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PRELIMINARY ASSESSMENT OF THE USE OF HEAVY GASES IN TWO-STAGE LIGHT GAS GUNS

DAVID W. BOGDANOFF

*Senior Research Scientist, AMA, Inc., Moffett Field, CA 94035

Summary—This paper discusses ballistic range testing at muzzle velocities of 0.7 to 2.7 km/s. Herein, we review several techniques for achieving these velocities - starting with the single stage gas gun and the powder gun. These techniques can have velocity limitations, both on the high end and on the low end, very high powder breech pressures, incomplete and inconsistent powder burn and can send unburned powder grains downrange to confound impact data. To try to resolve these issues, it was decided to study the use of the two stage light gas gun operated with a heavier working gas than is normally used. This would have the effect of lowering the usual muzzle velocity range of the two-stage gun using hydrogen to cover the desired low velocity range. Preliminary results are presented from firings with two NASA guns. Twenty-five shots were made with helium and nine shots with argon. Muzzle velocities of 1.1 to 4 km/s were obtained with helium and velocities of 0.7 to 2.7 km/s were obtained with argon. Overall, the heavy gas technique appears quite promising, but more firings are needed to fill out the database.

INTRODUCTION

There is interest in ballistic testing at velocities of 0.7 to 2.7 km/s. These velocities are below the usual range for two stage light gas guns. In this paper, we review various techniques for achieving these velocities and, in particular, using guns available at the NASA Ames and NASA Marshall Research Centers. Techniques discussed include the single stage gas gun with unheated or heated reservoir, the powder gun and the two stage light gas gun operated with a heavier working gas than is normally used. With a 70 MPa heated hydrogen reservoir, a single stage gas gun can access the entire desired muzzle velocity range. However, in many facilities, it may not be permitted to use high pressure hydrogen, especially if the gas is heated. Cold 14 MPa helium is likely to be permissible, but would limit the muzzle velocity to ~1.3 km/s, thus not allowing access to velocities of 1.3 - 2.7 km/s. A powder gun will typically require very high breech pressures (200 - 700 MPa) to reach muzzle velocities of 2 - 2.7 km/s. Also, at lower velocities (below ~1.3 km/s) one is likely to encounter incomplete and inconsistent powder burn and corresponding random muzzle velocity variations. Also, powder grains may be sent down range, confounding particle impact damage. These issues are discussed in the following sections, after which, attention is turned to two stage light gas guns using a "heavy" working gas - He or Ar. Preliminary results are presented from firings with two NASA guns. Twenty-five shots were made with helium and nine shots with argon. Muzzle velocities of 2 to 4 km/s were obtained with helium and velocities of 0.7 to 2.7 km/s were obtained with argon. Operation with argon produces very high temperatures and erosion and it would be better to switch from argon to nitrogen above ~1.4 km/s. The following sections describe the various techniques to obtain the desired lower muzzle velocities (with special reference to the guns available at the NASA Ames and NASA Marshall Research Centers).

Single stage gas gun

One possibility is a single stage gas gun. For a representative gun and launch mass, Fig. 1 gives the muzzle velocities expected for air, helium and hydrogen at room temperature and for hydrogen at 833.3 K. The data to construct the curves was taken from Ref. [1]. The temperature for the heated hydrogen was taken equal to that quoted for the driver of a hypersonic shock tunnel in Ref. [2]. If one is permitted to use hydrogen at 70 MPa and 833.3 K, it can be seen that a single stage gas gun can satisfy the requirements. However, for reasons of complexity and safety regulations, it may not be acceptable, in many laboratories, to use high pressure hydrogen, especially when heated. Room temperature helium at pressures of 14 and possibly 35 MPa, is likely to be acceptable. This would allow velocities of 1.1 to 1.4 km/s to be obtained. These velocities would allow only the lower 30% of the desired 0.7 - 2.7 km/s velocity range to be accessed. Also, the single stage gun normally requires a controlled diaphragm break which is not required with a powder gun or a two stage gas gun. This could be the double diaphragm technique, a lance or a burn wire, among others.

Powder gun

A second possibility is to use a powder gun. The Ames 44 mm and 61 mm powder guns have achieved maximum muzzle velocities of ~1.9 km/s (Figs. 2 - 4). The 89 mm powder gun at the Los Alamos Nevada Test Site has achieved a muzzle velocity of 2.3 km/s at a maximum powder breech pressure of 400 GPa (see Ref. [3] and Fig. 5). For the Nevada gun, Fig. 6 plots the maximum powder breech pressures versus muzzle velocity. Two data points from other references have been added to Fig. 6. Physics Applications, Inc. quotes muzzle velocities up to 2.7 km/s and breech pressures up to 700 MPa [4]. This data point - with asterisk - has been added to Fig. 6. Also, a data point from Ref. [5] (blue square) for a 406 mm gun has been added to Fig. 6. To reach the upper part of the desired velocity range, very high powder breech pressures would be necessary. In the lower part of the desired velocity range, one likely will have to deal with incomplete powder burn. This can lead to wide, random variations in muzzle velocities and ejection of unburned powder grains. This is discussed, with reference to the NASA Ames 44 mm powder gun, in the following section. Another problem with incomplete powder burn is that, where a single particle is launched against a target, the unburned powder grains impacting the target can completely confound the searched-for target damage information.

The NASA Ames 44 mm powder gun - incomplete powder burn

In Ref. [6], for the Ames 44 mm powder gun, it was shown that much more efficient, complete and consistent powder burns were obtained when a metal insert was placed in the powder chamber to reduce the chamber volume. Without an insert, the chamber volume was 425 cm^3. With the larger inside diameter (22.2 mm) insert, the chamber volume was reduced to 97 cm^3 and with the smaller inside diameter (15.9 mm) insert, the chamber volume was reduced to 62 cm^3. The insert with the smallest chamber volume produced the best burn performance. Figures 7 and 8 show the relevant graphs of powder mass versus muzzle velocity adapted from Ref. [6]. For the largest powder loads (120 g and above) the total variation in muzzle velocity is ~5% for a given powder load. However, at several points in the graphs, it can be seen that much wider variations in muzzle velocity can occur for a given constant powder load. For example, in Fig. 7 at a ~105 g powder load (red triangles) the muzzle velocity varies from 0.76 to 0.91 km/s (18% total variation) and at a ~48 g powder load (violet triangles) the muzzle velocity varies from 0.32 to 0.55 (52% total variation). In Fig. 8, with the 22.2 mm insert, at a ~9 g powder load the muzzle velocity varies 16% for the black circle data points and 28% for the red triangle data points.

By installing an insert or by changing to the smaller volume insert, the burn characteristics for the above cases were much improved. For example, with no insert, the violet triangle Mach number data at 48 g powder load produces a total muzzle velocity variation of 52%. On changing to the 22.2 mm insert, we obtain the black, red and violet filled circle data points. These points define a curve that is sloped (as it should be) with much less total horizontal variation (13%) than the violet triangle data points. Also, we note that to obtain a muzzle velocity of ~0.50 km/s with no insert requires 48 g of powder, whereas with the 22.2 mm insert, only ~16 g of powder is required. This strongly suggests that, without the insert, about 2/3 of the powder is unburned. With the 22.2 mm insert at ~9 g powder load, muzzle velocity variations from 1.0 to 1.34 km/s (28%) were obtained. On switching to the 15.9 mm insert with powder loads ranging from 1 to 7 g, muzzle velocities of 0.6 - 1.0 km/s were obtained with total velocity variations of 10 - 15%. Even with an insert in place CFD calculations for the Ames 44 mm powder gun indicate substantial amounts of unburned powder. For example, for IMR 4227 powder at 14 g powder load and with the 22.2 mm insert, CFD calculations indicate ~35% unburned powder, but, at a powder load of 30 g, ~10% unburned powder is calculated. Also, the gunners have observed substantial amounts of unburned powder after a shot. Even with the best powder chamber insert used to date, the total muzzle velocity variations range from 10 to 15%, better than the values without inserts at powder loads below 120 g (18 to 52%), but not nearly as good as the results with powder loads above 120 g without inserts (~5% total velocity variation). For the Ames 44 mm powder gun without a powder chamber insert to reduce the ullage, unacceptable random variations in muzzle velocity occur at velocities less than 0.8 - 1.2 km/s. This can be seen in Figs. 7 and 2.

The NASA Ames 61 mm powder gun

For the Ames 61 mm gun (Figs. 3 and 4) most of the data is likely at muzzle velocities where appreciable random velocity variations are known to occur and for velocities above ~0.6 km/s, the variations in muzzle velocities at a given gun operating condition range from 10 to 17%. At muzzle velocities below ~0.6 km/s, the variations increase to nearly 40%.

TWO STAGE GUN WITH A HEAVIER WORKING GAS THAN NORMAL

A third possibility is to use a two stage gun, but to operate it with heavier gases than is usually done. This is discussed in the following sections with reference to the NASA Ames AVGR (Ames Vertical Gun Range) 7.62 mm/63.5 mm gun and the NASA Marshall 5.58 mm/20 mm gun. One advantage of this technique is that, in many facilities, the two stage gun already exists and, by using heavy gases, we can drop its muzzle velocity range from the more usual 3 to 8 km/s to cover the range 0.7 - 2.7 km/s.

The NASA Ames Vertical Gun Range (AVGR) gun

The AVGR gun is a two-stage light gas gun with a pump tube diameter of 63.5 mm and a launch tube diameter of 7.62 mm. The first stage powder breech is chambered and has a diameter of 76.2 mm. (In the present context "chambered" means that the up range part of the powder breech is one diameter, followed by a conical taper section leading to the down range part of the breech, which has a smaller diameter.) The L/D of the pump tube is 30 and that of the launch tube is 183. The powder breech of the AVGR gun has 3 ports for breech plugs. One port lines up with the pump tube and the other two (side) ports are at 90 degrees to the pump tube. The normal gun configuration has the straight-on port and one side port plugged and the powder charge placed in the other side port. This results in a total breech volume of 1242 cm^3. A second (alternate) configuration, would have both side breech ports plugged and the powder charge placed in the straight-on breech port. This configuration has a total breech volume of 804 cm^3.

