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A Numerical Simulation of Gas Gun Performance

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ABSTRACT

A quasi one-dimensional Lagrangian compressible flow solver was used to simulate the gas dynamics of the DSTO transonic gas gun at Port Wakefield. The practice of initially locating the projectile partway down the barrel, in a bid to reduce muzzle velocity, was also investigated. We find excellent agreement between simulated and measured muzzle velocity, for both the case of full barrel-length projectile travel and reduced projectile travel. While the reduction in projectile travel is shown to be a valid means to significantly reduce muzzle velocity, we also show that this configuration results in shock loading to the projectile and increased barrel pressure.

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Executive Summary

Gas guns have been used by the Defence Science Technology Organisation (DSTO) and predecessor organisations to provide a readily accessible and cost effective means for investigating projectile flight characteristics. Currently, the transonic gas gun at Proof & Experimental Establishment Port Wakefield produces projectile speeds that allow simulation of flare ejection from high-speed aircraft. However, to simulate flare ejection from helicopters and slower aircraft, lower muzzle velocities must be generated.

One technique to achieve a lower muzzle velocity from the gun is to locate the projected mass partway down the barrel before firing. Computational fluid dynamics simulation of the gas gun interior ballistics was conducted to analyse the consequences of firing the gun in this manner, and estimate the resultant performance. Experimental trials were also conducted: excellent agreement between simulated and measured muzzle velocity was achieved, for both cases of full barrel projectile travel, and reduced projectile travel.

We also found that while the practice of initially locating the projectile partway down the barrel is a valid means to significantly reduce muzzle velocity, it also results in shock loading to the projectile and increased barrel pressure.

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After completing an honours degree in Mechanical Engineering at the University of Queensland, Ian Johnston conducted postgraduate research in the area of computational fluid dynamics at the same institution. Research included the creation of a new CFD code for the simulation of hypersonic blunt body flows, and he graduated in 1999 with a PhD. After completing one year in the field of defence operations research at DSTO Pyrmont, he accepted a three year position at the German Aerospace Center to work on international projects including the ESA Atmospheric Reentry Demonstrator, the NASA X-38 Crew Return Vehicle, and the DLR Tau code. He returned to Australia in 2003 to work in the area of ballistics at DSTO Edinburgh, where he leads the gun propulsion team within Weapons Propulsion Group, and acts as Project Science and Technology Adviser to several artillery-related acquisition projects.

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1. Introduction

Since the 1960s, gas guns have been used by the Defence Science Technology Organisation (DSTO) and predecessor organisations to provide a readily accessible and cost effective means for investigating projectile flight characteristics.

The principle of operation of a conventional gas gun is that gas, initially stored at high pressure, is suddenly released and allowed to act on the rear face of a projectile enclosed inside a long tube or barrel. The gas pressure difference across the projectile causes it to accelerate along the barrel until emerging from the muzzle.

Shannon [1] discusses the research and development activities within DSTO associated with the use of three such gas guns, the characteristics of which are summarised in Table 1.

Table 1: DSTO Gas Gun Designs

Name	Subsonic 1	Transonic	Subsonic 2
Gun Calibre (mm)	127	265	384
Barrel Length (m)	4.6	6.5	5.8
Effective Reservoir Volume (l)	32	570	680
Max Working Pressure (atm)	40	280	18
Max Velocity (m/s)	200 ¹	550 ²	270 ³
Working Gas	Nitrogen	Nitrogen	Air
Barrel Elevation (deg)	0-45	0-30	0-90
Type of Valve	Piston	Piston ⁴	Sleeve
Max Peak Acceleration (g)	500	5000	500
Status	Does not exist	Port Wakefield	Port Wakefield ⁵

The transonic gas gun (Figure 1) is situated in the canister battery at the Proof & Experimental Establishment range, Port Wakefield. Extensive study into the flight characteristics of half scale Mk82 bombs took place during 1992-1993, with the research activities ceasing following the termination of the research task. Currently this gas gun is used extensively in the measurement of the performance characteristics of Infrared Counter Measure (IRCM) flares under realistic ejection conditions and in this configuration is referred to as the Reusable Aerodynamic Flare Ejection Capability (RAFEC). The details of RAFEC and methodology of its operation and measurement can be found in [2] and [3].

