PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891
10, 1 (35), 2019, 9-24

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Laboratory Setback Activators and Explosive Suitability for Gun Launch

Ernest BAKER

Munitions Safety Information Analysis Center, NATO HQ,
Rue Léopold III, B-1110 Brussels, Belgium
Author's e-mail address and ORCID:
e.baker@msiac.nato.int; https://orcid.org/0000-0001-5400-0469

Received by the editorial staff on 7 August 2018
The reviewed and verified version was received on 6 March 2019

DOI 10.5604/01.3001.0013.0793

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. Laboratory setback activator testing has been used as an assessment tool for investigating the suitability of explosives for gun launch. Unfortunately, laboratory setback activator testing is not standardized and large variations exist in activator design, function, and results between different laboratories. However, it is the only currently available tool for assessing an explosives safety and suitability to launch-induced setback forces. In laboratory setback activator tests, ignitions are observed at setback loadings that are much higher than produced in actual gun launched projectiles. This may be related to the defects in actual projectiles, which appear to be very different than the laboratory tests.

Keywords: explosives, setback, gun, artillery

This work has been compiled from the paper presented during the 12th International Armament Conference on *Scientific Aspects of Armament and Safety Technology*, Jachranka, Poland, September 17-20, 2018.

1. INTRODUCTION

A major safety concern for energetic materials present in gun launched munitions is the exposure to severe set-back forces which develop as the shell is accelerated. Table 1 presents a listing of typical projectile accelerations associated with different gun launches [1, 2]. Under these conditions, energetic materials have been observed to occasionally react prematurely. The term in-bore premature is used for the explosion of a munition whilst it is still travelling down the barrel.

Table 1. Projectile maximum accelerations and pressures

Gun system	Max projectile acceleration range (kGs)	Max chamber pressure range (MPa)
Artillery	4-30	70-500
Mortars	1-13	20-140
Tank guns	25-120	200-830
Medium caliber	50-200	140-1400

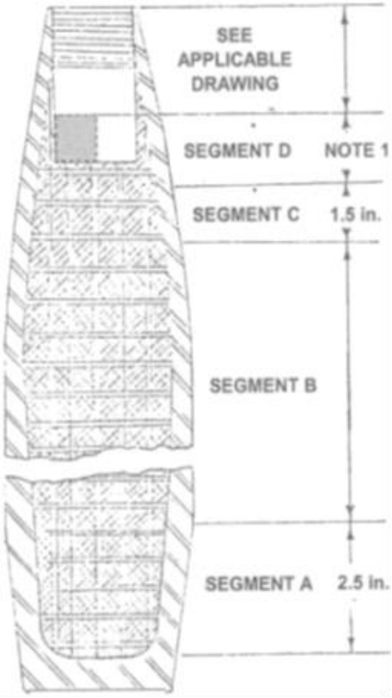
This is not a new phenomenon and a number of nations have developed laboratory setback activator testing that can be used to understand ignition mechanisms for energetic material when exposed to an acceleration environment. However, these capabilities appear to be used mainly for research purposes and there is little evidence that they are mandated as part of a nation’s formal qualification assessment process. None are included in NATO Standards on qualification of energetic materials.

2. MUNITION SAFETY ASSESSMENT PROCESS

The development of explosives requires a rigorous regimen of tests, both small-scale, and large-scale, before explosives can be judged safe and suitable for service use. NATO nations have agreed that all energetic materials be qualified in accordance with NATO STANAG 4170, with guidance provided in the associated AOP-7. Final or Type qualification is the process by which the safety and suitably of energetic material for its intended application and role are assessed. A number of STANAGs have been developed to cover the specific requirements for artillery as a part of the type qualification process, which includes STANAGs, 4667, 4493, 4224, and 4517.

However, the NATO Standards provide no guidance on how to set rejection criteria for defects. This is stated to be a role for the developing nation and the design authority. Projectile Safety criteria (STANAG 4224 Annex C) are that there should be no premature explosion or detonation in-bore or flight and further that there shall be no significant voids, crack etc.

There is no guidance on the types of defect that may be present in the shell prior to firing. As a result, individual nations have made their own decisions on worst case allowable defects. For example, MIL-DTL-60377C, sets the allowable defect criteria for the M107 155 mm projectiles using radiographic examination based on four segments as defined in Fig. 1. The bases for these maximum allowable defects' sizes are largely unknown, and they are believed to be based primarily on historical precedence. Whatever methodology was used for their definitions appears to be lost in antiquity.



