



NASA/CR-95- 207229

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IMPROVING THE PERFORMANCE OF TWO-STAGE GAS GUNS BY ADDING A DIAPHRAGM IN THE PUMP TUBE

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Summary—Herein, we study the technique of improving the gun performance by installing a diaphragm in the pump tube of the gun. A CFD study is carried out for the 0.28 in. gun in the Hypervelocity Free Flight Radiation (HFF RAD) range at the NASA Ames Research Center. The normal, full-length pump tube is studied as well as two pump tubes of reduced length ($\sim 75\%$ and $\sim 33\%$ of the normal length). Significant improvements in performance are calculated to be gained for the reduced length pump tubes upon the addition of the diaphragm. These improvements are identified as reductions in maximum pressures in the pump tube and at the projectile base of $\sim 20\%$, while maintaining the projectile muzzle velocity or as increases in muzzle velocity of ~ 0.5 km/sec while not increasing the maximum pressures in the gun. Also, it is found that both guns with reduced pump tube length (with diaphragms) could maintain the performance of gun with the full length pump tube without diaphragms, whereas the guns with reduced pump tube lengths without diaphragms could not. A five-shot experimental investigation of the pump tube diaphragm technique is carried out for the gun with a pump tube length of 75% normal. The CFD predictions of increased muzzle velocity are borne out by the experimental data. Modest, but useful muzzle velocity increases (2.5 - 6%) are obtained upon the installation of a diaphragm, compared to a benchmark shot without a diaphragm.

INTRODUCTION

The amount of space debris is rapidly increasing and the debris is distributed over a wide variety of orbits. Satellites, manned space vehicles and space stations will have to pay increasing attention to the dangers of impacts with space debris. Various armoring techniques (i.e., double or triple layer armor) will have to be tested extensively to determine the most effective armor per unit weight. Intersecting near-earth orbits can lead to impact velocities up to 15 km/sec. Conventional two-stage light gas guns can launch [1] intact, controlled-shape projectiles with a density of 1.2 gm/cm^3 and length-to-diameter (L/D) ratios of 0.5-1.0 at velocities up to 8-9 km/sec. Higher velocities (10-11 km/sec) can be obtained [1] for very light projectiles with smaller L/D ratios. The higher launch velocities tend to be very severe on the projectile, and the high-pressure coupling and barrel of the gun and can lead to projectile failure and short gun component lifetimes. Clearly, the ability to reduce the stresses on the projectile and gun, while maintaining launch velocity, would have significant benefits. This would also translate into the ability to raise the launch velocity somewhat at the same stress levels in the projectile and gun. Further, the pump tubes of two-stage guns tend to be very long; representative length-to-diameter ratios range from 100 to 300. Particularly for larger guns, a way of reducing pump tube length while maintaining performance would be desirable.

The technique studied here is to use multiple compressions, instead of a single compression, in the pump tube of the light gas gun. This would be done by installing one or more extra diaphragms in the pump tube. The diaphragms would be ruptured by the increasing pressure upon approach of the piston. In this paper, we present detailed CFD calculations that show that increases in

muzzle velocity or reductions in maximum gun pressures or reductions in pump tube length can be obtained with multiple compressions in the pump tube. Results of a preliminary experimental investigation of this technique are also presented.

BASIC DESCRIPTION OF TECHNIQUE

The basic advantage of using the pump tube diaphragm technique is as follows. Let a volumetric compression of the pump tube gas of 100 to 1 be required to achieve the necessary final gas temperature, using the conventional pump tube. Let the final volume of the pump tube be v_f ; the initial pump tube volume must then be $100v_f$. Using the pump tube diaphragm, the first compression could compress the gas from $10v_f$ to v_f . The diaphragm would then break and the gas would expand into the vacuum region without loss of temperature, since it does no work (ignoring the small amount of work required to break the diaphragm). The already hot gas is then compressed again from $10v_f$ to v_f , reaching, ideally, the same temperature achieved in the conventional pump tube. However, the total pump tube volume for the second case is only about $20v_f$ or about 5 times less than that of the conventional pump tube. Conversely, if a pump tube of volume $100v_f$ were divided into two $50v_f$ volumes and each section of the pump tube was compressed to v_f in succession by the piston, the effective volumetric compression would $50^2 = 2500$ to 1 instead of 100 to 1 for a pump tube operated in the usual way. Assuming an ideal gas, no losses, and taking the specific heat ratio to be 1.4, this would allow the pump tube with the diaphragm to achieve a final sound speed $(2500/100)^{(1.4-1)/2} = 1.903$ times that of the pump tube without the diaphragm.

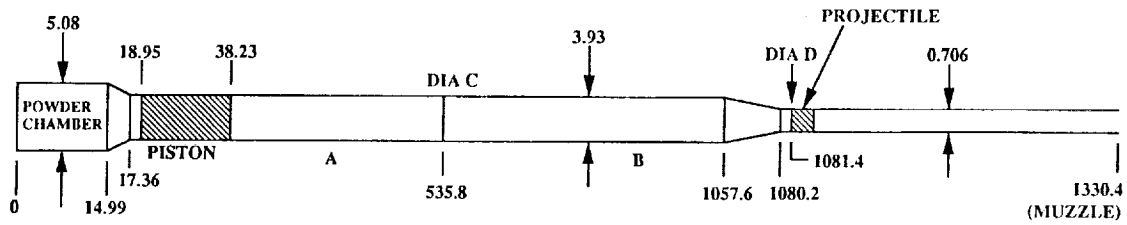
DESCRIPTION OF CFD CODE

The code is a quasi-one-dimensional Godunov solver which is third order accurate in space and second order accurate in time. The Riemann solver is exact for shocks (within the limitations of 6 to 12 iterations) and uses a very accurate isentropic expansion technique, in which the sound speed is taken to vary as the density to a locally calculated power, for expansion waves. Different zones are used for gunpowder, pump tube piston and hydrogen. This prevents mixing of materials with different equations of state. All results presented here were done with a mass point projectile. Accurate equations of state are used for all media. The friction and heat transfer models for the gases, piston and projectile are based on the work of Ref. [2]. Some modifications from these methods have been made, however. (These modifications will be described in a later publication.) A simple non-equilibrium gas turbulence model is used. The burn rate of the gunpowder grains is taken to follow the standard ballistics expression $r = ap^b$, where r is the burn rate and p is the gas pressure; a and b are given by the manufacturer of the powder. The code has been extensively validated against a number of exact analytic solutions and against piston and projectile velocity data and powder chamber and pump tube pressure data from a number of shots from the NASA Ames 0.28 in. gun. Excellent agreement between CFD predictions and exact analytic solutions and experimental results was obtained. Space limitations prevent the presentation of the code validation herein; a later publication will describe the code in detail.

