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DESIGN OPTIMIZATION FOR A HIGH PERFORMANCE REGENERATIVE LIQUID PROPELLANT GUN

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The regenerative liquid propellant gun (RLPG) concept offers a possible replacement for solid propellant (SP) cannons on future battle tanks. The current 120-mm gun using JA2 granular propellant develops a maximum pressure of 519 MPa and accelerates a 7.12 kg projectile to 1670 m/s in a projectile travel of 4.75 m. The advantages of the RLPG relative to the equivalent SP gun are: (1) more ammunition storage aboard the tank; (2) mechanical control of injection which results in a flat-topped pressure-time curve and thus a higher muzzle velocity for a given maximum pressure; and (3) no secondary muzzle flash. The disadvantages include greater mechanical complexity and higher maximum breech pressures (in the liquid reservoir) than in the SP case.

Simulation studies have been made of a high performance 120-mm RLPG tank cannon. The ground rules used in the study are: (1) maximum projectile travel of 6.3 m; (2) maximum liquid pressure of 700 MPa; (3) maximum combustion pressure of about 500 MPa; and (4)

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constant injection area. Three liquid propellants were considered; hydroxyl ammonium nitrate (HAN) propellants LGP1845 and LGP1846; and a hypothetical "liquid" JA2 propellant. The in-bore projectile mass was varied from 5 to 13 kg. The results show that a high performance RLPG tank gun providesa muzzle velocity equivalent to that of a comparable SP gun. (Keywords:) →

Initial studies were performed on the effect of substituting a 140-mm gun for the present 120-mm gun. Only small increases in performance were obtained.

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I. INTRODUCTION

The regenerative liquid propellant (RLPG) gun concept offers a possible replacement for solid propellant cannons on future battle tanks. The current 120-mm solid propellant (SP) gun using JA2 granular propellant develops a maximum pressure of 519 MPa and accelerates a 7.12 kg projectile to 1670 m/s in a projectile travel of 4.75 m. The advantages of the RLPG relative to the equivalent SP gun are:

a. More ammunition can be stored aboard the tank. The liquid propellant occupies significantly less space than does the equivalent solid propellant charges. This results in an increase in the number of rounds from 40 to 56.[1]

b. Mechanical control of the rate of injection of liquid propellant into the gun combustion chamber can be used to shape the pressure-time curve. Optimum control will result in a flat-topped pressure-time curve and a higher muzzle velocity for a given maximum chamber pressure.

c. There is no secondary muzzle flash, since liquid propellant combustion products will not react with air.[2]

The disadvantages of the RLPG are:

a. Greater mechanical complexity, because of the presence of a regenerative propellant injection mechanism in the breech of the gun.

b. Higher breech pressures because of the hydraulic differential pressure needed to inject the liquid into the combustion chamber. This can amount to a pressure increase of about 200 MPa, requiring a heavier gun.

In this study we investigate the ballistic performance of a conceptual 120-mm RLPG in comparison with an equivalent solid propellant system. Both SP and RLPG interior ballistic simulation models were used in this study to evaluate ballistic performance and to provide guidelines for the design of such a gun.

This interior ballistics study was performed as part of a more detailed systems study investigating the application of the RLPG in a tank.[1] Figures 1 and 2 from that study show a cutaway view of the conceptual RLPG tank cannon mounted in the modified M1A1 vehicle and an external view of the RLPG cannon.