Cast Defects		Segments (See figure 1)			
		A	B	C	D
Sum of projected areas of shrink porosity	(in^2)	5/16	5/8	5/8	-
Sum of projected areas of cavities, excluding pipes, cracks, annular rings and porosity.	(in^2)	*1/64	1/4	1/2	1/2
Projected length of any cavity excluding pipes, cracks, annular rings and porosity.	(in)	1/8	1/2	1/2	3/4
Piping cavities maximum projected area.	(in^2)	0	1/4	1/2	-
Piping cavities maximum projected width.	(in)	0	1/4	1/4	-
Cracks, maximum projected width.	(in)	1/32	1/32	1/16	-
Annular rings, maximum projected width.	(in)	0	0	1/4	-

Notes:

* If the length of the largest cavity is 1/16 inch or less, the maximum total projected area may be 1/20 in^2.

Piping cavitation is defined as cavitation located on or near the vertical center line of the projectile with the longitudinal axis three times or greater than the width.

An Annular ring is defined as cavitation that takes the form of a ring or portion thereof around the periphery of the cast.

Fig. 1. M107 inspection zones and maximum acceptable defect dimensions as defined by MIL-DTL-60377C

3. GUN LAUNCH CONDITIONS

When a projectile is accelerated by a gun launch, the actual pressure history in the high explosive filling is considerably less than the pressure history delivered by the propellant gases to the projectile. This is because the explosive is loaded by the acceleration of the projectile, and not by the propellant gases. During the acceleration of the projectile, the produced internal force is commonly called setback, as the acceleration produces a force in the negative direction of the projectile motion on the internal projectile components during the forward acceleration.

As a result, the explosive will see an increased pressure from the forward explosive surface to the explosive supported base surface, which theoretically sees the highest pressure. The pressure at the supported base surface of the explosive is called the explosive base pressure. Often literature will simply state "explosive pressure", when referring to the explosive base pressure. It is relatively difficult to measure the explosive base pressure and almost no measurements of the explosive base pressure during gun launch have actually been done. As a result, almost all studies of gun launch setback ignition rely on calculated explosive base pressures, which are commonly also called "theoretical" explosive base pressures. Rotational acceleration and associated body forces are also generated for rifled gun launch configurations.

3.1. Theoretical explosive base pressures

The theoretical explosive pressure is generated by the acceleration of the projectile, and it is calculated in the same manner as the pressure at any depth of a fluid. The theoretical pressure is simply, $P = \rho G h$ where ρ is the explosive density, G is the acceleration, and h is the explosive column height. For the explosive base pressure, h is the full length of the explosive. So, the explosive pressure is zero at the forward explosive surface and it increases proportionally with depth to a maximum at the explosive supported base surface. For 155 mm artillery projectiles, typical theoretical maximum explosive base pressure is ~100 MPa, pressurization rate is 5 to 50 MPa/ms and durations on the order of 10 ms. Figure 2 presents the calculated theoretical explosive base pressure histories for a 127 mm and 155 mm projectiles based on projectile base pressure histories.

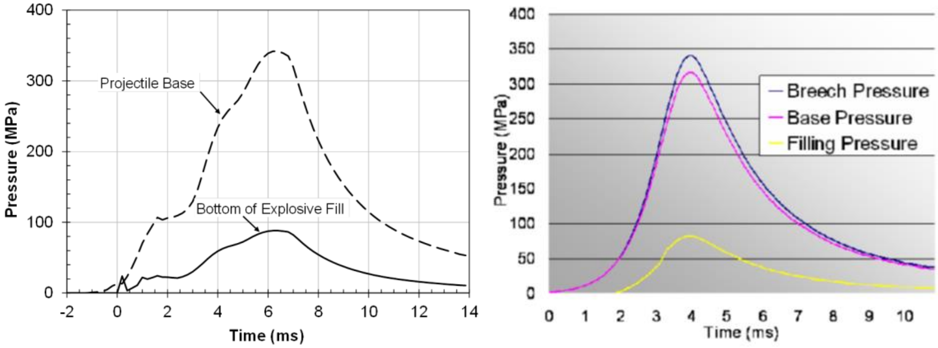


Fig. 2. Calculated maximum explosive base pressure histories for 127 mm projectile [3] (left) and 155 mm projectile [4] (right)

For 120 mm mortars, the typical theoretical maximum explosive base pressure is ~50 MPa, pressurization rate is ~18 MPa/ms, and the durations on the order of 10 ms.