DISCUSSION OF CFD ANALYSES

The gun modelled is sketched in Fig. 1. This gun models the normal configuration of the 0.28 in. gun used in the HFF RAD range at the NASA Ames Research Center. Of the two diaphragms shown in Fig. 1, diaphragm D is the normal stainless steel diaphragm located just behind the projectile. Diaphragm C is the extra pump tube diaphragm. Some CFD results were also obtained without the extra diaphragm C. Two shorter gun configurations were also studied computationally. These were constructed from the full length benchmark gun by removing, at locations A and B in the pump tube, the lengths shown in the table in Fig. 1. The 100% and 75% guns were used in the experimental study presented in the next section.

Most of the shots modelled in the CFD study have the following parameters held constant at the values given. Powder load - 50 gm IMR type 4227 powder; pump tube piston - 222 gm high density polyethylene, stainless steel diaphragm - rated break pressure, 680 bar, break pressure used in CFD, 1360 bar (see previous section); projectile - Lexan, mass 0.3706 gm. The following variables were varied in at least some of the studies: hydrogen fill pressure on both sides of the diaphragm, diaphragm break pressure and position of diaphragm.



GUN MODELLED	LENGTHS REMOVED AT	
	A (cm)	B (cm)
100%	0.	0.
75%	304.8	0.
33%	338.3	366.0

Fig. 1 Gun modelled in CFD study. All dimensions are in cm. DIA denotes diaphragms. Dimensions for full length gun shown in sketch. For the two shortened versions of the gun, the lengths shown in the table were removed at A and B.

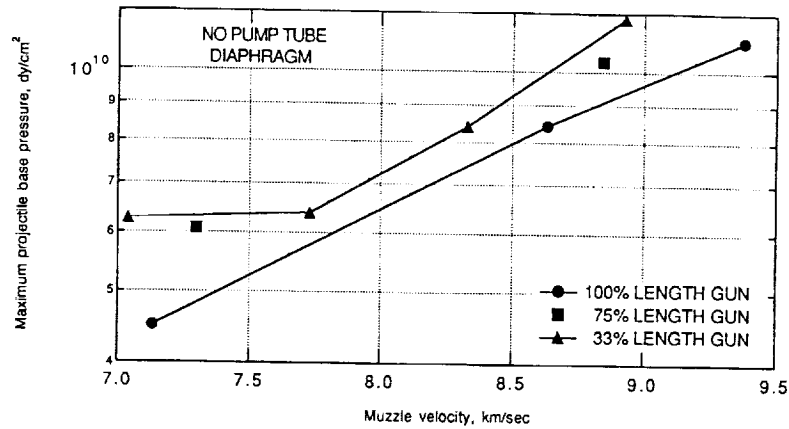


Fig. 2 Maximum projectile base pressure versus muzzle velocity for three different length guns, without a diaphragm. Along each curve, the initial pump tube fill pressure decreases towards the right.

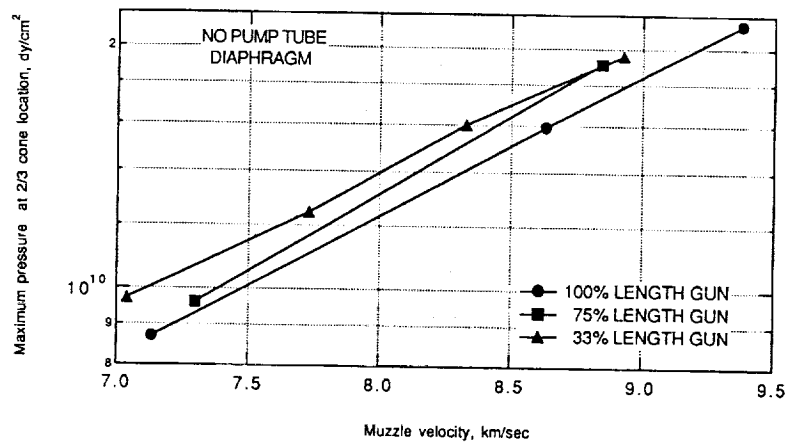


Fig. 3 Maximum pressure at 2/3 cone location versus muzzle velocity for three different length guns, without a diaphragm. Along each curve, the initial pump tube fill pressure decreases towards the right.

In this study, graphs were plotted at five locations in the gun, as follows: projectile base, 1/3 of the way along the contraction cone (see Fig. 1), 2/3 of the way along the contraction cone, center of the rightmost piston cell and the center of the leftmost hydrogen cell. Space limitations have prevented us from presenting all of these graphs here. An examination of all of the data shows that, by far the greater proportion of the conclusions can be demonstrated by looking at the graphs for the projectile base and the location 2/3 of the way along the contraction cone (which shows nearly the highest pressures reached anywhere in the gun). We will therefore present these two graphs herein for each case studied.

