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A PARAMETRIC STUDY OF A 40-MM AIR DEFENSE GUN USING CONVENTIONAL AND TRAVELING CHARGE PROPELLANT

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Work is proceeding on a project which will use the traveling charge effect to enhance the muzzle velocity of guns used in the air defense role. In such guns increasing the muzzle velocity offers two advantages: the time of flight of the projectile is reduced, increasing the likelihood of impacting a highly mobile target; and the terminal velocity is increased, increasing the likelihood of penetration and destruction of the target. A desirable air defense gun would have a 40-mm bore and be 100 calibers long. This gun should be capable of launching a 700 gram HE warhead at 2 km/sec, maximum pressure 544 MPa; and a 160 gram saboted KE penetrator at 3 km/sec, maximum pressure 680 MPa.

Using a 1-D traveling charge gun code, parametric studies were conducted with the above two projectile configurations in which the propelling charge configuration was varied from an all granular (7 perforated) booster charge to an all traveling charge. Web →

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and charge weight for the booster charge and ignition delay for the traveling charge were varied to get the highest muzzle velocity for that configuration with the maximum pressure constraint. Thermodynamic constants for both booster and traveling charge propellant were held the same; these values representing a composite of some experimentally produced traveling charge propellants. Realistic values for energy losses in the model gun were chosen from the values used in the modeling of earlier traveling charge gun firings. The results obtained indicate that use of the traveling charge represents an 18.6% increase in muzzle velocity for the 700-g projectile and 13.5% increase in muzzle velocity for the 160-g projectile over that for the conventional granular charge.

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I. INTRODUCTION

Work is being conducted on a project which will use the traveling charge effect to enhance the muzzle velocity of guns used in the forward air defense role. In the air defense application, projectile time-of-flight is a major controlling parameter in the estimation of hit probabilities for rapidly maneuvering targets. Studies have shown that increasing the muzzle velocity from 1 km/s to 2 or 3 km/s has substantial benefits in overall system effectiveness. Another benefit of higher muzzle velocity in an air defense weapon is that the terminal impact velocity is increased, increasing the likelihood of penetration and destruction of the target.

Weapon system studies have indicated the following characteristics for an improved air defense weapon:

Table 1. Air Defense Weapons

Bore Dia. mm	Bore Length cal	Projectile Weight gm	Projectile Type	Max. Chamber Pressure MPa	Muzzle Velocity km/s
40	100	160	KE	689	3.
40	100	700	KE	552	2.
40	62	960	HE	319	1.005

The last line in Table 1 is the L/70 Bolfers air defense weapon shown here with the other two improved air defense weapons.

In traveling charge gun propulsion, thrust and gas pressure from a fast burning propellant grain attached to the projectile accelerates the projectile-propellant system in a gun barrel. Typically, a traveling charge/projectile combination is initially accelerated by a conventional booster charge which also serves to ignite the traveling charge after the chamber is pressurized to the desired level. In order for the burning process to be completed before the projectile reaches muzzle exit, very high effective burning rates two to three orders of magnitude greater than typical propellants are required.

The localized, high solid-to-gas conversion rates result in substantial impulse forces at the gas/solid interface. It is the combined impulse loading and localized gas pressure near the projectile that results in increased efficiency when compared with conventional gun propulsion, which suffers from increasing energy losses at very high muzzle velocities.

Under idealized circumstances the burning of the traveling charge grain is tailored to provide nearly constant force to the base of the grain and thus to the base of the projectile until burnout of the propellant is reached. The propellant energy is delivered where needed, namely near the base of the projectile. A traveling charge gun, therefore, does not exhibit the pressure gradient limitation characteristic of the conventional solid propellant gun. This results in muzzle velocities higher than those which can be obtained using conventional gun propellant technology. A detailed discussion of the theory and characteristics of the traveling charge gun concept is given in reference 1.

The purpose of the current study is to evaluate the use of a gun in which both conventional granular propellant and traveling charge propellant is used. Earlier simulations of the traveling charge gun computer code[2] were restricted to cases in which the traveling charge was used alone. Recent enhancements[3] to the computer program have now allowed us to simulate the use of a granular "booster" propellant placed between the breech face and the base of the traveling charge grain. The purpose of this booster charge is to rapidly pressurize the chamber, ignite the traveling charge, and provide an initial velocity to the traveling charge-projectile combination prior to the development of a full thrust from the traveling charge grain. This is illustrated in Figure 1. In the parametric study with the two improved air defense weapon concepts, we evaluated propellant charge configurations ranging from an all-booster charge to an all-traveling charge with three intermediate combinations. The objective was to determine the optimum combination of a booster charge and a traveling charge which gives the highest muzzle velocity.

