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Characterization of the Interior Ballistics of a Single-Stage Air Cannon for Free-Flight Projectile Testing

by Macs Brown, Daniel Everson, and Edward Bukowski

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14. ABSTRACT
The Single-stage Air-Initiated Launcher (SAIL) was developed to enable precise, repeatable free-flight projectile testing for ARL research. This report presents a comprehensive assessment of SAIL's interior ballistics, combining theoretical modeling and experimental measurements. Simplified Newtonian models, which assume ideal gas expansion and neglect valve dynamics, were used to predict muzzle velocity but consistently overestimated performance. Empirical testing with mass simulant slugs, high-speed video, Doppler radar, and on-board recorders (OBRs) revealed that SAIL's piston valve delivers rapid pressure rise and transient acceleration spikes, with peak in-bore accelerations up to 30% higher than predicted by tank pressure alone. OBR data confirmed oscillatory forcing pressures at the projectile base, attributed to compression waves in barrel dead volume. These results demonstrate that valve dynamics and system geometry significantly influence air cannon performance, and direct measurement is essential for accurate characterization. OBR-equipped slugs proved effective for rapid, reliable interior ballistics assessment, supporting ongoing research and system optimization.

15. SUBJECT TERMS
Weapons Sciences, air cannon, internal ballistics, flight testing, range testing, soft launch, on-board recorder, OBR

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1. Introduction

The U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory's (ARL's) Guidance Technology Branch (GTB) recently undertook the design of a 3-inch smoothbore air cannon, referred to as the Single-stage Air-Initiated Launcher (SAIL),[1] to facilitate affordable early-stage proof-of-concept free-flight testing. A critical requirement for free-flight testing is the ability to achieve specific muzzle velocity targets accurately and repeatably, which in turn requires an in-depth understanding of the interior ballistic cycle of the SAIL system.

Several existing simplified theoretical models were applied to establish baseline relationships between tank pressure and muzzle velocity for a range of projectile masses. A firing campaign was conducted to verify these models using a series of cylindrical mass simulant slugs. Muzzle velocity measurements were captured using a high-speed camera and Doppler radar. A subset of the slug shots used mass simulant slugs with onboard accelerometers and data recording to onboard nonvolatile memory. These on-board recorder (OBR) slugs captured high sample rate acceleration data for the interior ballistic cycle. This report discusses an assessment of interior ballistics performance for the SAIL system and compares those observations to the simplified theoretical models.

2. Modeling of Air Cannon Interior Ballistic Performance

Theoretical and empirical methods were used to estimate expected performance of the SAIL system during development of the system. The benefit of a well-developed interior ballistic model for any air cannon is that it allows a test director to accurately predict the muzzle velocity of a projectile of a given in-bore mass at a given initial tank pressure. Additionally, being able to estimate the forces present during the interior ballistics cycle facilitates effective engineering development of the electromechanical components that will be exposed to those loads during the launch event.

Additional emphasis was placed on theoretically modeling the performance of the SAIL system because of the inability of existing simplified models to predict the performance of its predecessor—the legacy ARL air cannon. The SAIL system was devised as a direct replacement for the legacy ARL air cannon, which was previously used for low-velocity flight testing and subscale sabot petal testing.[2] It is worth noting that the performance of the legacy ARL air cannon was not well described by simple theoretical models, which grossly overpredicted muzzle velocity. This discrepancy is most likely caused by an inefficient plumbing setup and slow valve opening time on the legacy ARL air cannon. A significant performance increase in muzzle velocity was observed in the SAIL system over the legacy ARL air cannon despite both systems having the same barrel length, similar tank volumes, and the same operating pressure range.

2.1 Theoretical Modeling, Assumptions, and Limitations

A simple theoretical model described by Rohrbach et al.[3] was initially applied to predict the muzzle velocity of the legacy ARL air cannon for varying projectile masses. This theoretical model is derived from a simple Newtonian force balance assuming that gas pressure from a reservoir is released by an idealized valve and proceeds to act on the rear face of the projectile, thus accelerating it until it reaches the muzzle. The motion of this projectile is opposed by two forces: the friction of the projectile against the bore, and the ambient air pressure in front of the projectile. This model takes the form of the following equation:

$$F = m\frac{dv}{dt} = mv\frac{dv}{dx} = AP(x) - AP_{atm} - f\ , \tag{1}$$

where m is the mass of the projectile, v is the projectile velocity, A is the cross-sectional area of the cannon bore, $P(x)$ is pressure acting on the base of the projectile as a function of distance from the breech x, P_{atm} is the atmospheric pressure, and f is the force of friction.

This force balance can be solved for the projectile velocity at the muzzle by assuming that the gas either expands quasi-statically and adiabatically or quasi-statically and isothermally, which yields the following equations:

For adiabatic expansion:

$$mv\frac{dv}{dx} = A\left(\frac{P_0 V_0^{7/5}}{(V_0 + Ax)^{7/5}} - P_{atm}\right) - f \tag{2}$$

$$v = \sqrt{\frac{5}{m}\left(1 - \left(\frac{V_0}{AL - V_0}\right)^{2/5}\right) - 2ALP_{atm} - 2Lf} \tag{3}$$

For isothermal expansion:

$$mv\frac{dv}{dt} = A\left(\frac{P_0 V_0}{V_0 + Ax} - P_{atm}\right) - f \tag{4}$$

$$v = \sqrt{\frac{2}{m}\left(P_0 V_0 \ln\left(1 + \frac{AL}{V_0}\right) - LAP_{atm} - Lf\right)}\ , \tag{5}$$

where v is the projectile velocity, P_0 is the initial tank pressure, V_0 is the initial tank volume, and L is the barrel length. Calculating velocity for both adiabatic and isothermal expansion serves to bound the velocity prediction between the two cases. A practical air cannon is neither perfectly adiabatic nor isothermal although the rapid decompression of pressurized air from the tank of the legacy ARL air cannon would be expected to more closely reflect an adiabatic process (Figure 1).

These expansion equations can be used to plot muzzle velocity as a function of projectile mass at a given pressure, or muzzle velocity as a function of initial tank pressure at a fixed projectile mass, both of which are useful to a test director. These equations can also be used to create an interior ballistic model over a range of operating conditions by iteratively solving for muzzle velocity over a range of tank pressures. These equations were applied to the legacy ARL air cannon with the following input parameters as shown in Table 1.

