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LARGE CALIBER PROJECTILE FILL ADHERENCE

Ernest L. Baker

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ABSTRACT

There is currently no agreed standard methodology for assessing the suitability of explosives for gun launch or for the determination of acceptance criteria for explosive fill defects. As a result, the NATO AC/326 SG/A Gun Launch Setback Ignition Study Working Group (WG) was formed during 2017. As a result of discussions within the working group, it has become clear that there are varying opinions and very little data as to whether and when a projectile fill should be manufactured with the aim to adhere or not adhere to the projectile interior surface. As a result, a review of fill adherence technology for large caliber projectiles was conducted.

In particular, technologies associated with the non-adherence of cast cure explosives is presented and discussed. Clearly for cast cure explosives, intentional non-adherence is intended to overcome issues associated with thermal expansion of the explosive billet. This has the objective of avoiding tearing or cracking of the explosive caused by thermal cycling in combination with adherence to the projectile case. For comparison cast cure explosives typically have about ten times the thermal expansion of steel, whereas this is only three to five times for melt pour explosives.

As for safety concerns during gun launch, it appears that explosive movement would cause void collapse and adiabatic heating if any such voids or cavities exist. This effect is much larger nearer the projectile base regions. Based on very limited experimentation and modelling, it appears that increased wall friction and increased explosive stiffness makes considerable reductions to the strain and stress profiles. Therefore, any potential void collapse and associated adiabatic heating affects are likely to be significantly larger for non-adhered fillings compared to adhered fillings and for softer explosives compared to more rigid explosives.

Keywords:

Gun Launch, Setback, Explosive, Filling, Ignition, Artillery, Projectile.

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ABBREVIATIONS

2X	Two times
10X	Ten times
AC/326	NATO Ammunition Safety Group
IMX	Insensitive Munitions Explosive
NATO	North Atlantic Treaty Organization
PBX	Plastic Bound Explosive
SG/A	Subgroup A
TNT	Trinitrotoluene
WG	Working Group

INTRODUCTION

There is currently no agreed standard methodology for assessing the suitability of explosives for gun launch or for the determination of acceptance criteria for explosive fill defects. As a result, the NATO AC/326 SG/A Gun Launch Setback Ignition Study Working Group (WG) was formed during 2017. The purpose of the working group is to gather background information on types of defects, laboratory testing, gun launch conditions and their relation to safety for gun launch of munitions. As a community we need to gather information on what we believe are the important aspects related to this technical area, and develop standardized assessments and processes. This effort should be greatly beneficial for the safety and technical understanding of setback ignition.

As a result of discussions within the working group, it has become clear that there are varying opinions and very little data as to whether and when a projectile fill should be manufactured with the aim to adhere or not adhere to the projectile interior surface. As a result, a review of fill adherence technology for large caliber projectiles was conducted. In particular, technologies associated with the non-adherence of cast cure explosives was investigated. Less information on the adherence or non-adherence of pressed and melt pour explosives was found. This topic is under ongoing discussion within the WG.

1 PROJECTILE EXPLOSIVE FILLING

1.1 PRESSED FILLING

Projectiles are filled with explosives using three primary methods: pressed, melt pour or cast cure. Only one pressed explosive projectile was identified that is intended to have the explosive not adhere to the projectile interior surface: the Excalibur M982 155 mm projectile. However, it has a significantly different loading approach than most pressed explosive munitions which are loaded directly into a body. The M982uses a pressed PBXN-9 charge that is inserted into relatively thick plastic liner that appears to be several millimetres thick. Figure 1 presents a cross section diagram of the M982warhead section [1] . The explosive billet with plastic liner fit into the projectile steel body and a spacer is placed onto the warhead and the steel body is closed using a threaded end. As the liner is quite thick and the explosive billet is inside of it, it is quite different from other explosive fillings that are not meant to adhere to the projectile interior surface.

