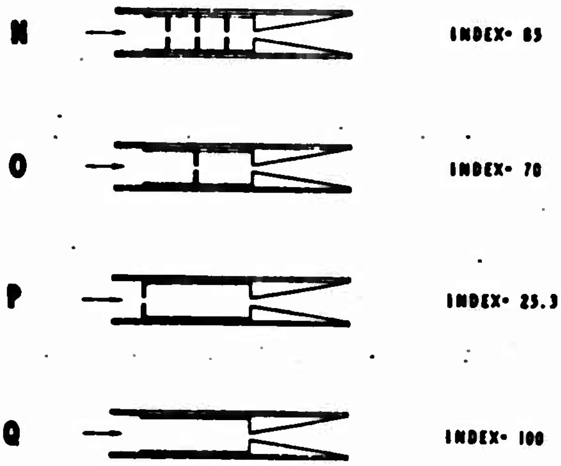
FLASH SUPPRESSOR TEST FIXTURE PROFILES

Figure 8.



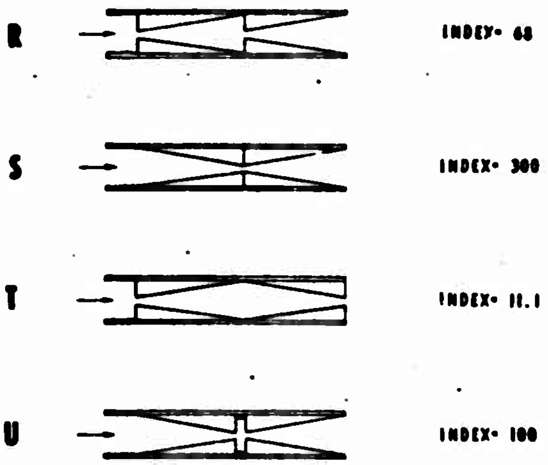
FLASH SUPPRESSOR TEST FIXTURE PROFILES

Figure 9.



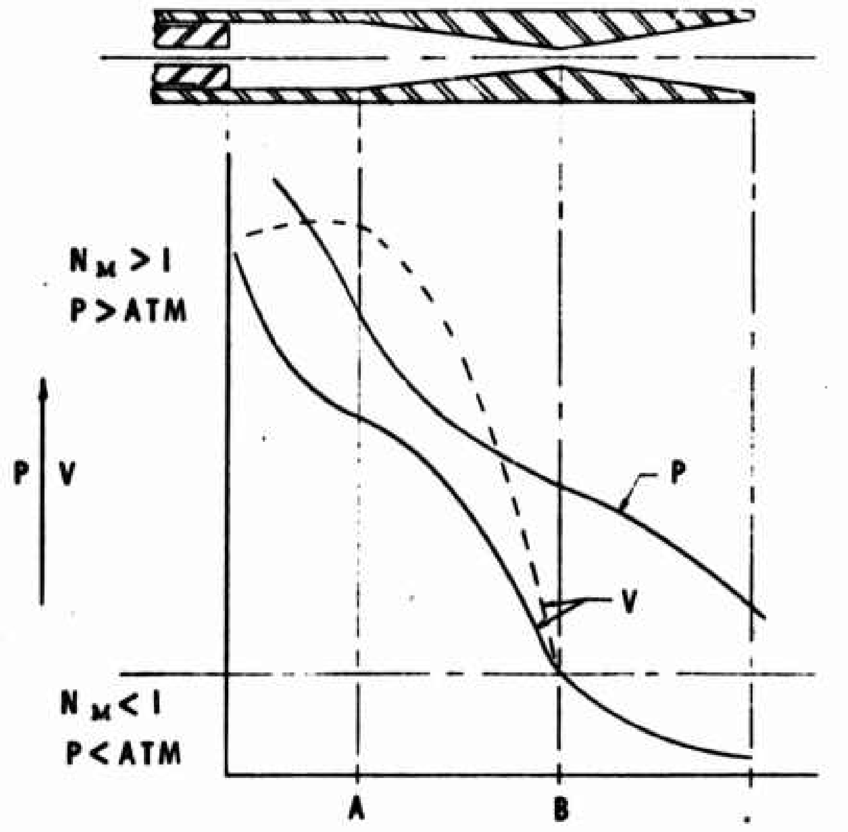
FLASH SUPPRESSOR TEST FIXTURE PROFILES

Figure 10.



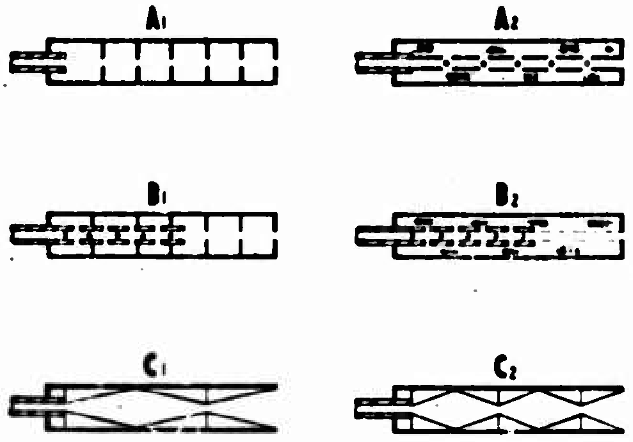
FLASH SUPPRESSOR TEST FIXTURE PROFILES

Figure 11.



THEORETICAL VELOCITY AND PRESSURE DISTRIBUTION ALONG AXIS OF CONFIGURATION "S"

Figure 12.



SOUND SUPPRESSOR CONFIGURATIONS

Figure 13.