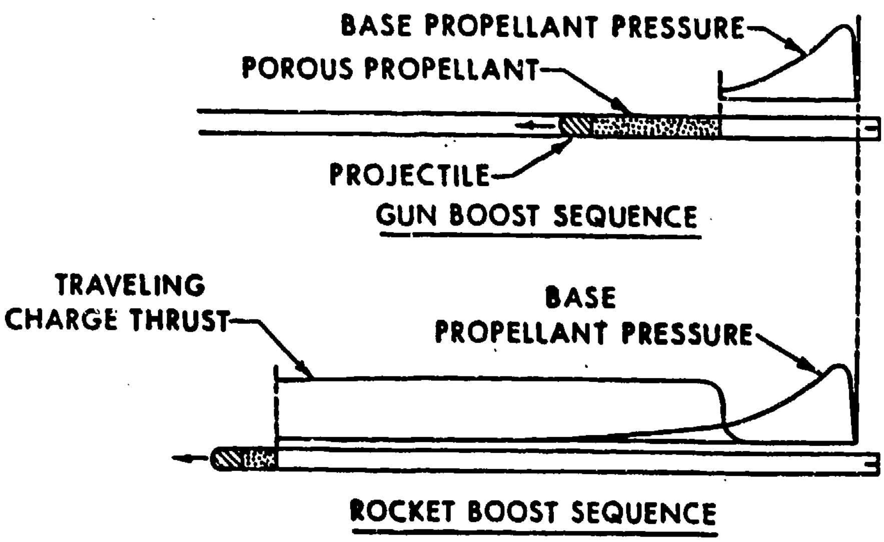

Figure 1. Sequence of Operation Traveling Charge Gun

II. BASIC ASSUMPTIONS

Certain basic assumptions were made prior to making the parametric simulation, in order to restrict the number of computer simulations and to provide a set of rules under which the simulations were to be made. The assumptions are:

1. The booster propellant will have the same chemical thermodynamic properties as the traveling charge propellant to avoid making simulations in which the booster propellant would have either higher or lower chemical energy than the traveling charge propellant. The thermodynamic values chosen represent a composite of thermodynamic values for a number of experimentally produced very-high-burning-rate (VHBR) traveling charge propellants. The values chosen are given in Table 2, where they are compared with that of the NC 1066 propellant used in the L/70 Bolfers air defense weapon.

Table 2. Thermodynamic Properties of Booster, Traveling Charge, and Bolfers NC 1066 Propellants

			Booster and Traveling Charge	Bolfers NC 1066
Impetus	Joules/g	:	1076	989
Chemical Energy	Joules/g	:	4304	4007
Specific Heat Ratio		:	1.25	1.247
Covolume	cc/g	:	1.189	1.042
Flame Temperature	^{o}K	:	2511	2827
Molecular Weight	mole/g	:	19.4	23.8

2. The booster propellant will use a 7 perforated propellant grain with a length-to-diameter ratio of 2.4 and an outside-diameter-to perforation-diameter ratio of 8.6. These ratios represent the grain dimension ratios for the propellant used in the 105-mm M68 tank cannon.

3. The burning rate used for the booster will be for the M9 propellant with a burning rate coefficient of 0.348 cm/s-MPa and a burning rate exponent of 0.865.

4. The propellant chamber lengths and volumes will be held constant for all combinations of booster and traveling charge propellants. The values chosen together with the expansion ratios based on a 4 m barrel are given in Table 3:

Table 3. Chamber Lengths, Volumes, and Expansion Ratios

Projectile Weight gm	Chamber Length cm	Chamber Volume cc	Expansion Ratios
160	35.37	444.5	12.31
700	64.30	808.0	7.22

Earlier simulations had been run using the traveling charge gun code to determine the amount of traveling charge propellant, which when used alone, would be necessary to accelerate an 160 g projectile to about 3 km/s and an 700 g projectile to about 2 km/s. These chamber lengths and volumes were chosen from these earlier simulations as being necessary to contain the initial weight of the traveling charge propellant.

No attempt was made to optimize the chamber volume for the booster only case. It will be noted that the expansion ratio, defined as the ratio of tube volume to chamber volume, for the 700 gm projectile case is close to an expansion ratio value of 7.57 for the 105-mm M68 cannon; thus the chamber volume for the 700 gm projectile case is close to an optimum booster only chamber volume. The expansion ratio value of 12.31 for the 160 gm projectile case is large compared to the 105-mm value indicating that the barrel is longer than necessary if one was firing the booster only propellant.

