The Blast Wave Accelerator - Feasibility Study

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Abstract. This paper describes a new concept for propelling a projectile to hypervelocities and demonstrates the feasibility by numerical simulations. The concept employs imploding blast waves to accelerate a projectile which travels down a launch tube. The launch tube can be open to the atmosphere or sealed and maintained at some low pressure to minimize drag. The launch tube has a liner that contains a suitable explosive or energetic material. The explosive is configured with inert annular rings so as to prevent upstream detonation. A suitable trigger detonates each explosive ring sequentially as the projectile passes. The resulting blast wave causes an elevated pressure on the aft-end of the projectile. The acceleration continues until the projectile leaves the tube. In theory, launch velocities exceeding 6 km/s are possible.

INTRODUCTION

Numerical simulations are conducted to demonstrate the feasibility of using the Blast Wave Accelerator (BWA) concept to meet the mission requirement defined by NASA. These mission requirements produce the following operational envelope for the BWA.

- Launch mass (kg): 1000 - 2000 (max payload = 500)
- Launch velocity (km/s): 7-9
- Peak acceleration (Kilograms [kG]): 50 - 250

The launcher design is constrained by economics, material strength, and explosive properties. The requirements are listed below.

- Tube diameter (m): 0.5 - 1
- Tube length (m): ~ 400
- Launch mass density (kg/m^3): 1000 - 4000
- Launch mass length to diameter ratio (L/D): 3-5
- Peak pressure(GPa): ~ 2
- Explosive energy density (MJ/kg): 5
- Explosive density (kg/m^3): 1600

This is an initial study of the feasibility of the BWA concept. We are interested in whether the launch velocity can be obtained under the constraints. We are also interested in determining the effect of initial launch tube pressure on the acceleration.

MATHEMATICAL MODEL AND SOLUTION METHOD

For simplicity, the mathematical model ignores the launch tube boundary condition at the breech, i.e. we assume that the length of the launch tube is infinite. A fixed domain is used to solve the moving boundary problem by fixing the computational coordinate system on the projectile. The detonation of the explosion is assumed to be instantaneous, so that the energy and mass are released in a short time. The masses of the projectile and each explosive charge are fixed at \( m_p = 1000 \) kg and \( m_e = 10 \) kg, respectively. The axial spacing between explosive charges is \( l_e = 0.3 \) m, and...
the energy density of the explosive is \( e = 5 \) MJ/kg. In this work, a constant \( m_e \) is assumed for all charges. In future work, \( l_e \) and \( m_e \) may change for different charges, to achieve higher efficiency.

We also assume that the flow is axisymmetric and the detonation products and the surrounding gas are perfect and inviscid. The specific-heat ratio \( \gamma \) is 1.4 everywhere. The barrel and the projectile are assumed to be rigid. The friction between the barrel and the projectile is neglected. Unless specified, the launcher is located at 3000 m above sea level, which sets the initial pressure and density of the launch tube at: \( p_\infty = 0.070117 \) MPa and \( \rho_\infty = 0.90895 \) kg/m\(^3\).

**Modeling of the Explosive Charge**

The explosive is modeled as a mass and energy source that is released to the surrounding flow instantaneously. The volume of the explosive ring is determined by the density and mass of the explosive charge. The energy of the explosive ring is determined by the energy density and mass of the explosive charge. We assume that the mass and energy source is uniformly distributed inside the volume of the explosive ring.

**Projectile Geometry**

Two projectile shapes are considered in this initial study. The 96% subcaliber shape (Figure 1) is used for the calculations in this report. The full caliber shape (Figure 2) is used to study of the effect of the high base pressure. The dimensions shown in Figure 1 and 2 are in meters. Based on the geometry, the volume of the subcaliber projectile is 0.4975 m\(^3\), and of the full caliber projectile is 0.5307 m\(^3\). This yields projectile densities of 2010 kg/m\(^3\) and 1884 kg/m\(^3\), respectively. The rear ramp angle of the projectile base is 19.5° from the tube axis.