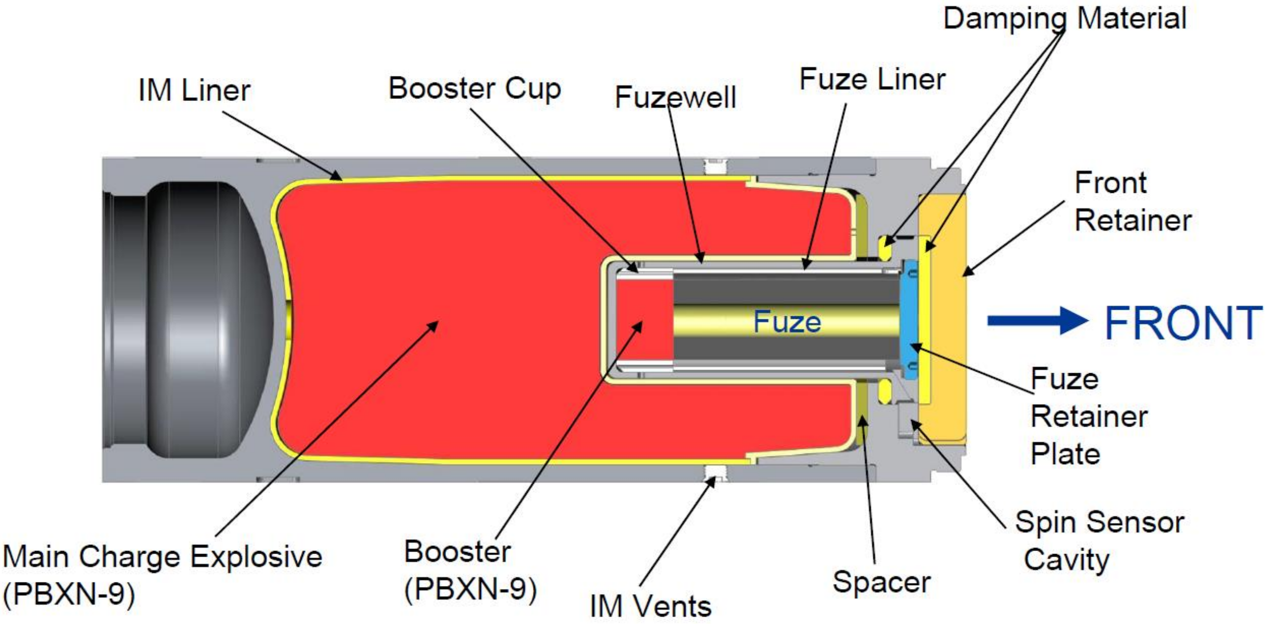

Figure 1. The M982 warhead section.

1.2 MELT POUR FILLINGS

Melt pour fillings based on TNT typically shrink during solidification. TNT contracts by about 12% on solidification. As a result, with no or low explosive to projectile interior surface adhesion, melt pour projectile fillings sometime result in gaps between the explosive and the projectile interior surface. These gaps are typically observed from x-ray inspections. Figure 2 presents an x-ray showing base gaps between the explosive and a steel projectile body.