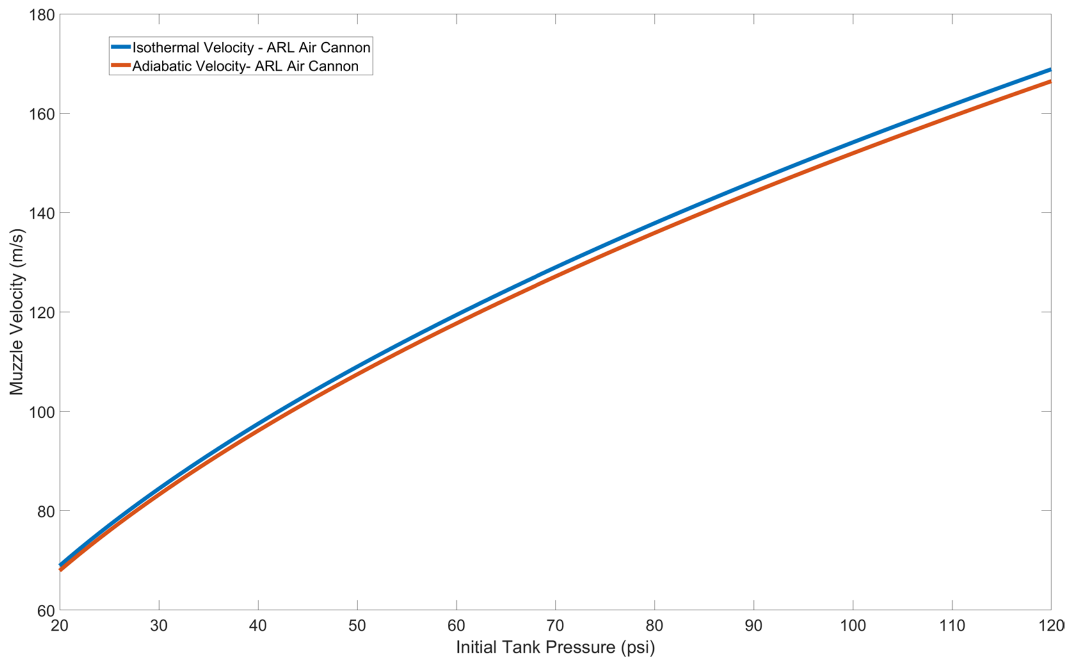

Figure 1. Theoretical model of ARL air cannon performance assuming either isothermal or adiabatic expansion. These calculations were run with barrel friction equal to zero, because that effect is unknown and typically small. The simple theoretical models do not account for valve performance or aerodynamic drag.

Table 1. Legacy ARL air cannon code input parameters.

Input parameter	Value	Unit
Barrel diameter	3	Inches
Barrel length	8	Feet
Tank volume	2.540	Cubic feet
Initial tank pressure (absolute)	20–100	Pounds per square inch (psi)
Driving gas specific heat ratio	1.4	Unitless
Projectile mass	600	Grams

Note: All calculations assume no barrel friction.

While this method of muzzle velocity estimation is computationally simple, it ignores several physical phenomena that play a large role in air cannon performance—namely valve flow rate and valve opening time. This is directly addressed by Rohrbach et al.,[3] which states both simplified models overpredict air cannon muzzle-velocity performance and a numerical model that incorporates the flow rate of the valve is significantly more accurate.

A numerical model incorporating the valve flow rate was not used to predict performance of the legacy ARL air cannon because the valve flow coefficient (C_v) must be known. Estimation of this coefficient for the operating conditions of the air cannon would require high-rate experimental measurements of pressure within the tank and barrel. It is technically feasible to collect this data using piezoelectric pressure gauges but implementing these sensors was outside the scope of available resources. Additionally, the numerical model with incorporation of valve flow rate does not include terms to describe valve opening speed. It instead assumes that C_v is a constant throughout the valve cycle. Performance characterization of the legacy ARL air cannon highlighted that the "assertiveness" of the test operator actuating the manual valve significantly impacted the muzzle velocity achieved. Given the observed impact of valve opening time on performance and the lack of an established C_v, a numerical model incorporating valve flow rate was not implemented. The simple theoretical model without valve performance incorporated serves as a useful baseline to establish a performance ceiling for a given configuration, acknowledging that it is an overprediction of real-world performance for a valved system.

The SAIL system incorporates a faster operating and more efficient piston valve configuration than the manually operated ball valve of the legacy air cannon. It was expected that the SAIL system would achieve performance closer to the idealized models, but the valve performance of the SAIL system was unknown prior to execution of firing experiments.

2.2 Empirical Muzzle Energy Curve Establishment for SAIL System

One of the objectives for initial SAIL system testing was the establishment of muzzle energy curves using mass simulant slugs as an empirical means for estimating muzzle velocity for a given air cannon configuration. This approach is described in detail for both the legacy ARL air cannon and the SAIL system in ARL-TR-10328.[1] The relationship between tank pressure and muzzle energy for these two systems for the firing of cylindrical slugs (Figure 2) is shown in Figure 3. This empirical method based on experimental data is a useful tool for prediction of air cannon muzzle velocity as it removes the need to model more complex system variables such as valve flow rate, valve opening time, and dead space that would require physical measurements to accurately determine. However, this method is somewhat limiting since changing a physical parameter of the air cannon system (bore diameter, barrel length, valve opening speed, and driving gas) will invalidate previously captured empirical data.

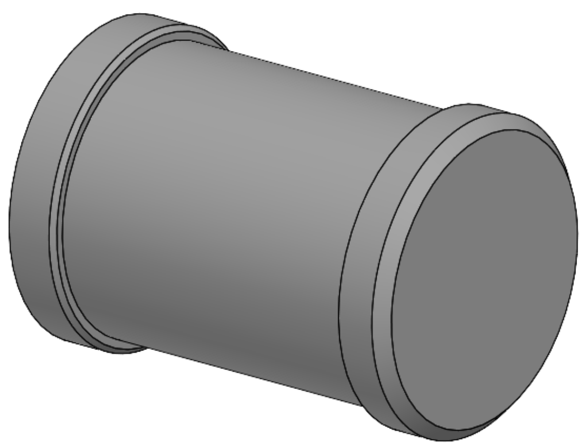

Figure 2. Rendering of 3-inch mass simulant cylindrical slug. A 500-g nominal mass was selected to simulate the mass of a 40-mm projectile launch and flight package to be fired from the SAIL system for free-flight testing. An undercut was added to the midbody section of the slug to reduce in-bore friction.

