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Pneumatic Mortar Development for the NASA/Orion Capsule Drogue Parachute System

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During development of the drogue parachute system for the NASA Orion capsule, the need arose for an inexpensive and robust mortar system that would allow a high volume of drogue parachute deployments in ground testing. The Orion capsule drogue parachute system utilizes a multiple strand stainless steel wire rope riser to meet strength and abrasion requirements during off attitude deployments. This wire rope riser system presents new challenges in the areas of packaging and deployment dynamics management. A deployment test system was required that could replicate the performance of the flight pyrotechnic mortar system within the same parachute packaging and bore stroke dimensions yielding very high fidelity results that are directly applicable to the flight system. Airborne Systems North America developed a pneumatic mortar system and is currently engaged in a successful test series that is providing critically important drogue parachute development data. The cost of a series of comparable pyrotechnic mortar tests is approximately ten times that of the same series of tests run with the pneumatic mortar. The simplicity and economy of the system also allows testing and development of design concepts with a very short turnaround time, limited only by the amount of time required to develop the desired parachute test configuration. Additionally, between-test down time is greatly reduced due to a very limited amount of system refurbishment required to cycle the mortar system between tests.

I. History

Mortar launched parachute systems have been widely utilized in aerospace recovery systems. Both the Gemini and Apollo drogue parachute systems utilized a mortar for a repeatable and reliable deployment of the drogue parachutes into the free air stream. The Orion program has adopted this design heritage as well. The Orion program has incorporated two Variable Porosity Conical Ribbon Drogue Parachutes which utilize wire rope risers that attach the drogue parachute system to Orion capsule and serve to protect the integrity of the drogue parachute system during off angle deployments. These wire rope risers require a dedicated development program to optimize the packing a deployment characteristics. On the Gemini and Apollo systems, several hundred mortar tests were conducted to validate the deployment dynamics of the drogue parachute systems, including the wire rope risers. Orion development schedules and other concerns made performing this quantity of mortar based drogue deployment tests impossible on the Orion program and a new development technique was required. Airborne Systems North America proposed the use of a pneumatic mortar system which would use compressed nitrogen to provide the propulsive force that deploys the drogue parachute.

II. Research and Development

Several critical parameters needed to be optimized during the development phase of the pneumatic mortar project. The system was required to mimic performance of a pyrotechnic mortar with a known internal parachute storage volume, known parachute ejected mass and a specific range of velocity performance.

The cross sectional flow area of the gas delivery path was the first parameter that needed to be determined. There were practical limitations on the upper size of the gas delivery path not related to performance so the task at hand was to determine the largest practical hardware (from a handling standpoint) that could be implemented and still meet performance requirements. The trigger system for the pneumatic mortar is a set of rupture discs placed in series, the fixture for these rupture discs is a commercially manufactured item used in industrial fluid and gas delivery systems. A design goal for the entire system was to remain somewhat portable such that the mortar could be transportable to remote filed sites for testing so a balance was required between the size and mass of the system and the performance requirements. A trade study was performed and combined with analytical results, it was determined that sufficient mass flow rate could be achieved with a 6” diameter gas flow path while preserving practical handling characteristics. A commercial set of rupture discs and disc fixtures was available in this size so the system was optimized around this geometry.

Parachute mass and desired muzzle velocity were both known quantities so the system had to be optimized around this mass. Current mass estimates for the CPAS drogue parachute system call for a maximum ejected mass of 80 lbs. and muzzle velocities ranging from 125 ft/sec to 180 ft/sec. Airborne performed analytical predictions based on the decided upon 6” internal passageway of the mortar system and performance requirements to determine the gas storage volume and pressure requirements to achieve the required range of ejection velocities. It was determined that velocities of 125 ft/sec to approximately 165 ft/sec could be achieved with a 15 gallon nitrogen reservoir pressurized from 260 to 300 psi. Achieving the upper spectrum of velocity requirements from 165 ft/sec to 180 ft/sec will be accomplished by changing the charging gas from nitrogen to helium. This will result in a higher mass flow per volume at a given pressure and should yield higher velocities that reach the upper spectrum of the requirements. Helium testing has not been performed at this time so the remainder of this paper focuses on results achieved to date with nitrogen.

