On How to Make The Fastest Gun in the West

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ABSTRACT

A new gasdynamic launcher is described, in which intact projectiles weighing at least one gram can be accelerated to mass velocities of 20 km/s. The system employs a conventional 2-stage light gas gun, with the barrel modified and filled with helium to act as a pump tube for a third stage. It is demonstrated that inter-stage kinetic energy efficiencies of 45% are possible and that these results can be achieved while maintaining the peak pressure applied to the projectile below 2.5 GPa. A simple analysis of this system is given, from which design parameters can be readily derived, and hydrocode calculations are presented to validate the model.

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INTRODUCTION

The maximum velocity attainable in a gasdynamic launcher is limited by the maximum sound speed in the driver gas. For a conventional 2-stage light gas gun, the limit is ~ 10 km/s. To achieve higher velocities requires adding additional stages. Staging methods have been reported whereby a pusher of high shock impedance impacts a stack of target plates in which the impedance decreases from plate to plate in the desired direction of motion\(^1,2\), and velocities up to 14 km/s have been obtained in this manner. Chhabildas and his colleagues at Sandia National Laboratory have reversed this strategy with a graded density pusher, and they have demonstrated velocities up to 15.8 km/s with a 6 mm-diameter \times 0.56 mm thick titanium projectile\(^3\). A difficulty with this method is that the loading pulse is applied in a very short period of time and to achieve such a high velocity in this period requires a very high pressure, up to 100 GPa or even more. This means that the projectile thickness must be kept very thin to prevent spall fracture, and the impactor design is highly constrained to avoid shock-melting or even vaporizing the projectile. Also, such high pressures effect large energy losses via \(pdV\) work on the walls of the launcher; in the 15.8 km/s experiment cited above, the kinetic energy efficiency of the third stage (ratio of the kinetic energy of the flyer to that of the impactor) was only 0.6%.

It may be possible to avoid many of these problems by slightly modifying the configuration of the conventional 2-stage system, as shown in Figure 1.

![Figure 1. Sketch of three-stage light gas gun](image)

Normally, a vacuum is drawn in the 2nd stage launch tube of the gun, so that after the burst diaphragm is broken by the compressed hydrogen, the 2nd stage projectile is accelerated with no downstream resistance. If instead, this launch tube is closed at the downstream end with a second burst diaphragm, and filled with an appropriate mass of light gas, the second-stage projectile will act to compress the gas in much the same manner as does the piston in the first stage. The third stage projectile is placed downstream of the second burst diaphragm in a smaller diameter barrel, which now becomes the final launch tube. In what follows we present an analysis of this system. The analysis is used to define model parameters, which are then employed as input for hydrocode computation. It is then shown to be possible to achieve projectile velocities of 20 km/s, or even greater, with kinetic energy efficiency of the third stage as high as 45%. Moreover, the maximum pressure in the system can be as low as 5 GPa, with less than half that acting on the projectile itself.
MODEL

The approach followed is similar to that used in our earlier work, developed in collaboration with A. Latter and E. Martinelli\(^4\), except that this time the cross section will be allowed to change from stage to stage, a crucial step. Consider the simplified sketch of the third stage depicted in Figure 2.

![Sketch of third stage](image)

**Figure 2.** Simplified sketch of third stage

The second stage projectile, with mass \(m_2\), is the pusher for the third stage, and is shown moving down the second stage launch tube (now the third stage pump tube) from left to right with velocity \(v_2\). The cross sectional area of this projectile is \(A_2\). The gas mass, \(m_g\), is contained between the pusher and the third stage projectile, with smaller cross section, \(A_3\), and mass, \(m_3\). We ignore any taper between \(A_2\) and \(A_3\) and define a coordinate system wherein the motion of \(m_2\) is constrained in the range \(0 \leq x \leq X\) and that of \(m_3\) in the range \(0 \leq y \leq Y\). The pressure, \(p\), generated by the gas compressed between \(A_2\) and \(A_3\) accelerates the mass \(m_3\) to a final velocity \(v_3 = \gamma_i = g v_2\), where \(g\) is the velocity gain in the stage. We make the simplifying assumption that pressure gradients in the gas can be ignored.