Experimental data and CFD results for the NASA Ames AVGR gun

Figure 9 shows muzzle velocity versus powder load data for 66 experimental shots for the normal AVGR gun configuration with hydrogen working gas; for these shots the powder was IMR 4895 and the launch mass was ~0.60 g. (Note that "break valve", "diaphragm" and "disk" all refer to the rupture diaphragm located just uprange of the projectile.) Figure 10 shows 25 corresponding data points for launch masses of ~0.33, ~0.43 and ~0.52 g. Figure 11 shows 7 data points for a helium working gas and a launch mass of ~0.60 g. Figure 12 shows the region of overlap between the data of Figs. 9 and 11. We note that the scatter of the data is large. For the Fig. 9 data the total scatter is 20 - 30% of the mean values. For the data of Figs. 10 and 11, the corresponding values are 9 - 22% and 10 - 15% respectively. Figure 13 shows data from the Ames two-stage gun with a pump tube diameter of 158.8 mm and a launch tube diameter of 38.1 mm. It is seen that the data scatter is much smaller for this gun than for the AVGR gun. Scatter values for the HC-33-FS powder (no longer used) range from 2 to 6% and that for the currently used WC 886 powder is 1.5%. CFD simulations for the two guns indicate that of the order of 40% of the powder is unburned in the AVGR gun, whereas, for the 1.5" gun, powder combustion is complete. Figure 13 also demonstrates that a two stage light gas gun operated with hydrogen working gas can produce repeatable muzzle velocities above ~2.7 km/s.

Figure 14 repeats the experimental data points of Fig. 9, but deletes the trend lines of Fig. 9 and, instead, shows CFD calculated curves. The CFD calculations were performed with hydrogen working gas for IMR 4895, 4831 and 4227 powders in the normal breech configuration and with IMR 4895 powder in the alternate breech configuration. The calculations were made for powder loads of 40, 60 and 100 g. The CFD curves with 4895 and 4831 powder in the normal gun configuration fit the experimental data fairly well, but, as noted previously, there is a large amount of scatter in the experimental data. The CFD curves with 4227 powder in the normal gun configuration and with 4895 in the alternate gun configuration are significantly above the experimental data.

Figure 15 repeats the experimental data points of Fig. 11 for helium working gas, but also shows a CFD calculated curve. The experimental results are in rough agreement with the CFD results for powder loads of 30 and 40 g. The experimental results for a 55 g powder load are very low, barely exceeding the experimental results at a 40 g powder load and being well below the CFD curve.

Figure 16 shows the CFD calculated unburned powder fraction when the projectile exits the muzzle plotted versus powder load for the four cases with hydrogen working gas shown in Fig. 14 above. It is seen that the predicted fraction of unburned powder for the 4895 powder is substantial, ranging from ~0.34 to ~0.47. If, because of variations in packing the powder, ignition, etc. the unburned powder fraction is ~0.3 on one shot and ~0.5 on the next shot, this would produce a substantial variation in energy release and correspondingly in muzzle velocity. If one changed to the 4227 powder, the unburned powder fraction is predicted to drop to ~0.02 to ~0.18, making the variation in energy release and in muzzle velocity much smaller than for the 4895 powder. In this way, more repeatable muzzle velocities should be achievable. Changing from 4895 powder to 4227 powder with the Ames 44 mm powder gun has been shown to increase the muzzle velocity and decrease the amount of unburned powder. In Fig. 4, the higher muzzle velocities produced by the 4227 powder, relative to those of the 4895 powder can be seen between powder masses of 40 and 60 g (solid circle versus hollow square data points).

From Fig. 14, we can estimate the amount of 4227 powder needed to obtain a given muzzle velocity. For example, for a muzzle velocity of 5.4 km/s, we can estimate that ~69 g of 4227 powder would be needed versus ~98 g of 4895 powder. Figure 17 shows that the maximum pressures vary with muzzle velocity, but, to first order, are independent of the powder choices and the breech configurations studied here. Thus, switching from 4895 powder to 4227 powder (with the correct reduced powder load) should not increase the risks to the gun and the launch package.

Figure 18 shows CFD calculated muzzle velocity versus powder mass curves for the Ames AVGR gun using H_2, He, N_2 and Ar working gases at two different load pressures. [Note that the H_2 curve has already been presented in Fig. 14 and the He curve has already been presented in Fig. 15.] Figure 19 presents a cross plot of Fig. 18. For these possible gun operating conditions, one must check the maximum pressures at the projectile base and in the gun. Figure 20 shows, plotted versus muzzle velocity, the CFD calculated maximum projectile base pressures for the conditions of the curves of Fig. 18. Figure 21 shows the corresponding plot for the maximum gun pressures. Figures 20 and 21 also show (data points and trend line) the maximum powder breech pressures for the Nevada 88.9 mm powder gun. It is seen that for muzzle velocities above 1.8 km/s, the maximum pressures in the powder gun are 3 or more times those for optimized two-stage guns using hydrogen or helium working gas. On the other hand, for argon and nitrogen working gases, the heavy gas maximum pressures range from somewhat better to somewhat worse than the maximum pressures in the powder gun.

Figures 18 - 21 show, that for a given required muzzle velocity, various combinations of working gas and working gas pressures can be used. For each muzzle velocity, the various options will have different maximum pressures and required powder load. Table 1 shows the gun operating conditions and maximum pressures taken from Figs. 20 and 21 for seven different muzzle velocities. (We note that not all of the possible operating conditions seen in Figs. 20 and 21 are shown in Table 1.) From Table 1, we see that, for each muzzle velocity, by changing the working gas and its pressure, we can play off maximum pressures versus powder loads. Higher powder loads produce a more complete powder burn (see Fig. 16) and hence, should produce more consistent muzzle velocities. To get the maximum powder load for a given muzzle velocity, one would have to use the conditions which produce the highest maximum pressures.

However, we note from Table 1 that these pressures are about 4 times lower than those which occur in routine operation of the AVGR gun with hydrogen working gas at muzzle velocities of ~5.5 km/s. Thus, we should be able to use powder loads of 60 - 71 g for all muzzle velocities of 1.0 km/s and above.

Figure 22 reproduces Fig. 9 with the addition of experimental data for helium from Fig. 11 and data for argon. The experimental data for argon are about 25% below the CFD line, which, however, has been scaled using CFD results for helium. They do show that muzzle velocities of 0.7 - 0.8 km/s can be achieved using argon as the gun working gas.

Table 1. Gun operating conditions and maximum pressures taken from Figs. 20 and 21.

Muzzle velocity (km/s)	Gas	Gas pressure (kPa)	Max gun pressure (MPa)	Powder load (g)	Max projectile base pressure (MPa)
5.48	H_2	269	586.1	100	331.0
3.0	He	276	157.2	71.3	73.1
	H_2	269	123.4	61.3	77.2
2.0	He	552	80.0	71.2	29.0
	He	276	57.9	50.7	31.7
	H_2	269	44.8	32.5	32.4
1.6	Ar	276	158.6	65.5	57.9
	He	552	41.4	56.3	21.4
	He	276	31.7	40.4	19.3
1.2	Ar	552	120.7	69.8	55.2
	Ar	276	69.0	49.1	22.8
	He	552	17.2	40.0	13.1
	He	276	15.9	30.0	12.4
1.0	Ar	552	72.4	60.3	25.5
	Ar	276	38.6	41.0	13.8
	He	552	11.0	30.0	9.7
0.85	Ar	552	33.1	47.7	15.2
	N_2	552	26.9	37.1	11.7
	Ar	276	22.1	33.4	10.3

The NASA Marshall 5.59 mm/20 mm gun

The NASA Marshall gun is a two-stage light gas gun with a pump tube diameter of 20 mm and a launch tube diameter of 5.59 mm. The first stage powder breech is chambered and has an up range diameter of 25.4 mm and a down range diameter of 20 mm to match the pump tube. The L/D of the pump tube is 75 and that of the launch tube is 212. The total powder breech volume is 45.93 cm^3.

Experimental data and CFD results for the NASA Marshall 5.59 mm/20 mm gun

NASA Marshall also has an interest in low muzzle velocities, 0.7 - 2.7 km/s, and to achieve these velocities, test shots have been made with the 5.59 mm/20 mm gun using He and Ar working gases. The gun operating conditions were as follows.

Working gases:
- Ar at 35 psia - 4 shots
- Ar at 70 psia - 3 shots
- He at 70 psia - 16 shots

Powder load: 2 - 4.6 g Unique
Piston mass: 37 g
Launch mass: 0.22 - 0.24 g

CFD code calculations of powder mass sweeps of gun performance were made for the three gas/gas pressure conditions given above. CFD powder mass sweep calculations were also made for nitrogen and hydrogen at 483 kPa. For these sweeps, the gun operating parameters were kept as given in the above list, except for the working gas. To date, there is no experimental data to compare with the latter two powder mass sweeps. (Note that two of the CFD powder mass sweeps were carried out to 6.5 g powder load.) Figure 23 shows the CFD and experimental results for muzzle velocity versus powder load. The CFD code was tuned [Ref. 7] for the He experimental data at 3.25 - 3.5 g powder load and thereafter (for both He and Ar) no further tuning was performed. Over all, the agreement of the CFD and experimental results is very good. The extension of the CFD line for argon at 35 psia passes close to the scaled AVGR gun experimental data. The CFD - experiment agreement for He at 483 kPa is very good at powder loads of 3.2 to 4.6 g, but the experimental data shows somewhat more scatter and is somewhat low at a powder load of 2.4 - 2.5 g. For helium at 483 kPa, the CFD code predicts erosion starting at about 4.5 km/s muzzle velocity.

The CFD code also predicts the maximum working gas temperatures for each case. Figures 24 and 25 show the maximum gas temperatures plotted versus the muzzle velocity and the powder load, respectively. Note very high maximum temperatures with argon - up to 5600 K at 483 kPa gas pressure (muzzle velocity ~2.1 km/s) and up to 8000 K at 241 kPa gas pressure (muzzle velocity ~2.8 km/s). This may well be connected with the observed barrel erosion with argon. However, maximum tube wall temperatures predicted by CFD calculations with argon are ~600 K, far below the steel melting point of 1723 K and thus the CFD code does not predict erosion for shots with argon. However, the current code does not include radiative heating of the gun barrel wall. A separate calculation of radiative heating of the barrel wall with black body radiation at 8000 K was made. This indicated that that radiative heating at this condition could cause wall erosion comparable with that predicted for convective heating. The high temperatures for operation with argon at 241 kPa (for example, a temperature of 8000 K at a muzzle velocity of ~2.8 km/s) are in contrast to the corresponding maximum temperatures of 2500 K for 483 kPa He and 3000 K for 483 kPa N_2.

PRELIMINARY CHOICE OF HEAVY GAS

Based on the information presented above, one may make a preliminary choice of the heavy gas to use in a light gas gun to obtain low muzzle velocities (0.7 - 2.7 km/s). Figure 23 shows a fairly consistent CFD and experimental muzzle velocity versus powder load trend for Ar at 241 or 275 kPa from 0.7 to 2.8 km/s. If we take the maximum allowable gas temperature to be ~3000 K, from Fig. 24, the maximum muzzle velocity for argon would be 1.4 km/s. Thus, Ar could be recommended for muzzle velocities of 0.7 to 1.4 km/s.