In general, the maximum explosive base pressures and rates of explosive pressurization of mortars are well below those of artillery projectiles. This provides some basis for much lower likelihood of ignitions for mortars as compared to 155 mm projectiles, as it is believed that these parameters are strongly associated with explosive setback ignitions. Figure 3 presents calculated theoretical explosive base pressure history for a 120 mm M62P3 mortar [5] based on projectile base pressure history [6].

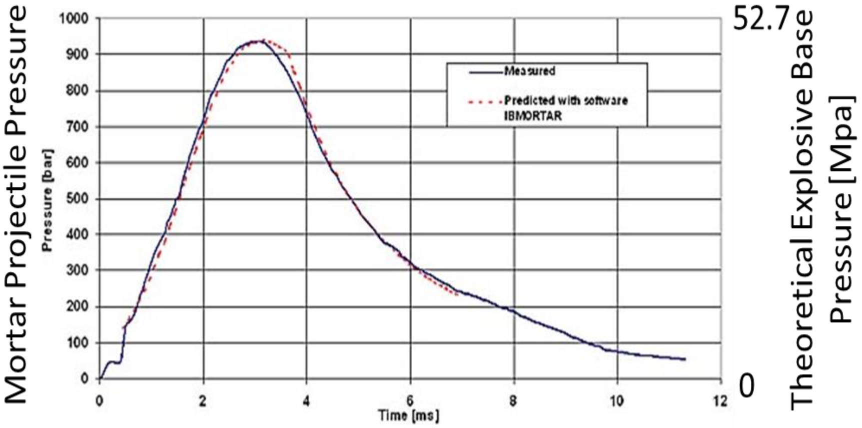


Fig. 3. Calculated maximum explosive base pressure history for 120 mm mortar

3.2. Actual explosive base pressures

Actual explosive base pressure history measurements were made by ARDEC personnel of the explosive pressure inside projectiles during launch [7]. Good fill castings had between 14% and 20% (15.4% average) of the theoretical base pressure, whereas lubricated case good castings had between 9% and 32% (21.8% average) of the theoretical base pressure. A conclusion from these tests was that large variations in stress distribution occur from shot to shot without any obvious cause. This ranges over a factor of three. No parameter external to the projectile would indicate this variation. Nominal setback explosive base pressure appears to be only a fraction of the theoretical explosive base pressure.

3.3. Projectile acceleration perturbations

Projectile acceleration perturbations can be caused by projectile balloting, erratic propellant burning, and associated pressure waves during projectile launch. The yawing or wobbling motion of a projectile within a gun tube is an important consideration in internal ballistics and is known as balloting.

This motion is a function of a number of small, difficult-to-measure parameters such as manufacturing tolerances, lack of concentricity of the engraving of the obturator, projectile and tube deformation, obturation of the propellant gases, and obturator wear [8]. Unstable or erratic burning of the propelling charge may be an inherent characteristic of the charge caused by exceeding or failing to meet some critical value of a design parameter, or due to the failure of some component in the ignition train giving rise to an undesirable ignition mode [9, 10]. The resulting projectile acceleration perturbations can potentially cause malfunctions to occur which include poor projectile launch, damage to the fuze mechanism, and perhaps even explosive fill ignition. There is some published information on projectile balloting, indicating that the resulting acceleration perturbations in the radial direction are commonly up to 5% of the maximum axial accelerations [11]. Actual axial acceleration perturbation levels produced by erratic burning or other pressure wave sources are commonly up to 10% of the maximum axial accelerations [11]. Figure 4 presents a 155 mm projectile acceleration measurement [11].

