Detailed Ballistic Performance Characterization of 120-mm Mortar System with Different Flash Tube Configurations

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Background and Research Objectives

Background:

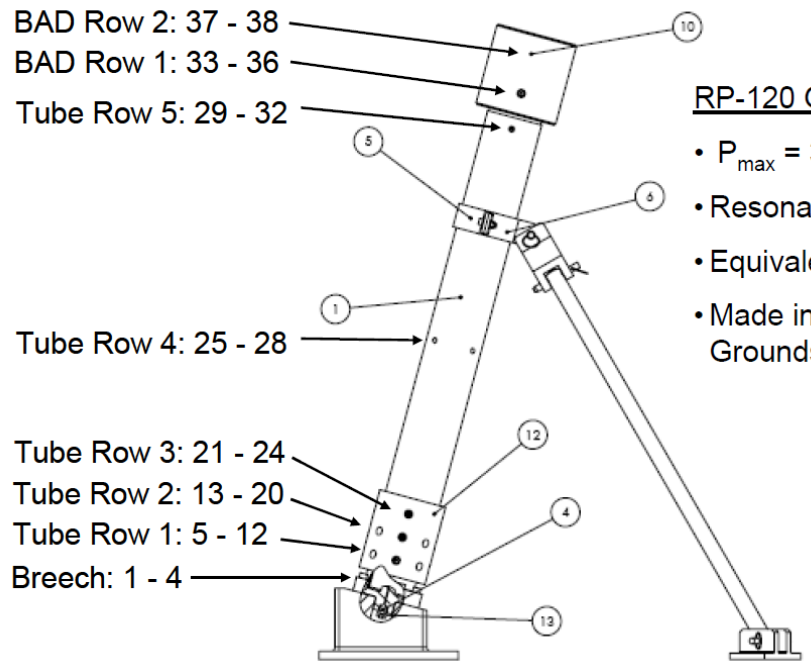
- In collaboration with the U.S. Army - ARDEC, a detailed model and code (called Three-dimensional Mortar Interior Ballistic code or 3D-MIB) have been developed for realistic simulation of the interior ballistics of 120-mm mortar system.
- A series of 90 test firings was conducted at the U.S. Army's Aberdeen Test Center (ATC) using a specially designed 120-mm instrumented mortar simulator (IMS).

Objectives:

- To obtain detailed interior ballistic data for use in validation of 3D-MIB code
- To achieve better understanding of the combustion processes inside the mortar tube

Instrumented Mortar System (IMS)

- The IMS, which was designed and fabricated at PSU, contains a total of 38 pressure transducer ports distributed in various longitudinal and circumferential locations.
- Up to 34 channels of pressure data were recorded at a rate of 400 kHz.
- Custom RP120 tourmaline piezo-electric dynamic pressure gauges were used.
- Two Weibel radar systems were used for velocity data:
  - a short-range system for muzzle velocity only
  - a tracking system for both muzzle velocity and trajectory determination
- High-speed video recordings (5000 – 10,000 pictures per second) of the rounds leaving the muzzle were obtained with a Phantom camera.

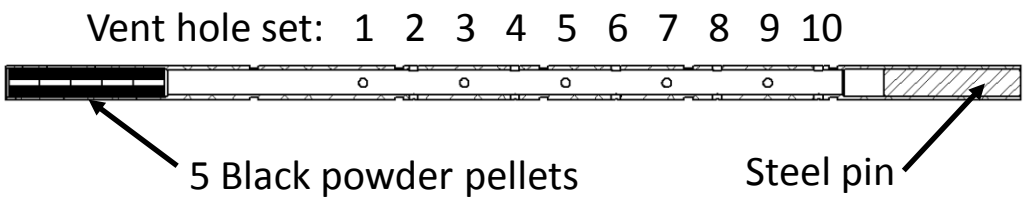


RP-120 Gauge Specifications

- P_{max} = 30,000 psi
- Resonant freq. = 15 -20 kHz
- Equivalent rise time = 5.6 μs
- Made in Yuma Proving Grounds, AZ

Flash Tube Modifications

- Previous investigations of flash tube behavior have indicated that the venting of combustion products from the flash tube is highly non-uniform.
  - To mitigate this non-uniformity, a modification to the flash tubes vent-hole size distribution was made. This case is called Mod 1.
- Moisture Resistant Black Powder Substitute (MRBPS) pellets were found previously to provide greater reproducibility in pressure-time behavior with significantly higher pressure levels in the flash tube than black powder (BP) pellets.
  - Mod 2: replacement of 5 BP pellets with 3 MRBPS pellets and 2 inert pellets



	Vent Hole Diameter (mm)									
Configuration	1	2	3	4	5	6	7	8	9	10
Baseline	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
Mod 1	2.18	2.18	2.06	2.06	1.93	1.93	1.40	1.40	1.40	1.40
Drill size	*#44*	*#44*	*#46*	*#46*	*#48*	*#48*	*#54*	*#54*	*#54*	*#54*