The gas gun is predominately used over a muzzle velocity range of 200 to 310 m/s, with projectile masses up to 15 kg. Under these conditions the IRCM flares experience release speeds that correspond to those of high speed aircraft such as the F/A-18. In order to

¹ 3 kg projected mass

² 35 kg projected mass

³ 5 kg projected mass

⁴ Ejected at each firing

⁵ Currently being established

reproduce release speeds corresponding to helicopters and transport aircraft, such as the C-130 and P-3C, lower muzzle velocities must be produced.

New firing hardware incorporating a heavier projected mass (see Reference [4]) has been designed to achieve the required lower muzzle velocities. While velocities of 130 m/s at 2 MPa have been achieved, the reliability in firing at low reservoir pressures (<2 MPa) has been problematic and the development of this hardware is still continuing.



Figure 1: Transonic Gas Gun in Canister Battery at P&EE Port Wakefield

An alternative means to reduce muzzle velocity, that does not necessarily require a heavier projectile or a low reservoir pressure, is to simply reduce the length of projectile travel through the barrel. Varying the length of barrel itself, in a physical sense, is not practicable once the facility is established. An alternative way of achieving the reduced travel is to locate the projected mass partway down the barrel before firing. Trials were conducted to test this hypothesis and the results are included in this report.

When the gas gun is operated normally, with full projectile travel, a relatively simple calculation [5] yields the muzzle velocity in terms of reservoir pressure and projected mass. However, this method is not suitable for determining gas gun performance in the case of reduced travel. When the projectile is initially located partway down the barrel, more sophisticated simulation is required to model the resulting complex gas dynamics behaviour in order to obtain an accurate muzzle velocity prediction.

This report details computational fluid dynamics simulations used to predict gas gun muzzle velocity, for both the full- and reduced-projectile travel cases. Also included is a comparison of the predicted results with those experimentally obtained from the gun, for a range of operating conditions.

2. Numerical Simulation

2.1 Numerical Method

The flow within the gas gun is simulated using a quasi-one-dimensional Lagrangian compressible flow solver, L1d [6]. The solver operates by representing the flow domain by a series of control masses, and calculates the movement and volume change of these mass elements. The Lagrangian framework is particularly suited for simulation of flow systems incorporating pistons or projectiles, as these may be conveniently inserted between slugs of mass elements.

The code is nominally second-order accurate in both space and time. Interpolation of flow states adjacent to cell interfaces is moderated by a MINMOD limiter function to enhance stability, and these states are subsequently used to calculate conditions at cell interfaces with an approximate Riemann solver.

When flow mass elements move during simulation, their cross sectional areas adjust to conform to a predefined geometry. In this manner, the one-dimensional discretization can be used to approximate a two-dimensional geometry, providing cross section changes are reasonably gradual and that flow effects in the transverse direction are negligible. Further limitations of the Lagrangian approach are that gas mixing between control masses is not allowed, and that under conditions of extreme compression or expansion the mass elements may become an undesirable size. However, none of these limitations are an issue for simulation of the transonic gas gun.

L1d includes support for a variety of gases and gas mixtures. Viscous losses are also simulated, through use of engineering correlations for friction and heat transfer. While these correlations were originally developed for incompressible flows, Jacobs [6] reports success with their application on very highly compressible flows.

In practice, the L1d code supports a flexible, programmable input format in the Python language, and is reasonably fast to run. A high-resolution 2000-element simulation of the transonic gas gun typically takes less than half-an-hour to complete on a modern PC workstation.

2.2 Gas Gun Representation and Meshing

Representations of the transonic gas gun, for simulation purposes, is shown in Figure 2. The figure shows two distinct initial conditions: Case A shows the setup for simulations of the gas gun with full projectile travel, while Case B shows the setup for reduced projectile travel.

For Case A, the 570 litre reservoir of nitrogen gas is discretized into a slug of 1600 mass elements, which in turn abuts the left face of the projected mass. The right face of the projectile mass is connected to 400 mass elements representing the ambient air. In this way, the resistive effect due to compression of the precursor air is included in the

simulation. The right side of the reservoir is represented by a gradual constriction to avoid an abrupt change in cross-section, to satisfy the limitations of the quasi-one-dimensional approximation. The effect of viscous losses, as the reservoir gas flows through the transition into the barrel, is included in the model. The initial position of the projected mass is approximately 300 mm downstream from the barrel origin, to reproduce the displacement occurring in the actual gun. While the modelled reservoir volume reproduces that of the gun, the dimensions depicted in Figure 2 have been slightly modified from the real gas gun dimensions in order to account for volume losses due to internal reservoir parts.