As an initial design point study, the predicted performance of the pneumatic mortar was analyzed for a 300 psi charging case with an 80lb ejected mass. A 12 inch bore stroke was assumed based on known pyrotechnic mortar dimensions. The study yielded a predicted muzzle velocity of 160 ft/sec with a 10.3 m/s actuation (stroke) time. Because friction was ignored in the model, this result was assumed to be higher than the actual velocity that could be achieved but it was sufficient to confidently proceed with building hardware.

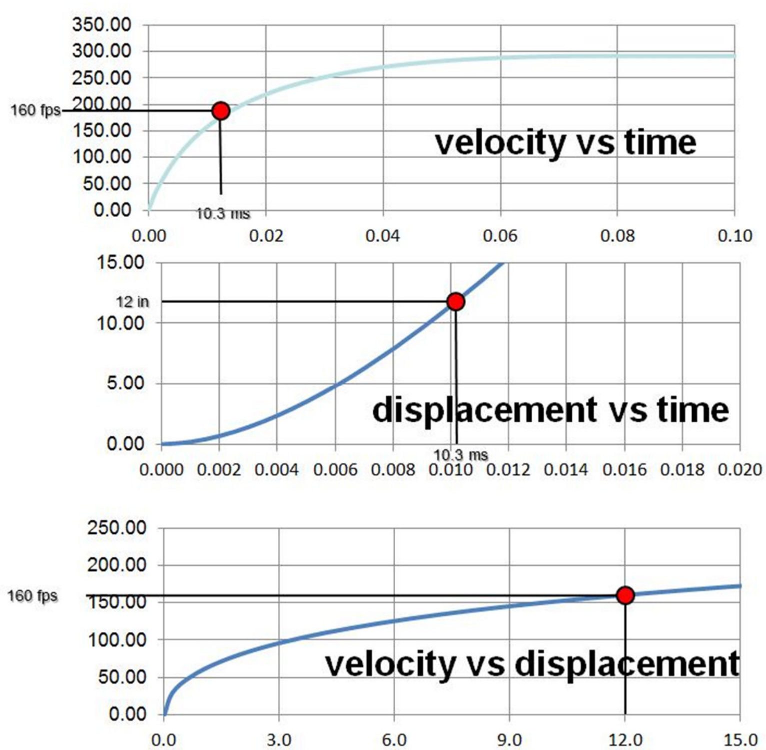


Figure 1. Mortar Performance Predictions

III. Mortar Design

A custom 15 gallon capacity pressure vessel was manufactured with a 6” ANSI flange interface. The mortar body was manufactured with a 6” ANSI flange interface as well. This interface was chosen as a result of design heritage information provided by the rupture disc manufacturer who had extensive history utilizing an ANSI flange interface with their rupture disc fixtures. The mortar assembly which includes the tank, rupture disc assembly and the mortar body is secured as a unit by twelve ¾” diameter studs. This arrangement allows for rapid assembly and disassembly between test firings. The entire mortar system can be build up from individual components to a ready to fire state in less than one hour. Integration of the pneumatic portion of the mortar is a simple vertical stacking operation

The mortar body is manufactured from rolled 6060-T6 aluminum. The mortar body was rolled, seam welded and straightened to ensure a smooth and cylindrical bore. The body was then bonded to the machined ANSI flange base via dip brazing. The mortar body has proven to be robust and reliable after 8 of 14 planned shots have been performed.