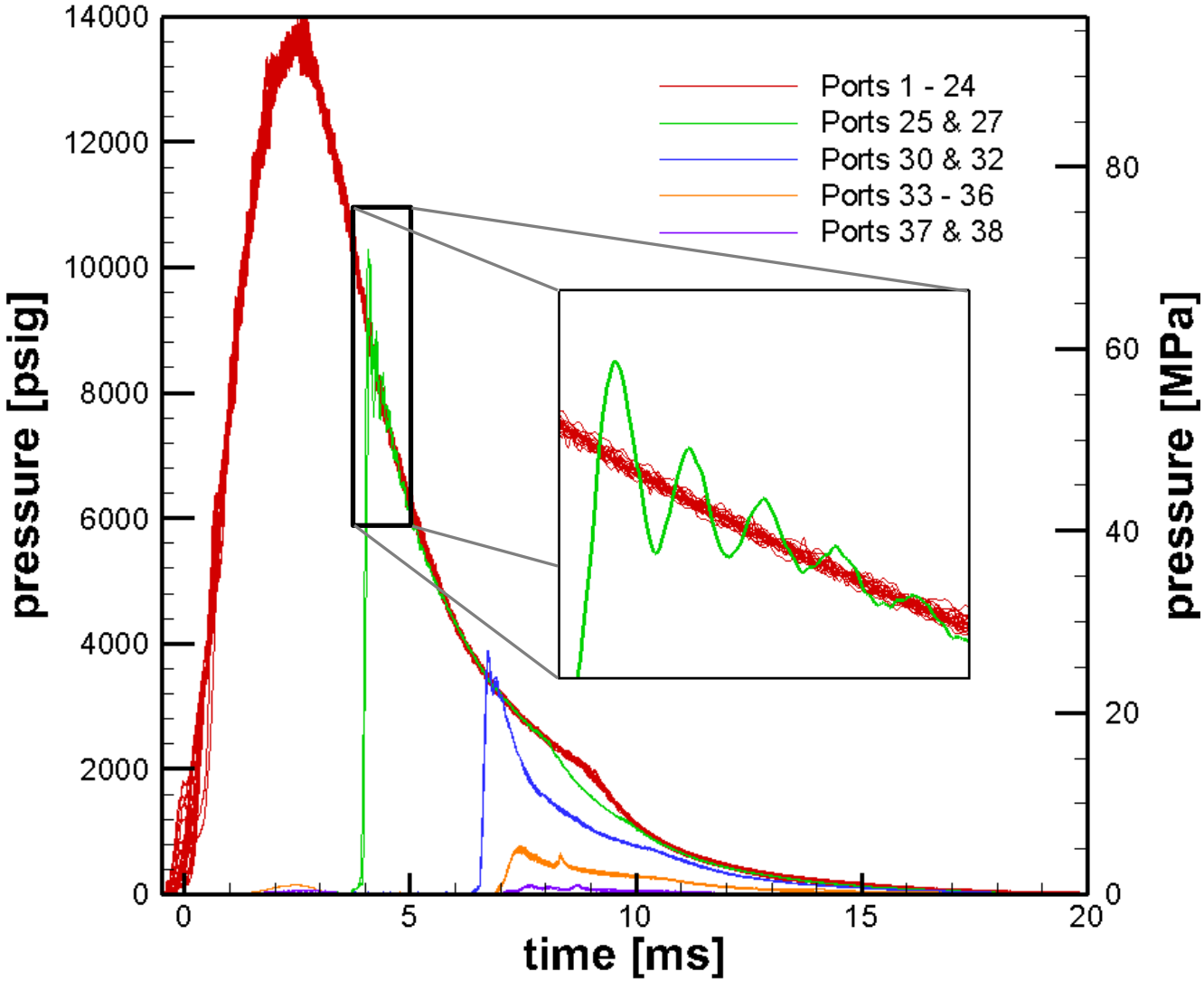
Test Matrix (T_i = 21°C)

Flash Tube Configuration	Charge Increments					
	0	*1*	*2*	*3*	*4*	*Total*
Baseline[a]	7	6	7	0	20	40
Mod 1 (different flash tube hole config.)	5	5	5	0	20	35
Mod 2 (3 MRBPS & 2 MXB360 pellets)	5	0	0	0	10	15
						90

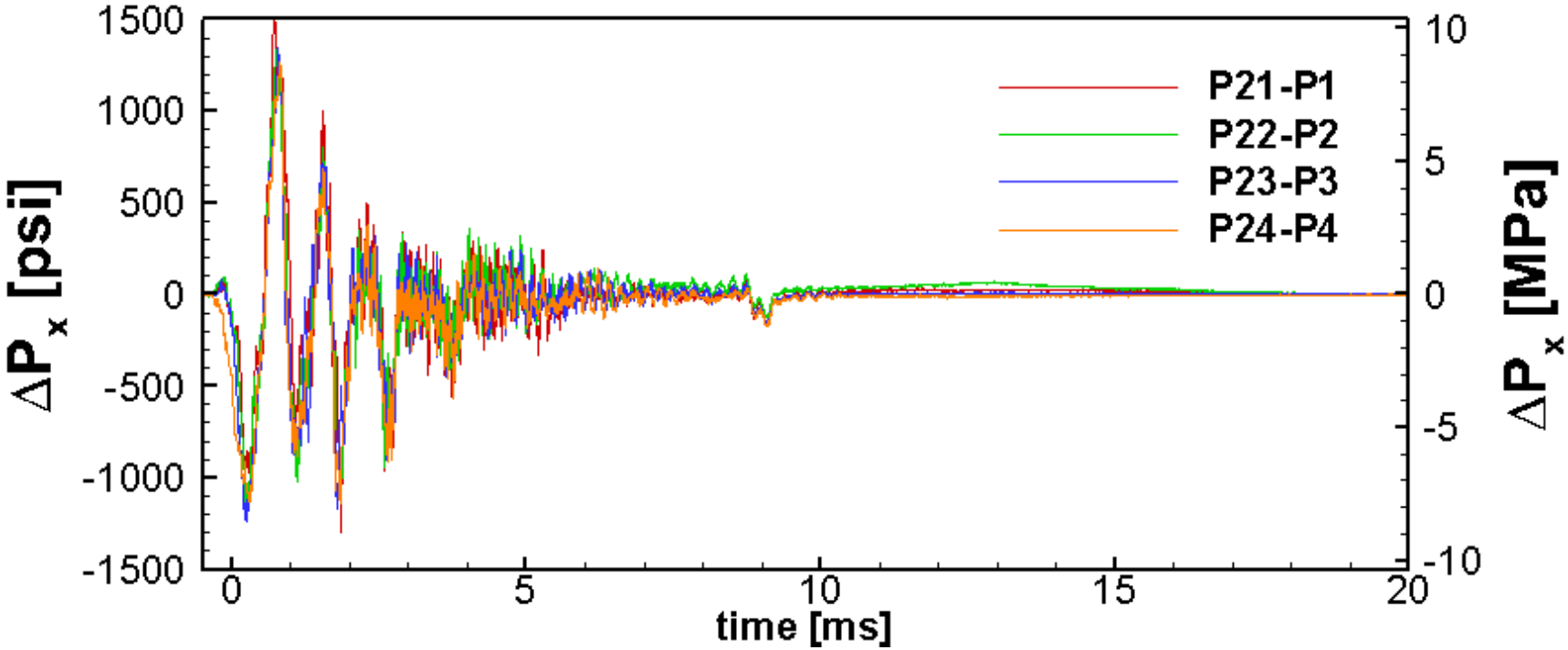
- In view of the limited total number of firing tests, the emphasis was placed on the 4 charge increments. Fewer test were conducted for Mod 2 flash tubes.
- Charge 2 and Charge 0 increment cases also have limited test runs.

Charge 4 Baseline Firing

- Ports 1 – 24 are initially below the obturating ring of the projectile, and thus have the earliest and highest pressure rise.
- Once the obturating ring passes a port location, the pressure quickly equilibrates to the pressure levels near the breech.
- The *P-t* traces from ports 25 – 32 exhibit an overshoot and ringing phenomenon that occurs after the sharp pressure rise.
  - Due to recessed mounting of pressure transducers from tube wall.
  - The observed ringing frequency of 6.7 kHz is close to the resonance frequency of the cavity of 1.27 cm.