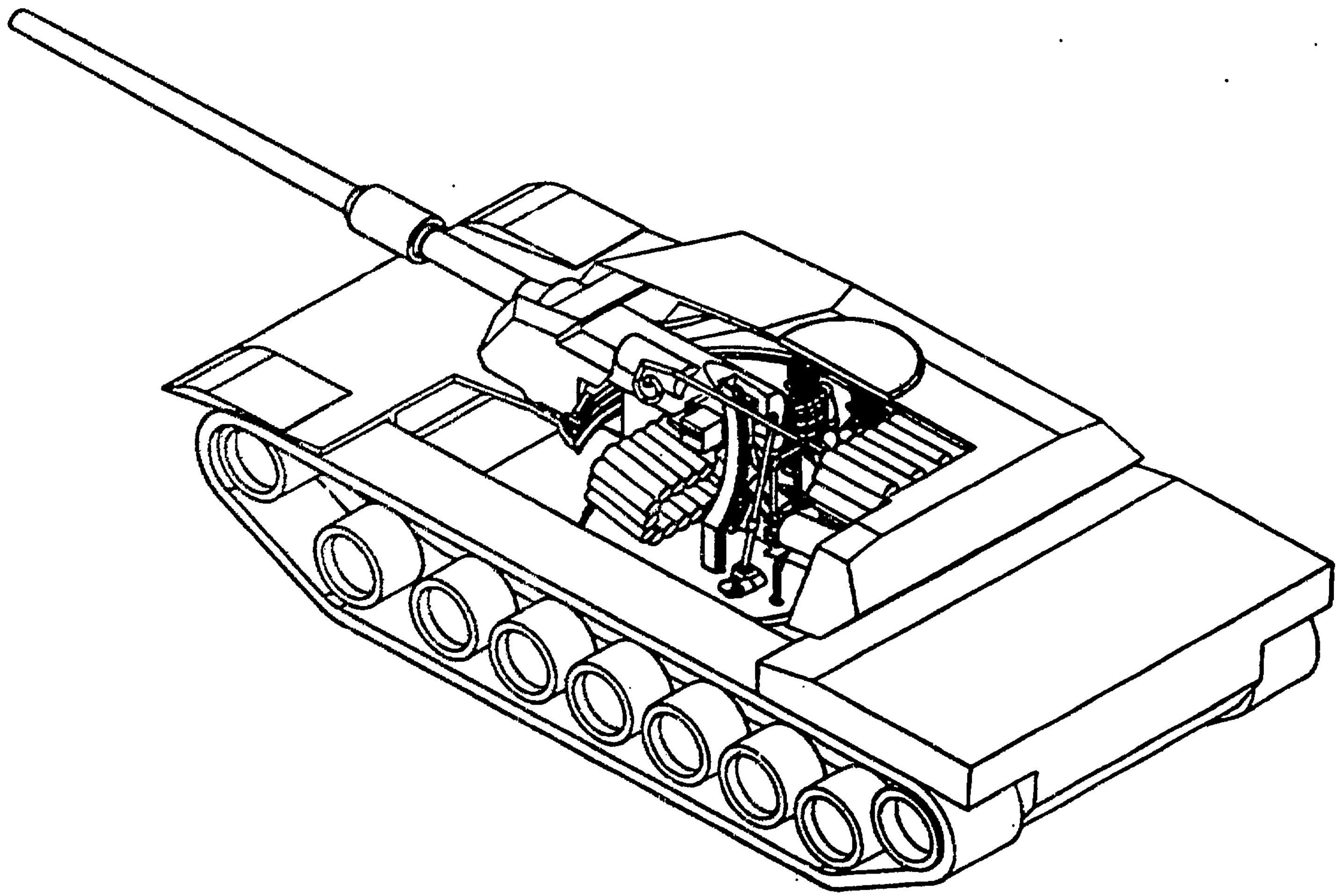

Figure 1. Cutaway View of M1A1-LP Vehicle

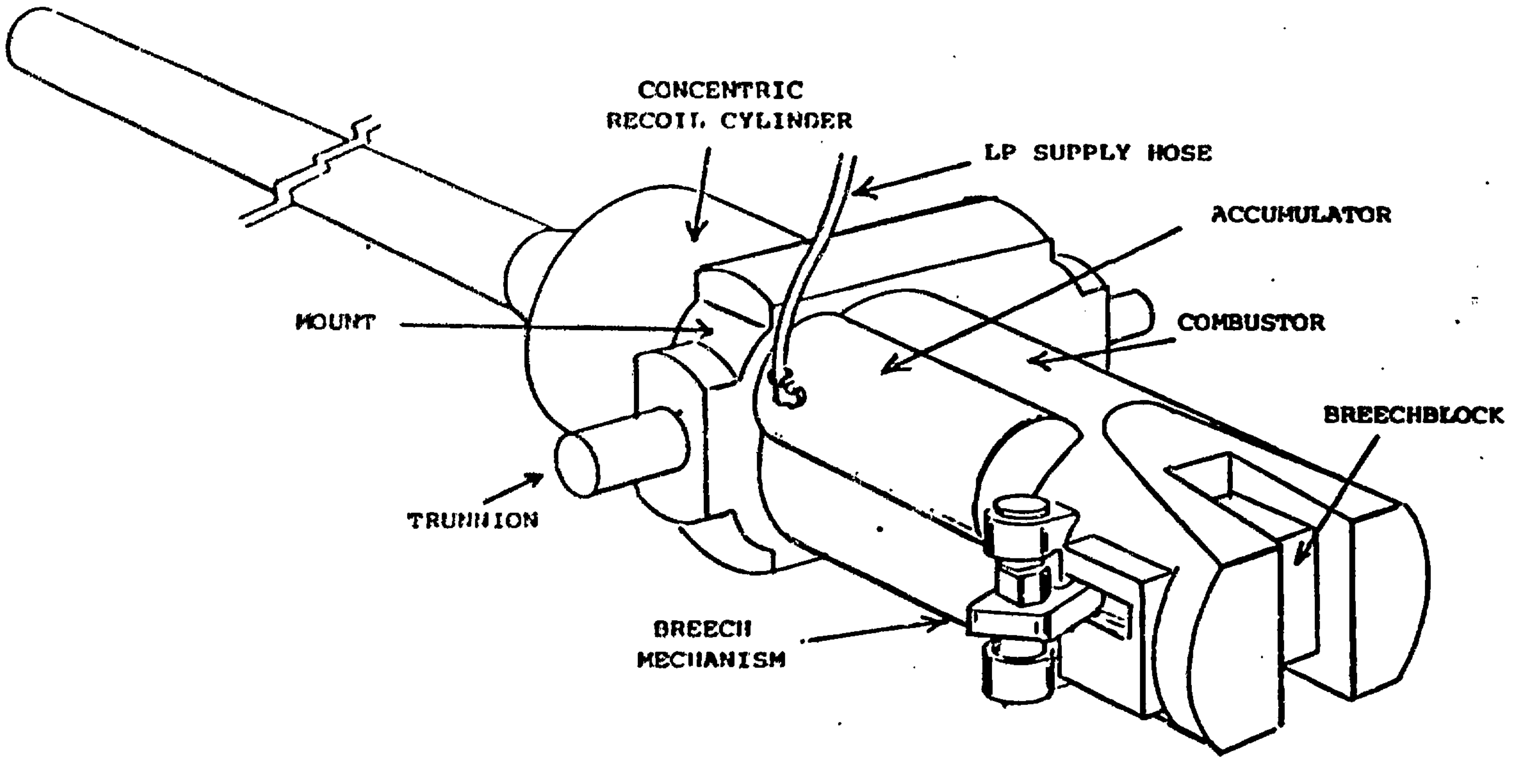

Figure 2. Reverse Annular Piston RLPG, External Configuration

II. SIMULATION MODELS

In the overall simulation of a high performance tank gun firing a saboted kinetic energy (KE) penetrator, we use models which will allow us to:

a. Determine the mass of a sabot capable of supporting a fin-stabilized KE penetrator in the gun bore and capable of withstanding the launch stresses.

b. Estimate the interior ballistic performance of the gun when projectile, gun, and propellant parameters are varied.

c. Estimate the external configuration and weight of the gun, recoil system, and loader in sufficient detail to conduct a vehicle integration study.

1. SABOT MODEL

The model used to estimate sabot weight was developed by Drysdale.[3] Given the geometry and weight of the penetrator, the physical properties (density, stress characteristics, etc) of the sabot, the maximum projectile base pressure, and the maximum projectile acceleration, the model estimates the sabot weight and thus the total in-bore weight of the projectile. The derivation of the algebraic equations used in the model and the assumptions made in the derivations are discussed in reference 3.

2. SP AND RLPG INTERIOR BALLISTIC MODELS

The first of the three interior ballistic models used in this study is the SP gun model, IBHVG2,[4] which is based on the earlier Baer-Frankle[5] model. The IBHVG2 model numerically integrates the ordinary differential equations describing the interior ballistic process of the SP gun. The model is widely used at the BRL and elsewhere to simulate the interior ballistic performance of a wide variety of guns.

The first RLPG model was developed by Coffee.[6] It is similar to the IBHVG2 model in that the physics of the RLPG are described by ordinary differential equations, which are then numerically integrated. The second model was developed by Gough.[7] Unlike the IBHVG2 and Coffee models, the Gough model integrates ordinary differential equations which describes piston motion and propellant injection and combustion, and one-dimensional partial differential equations which describe the flow of burning liquid droplets and gas in the barrel. Barrel pressure gradient in the IBHVG2 model was described by the Pidduck-Kent equations and in the Coffee model by modified Lagrange equations[8] which takes into account the velocity of the gas flow into the breech end of the barrel. All three models assume heat loss to the bore, and bore friction between projectile and the bore.

III. GROUND RULES

1. PROJECTILE DESIGN

In this study, we consider a broad range of projectile in-bore masses. Using the sabot model we compute a series of sabot masses and in-bore projectile masses making a conservative assumption that the maximum in-bore projectile base pressure and acceleration would correspond to the maximum chamber pressure of 500 MPa. This resulted in a set of in-bore projectile masses ranging from roughly 5 to 13 kg. For this study, only the total in-bore masses are important.

2. RLPG GUN DESIGN

Pasko,[9] GEOSD, developed two conceptual RLPG designs for a 120-mm tank gun, see Figures 3 and 4. The primary constraint was that the cannon fit into the present space for the tank gun. The most efficient cannon envelope was obtained using a reverse annular piston (RAP) design, Figure 3.

In the RAP configuration, the piston is mounted around the gun barrel, and moves in the same direction as the projectile. As the piston moves, the propellant is injected from the liquid reservoir into the combustion chamber. The gas then flows into the gun barrel. It is also possible to inject propellant from the liquid reservoir directly into the gun barrel. The piston was designed to survive the stresses placed on it during acceleration and deceleration, and the piston mass was then calculated based on this design as 76.7 kg. The projectile travel is based on the maximum desired length of the gun tube. The projectile must be offset from the end of the combustion chamber to leave room for the fins. Table 1 shows the dimensions for the RAP gun.

TABLE 1. Reverse Annular Piston Gun Dimensions

	Volume liters	Cross-Sectional Area cm^2
Liquid Reservoir:	11.7	547.1
Intermediate Chamber:	3.19	743.9
Combustion Chamber:	4.92	452.4
Piston Orifice:		53.6