If one adds an extra diaphragm or varies any of the variable parameters such as pump tube initial fill pressure, pump tube diaphragm break pressure or pump tube diaphragm location, in general, the predicted muzzle velocity of the gun will change. However, an increase in muzzle velocity does not necessarily mean that the gun performance has been improved. As is well known, [3] simply by decreasing the initial fill pressure in the pump tube, other parameters being kept constant, the muzzle velocity of the gun can be increased. However, this increase is achieved at the cost of increased maximum pressures in the gun and at the projectile base. Therefore, improved gun performance is interpreted as an increase in muzzle velocity while maintaining peak pressures or as a decrease in peak pressures while maintaining muzzle velocity.

Results Without Pump Tube Diaphragm

Figures 2 and 3 show calculated curves of the maximum pressures at the projectile base and the contraction cone location versus muzzle velocity for each of the three gun lengths studied for pump tubes without a diaphragm. For each gun length studied, the muzzle velocity can be increased, as noted above, by decreasing the initial pump tube fill pressure. We note that the calculated maximum pressures increase very steeply as the muzzle velocity is increased. Also, we note that as the gun length is shortened from 100% to 75% to 33%, the gun performance deteriorates somewhat, in that higher pressures at both the projectile base and the contraction cone location are required to maintain the same muzzle velocity. This is due to the smaller amount of volumetric compression available with the shorter pump tubes.

Results With Pump Tube Diaphragm

We now turn to comparisons between cases without and with pump tube diaphragms. We will consider each gun length in turn. To decide whether the cases with a pump tube diaphragm are superior to cases without a diaphragm, the following approach has been taken. For each gun length, we use, as benchmarks, the curves of maximum pressures versus muzzle velocity for cases without a diaphragm, i.e., the appropriate curves taken from Figs. 2 and 3. Then, calculations were made for a number of gun cycles with a diaphragm. (Each gun "cycle" is the complete gun process from powder ignition to projectile leaving the muzzle for a particular set of initial conditions. The word "cycle" is not, of course, strictly true for a gun, but is used here in the interests of brevity.) The points for these latter cycles were then plotted on the same graphs showing the corresponding curve for operation without a diaphragm. If, for a given gun cycle with a diaphragm, all of the points on all graphs (including those not shown herein) are below (or at least, not above) the curves for operation without a diaphragm, this "with diaphragm" cycle can be regarded as an improvement. This performance improvement could be used to operate the gun at the same maximum pressures and achieve higher muzzle velocities or to operate the gun at the same muzzle velocities at lower maximum pressures.

Results for 100% Length Gun with a Diaphragm

The data is shown in Figs. 4 and 5. Each figure shows the corresponding benchmark, "no diaphragm" curve and two curves for two sets of cases with a diaphragm. The pump tube initial fill pressures and diaphragm break pressures are shown at the bottom of the two graphs. There are three cases with a diaphragm at a pump tube fill pressure of 1.711 bar and two cases with a fill pressure of 2.57 bar. (Along any curve, tube fill pressure or diaphragm break pressure increase as one moves towards the left.) The "with diaphragm" cases with tube fill pressures of 1.711 bar are actually slightly inferior to the cases without diaphragm and the "with diaphragm" cases at the higher tube fill pressure show a very small improvement at the projectile base and no improvement at the contraction cone location. Hence, for this length gun, there is very little advantage to using

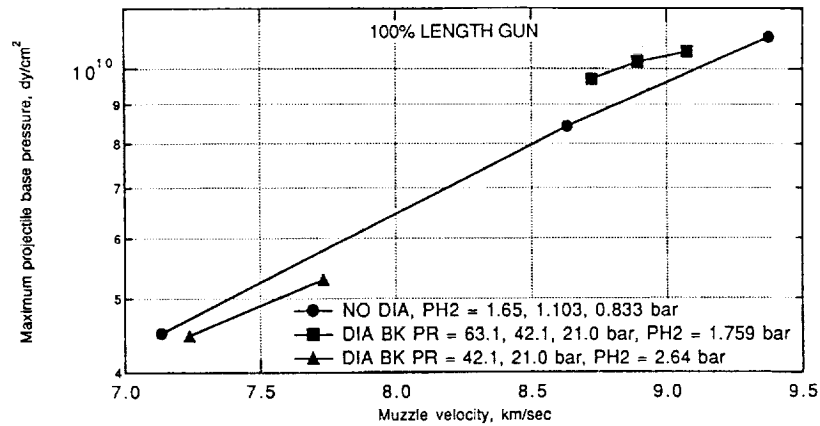


Fig. 4 Maximum projectile base pressure versus muzzle velocity for 100% length gun. Along each curve, the initial pump tube fill pressure or the diaphragm break pressure decreases towards the right.

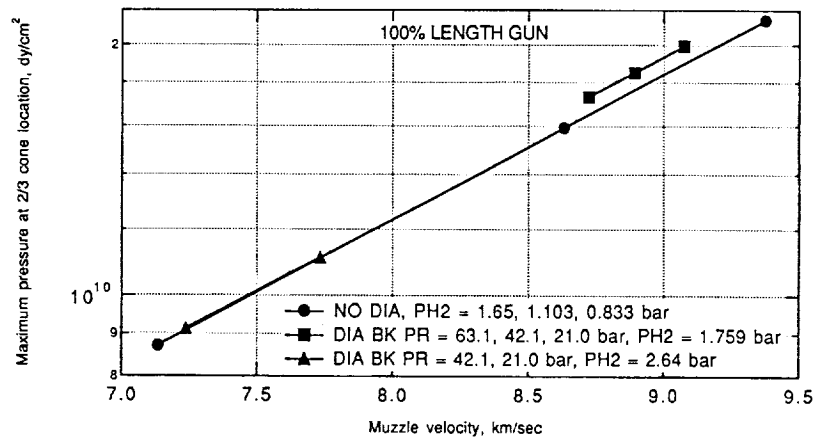


Fig. 5 Maximum pressure at 2/3 cone location versus muzzle velocity for 100% length gun. Along each curve, the initial pump tube fill pressure or the diaphragm break pressure decreases towards the right.

the pump tube diaphragm, at least for the cases studied to date. Use of the diaphragm is thus probably not worth the extra trouble for the 100% length gun, unless other "with diaphragm" cases were to be found with substantially better performance than those shown in Figs. 4 and 5.