![FIGURE 1. Geometry of the 96% Caliber Mass Launcher.](image1)

![FIGURE 2. Geometry of the Full Caliber Launcher.](image2)
Governing Equations and Numerical Method

The Euler equations, boundary conditions, and the numerical method are described in Tan (1993) and Tan et al., (1996). We use a second-order upwind finite element method for the Euler equations. To reduce the chance of negative density or pressure, the HLLEM Godunov type scheme of Einfeldt et al., (1991) is used.

Treatment of the Axi-Symmetry Term

After operator splitting, the equation for marching the axi-symmetry contribution is

\[
\begin{bmatrix}
\rho \\
\rho u \\
\rho v \\
e
\end{bmatrix}
\begin{bmatrix}
\frac{d}{dt} \\
-pv \\
-pv \\
yy
\end{bmatrix}
\begin{bmatrix}
1 \\
u \\
v \\
H
\end{bmatrix}
\]

(1)

It turns out that the above ODEs have the following analytic solution

\[
\begin{bmatrix}
P(t)u(t) \\
p(t)v(t) \\
\rho(0)v(0)e^{-\lambda t} \\
\rho(0)e^{-\lambda t}
\end{bmatrix}
= 
\begin{bmatrix}
P(0) \\
\rho(0)u(0) \\
\rho(0)v(0) \\
\rho(0)e^{-\lambda t}
\end{bmatrix}
\]

(2)

This solution preserves the sign of density and pressure, and therefore improves the robustness of the program. This analytical solution is used to replace the finite difference formulation used by Tan et al., (1996).

Despite the special care taken to avoid negative densities, it is found in this work that an occasional negative density still occurs, mainly due to the finite difference treatment of the axi-symmetry term. This is possibly caused by the treatment of the hanging nodes in our finite element method.

Fast Simulation of Periodic Charges

For the configuration specified in the Introduction, it is estimated that thousands of explosive detonations are needed to reach the desired projectile velocity (7 to 9 km/s) without material damage. This would require weeks of CPU time for a single simulation on a PC. This excessive computational time is unacceptable, especially in future design stages where rapid turnaround is essential.

In the feasibility study, the explosives are uniformly distributed and the same charge size is used for all detonations. From previous experience, we know that the flow field and all the key global parameters - projectile velocity increase, traveling time between charges, peak pressure and thrust - vary slowly from one detonation to another. Therefore, if we can calculate the results for a few selected charges, results for other periods can be interpolated with little loss of accuracy.

Instead of simulating the effect of a given charge along the launcher axis, with specified initial travel and end travel, we specify the initial projectile velocity \(v_0\), then simulate the launching process due to one charge. At the beginning, the state of the incoming air is given by the normal shock wave relations.

Obviously, this initial condition does not yield the same results as the full simulation. However, we can continue the simulation for several more detonations \(n\), where \(n = 5\sim20\), \(l\) is the period, i.e., the charge distance. We expect that after a few detonations, the influence of the initial condition is lost, so the final period will mimic the full simulation results at a given projectile velocity.
Experience shows that the interpolation will be quite accurate if the simulations are done for \( v_0 \) at 0 km/s, 1 km/s..., and 8 km/s. Note that for \( v_0 = 0 \) km/s, the initial condition is realistic, so only one detonation is needed.

This method reduces the number of detonations needed to simulate the process to about 60. Each simulation of the entire launching process now requires 10-14 hours of CPU time on a PC with a Pentium II 300 MHz processor.

Another benefit of this fast simulation idea is that calculations are done independently for different projectile initial velocities. This allows us to examine the design by concentrating on extreme velocities (very high and very low \( v_0 \)). This independence also enables us to perform calculations in parallel for a given design.