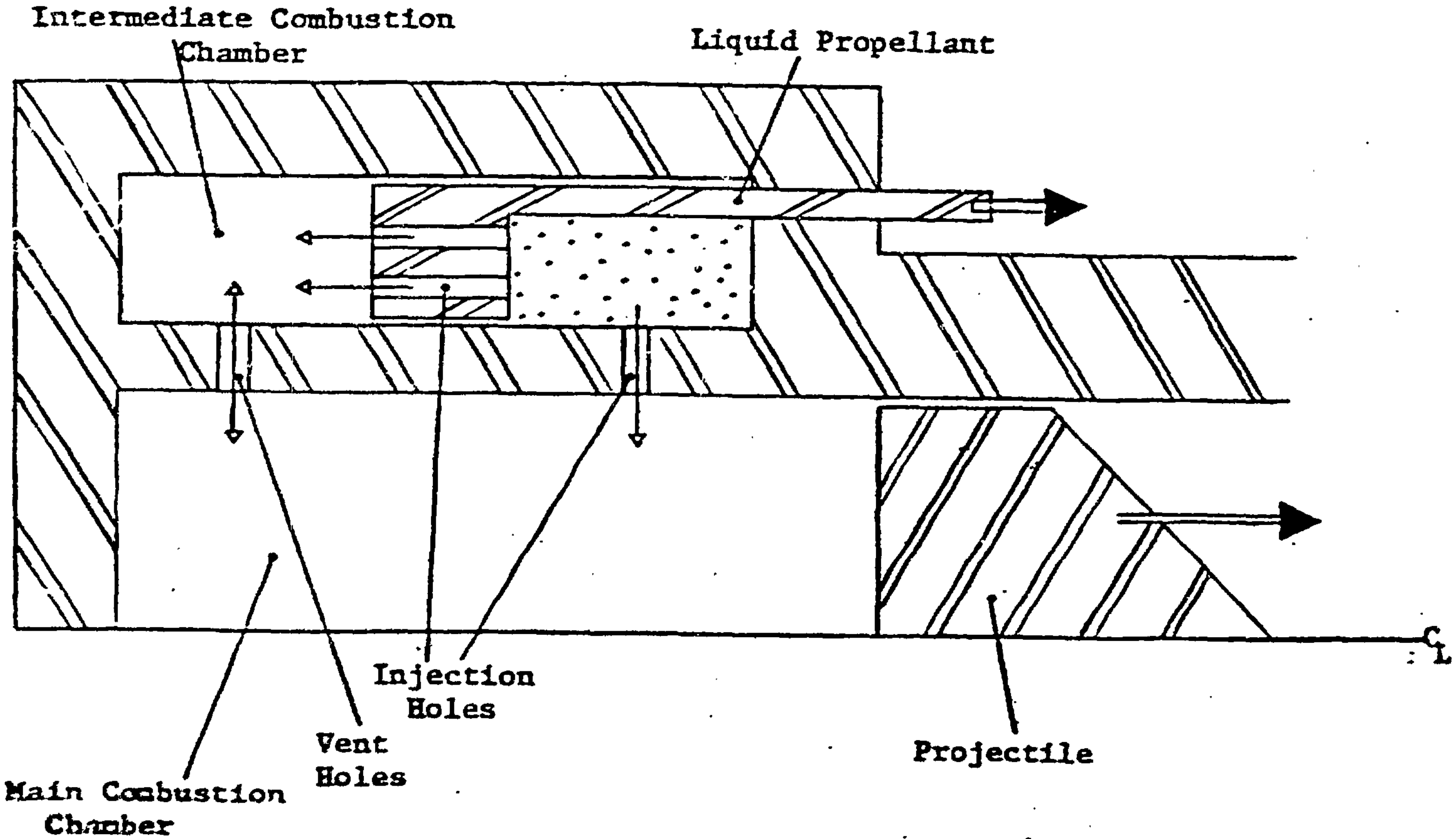

Figure 3. Reverse Annular Piston RLPG, Internal Configuration

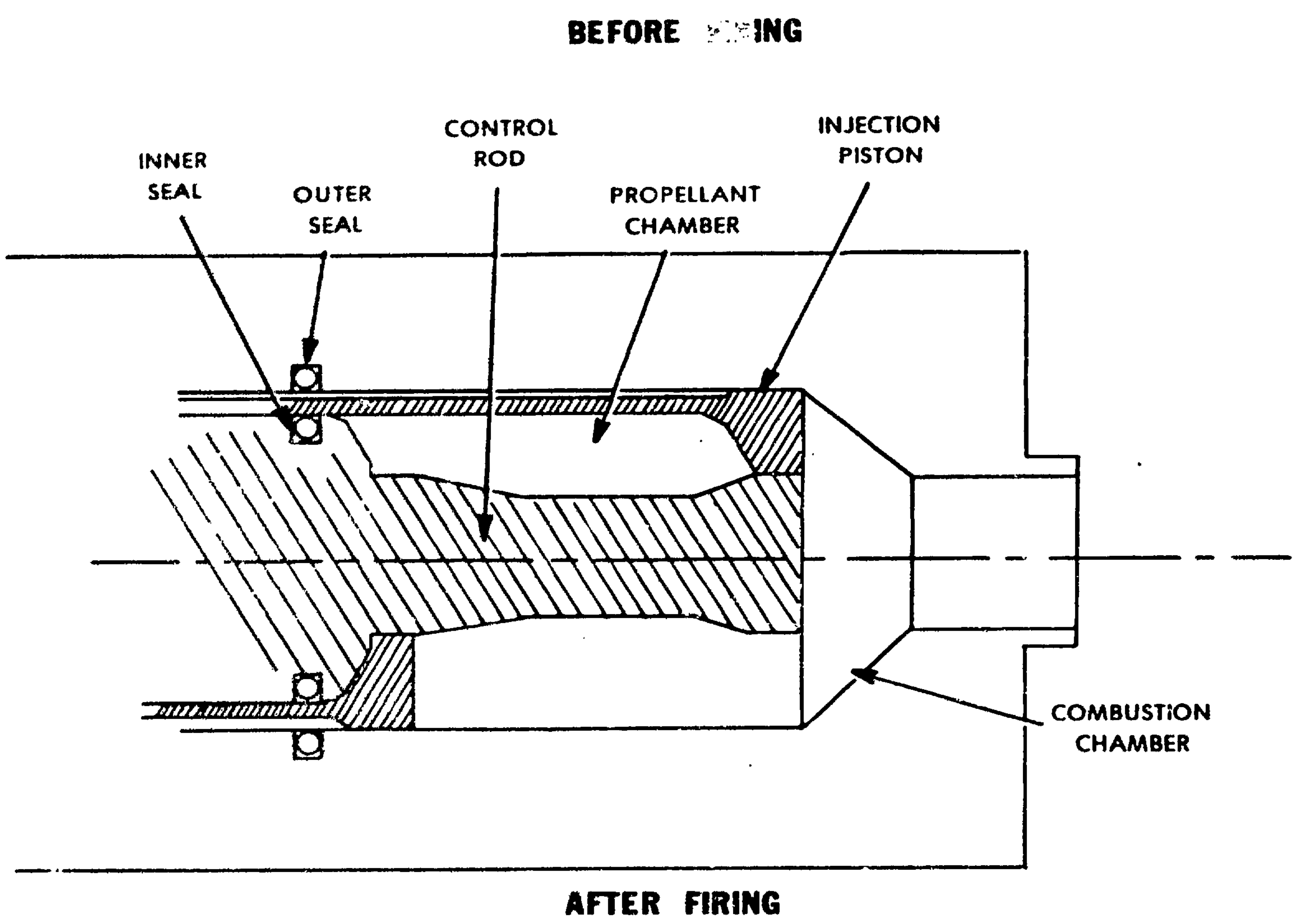

Figure 4. In-Line Annular Piston RLPG, Internal Configuration

To model this configuration, we need to choose not only the size of the vent in the piston, but also the size of the vents between the intermediate and combustion chamber and between the liquid reservoir and the gun tube. The vent into the gun tube normally opens during the firing. We moreover must choose when and how rapidly this vent opens. The gun performance depends strongly on the choice of the various vent sizes. At the moment we do not have enough experience to choose these vent sizes intelligently. So for simplicity, the in-line annular piston (IAP) configuration was utilized for this study.

The dimensions of the liquid propellant injector are chosen to preserve the hydraulic difference of 1.4 between the liquid reservoir and the combustion chamber. The IAP configuration consists of a central bolt surrounded by the piston. Normally, the bolt is tapered, such that the liquid reservoir is initially closed. As the piston moves, the vent area gradually increases. The bolt has a long straight section, where the vent area is constant. Finally, the piston must be decelerated, either by tapering the bolt to compress the liquid propellant or by a buffer acting on the piston shaft. For this level of approximation, we do not consider the optimum design for the bolt taper. Instead, we use a constant radius bolt, and the vent area is then fixed for the entire piston motion. The piston dimensions are also kept constant. The vent area is changed by varying the size of the central bolt. Dimensions are given in Table 2.

TABLE 2. In Line Piston Gun Dimensions

	Volume liters	Cross-Sectional Area cm^2
Liquid Reservoir:	11.7	719.6
Combustion Chamber:	8.11	916.3
Piston Orifice:		226.0

For the comparative purposes of this study, we assume a hypothetical liquid propellant, more energetic than those presently used. This pseudo propellant, called liquid JA2, has the thermochemical properties of the solid propellant JA2, and the physical properties of the liquid propellant LGP1846. This also makes it convenient to compare our results with a solid propellant gun model. The properties of all the propellants considered in this study are given in Table 3.

TABLE 3. Propellant Properties

Propellant Type:	SP-JA2	LGP-JA2	LGP-1845*	LGP-1846*
Density (g/cc):	1.578	1.430	1.461	1.430
Bulk modulus (MPa):	-----	5103.5	5103.5	5103.5
Bulk modulus derivative:	-----	8.2173	8.2173	8.2173
Chemical energy (j/g):	5067	5067	4556	4293
Specific heat ratio:	1.225	1.225	1.214	1.219
Molecular weight (g/mole):	24.865	24.865	23.074	22.849
Covolume (cc/g):	0.996	0.996	0.720	0.693

The projectile properties are given in Table 4. The projectile mass was varied over the range of interest, as indicated above. For the sake of simplification, the original offset of the projectile is taken to be zero. Hence the initial volume of the system is just the sum of the liquid reservoir and combustion chamber volumes. Empirical models for the air shock in front of the projectile and the heat loss to the gun tube are included. The heat loss model is adjusted such that approximately 5% of the energy in the system is lost to the tube walls, comparable to standard assumptions in solid propellant simulations.

TABLE 4. Projectile Properties

Offset: 0.0 cm

Travel: 629.9 cm

Gun Tube Diameter: 12.0 cm

Shot Start Pressure: 34.0 MPa

Frictional Resistance: 5.5 MPa

Additional assumptions were required in order to conduct the computer simulations. The flow into the combustion chamber is governed by a steady

*Obsolete Data. Current data may be obtained by a request to the authors.

state Bernoulli equation. The losses in this process are lumped into the discharge coefficient, which is given a typical value of 0.75. There should be some liquid accumulation in the combustion chamber, especially early in the gun cycle when pressures are low. But a reasonable approximation[5] is to assume that the liquid combusts instantaneously as it enters the combustion chamber. The gas flow into the gun tube is assumed to be isentropic with a discharge coefficient of one. The pressure in the gun tube is assumed to follow a Lagrange pressure distribution which has been modified to take into account the non-zero fluid velocity into the throat of the gun tube. The liquid in the reservoir is normally pre-pressurized to 7.0 MPa in order to reduce the effects of gas bubbles. Finally, the burning of the primer is not modeled in detail. Rather, it is assumed that the primer has burned completely at the start of the simulation, leading to an initial pressure in the combustion chamber of 15.0 MPa.

