EFFECT OF INITIAL TEMPERATURE ON THE INTERIOR BALLISTICS OF A 120-mm MORTAR SYSTEM

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The effect of the initial temperature (T_i) on the interior ballistics of a 120-mm mortar system was investigated using four different experiments: temperature-conditioned closed bomb firings for determining the temperature sensitivity (σ_p) of the ignition cartridge's M48 double-base propellant and instrumented firings of temperature-conditioned flash tubes, ignition cartridges, and an instrumented mortar simulator (IMS). The results of these experiments reveal that for $T_i \geq -12$°C, the mortar system and its sub-components exhibited regular T_i-dependent behavior, with increasing T_i causing monotonically-increasing propellant burning rates, which produce monotonically-increasing system pressures and pressure differentials in the flashtube, ignition cartridge, and IMS. However, some anomalous behavior was discovered for T_i around −46°C. Brittle fracture of the M48 propellant granules occurs at extremely low T_i. This phenomenon explains the dramatically increased variation in *P*-*t* behavior and projectile muzzle velocity at−46°C for Charge 4 firings as compared to higher T_i. Test data suggest a fundamental change in reaction kinetics occurring at extremely low T_i. This supposition is bolstered by evidence of a liquid layer existing on the surface of M48 propellant granules ejected from the ignition cartridge during T_i = −46°C firings -- a phenomenon that does not occur at the higher T_i. Based on the flash tube experiments alone, the flash tube was determined to have a weak effect on the T_i-dependent behavior of the mortar system; however, IMS testing with two different flash tube configurations revealed significant differences in longitudinal pressure wave amplitude and projectile muzzle velocity in Charge 4 firings between the two configurations at −46°C, suggesting that the uniformity of combustion product discharge from the flash tube could improve the performance of the mortar at low temperatures.

INTRODUCTION

The initial temperature (T_i) of a solid propellant has a significant effect on its burning rate as it affects the chemical reaction rates in both the gaseous and condensed phases, as well as the heat-transfer rate from the gaseous flame to the burning surface of the propellant. Weapon systems employing solid propellants may be deployed in any climate throughout the world, yet must deliver predictable performance in terms of both range and accuracy regardless of ambient conditions. In order to ensure this capability, knowledge of a weapon's response to extreme temperature conditions is required to use the weapon safely and effectively. An experimental study was therefore undertaken to determine the effect of T_i on the interior ballistics and performance of the U.S. Army's 120-mm mortar system. A cross-sectional view of a 120-mm mortar round is shown in Fig. 1 along with an inset of its constituent M1020 ignition cartridge. The primary propulsion of the mortar rounds is provided by the charge increments, which consist of a charge of M47 nitrocellulose/nitroglycerin (NC/NG) granular propellant contained in a combustible casing.

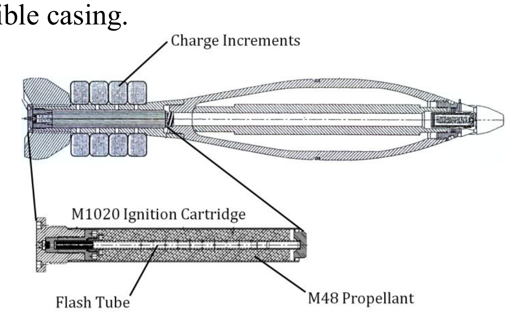


Figure 1. Cross-sectional view of 120-mm mortar with inset of M1020 ignition cartridge.

As shown in Fig. 1, as many as four charge increments (Charge 4) may be employed simultaneously in a single mortar firing, though as few as zero (Charge 0) may be used depending on the desired range and trajectory of the projectile. If no charge increments are used, the mortar projectile is propelled solely by the M1020 ignition cartridge, which is contained within the mortar round's tail boom and consists of a pyrotechnic percussion primer, a flash tube containing five cylindrical center-perforated black powder pellets, and a charge of M48 NC/NG granular propellant. The detailed studies of M48 propellant σ_p, ignition cartridge combustion behavior, and mortar interior ballistics are given in references [1-3].

TEMPERATURE SENSITIVITY OF M48 PROPELLANT

A temperature-conditioned closed bomb facility was employed to determine the temperature sensitivity (σ_p) of granular M48 double-base propellant. In order to determine σ_p of the propellant over a broad range of T_i, at least three test runs were performed at: T_i = −47, −12, 21, and 63°C [1]. The gas pressure generated during the propellant burning within the bomb was measured with a high-frequency piezoelectric pressure transducer, whose output was analyzed using the XLCB code to deduce the linear burning rate. In addition to the pressure measurements, non-intrusive acoustic emission technology was utilized in the closed bomb tests to study the effect of T_i on the ignition delay of this propellant. It was found that $\sigma_p = 0.37\%/°C$ for $-12 < T_i < 63$ °C and $\sigma_p = -0.07\%/°C$ for -47 °C $< T_i < -12$ °C.