In section 2.2, it was noted that a two stage light gas gun operated with hydrogen can produce repeatable muzzle velocities (see Fig. 13) at muzzle velocities above ~2.7 km/s. Hence, we assume that heavy gases need not be used in two stage light gas guns at muzzle velocities above 2.7 km/s.

For the muzzle velocity range of 1.4 to 2.7 km/s, two gases studied in this report may be usable as the heavy gas - helium and nitrogen at 70 psia pressure. From Fig. 23, helium at 483 kPa produces repeatable data from 4.1 km/s down to 3.0 km/s but somewhere between 3.0 km/s and 2.5 km/s, the repeatability deteriorates. It would likely be possible to extend the range of helium downward by increasing the pressure, say, to 760 kPa. The pressure effect can be seen in Fig. 23 and in the CFD results of Figs. 18 and 19. From Fig. 24, we see that, above muzzle velocities of ~2.4 km/s, He produces lower maximum temperatures than N_2, while, for velocities below 2.4 km/s, the reverse is true. Hence, nitrogen at 483 kPa is a preliminary choice for the muzzle velocity range 1.4 to 2.4 km/s. For the velocity range 2.4 to 2.7 km/s, there are several possible choices:

1. Helium at 483 kPa - repeatability must be checked
2. Helium at ~760 kPa
3. Nitrogen at 483 kPa - accept high gas temperatures

SUMMARY AND CONCLUSIONS

In the plots of muzzle velocity versus powder load for the AVGR gun (Figs. 9 - 12) there is a large amount of scatter (10 - 30% of the mean values, with many scatter values above 20%). By contrast, for the Ames 38.1 mm two stage gun (Fig. 13), the scatter is much less, 2 - 6% with the Hercules HC-33-FS powder (no longer used) and ~1.5% with the currently used St. Marks WC 886 powder. CFD calculation indicate ~40% unburned powder for the AVGR gun versus complete combustion for the Ames 38.1 mm gun. The normalized powder breech volume for the AVGR gun is about 7 times greater than that for the Ames 38.1 mm gun. (The normalized powder breech volume is the powder breech volume divided by the launch tube diameter cubed.) The powder densities for the AVGR gun are 0.024 - 0.084 g/cm^3, whereas for the Ames 38.1 mm gun, they are 0.051 - 0.202 g/cm^3. The low powder loads and powder densities for the AVGR gun lead to more incomplete and inconsistent powder burns. (See Fig. 16 and discussion of section on the NASA AVGR gun.) It may be desirable to switch from the IMR 4895 powder to a faster burning powder, such as IMR 4227. It also may help to have both side breech ports plugged and the powder charge placed in the straight-on breech port. This would produce a 35% reduction in powder breech volume.

The lower velocity experimental data for the NASA AVGR gun is shown in Fig. 12. The data of Fig. 12 shows the large scatter mentioned earlier and also shows that the helium data trends to somewhat lower muzzle velocities than the data with hydrogen. At the lowest muzzle velocities, the data scatter may well be aggravated by the very low powder loads (30 to 40 g) and powder densities (0.024 - 0.032 g/cm^3). If we raise the gas pressure or switch to a heavier gas, we can raise the powder load at a given velocity (see Fig. 18), likely leading to more complete and consistent powder burns. For example, from Table 1, for a muzzle velocity of 2 km/s, we could use 276 kPa helium and a powder load of 50.7 g. If 552 kPa helium were used, the required powder load would be 71.2 g (see Fig. 18). We must re-iterate here that the NASA AVGR gun has a long history of substantial random variations of muzzle velocity (see Figs. 9 - 12 and 22).

For the NASA Marshall gun, the overall agreement of the CFD and experimental results for muzzle velocity for He and Ar is very good (Fig. 23). Experimentally, there is some increased muzzle velocity variation at powder loads of ~2.5 g for He at 483 kPa. The CFD code predicts maximum working gas temperatures with argon up to 5600 K at 483 kPa gas pressure and up to 8000 K at 241 kPa gas pressure (see Figs. 24 and 25). Radiation heating of the gun tube wall at these very high temperatures is consistent with erosion seen by the gunners with argon. (The CFD code does not predict gun erosion with convective heating only for Ar. The code does not presently include radiative heating.) Switching from argon to nitrogen on exceeding muzzle velocities of ~1.4 km/s would produce large reductions in the maximum gas temperatures (Fig. 24). To build a database, it is suggested that firings with 483 kPa N_2 be made with the NASA Marshall gun at powder loads from 1 to 4 g. This would help to fill out Fig. 23. It is also suggested to try 276 kPa N_2 and 276 kPa Ar at powder loads of 30, 40 and 55 g in the Ames AVGR gun. This would put some N_2 data on Fig. 22 and check the reproducibility of the argon data for the same plot. Note that using a two-stage gun with a heavy gas (including He) for low velocities avoids two problems with powder guns - sending powder grains down the range to confound impact data and the very high pressures required to reach muzzle velocities of 1.8 - 2.7 km/s.

This study is clearly a preliminary investigation since it is based on a limited number of shots with the proposed "heavy" gases:

He - 25 shots
Ar - 9 shots
N_2 - no shots to date

From the previous sections, it does appear that the "heavy" gases He, N_2 and Ar can be put to good use with two-stage light gas guns to obtain good data in the low velocity range of 0.7 - 2.7 km/s. The list of heavy gases could also be expanded to include Ne, CO_2 and mixtures such as He/Ar or H_2/N_2. This proposed technique may have advantages over the use of single stage gas guns or powder guns, but more test firings are needed to develop the technique.

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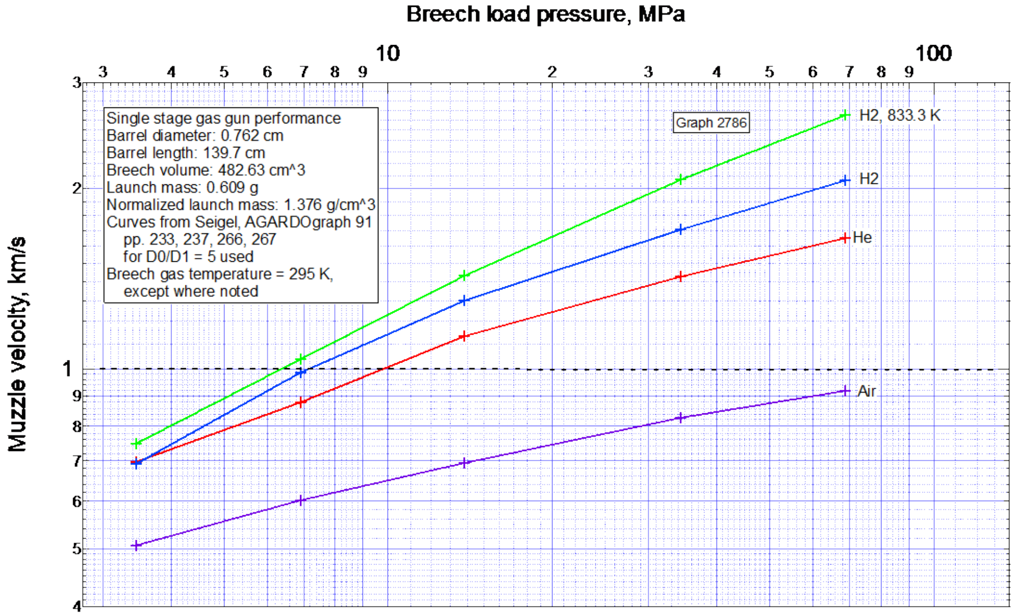

Figure 1. Single stage gas gun performance. Muzzle velocities versus breech load pressure.

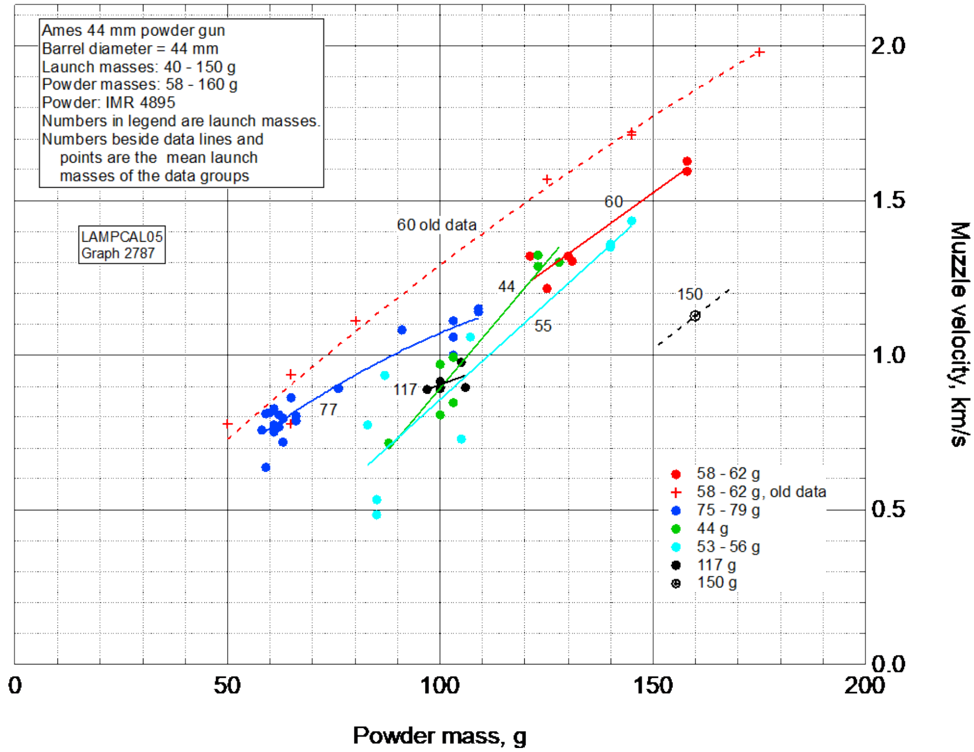

Figure 2. Performance of Ames 44 mm powder gun. Muzzle velocities versus powder mass.