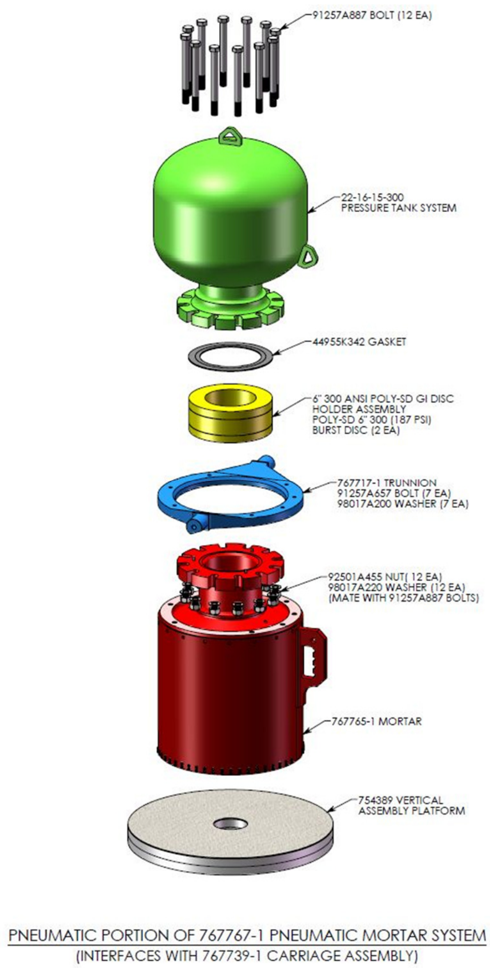


Figure 2. Exploded View of Pneumatic Mortar

The assembled mortar is secured in a steel carriage assembly that allows the mortar to sit in either transportation or firing position. The transportation position holds the mortar in a horizontal orientation for crane lifting via the lift points. Once the mortar is transported to the desired firing location, the mortar is rotated to its 68° firing position and locked in place.