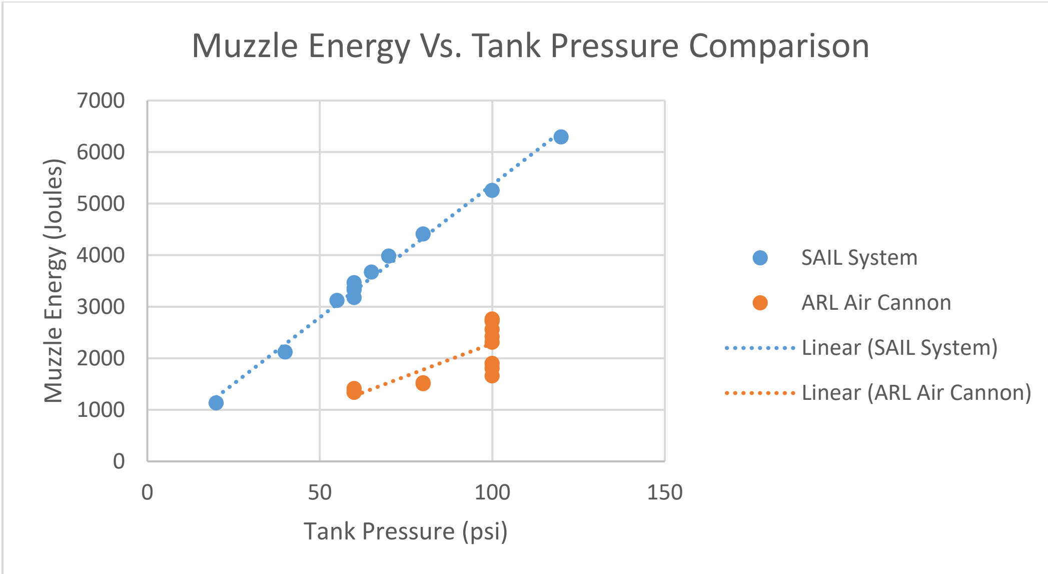

Figure 3. Muzzle energy comparison of ARL air cannon and SAIL system. Not only does the SAIL system outperform the ARL air cannon at any tank pressure, but it also shows a more consistent linear increase in muzzle energy as tank pressure is raised.

2.3 Observation of In-bore Motion Profile Using High-Speed Video

Both the legacy ARL air cannon and the SAIL system use a clear polyvinyl chloride (PVC) barrel that allows the projectile to be viewed by high-speed cameras during its interior ballistic travel. High-speed imagery captured by a camera positioned orthogonal to the barrel provides a means to analyze the in-bore performance of the systems (Figure 4). Frames from the high-speed video are postprocessed to estimate the position of the projectile as a function of time. Computer vision algorithms are implemented to track fiducial stripes applied to the side of the cylindrical slugs from one frame to the next and estimate the position of those fiducials in pixel coordinates. Fiducial markings on the exterior of the barrel provide a complimentary means to convert from pixel coordinates to physical distance at the vertical plane of the barrel. This is a simplified approach to physical measurement using computer vision that could be improved by implementation of a calibrated camera intrinsics model, but assumptions made to treat the pixel coordinates as uniformly spaced at the vertical plane of the barrel are adequately accurate for this application.

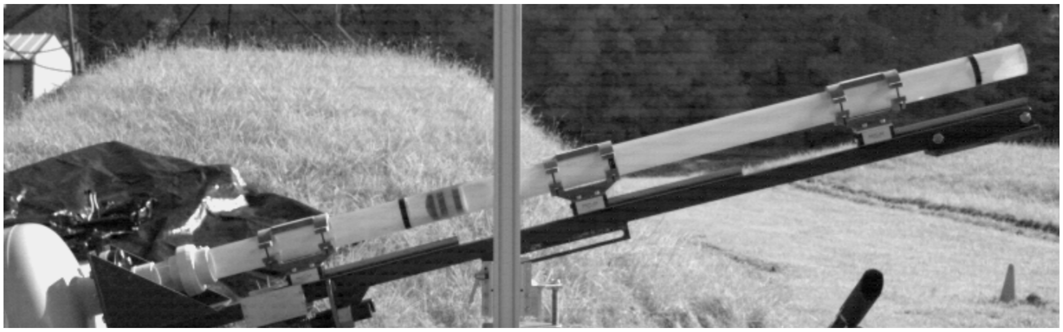

Figure 4. High-speed video frame showing a cylindrical slug traveling down the clear barrel of the SAIL system. The black fiducial stripes on the slug are used for estimating the position of the slug in pixel coordinates. The black fiducial stripes on the barrel are used for reference in converting between pixel coordinates and relative position within the vertical plane of the barrel.

The most valuable parameter for characterizing the interior ballistics cycle of an air cannon is the projectile acceleration as a function of time. Given the known in-bore mass of the projectile, the linear acceleration of the projectile captures the sum of forces acting parallel to the barrel throughout the in-bore cycle. These are namely the base pressure from expanding gases acting on the rear face of the projectile and two forces that oppose forward motion of the projectile. These are the force of friction between the projectile and the barrel wall and the aerodynamic loads acting on the front face of the projectile—a combination of ambient atmospheric pressure and aerodynamic drag.

Postprocessing of high-speed video provides relative position of the projectile in the vertical plane of the barrel as a function of time. Computer vision coordinates of visible fiducials on the projectile inherently contain some measurement noise associated with the digital imaging sensor on a high-speed camera. Estimating acceleration of the projectile requires double differentiating this noisy position estimate. Double differentiation of a noisy signal amplifies noise, necessitating the application of a low-pass filter to suppress noise in the acceleration estimate. Optical measurement of projectile acceleration is a feasible method for quantifying general characteristics of the acceleration profile but is limited in its ability to capture high-frequency components of the profile due to spatial resolution of the imager, video frame rate, and the need to low-pass filter the acceleration time history estimate.