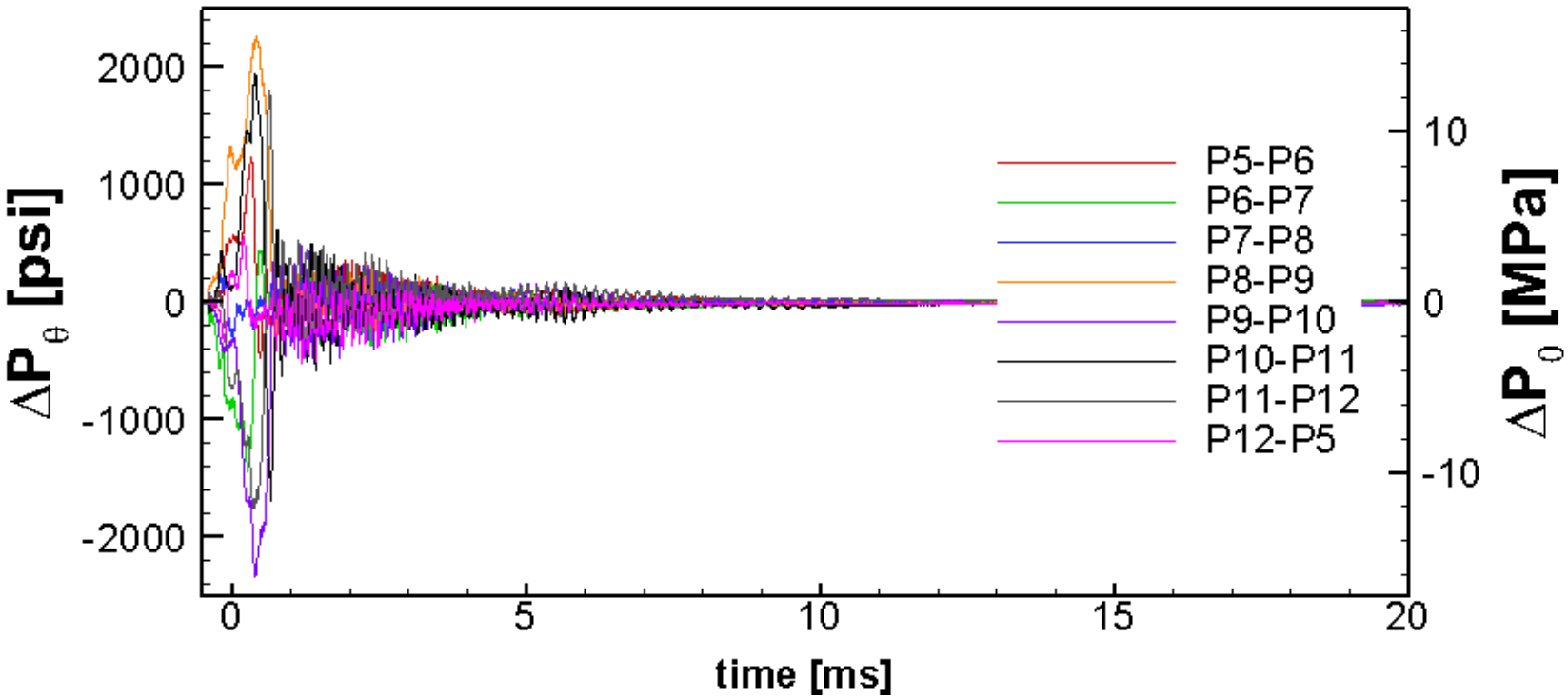


Longitudinal Pressure Waves (Charge 4 Baseline)



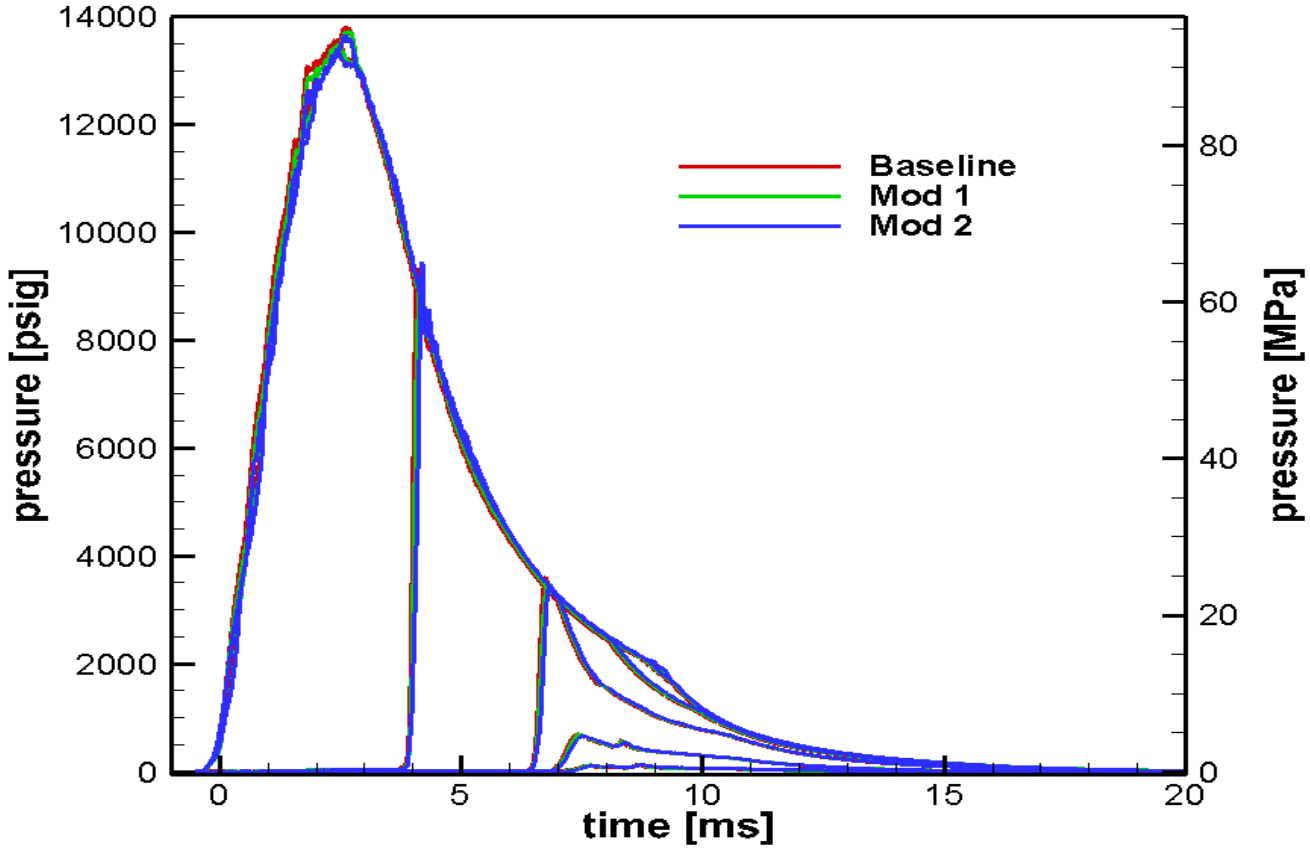
- The 4 charge increment (Charge 4) firings with the baseline flash tube configuration demonstrate significant longitudinal pressure waves.
- These waves are induced by the non-uniform ignition and flame-spreading processes present in the ignition cartridge and mortar tube.
- The existence of strong longitudinal pressure-wave phenomena in the mortar tube is undesirable as it dissipates combustion energy and introduces additional variability into the system.