It should be noted that many restrictions for using this method could be removed. In fact, we only require that the histories are similar and vary smoothly from one detonation to the next. The charge locations relative to the projectile, the distance between charges, the charge mass, and even the projectile design, are allowed to change smoothly from charge to charge. This property will be exploited in future studies.

**RESULTS - DESIGN OF THE PROJECTILE SHAPE AND EXPLOSIVE LOCATIONS**

The projectile length and diameter is chosen to meet the design requirements (volume, L/D ratio and diameter). The fore body cone angle \( (45^\circ) \) is arbitrarily set since its effect on the in-bore dynamics is insignificant. Two aft body ramp angles, 20° and 30°, were tried. Our investigation revealed that the latter is unable to deliver the desired 8 km/s launch velocity for a realistic tube length.

**Truncation of the Aft Body Cone**

It is found that the implosion of the explosive rings can create a high-pressure jet on the axis. The jet pressure is much higher than the material strength and can destroy the tip of the aft body cone if the cone is not truncated. After truncation, the high-pressure jet is still present, and yields a high-pressure spot on the center of the projectile end. However, the peak pressure is lower. Furthermore, the shape near the high-pressure spot is flat which implies that this design would survive the in-bore launch. Actual structural calculations, however, were not performed as part of this study.

**Explosive Positions**

The charge mass is set such that the material strength is not exceeded anywhere on the projectile surface except along the tube axis where the projectile aft end is flat. It is found that 10 kg is appropriate. Different charge shapes were tested. The calculations showed that a concentrated circular wire (torus) charge is the worst. It yields a pressure higher than material strength on the ramp and its' explosive energy efficiency is the lowest. Thus, a thin annular ring is adopted. The length of the ring is 0.21 m and the thickness is 16 mm. Note from Figure 1, the clearance between the projectile and the tube wall in 12 mm so the charge would have to be recessed slightly (4 mm) inside the tube. The distance between charges is 0.3 m, so there is a 0.09 m gap between each explosive charge.

**Full Caliber vs. Sub-Caliber**

In the full caliber case, there is a "dead end" corner where the aft body shoulder meets the tube wall. At low projectile speed, the high-pressure explosive product is compressed and reflected in the corner, which yields a very high pressure. Therefore, full caliber is not recommended, even though its efficiency is higher than a sub-caliber design. We use the full caliber design only to study the effect of environment pressure.
Simulations at Selected Initial Projectile Velocities

The simulations were performed for initial velocities of: \( v_0 = 0 \) km/s, 1 km/s, 2 km/s, ..., 8 km/s. Figure 3 shows snapshots of the pressure distribution for \( v_0 = 1 \) km/s, 4 km/s and 7 km/s, respectively. The high pressure jets on the axis are clearly seen. Figure 4 shows the history of several key parameters for \( v_0 = 1, 4, \) and 7 km/s: projectile speed, time, acceleration (displayed as "thrust"), and maximum pressure on the projectile surface.

It is found that the maximum pressure is below the material strength (2 GPa) most of the time. Further inspection of the pressure contour plots reveals that those high pressures occur only at the center of the projectile's back flat end.

The peak acceleration is found well under the specified limit (50 to 250 kG).

It is seen that the numbers of charges chosen (3 for \( v_0 = 1 \) km/s, 8 for \( v_0 = 4 \) km/s, and 12 for \( v_0 = 7 \) km/s) are sufficient to yield nearly identical profiles for the last two detonations. For each figure, the results of the last detonation, are used to produce the results shown in Table 1 and 2.