One may ask why, with the full length gun, essentially no performance gains are achieved by using the pump tube diaphragm technique, when substantial performance gains would be predicted according to the simple, inviscid analysis presented in Sec. II. The answer is very likely is due to heat transfer effects to the pump tube wall. First, for the conventional, no diaphragm case, the gas total temperature rises only slightly for the majority (say, 80% or more) of the piston stroke. By far the greater fraction of the temperature rise occurs in the very last part of the stroke. By contrast, using the pump tube diaphragm technique, after the first compression and the breaking of the diaphragm, the gas already has achieved a substantial total temperature rise. Hence, with the pump tube diaphragm technique (assuming the same length pump tube and piston velocity), the gas is (ideally) hotter for a considerably larger fraction of the piston stroke and heat transfer losses would thus be expected to be larger. Secondly, for the no diaphragm case, the gas velocity in the pump tube ranges roughly between zero and the piston velocity. (The latter is typically of the order of 800 m/sec.) However, for the case with a pump tube diaphragm, upon the bursting of the diaphragm, gas velocities ranging up to 2 - 4 km/sec can be achieved transiently. This would also tend to make the heat transfer to the walls worse for cases with a pump tube diaphragm. For the 100% gun length case, it appears, from Figs. 4 and 5, that these effects essentially counterbalance the favorable double compression effect predicted by the simple, inviscid analysis.

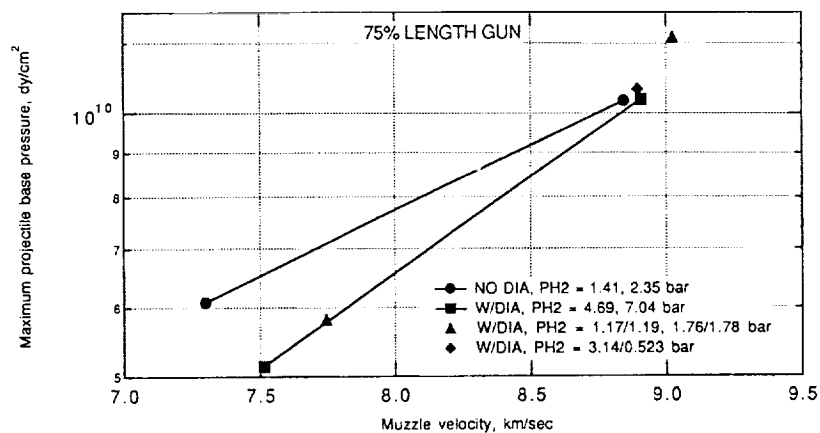


Fig. 6 Maximum projectile base pressure versus muzzle velocity for 75% length gun. Diaphragm break pressure is 61.4 bar. Along each curve, the initial pump tube fill pressure decreases towards the right. Isolated data points have hydrogen on both sides of diaphragm.

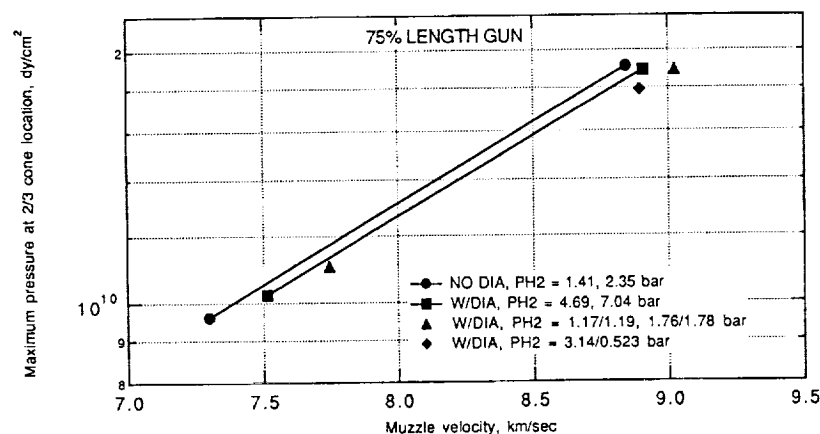


Fig. 7 Maximum pressure at 2/3 cone location versus muzzle velocity for 75% length gun. Diaphragm break pressure is 61.4 bar. Along each curve, the initial pump tube fill pressure decreases towards the right. Isolated data points have hydrogen on both sides of diaphragm.

Results for 75% Length Gun with a Diaphragm

Figures 6 and 7 show, for the 75% length gun, data roughly corresponding to that of Figs. 4 and 5 for the 100% length gun. Some different parameters are varied for the cases shown in Figs. 6 and 7, however. There are two benchmark "no diaphragm" cases (circle data points), two cases with a diaphragm with hydrogen on the upstream side only of the diaphragm (square data points) and three cases with a diaphragm with hydrogen on both sides of the diaphragm (triangle and diamond data points). We first compare the "with diaphragm" cases with hydrogen only upstream of the diaphragm and the lowest velocity case with hydrogen on both sides of the diaphragm with the benchmark cases. The improvement gained upon addition of the diaphragm is now considerably larger than for the cases with the 100% length gun. At the 2/3 cone location, these three "with diaphragm" cases now show an improvement rather than no change or a deterioration, as was the case for the 100% length gun. At the projectile base, a significant improvement is apparent in the 7.5 - 7.7 km/sec range and a very small improvement in the 8.9 km/sec range. These results are significantly better than for the 100% length gun. In the lower velocity range, from the projectile base pressure data (Fig. 6), this gain could be interpreted as about a 22% reduction in maximum projectile base pressure at the same muzzle velocity or a muzzle velocity increase of ~ 0.5 km/sec at the same maximum projectile base pressure. From the 2/3 cone location data (Fig. 7), these gains are obviously much smaller. However, there are cases where projectile failure is the critical issue and for which the performance increases shown in Figs. 6 and 7 could be useful.