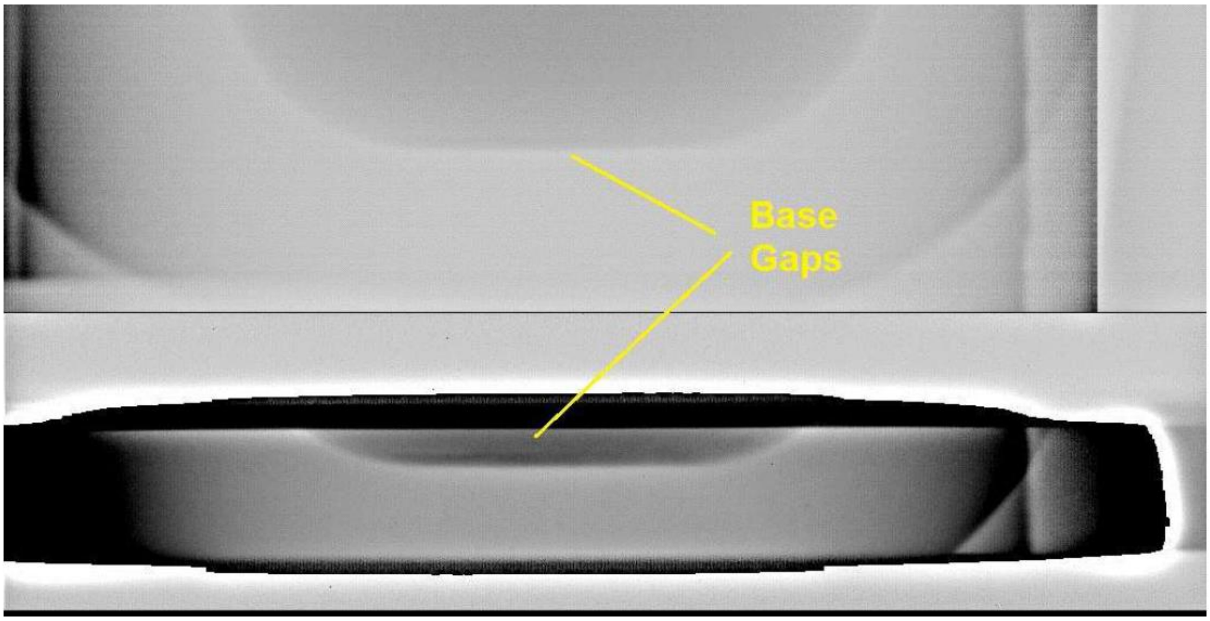

Figure 2. Explosive base gaps observed from fillings x-ray inspection.

It has been a common practice for melt pour fillings that the surface of all ferrous metals used in contact with explosive is varnished (traditionally copal varnish) [2] or coated with a bituminous composition [3]. The stated goals of such a coating is to prevent corrosion and possible chemical action with the explosive [2] and to avoid premature ignitions during gun launch [3]. Normally, the use of a bituminous composition coating is associated with the objective of achieving adherence of the high explosive filling to the internal projectile surface [3]. Little information has been found as to projectile melt pour filling of projectiles that are intended not to adhere to the projectile interior surface. However, discussions within the Gun Launch Setback Ignition Study Working Group (WG) indicate that avoiding adhesion has been an objective during some melt pour projectile fillings with the stated goal to avoid premature ignitions during gun launch. Some groups within the community have indicated that melt poured explosives do not adhere to some varnished surfaces. Technical opinions vary largely between avoiding adhesion, promoting partial adhesion and promoting total surface adhesion. The opinions are largely based on physical hypothesis, with little experimental evidence or modeling supporting the different opinions.

1.3 CAST CURE FILLINGS

BAE Systems Land UK reported that developmental 105mm L50 ROWANEX 1100 cast cure projectiles were cast using a thin flexible shell liner [4]. A thin elasticized plastic liner between the explosive filling and the projectile interior surface prevents filling adhesion.   Figure 3 presents a photograph of the 105mm L50. BAE Systems Land UK is now concentrating on the development of IMX-104 melt pour filled artillery projectiles.

Figure 3. The 105mm L50 artillery projectile.

Eurenco (SME Explosive & Propellants Groupe SNPE at that time) presented that they sometimes filled projectiles using a thin liner in order to produce projectiles where the cast cure explosive did not adhere to the projectile interior surface [5], [6]. The first presentation noted that a patent exists for the filling process.

There exists a number US and European patents related to filling cast cure explosives using thin elastic plastic liner into projectiles [7], [8], [9], [10]. These patents are assigned to Rheinmetall W & M GmbH, Unterliss (DE) and BAE Systems plc (GB).

The earliest patent from 2005 [7] states:
“The explosive charge is disposed in a plastic casing, comprised of an elastic material, inside the chamber of the high-explosive projectile. Additional tensioning means are provided to compensate for the varying volume of the explosive charge relative to the projectile casing if the temperature fluctuates dramatically and maintain the explosive charge under a pre-stress, particularly when using a plastic bound explosive charge.”
“A drawback of plastic-bound explosive charges, however, is that they have a relatively large thermal-expansion coefficient, which may be eight to twelve times larger than that of a steel projectile casing of a corresponding high-explosive projectile. In this type of explosive-filled projectile, tensions occur at positive temperatures, so the explosive body is held in the projectile casing, whereas the explosive body compresses at lower temperatures and rests loosely in the projectile casing.”
“It is the object of the invention to provide a method for producing a large-caliber, high-explosive projectile in which the explosive body is always held with a prestress in the projectile casing, even when the temperature fluctuates dramatically, in the use of plastic-bound explosive charges.”

Clearly the plastic liner is intended to overcome issues associated with thermal expansion of the explosive billet. Presumably this would be tearing or cracking of the explosive caused by thermal cycling and adherence to the projectile case. Figure 4 presents a cross sectional projectile diagram taken from [7] that shows the plastic liner (10 in figure).