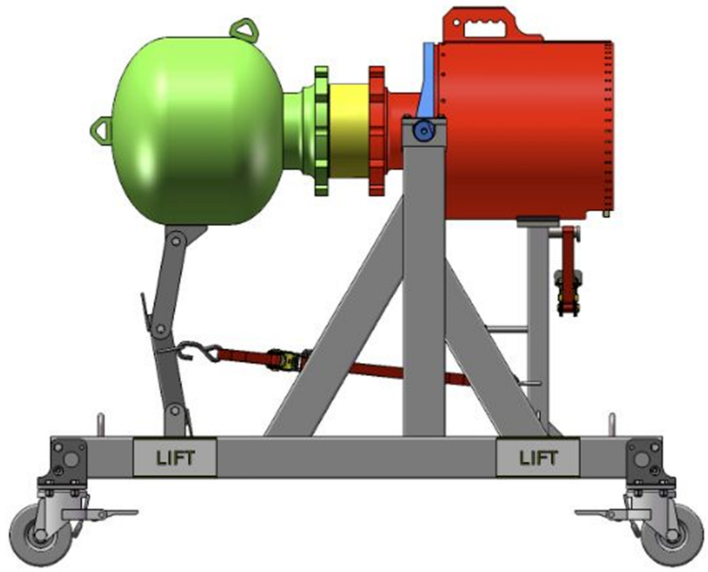


Figure 3. Mortar Installed In Carriage and in Transportation Position

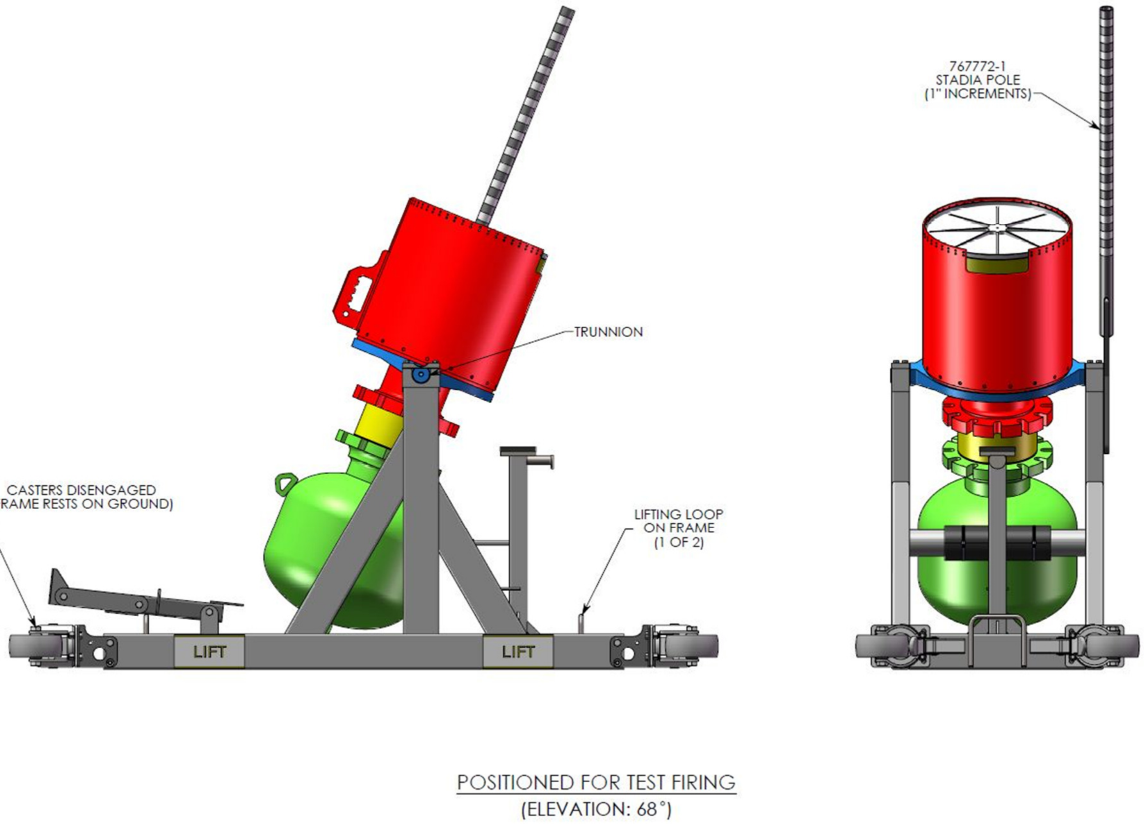
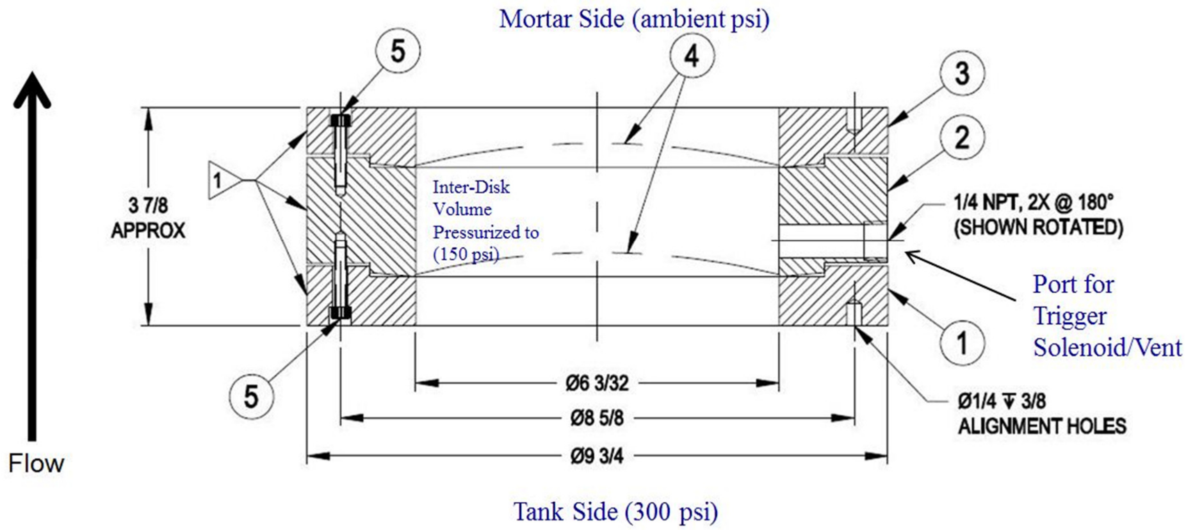


Figure 4. Pneumatic Mortar in Firing Position

The pyrotechnic mortar being replicated has a 16.5" bore diameter and a 12" effective stroke. This yields a bore to diameter aspect ratio of .72. This geometry requires a very aggressive pressure onset and virtually instantaneous release of the stored gas into the mortar body. This is accomplished by using two rupture discs in a tandem arrangement and utilizing a differential pressurization and rapid depressurization technique. Additionally, the mortar lid that retains the parachute in the mortar body is secured using 41 rivets. A force of 10,000 lbs is required to fracture the 41 rivets and release the lid. This release force mimics the pyrotechnic mortar design and also ensures a very high pressure has been generated behind the parachute pack prior to first movement of the pack in the mortar bore.