![Figure 3](image_url)

**FIGURE 3.** Pressure Distribution Snapshots for Different Initial Projectile Velocities. (a) \( v_0 = 1 \) km/s. (b) \( v_0 = 4 \) km/s. (c) \( v_0 = 7 \) km/s.
FIGURE 4. Projectile Speed, Time, Thrust and Maximum Pressure on the Projectile as Functions of Projectile Travel. (a) $v_n = 1$ km/s. (b) $v_n = 4$ km/s. (c) $v_n = 7$ km/s.
Estimated Detonations and Launcher Length

Table 1 summarizes the major results for the launcher performance. The projectile velocity increase due to one detonation, $\Delta v$, is calculated from the last charge in Figure 4. The fuel efficiency is calculated as

$$\eta = \frac{1}{2} \frac{m_p (v_0 + \Delta v)^2 - v_0^2}{m_e e} = \frac{m_p v_0 \Delta v}{m_e e}, \quad v_0 = 0$$

where $m_p = 1000$ kg, $m_e = 10$ kg, and $e = 5$ MJ/kg. The number of charges needed to increase the projectile velocity by 1000 m/s is estimated by

$$n = \frac{v_i + v_{i+1}}{2}$$

or

$$n = \frac{2000 \text{ m/s}}{v_i + v_{i+1}}.$$

For example, the number of charges needed to increase the projectile speed from 2 to 3 km/s is $n = 2000/(8.70+5.95) = 136.51 \sim 137$. Since the distance between charges is always 0.3 m, the launcher length needed to increase the projectile velocity by 1000 m/s is $0.3n$ meters. For convenience, the total number of charges and launcher length to accelerate the projectile from zero velocity are also shown.

From Table 1 we see that to obtain a launch speed of 7 km/s, about 1870 explosive charges are needed and the launch length is about 560 m. For a launch speed of 8 km/s, about 2870 charges and 860 m of launcher length are needed. The overall energy efficiency is 26.2% for launch speed 7 km/s, or 22.3% for 8 km/s. The efficiency is higher than the simulation performed in a previous study by Tan et al., (1996) using thin wire, (torus) charges.

**TABLE 1. Summary of Simulation Results**

<table>
<thead>
<tr>
<th>$v_0$ (m/s)</th>
<th>$\Delta v$ (m/s)</th>
<th>Efficiency (%)</th>
<th>Number of charges needed</th>
<th>Launcher length needed (m)</th>
<th>Total number of charges</th>
<th>Total launcher length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.72</td>
<td>0.28</td>
<td>74</td>
<td>22.1</td>
<td>74</td>
<td>22.1</td>
</tr>
<tr>
<td>1000</td>
<td>10.42</td>
<td>20.8</td>
<td>105</td>
<td>31.4</td>
<td>179</td>
<td>53.5</td>
</tr>
<tr>
<td>2000</td>
<td>8.70</td>
<td>34.8</td>
<td>137</td>
<td>41.0</td>
<td>316</td>
<td>94.5</td>
</tr>
<tr>
<td>3000</td>
<td>5.95</td>
<td>35.7</td>
<td>196</td>
<td>58.8</td>
<td>512</td>
<td>153.3</td>
</tr>
<tr>
<td>4000</td>
<td>4.26</td>
<td>34.1</td>
<td>282</td>
<td>84.5</td>
<td>794</td>
<td>237.8</td>
</tr>
<tr>
<td>5000</td>
<td>2.84</td>
<td>28.4</td>
<td>426</td>
<td>127.7</td>
<td>1220</td>
<td>365.5</td>
</tr>
<tr>
<td>6000</td>
<td>1.86</td>
<td>22.3</td>
<td>651</td>
<td>195.4</td>
<td>1870</td>
<td>560.9</td>
</tr>
<tr>
<td>7000</td>
<td>1.21</td>
<td>16.9</td>
<td>100</td>
<td>300.0</td>
<td>2870</td>
<td>860.9</td>
</tr>
<tr>
<td>8000</td>
<td>0.79</td>
<td>12.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Influence of the Initial Launch Tube Pressure