It is interesting that an invention disclosed in 2013 [8] and presented in Figure 5 is intended to stop the liner (5 in figure) from moving down the explosive billet and exposing the explosive billet directly to the projectile body interior. This implies that direct exposure of the explosive billet to the projectile body interior occasionally occurs. From [8]:
“In some cases, the liner is not stiff enough to be able to compensate its own thermal expansion in line with the expansion of the high-explosive charge. Due to its great thermal expansion, the high-explosive charge contracts and expands by several mm during cooling and heating, respectively. The liner contracts with the high-explosive charge but does not expand with it to the same extent. This causes a displacement of the liner on the high-explosive charge. Over many changes in temperature, the liner shifts to the rear relative to the high-explosive charge, so that the charge can become partially exposed.”

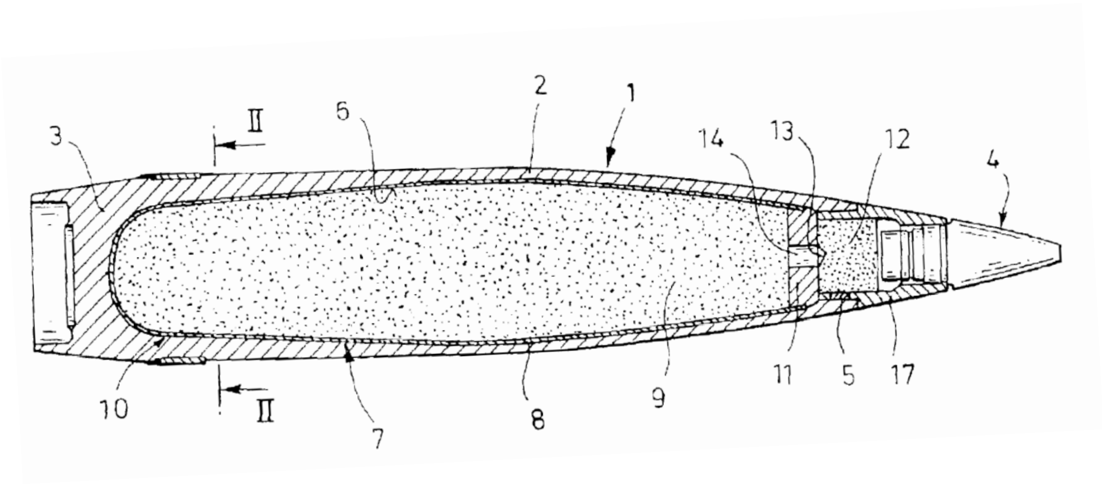

Figure 4. First known patent showing a thin plastic liner intended to help compensate for cast cure explosives high coefficient of thermal expansion.

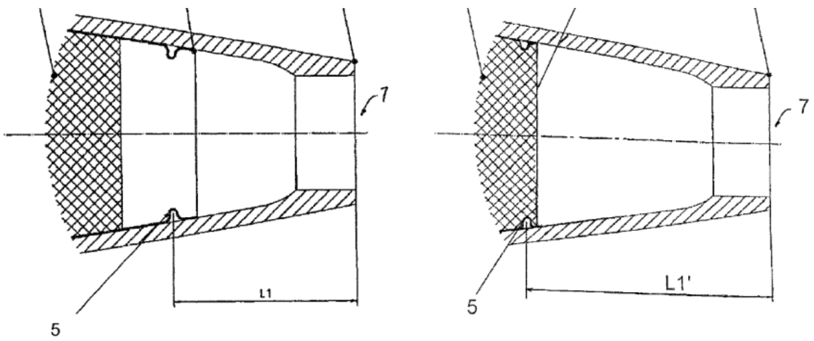

Figure 5. Invention to stop the liner from moving down the explosive billet and exposing the explosive billet directly to the projectile body interior.

BAE Systems plc (GB) patented a method for vacuum filling a thin projectile liner (elastomeric bag) [10]. Figure 6 presents diagrams from the patent describing the invention and show the elastomeric bag (36 in figure).