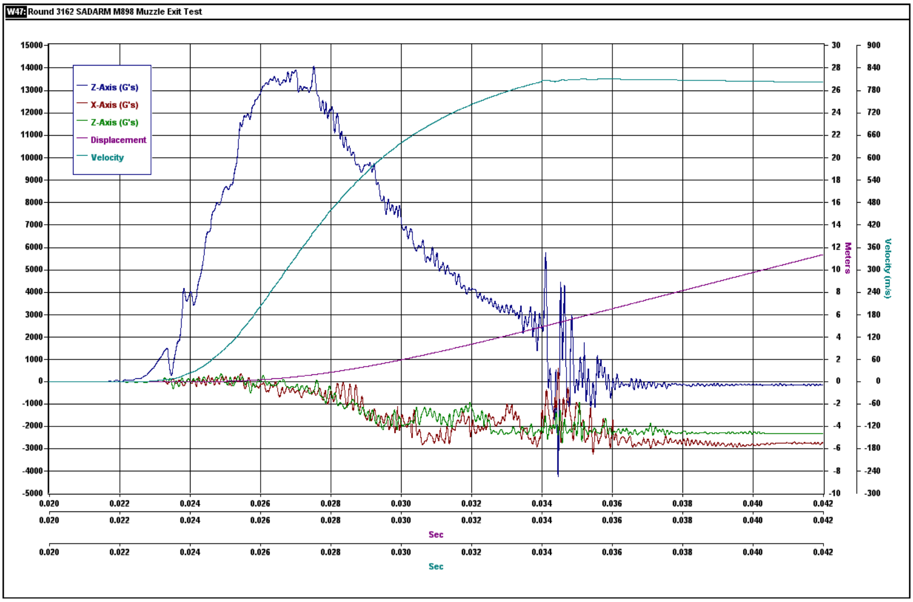


Fig. 4. Acceleration, velocity and distance measurements during launch of a 155 mm projectile [11]

There is little information on the occurrence of larger perturbations and how often this occurs. The investigation and effect of these larger potential acceleration perturbations on projectile explosive fills has received surprising little investigation.

4. DEFECTS

Defects are important because they act as sites for stress strain concentrations which can lead to localized heating, hot spot formation, and potentially ignition. A review of literature, accident results and attributed potential causes in the MSIAC database indicates that gun launch candidate high explosives are unlikely to react without voids or interface defects to allow shear or adiabatic heating to drive the formation of hot spots [12-15]. To give an idea of the sort of defects that can be observed in artillery shell, a listing is given. It should be noted that where multiple defects occur, they may potentially act together.

Defects observed in artillery shells include voids, cracks, porosity, cavities, geometric discontinuities, and foreign material. Voids of 0.1-10 mm in diameter are common in cast cure and melt pour explosive fillings. Cracks are often observed in explosive fillings and can be caused by a number of factors. Shrinkage during processing, ageing or environmental stresses, rough handling etc. Figure 3 presents a photograph of a cross sectioned 155 mm Comp-B cast projectile with observable cracks in the explosive fill. Any explosive charges can exhibit regions of porosity due to poor mixing or via chemical reaction or incompatibility. Formulations which do not meet the specification may also have increased porosities due to insufficient binder to filler ration. Figure 5 presents a photograph of a cross sectioned 155 mm Comp-B cast projectile with observable porosity in the explosive fill. Larger than voids, cavities are a consequence of poor fill quality.