5. The maximum projectile travel, based on the motion of projectile base, was fixed at 100 calibers (4 m) in the 40-mm gun.

6. The gun energy losses and initial conditions would be the same for all combinations of booster and traveling charge propellant. These energy losses were based on simulations used to match predictions to experimental 40-mm traveling charge firing results. The energy losses and initial conditions assumed are:

a. Air shock build up ahead of projectile.
b. Projectile shot-start pressure is 6.89 MPa.
c. Bore Friction Resistance:

Projectile Travel cm	Resistance Pressure MPa
0.	5.52
1.27	3.45
400	3.45

d. Heat loss from barrel with barrel temperature of 300 K.

e. Traveling charge propellant is assumed to be compressible with a density of 1.29 g/cc and a sound velocity of 3 km/s.

III. PROCEDURE

Two gun interior ballistic models were used for these simulations: the 1-D traveling charge gun model[2] and a conventional gun model.[4] The conventional gun model obtains a solution by integrating ordinary differential equations in contrast to the integration of the partial differential equations used in the 1-D traveling charge gun model. The difference in the Cyber 76 computer time necessary to simulate a complete interior ballistic trajectory is large: about 0.2 seconds for the conventional gun model and about 30 seconds for the 1-D traveling charge gun model. Due to the difference in computer time, the conventional gun code was used as much as possible to obtain estimates of the propellant weights and web sizes. The 1-D traveling charge code was then used with the best charge weight and web estimates adjusted to obtain the final interior ballistic trajectory results.

The detailed procedure is as follows:

1. The booster-only simulations were run using the conventional gun code with propellant weight and web being varied so that the desired maximum pressure was attained (680 MPa for 160 g projectile and 544 MPa for the 700 g projectile) and that propellant burnout occurred at a time close to projectile exit from the muzzle. This condition represents the maximum muzzle velocity attainable.

2. The best estimates of charges and webs were then used in the 1-D traveling charge gun code, operating in the booster-only mode. This resulted in about a 30% drop in maximum pressure and an increased muzzle velocity of about 3%, an indication of a reduced pressure gradient in the 1-D model. Small adjustments were then made in charge weight and web until the maximum muzzle velocity was obtained, maintaining the desired maximum breech pressure.

3. The traveling-charge-only simulations were run on the 1-D traveling charge gun code. It was established that the 160 g projectile required 514 g of propellant of which 23 g were needed to initially pressurize the chamber to 680 MPa. The 700 g projectile required 980 g of propellant of which 20 g was needed to initially pressurize the chamber to 544 MPa. It was assumed that once the traveling charge propellant started to burn, the traveling charge propellant burning rate could be tailored such that the flow would keep a constant force on the base of the propellant until the velocity of the flow reached a Mach level of 0.999. After that, the burning rate of the propellant would be tailored to keep the Mach level constant even though the force on the propellant

base would decrease. This would continue until propellant burnout; tailoring the burnout to occur about one caliber of travel prior to projection muzzle ejection. The force level for the 160 g projectile was maintained at a level corresponding to the design pressure of 680 MPa and for the 700 g projectile at 544 MPa.

4. The traveling charge propellant remaining (491 g for the 160 g projectile and 960 g for the 700 g projectile) was divided by four to give three intermediate cases:

   a. Booster propellant plus 1/4 of traveling charge.
   b. Booster propellant plus 1/2 of traveling charge.
   c. Booster propellant plus 3/4 of traveling charge.

5. Using the conventional gun code and assuming that the projectile and the fraction of the traveling charge represented an inert mass, we determined the booster propellant weight and web necessary to get the highest possible velocity at the projectile travel position of maximum breech pressure. The initial chamber volume occupied by the booster propellant was computed from the total chamber volume minus the volume occupied by the traveling charge propellant.

6. The 1-D traveling charge gun code was run for each of the booster-traveling charge combinations using the booster propellant weight and web size estimates provided by the previous step. Booster propellant weight, web size, and a new parameter, ignition delay time for the traveling charge propellant, were varied until the maximum muzzle velocity was reached for each of the cases, keeping the maximum pressure within the design constraints.

7. All of the muzzle velocity results from each of the intermediate cases were compared to the booster-only and the traveling-charge-only cases to see if any booster-traveling charge combination attained a higher velocity than either the booster alone or the traveling charge alone.