The maximum pressure allowed in the reservoir is 700 MPa. In this study, we are seeking the best performance possible with the desired pressure limits. So the vent area is adjusted until the maximum liquid pressure reaches 700 MPa. As a result of the hydraulic difference chosen, this will usually guarantee that the gas pressure does not exceed 500 MPa.

3. INTERIOR BALLISTIC SIMULATIONS - 120-mm GUN

Preliminary calculations were conducted using both the Gough and the Coffee models. The predicted muzzle velocities agreed to within a fraction of a percent. Since the Coffee code runs more rapidly, it was used for the majority of the calculations in this study.

The total initial volume of the gun is the sum of the liquid reservoir and combustion chamber volumes. This volume can be varied to some degree and still fit into the designated space. It is important in optimizing system performance to choose reasonably good values for these volumes.

The initial liquid reservoir volume was chosen to match propellant charge weight (16.7 kg). To determine the effect of loading density on performance, the charge was fixed and the combustion chamber volume was varied.

To cover the extreme cases, the lightest and the heaviest projectile masses were considered. The chamber volume was then varied between 2 and 10 liters. In each case, the vent area was adjusted such that the maximum liquid pressure obtained was 700 MPa. Results are given in Figures 5 and 6 in terms of loading density (charge/initial volume).

For the light projectile, the muzzle velocity is quite high. The vent area is chosen to be fairly large, since the projectile accelerates rapidly, opening up a larger area in the gun tube. The best performance occurs for a low chamber volume, which corresponds to a loading density of about 1.1 g/cc. For the heavy projectile, the vent area must be kept smaller, since the projectile moves more slowly, and the best performance occurs for a larger chamber volume corresponding to a loading density of about 0.85 g/cc. Based

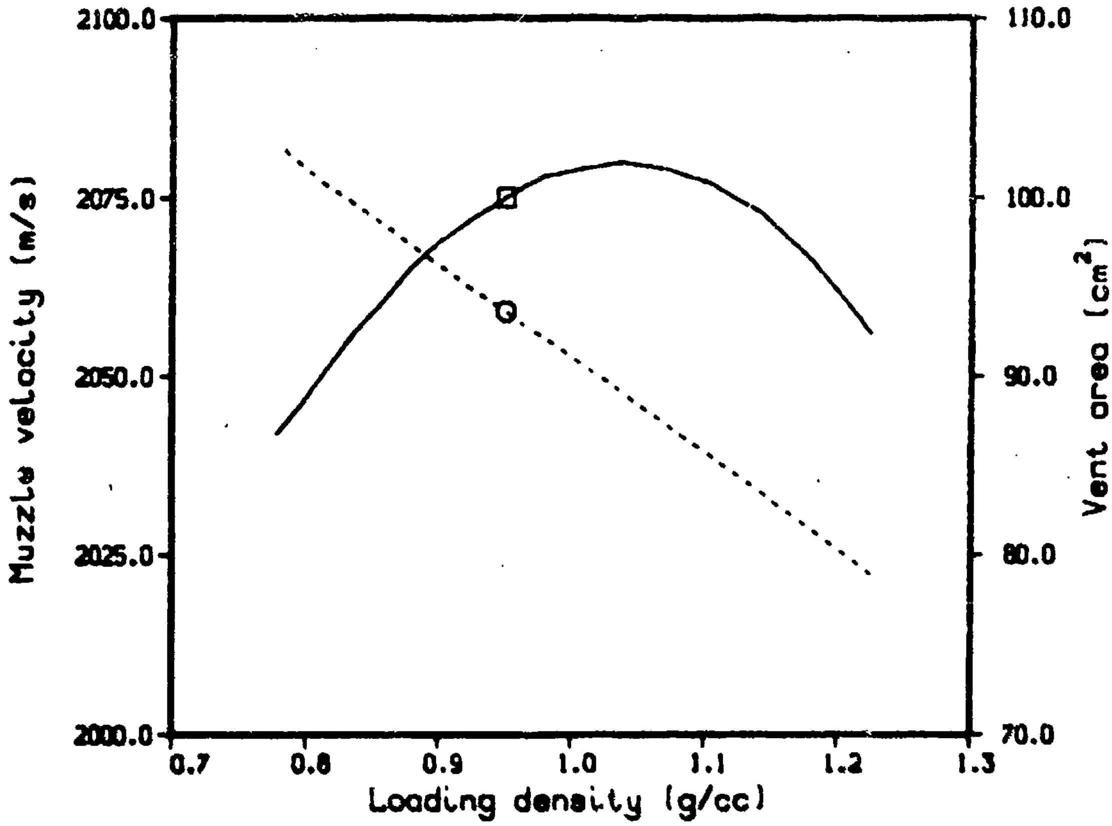

Figure 5. Muzzle Velocity vs Loading Density for the RLPG Using the Lightest Projectile, 120-mm Gun.

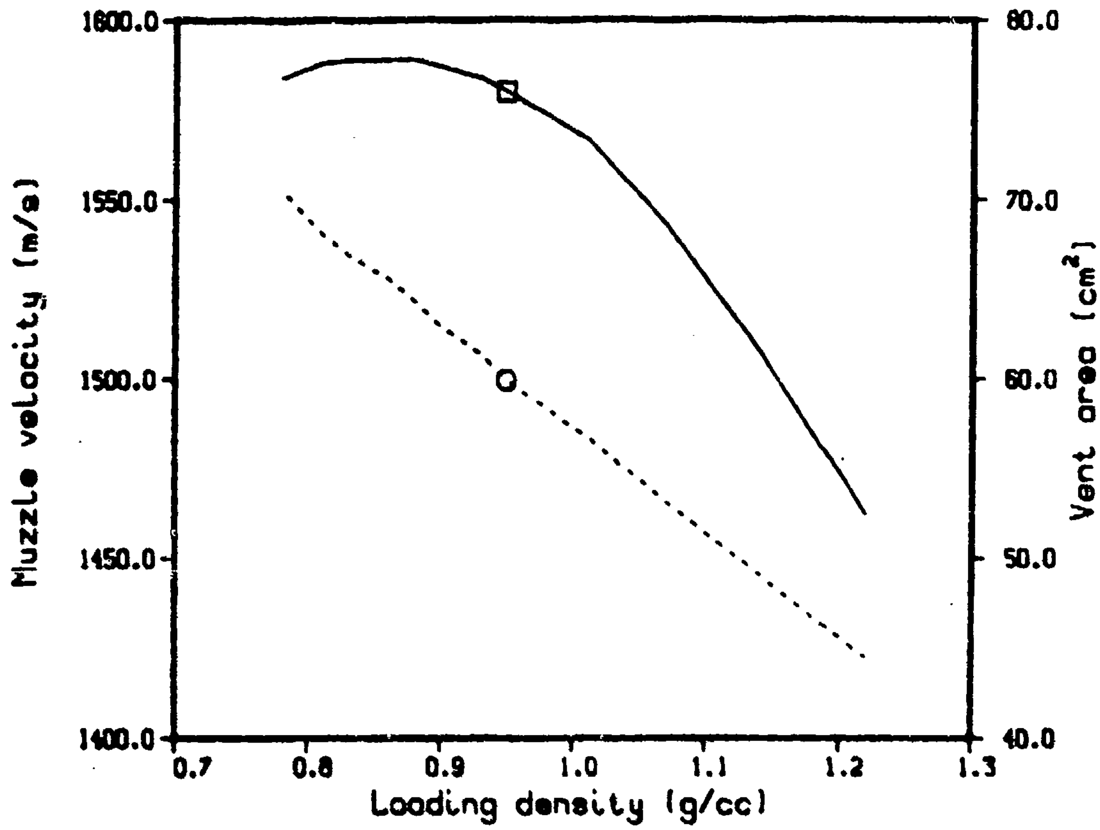

Figure 6. Muzzle Velocity vs Loading Density for the RLPG Using the Heaviest Projectile, 120-mm Gun.

on these results, an initial chamber volume of 6 liters was chosen. This is close to the best possible performance for both projectiles.

To determine the effect of varying the charge, the liquid reservoir volume was varied with the chamber volume kept constant at 6 liters. This changes the ratio of the propellant charge to the projectile mass (C/M). Figures 7 and 8 show the results for the lightest and heaviest projectiles respectively. The symbols mark the default values of propellant charge used above. For the light projectile, the charge to mass ratio is just about optimum. For the heavy projectile, a slight increase in performance is possible by increasing the charge mass. We chose to fix the propellant charge at 16.7 kg.