The tandem rupture disc arrangement also allows precise control over the firing time of the mortar, allowing all data acquisition systems and cameras to be initiated and in the process of recording data shortly before the mortar is fired. The figure below is a schematic of the tandem rupture disc fixture. Refer to the figure legend for locations of components.



1 – Rear Plate
2 – Mid Flange
3 – Forward Plate
4 – Burst Disks (190 psi rating)
5 – Assembly Screws

Figure 5. Rupture Disc Assembly

The charging and firing sequence for the pyrotechnic mortar is a five stage process. Charging is accomplished using two nitrogen bottles and a dual pressure channel charging station manufactured by Airborne Systems which allows separate pressurization to the tank and volume between the two rupture discs. Charging must be performed incrementally to avoid exceeding the 190 psi rupture disc rating while still charging the storage tank to 300 psi.

Stage 1 – The storage tank is charged to 150 psi which exerts pressure on the rear rupture disc at a level lower than its 190 psi rating.

Stage 2 – The small volume between the front and rear rupture discs is pressurized to 150 psi. This loads the forward rupture disc to 150 psi and reduces the net pressure on the rear rupture disc to 0 psi.

Stage 3 – The storage tank pressure is increased to 300 psi. Both the front and rear rupture discs are now under 150 psi of pressure. The differential pressure across the rear disc is 150 psi in spite of the tank being pressurized to 300 psi. The system is now fully charged and ready to fire.

Stage 4 – After a countdown, the solenoid valve installed into the rupture disc fixture bleed port is opened allowing the pressure in the volume between the two discs to vent. As the pressure bleeds off, the differential pressure across the rear disc exceeds the discs 190 psi rating.

Stage 5 – Once the differential pressure across the rear disc exceeds 190 psi, the rear disc ruptures, followed by the front disc rupturing approximately 1-2 milliseconds (ms) later. The tank then vents into the mortar and the drogue parachute is fired, exiting the bore approximately 10 ms after forward disc rupture at a velocity of 160 ft/sec given a 300 psi nitrogen charge.