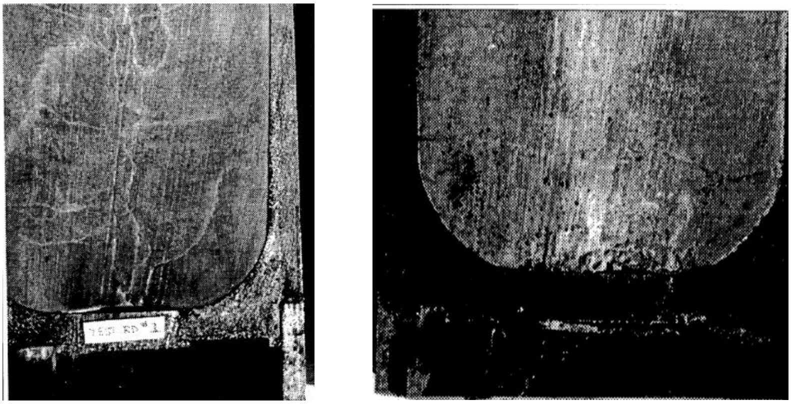


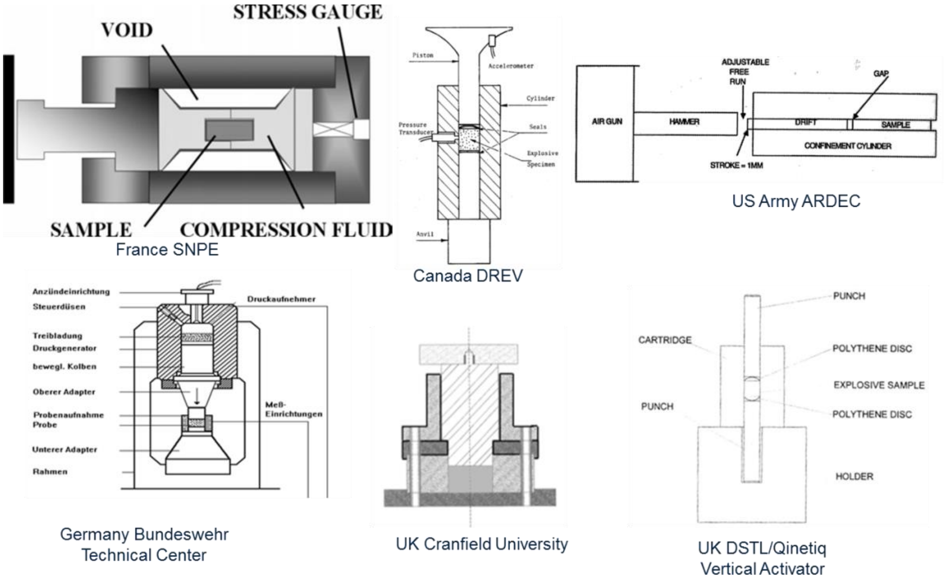
Fig. 5. Photographs cross sectioned 155 mm Comp-B cast projectiles with observable cracks (left) and porosity (right) in the explosive fill [16]

Cavities can take the form of long axially oriented voids, known as piping that form in melt cast filled shells, as a consequence of air entrainment during explosive pouring.

Another form of the observed cavity is a gap at the explosive and projectile body interface. This type of a cavity often forms at the projectile base, and is commonly referred to as an explosive base gap. Stepped cases or other complex geometries can produce high local stresses during gun launch. The presence of foreign material such as paint flecks, grit, screws, or tools is occasionally observed.

5. EXISTING LABORATORY SETBACK TESTS

A variety of different laboratory setback activators have been developed with the objective of subjecting explosive samples to setback forces intended to replicate gun launch conditions. There have been two main approaches: 1) the use of gun propellant to drive a piston into the sample, or 2) developing loading conditions by modifying a pressure pulse derived from an alternative mechanical means such as a drop weight or gas gun. The key launch parameters that are attempted to be replicated are the peak pressure P, pressurization rate dP/dt, and pressure duration t_P. To varying degrees, these parameters are tailored to match and over stress specific launch conditions for different gun systems and propellants. None of the laboratory setback activators include rotational acceleration. Figure 6 presents the diagrams of some laboratory setback activators that were investigated. Two of the activators are highlighted, as they appear to produce loadings more similar to actual gun launch.



France SNPE

Canada DREV

US Army ARDEC

Germany Bundeswehr Technical Center

UK Cranfield University

UK DSTL/Qinetiq Vertical Activator

Fig. 6. Setback laboratory activators

The US Navy Naval Surface Warfare Center Indian Head Division (NSWC-IHD) setback tester [17] consists of a small propellant bed that drives a hardened steel piston into an explosive sample. The apparatus has a 25.4-mm diameter by 21.2-mm long sample in a thick-wall steel tube with a stationary anvil on one end and a piston on the other. Figure 7 presents a diagram of the apparatus and a plot of driver pressure histories. Driving pressure on the piston and sample pressure on the anvil are both measured. The 1X curve attempts to replicate the 127 mm gun theoretical explosive base pressure history and does so very well. Typically, 12.7-mm diameter cavities are introduced to the sample with depths being varied from about 3.2 to 6.3 mm. These cavities are much larger than any acceptable by production standards. Normally, loading rates of 2X or greater are required to observe ignitions.