Circumferential Pressure Gradients (Charge 4 baseline)



- During the early phase of the ballistic cycle, significant circumferential pressure gradients are present, even when the charge increments were alternated.
- These gradients mainly due to the horseshoe-shaped charge increments, which only supply propellant grains within 270 .
- In some extreme cases, strong circumferential gradients can cause tail boom fins to bend, leading to “short” rounds. The probability for fin-blade damage is very likely if the charge increments are aligned.

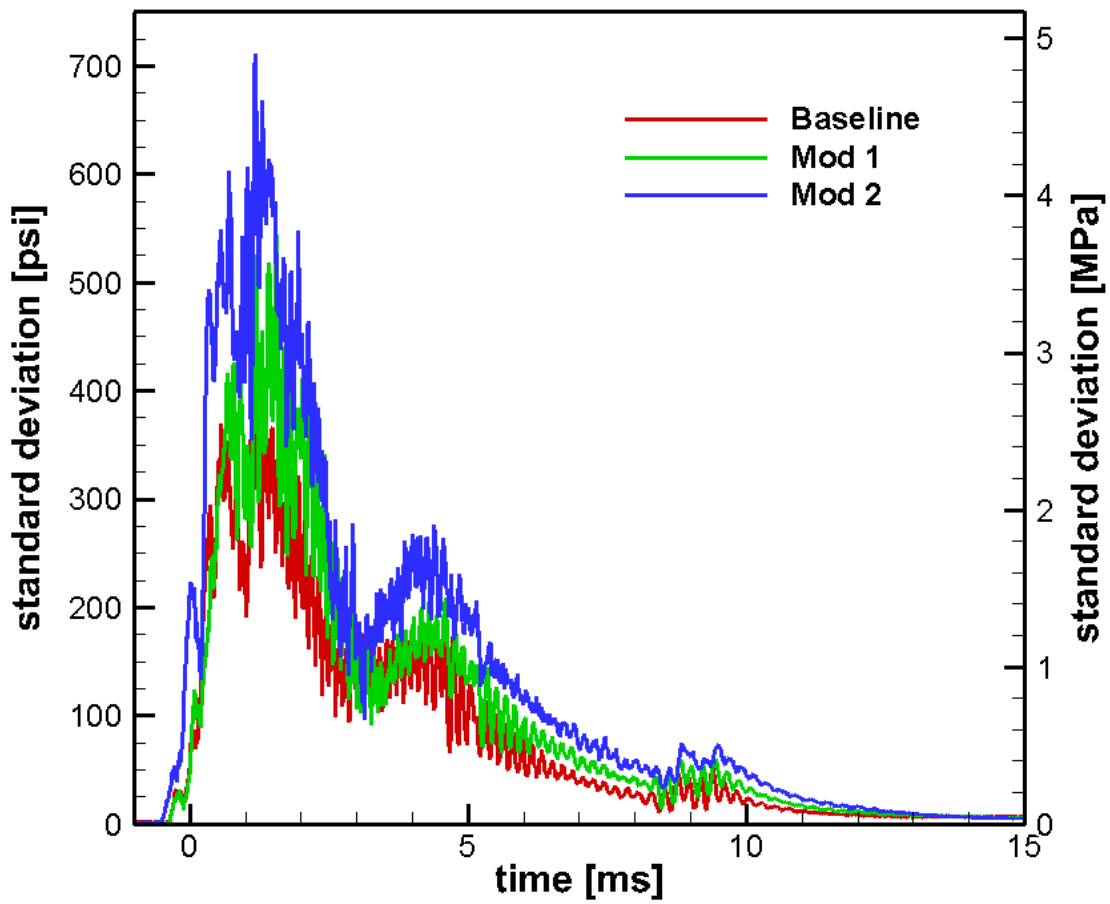
Comparison of Averaged *P-t* Traces for Charge 4



- Average P-t traces for the two modified flash tube configurations showed only minor differences from the baseline case in firings with 4 charge increments

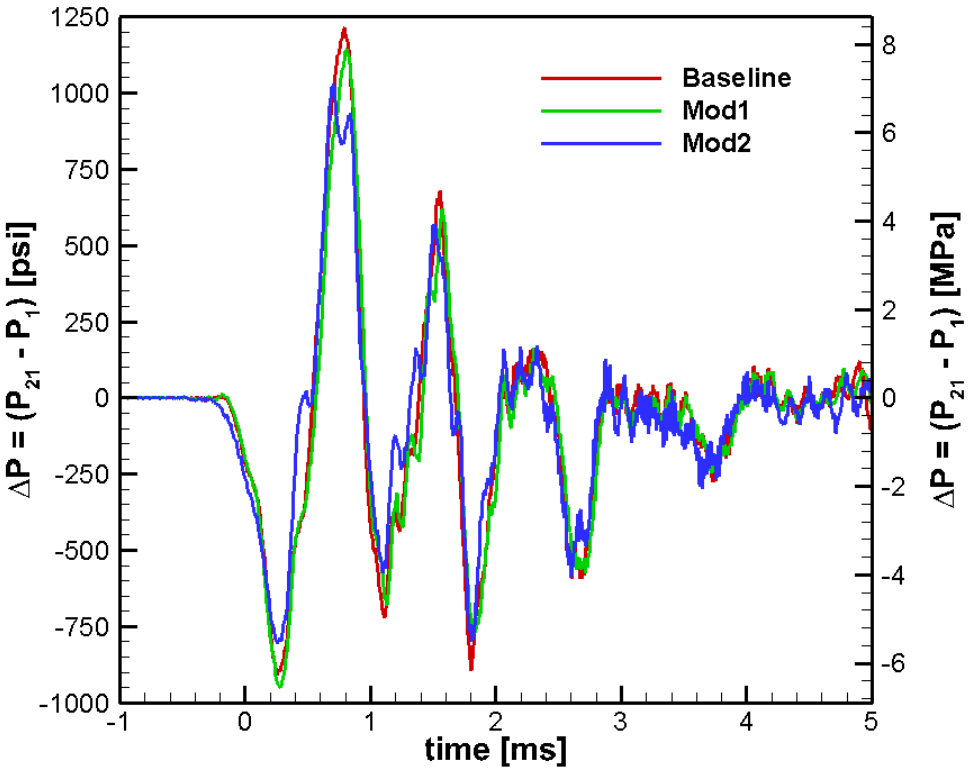
Comparison of Standard Deviation in P-t Traces