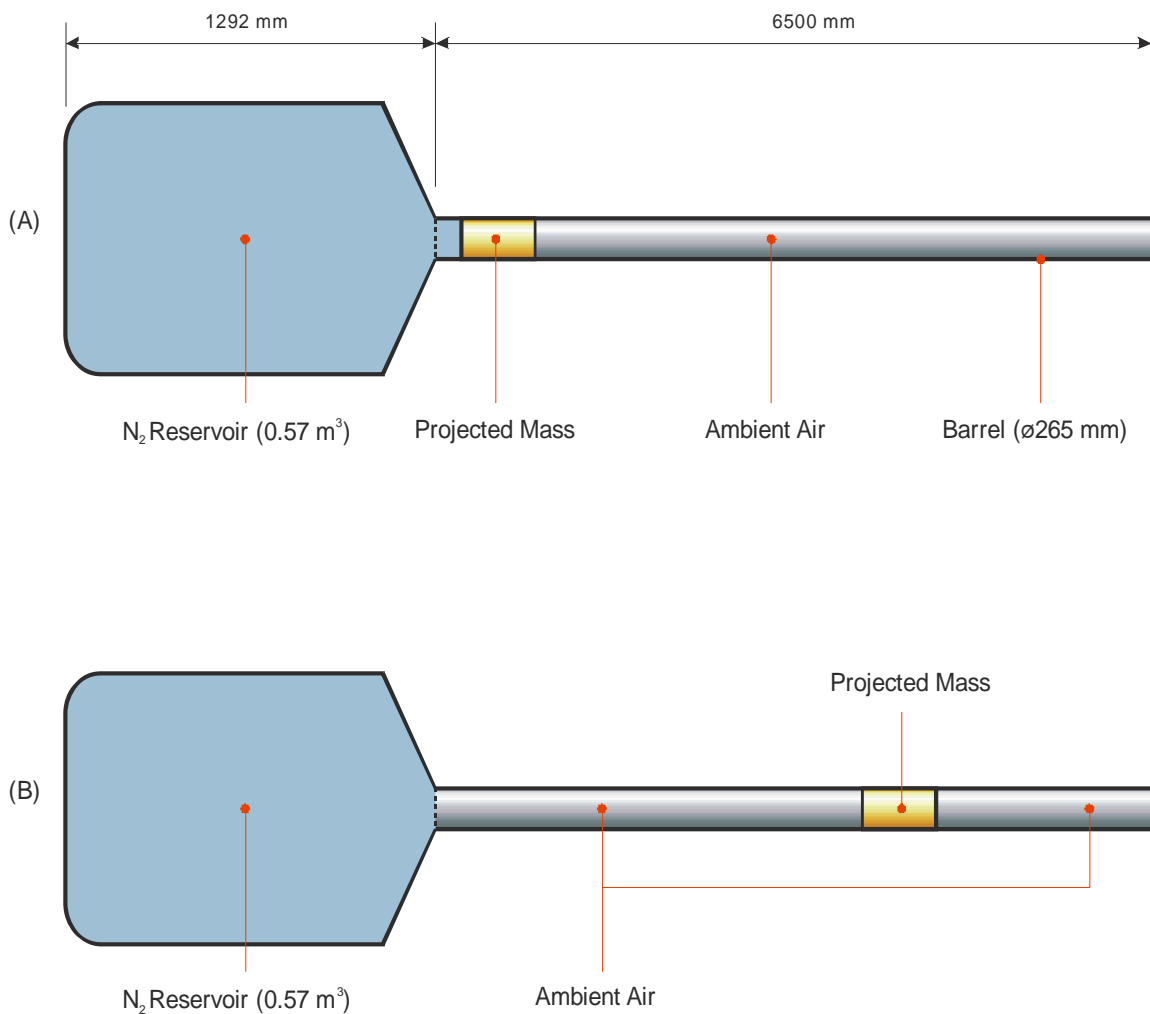


Figure 2: Representation of the gas gun geometry for numerical simulation, showing initial conditions for the cases of (A) full projectile travel, and (B) reduced projectile travel

For Case B, representing the case of reduced projectile travel, the initial position of the projected mass is part-way down the barrel. The pressurized nitrogen reservoir is positioned adjacent to a slug of ambient air within the gas gun, which is in turn connected to the projectile. Like Case A, losses are included at the reservoir constriction, and mass elements of initially ambient air are used to simulate the effect of precursor flow compression.