We now make a brief comparison between the data with hydrogen on one side only of the diaphragm (square data points) and the data with hydrogen on both sides of the diaphragm (triangle and diamond data points). For brevity, we will refer to these types of data as "SH" and "DH"

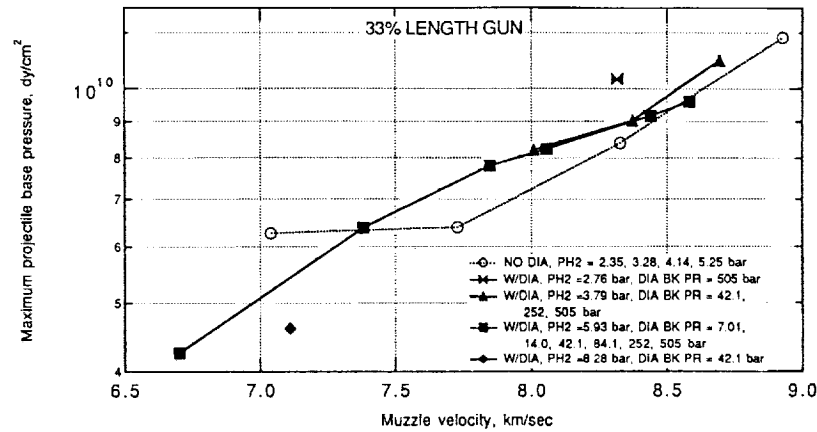


Fig. 8 Maximum projectile base pressure versus muzzle velocity for 33% length gun. Along each curve, the initial pump tube fill pressure or the diaphragm break pressure decreases towards the right.

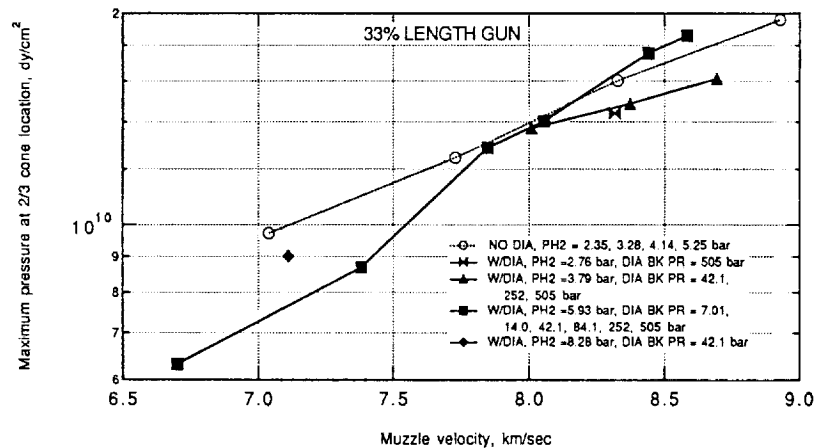


Fig. 9 Maximum pressure at 2/3 cone location versus muzzle velocity for 33% length gun. Along each curve, the initial pump tube fill pressure or the diaphragm break pressure decreases towards the right.

data, respectively. The DH point at 7.75 km/sec lies essentially on the curve of the SH data; the DH points near 9.0 km/sec are slightly below the SH curve at the 2/3 cone location, but above the SH curve at the projectile base. Since these results for DH versus SH cases were not particularly encouraging for the 75% length gun, no DH cases were run for the 33% length gun.

Results for 33% Length Gun with a Diaphragm

Figures 8 and 9 show the maximum pressure versus muzzle velocity curves for the 33% length gun. There are four benchmark “no diaphragm” cases; this data is denoted by the hollow circle data points. All “with diaphragm” cases have gas only on the upstream side of the diaphragm. CFD results were obtained for four different hydrogen load pressures, 2.76, 3.79, 5.93 and 8.28 bar (butterfly, triangle, square and diamond data points, respectively). For these four hydrogen load pressures, calculations were done at 1, 3, 6 and 1 different diaphragm break pressures, respectively, as shown in Figs. 8 and 9. The three lowest velocity “with diaphragm” cases (at 6.7 - 7.4 km/sec) show a performance improvement with respect to the “no diaphragm” cases. Here, the improvements could be interpreted as a reduction in maximum pressures at both the 2/3 cone location and the projectile base of the order of 20% at the same muzzle velocity or a muzzle velocity increase of ~ 0.5 km/sec while holding the same maximum pressure levels.

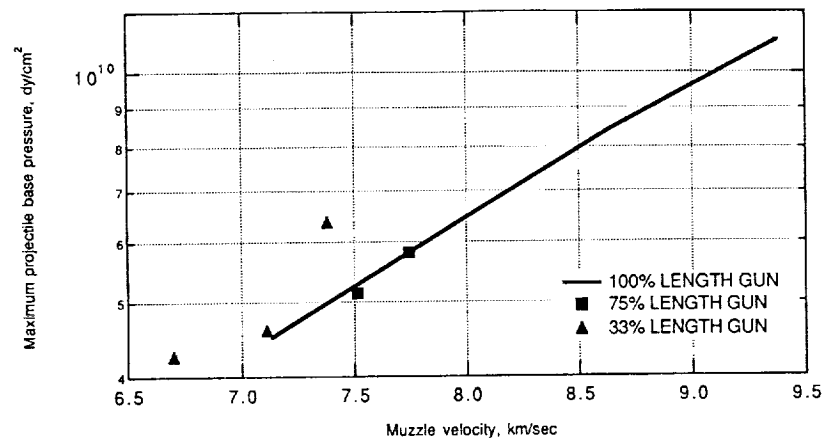


Fig. 10 Maximum projectile base pressure versus muzzle velocity for benchmark 100% length gun without diaphragm and selected cases for 75% and 33% length gun, with diaphragms. See text for details.