High-speed video analysis of slug firings during initial implementation testing of the SAIL system identified what appeared to be an unexpected acceleration profile. Noisy measurements and limited high-speed frame rate make it difficult to analyze the acceleration profile with a high level of certainty, but it appears that the projectile experienced a higher-than-expected level of acceleration early in the in-bore cycle. Theoretical modeling of an air cannon, as presented in Section 2.1, suggests that the maximum acceleration experienced by the projectile is limited by the force produced by the initial tank pressure acting over the circular base area of the projectile. For a 508-g projectile fired with an initial tank pressure of 120 psi (gauge), the peak acceleration with no valve losses should be approximately 755 g's. Given rough approximations of valve performance for the SAIL system, the peak acceleration would be expected to be even lower, less than 600 g's. However, as shown in Figure 5, the estimated peak acceleration from high-speed video analysis of a slug firing from the SAIL system with these parameters was more than 900 g's. It appears that the projectile may be exposed to a pressure transient that exceeds the initial tank pressure. The setback acceleration produced by the SAIL system for a given set of firing parameters is an important metric to characterize from an engineering perspective because launching projectiles with relatively low setback acceleration is a key motivation for implementing an air cannon as an alternative to a traditional powder gun.

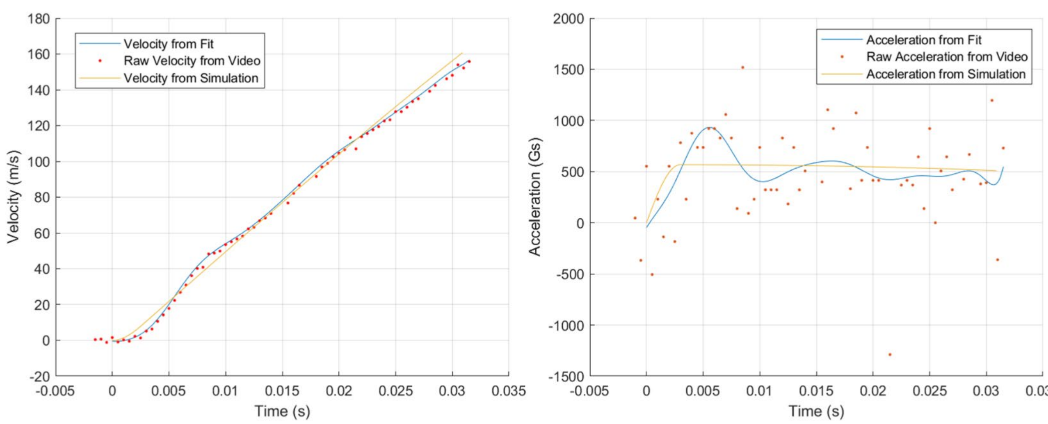

Figure 5. Results of high-speed video analysis of the in-bore cycle of the SAIL system for firing of a 508-g cylindrical slug at a tank pressure of 120 psi (gauge).

2.4 SAIL System Interior Ballistics Characterization Using OBRs

The SAIL system was ultimately developed as a more capable replacement of the legacy ARL air cannon. At the onset of this development effort, it was proposed that accurate measurements of air cannon interior ballistics performance could be recorded by using mass simulant slugs that contained high sample rate accelerometers and an OBR. Initial implementation and testing of the SAIL system to establish basic performance was conducted without collecting any OBR data due to time constraints of the overall development schedule for support of associated ARL research. However, analysis of high-speed video data as described in Section 2.3 further motivated collection of OBR data to better assess the interior ballistics performance and confirm the higher-than-expected peak in-bore acceleration.

2.4.1 Behind Helmet Blunt Trauma (BHBT) OBR

An OBR system capable of meeting the data capture requirements for characterizing the interior ballistics of the SAIL system was previously designed by ARL to support BHBT research.[4] For the BHBT research effort, an OBR was designed and integrated into a 1.7-inch-length × 1.85-inch-diameter projectile that was fired from a 3-inch air cannon to measure the projectile deceleration upon impacting a stationary target. The OBR consists of several modules including the data recorder, analog-to-digital (ADC) converter, inertial sensor, power, and user interface. The data recorder and ADC converter modules are part of the Slice Nano, a modular, commercial off-the-shelf (COTS) data acquisition system manufactured by Diversified Technical Systems (DTS). These modules were G-hardened and repackaged by ARL before integration into the projectile to ensure survivability during launch and recovery. The data recorder has 16 GB of nonvolatile, flash memory (15 GB for data storage) and can record up to 500,000 samples per second. The ADC has three differential input channels with programmable gain and filtering. Projectile acceleration is measured both axially and radially using a piezoresistive, three-axis accelerometer, the PCB Piezotronics model 3503A1120kG, which has the capability to measure accelerations up to 20 kG.

The OBR requires a minimum input voltage of 9 V and consumes a minimum of 50 mA while at idle and a maximum of 350 mA while recording. Power is supplied by an embedded battery consisting of three rechargeable, lithium-ion polymer cells connected in series. The battery has a nominal voltage of 12.6 V, nominal capacity of 100 mAh, and can typically power the OBR for over an hour before needing to be recharged.

An external user interface is provided by a custom-printed circuit board designed by ARL and integrated into the OBR design. This interface uses a 15-pin Micro-D MDM connector used for turning on the OBR, recharging the embedded batteries, supplying external power, switching from external power to battery power, arming and triggering the OBR, and communicating with the OBR via USB. The board also includes an array of LEDs that provide the user with a visual indicator of the OBR status such as power on, successful USB communication, armed, triggered, and low battery.

Operation and programming of the OBR is done using Sliceware, a commercial software program developed by DTS. The software is used to configure a variety of programmable parameters within the OBR such as sensor scale factor, excitation and range, sample rate, data filtering, recorder mode, trigger level, and record time. The software can also display real-time sensor data and allows easy data download, viewing, and export.