For both cases, the nitrogen and air are assumed to be ideal gases. As sliding friction between the projectile and barrel is minimal, this is ignored in the numerical simulation. Ambient air is assumed to be at a temperature of 300 K and a pressure of 100 kPa, while the nitrogen reservoir is slightly cooler at 283 K. The nitrogen temperature is based on measured values, and is due to the expansion process during reservoir filling.

For the purposes of this report, muzzle velocity is quoted as the speed of the projectile upon complete emergence from the barrel end.

3. Results

Simulation results for two specific conditions, one each of Case A and B, are discussed in detail in Sections 3.1 and 3.2. Following the discussion, Section 3.3 compares simulation results with measurements made during actual gas gun firings.

3.1 Projectile Full Travel (Case A)

For this test case, a reservoir pressure of 4 MPa nitrogen gas is assumed. The total projected mass is 27 kg, and this mass travels the full barrel length before exiting the gun muzzle.

Figure 3 shows the simulation results as pressure versus axial distance along the barrel at three different points in time: 0 ms, 25 ms and 40 ms after shot start. The results show the pressure in the reservoir and tube decreasing monotonically with time, as the driver gas expands, does work to accelerate the projectile, and fills the increasing space left behind the projectile in the barrel. A slight pressure drop between reservoir and tube is visible, accounted for by the accelerating driver gas and viscous losses at this point.

Figure 4 shows similar information to Figure 3, in a space-time diagram format. On this diagram, the compression of the precursor gas (ahead of the piston) is more easily visible. The resultant muzzle velocity for this case is 233 m/s.