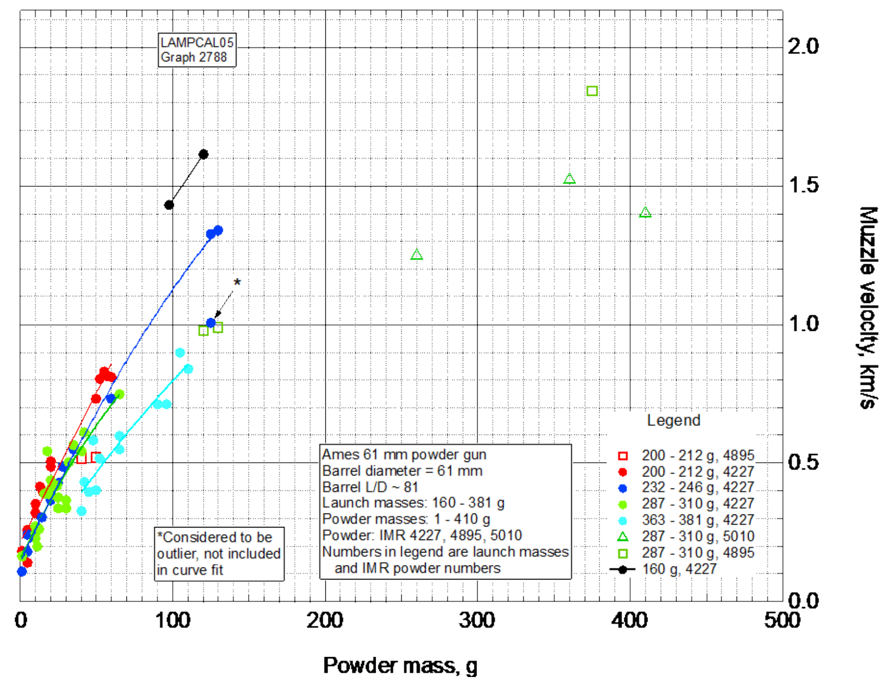

Figure 3. Performance of Ames 61 mm powder gun. Muzzle velocities versus powder mass.

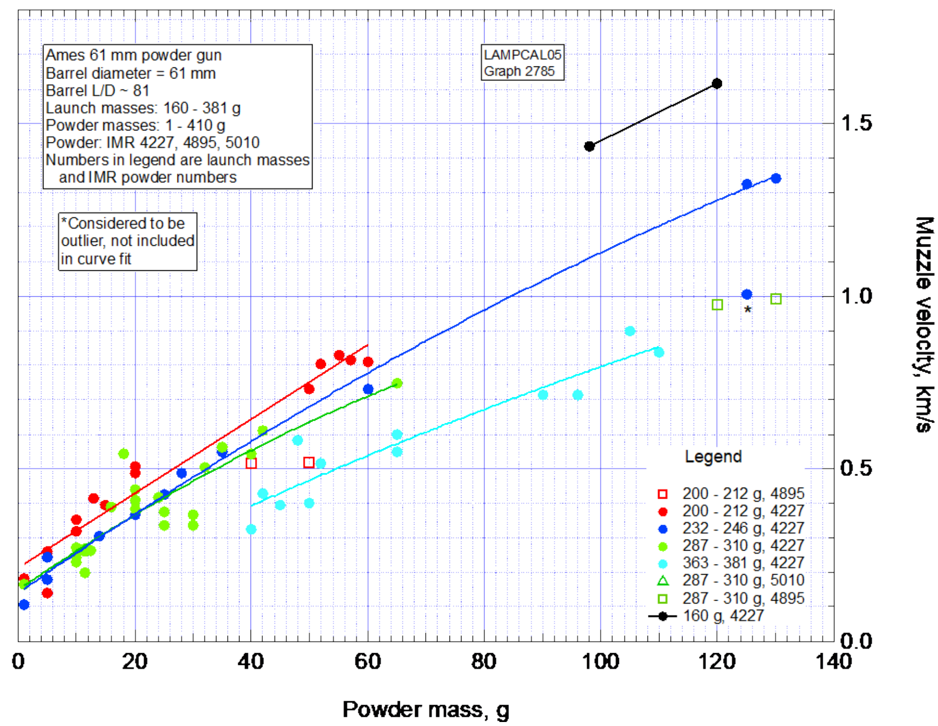

Figure 4. Performance of Ames 61 mm powder gun. Muzzle velocities versus powder mass. Rescaled version of Fig. 3.

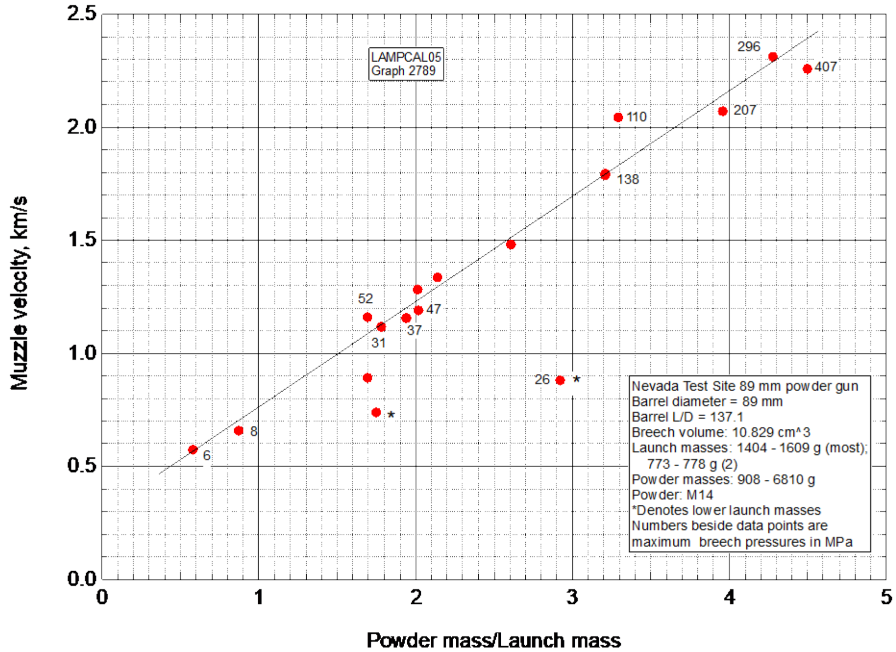

Figure 5. Performance of Nevada test site 88.9 mm powder gun. Muzzle velocities versus (powder mass)/(launch mass). Numbers by data points are maximum breech pressures in MPa.

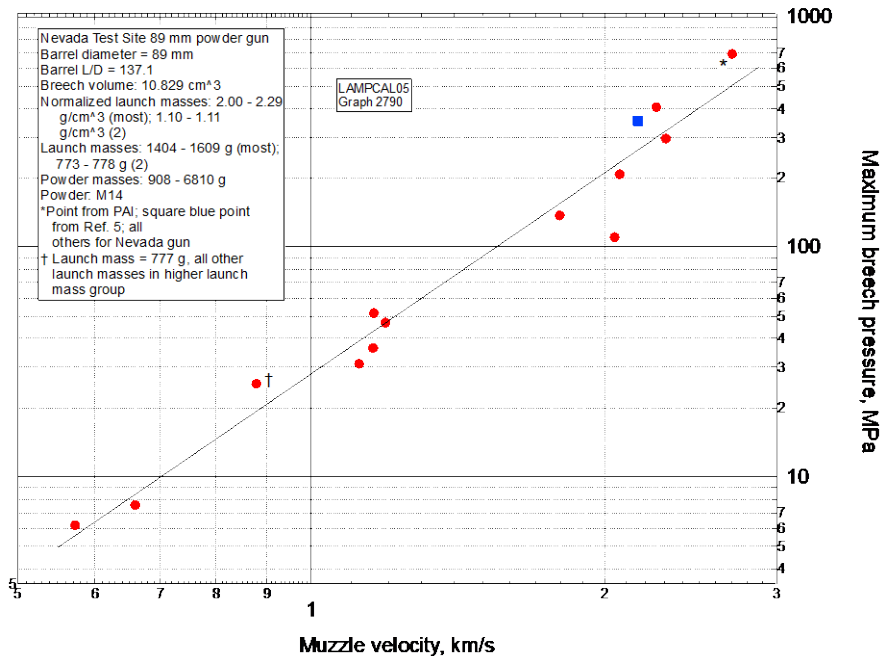

Figure 6. Maximum breech pressures versus muzzle velocity for Nevada test site 88.9 mm powder gun. Highest data point is quoted by Physics Applications, Inc. [4]. Blue square data point is from Ref. [5].

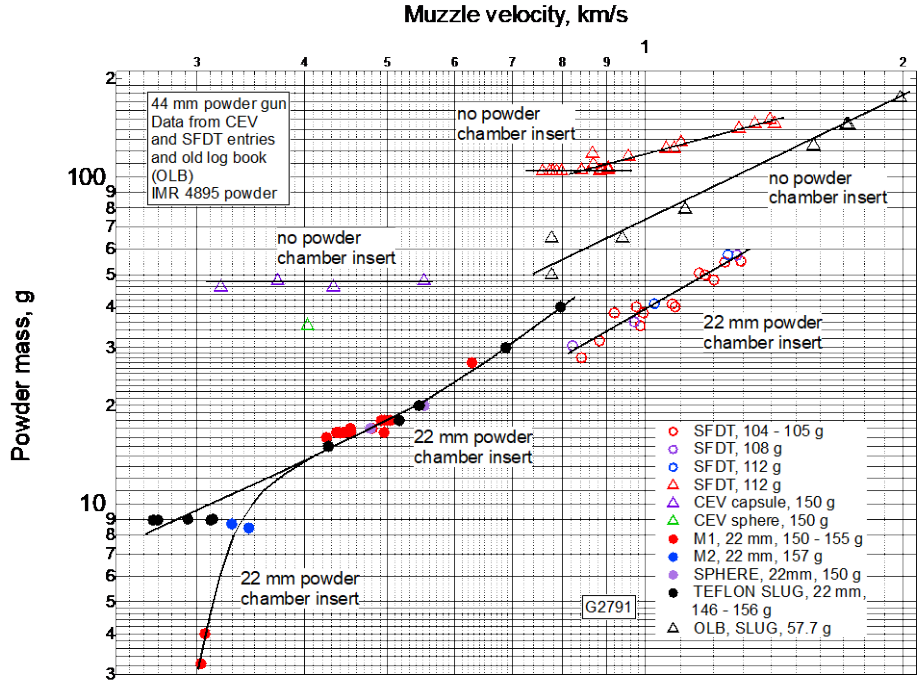

Figure 7. Powder mass versus muzzle velocity for Ames 44 mm powder gun. Launch masses indicated; "22 mm" denotes 22 mm powder chamber insert used.