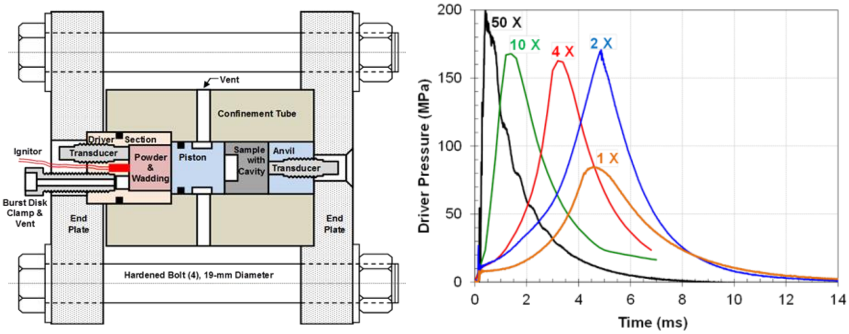


Fig. 7. Diagram of the NSWC-IHD setback tester (left) and typical driver pressure histories that can be applied to the explosive sample (right)

The BAE Global Combat Systems (BAE-GCS) Gun Launch Simulator (GLS) [4] is a laboratory setback activator that consists of a breech section, bursting disk and six identical symmetrically mounted test rigs. Each test rig consists of a piston assembly that loads an explosive test sample. The pistons are driven by a central propellant charge which is ignited in the breech section. The burst disk is designed to allow the pressure relief at a preselected peak pressure. The breech pressure history is recorded, but no pressure measurements are made of the test samples. The GLS is designed to provide the explosive test samples with pressure loading similar to the axial pressure loading during launch. Figure 8 presents a schematic of the BAE-GCS GLS and pressure time history plots from actual 155 mm gun system firings and the GLS. The presented GLS peak pressure, pressurization rate and durations are very different.

The GLS pressure history with the closest peak pressure to the presented 105 mm result has about 1/4 of its rate and about 3 times of its duration. The GLS pressure history with the closest peak pressure to the presented 155 mm result has about twice its rate and about 1.5 times of its duration.

To our knowledge, the GLS results are the only laboratory setback activator test results that have been reduced using statistical analysis [18]. The results have been presented for a single defect type (a small spherical air filled defect) as a probability of ignition for a given peak pressure, as well as probability of ignition versus spherical void size and peak pressure.

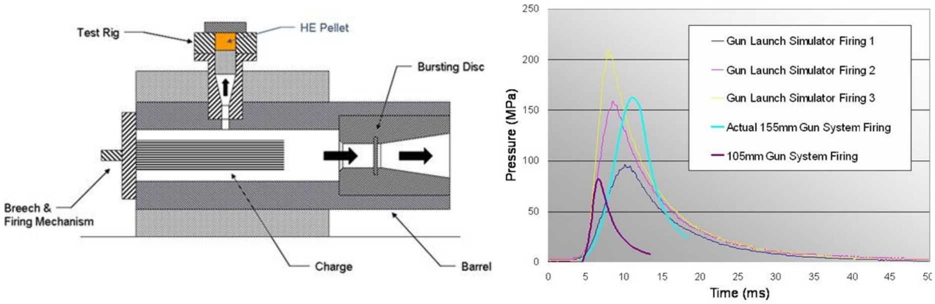


Fig. 8. Schematic of the BAE-GCS GLS (left) and pressure loading plots (right)

6. LABORATORY SETBACK ACTIVATOR IGNITIONS

There are two experimental facts that are firmly established. First, Bridgman [19] showed that explosive could be isothermally compressed to 5 GPa without ignition. Thus, slow compression to extremely high pressure and small pressurization rate d*P*/d*t* will not cause ignition of explosive. Second, Liddiard [20] showed that shock compression (<0.1 ms rise time) of pressed Comp-B would cause ignition at the 0.40 GPa pressure level (d*P*/d*t* > 4 GPa/ms). This establishes that the pressures and pressurization rates, associated with setback accelerations, are not capable of igniting pristine explosive fills. Other mechanisms associated with explosive fill defects are required.