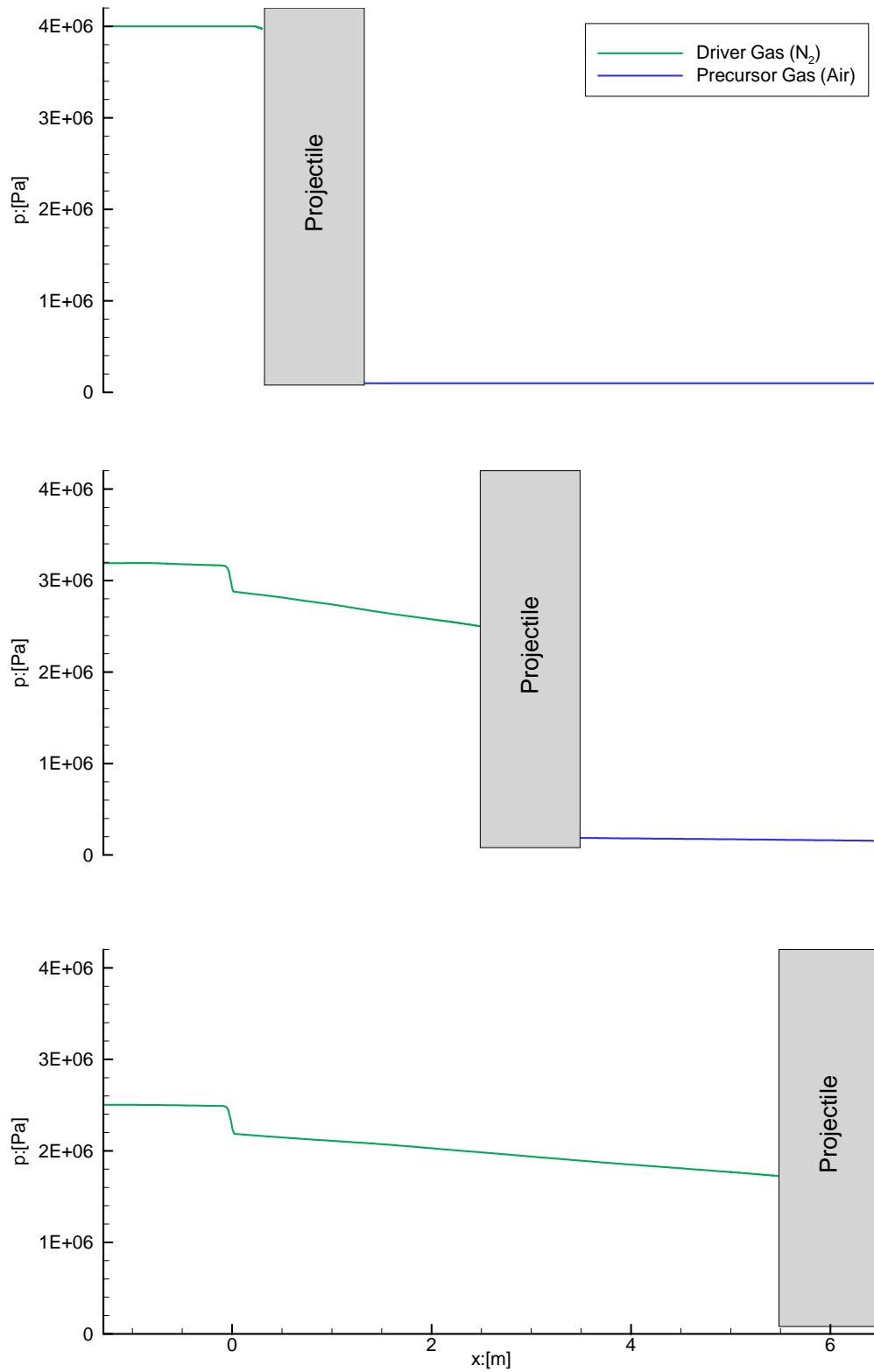


Figure 3: Calculated pressure within the gas gun for Case A at 0, 25 and 40 ms after shot start