For the SAIL flight experiments, the BHBT OBR was integrated into 3-inch-diameter cylindrical slugs to be fired from the SAIL system (Figure 6). This allowed the existing OBR to be reused for this application and for a single OBR unit to be swapped between slugs of multiple sizes. The OBR recorded three channels of accelerometer data and was configured in circular buffer mode using the axial accelerometer for the trigger. The trigger level was set at 100 g's, and 0.5 s of pre-trigger data and 2.5 s of post-trigger data was recorded during each shot. The sample rate was increased as the flight experiments were conducted with the initial one set at 25 kHz, the next two at 50 kHz, and the final five at 100 kHz. Each data channel was recorded using a hardware anti-aliasing filter set to one-fifth the sample rate and the exported data had a 1650-Hz filter applied by the software.

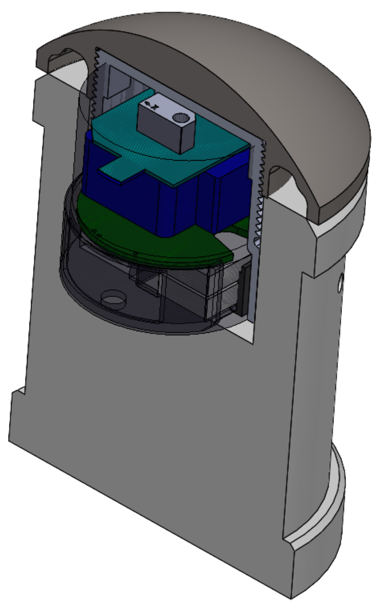

Figure 6. Cross-section rendering of BHBT OBR assembled into a custom housing for adaptation to a 3-inch cylindrical slug. BHBT OBR is shown installed within a medium mass cylindrical slug in this rendering.

During each flight experiment, the OBR was powered up, the sensors were checked in real time to verify proper operation, the method of data collection was configured, power was switched from external to internal, the OBR was armed, inserted into a cylindrical slug, loaded, fired, recovered, and then the recorded data was downloaded, reviewed, and saved. The typical OBR on time for each shot was less than 20 min from arming to data download with the internal battery running uninterrupted the entire time. A single OBR was used on eight shots in the test matrix, using slugs of different mass and shot at various pressures. Data was successfully recorded and downloaded for each shot. The OBR remains fully functional and is available for future testing.

2.4.2 OBR Mass Simulant Slugs

A series of three slugs of varying masses were fabricated to accept the BHBT OBR in its housing (Figure 7). Fabrication of slugs of various mass allows the test engineer to collect interior ballistics data across a wider range of muzzle energies by varying both tank pressure and in-bore mass. Each slug incorporates a pocket that allows the BHBT OBR to be fit into the slug with three radial set screws to impinge on the OBR body and hold it in place (Figure 8). The mass of each slug is determined by its overall length, the lightest having a nominal mass of 300 g, the middle weight slug having a nominal mass of 500 g, and the heaviest having a mass of 1000 g. The design of the mass simulant slug incorporates an undercut on the outermost surface that allows the bore riding surface to maintain the same contact area regardless of the slug's overall length, thus minimizing variability of in-bore friction between the different configurations. Each slug is manufactured from Acetal Copolymer (Delrin) for its high density and dimensional stability in humid environments.

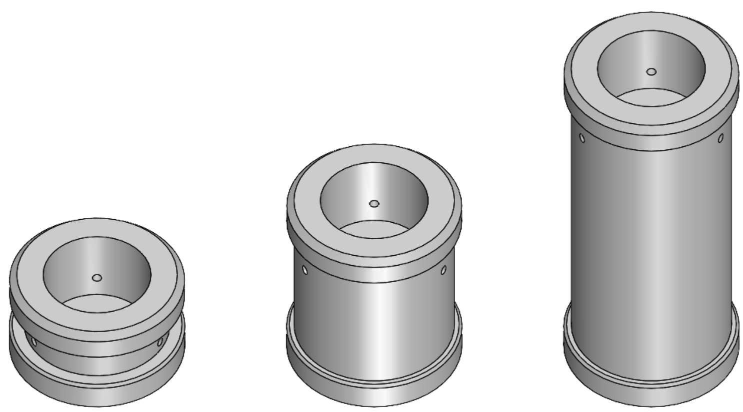

Figure 7. SolidWorks rendering comparing the three different OBR mass simulant slugs. Mass is adjusted by changing the overall length of the slug.

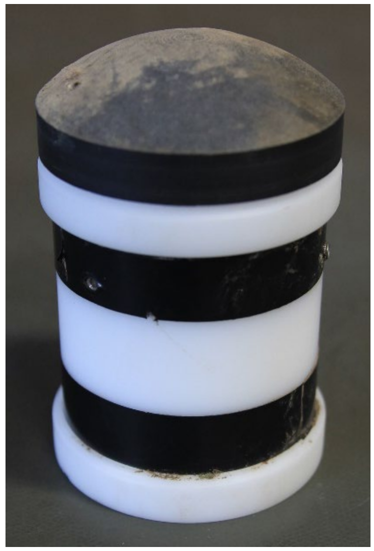

Figure 8. Medium mass cylindrical slug with BHBT OBR installed.

3. Firing Experiment Execution and Discussion of Results

A firing experiment using the SAIL system to support another ARL research effort was conducted from July 7–10, 2025 (Figure 9). This experiment setup included a full suite of diagnostic instrumentation including high-speed video and muzzle velocity radar and provided an ideal opportunity to collect OBR data of the SAIL system interior ballistics. Due to the rapid firing cadence of the SAIL system and the existing need to fire slugs for instrumentation checkout, eight OBR slug shots were added to the test matrix without impacting the testing cadence of the primary effort. Data was collected over a range of muzzle energies by firing the three different mass slugs at various tank pressures, as shown in Table 2.

Figure 9. SAIL system set up for firing experiment on July 9, 2025.

Table 2. Subset of shot matrix for SAIL system firing event. Only the shots associated with OBR slug firings are shown.

Shot no.	Flight vehicle	In-bore mass (g)	Tank pressure (psi, gauge)	Muzzle velocity (m/s)
3	OBR slug – medium	573.82	65	115.4
11	OBR slug – medium	573.82	65	115.2
12	OBR slug – light	300.14	65	140.4
13	OBR slug – heavy	1014.85	65	87
15	OBR slug – medium	573.82	120	156
17[a]	OBR slug – light	300.14	120	195
18[b]	OBR slug – heavy	1014.85	102.5	109.4
21	OBR slug – medium	573.82	65	112.8

[a] OBR and slug became separated during in-bore travel. Both components were individually recovered.
[b] Shot 18 was planned for 120 psi but was fired at a pressure of 102.5 psi due to a mechanical failure of the air compressor being used to charge the SAIL system.