IV. RESULTS

The final results of this study are shown in Table 4 and Figures 2 and 3. The summary of the results for all the parametric cases is given in Table 4. In the first four columns are the weights of the traveling charge and the booster propellant used, the web of the booster propellant, and the ignition delay of the traveling charge. The next two columns give the maximum pressure attained in the gun and the muzzle velocity. The last three columns give the ratio of the total propellant (booster and traveling charge) weight to the projectile weight (C/M), the percentage increase in muzzle velocity relative to the muzzle velocity of the booster-only case, and the percentage increase in projectile kinetic energy at the muzzle relative to the projectile kinetic energy of the booster-only case.

TABLE 4. Booster and Traveling Charge Parametric Series Summary

40 mm Gun 100 calibers long
700 g Projectile

Run	TC Weight gm	Booster Weight gm	Booster web mm	TC Ign. Delay ms	Maximum Pressure MPa	Muzzle Velocity m/s	C/M	% Vel	%KE	Thermo. Eff.
Booster Only	-	725.0	2.46	-	550.6	1547	1.037	0.0	0.0	0.2678
1/4 TC	240.0	612.3	2.71	5.6	553.4	1802	1.218	16.47	35.66	0.3094
1/2 TC	480.0	428.2	2.44	4.7	550.6	1914	1.297	23.74	53.12	0.3278
3/4 TC	719.8	277.0	2.33	3.2	551.2	1958	1.424	26.56	60.18	0.3124
All TC	959.8	20.5*	-	0.0	551.6	1981	1.400	28.06	63.99	0.3252

160 g Projectile

Run	TC Weight gm	Booster Weight gm	Booster web mm	TC Ign. Delay ms	Maximum Pressure MPa	Muzzle Velocity m/s	C/M	% Vel	%KE	Thermo. Eff.
Booster Only	-	424.3	0.99	-	687.9	2345	2.655	0.0	0.0	0.2406
1/4 TC	122.8	317.0	0.98	2.6	684.7	2681	2.749	14.34	30.73	0.3034
1/2 TC	245.6	241.6	1.00	2.0	688.3	2872	3.046	22.46	49.97	0.3143
3/4 TC	368.4	153.3	0.87	1.4	689.0	2933	3.261	25.09	56.47	0.3062
ALL TC	491.2	23.2*	-	0.0	689.5	2894	3.216	23.42	52.33	0.3023

* Booster all burned at beginning of motion.