- The plot of standard deviation of *P-t* traces are similar for all gauges in the breech region.
- The averaged *P-t* traces at Port 21 were used for comparing the two modified flash tube configurations with the baseline case.
- The standard deviations for both types of modified flash tubes do not demonstrate decreased variability in comparison with the baseline case.
- The higher standard deviation for the Mod 2 firings may be partially due to the smaller number of Mod 2 firings (10 compared to 20 each for Baseline and Mod 1).



Comparison of Longitudinal Pressure Waves

- This figure displays the pressure difference between ports 21 and 1 ($P_{21} - P_1$) for the averages of the various flash tube configurations.
- These traces display the same general behavior as the single baseline firing.
  - Two distinct types of waves: High-amplitude, low frequency; and low-amplitude, higher-frequency.
- Mod 2 does exhibit lower peak amplitudes than the other configurations.
  - This seems due to destructive interference of the high-frequency waves with the low-frequency waves rather than any alteration in the fundamental cause of the low-frequency waves.
- The flash tube modifications do not show any significant effect on the presence of strong longitudinal pressure waves in the mortar tube.



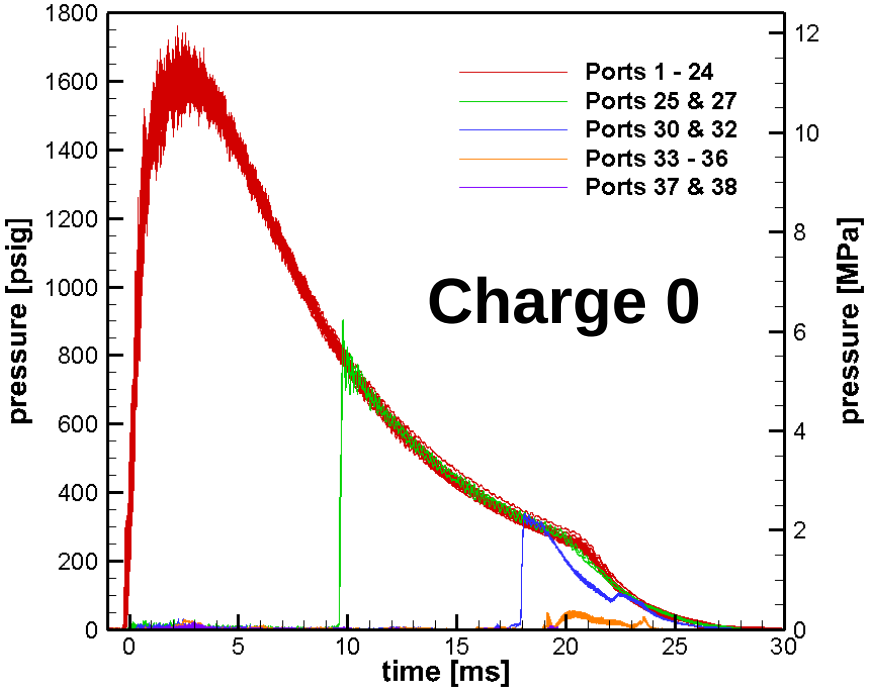
Plot of ($P_{21} - P_1$) vs. time for 4 charge increments

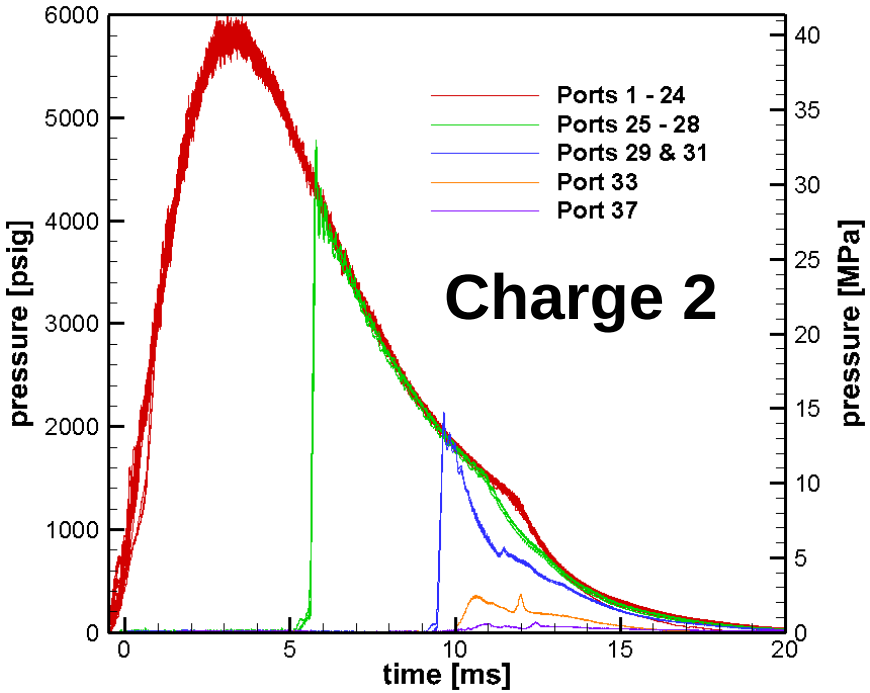
Comparison of Muzzle Velocities

[m/s]	Tests	Mean	Std Dev	95% Conf	Variability (% of mean)
Baseline	20	325.3	0.74	0.35	0.11%
Mod1	20	325.0	0.87	0.41	0.13%
Mod2	10	324.5	1.18	0.84	0.26%

- This data demonstrates that there is no statistically significant difference among the average muzzle velocities for the various ignition cartridge configurations
  - This finding corroborates that from the pressure-time behavior.
- The trend in the standard deviations from the muzzle velocities also mirrors that from the pressure-time behavior, with the baseline configuration having the lowest by a small margin, and the Mod 2 configuration having the highest, due to smaller number of tests.
- The remarkably small value of variability is noted in the table by the ratio of the 95% confidence interval to the mean muzzle velocity . For all configurations, this value is merely a fraction of a percent, which is remarkable given the complexities of the interior ballistics of the mortar system.