3.1 Results from OBR Slug Firing

Implementation of the BHBT OBR for slug firing from the SAIL system was successful in capturing in-bore acceleration data for all eight shots. Setting, data recovery, and subsequently resetting the BHBT OBR for the next shot was a relatively fast and easy process. The mass simulant slugs traveled 100–200 m from the firing line due to their un-aerodynamic shape and mass distribution, which induced tumbling shortly after muzzle exit. The OBR slugs were manually recovered from the open field in front of the firing line and returned to the experiment control center for immediate data download. The BHBT OBR was robust enough to survive both the launch event and the impact of the slug with the ground; all eight of the shots recorded reused the same BHBT OBR unit.

Velocity versus time curves were created by applying MATLAB's simple built-in cumulative trapezoidal integration function to the acceleration data record by the OBR. Velocity at muzzle exit from the integrated acceleration data was compared to muzzle velocity measurements from external instrumentation (radar and high-speed video). Muzzle velocity estimates from the OBR were within approximately 5% of the other measurements, confirming that the OBR accelerometer was appropriately calibrated for quantifying in-bore acceleration.

The "acceleration waves" that were suspected based on high-speed video analysis of prior slug firings were confirmed by acceleration data recorded by the BHBT OBR. These waves were observed on each of the eight shots, regardless of tank pressure or slug mass.

Acceleration measurements from the OBR were reformatted into units of forcing pressure using the equation:

$$P_f = \frac{m_{ib} * a_{OBR}}{A_b}, \tag{6}$$

where a_{OBR} is the acceleration measured by the OBR, m_{ib} is the in-bore mass of the projectile, and A_b is the circular area of the projectile base. Practically, the forcing pressure is the base pressure (pressure of expanding gases acting on the projectile base) minus the frontal pressure (atmospheric pressure plus aerodynamic drag) and the friction force (between projectile and barrel). The frontal pressure and friction forces are relatively small with respect to the base pressure in a system such as the SAIL but the true base pressure is higher than the forcing pressure. Quantifying the in-bore environment in terms of forcing pressure is helpful for intuitively comparing the acceleration of the projectile against the acceleration that would be achieved by perfectly applying tank pressure to the base of the projectile without any opposing forces from friction or frontal pressure.

Evaluating the interior ballistics in terms of forcing pressure also allows direct comparison to the initial tank pressure. Figures 10 and 11 show examples of forcing pressure time history estimates for two of the OBR slug shots.

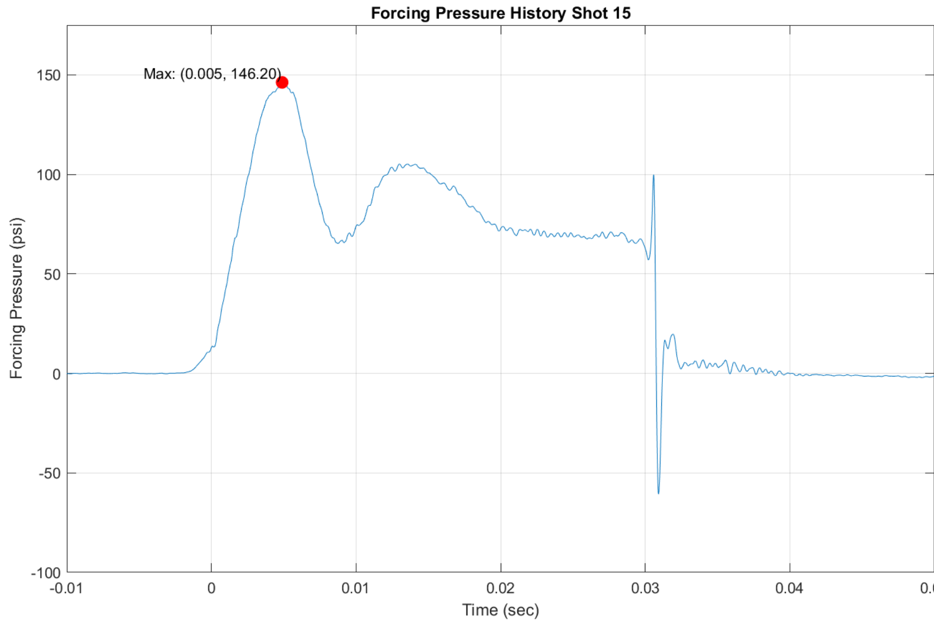

Figure 10. Forcing pressure time history for medium mass OBR slug fired from the SAIL system at a tank pressure of 120 psi. The forcing pressure associated with the peak acceleration is equivalent to approximately 146 psi, which significantly exceeds the initial tank pressure.

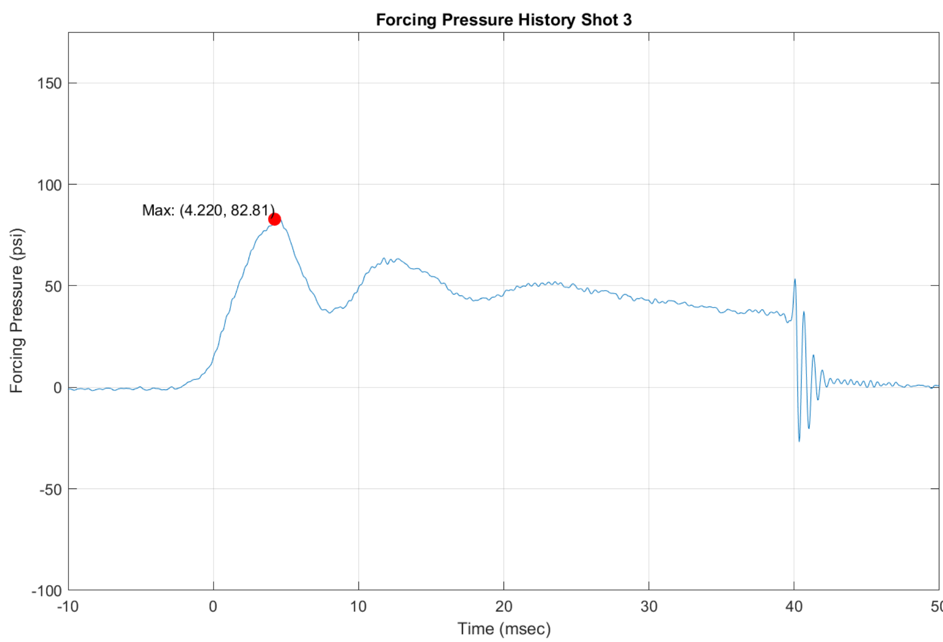

Figure 11. Forcing pressure time history for medium mass OBR slug fired from the SAIL system at a tank pressure of 65 psi. The forcing pressure associated with the peak acceleration is equivalent to approximately 83 psi, which significantly exceeds the initial tank pressure.