The equations of motion describing this system are:

\[
\begin{align*}
    m_2 \ddot{x} &= A_2 p \\
    m_3 \ddot{y} &= A_3 p
\end{align*}
\]  

with the initial conditions \(x(0) = X, \dot{x}(0) = v_2, \dot{y}(0) = V, y(0) = 0\). If we define the volume of the gas to be

\[V = A_2 x + A_3 y,\]

and let

\[\Phi = \frac{A_3^2 m_2}{A_2^2 m_3},\]

a differential equation for \(V\) can be derived from (1):

\[
\left( \frac{\dot{V}}{A_2 v_2} \right)^2 = 1 + \left( \frac{y + 1}{2} \right) \frac{m_g}{m_2} (1 + \Phi) \left[ 1 - \left( \frac{V}{V_s} \right)^{y-1} \right].
\]

\(V_s\) is the volume of the gas at the instant the shock induced by the pusher \((m_2)\) just reaches the projectile \((m_3)\). This occurs when \(x = x_s = (y - 1)X/(y + 1)\). We
have assumed that the gas obeys a $\gamma$-law equation of state, and that after the first shock, the gas is effectively isentropically compressed. The coefficient $(\gamma + 1)/2$ in equation (4) takes approximate account of the kinetic energy in the gas when $V = V_s$. From here on, the further simplifying assumption is made that the gas is monatomic, so that $\gamma = 5/3$; it will be shown later that this is indeed the ideal situation.

If $\dot{V}$ is now defined as the minimum volume, which occurs when $\dot{V} = 0$, and $\dot{\rho}$ is the (maximum) pressure occurring at this same time, equation (4) leads to

$$\left(\frac{\dot{V}}{V_s}\right)^{2/3} = \frac{\alpha}{1 + \alpha} = \frac{4 m_g v_0^2}{9 \dot{\rho} V_s},$$  

(5)

where

$$\alpha = \frac{4}{3} \frac{m_g (1 + \Phi)}{m_2}.$$  

(6)

Equation (4) can be integrated for $V(t)$:

$$\frac{A_2 v_2}{V_s} (\ddot{t} - t) = \left(\lambda^{3/2} + 3 \lambda^{1/2}\right) \frac{\alpha^{3/2}}{(1 + \alpha)^2},$$  

(7)

where

$$\lambda = \left(\frac{V}{V_s}\right)^{2/3} = 1,$$  

(8)

and $\dot{t}$ is the time when $V = \dot{V}$. From equations (7) and (8),

$$\frac{A_2 v_2}{V_s} (\ddot{t} - t) = \frac{1 + 3\alpha}{(1 + \alpha)^2},$$  

(9)

where $t_s$ is the time at which the shock reaches $m_3$.

From equations (1), a relationship can also be derived among the quantities $\alpha$, $\Phi$, and $A_2 \ddot{x}/V_s$, where $\ddot{x}$ is the position of $m_2$ at $t = \dot{t}$:

$$\Phi = \frac{\left(\frac{\alpha}{1 + \alpha}\right)^{3/2} - \frac{A_2 \ddot{x}}{V_s}}{\frac{A_2 \ddot{x}}{V_s} + \frac{\alpha (1 - \alpha)}{(1 + \alpha)^2}}.$$  

(10)

This equation is only valid if $\ddot{x} \geq 0$. But, if $\ddot{x} > 0$, the pusher mass $m_2$ might rebound with an appreciable fraction of its initial kinetic energy. To minimize this potential loss, $\Phi$ should be chosen such that $\ddot{x} = 0$, which leads to the constraint equation

$$\Phi = \frac{[\alpha (1 + \alpha)]^{1/2}}{1 - \alpha}.$$  

(11)

The quantity $\alpha$ can also be related to the velocity gain, $\gamma$:

$$\frac{1}{\alpha} = \frac{3}{4k m_g} \left[ \gamma^2 - \left(\frac{\dot{V}}{V_s}\right)^2 \right] - 1,$$  

(12)

where $k$ is the fraction of the peak internal energy of the gas that goes into increasing the kinetic energy of the projectile $m_3$ from $m_3 \dot{y}_s^2/2$ to $m_3 \dot{y}_s^2/2 = m_3 v_0^2/2$. 

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\( \dot{y} \) is the velocity of the mass \( m_3 \) at the time of peak pressure. It can be shown that
\[
\frac{\dot{y}}{v_2} = \phi^{1/2} \left( \frac{m_2}{m_3} \right)^{1/2}.
\] (13)

\( \dot{y}_f = v_3 \) is the final velocity of the mass \( m_3 \), when \( y = Y \). The quantity \( k \) is, of course, related to the third stage barrel length, \( Y \); specifically,
\[
k = 1 - \left( \frac{\dot{y}}{Y} \right)^{2/3},
\] (14)

where \( \dot{y} \) is the value of \( y \) at \( t = \dot{t} \). It is easily shown that
\[
\dot{y} = \frac{\dot{v}}{A_3}.
\] (15)