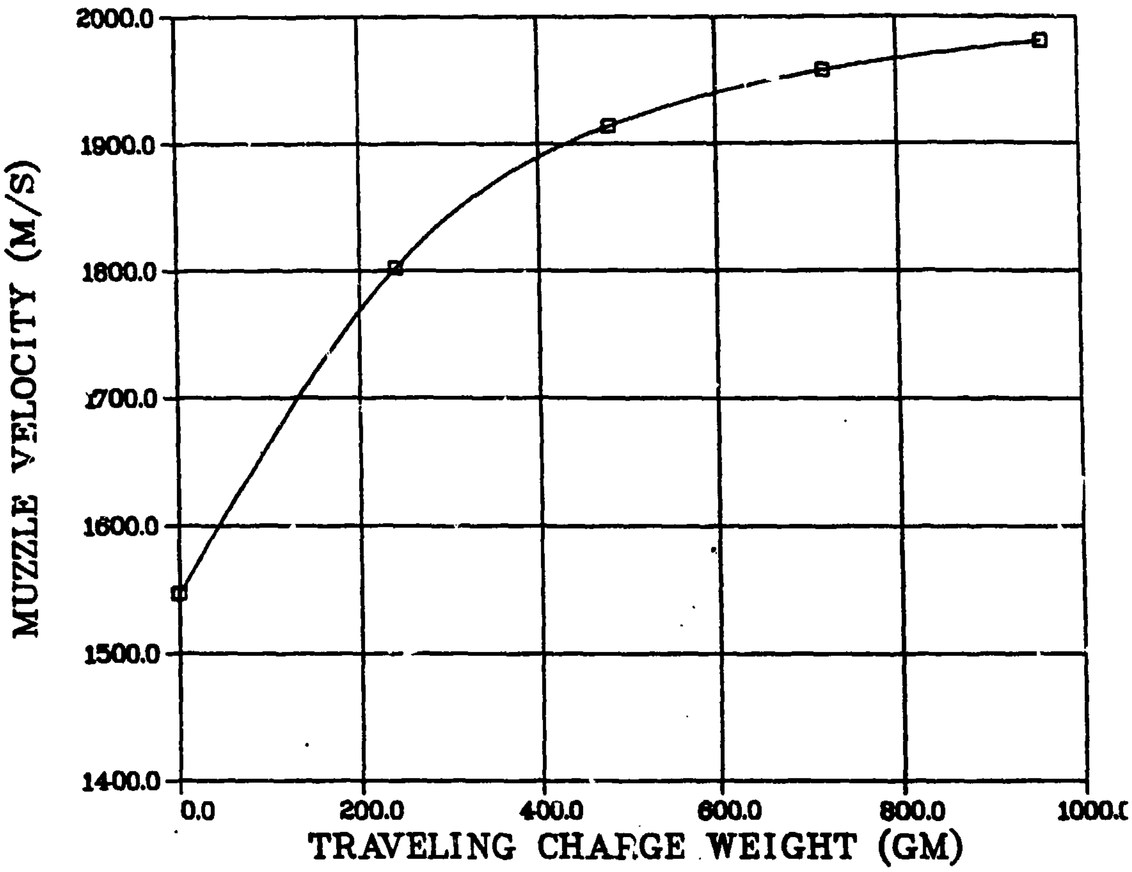

Figure 2. Optimum Muzzle Velocity Versus Traveling Charge Weight for the 40 mm Gun Using the 700 g Projectile.

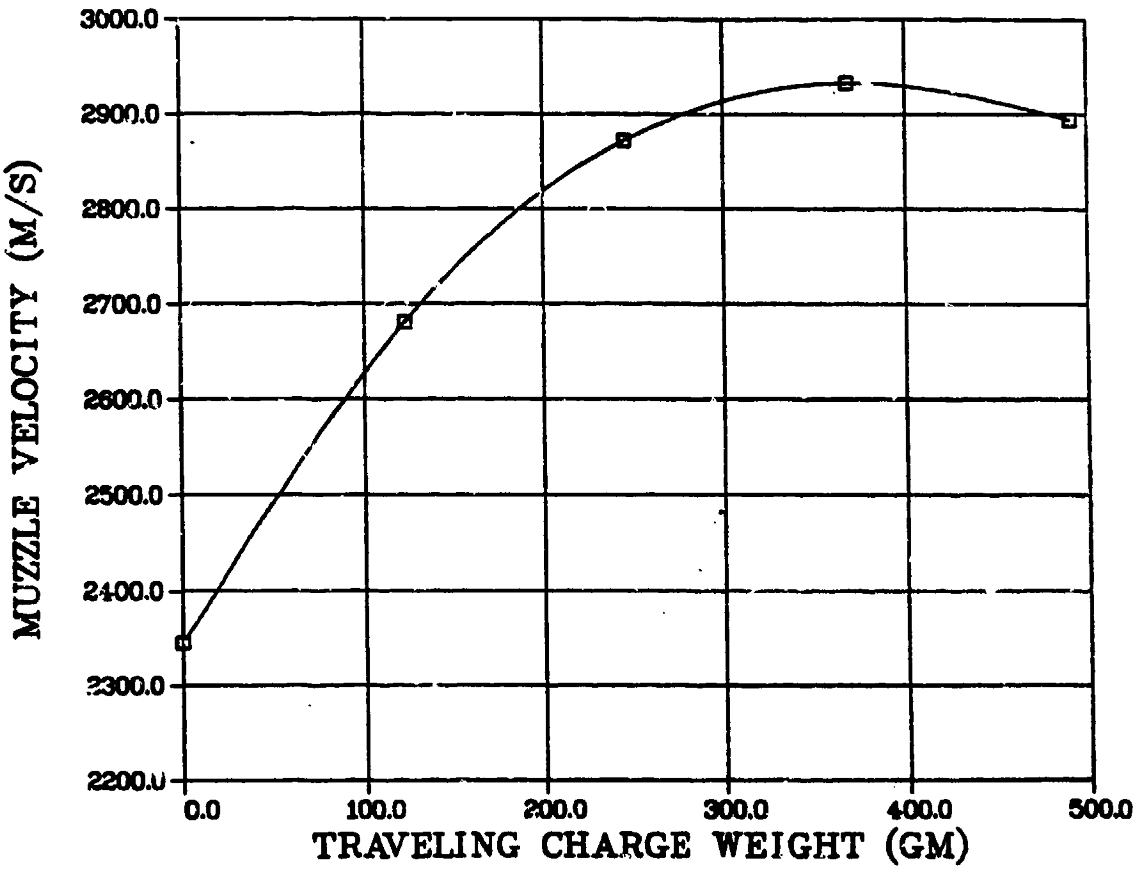

Figure 3. Optimum Muzzle Velocity Versus Traveling Charge Weight for the 40 mm Gun Using the 160 g Projectile.