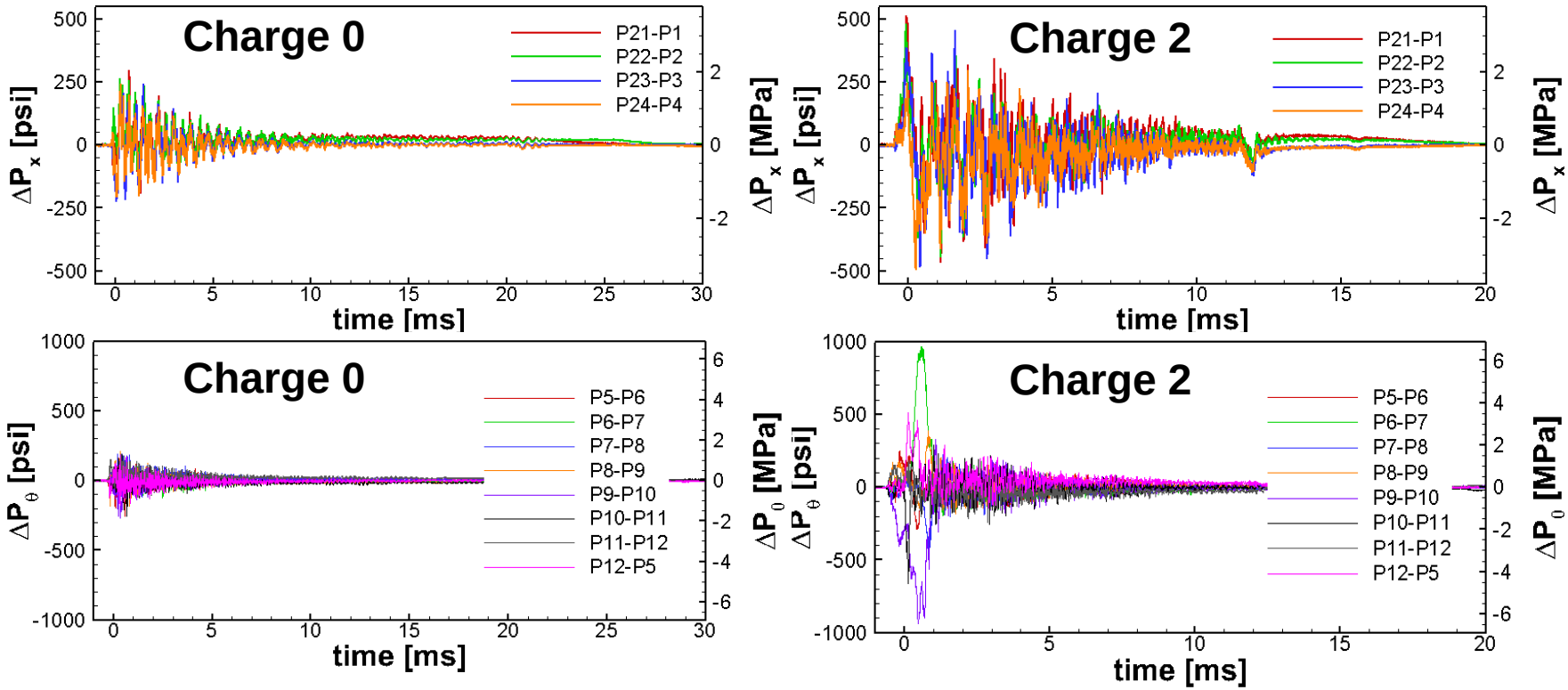
Charge 0 and 2 Baseline Firings





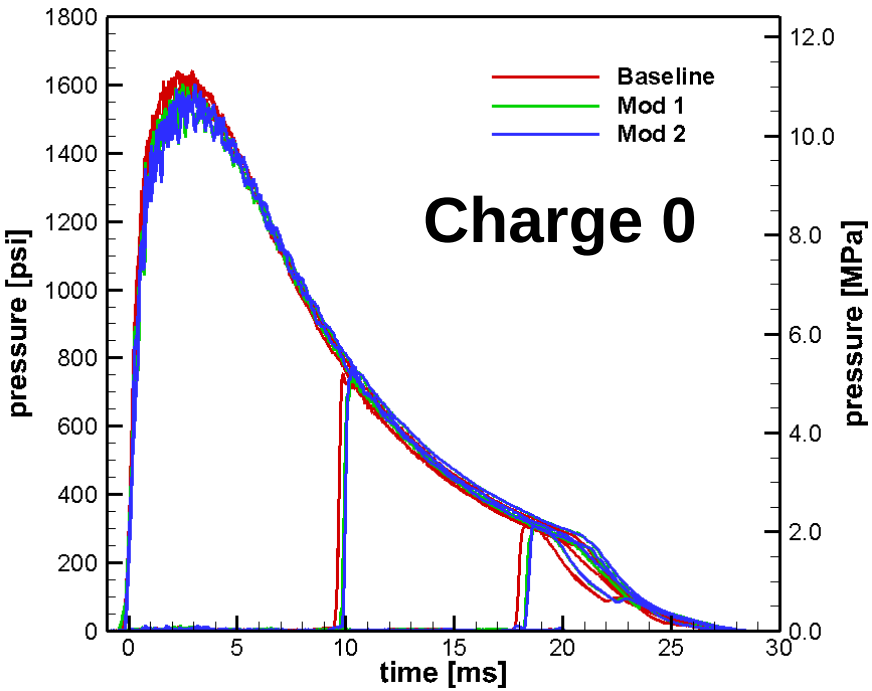
- These are representative firings of the Baseline configuration with 0 and 2 charge increments.
- The pressurization behavior for these charge increment levels is similar to that for the charge 4 firings with predictably reduced pressure magnitudes and projectile velocities resulting in slower depressurization of the mortar tube.