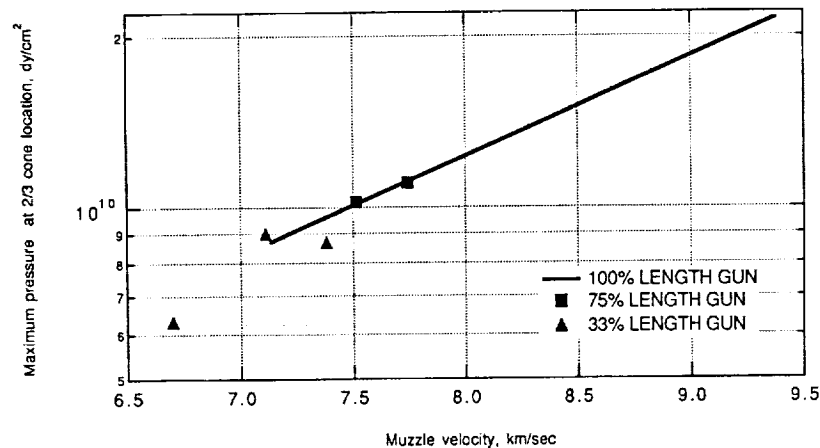


Fig. 11 Maximum pressure at 2/3 cone location versus muzzle velocity for benchmark 100% length gun without diaphragm and selected cases for 75% and 33% length gun, with diaphragms. See text for details.

Results Applied to Shortening the Pump Tube Length

Here, we study the use of diaphragms to shorten pump tube length, rather than to decrease maximum pressures or increase muzzle velocity. The approach involves primarily the cross-plotting of data already presented. Two graphs are presented, Figs. 10 and 11. Each graph presents the maximum pressure at a given location versus muzzle velocity for the benchmark 100% gun length without a diaphragm and for selected data for 75% and 33% gun lengths with a diaphragm. The intent here is to equal (or better) the maximum pressure - muzzle velocity characteristic of the 100% length gun without a diaphragm by using shorter gun (i.e., pump tube) lengths with a diaphragm. The data selected for the 75% length gun are the two lowest velocity data points of Figs. 6 and 7. For the 33% length gun, the data selected are the three lowest velocity data points of Figs. 8 and 9.

Figures 10 and 11 show the comparisons at the projectile base and the 2/3 cone location. From these figures, it can be seen that the two selected conditions for the 75% length gun with a diaphragm can equal or surpass the performance of the benchmark 100% length gun without a diaphragm. Further, the best condition for the 33% length gun with a diaphragm (at 7.1 km/sec muzzle velocity) can essentially match the performance of the 100% length gun without a diaphragm. It appears that a very useful application of the diaphragm technique would be to maintain gun performance while permitting substantial reduction in pump tube length to be obtained. This would be most useful, of course, for larger guns.

Results at Muzzle Velocities Above 7.5 km/sec

For the limited range of CFD calculations of the gun cycles discussed above, it is clear that no significant performance improvements were obtained above velocities of 7.5-8.0 km/sec. Performance increases at higher velocities would be very desirable. The authors believe that gun cycle surveys with wider ranges of parameters, in particular, with larger powder loads, may be able to provide such performance improvements. It is intended to perform the necessary CFD calculations and, possibly, experimental verifications at a later time.

EXPERIMENTAL INVESTIGATION OF TECHNIQUE

Before firing any shots in the diaphragm test program proper, it was necessary to determine the rupture pressure of the pump tube diaphragms. The diaphragms consisted of one or two sheets of Mylar A, 0.014" in thickness. The Mylar diaphragm(s) were mounted in the pump tube exactly as they would be for actual gun shots and they were then ruptured by applying a gradually increasing nitrogen pressure on one side of the diaphragm(s). Single and double thicknesses of 0.014" Mylar A were found to rupture at pressure differences of 28.3 and 58.3 bar, respectively. These rupture values were then used in the relevant CFD simulations.

The conditions used throughout the CFD study presented in the previous section (powder load - 50 gm; pump tube piston mass - 222 gm; projectile mass - 0.3706 gm) are rather heavy for the NASA Ames 0.28" gun. Since there is always a risk to the gun in implementing a new technique, it was decided to perform the first experimental tests of the diaphragm technique at somewhat milder conditions, as follows: powder load - 40 gm; pump tube piston mass - 205 gm; projectile mass - 0.335 gm. CFD calculations and experiments were performed for a 75% length gun. CFD results for the maximum pressures at the projectile base and the 2/3 cone location for the 75% length gun with a 40 gram powder load are presented in Figs. 12 and 13. (These figures are analogous to Figs 6 and 7 for the more severe, 50 gram powder load condition.) Two benchmark cases were calculated without a diaphragm (circle data points), two cases were calculated with a diaphragm break pressure of 58.3 bar (square data points) and two cases were calculated with a diaphragm break pressure of 28.3 bar (diamond and triangle data points). Three of the four cases with a diaphragm had hydrogen only upstream of the diaphragm; one case (diamond data point) had hydrogen on both sides of the diaphragm. It can be seen that, for the cases of Figs. 12 and 13, a performance increase in the 6.5 - 7.0 km/sec muzzle velocity range is gained upon the installation

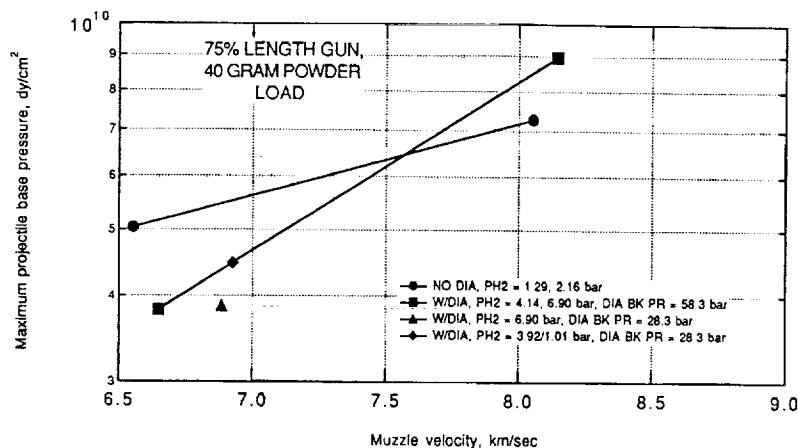


Fig. 12 Maximum projectile base pressure versus muzzle velocity for 75% length gun with 40 gram powder load. Along each curve, the initial pump tube fill pressure decreases towards the right. Isolated data points are for 28.3 bar diaphragm break pressure.