For the cases using the 700 g projectile, the muzzle velocity increased from 1547 m/s for the booster-only case to 1981 m/s for the all-traveling-charge case. This represents an increase of 28.06% in muzzle velocity and an increase of 63.99% in projectile kinetic energy over that of the booster-only case. For the cases using the 160 g projectile, the muzzle velocity increased from 2345 m/s for the booster-only case to 2933 m/s for the booster-plus-3/4-traveling-charge case. The all-traveling-charge case had a muzzle velocity of 2894 m/s representing a decrease of 1.67% in muzzle velocity from the maximum value. The maximum percentage increase in muzzle velocity over that of the booster-only case was 25.09% and the maximum percentage increase in projectile kinetic energy was 56.47%.

It will be noted that there is an increase in the C/M ratio as more of the traveling charge is used both for the 700 g and the 160 g projectile cases. For a given projectile weight, this represents an increase in total propellant weight which can be loaded into the fixed chamber volume (808 cc for the 700 g projectile and 444.5 cc for the 160 g projectile) and be completely burned prior to projectile exit from the gun. More propellant, either booster or traveling charge, can be added to the chamber, but maintaining the peak pressures at the maximum values (689 MPa for the 160 g projectile and 552 MPa for the 700 g projectile) will result in propellant being thrown out of the gun unburnt. Therefore, some of the muzzle velocity increase is due to the increased weight of propellant which can be burned in the gun, but part is due to the thrust from the burning of the traveling charge being imparted to the projectile. We can check this by computing the ratio of the projectile kinetic energy at the muzzle to the total propellant chemical energy, that is, the thermodynamic efficiency of the gun. This is shown in the last column of Table 4. For the booster-only case the thermodynamic efficiency is 0.268 for the 700 g projectile and 0.241 for the 160 g projectile. Use of the traveling charge increases the efficiencies to values ranging from 0.303 to 0.328 thus indicating that the thrust from the burning of the traveling charge will increase the thermodynamic efficiency and thus the gun muzzle velocity.

The muzzle velocity versus weight of the traveling charge is plotted for the cases using the 700 g projectile in Figure 2 and for the cases using the 160 g projectile in Figure 3. It can be seen that the greatest change in muzzle velocity using the traveling charge is for the 1/4- and 1/2-traveling-charge cases. The use of the 3/4-traveling charge or the all-traveling charge case causes less of an increase in muzzle velocity.

A representative interior ballistic trajectory for a booster-plus-traveling-charge case is shown in Figure 4. This is a booster propellant plus 3/4 of the traveling charge for the 160 g projectile case. Plotted is breech pressure, stress pressure, and projectile velocity versus projectile travel. Stress pressure is defined as the force acting on the end of the traveling charge propellant divided by the bore area. This force is the sum of two components: the force due to the thrust produced by the rapid burning of the traveling charge and the force due to the gas pressure at the base of the traveling charge grain. It will be noted that the stress pressure is equal to the projectile base pressure of a normal interior ballistic trajectory until the traveling charge is ignited at 1.4 ms, corresponding to a projectile travel of 0.30 m. After traveling charge ignition, the stress pressure rapidly increases to the maximum pressure value of 68^ MPa and maintains that value to a projectile travel location of 0.8 m, after which the stress pressure decreases due to the traveling charge burning rate being tailored to keep the gas velocity Mach limit at 0.999. Traveling charge burnout occurs at 3.90 m of travel, this being indicated by a sharp reduction in stress pressure caused by the termination of the thrust.