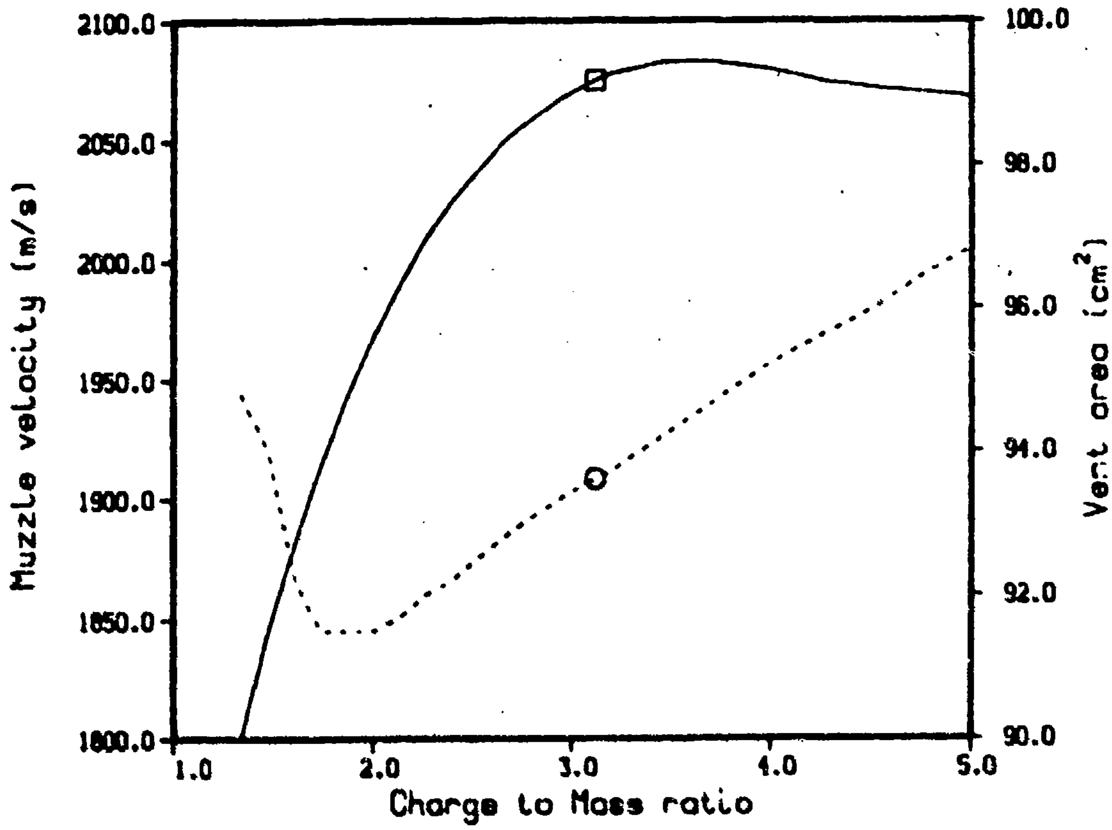

Figure 7. Muzzle Velocity vs Charge to Mass Ratio for the RLPG Using the Lightest Projectile, 120-mm Gun.

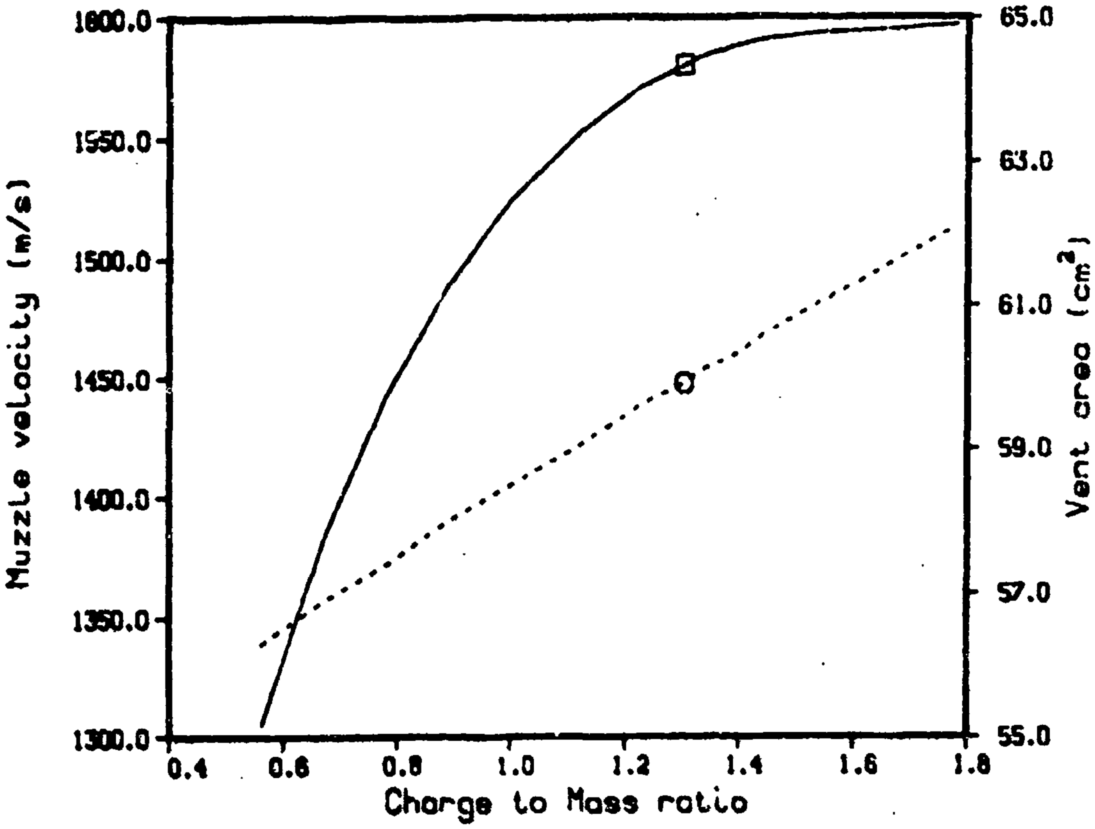

Figure 8. Muzzle Velocity vs Charge to Mass Ratio for the RLPG Using the Heaviest Projectile, 120-mm Gun.

Figure 7 shows unusual behavior in the vent area. For the smallest charge, the fuel burns out just as the pressure limit of 700 MPa is reached. As the charge increases, the vent area must decrease. A slightly slower injection rate allows the liquid pressure to remain under 700 MPa for the longer injection stroke. Eventually, we reach the point where the length of the liquid column becomes important. For a larger liquid reservoir, it takes longer to compress the liquid, which delays the injection. At a charge to mass ratio of about 1.9 we reach the transition point, and the vent must be chosen larger to keep up the injection rate. Finally, for very large charges, the long liquid column length actually decreases the performance.

Using the above optimum values for liquid and combustion chamber volumes (liquid volume= 11.7 liters, liquid weight = 16.7 kg, and chamber volume= 6 liters), the muzzle velocity was then computed over the range of projectile weights (Figure 9). For comparison, the velocities predicted using two actual

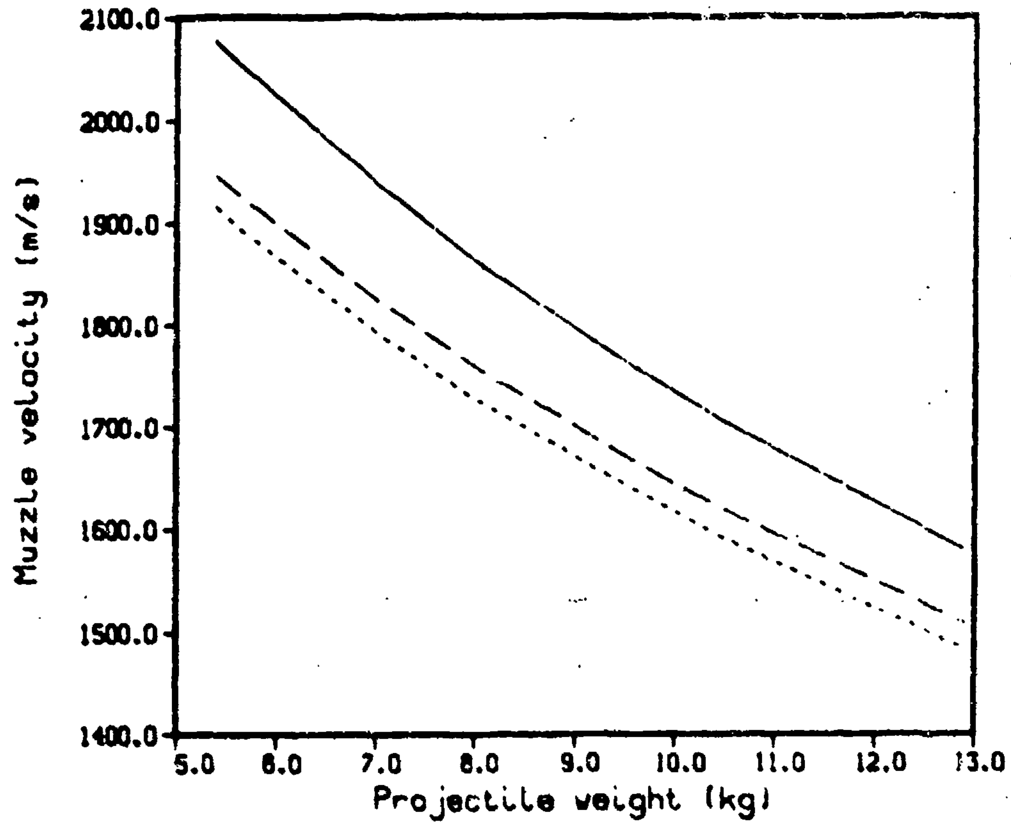

Figure 9. Muzzle Velocity vs Projectile Weight for Liquid JA2 (line), HAN1845 (dot), and HAN1846 (dash), 120-mm Gun.