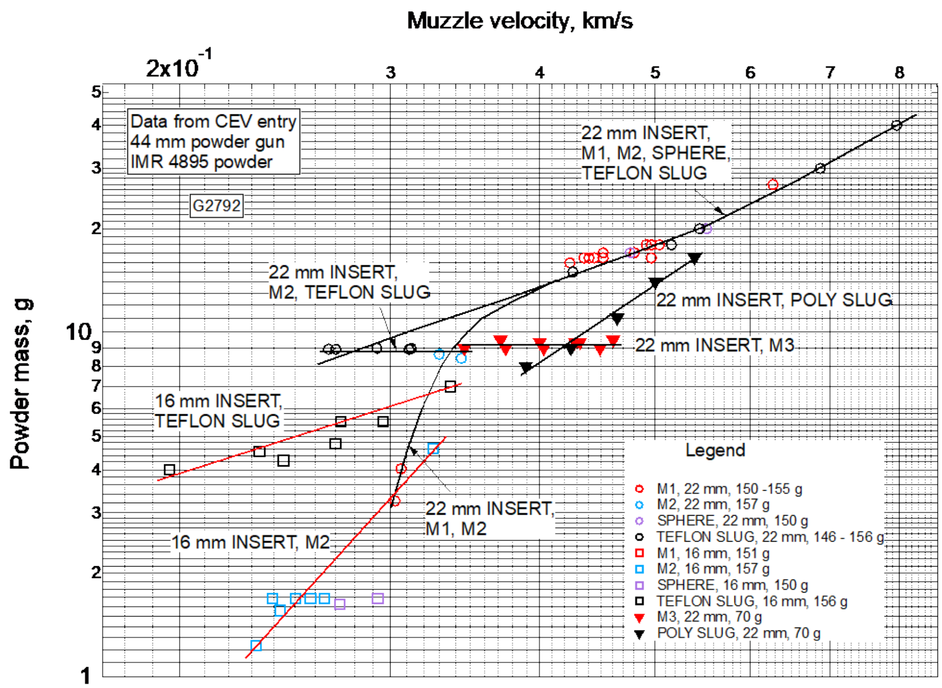

Figure 8. Powder mass versus muzzle velocity for Ames 44 mm powder gun. Launch masses indicated; "22 mm" denotes 22 mm powder chamber insert used; "16 mm" denotes 16 mm powder chamber insert used.

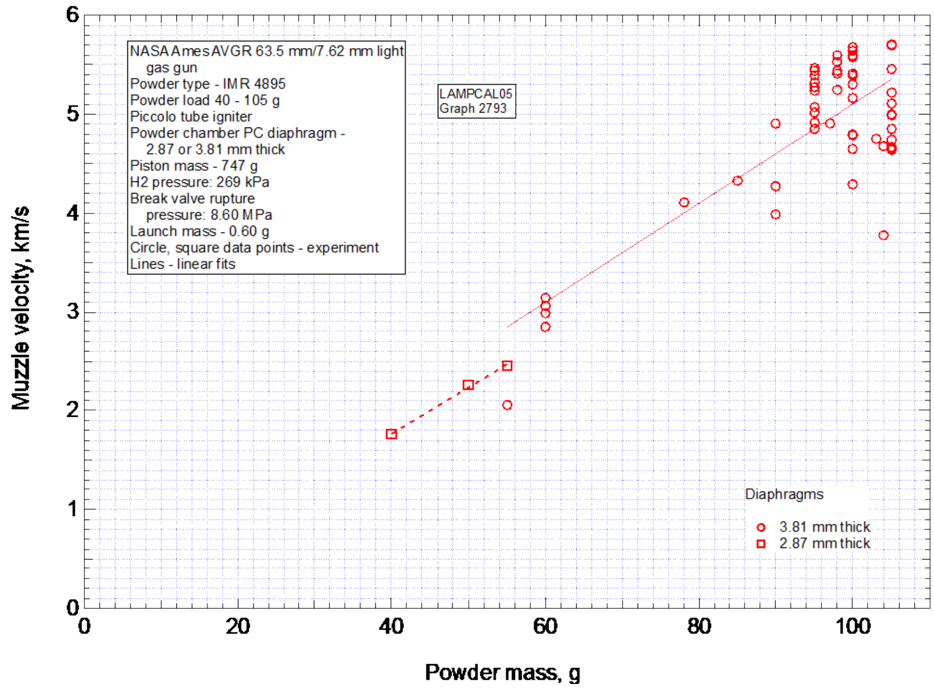

Figure 9. Experimental data for the Ames AVGR gun operated with hydrogen. Muzzle velocity versus powder load. Launch mass ~0.60 g.

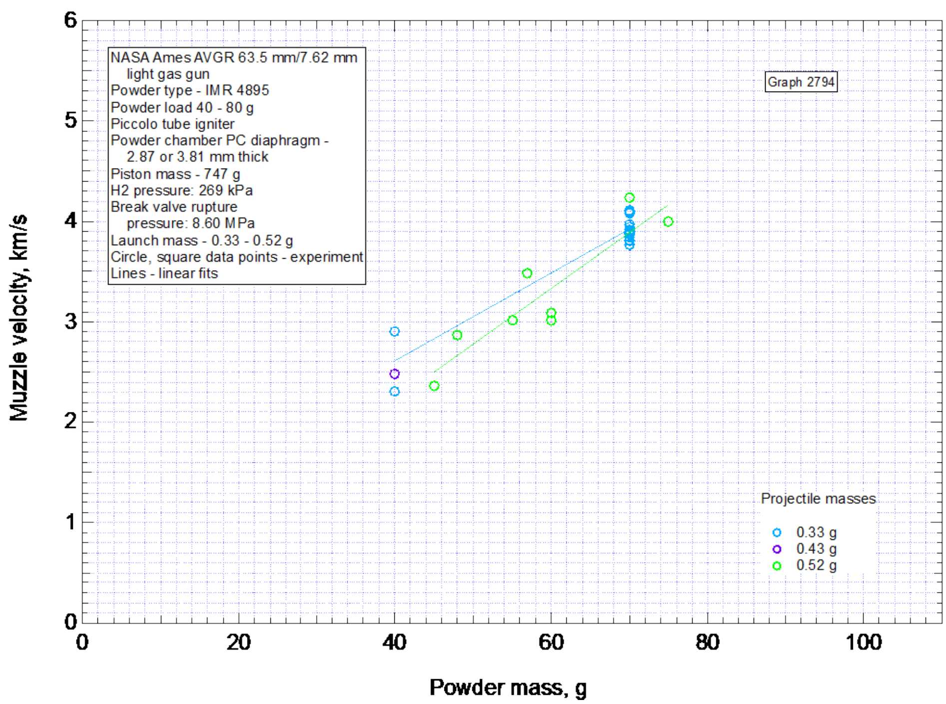

Figure 10. Experimental data for the Ames AVGR gun operated with hydrogen. Muzzle velocity versus powder load. Launch masses ~0.33 to ~0.52 g.

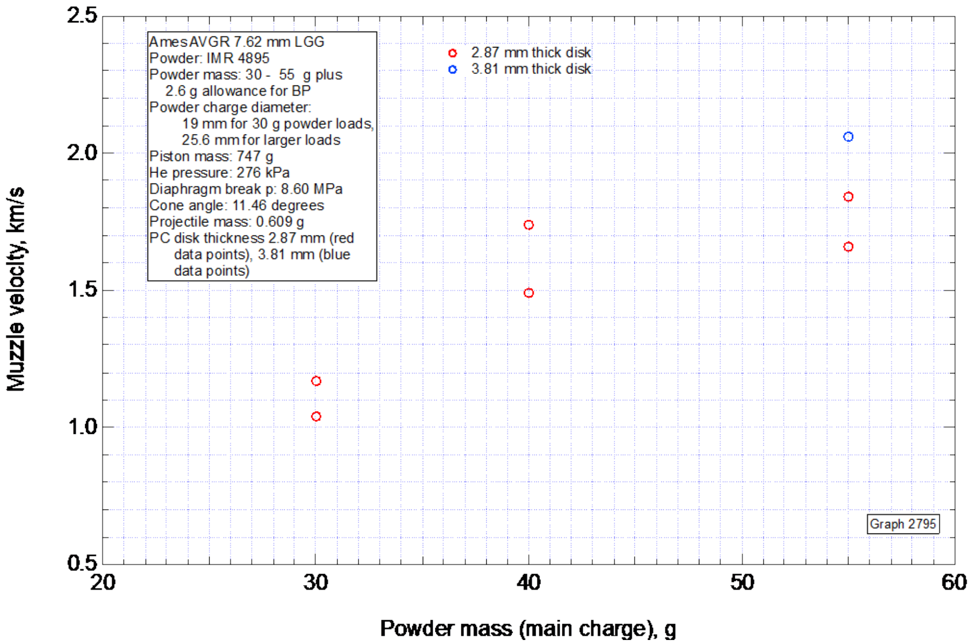

Figure 11. Experimental data for the Ames AVGR gun operated with helium. Muzzle velocity versus powder load. Launch mass ~0.60 g.

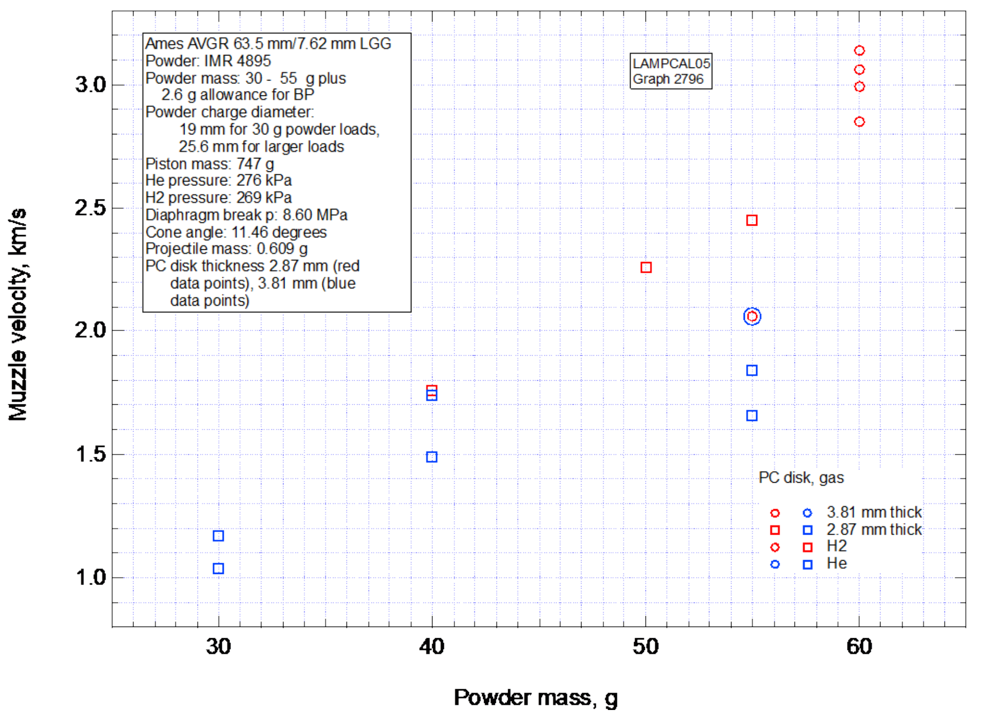

Figure 12. Experimental data for the Ames AVGR gun operated with helium and hydrogen. Muzzle velocity versus powder load. Launch mass ~0.60 g.