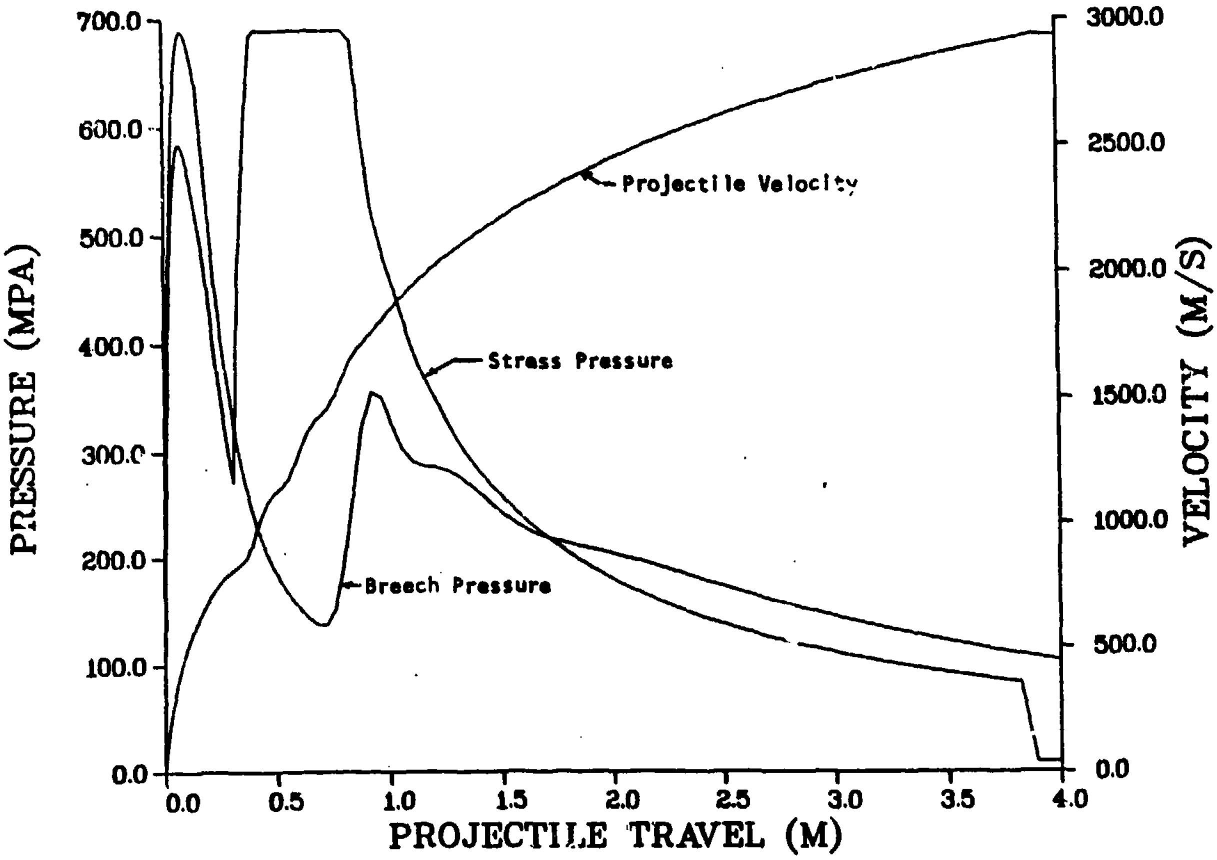

Figure 4. Interior Ballistic Trajectory for 40 mm Gun with 160 g Projectile for Booster Plus 3/4 Traveling Charge Arrangement

The interior ballistic trajectory of Figure 4 can be contrasted with that due to the traveling charge burning with only enough booster propellant being used to pressurize the chamber to a shot-start pressure of 689 MPa for the 160 g projectile case. This is shown in Figure 5. The stress pressure curve for this case shows the maximum stress pressure being maintained up to a projectile travel of 0.71 m followed by a decay in pressure as the burning rate is tailored to meet the gas velocity Mach limit.