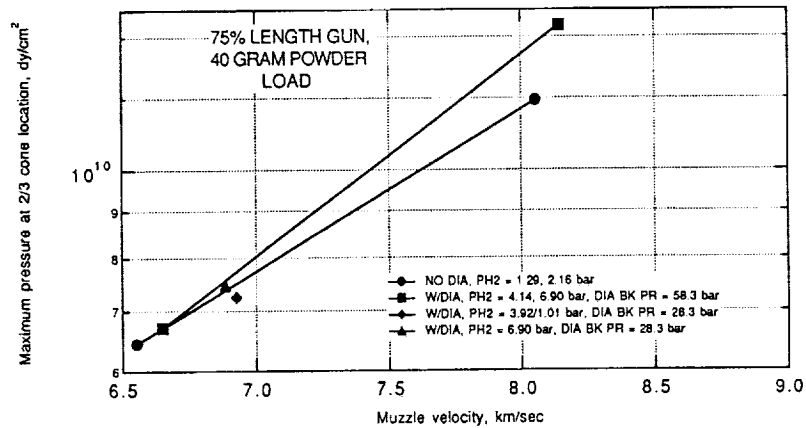


Fig. 13 Maximum pressure at 2/3 cone location versus muzzle velocity for 75% length gun with 40 gram powder load. Along each curve, the initial pump tube fill pressure decreases towards the right. Isolated data points are for 28.3 bar diaphragm break pressure.

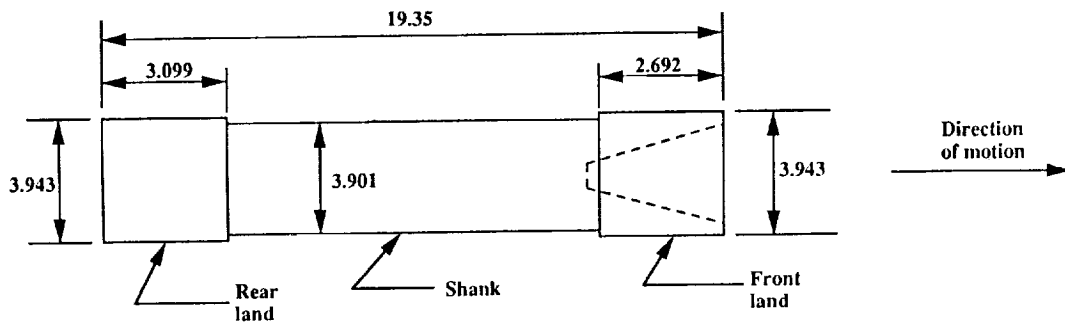


Fig. 14 Representative pump tube piston for NASA Ames 0.28" gun (not to scale). Dimensions in cm.

Table 1 Experimental and CFD data for shots on NASA Ames 0.28" gun

SHOT NUMBER	POWDER MASS	PISTON MASS	PROJ MASS	H2 PRESS	DIA BK PRESS	GUN LENGTH	CFD PISTON VEL	EXP PISTON VEL	CFD PROJ VEL	EXP PROJ VEL
	(gm)	(gm)	(gm)	(bar)	(bar)		(m/s)	(m/s)	(km/s)	(km/s)
592	40	206	0.339	6.9	58.3	75%	684.5		6.65	5.623
593	40	204	0.335	2.16		75%	710.5	706.5	6.553	5.73
594	40	206	0.323	6.9	28.3	75%	697.6		6.885	6.714
595	40	207	0.336	2.16		75%	710.5	688.5	6.553	6.346
596	40	206	0.336	3.92/1.01	28.3	75%	700.5	710.1	6.926	6.504

of the diaphragm for the projectile base pressures, but not for the 2/3 cone location pressures. For the projectile base pressures the gain could be interpreted as about a 26% reduction in maximum pressure at the same muzzle velocity or a muzzle velocity increase of ~ 0.6 km/sec at the same maximum pressure. The curves for the maximum pressures at the 1/3 cone location (not shown here) show corresponding reductions in maximum pressures of 5 - 17% gained upon installation of the diaphragm. The single case with a diaphragm at a muzzle velocity of ~ 8.1 km/sec shows a deterioration of performance with respect to the benchmark "no diaphragm" case.

Data from the actual tests used to investigate the diaphragm technique are given in Table 1. Three tests were performed with diaphragms and two benchmark tests (shots number 593 and 595) were performed without diaphragms. These tests showed that it was possible to shoot the pump tube piston through two thicknesses of 0.014" Mylar without damage to the gun. After shot 592, the piston and pump tube were examined, searching for the remnants of the diaphragm material. Some material was found to have ridden over the front land of the piston (see Fig. 14) and to have

lodged around the shank of the piston. Some material was also found in the pump tube in front of the piston (which usually ends up jammed in the contraction cone). These diaphragm fragments did not appear to cause any problems and were cleaned out of the pump tube before the next shot. Next, we discuss tests 592 (with double Mylar diaphragm) and 593 (without diaphragm). The measured muzzle velocities for these shots were well below the predicted values (by 0.8 - 1.0 km/sec). The gun barrel was considerably eroded near the main (stainless steel) diaphragm and a projectile fabrication technique involving building up the projectile diameter with super glue was used to attempt to deal with this erosion problem. It is believed that the super glue was removed early in the launch cycle and that fairly extensive gas blow-by occurred at the projectile, leading to the low launch velocities.