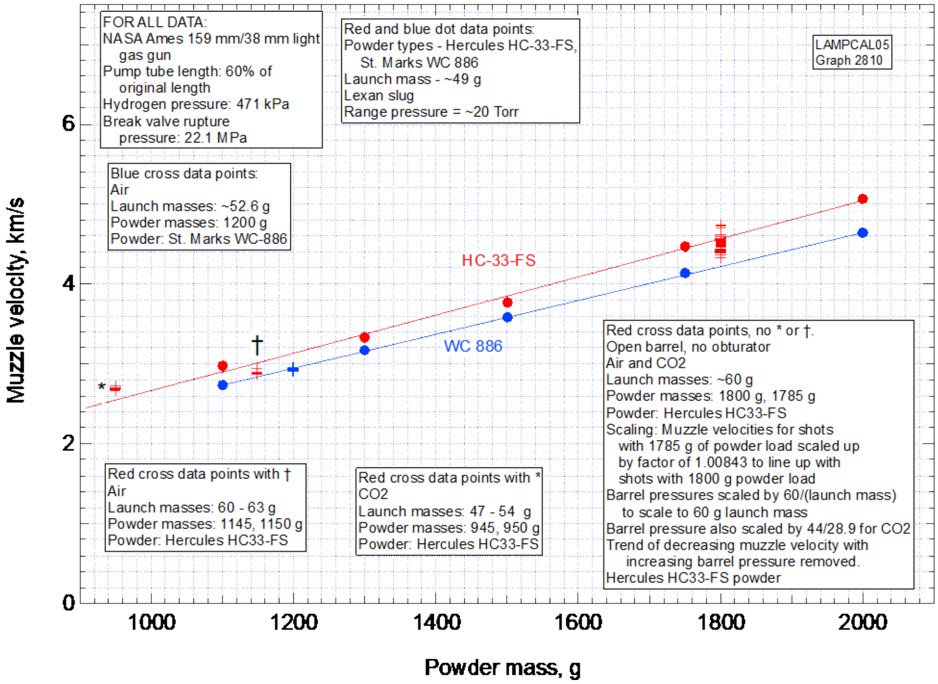

Figure 13. Experimental data for the Ames 159 mm/38 mm gun operated with hydrogen. Muzzle velocity versus powder load.

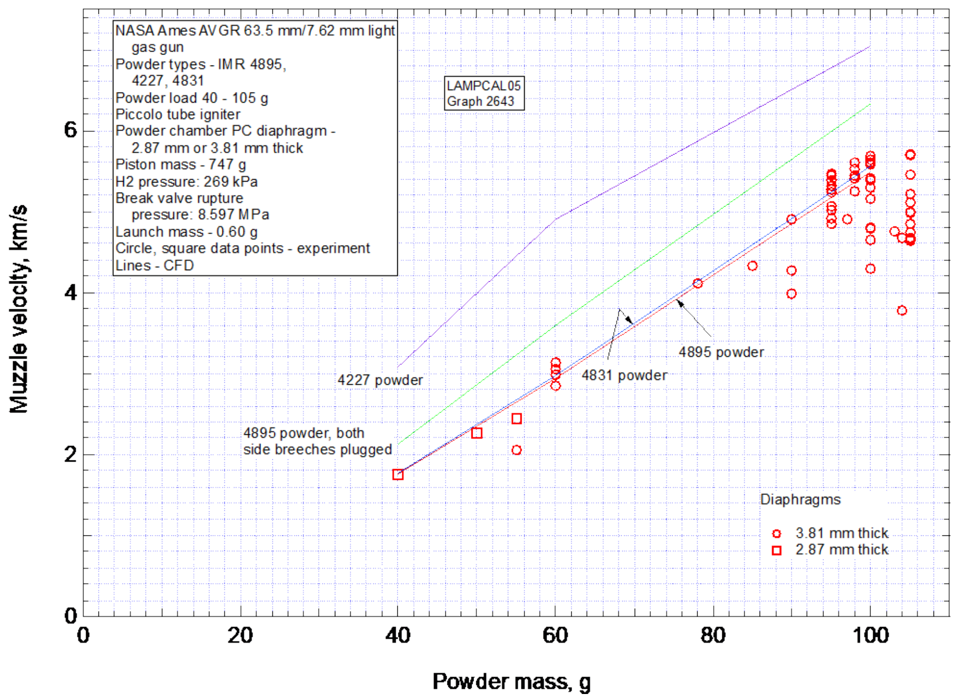

Figure 14. Experimental data and CFD results for the Ames AVGR gun operated with hydrogen. Muzzle velocity versus powder load. Launch mass ~0.60 g.

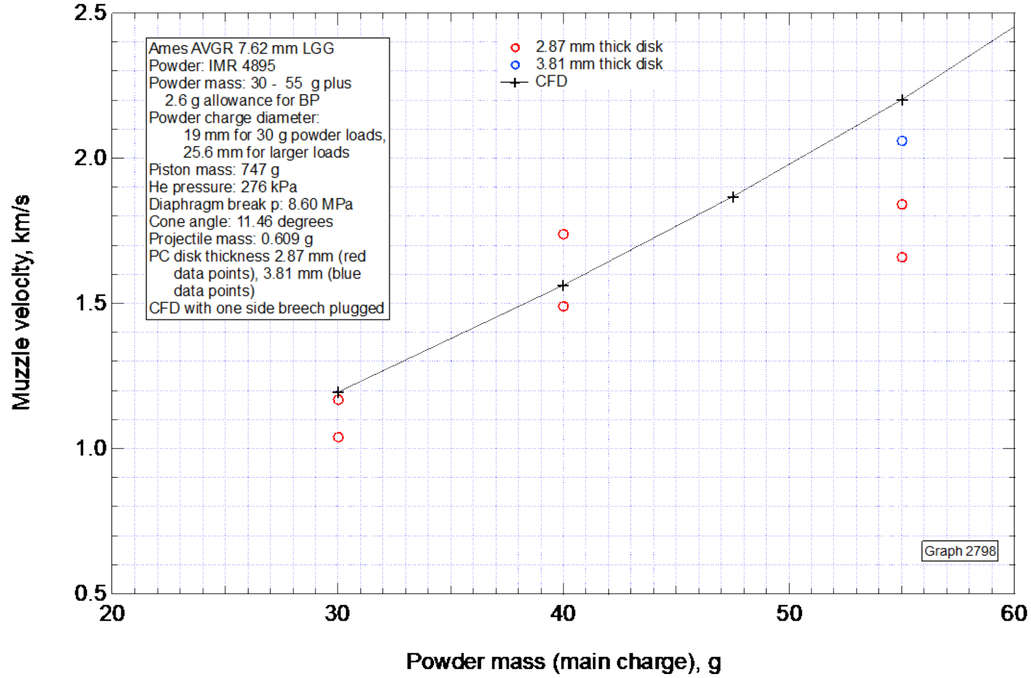

Figure 15. Experimental data and CFD results for the Ames AVGR gun operated with helium. Muzzle velocity versus powder load. Launch mass ~0.60 g.

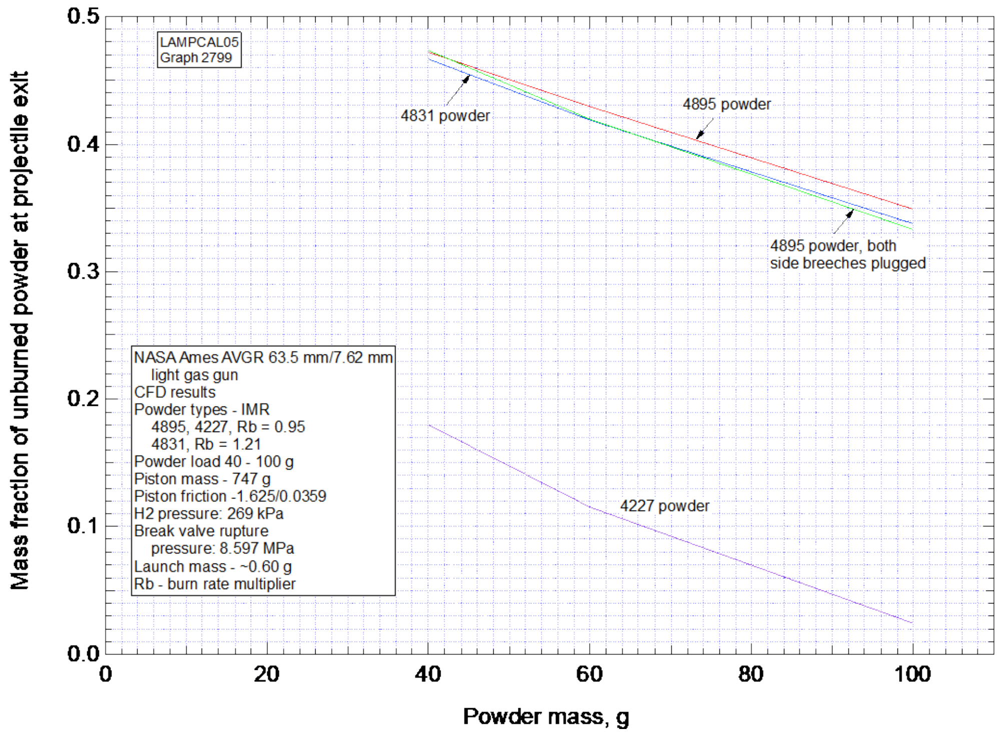

Figure 16. CFD results for the Ames AVGR gun operated with hydrogen. Mass fraction of unburned powder at projectile exit time versus powder load.