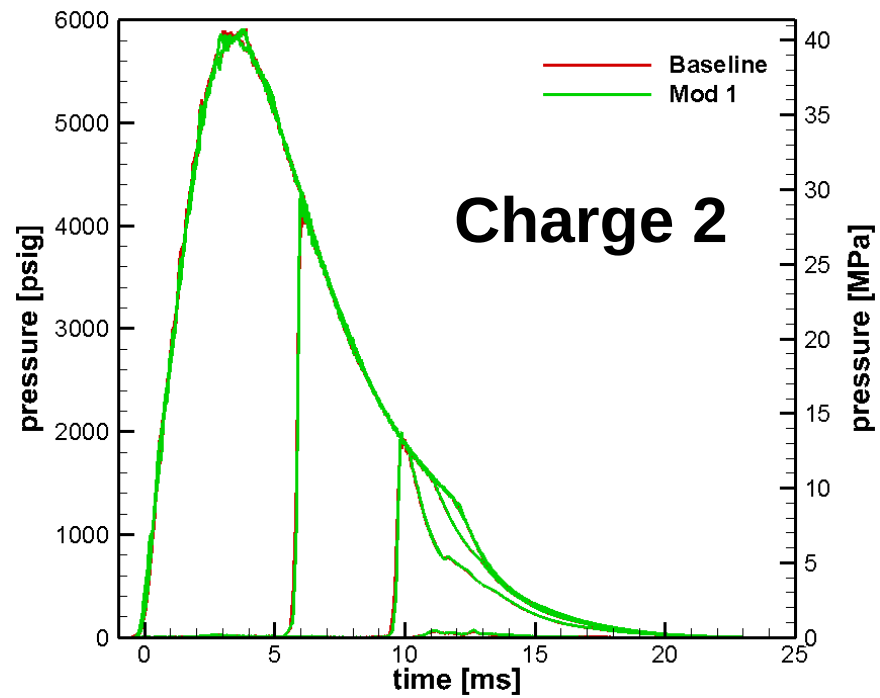
Longitudinal Pressure Waves & Circumferential Pressure Gradients



- The maximum absolute amplitude of longitudinal pressure waves for charge 0 and charge 2 firings are much smaller than those of charge 4 firings (~1500psi). ⟹ A nonlinear effect.
- Circumferential pressure gradients are negligibly small for charge 0; as expected due to the lack of charge increments.
- The strongest pressure gradients for charge 2 are approximately half those for charge 4.
  - This indicates almost a linear relationship.

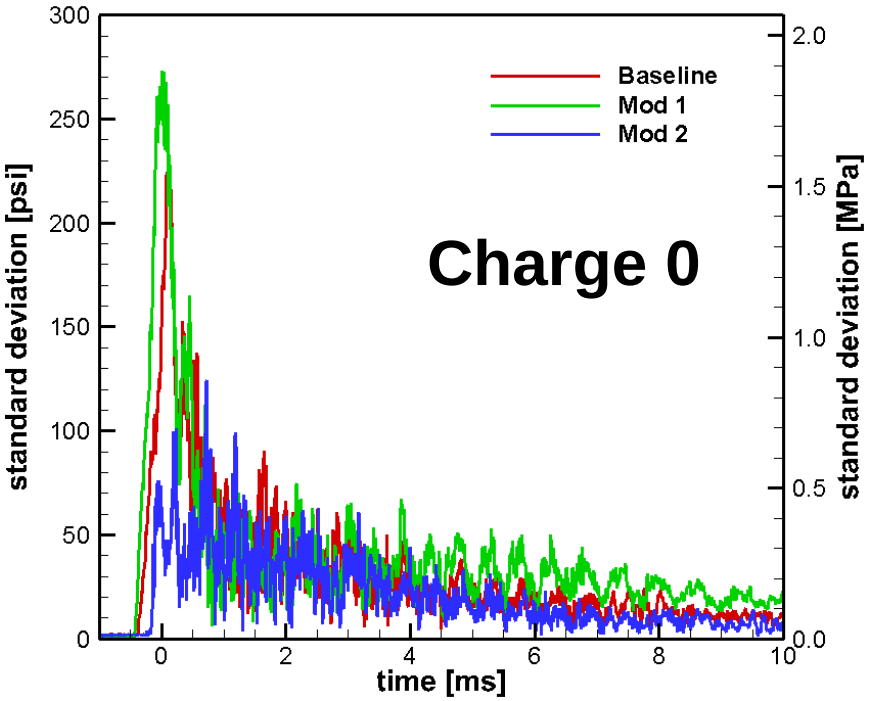
Charge 0 and Charge 2 Average P-t Traces

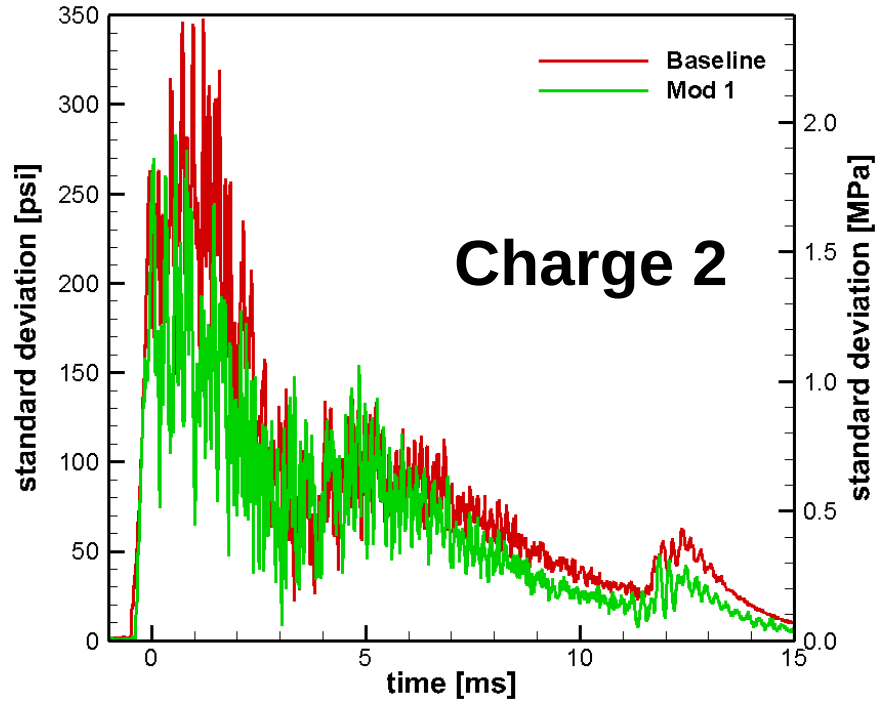




- The flash tube effect is more visible from Charge 0 configuration.
- The baseline configuration for Charge 0 demonstrates slightly higher peak pressures and earlier pressure rises for downstream ports compared to the modified ignition cartridges.
- No discernable difference exists between the average tube pressures for the baseline and Mod 1 configuration with 2 charge increments.