FLASH TUBE EXTREME TEMPERATURE BEHAVIOR

Flash tube experiments were performed using a fixed test apparatus and a pendulum hammer for triggering the flash tube's primer. In each test, high-frequency pressure measurements were taken in at five different axial locations along the flash tube. Eight flash tube firings were performed at each of the two T_i: −46 °C and 63 °C. All flash tubes used were all taken from the same lot to minimize the influence of confounding factors on the results.

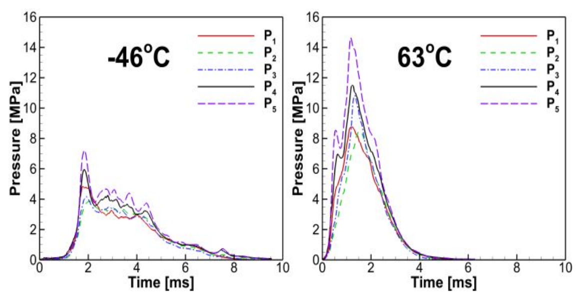


Figure 2. Average flash tube pressure histories for T_i = −46 and 63°C.

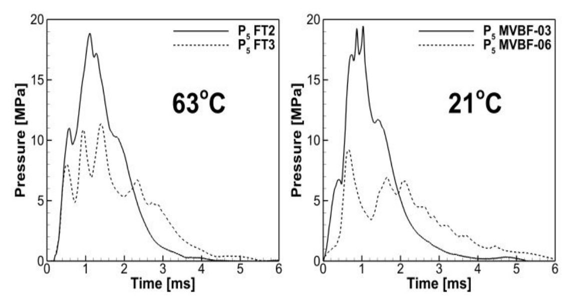
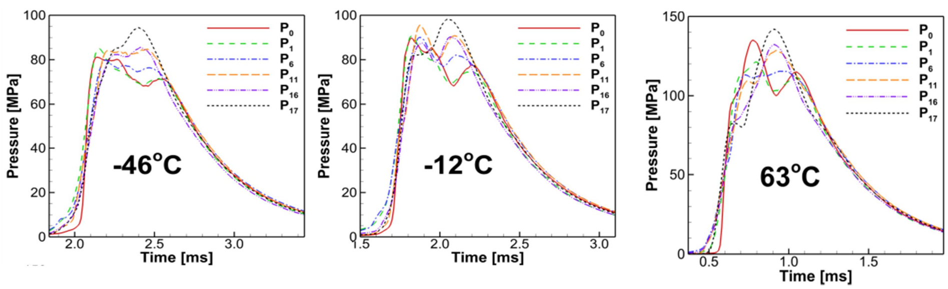


Figure 3. Pressure histories for the P_5 location from two 63°C and two 21°C flash tube firings.

For each of the two extreme T_i tested, the pressure histories from each transducer location in the flash tube were averaged and plotted in Fig. 2. As anticipated, both the peak and average pressures during the burning event are significantly higher for the hotter flash tubes, while the event duration is concomitantly shorter. What was unexpected, however, is the difference in overall behavior. The pressure histories for each axial location for T_i = −46°C firings demonstrate a relatively strong initial pressurization followed by slowly decaying oscillatory behavior during the remainder of the black powder burning, while the average pressures from the 63°C firings essentially climb to a single peak before decaying to zero. Such behavioral differences suggest that the change of T_i is not simply modifying the burning rate of the black powder but is rather affecting the combustion physics in a more profound manner. Investigating the pressure histories for individual firings reveals two distinct modes of burning are encountered among the pressure histories of the 63°C firings. Shown in Fig. 3, the P_5 pressure history from Test #FT2 exhibits the "peaking" behavior, while that from Test #FT3 exhibits the oscillatory behavior more similar to that at −46°C. As part of a previous study [4], six flash tubes were fired at 21°C with pressure histories being measured in the same manner. The P_5-t traces of Test #MVBF-03 and #MVBF-06 are shown in Fig. 3, and demonstrate that these two different burning modes are present among these firings as well. The root cause of these behavioral differences among flash tubes of the same lot at the same temperature cannot be definitively deduced from the available experimental data or theory; however, it is suspected to lie in the capricious nature of black powder pellet break-up process.

M1020 IGNITION CARTRIDGE

The M1020 ignition cartridge was tested using stainless steel tail booms, which were instrumented with six piezoelectric pressure transducers located at different axial locations along the tube with P_0 located nearest the primer end and P_{17} located nearest the projectile end [5]. Ten ignition cartridge firings were conducted at each of three different initial temperatures: −46, −12, and 63 °C, with averaged results displayed in Fig. 4.