Several important observations made from the OBR collected data are as follows.

1) Forcing pressure ramps up from atmospheric pressure to a level exceeding the initial tank pressure in approximately 5 ms. This rapid increase in forcing pressure confirms the fast action time associated with the piston valve of the SAIL system.
2) OBR acceleration data confirms the observation made using high-speed video analysis suggesting that forcing pressure temporarily exceeds the maximum tank pressure available to the system as set by the initial tank pressure. This behavior was observed consistently for all eight OBR slug shots.
3) Qualitatively, the forcing pressure was expected to ramp up to a level below the initial tank pressure, as dictated by pressure drop across the imperfect valve passage. From this peak, the forcing pressure was expected to decay with increasing barrel volume as the projectile travels down bore, consistent with the gas expansion models presented in Section 2. It appears that a decaying sinusoid is superimposed on this expected forcing pressure behavior, resulting in a series of attenuating peaks above and below the expected forcing pressure. All eight of the OBR slug shots exhibited this behavior.
4) Peak acceleration of the OBR slugs exceeded the theoretical maximum acceleration based on initial tank pressure acting unopposed on the projectile base by up to 30%. This relationship provides a useful guideline to estimate peak acceleration that a projectile may experience when launched from the SAIL system.
5) High-frequency content in the acceleration signal is observed at muzzle exit. A brief increase in forcing pressure is observed in most cases as the slug starts to exit the muzzle resulting in reduced friction and aerodynamic drag forces. This is followed by projectile set-forward, which is a structural vibration phenomenon caused by uncorking and a rapid loss of base pressure and the associated setback acceleration.
6) Low-amplitude setback acceleration persists for 10+ ms after the set-forward ringing event at muzzle exit. High-speed video shows a jet of expanding gas shooting out of the muzzle that continues to interact with the base of the projectile for a short period of time after muzzle exit. This extension of the in-bore cycle is potentially imparting some small additional velocity increase after muzzle exit.

3.2 Potential Mechanisms to Create In-bore Pressure Spikes

Definitively establishing the physical mechanism that is generating in-bore pressure spikes exceeding the initial tank pressure is outside the scope of this report. It is, however, worthwhile to discuss some potential mechanisms to explain the presence of this phenomenon. More testing focused on the in-bore dynamics of the SAIL system would be required to verify the exact mechanism driving the observed behavior.

3.2.1 Variable In-bore Friction

It is possible for friction between the moving projectile and the gun barrel to affect the overall projectile acceleration over the course of the in-bore stroke. The barrel used in the SAIL system is an unmodified COTS 8-ft section of clear PVC pipe. These pipes are not manufactured to meet the same narrow tolerances that would be applied to a purpose-built barrel. When muzzleloading the SAIL system, it was qualitatively observed that at certain points along the barrel, additional force was required to advance the projectile to the breech. In theory, as the projectile encounters these points of reduced bore diameter, the acceleration of the projectile would be reduced by increased friction, resulting in reduced forcing pressure. As the projectile "slips" past these tight spots, acceleration would increase again, and the forcing pressure would increase. Overall assessment of SAIL system performance and practical observations from loading the projectiles suggests that the friction force is very low with respect to the force produced by the forcing pressure. It is possible that friction inconsistency causes small oscillations in the projectile acceleration, but the oscillations present in the recorded OBR data are several orders of magnitude larger than the expected friction forces. Variability of the friction forces would also not explain forcing pressures that exceed the initial tank pressure.

3.2.2 Pidduck–Kent Special Solution

The Pidduck–Kent Special Solution[5] is a method for predicting the in-bore motion of a projectile in a pre-burned propellant gun (and by extension, an air cannon, which is a type of pre-burned propellant gun). This solution is a direct extension of fundamental interior ballistic theories proposed by Lagrange and wave theories proposed by Reiman in Seigel.[6] The relevant observation of Pidduck (expounded upon by Kent[5]) is that in a pre-burned propellant gun the ratio of breech pressure to projectile base pressure oscillates, and that these oscillations damp out to a certain limiting value (Figure 12). This occurs due to a rarefaction wave initiated by the initial motion of the projectile. This wave then reflects between the breech of the gun and the base of the projectile. The pressure gradient associated with the refraction wave is reduced with each reflection resulting in the disturbance damping out after several oscillations.

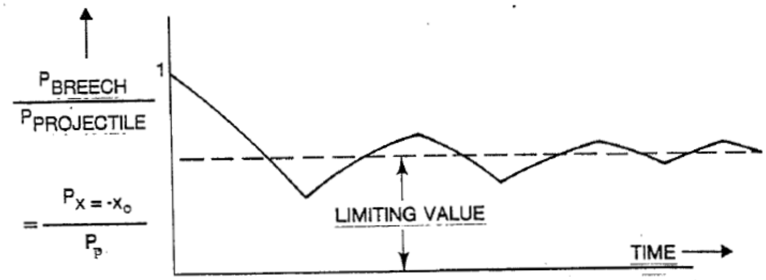

Figure D-1. Oscillation of Frictionless Gun.