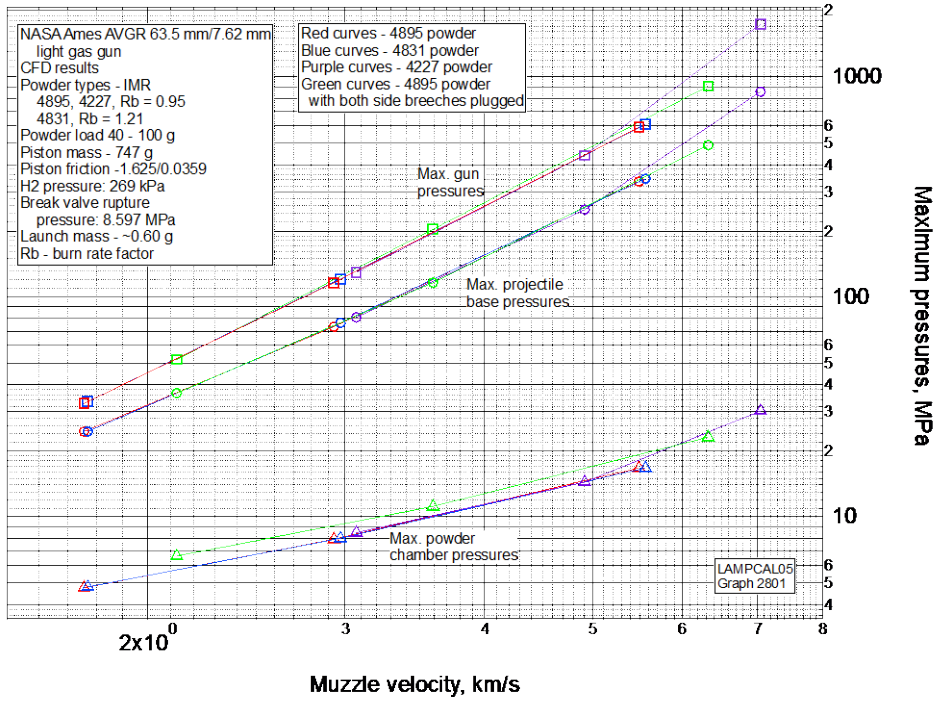

Figure 17. CFD results for the Ames AVGR gun operated with hydrogen. Maximum pressures versus muzzle velocity.

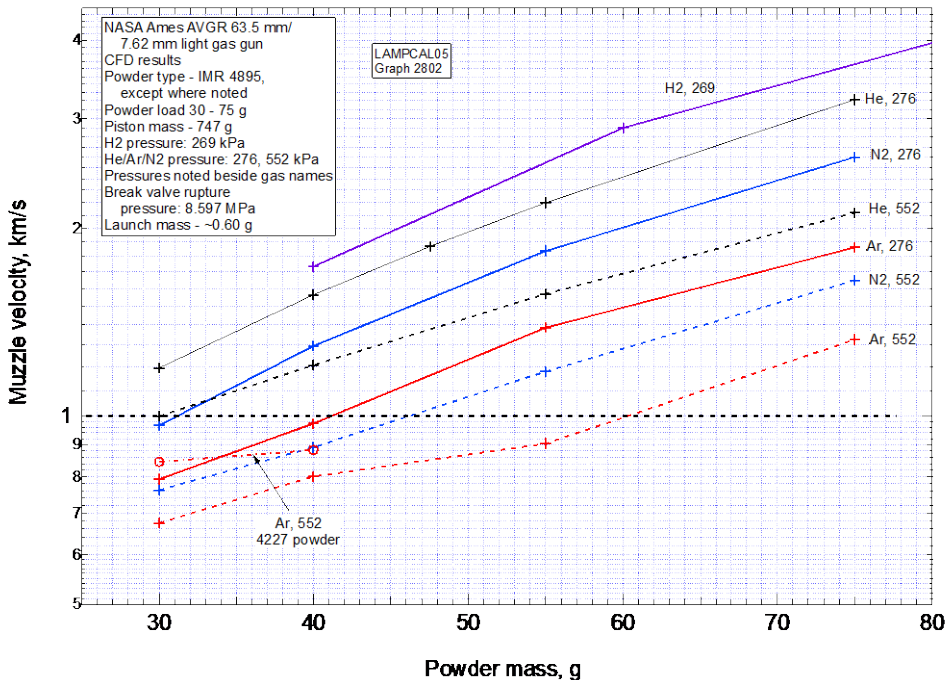

Figure 18. Results from CFD calculations of muzzle velocities versus powder load for the Ames AVGR gun with H_2, He, N_2 and Ar working gases at two different pressures.

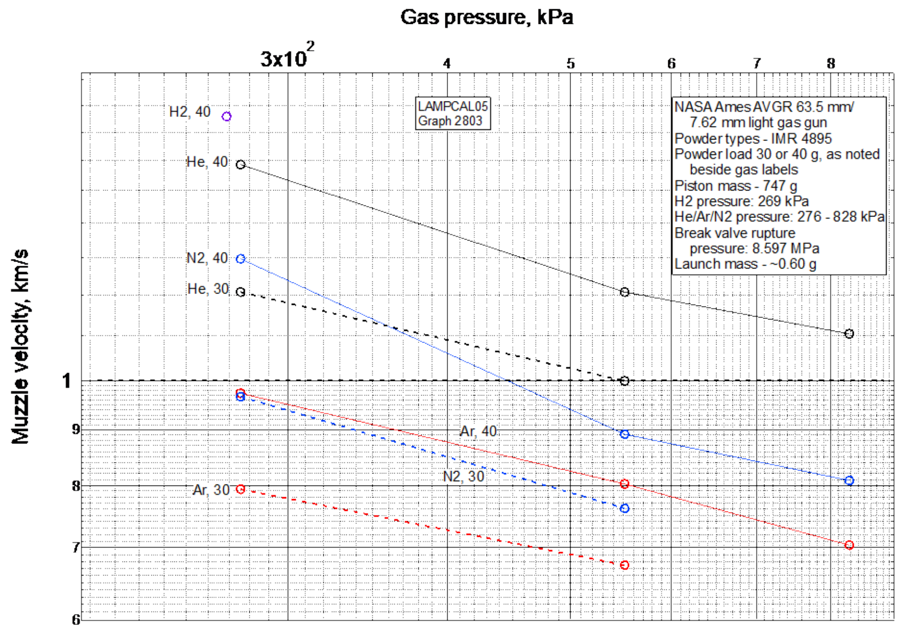

Figure 19. Results from CFD calculations of muzzle velocities versus gas load pressures for the Ames AVGR gun with H_2, He, N_2 and Ar working gases at two different powder loads. Cross plot of Fig. 18.

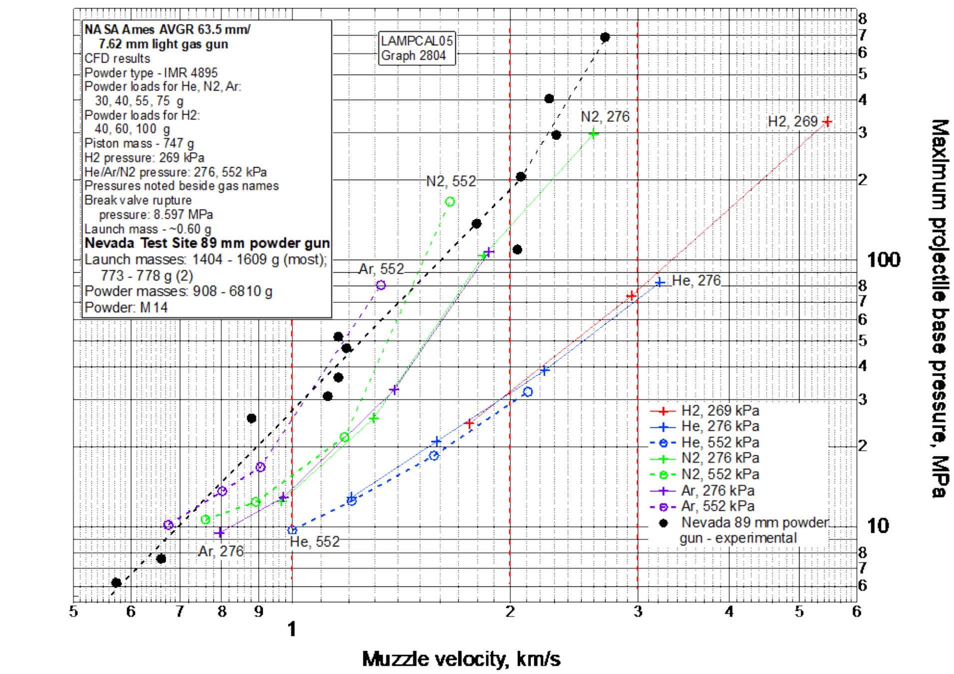

Figure 20. Results from CFD calculations of maximum projectile base pressures versus muzzle velocities for the Ames AVGR gun with H_2, He, N_2 and Ar working gases. Also shown are experimental breech pressures versus muzzle velocities for the Nevada 88.9 mm powder gun.

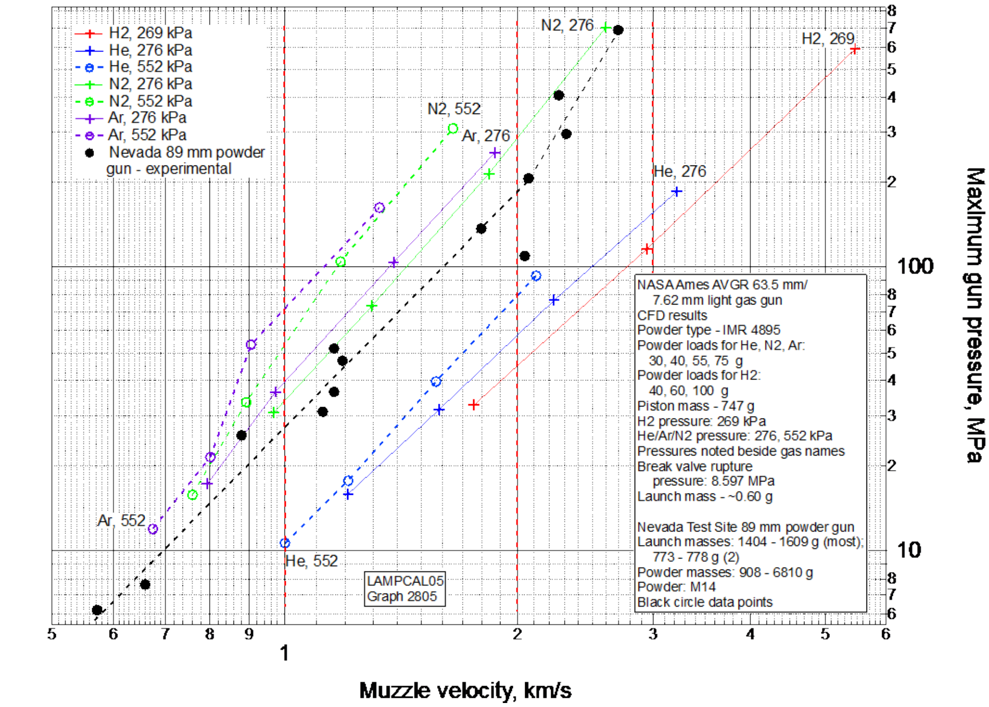

Figure 21. Results from CFD calculations of maximum gun pressures versus muzzle velocities for the Ames AVGR gun with H_2, He, N_2 and Ar working gases. Also shown are experimental breech pressures versus muzzle velocities for the Nevada 88.9 mm powder gun.