The experimental evidence to date indicates that the ignitability and reaction violence of explosive samples in laboratory setback tests is governed by a number of factors. The processes may be the same as the processes leading to actual projectile premature ignitions, but there is little evidence linking the two. Specifically, the observed factors that affect laboratory setback activator test ignitions are: introduced defect, sample total run, peak pressure, pressurization rate, initial air gap thickness, air leakage, initial air pressure, piston thermal conductivity, and state of the explosive surface. Generally speaking, increased total run, peak pressure, pressurization rate, initial air gap thickness, and initial air pressure increase ignitability and reaction violence, whereas air leakage and high piston thermal conductivity tend to reduce ignitability and reaction violence [3, 21]. For actual laboratory setback activator testing, either air filled gaps or air filled cavities are almost the only configurations used. For these configurations, three ignition sources appear to dominate: explosive extrusion and pinching, adiabatic air heating, and shear.

6.1. Explosive extrusion and pinching

This type of ignition is very common in earlier setback activator tests and is sometimes observed in later testing as well. It consists of the unintentional ignition associated with sample holding geometry and materials. Due to fit configuration tolerance typically between a loading piston and a cylinder, explosive can be extruded into the associated small gaps during loading and then subsequently pinched to cause ignition [22, 23]. For pristine samples without introduced defects or gaps, it is believed that these are the dominant observed ignition phenomena. Various approaches have been used in order to eliminate or minimize the occurrences. The approaches include higher precision hardware with tighter tolerances [6, 22,] or sealing the cylindrical surface by using plastic materials on the piston surface [24, 25]

6.2. Adiabatic air heating

This ignition mechanism is due to the air compression in the introduced gaps or cavities. For smaller gaps and voids, it requires small (less than 50 μm) energetic particles to be present [26]. This appears dominant for cast cure explosives, where energetic particles are ejected into the sample cavity as a result of the initial impact. Whether or not a collapsing defect ignites the sample depends on its size and rate at which it is collapsed, the ease of deformation, the condition of the cavity surface, and the filler particle size. The ability of a cavity surface to entrap or bind energetic crystals during its collapse, small crystal size, and a non-cracking binder all contribute to insensitiveness. The reaction of coarse energetic crystals, ejected from the surface during the collapse of an air-filled cavity along with adiabatic heating from entrapped air, appears to be the mechanism for deformable explosives [3]. This has been in part verified through vacuum experiments. The ignition threshold increases with evacuation of air from the cavity, which reduces heating but also back pressure which is required to achieve high burning rates. Additionally, coating of the cavity surfaces with binder materials has been shown to inhibit ignition. Internal cavities have been shown to ignite easier and produce much more violent responses than surface cavities of the same volume [27]. Possible reasons for this observation are reduced air leakage, increased pressurization durations, and lack of heat transfer mechanisms.

6.3. Shear

This mechanism is associated with the mechanical deformation work causing heating, as well as the associated material damage and creation of fine debris. Strong hard explosives, such as most melt pour formulations, are heated by shear deformation.

Fracture and mechanical failure of the sample creates debris, as well as additional surface area for increasing the reaction violence. For melt pour explosives, this mechanism appears to be coupled with adiabatic heating to cause ignition [3].

6.4. Friction

There is little information in the literature and it appears that only limited frictional laboratory setback activator testing has been conducted. Taylor [12] demonstrated frictional ignitions in laboratory setback activator testing when sufficient large grit was present. However, no ignition was observed using the grit in standard primer paints. Frictional ignitions were produced only when high-melting-point grit was present at the sliding surface [12]. Bélanger [27] noted that the friction reaction depends upon (1) the explosive type and (2) the amount of friction which varies with surface roughness and the presence of hard inclusions. Such friction is found negligible on smooth surfaces for all explosives tested, except when hard inclusions are present. With hard inclusions, Comp A-3, CX-84A, and Comp-B are highly sensitized, but TNT is not.

6.5. Accelerating affects

Adiabatic compression model calculations predict the highest possible values of the explosive-air interface temperature. However, such calculations indicate that sufficiently high temperatures can only be produced at compression ratios higher than many at which ignition is observed [21]. In addition, at finite pressurization rates even lower temperatures are predicted and in no case can the experimentally observed ignitions be accounted for. The situation is further aggravated by the fact that air leakage in laboratory setback activators can render the environment even less hostile. Among the real world effects that may come into play there are: enhanced energy transport due to turbulent air flow, rapid pressurization due to increased air mass as a result of convergent flow, convergent air flow near the end of defect closures, dieseling, alternate gas, large exposed surface crystals, multiple defects and precompression [12, 26].