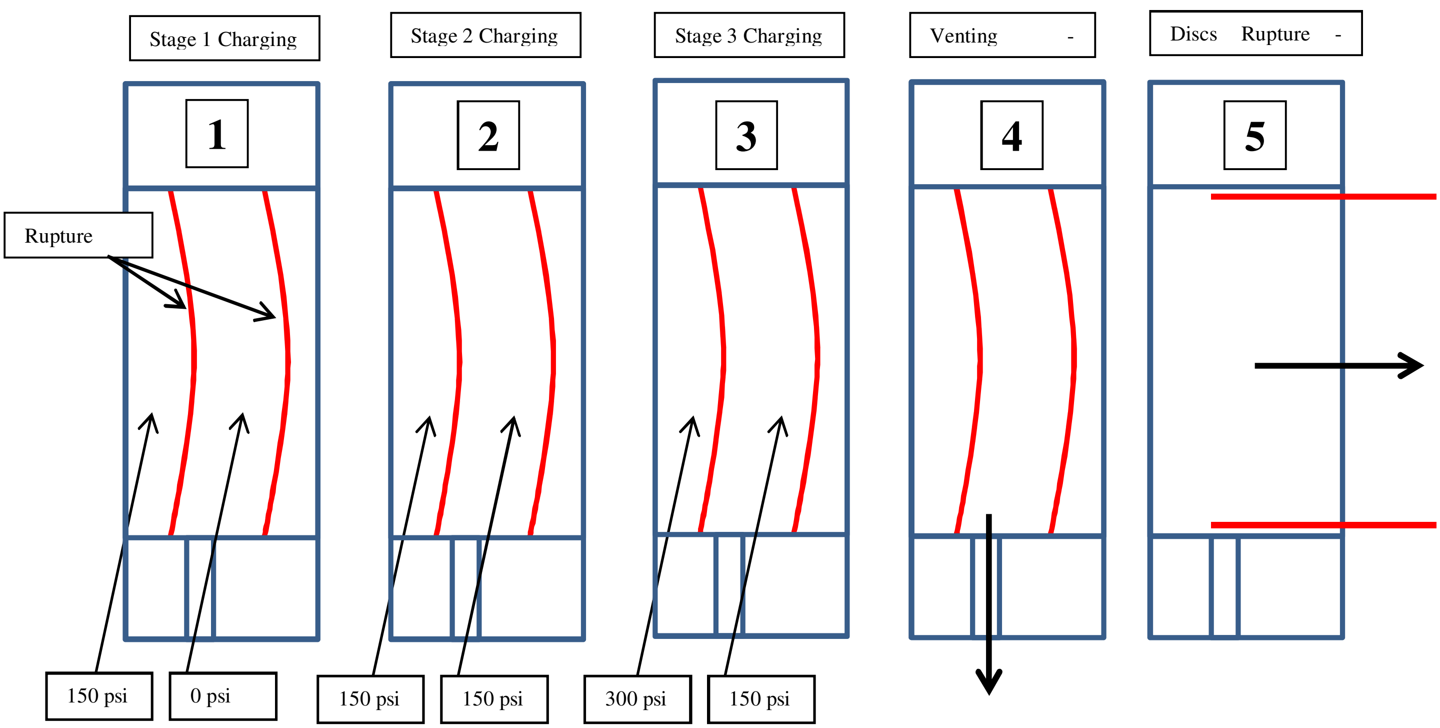


Figure 6. Charging Sequence

IV. Testing

A firing sequence is shown in figure …. . . Frame 1 is immediately prior to the mortar firing, the solenoid dump valve is exhausting pressure from the rupture disc fixture. Frame 2 shows the parachute pack beginning to exit the mortar body with the mortar cover on top of the parachute pack. In frame 3, the pack has completely exited the mortar body and the parachute riser (attached to the mortar frame) is beginning to come under tension. A significant cloud of condensation can be seen as the high pressure nitrogen vents into the atmosphere. In frame 4, the parachute riser is beginning to deploy from the deployment bag and the sabot can be seen coming clear of the pack. This entire sequence occurs in a time span of less than 20 ms.