We are interested in applying this model to the solution of the following problem: Given the fixed characteristics of a two-stage light gas gun \( (m_2, v_2, A_2, \text{ and } X) \), find the largest projectile mass, \( m_3 \) that can be accelerated to a final velocity, \( v_3 \), subject to the constraint that the maximum pressure on the projectile, \( \dot{\rho} \), is less than some prescribed value. It is required to also find the corresponding third stage characteristics, \( A_3, m_3, \text{ and } Y \). To accomplish this, we combine equations (5) and (11), taking into account the fact that, for \( \gamma = 5/3 \), \( x_r = X/4 \):
\[
\left( \frac{1 + \gamma}{\gamma} \right)^{5/2} \frac{\alpha(1 - \alpha)}{1 - \alpha + \alpha(1 + \alpha)^{1/2}} = \frac{3A_2X}{4} \frac{\dot{\rho}}{m_2v_2^2}.
\] (16)

All the quantities on the right-hand side of equation (16) are given, so that \( \alpha \) is readily evaluated. Then equation (11) gives \( \Phi \), and \( m_3 \) is found from equation (6). Then, combining equations (12) and (13) gives
\[
m_3 = \frac{4k m_3}{3} \left[ (1 + \frac{1}{\alpha}) - \frac{1}{k} \left( \frac{\Phi}{1 + \Phi} \right) \right].
\] (17)

Remembering that \( g = v_3/v_2 \) allows \( m_3 \) to be found once \( k \) is fixed. \( k \) is essentially a free parameter; however, choosing a value of \( k \) much larger than 0.75 leads to diminishing returns, the energy saved being at the expense of greatly increased barrel length. Once \( m_3 \) is found from equation (17), \( A_3 \) is found from (3), which allows \( Y \) to be found from (15) and (5):
\[
Y = \frac{\frac{1 + \gamma}{\gamma} m_2v_2^2}{3A_3(1 - k)^{3/2}}.
\] (18)

We have not accounted for losses thus far. These are from two principal sources. It can be shown that heat loss to the walls and projectile faces will be insignificant in the brief time from first motion of \( m_3 \) until exit from the barrel as long as the temperature in the gas remains below \( \sim 10 \) eV, which we expect to be the case in all practical designs. Also, we would like to choose \( \dot{\rho} \) well below the spall strength of the projectile material, so that \( \rho dV \) work on the walls should also be negligible. We will take wall motion into account in the next section and show that this is indeed true.

To illustrate, the intermediate LLNL two-stage light gas gun has been shown to fire a projectile, \( m_2 = 37 \) g at a velocity \( v_2 = 6.2 \) km/s. The launch tube bore
diameter is $D_2 = 28$ mm (so that $A_2 = 6.16$ cm$^2$) and the length is $X = 9$ m. Assuming it is desired that the projectile velocity from the added third stage be $v_3 = 20$ km/s, $g = 3.23$. If the third stage projectile is made of titanium alloy ($\rho_3 = 4.51$ g/cm$^3$), we choose $\bar{p}$ to be 2.5 GPa, less than half the ~ 5.5 GPa spall strength. Equations (16)-(18) then yield $\alpha = 0.267$, $\phi = 0.793$, $m_3 = 1.65$ g, and $A_3 = 1.158$ cm$^2$, so that the bore diameter of the third stage barrel is 12.1 mm and the projectile length is $m_3/A_3\rho_3 = 3.16$ mm. Also, $m_g = 4.13$ g, which leads to a fill pressure of 0.46 MPa assuming helium is employed, and $Y = 9.3$ m. Although this represents a quite acceptable parameter set, it might be desirable to reduce the barrel length. This could be accomplished by reducing the projectile mass (length) somewhat. Another alternative is to accept a slightly lower final projectile velocity. It will be shown in the next section that the mass $m_3$ attains 0.95 $v_3$ in the first 3.9 m, and is already at 0.9 $v_3$ in 2.7 m.

HYDROCODE CALCULATIONS

In order to make the model analysis tractable, a number of simplifying assumptions had to be made. Apart from the step geometry and the neglect of pressure gradients in the gas and projectile, an ideal monatomic gas was employed, and radial wall motion was ignored. All these simplifications will be removed in the calculations described below. GGUN2 is an extension of earlier codes (GGUN$^3$ and IGUN$^5$) employed to study the performance of the two-stage light gas gun and various implosion and multistage launchers. It is an arbitrary Lagrange-Eulerian (ALE) code that solves the equations of motion in one dimension, but takes into account arbitrary flow cross section (including discontinuities) and gasdynamic wall drag. Tabular equations-of-state can be employed, as well as Grüneisen, polynomial, and $\gamma$-law models, and JWL-explosive and Noble-Abel propellant burn packages have recently been added. There is also a coupled wall motion algorithm that allows the gun-barrel walls to move in response to the developing internal pressure. The equations of motion and other details have been described earlier$^6$.