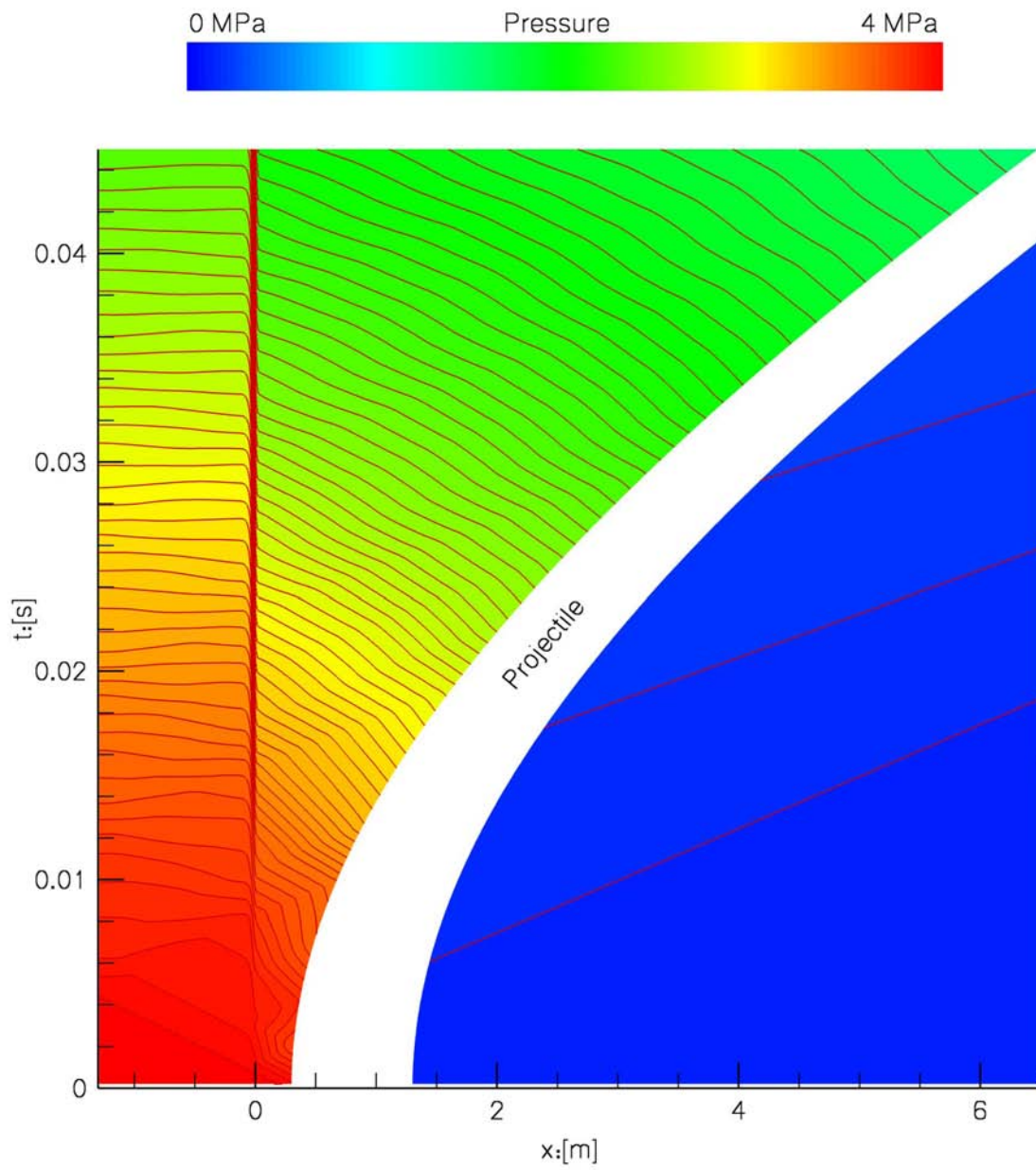


Figure 4: Space-time diagram showing pressure within the gas gun for Case A

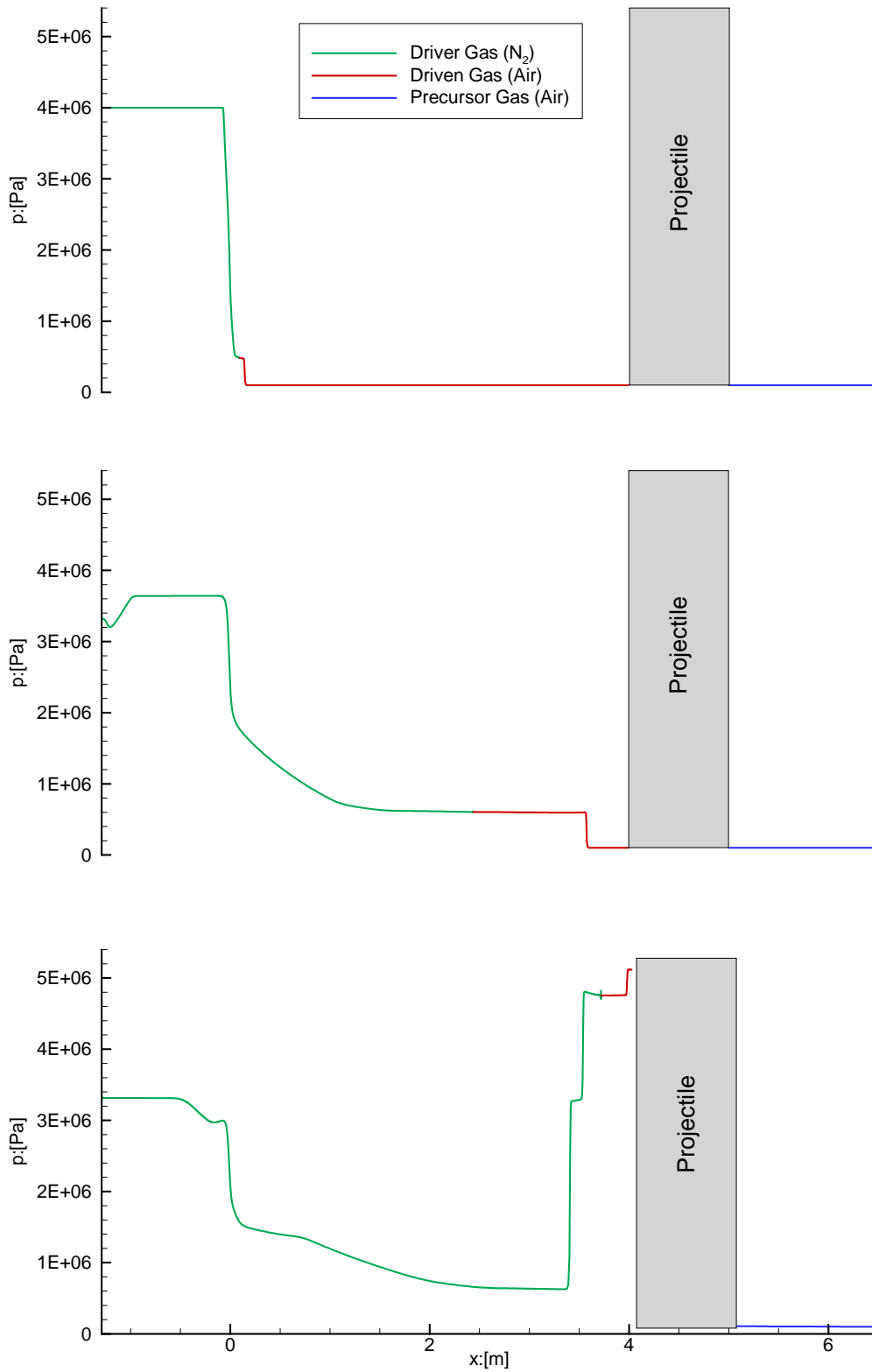


Figure 5: Calculated pressure in the gas gun for Case B at 0, 4.6 and 8.4 ms after driver gas release