HAN propellants are also given. Assuming a more energetic propellant increases the performance by about 100 m/s.

Calculations were also done for the SP gun, using the IBHVG2 model. In each case, the propellant web was varied in order to obtain a maximum pressure of 500 MPa. The same loading density (0.95) as for the RLPG was used. The muzzle velocities were similar to the RLPG model using the HAN propellants (Figure 10).

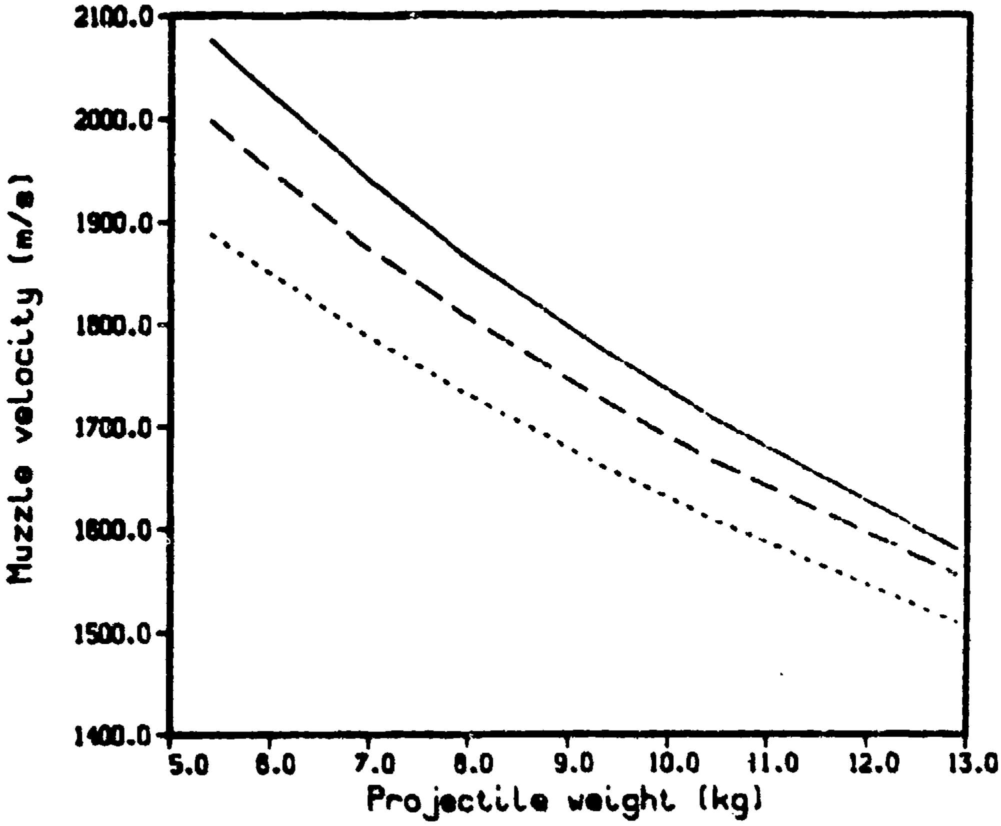

Figure 10. Muzzle Velocity vs Projectile Weight for Liquid JA2 (line), and Solid Propellant at Two Loading Densities [0.75 g/cc (dot) and 0.95 g/cc (dash)], 120-mm Gun.

The SP predictions using JA2 propellant were expected to be comparable with those of the RLPG with liquid JA2. Instead, the muzzle velocities were substantially lower. This can be explained by comparing muzzle velocity versus loading density curves for both the SP and RLPG models (Figure 11). The standard projectile weight of 7.12 kg was used, and two different charge weights were considered, 8.1 kg and 16.7 kg.

In each case, the SP performance drops off sharply with increasing loading density. The RLPG has an advantage in this regime, since the liquid can be injected and hence burned gradually, while the entire SP charge is exposed to the combustion chamber conditions. The SP web must be increased in order to stay within the maximum pressure limit, but combustion is then less efficient, and burnout does not occur prior to projectile exit. For this reason, the RLPG is relatively more efficient for a larger charge.

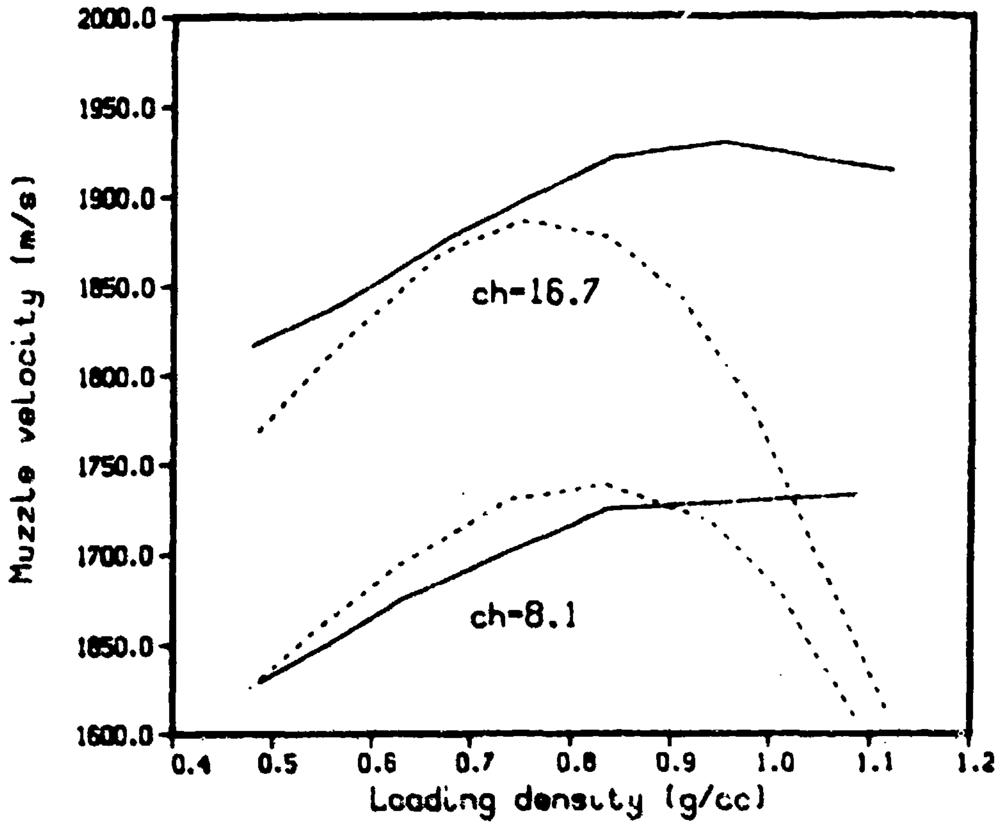

Figure 11. Muzzle Velocity vs Loading Density for Liquid JA2 (line) and Solid Propellant (dot). Cases with a 7.12 kg Projectile, 120-mm Gun.

The optimum loading desity for the SP from Figure 11 is around 0.75. Therefore, a series of calculations using this loading density (Figure 10) were also done. Note that decreasing the loading density requires that the chamber volume be increased by about 5 liters. The SP velocities are closer to, though still below those of the RLPG with liquid JA2.

4. INTERIOR BALLISTIC SIMULATIONS - 140-mm GUN

We would also like to know if improved performance is possible by replacing the 120-mm gun with a 140-mm gun. As in the 120-mm study we choose to use an in-line liquid propellant injector for this gun. As a first approximation, we used the same reservoir and chamber dimensions as for the 120-mm gun, and just attached a larger gun tube.

The same set of penetrators were used. Because of the larger gun tube, the sabot weight must be increased. Thus the total in-bore projectile weights are heavier ranging from about 6 kg to 15 kg.

As before, we did a preliminary set of runs varying the chamber volume (Figures 12 and 13). For the light projectile, the best performance is obtained when the combustion chamber is as small as possible (high loading density). Since the gun tube is larger, a larger volume is opened up as the light projectile is accelerated. Thus the maximum chamber pressure is less likely to exceed the desired limit.