To validate the GGUN2 code, the first two stages of the two-stage light gas gun discussed in the previous section were first modelled. A burst diaphragm was placed at the entrance to the barrel and a vacuum was drawn downstream thereof. The initial hydrogen fill pressure in the pump tube was 1.0 MPa and the diaphragm burst pressure was set at 82.7 MPa$^5$. The gun breech was filled with 2.9 kg of M6 propellant, and a piston of mass $m_1 = 4.54$ kg was placed at the entrance of the 10 m-long pump tube. The projectile mass, $m_2 = 37$ g, was placed just downstream from the burst diaphragm in the 9 m-long barrel. Figure 3 shows the piston and projectile velocity obtained, both of which are in good agreement with experiment. The barrel-exit velocity of the projectile was $v_2 = 6.2$ km/s.

Next, the third stage described earlier was added. The second stage barrel is now the pump tube for the third stage and was filled with gas. At the end of this tube, a short 100 mm-long transition section was added which served to decrease the diameter from 28 mm to the 12.1 mm that was employed for a 7 m-long third stage barrel (calculations were also done with a step change in cross section, but the transition section produced slightly better results). A burst diaphragm similar to that used at the entrance to the second stage was set at the entrance to this barrel and the 1.65 g titanium alloy projectile was placed immediately in front. The results of 3 calculations of the overall system are shown in figures 4-6. The only difference in the 3 calculations was the equation of state (EOS) of the gas in the third stage pump tube. Both hydrogen and helium tables$^7$ were used, and
a γ-law helium was included to contrast the behavior when ionization is ignored. All calculations employed the 'standard' configuration with M6 propellant driving the heavy piston against hydrogen in the second stage, the results of which were shown in figure 3.

Figure 3. Computed piston and projectile velocity as a function of time for the 2-stage light gas gun with 2.9 kg of M6 propellant used to drive a 4.54 kg piston. The H₂ fill-pressure was 1.0 MPa, the projectile mass 37 g, and the barrel was 9 m long.

Figure 4 depicts the mass-averaged projectile velocity and maximum pressure experienced by the third stage projectile as a function of time. Both calculations with helium in the third stage produced a final velocity of 19.7 km/s, in excellent agreement with the model prediction of 20 km/s. The final velocity achieved with hydrogen as the third-stage working fluid was 17.7 km/s. The peak pressure experienced by the titanium-alloy projectile was more than double when hydrogen was used, however the pulse width and average pressure were greater with helium. The peak pressure calculated with both helium EOS was ~ 2 GPa. Although this was lower than the 2.5 GPa used in the model, it will be seen below that higher pressures are calculated in the transition section behind the projectile; the model does not account for pressure gradients.

Helium is the preferred working fluid for all stages beyond the second because a higher final sound speed can be produced for given initial and final pressures. This is true also for the second stage. For example, when we recalculated the two-stage launcher discussed in connection with figure 3, using helium in place of hydrogen (all other parameters remained the same, including the initial gas density and temperature), the final velocity increased by about 3%, notwithstanding the lower atomic mass of the hydrogen. However, practical considerations preclude the use of helium in the second stage. Although the velocity was slightly higher, the peak gas temperature in the AR (transition) section with helium was 6360 K, compared with 1880 K with hydrogen. The slight increase in performance is more than countered by the potentially severe erosion that would be engendered by repeated use of the gun with helium. In the third stage, however, this is no longer
a problem since the barrel in this stage cannot be salvaged and must be replaced after each shot.

Figure 4. Computed third stage projectile velocity and maximum pressure. The tabular results are shown in black (solid for helium and dashed for hydrogen); the grey solid curve shows the results obtained with γ-law helium.