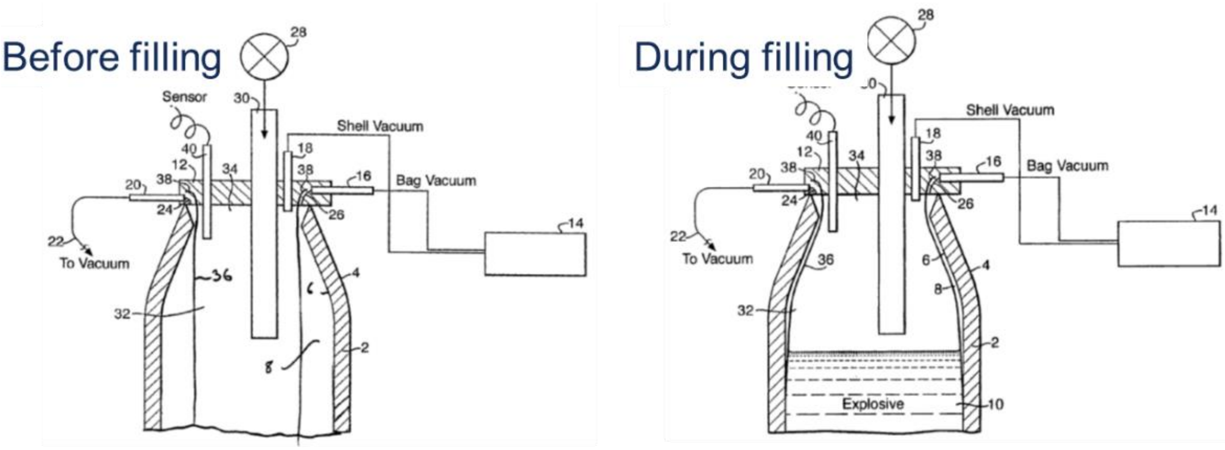

Figure 6. Method for vacuum filling an elastomeric bag (36 in figure) that prevents explosive adherence to the projectile interior surface [10].

Reference [11] presents a 76 mm naval gun projectile with the explosive partially adhered to the projectile interior surface: “Anti-adhesive liner is put on the internal parts of the structure except on a specific zone where the explosive loading bonds directly to the metal part.” (Figure 7). Stress and strain were calculated using maximum axial and spin accelerations at high and low temperatures (Figure 8). Based on these calculations, it was decided that the physical integrity of the explosive loading is ensured during the gun launch.

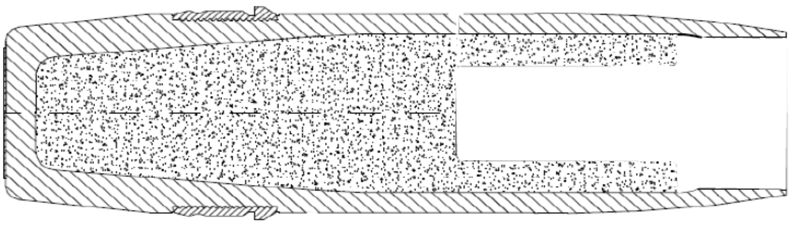

Figure 7. Naval gun system 76 mm projectile with partially adhered explosive.

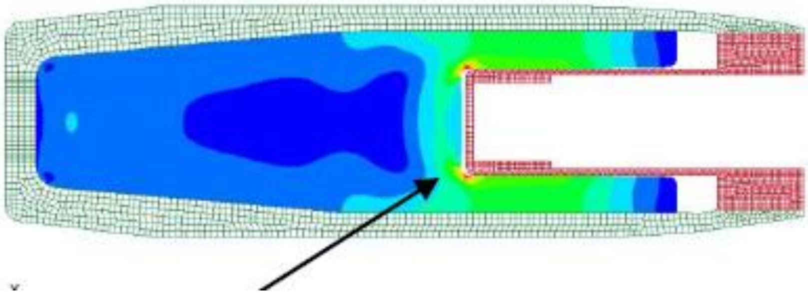

Figure 8. Calculated maximum stress for launch at -30°C.