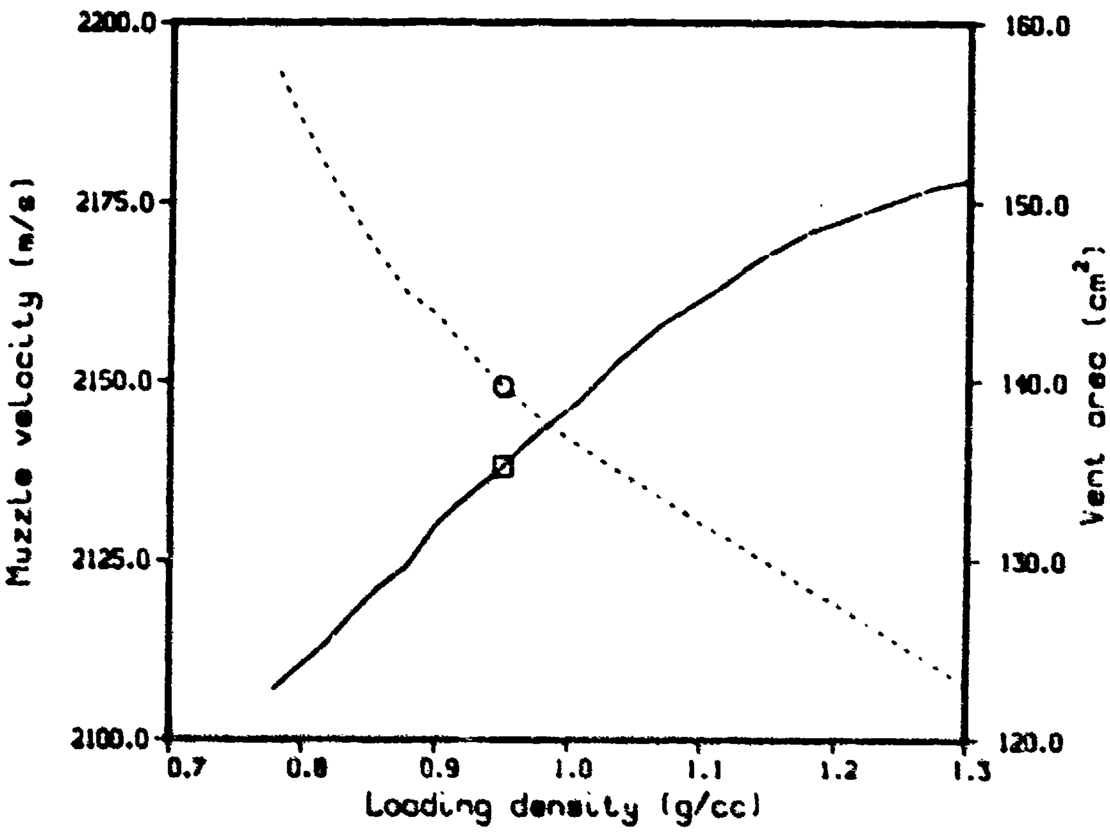

Figure 12. Muzzle Velocity vs Loading Density for the RLPG Using the Lightest Projectile, 140-mm Gun.

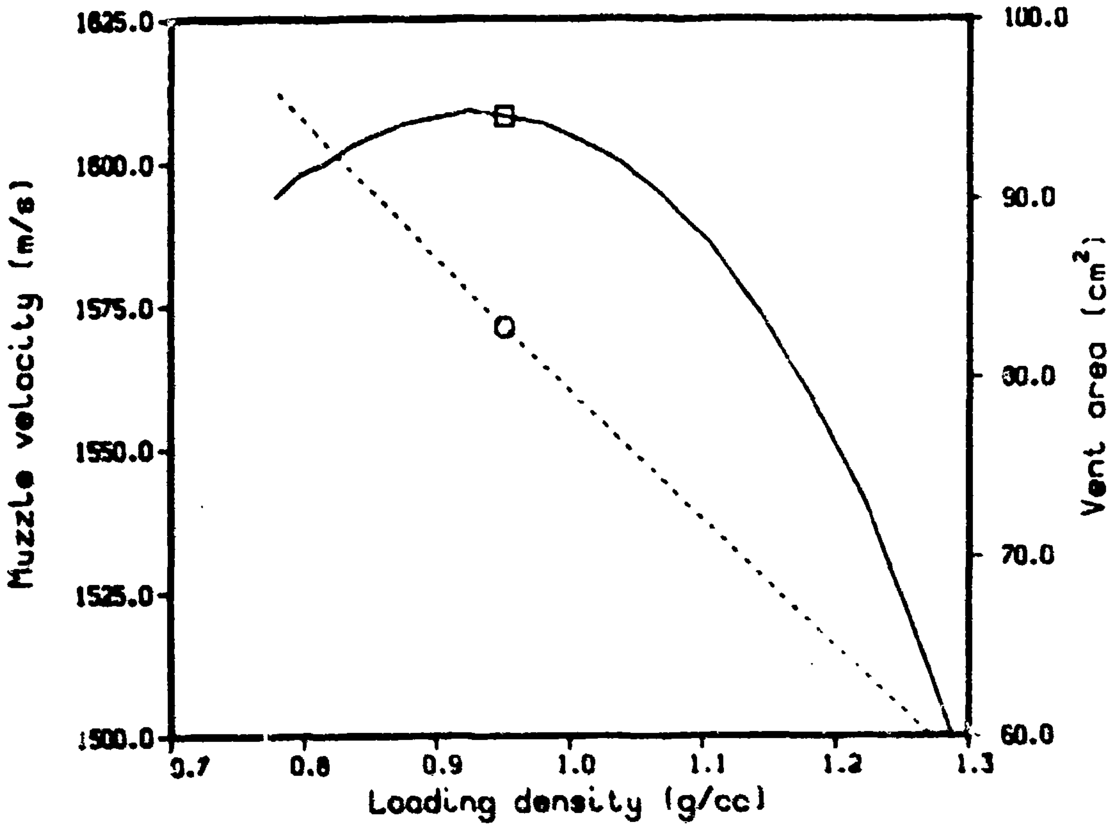

Figure 13. Muzzle Velocity vs Loading Density for the RLPG Using the Heaviest Projectile, 140-mm Gun.

For the heavy projectile, a larger chamber volume is better, since the projectile does not accelerate as rapidly. If the chamber volume is too small, the vent area must be made very small to prevent over-pressurization.

There is no longer a good compromise value for the initial chamber volume. For the sake of consistency, we use to same value as used for the 120-mm study (6.0 liters).

We also varied with charge weight, with the initial chamber volume fixed at 6.0 liters. The results are shown in Figures 14 and 15. In this case, better performance for both the light and the heavy projectile can be obtained by increasing the initial charge. This would of course result in a larger gun. For the purposes of comparison with the 120-mm cases, we keep the same initial reservoir volume of 11.7 liters.

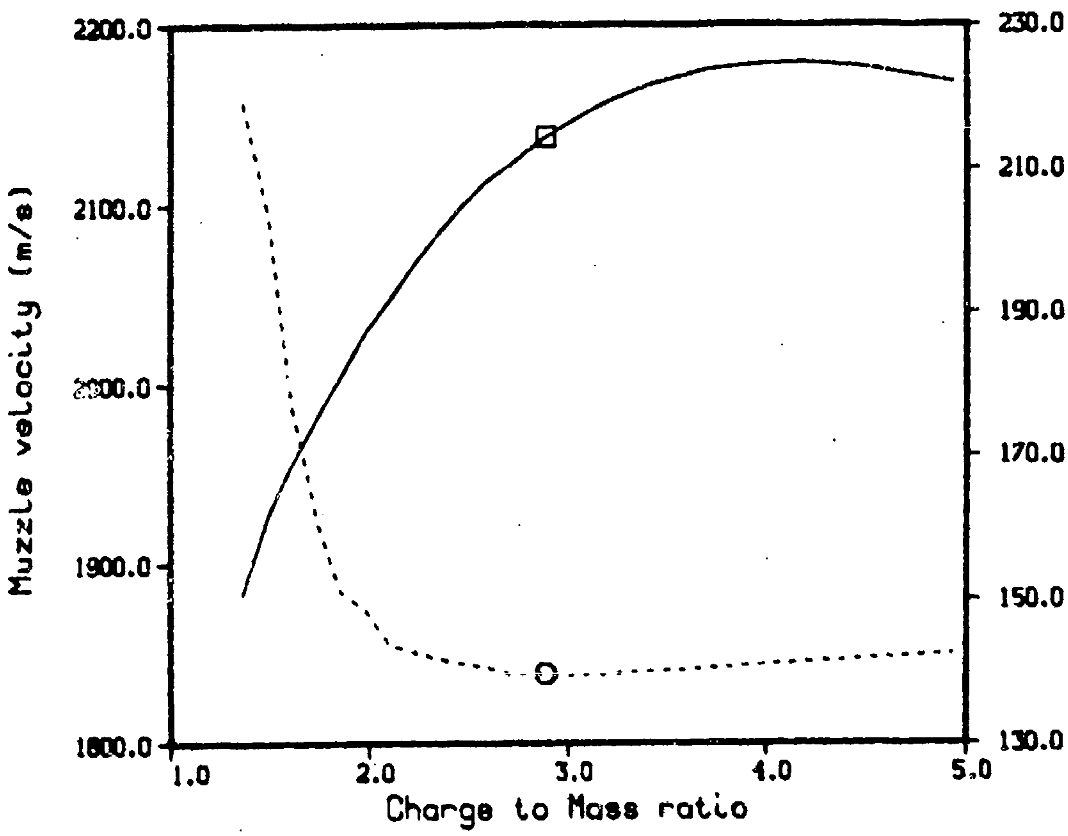

Figure 14. Muzzle Velocity vs Charge to Mass Ratio for the RLPG Using the Lightest Projectile, 140-mm Gun.