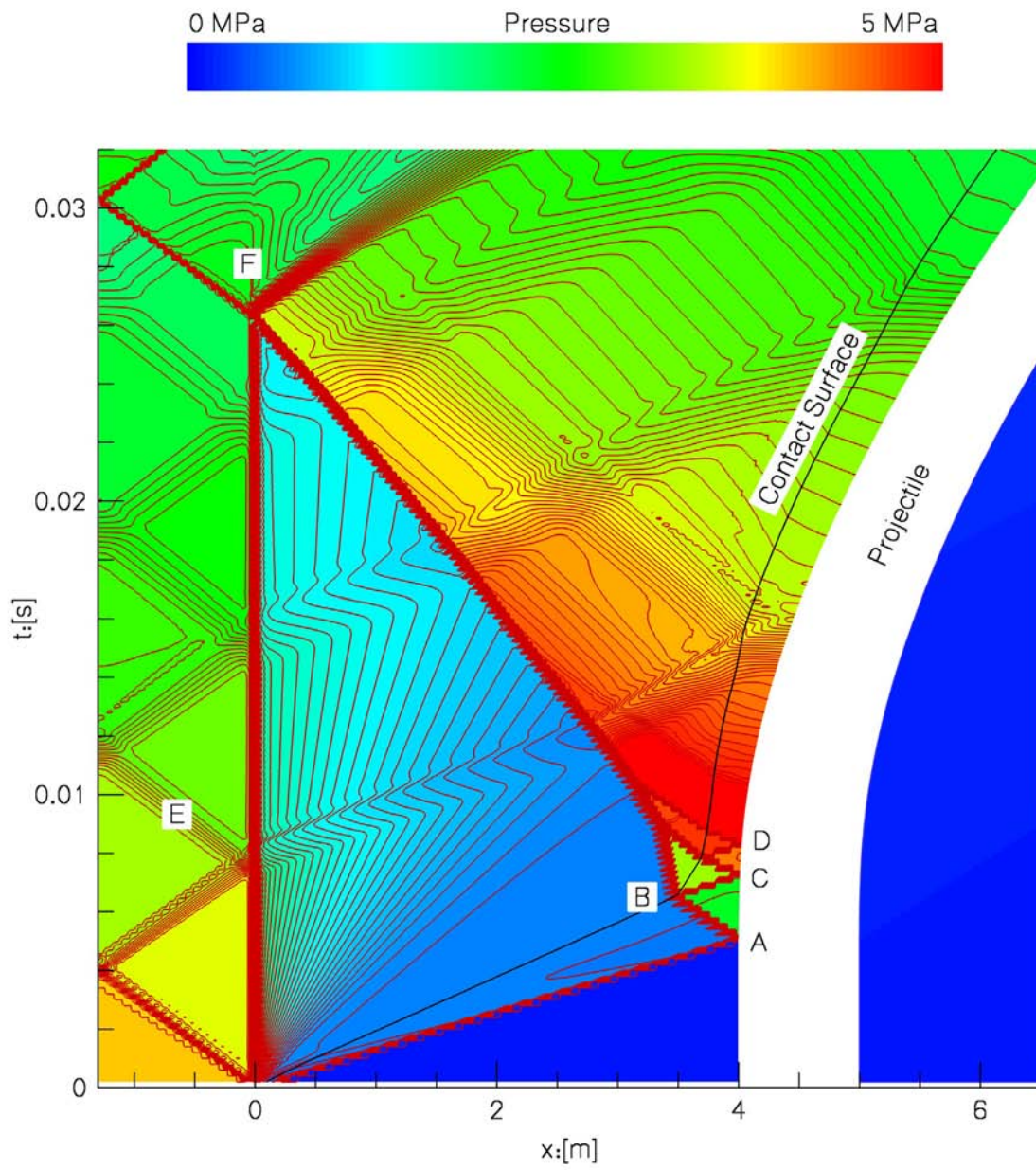


Figure 6: Space-time diagram showing pressure within the gas gun for Case B

3.2 Projectile Reduced Travel (Case B)

For this test case, reservoir pressure and projected mass are kept the same as for the case of Section 3.1. The initial projectile position, however, is now located 4 m downstream of the barrel origin.

Figure 5 shows the simulation results as pressure versus axial distance along the barrel at three different points in time: 0 ms, 4.6 ms and 8.4 ms after driver gas release. This same information can be seen in the format of a space-time plot in Figure 6.