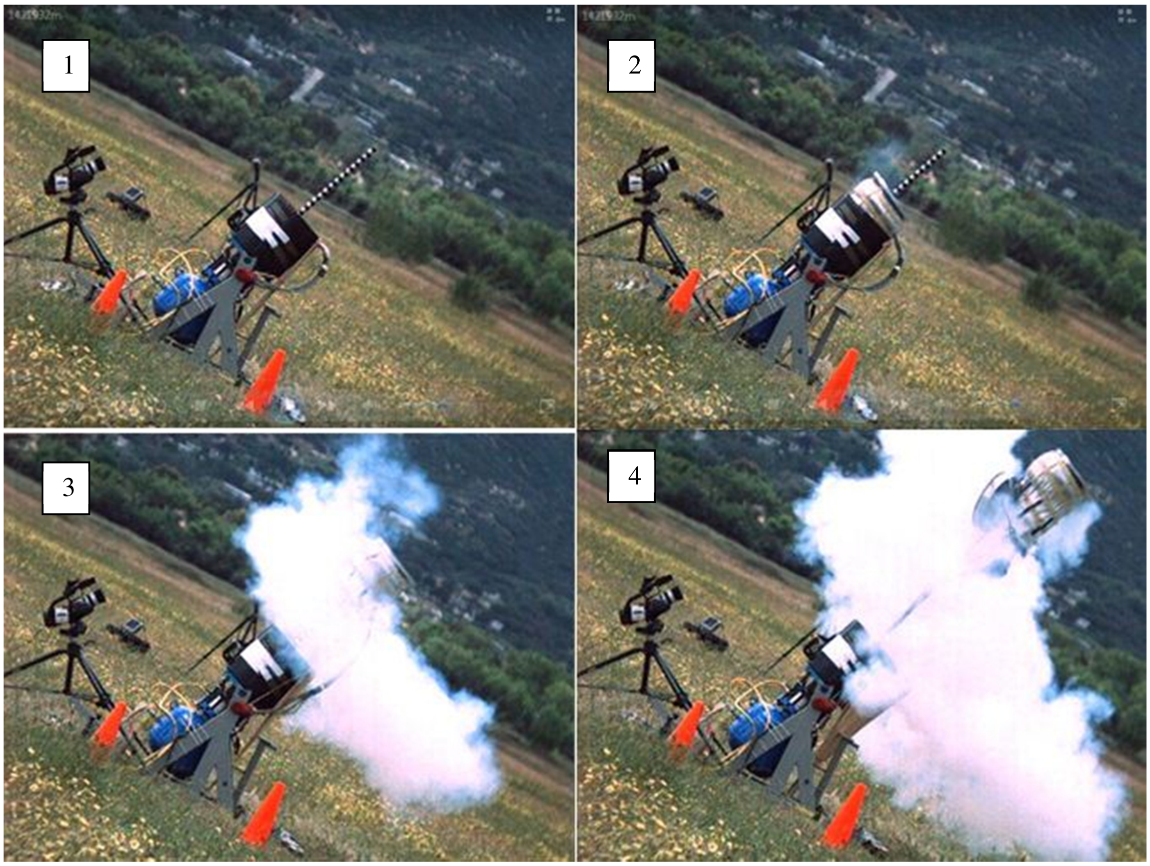


Figure 7. Firing Sequence

A typical trace of pressure vs time during a pneumatic mortar test is shown for reference. The rupture disc pressure trace is in red and can be seen dropping abruptly at approximately .270 seconds. Tank pressure (shown in blue) and can be seen dropping off rapidly as a result of the rupture discs being functioned. Note that tank pressure in this shot was set to 270 psi rather than 300 psi. Mortar tube pressure (shown in green) can be seen peaking at approximately .280 seconds and then dropping off corresponding to when the parachute pack leaves the bore of the mortar. Actual test results correlate well to analytical predictions