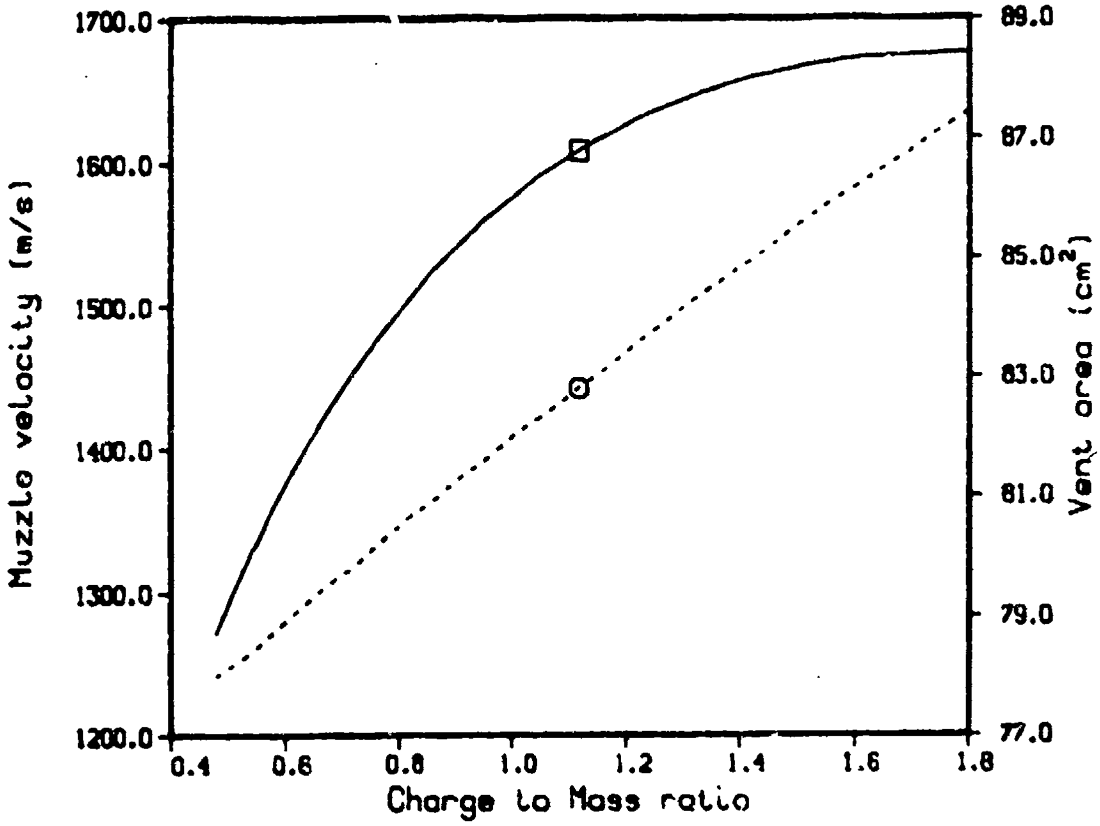

Figure 15. Muzzle Velocity vs Charge to Mass Ratio for the RLPG Using the Heaviest Projectile, 140-mm Gun.

The results for our series of projectile weights are given in Figure 16. The curve is similar to the 120-mm curve (also shown). The muzzle velocities average about 2.5% larger. So a slight increase in performance can be obtained by using the larger 140-mm gun. This can be increased further if it is possible to increase the charge weight.

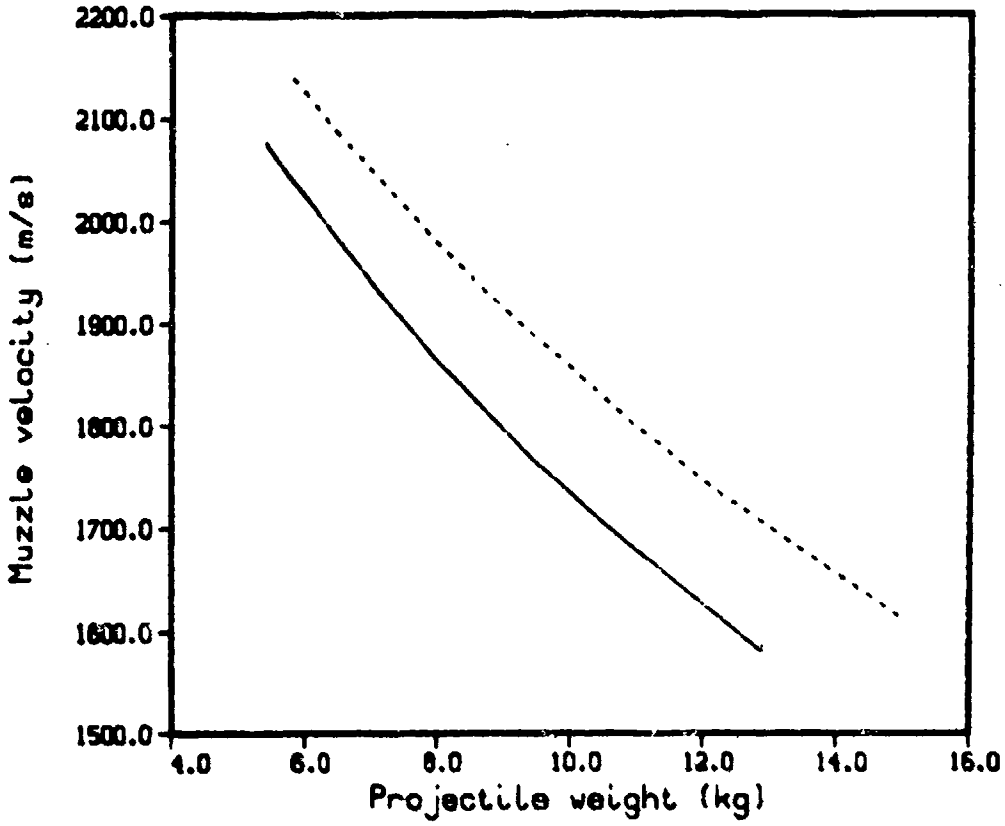

Figure 16. Muzzle Velocity vs Projectile Weight for Liquid JA2. 120-mm Gun (line). 140-mm Gun (dot).

IV. DISCUSSION AND CONCLUSIONS

Simulations were carried out using a SP gun model and two RLP gun models. The RLP gun models using "liquid JA2" predicted muzzle velocities slightly higher than the SP gun model with JA2. If actual liquid propellants LGP1845 or LGP1846 are used instead, the performance is lowered by 5% to 10%. These results highlight the need for higher energy liquid propellants.

For the RLP gun models, a simple cylindrical center rod in the LP injector was used. Additional increases in performance can be obtained by using a tapered rod or other means to tailor the propellant injection and thus pressure time curve. Also, a buffer to slow down the piston at the end of its stroke will result in lower liquid pressures, allowing the vent area to be chosen larger, further increasing the performance.

The RLP and SP gun models show some interesting differences. In particular, the optimum loading density for a SP gun is sharply peaked. Increasing propellant charge forces a web increase so as to stay within the pressure limits, causing a performance decrease. The RLP gun instead shows a broad maximum for performance versus loading density. The fact that the propellant is injected gradually makes the choice of the charge weight less critical.

Based on these computer simulations, it appears that the RLP gun is capable of providing performance equivalent to that of high performance solid propellant guns. The advantages of the LP are realized at the system level in the tank, particularly for the very high C/M, high gun velocities.

The advantages of the RLP gun system include: increased ammunition stowage (56 rounds instead of the current 40 in the M1A1) while doubling the C/M thus increasing gun performance; simplification of autoloader design since only the projectile is handled mechanically; and reduced system vulnerability due both to the low vulnerability characteristics of the HAN-based LPs and the ability to stow the propellant external to the crew compartment.

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