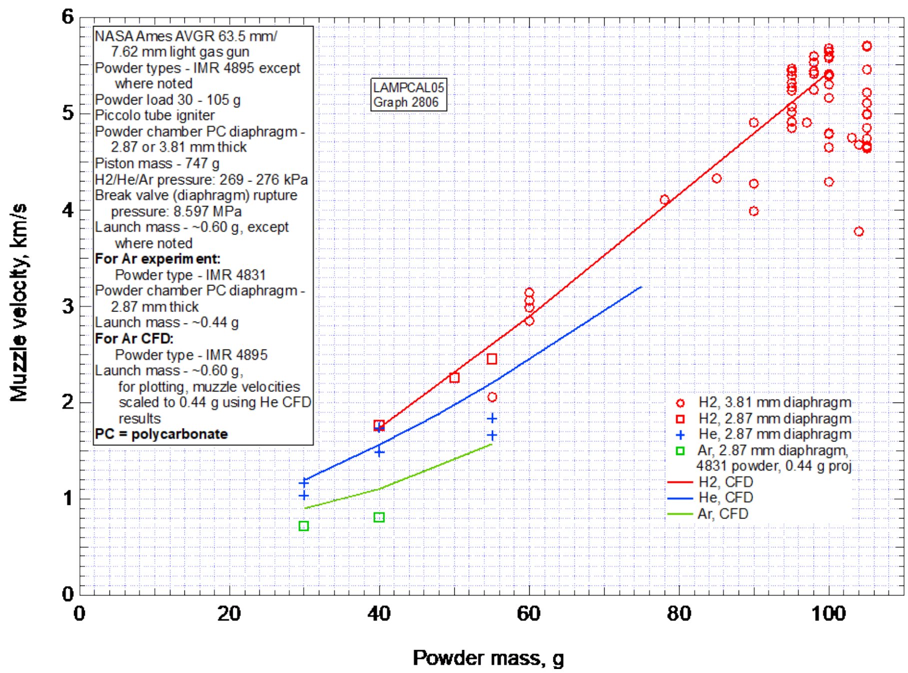

Figure 22. Experimental data for the Ames AVGR gun operated with hydrogen, helium and argon. Muzzle velocity versus powder load. Launch masses ~0.44, ~0.60 g.

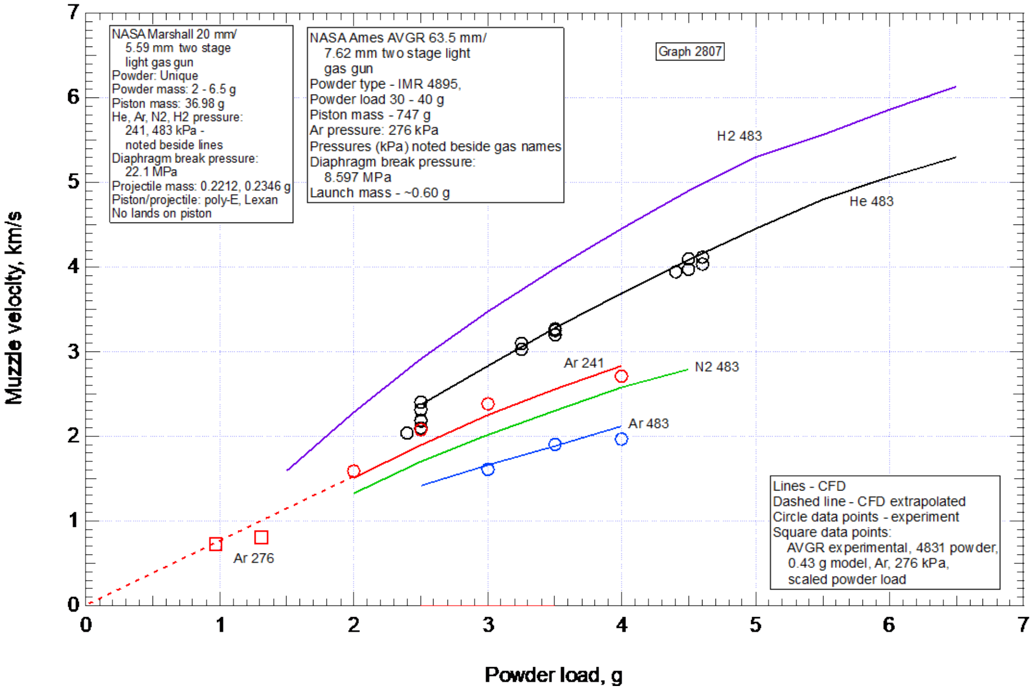

Figure 23. Experimental data and CFD results for the NASA Marshall gun with H_2, He, N_2 and Ar working gases. Muzzle velocity versus powder load. Launch masses 0.22 - 0.24 g.

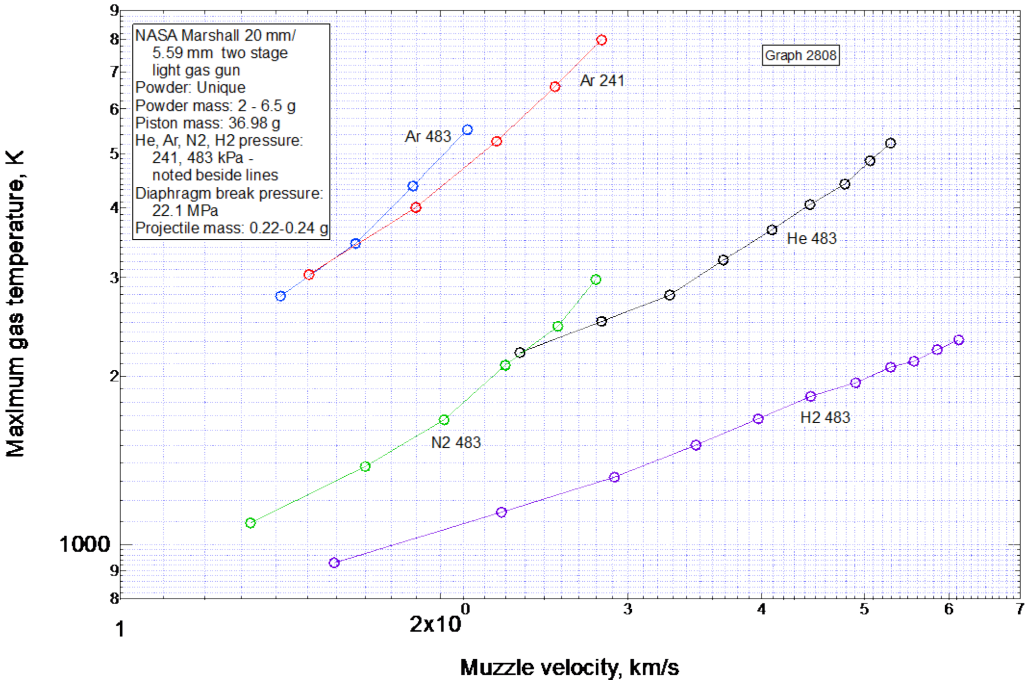

Figure 24. CFD results for the NASA Marshall gun with H_2, He, N_2 and Ar working gases. Maximum gas temperatures versus muzzle velocity. Launch masses 0.22 - 0.24 g.

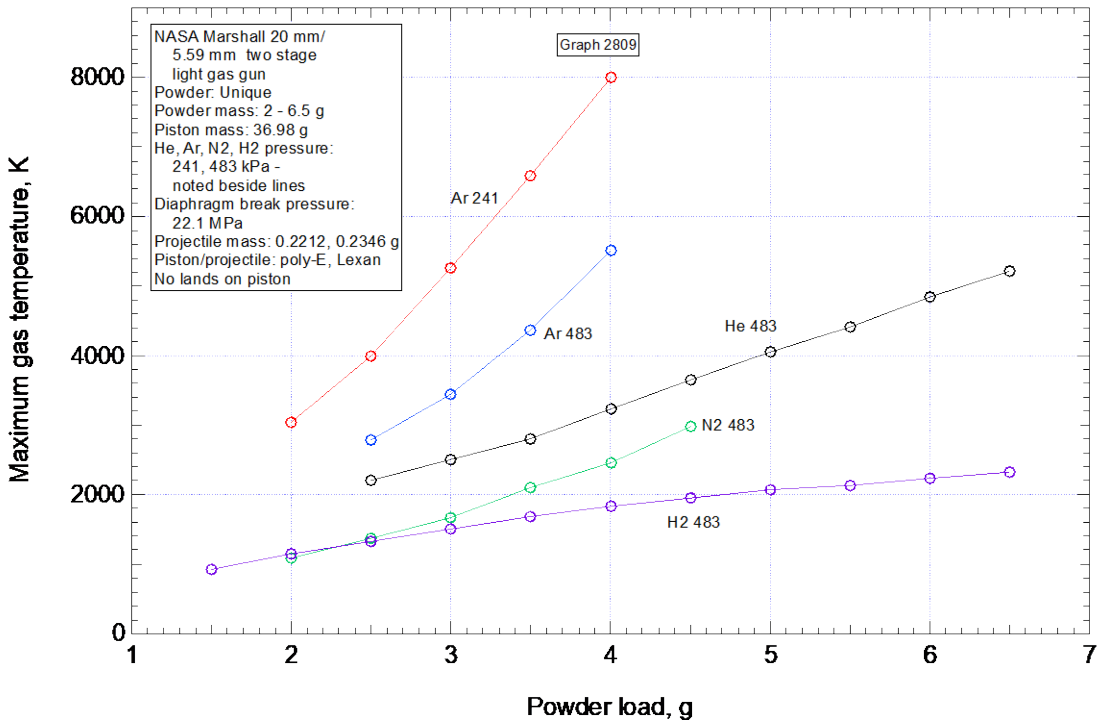

Figure 25. CFD results for the NASA Marshall gun with H_2, He, N_2 and Ar working gases. Maximum gas temperatures versus powder load. Launch masses 0.22 - 0.24 g.