Port	x [cm]
P_0	0.11
P_1	2.94
P_6	5.86
P_{11}	8.78
P_{16}	11.70
P_{17}	14.72

x = 0 at primer end of propellant bed.
t = 0, 1st discernible pressure rise.

Figure 4. Average ignition cartridge pressure histories for each initial temperature

These pressure histories exhibit the theoretical trends with increasing initial temperature: monotonically increasing flame spreading and pressurization rates, increasing peak and average pressures, and exaggerated pressure variation features for all gauge locations [6]. Unlike the flash tubes, however, the total event time is nearly unaffected by changing initial temperature. Therefore, the slower burning of the propellant at lower initial temperatures is primarily revealed by longer pre-ignition and flame-spreading times and lower overall pressures.

INSTRUMENTED MORTAR SIMULATOR

Two series of test firings were conducted at the U.S. Army's Aberdeen Test Center (ATC) using a specially-designed 120-mm instrumented mortar simulator (IMS), in which up to 35 channels of pressure data were captured from a total of 38 available pressure transducer ports, whose locations were selected to provide pressure measurements at positions where the transient 3D behavior can be resolved to provide better understanding of the interior ballistic processes. Two Weibel radar systems were used for measuring the muzzle velocity. In order to reduce intensity of pressure wave phenomena observed in the ignition cartridge, a modified flash tube was also used in some of the firings. It features variation of vent-hole sizes with distance [7,8] in contrast to the baseline flash tube, which has uniform vent-hole diameters. The first test series consisted of 90 firings, all conducted with inert 120-mm M934 HE rounds conditioned to 21°C, and the second test series consisted of 95 firings, which were conducted with rounds conditioned at −46, 21, or 63°C.

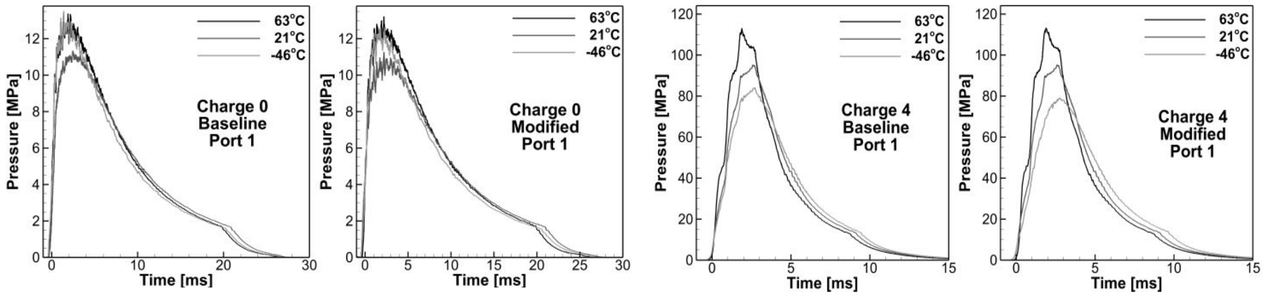


Figure 5. Comparison of median IMS port 1 pressure histories for different initial temperatures.

In order to simplify the evaluation of the *P-t* behavior of the IMS among different T_i, the median pressure histories from port 1 (at the base of IMS tube) for a given charge increment level and flash tube modification are plotted together in Fig. 5. Port 1 is considered sufficient for comparison as it is representative of the mean pressure in the mortar tube behind the projectile. Interestingly, for Charge 0 firings, the peak pressure reached for -46°C is essentially the same as that reached for 63°C and the peak for 21°C being lowest. For Charge 4 firings, the evolved peak pressures are directly related to the T_i, with the lowest peak pressure at -46°C and highest peak pressure at 63°C.

CONCLUSIONS

The effect of T_i on interior ballistics of a 120-mm mortar system was investigated using four different experiments. Major findings are listed below.

1. For $T_i \geq -12$°C, the mortar system and its sub-components exhibit behavior consistent with physical intuition: increasing T_i causing monotonically-increasing propellant burning rates and monotonically-increasing system pressures and pressure differentials in the flashtube, ignition cartridge, and IMS.
2. For $T_i = -46$°C, evidence exists that the flame structure around the propellant grain or its decomposition mechanism is different from those at higher T_i.
    a. The σ_p of the M48 propellant deduced from the closed bomb data below -12°C deviates significantly from that for temperatures above -12°C.
    b. Large agglomerations of partially burned M48 propellant granules recovered from ignition cartridge firings $T_i = -46$°C indicate the presence of a liquid layer on the surface of the propellant granules.
3. The occurrence of brittle fracture of propellant granules is indicated in the results of IMS tests
    a. Maximum pressure developed in -46°C Charge 0 IMS firings more or less equal to that developed in 63°C Charge 0 firings and greater than that in 21°C Charge 0 firings.
    b. Substantially increased variation among pressure histories and muzzle velocities for Charge 4 firings at -46°C as compared to those from 21 and 63°C firings.

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