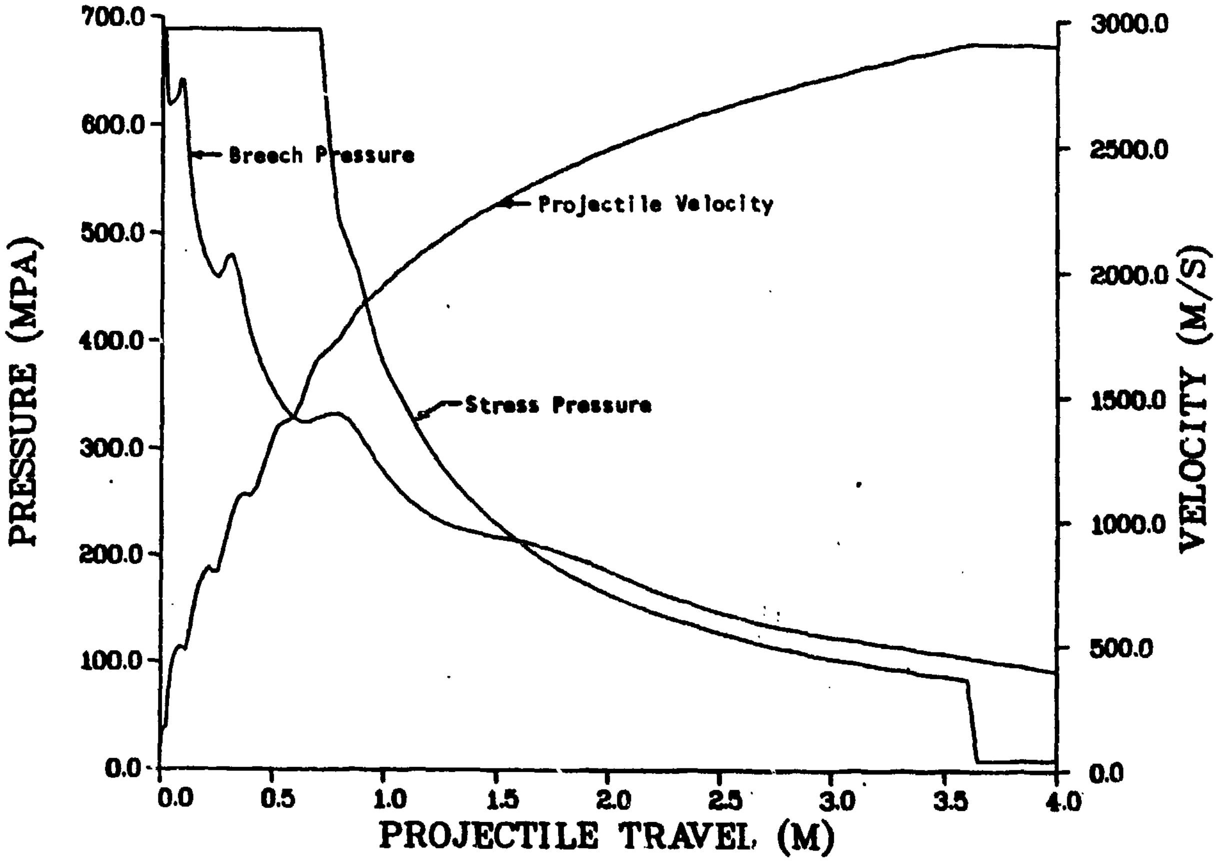

Figure 5. Interior Ballistic Trajectory for 40 mm Gun with 160 g Projectile for an All Traveling Charge Arrangement.

V. DISCUSSION AND CONCLUSIONS

The results given in Table 4 indicate that using a traveling charge and a granular booster charge will produce a significant increase in muzzle velocity over that of using a granular charge only. Increases of up to 28% in muzzle velocity for the 700 g projectile case and up to 25% for the 160 g projectile case are noted. For the cases using the 700 g projectile, all combinations of booster and traveling charge propellant arrangements gave less muzzle velocity than the traveling charge used alone. For the cases using the 160 g projectile, an optimum arrangement of booster propellant plus 3/4 of the traveling charge gave the maximum velocity. The reduction in velocity from 2933 m/s for the 3/4 TC case to 2894 m/s for the all TC case is caused by a reduction in burnout position for the all TC case. Comparing Figures 4 and 5, the burnout position for the 3/4 TC case, as indicated by the discontinuous reduction in stress pressure, occurs at 3.90 m of projectile travel, where as for the all TC case the burnout occurs at 3.65 m of projectile travel.

The implication of these results on the design of an air defense weapon is that for chamber-volume-limited problems where one desires to increase the muzzle velocity of an existing weapon, addition of relatively small amounts of a traveling charge (such as 28% of the total charge in the 1/4 traveling charge case using the 700 g projectile) can give a 16.5% increase in muzzle velocity if can meet burning requirements and tailor burn curve. More increase will occur as one increases the proportion of the traveling charge to the granular booster charge.

Some consideration should be given to the maximum pressure applied to the various sections of the barrel as the amount of the traveling charge is increased. However, even for the 3/4-traveling-charge case using the 160 g projectile only about 0.8 m of a 4 m long barrel is subjected to the maximum pressure of 689 MPa. This is contrasted to a booster-only case where 0.35 m of the barrel is subjected to the maximum pressure of 689 MPa. For this reason, barrels using the booster-plus-traveling-charge arrangement would be somewhat heavier.

A major problem which will have to be addressed before one can use the traveling charge principle in an air defense weapon is being able to tailor the traveling charge burning rate so that the desired stress pressure-projectile travel trajectory is attained. One procedure would be to cement traveling charge propellant segments together, each segment having differing burning rate properties, which when burned would produce some approximation to the desired stress pressure-projectile travel curve. A current project in the Interior Ballistic Division is the evaluation of this procedure using experimental traveling charge propellant with known burning rate characteristics.

Other problems involved in the use of the traveling charge propellants such as safety, mechanical properties, etc. have been discussed earlier[1] and will not be repeated here.

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