2 MECHANICAL RESPONSE OF EXPLOSIVES DURING GUN LAUNCH

2.1 FILL STRESS

There is a significant lack of experimental data for the response of energetic materials during gun launch. We have only found one openly published report measuring artillery fill stress profiles during gun launch. This study by Collet [12] used both adhered explosive and non-adhered (greased) explosive Comp-B filled projectiles. The non-adhered explosively filled projectiles showed higher explosive base stresses (~40% increase) compared to the adhered explosively filled projectiles, but still well below the theoretical values calculated based on projectile acceleration and explosive head heightWe are also aware of unpublished artillery fill stress measurements conducted by BAE Land Systems UK that are available through the NATO Gun Launch Setback Ignition Study Working Group. The two data sets show very different stress profiles, with the melt pour Comp-B measurements of Collet showing lower stress histories, well below the theoretical values calculated based on projectile acceleration and explosive head height and the BAE Land Systems UK results much closer to the theoretical values. As the BAE Land Systems UK experiments were conducted using a cast cure simulant formulation, one hypothesis is that the very different mechanical responses could be due to significantly different mechanical properties. The cast cure formulations are generally known to be less rigid than the melt pour formulations. There is no known similar data for pressed explosive formulations or simulants.

2.2 X-RAY STUDY OF EXPLOSIVE DYNAMICS DURING GUN LAUNCH

There is only one known experimental set of flash radiography data on the mechanical response of explosives during gun launch conditions, reported by Qinetiq [13], [14]. Figure 9 presents an x-ray of a 40mm diameter projectile filled with a cast cure explosive simulant from that study. There is a small gap formed at the front end of the projectile at maximum acceleration. The gap shape indicates that wall friction may be a major contributor to the explosive mechanical response. This study concludes that setback strain response is relatively modest and occurs around the maximum load on the projectile and then is maintained along the barrel. It also concludes that the friction between the filling and the shell case is a very important factor and that the stress response is likely to be quite severe. Associated modelling predicted that the high explosive remains in compression until the projectile leaves the barrel. Upon barrel exit significant bouncing of the explosive billet occurs due to stress relief as can be seen in Figure 10.

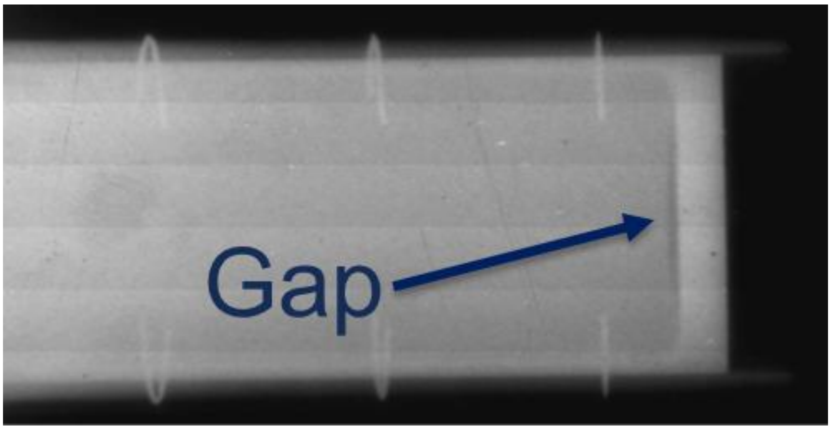

Figure 9. X-ray of a 40mm diameter projectile filled with a cast cure explosive simulant exhibiting a gap between near maximum acceleration (movement from left to right).

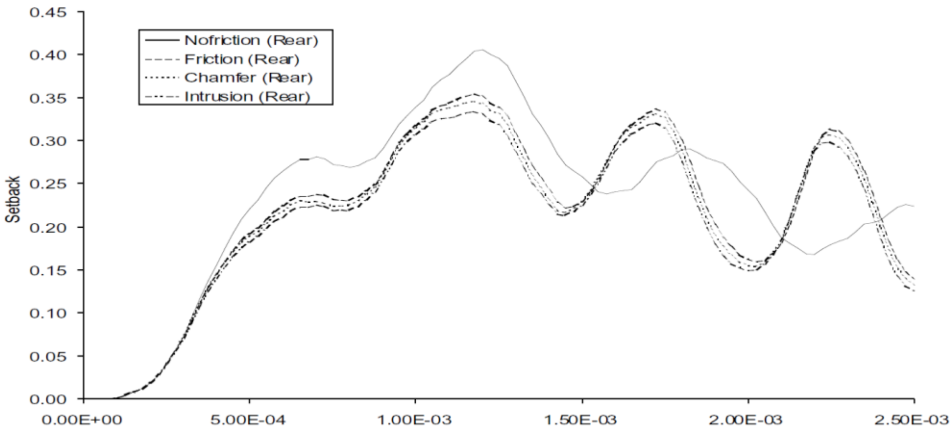

Figure 10. Displacement versus time simulation of a 40mm diameter projectile filled with a cast cure explosive simulant.