Figure 5. (a) Maximum pressure, (b) Maximum Temperature and (c) Final inner wall radial profile for the 3 cases discussed in Fig. 4. Note that the ordinate scale in (c) is highly magnified to exhibit the radial wall motion.
Figure 5 shows why replacement of the third stage barrel is necessary. Figure 5(a) plots $\rho(x) = \max_{0 \leq x \leq L} p(x, t)$, and figure 5(b) plots $\bar{T}(x) = \max_{0 \leq x \leq L} T(x, t)$, where $x$ here is the coordinate along the launcher, $L$ is the overall length of the launcher, and $p$ and $T$ are the pressure and temperature in the gas. Even with helium, the peak pressure in the third stage transition region is almost 5 GPa and is roughly 2 GPa along an ~1.5 m-long section immediately downstream. These values are well above the burst pressure of any known barrel material. The barrel is designed therefore to survive long enough for the projectile to exit. We assume that an inner liner of high strength steel resists outward motion until $p(x, t)$ exceeds a threshold value, typically 1 GPa. Beyond the inner liner is a thick-walled section made of a high-density, low-sound-speed material whose function it is to inertially confine the inner layer for the requisite residence time of the projectile. Once the threshold pressure is exceeded, the inner wall surface can move only after displacing the heavy confining mass. A low sound speed is desirable to minimize the propagation of upstream disturbances through the walls and ahead of the projectile before the latter has a chance to accelerate. Figure 5(c) shows the calculated inner wall displacement, with the radial scale greatly exaggerated, at the time when the projectile has just exited the barrel. Tungsten was used as the confining material, but lead might serve almost as well. The fraction of the second stage projectile's kinetic energy that was "wasted" on $p dV$ work on the barrel walls was 0.25 for hydrogen and 0.15 for helium (tabular case), consistent with the higher peak pressure with hydrogen; the corresponding fraction converted to third stage kinetic energy was 0.36 for hydrogen and 0.45 for helium.

Figure 6. Computed third stage projectile velocity profiles for the 3 cases discussed in Figs. 4-5

Although the pressure and projectile velocity differ relatively little between the calculations employing $\gamma$-law helium and tabular helium, figure 5(b) shows that
the peak temperature is much higher in the former case (10.9 eV, compared with 4.1 eV - and only 1.7 eV with hydrogen). The lower temperature obtained with the tabular EOS results from the inclusion of ionization (and dissociation, in the case of molecular hydrogen).

Figure 6 shows the third stage projectile velocity for the 3 cases as a function of length, measured from the back of the breech; the initial position is at 20.1 m. Viewed in this manner, the y-law helium and tabular helium cases are virtually indistinguishable. Although the helium system requires a longer barrel to attain maximum performance, the third stage velocity is the same as with hydrogen in less than 2 m; the peak velocity with helium is 17.7 km/s in 2.7 m and 18.7 km/s in 3.9 m (90 and 95%, respectively, of the maximum value of 19.7 km/s).

SUMMARY & CONCLUSIONS

We have developed a model for a 3-stage light gas gun that is capable of launching intact projectiles of at least one gram to velocities of 20 km/s. The system employs a conventional 2-stage light gas gun, with the barrel modified and filled with helium to act as a pump tube for the third stage. Although a number of simplifications were employed in the analysis of the model, hydrocode calculations confirm the validity of the results, which are fully scalable to still larger launchers, such as the SHARP gun that is now operating at LLNL.

The most important feature of this device is its ability to achieve outstanding performance while maintaining the pressure on the projectile well below the spall strength of readily available materials. In our calculations, the maximum pressure experienced by the third stage (titanium alloy) projectile was 2 GPa. This is 2 orders of magnitude below other methods that have demonstrated velocities exceeding 15 km/s and is the main reason why it is possible to launch intact 'massive' projectiles to such high velocities. Relative to the second stage kinetic energy, our calculations showed that the kinetic energy efficiency of the third stage was 45%, which is the same as the efficiency of the second stage relative to the first, and again, is 2 orders of magnitude higher than obtained with graded density pushers acting directly on condensed phase projectile systems.

We are confident that the system, as described, will yield higher performance than any other launcher developed to date, however additional calculations are required before testing the concept. Although the predicted peak pressure is low by comparison with other systems, it is clear that the barrel and transition section (the so called accelerating reservoir or AR) in the third stage will not survive intact and must be replaced after each shot. Our calculations, thus far, of the disassembly process have only been approximate and fully 2D hydrocode calculations need to be made before the final design is built and tested. We note that the high pressure is confined to a 1.5-2 m zone beginning just in front of the third stage AR. The existing second stage barrel should survive intact, without any damage, so long as a small extension is added, which would connect the second stage to the expendable third stage.

Other issues that have not been fully studied include gas leakage due to possible blow-back of the hot compressed helium behind the second stage projectile, and blow-bye ahead of the third stage projectile, the effect of radial gradients, heat losses, and third stage projectile stability, i.e., the resistance to tumbling.
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