At the point of driver gas release, the initial conditions at the nitrogen-air contact surface represent a classic Riemann problem. The high pressure driver gas forces a shock wave through the initially ambient air, compressing the air as it moves towards the projectile. Meanwhile, upstream of the nitrogen-air contact surface a forward-travelling expansion fan (in the gun frame of reference) is generated. Expansion waves also travel back into the reservoir tank, reducing reservoir pressure (point E). This state is visible in the 4.6 ms snapshot of Figure 5.

After approximately 5 ms, the shock wave arrives at and reflects from the rear of the projectile (point A in Figure 6). At this point, the projectile is first subject to a pressure difference and begins to accelerate down the barrel. It should be noted that this initial loading of the projectile is impulsive, and may present implications for shock-sensitive projectile payloads. The gas shock subsequently travels back upstream reprocessing the air until arriving at the nitrogen-air contact surface (point B). Here, the shock is in part transmitted into the nitrogen, and in part reflected back towards the projectile. The reflected shock again processes the air, increasing its pressure further until reflecting from the projectile a second time (point C). This process is repeated (to point D) until the shock degenerates into weak waves and projectile movement starts to offer pressure relief. Figure 5, at 8.4 ms, shows a pressure-distance snapshot at a moment in time just after point C.

It is important to note that the compounding recompression of the air results in a maximum pressure of 5.1 MPa in the barrel, which is higher than that of the original driver gas.

Eventually the reflected shocks coalesce into one strong shock, which travels towards the reservoir and arrives at the barrel origin at approximately 26 ms (point F). Waves travelling back downstream at this point will not be encountered by the projectile, as the projectile exits the muzzle shortly thereafter.

Calculated muzzle velocity is 174 m/s for this case, 25% lower than that of the previous case where full projectile travel occurs.

3.3 Comparison with Measurement

Experimental muzzle velocities were measured in two different ways: (1) using the TERMA 5000 tracking radar to track the carrier projectile exiting the gas gun and extrapolating the track to the muzzle, and (2) using the time required to travel a distance of 0.5 metres before the end of the barrel. For method (2), time signals were generated by

the firing hardware-pusher passing through a magnetic field over this distance. There is good agreement (5%) between the two methods.

Table 2: Comparison between simulated and measured muzzle velocity

Reservoir Pressure (MPa)	Projected Mass (kg)	Projectile Initial Position (m)	Modelled Muzzle Velocity (m/s)	Measured Muzzle Velocity (m/s)	Muzzle Velocity Difference
4.0	27.0	0.3	233	231	0.9%
4.0	32.5	0.3	216	216	0.0%
4.0	42.5	0.3	193	199	3.0%
5.0	27.0	0.3	256	252	1.6%
7.8	27.0	0.3	306	305	0.3%
2.0	27.0	2.0	123	124	0.4%
4.0	27.0	2.0	195	206	5.3%
4.0	27.0	4.0	174	171	1.8%
2.0	48.0	0.3	131	-	-
3.0	48.0	0.3	160	-	-
4.0	48.0	0.3	183	-	-
5.0	48.0	0.3	203	-	-

A comparison between simulated and measured muzzle velocities is shown in Table 2, for the cases of full projectile travel (top) and reduced projectile travel (middle). Calculated results for anticipated future gas gun conditions are also included at the bottom of the table. It should be noted that the modelled values given in the table are true “predictions”, where the measured values remained undisclosed during conduct of the simulations. The results in general show excellent comparison between simulation and measurement. Discrepancy exceeds the limit of experimental uncertainty in one case only, and even then by a very small margin.

4. Conclusions

A quasi one-dimensional Lagrangian compressible flow solver was used to simulate the gas dynamics of the DSTO transonic gas gun at Port Wakefield. The practice of initially locating the projectile partway down the barrel, in a bid to reduce muzzle velocity, was also investigated. We find that:

1. Excellent agreement between simulated and measured muzzle velocity was achieved, for both the case of full barrel projectile travel, and reduced projectile travel.

2. The practice of initially locating the projectile partway down the barrel is a valid means to significantly reduce muzzle velocity.
3. By initially locating the projectile partway down the barrel, complex gas dynamic behaviour results. This can generate peak barrel pressures substantially higher than the reservoir pressure. The possibility of increased barrel pressure should be kept in mind when designing experiments, so as not to overpressure the gun.
4. It should also be noted that, when initially locating the projectile partway down the barrel, impingement of a gas shock wave against the projectile base will result in impulsive shock loading to the projectile.

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