When the launcher is placed at high altitude (say, 3000 m above sea level), the shock wave drag inside the launcher will decrease. If the launch tube is evacuated, there will be no wave drag. To test the influence of the initial launch tube pressure, we simulated the full caliber launcher with $v_0 = 5$ km/s. The velocity increases due to one charge are:

$$Av = 2.68 \text{ m, when } p_0 = .101 \text{ MPa},$$

$$Av = 2.84 \text{ m, when } p_0 = 0.071 \text{ MPa},$$

and

$$Av = 3.31 \text{ m, when } p_{oo} = 0 \text{ MPa}.$$

It can be seen that launching at 3000 m (where $p_{oo} = 0.071 \text{ MPa}$), the wave drag reduction is small compared to that incurred when launching at sea level. On the other hand, evacuation of the tube can increase the efficiency to 33.1\% at this initial projectile speed.

Validations of the Numerical Results

Different mesh sizes (0.02 m, 0.01 m, and 0.007 m) were used to ensure that the results are grid independent. The influence of mesh size on $Av$ is shown in Figure 5. It can be seen that the difference among the results is small. The estimated number of charges and launcher length to obtain a launch speed 8 km/s using different mesh sizes are shown in Table 2.

![FIGURE 5. Influence of Mesh Size $h$ on Projectile Velocity Increase Due to One Charge.](image)

<table>
<thead>
<tr>
<th>Mesh size (m)</th>
<th>Total number of charges</th>
<th>Total launcher length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>2617</td>
<td>787</td>
</tr>
<tr>
<td>0.01</td>
<td>2912</td>
<td>873.3</td>
</tr>
<tr>
<td>0.007</td>
<td>2870</td>
<td>860.9</td>
</tr>
</tbody>
</table>
Fast Simulation Method

To validate the fast simulation method used in this work, a simulation for $v_0 = 6500$ m/s is performed. The $\Delta v$ variation is plotted as a function of charge numbers in Figure 6. Convergence of $\Delta v$ to about 1.57 m is clearly seen. This means that after about 12 detonations, the influence of the initial condition is nearly lost, in agreement with the assumption of our fast simulation method. Similar trends can be found from Figure 5.

The $\Delta v$ of the final detonation is 1.574 m. The linear interpolation using the data from Table 1 gives 1.54 m. Their difference is about 2%.

![Graph showing convergence of $\Delta v$ as the number of charges increases.](image)

**FIGURE 6.** Convergence of $\Delta v$ as the Number of Charges Increases.

CONCLUSIONS

In this work numerical simulations were performed for a Blast Wave Accelerator. The feasibility of the BWA concept to accelerate a one-ton projectile to hyper-speed (7-9 km/s) is studied.

- It is found that the launcher length needed is about 560 m for a launch speed of 7 km/s and 860 m for a launch speed of 8 km/s.
- About 1870 charges (or 18700 kg of explosives) are needed for a launch speed of 7 km/s and 2870 charges (or 28700 kg of explosives) are needed for a launch speed of 8 km/s.
- The peak pressure on the projectile does not exceed the material strength specified (2 GPa) except in a tiny spot around the center of the projectile back.
- The peak acceleration is well under the specified limit (50-250 kG).
ACKNOWLEDGMENTS

Support from the US Army Research Laboratory under grant DAAD 17-00-P-0798 and assistance from M. Nusca and H. Elliott are gratefully acknowledged.

NOMENCLATURE

\[ m_p = \text{mass of projectile (kg)} \]
\[ m_e = \text{mass of explosive charge (kg)} \]
\[ l_e = \text{axial spacing between explosive charges (m)} \]
\[ e = \text{energy density (MJ/kg)} \]
\[ POO = \text{initial pressure of air inside launch tube (MPa)} \]
\[ \rho_o = \text{initial pressure of air inside launch tube (MPa)} \]
\[ \nu_0 = \text{initial projectile velocity (km/s)} \]
\[ u, v = \text{gas velocity (m/s)} \]
\[ H = \text{total enthalpy (kJ/kg)} \]
\[ t = \text{time (s)} \]
\[ Y = \text{ratio of specific heats} \]

REFERENCES