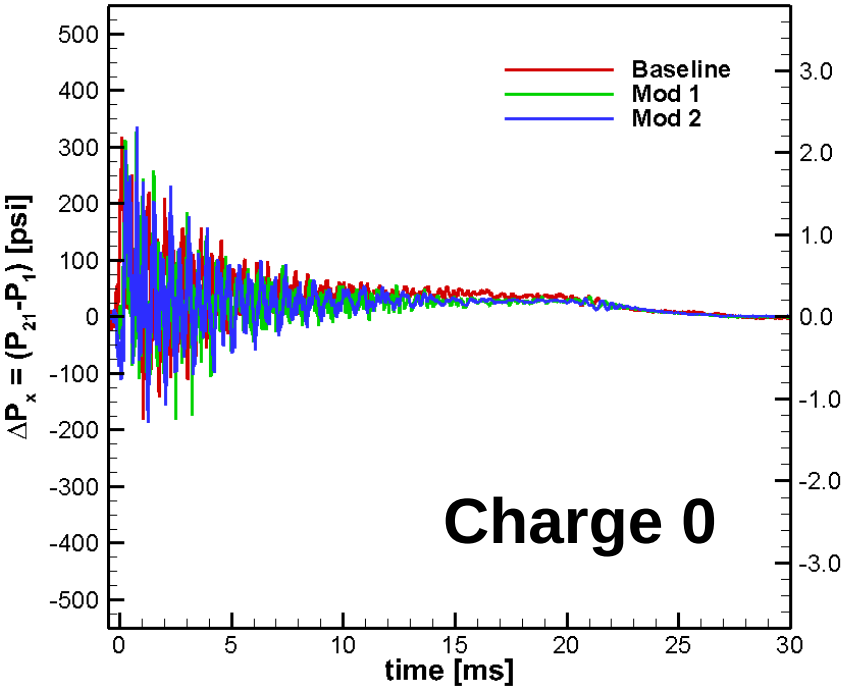
Charge 0 and Charge 2 Standard Deviations

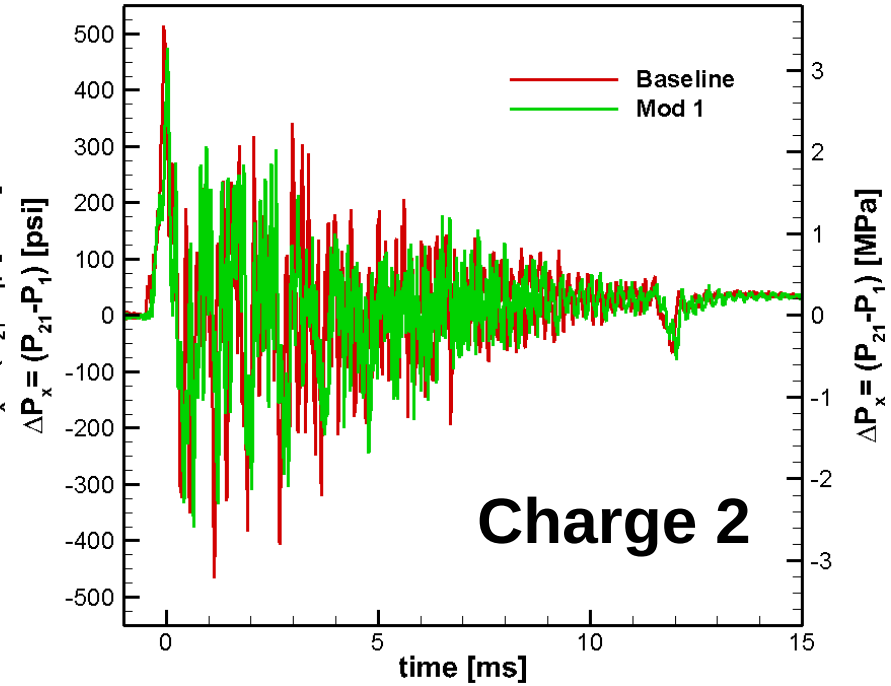




- Standard deviations of the averaged pressure histories at Port 21 for Charges 0 and 2 are shown in the above plots.
- For Charge 0, Mod 2 appears to reduce the variability in the pressure, though Mod 1 does not.
- For Charge 2, Mod 1 demonstrates a slight reduction in pressure variability.

Charge 0 and 2 Longitudinal Pressure Waves





- These figures display the pressure difference between Ports 21 and 1 ($P_{21} – P_1$) for a representative firing from each of the flash tube configurations.
- For Charge 0, there is no significant difference among the Baseline, Mod 1, and Mod 2 configurations.
- For Charge 2, the difference between the Baseline and Mod 1 configurations are insignificant, as well.

Muzzle Velocities (in m/s)

- Fewer Charge 0 and Charge 2 firings were conducted than for Charge 4.
  - Caution is urged in the interpretation of data from such a small sample size.
- For Charge 0:
  - The Baseline ignition cartridge demonstrates a slightly higher average muzzle velocity than the modified configurations.
  - This observation is consistent with the measured pressure-time data.
- For Charge 2:
  - The Baseline and Mod 1 configurations are nearly indistinguishable.
- The ignition cartridge modifications are demonstrated to have a negligible influence on both the magnitude of muzzle velocity and its variability.

Charge 0	No.	Mean	Std Dev	95% Conf	Variability (% of mean)
Baseline	7	99.6	0.32	0.29	0.29%
Mod1	5	98.4	0.78	0.97	0.98%
Mod2	5	98.4	0.56	0.69	0.71%

Charge 2	No.	Mean	Std Dev	95% Conf	Variability (% of mean)
Baseline	7	227.2	0.27	0.25	0.11%
Mod1	5	227.2	0.27	0.34	0.15%

Charge 4	Tests	Mean	Std Dev	95% Conf	Variability (% of mean)
Baseline	20	325.3	0.74	0.35	0.11%
Mod1	20	325.0	0.87	0.41	0.13%
Mod2	10	324.5	1.18	0.84	0.26%

Conclusions

- Through detailed measurements in the instrumented mortar tube, significant longitudinal pressure waves and circumferential pressure gradients were found to exist during the early period of the ballistic cycle.
  - Both phenomena are undesirable to the performance of the mortar system.
  - The circumferential pressure gradients have the potential to cause damage of tail-boom fin blades.
- The two flash-tube modifications have negligible effect on both the magnitude of the muzzle velocity and its variability for different propellant charge increments.
- The flash-tube modifications also have a negligible effect on the magnitude of the longitudinal pressure waves for all charge increment levels.
- For Charge 0, Mod 2 seems to produce a reduction in the variability of the pressure-time behavior.
- For Charge 4, the flash-tube modifications do not reduce the magnitude of P_{max} or the variation in the pressure histories within the mortar tube.
- The results presented in this study have been very useful for model validation.

Acknowledgements

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- Thanks to Mr. Joe Nimphius of the U.S. Army-ARDEC for his effort in arranging the mortar test firing schedules.
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- We would also like to thank Dr. Ragini Acharya of our team for her simulation study and the comparison of calculated results with the mortar test data.

Thanks very much for your attention.

Any Questions?