7. IGNITION SENSITIVENESS VS. EXPLOSIVENESS

The susceptibility of explosives to premature ignition is often assessed by comparing their ignition thresholds in laboratory setback activator tests to those of Comp-B and TNT. However, the issue is complicated by the fact that the explosiveness of the burning response is also a factor.

Explosiveness has been defined as the reaction violence that is normally characterized by the degree of damage that occurs to the test fixture. It has been speculated that the infrequency of the reported premature with TNT may be due to its relatively slow burning response rather than a lower ignitability. This would lead to the premature explosion occurring down range rather than in the gun tube for which there is anecdotal evidence. If this is the case, the sensitiveness assessment is more difficult as both ignitability and explosiveness must be considered. There is a noted trend in results to exhibit some tendency toward an increase in reaction violence with decreasing ignition sensitiveness [27].

There are significant discrepancies in the literature related to the ignitability and explosiveness of TNT compared to Comp-B. Taylor [12] conducted planar gap tests that show TNT is somewhat more ignitable than comp-B. Sandusky [3] noted that unlike TNT, the initial sealing of cavities made Comp-B much more ignitable. Sandusky [3] also noted that Comp-B exhibits one of the highest sensitiveness levels and responds violently. Starkenberg [26] states that the data for TNT provide no reason to believe that it is less sensitive to ignition than Comp-B. For friction ignition studies, Bélanger [27] found that Comp-B was highly sensitized by the addition of hard inclusion, whereas TNT was not. Meyers [28] had less consistency, but the explosive responses showed extensive burning for TNT, and explosions for Comp-B.

Comp A3 Type II was the least sensitive explosive tested by Starkenberg [26]. It exhibited a moderately high level of response violence. LX-14 exhibited a sensitiveness intermediate between those of Comp-B and Comp A-3 Type 11 and reacts very violently. PBXW-113, was by far the most sensitive. Late ignitions were observed in LX-14 that occurred on the second strike of the driving. Sandusky [3] noted that ignition of cast-cure samples was always delayed with respect to cavity collapse, often several milliseconds after maximum pressure. He observed delays as long as 24 ms when the driver pressure was fully vented. He noted extensive burning for TNT, explosions for Comp-B, mild reactions for cast-cure PBXs, and little decomposition for TATB-based explosives.

8. FORMULATION FOR REDUCED PREMATURES

The path toward more premature-resistant explosives is not clear. Velicky has suggested that an explosive's mechanical strength should be increased to reduce the probability of collapse of casting flaws [29].

However, it seems likely that this will have little effect on cavities large enough to present a problem since the launch acceleration environment appears to produce stresses well above those required to collapse larger cavities. Because of the importance of the gas pressurization rate, increasing mechanical strength might even have a negative effect.

Delaying cavity collapse, until higher stress levels have been reached, could increase the pressurization rate.

Cavities in a softened material, meanwhile, might collapse slowly during the very early portion of launch, thus resisting ignition. On the other hand, they might better trap hot air, thus promoting ignition. In the latter case, the low ignited surface area can be expected to yield low initial reaction rates which may sufficiently delay any violent response. Approaches, which reduce the incidence of flaws in explosive fills, reduce the ignitability of the explosive or retard the burning response of the explosive are, of course, desirable. Because of the complexity of the issues involved, characterization of explosives through testing is the only available approach to discovering premature resistant formulations [28].

9. CONCLUSIONS AND DISCUSSION

Observations indicate that actual gun launch setback ignitions cannot be clearly correlated with the results of ignition sensitiveness results from laboratory setback activator tests. The laboratory setback activator tests normally indicate ignitions at much higher setback than they are believed to be produced in actual gun launched projectiles. Additionally, the defects in actual projectiles appear to be very different than the laboratory tests. Both ignitability and explosiveness have been considered in assessing an explosive's resistance to launch-induced explosion. For this reason, some explosives have not been initially rejected on the basis of exhibiting high ignition sensitiveness in the activators unless the reaction violence levels are also high. In the controversy between brittle and soft explosives, ignition sensitiveness results are biased towards the strong brittle materials, often observed for melt pour explosives. In spite of all these issues, the setback activator, remains the currently only available tool for assessing an explosives resistance to launch-induced premature explosions. It is recommended that the munitions community should work toward developing an understanding of the ignition phenomena and laboratory setback activator technology as part of a process development for defining physically based acceptable defect criteria.

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