For the remaining three shots (shots 594 - 596), a different projectile design was adapted, which did not involve the use of super glue to build up the projectile. For these shots, the projectile muzzle velocities were much higher and agreed much better with the CFD predictions. (The CFD predictions are, in general, about 4.5% high, but once this factor of 4.5% has been allowed for, the experimental and CFD predicted velocities track to within 2% over a wide variety of shot conditions.) These shots comprised the following: (1) a benchmark shot without a diaphragm (shot 595, lowest velocity circle data points in Figs. 12 and 13), (2) a single Mylar diaphragm shot with hydrogen on the upstream side of the diaphragm (shot 594, triangle data points in Figs. 12 and 13) and (3) a single Mylar diaphragm shot with hydrogen on the both sides of the diaphragm (shot 596, diamond data points in Figs. 12 and 13).

Switching from the "no diaphragm" case (shot 595) to the "with diaphragm" cases produced increases in the measured muzzle velocities of 5.8% (shot 594) and 2.5% (shot 596). According to the CFD calculations these gains in muzzle velocity should be accompanied by decreases in the maximum projectile base pressure of 10 - 22% (Fig. 12). The calculations indicate that the maximum pressures at the 2/3 cone location increase, rather than decrease, on going from shot 595 to shots 594 and 596, but are no better or worse than the corresponding "no diaphragm" pressures (Fig. 13) for the same muzzle velocity. The calculated maximum pressures at the 1/3 cone location (not shown) show decreases of 2 - 9% on going from the "no diaphragm" case to the "with diaphragm" cases of shots 594 and 596. Of the two shots "with diaphragm", shot 594 (with hydrogen on one side only of the diaphragm) produced the larger measured muzzle velocity increase and the CFD calculations predict that it will produce the larger decrease in maximum projectile pressure (see Fig. 12). It was, however, calculated to produce slightly higher pressures at the 2/3 cone location (see Fig. 13) and at the 1/3 cone location (not shown).

Summing up the results for shots 594 - 596, the shots with diaphragms were found to produce modest, but useful, increases in muzzle velocity (2.5 - 6%) at muzzle velocities of ~ 7 km/sec. CFD calculation indicated that these muzzle velocity increases should be accompanied by significant decreases in the maximum projectile base pressures (10 - 22%) and by more modest decreases in the maximum pressures at the 1/3 cone location. The CFD calculations indicate that the maximum pressures at the 2/3 cone location are no better or worse than the corresponding pressures which would be expected for operation at the same muzzle velocity without a diaphragm.

SUMMARY AND CONCLUSIONS

The technique of installing a diaphragm in the pump tube of a two-stage light gas gun in order to improve gun performance was studied computationally and experimentally. The performance increases can be in the form of muzzle velocity increases at the same maximum pressures in the gun, or reductions of the maximum pressures in the gun at the same muzzle velocity or a reduction in the length of the pump tube, while maintaining gun performance. A computational study was carried out on the 0.28 in. gun of the HFF RAD facility at the NASA Ames Research Center. CFD calculations were performed for the normal pump tube length of the gun and for reduced pump tube lengths of $\sim 75\%$ and $\sim 33\%$ of the normal length. Little or no advantage was found upon installing the diaphragm in the full length pump tube. This failure to achieve improvement is believed to be due to increased heat transfer losses in the pump tube for the cases with a diaphragm. For both reduced length pump tubes, significant performance improvements were found, greater improvements being found for the 33% length pump tube. These performance improvements, for the best cases with a diaphragm, could be interpreted as reductions in the maximum pressures in the pump tube and at the projectile base of $\sim 20\%$ while maintaining the

projectile muzzle velocity or a muzzle velocity increase of ~ 0.5 km/sec (at muzzle velocities of ~ 7 km/sec) while not increasing the maximum pressures in the gun.

As one decreases the pump tube length, without a diaphragm, the gun performance was calculated to deteriorate due to the reduction in the volumetric compression available in the pump tube. Another way to apply the diaphragm technique is to maintain the performance of the 100% pump tube (without diaphragm) by installing a diaphragm in the 75% length and 33% length pump tubes. Our CFD studies showed that the best conditions with diaphragms in both of the shorter pump tubes were able to maintain the performance of the 100% length pump tube (without diaphragm). This could be a very useful way to employ the diaphragm technique, particularly for larger guns, where the normal pump tube lengths can become very large.

An experimental investigation of the diaphragm technique was carried out on the NASA Ames 0.28 in. gun configured with a pump tube length of $\sim 75\%$ of the normal value. The conditions for the experimental study were slightly different (less severe) than those investigated computationally. Five shots were fired in this study (three with diaphragms). It was found that the pump tube piston could be fired through one or two thicknesses of 0.014" Mylar A without causing damage to the pump tube. Two of the diaphragm shots (with single Mylar diaphragms) were found experimentally to provide modest, but useful increases (2.5 - 6%) in projectile muzzle velocity over a benchmark shot without a diaphragm. CFD calculation indicated that these muzzle velocity increases should have been accompanied by significant decreases in the maximum projectile base pressures (10 - 22%) and by decreases in the maximum pump tube pressures at some locations and increases at other locations. However, the predicted increased pressures in the pump tube did not exceed the corresponding pressures which would be expected for operation at the same muzzle velocity without a diaphragm.

The authors believe that it is likely that larger performance increases than those presented herein can be obtained using the pump tube diaphragm technique. More extensive CFD parameter surveys would be required. In particular, performance increases at still shorter pump tube lengths (perhaps as short as 10 - 20% of the normal lengths) and at higher muzzle velocities (above 8 km/sec) may well be possible. Further CFD studies and experimental verification would, of course, be required to establish such performance increases.

ACKNOWLEDGEMENTS

The experiments on the NASA Ames 0.28" gun were performed with the able assistance of the gun crew, Warren C. Norman and Michael R. Reeves. Support for D. W. B. by NASA (Contract NAS-2-14031) to Eloret is gratefully acknowledged.

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