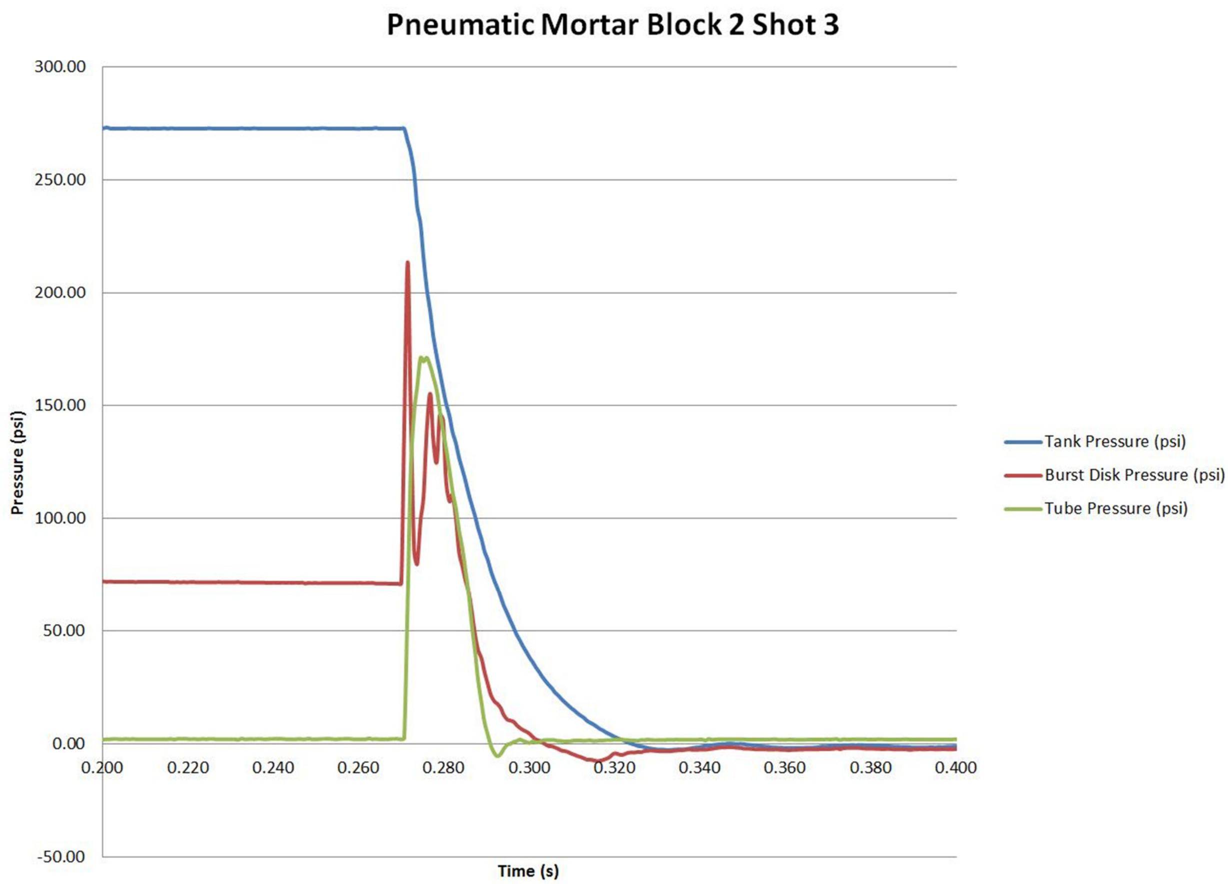


Figure 8. Pressure Traces from Test

A matrix of 14 firing tests of the pneumatic mortar system is currently planned. The test matrix consists of three blocks of testing. Block 1 is a series of three tests design to confirm the analytical predictions for mortar performance and allow for adjustments in pressure levels based on velocities achieved. Block II is a series of three tests designed to optimize the interface of the parachute system to the mortar and allow for tuning of this interface.

Block III is the main portion of testing and is the primary thrust of the entire test program. The eight tests in block III facilitate optimization of parachute packaging and deployment dynamics. This block of testing is currently in progress and has already yielded critically important results that have resulted in changes to the drogue parachute packaging and deployment dynamics.

8 tests have been completed so far and are summarized in figure

	Test 1 (Block 1)	Test 2 (Block 1)	Test 3 (Block 1)	Test 4 (Block 2)	Test 5 (Block 2)	Test 6 (Block 2)	Test 7 (Block 3)	Test 8 (Block 3)
Pack Weight (lb.)	81	75	76	76	76	76	77	79
Velocity (ft/sec)	No Data	150	134	129	143	137	159	151
Tank Pressure (psi)	300	300	270	270	270	270	300	300

Figure 9. Test Data from Testing Completed

Real world test results have shown very good correlation with analytical predictions that were made during the development phase of the mortar. Initial predictions for an 80 lb. parachute pack and a 300 psi tank charge are compared to test results when a 300 psi charge was utilized and pack weight was within 3 lb. of the 80 lb. prediction. Velocities in actual testing are slightly lower than predictions falling 1-9 ft/sec short of the predicted 160 ft/sec velocity. Much of this can be attributed to friction being ignored in the analytical model which results in velocity predictions being slightly higher than actual results.

	Analytical Prediction	Test 7 (Block 3)	Test 8 (Block 3)
Pack Weight (lb.)	80	77	79
Velocity (ft/sec)	160	159	151
Tank Pressure (psi)	300	300	300

Figure 10. Test Data Compared to Analytical Predictions

V. Conclusion

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The pneumatic mortar has been a critical tool in the CPAS drogue parachute development effort. The development of the pneumatic mortar has decoupled the pyrotechnic mortar development schedule from the drogue parachute development schedule and allowed a very aggressive engineering effort focused on drogue parachute design and deployment dynamics to proceed.

Additionally, the cost of drogue parachute development is reduced significantly and a great deal of flexibility has been introduced into the development process. Changes to parachute or rigging configurations can be tested within days of the changes being implemented to the parachute design. The logistical complexities of storing, transporting and utilizing pyrotechnic devices have been removed from the development effort.