Figure 12. Graph of breech pressure to base pressure ratio as described by the Piddick–Kent Special Solution.[5]

An oscillating wave of base pressure appears to accurately describe the phenomenon being observed during SAIL system OBR slug tests. However, the premise of the special solution is a rarefaction wave associated with projectile motion resulting in a pressure gradient whereby ratio of base pressure to breech pressure is always less than 1. This phenomenon would not explain base pressures that exceed the initial tank pressure of the SAIL system. Numerical modeling of the Pidduck–Kent Special Solution[5] for application to the SAIL system is outside the scope of this report; however, the interested reader can find a significantly more detailed explanation in *Performance Calculations and Optimization of Gas Guns* by Arnold E. Seigel.[6]

3.2.3 Compression of Dead Volume Air

The configuration of the SAIL system differs from the theoretical geometry of an ideal pre-burned propellant gun in two fundamental ways. At shot start in a theoretical pre-burned propellant gun, the base pressure is equal to the breech pressure, with a volume of compressed gas immediately available to do work on the projectile. In the SAIL system, the piston valve must be opened to release tank pressure into the barrel, resulting in a breech pressure time history that is dependent on the performance of the valve mechanism. There is also a small but significant amount of dead volume between the valve and the base of the projectile at the start of the in-bore cycle. This dead volume is unavoidable given the geometry of the COTS components of the SAIL system. Virtually any air cannon that uses a valve to initiate firing will suffer from this limitation given that the pressure tank must be physically separated from the barrel by the valve. The valve opening dynamics and the dead volume between the pressure tank and the projectile base at shot start will establish a pressure gradient between the breech and the projectile when the SAIL is fired. This is like the pressure gradient described by the Pidduck–Kent Special

Solution[5] except instead of a rarefaction wave initiated by motion of the projectile, it is a compression wave initiated by the piston valve releasing compressed air into the dead volume between the valve and the projectile. It is possible that this compression wave can produce localized pressure at the projectile base that exceeds the tank pressure when it reflects off the projectile base. It is also likely that this compression wave reflects between the projectile base and breech with the pressure gradient being reduced on each reflection, similar to what was described by the Pidduck–Kent Special Solution.[5] Numerical modeling of a pressure gradient propagating through the dead space between the valve and projectile in the SAIL system is outside the scope of this report, but a compression wave traveling through the dead space and reflecting off the base of the projectile appears to be a likely explanation for the forcing pressure profiles presented in Section 3.1.

4. Conclusions

Data recorded by OBR slug firings out of the SAIL system verified the presence of an unsteady acceleration time history that was previously observed with low confidence using high-speed video analysis. OBR data confirmed that peak acceleration exceeds a level equivalent to full initial tank pressure acting on the projectile base by up to 30%. This observation has practical implications for use of the SAIL system as the in-bore acceleration profile dictates the level of G-hardening required for launch and flight packages to be shot out of the system. The SAIL system is still a comparatively low-G means to achieve a given launch velocity, especially in comparison to traditional powder guns, but the peak acceleration exceeds what is predicted by simple theoretical models.

Future work may include an effort to better model the unsteady acceleration of a launch package being fired from the SAIL system. The Pidduck–Kent Special Solution provides the theoretical foundation necessary to model a pressure gradient propagating between the valve and the projectile base. Modern computational fluid dynamics tools would also be capable of modeling the in-bore environment given either an adequate characterization of flow conditions at the valve exit or incorporation of the valve passageways into a computational solution. Future modeling effort would benefit from the availability of experimental data from high-rate pressure port measurements at various locations in the SAIL system. The OBR slug data presented in this report also serves as a foundation from which an empirical model could be constructed to fit the experimentally observed acceleration profile.

Some amount of dead volume in the SAIL system is unavoidable due to the mechanical configuration of the COTS components providing a piston valve integrated within the pressure tank. Rework of how the barrel mounts to the flange of the pressure tank could, however, reduce dead volume by 30% or more. It is unclear without more explicit modeling of the unsteady forcing pressure what effect adjustments to the dead volume will have on the in-bore acceleration profile. It would be possible to experimentally investigate this relationship by collecting OBR data for shots with the slug placed at different seating depths to vary the volume of dead space present when firing is initiated.

The value of the OBR slug data presented in this report to the test engineer is that it precludes the need for detailed modeling of the SAIL system; the in-bore acceleration environment was measured directly for a limited range of firing parameters. While it is useful to have a reliable model to predict interior ballistics performance prior to field testing, especially for introduction of new firing parameters, the ability to rapidly collect direct measurements using an OBR slug alleviates the need for a highly accurate model. OBR slugs will continue to be used on future firings of the SAIL system to characterize the in-bore environment. OBR data is an efficient means to verify the estimated acceleration profile for a given set of firing parameters prior to firing more expensive launch and flight packages.

5. References

1. Brown M, Everson D. Design, implementation, and testing of a versatile, low-cost air cannon system (SAIL system) intended for free-flight experiments of EAGLE 40-mm projectiles. DEVCOM Army Research Laboratory (US); 2026 Apr. Report No.: ARL-TR-10328.

2. Celmins I. Sabot concept evaluation using subscale airgun-launched 3-D printed components. Army Research Laboratory (US); 2015. Report No.: ARL-TR-7187.

3. Rohrbach ZJ, Buresh TR, Madsen MJ. Modeling the exit velocity of a compressed air cannon. Am J Phys. 2012;80:24–26. https://doi.org/10.1119/1.3644253

4. Eidsmore AE et al. Behind helmet blunt trauma (BHBT) experimental program. Army Research Laboratory (US); 2019 Jan. Report No.: ARL-TR-8614.

5. Kent RH. Special solutions for the motion of the power gas (comments on Mr. Pidduck's note). J Appl Phys. 1937;8:144–145. https://doi.org/10.1063/1.1710270

6. Seigel AE. Performance calculations and optimization of gas guns. Army Electronics Research and Development Command (US); 1981. Report No.: HDL-CR-81-723-1.

List of Symbols, Abbreviations, and Acronyms

ADC	Analog-to-Digital
ARL	Army Research Laboratory
BHBT	Behind Helmet Blunt Trauma
COTS	Commercial Off-The-Shelf
C_v	Valve Flow Coefficient
DEVCOM	U.S. Army Combat Capabilities Development Command
DTS	Diversified Technical Systems
GTN	Guidance Technology Branch
LED	Light-Emitting Diode
OBR	On-Board Recorder
PCB	Printer Circuit Board
PVC	Polyvinyl Chloride
SAIL	Single-stage Air-Initiated Launcher
USB	Universal Serial Bus

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