3 GUN LAUNCH SETBACK IGNITIONS

There exists significant literature and testing of high explosives in laboratory setback actuators that are meant to reproduce gun launch conditions [15], [16]. However, typical loadings to cause ignitions are typically 2X to 10X theoretical gun launch loadings. Defects must be introduced to laboratory explosive samples in order to produce ignitions. These defects often have little or no resemblance to actual artillery projectile defects, so there is no direct evidence that laboratory actuator test data correlates to premature ignitions in actual production ammunition. For the cast cure formulations and softer binder pressed formulations tested to date, there is strong evidence that ignitions are caused by adiabatic air heating of small crystals introduced into the defect volume by the dynamic event, or through the ignition of exposed crystals on the defect surfaces. For stiffer binder pressed formulations and for melt pour explosives, there is strong evidence that shearing also plays a role in the sample ignitions [17]. Sandusky et al [17] conclude that:

"Reactions in soft pressed and most cast-cure PBXs were delayed from the binder around filler crystals except for those ejected from the surface. Soft pressed PBXs, even with half the amount of binder as cast-cure PBXs, were no more sensitive, probably because of better binder adhesion to the crystals. When ignition occurred there was burning because of the time required to spread from one crystal to another. With catastrophic cavity collapse in the harder pressed and melt-cast explosives, there were many crystals exposed by fracturing, resulting in deflagrations and explosions."

The Excalibur program reportedly decided not to use the cast cure explosive, PBXW-114, as it "seriously failed a setback safety test and was discarded from further consideration" [18]. The pressed explosive, PBXN-9, was therefore chosen over PBXW-114 and PBXN-112, which leads one to believe that it performed significantly better in the setback safety test.

A limited amount of actual gun firing test results with base gaps and voids are published by Sandusky [19] along with laboratory actuator test data for the same explosives. Sandusky concluded that the cast cure explosive, PBXN-106, was more sensitive than the pressed explosive, PBXN-9, to cylindrical cavities in the piston of the setback simulator and to base gaps in faulted explosive fills subjected to gun firing. He went on further to conclude that cast cure compositions had a higher sensitivity to base gaps than the pressed compositions. We have not been able to locate any open literature for melt pour explosive actual gun firing test results with base gaps and voids.

CONCLUSIONS

Cast cure explosive projectile fillings are typically intended to not adhere or only partially adhere to the projectile interior. This intentional non-adherence is intended to avoid inconsistent body adhesion and explosive tearing or cracking due to the relatively high thermal expansions of cast cure explosives. There is some literature on the use of plastic liners with cast cure explosives to achieve a non-adhering fill. This method may have the drawback that the liners may move during thermal cycling to expose the high explosive directly to the projectile inside casing. For melt cast fillings, only one investigative report using grease on Comp-B fillings to achieve a non-adhering fill was found. It showed a significant average increase in base explosive stress when compared to a fill not using a greased projectile interior surface. It is clear that high explosives can move during gun launch setback, as observed with a very limited amount of data. It is also believed that significant bouncing of high explosives can occur, at least for cast cure formulations, upon exit from the gun barrel. This bouncing of the explosive billet could potentially be detrimental for projectile trajectory accuracy.

As for safety concerns during gun launch, it appears that explosive movement would cause void collapse and adiabatic heating if any such voids or cavities exist. This effect is much larger nearer the projectile base regions. Based on very limited experimentation and modelling, it appears that increased wall friction and increased explosive stiffness makes considerable reductions to the strain and stress profiles. Therefore, any potential void collapse and associated adiabatic heating affects are likely to be significantly larger for non-adhered fillings compared to adhered fillings and for softer explosives compared to more rigid explosives.

It is clear that significantly more data is required in order to understand the explosive response to gun launch setback. The subject matter has not been heavily researched and there exists many gaps in understanding and related standardization.

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