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Explosive Characterization for Improved Impact Response

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(U) The United States Army is currently working to develop less sensitive explosive and Particle Impact Mitigation Sleeve (PIMS) upgrades to warhead configurations in order to mitigate Fragment Impact (FI) threat, in accordance with MIL-STD-2105D, while maintaining warhead performance. Shock sensitivity as measured by Large Scale Gap Test (LSGT) is often used as a means to select explosives for improved munition FI response. This paper discusses recent LSGT and FI testing, utilizing different particle size distribution of LX-14 and PBXN-9 in various anti-armor warhead (AAW) configurations, which suggests that LSGT alone is not an adequate tool to evaluate/depict munition FI response. Since LSGT testing may not represent the shock dynamics associated with the shock initiation from FI or may not have the fidelity to discriminate a difference, an alternate small scale test is being investigated.

INTRODUCTION

Anti-Armor Warheads (AAWs) include warheads with shaped charge or explosively formed penetrator liners that commonly use high energy, metal pushing, energetic formulations. AAWs generally react violently to IM threats, owing to the high performance, sensitive explosives commonly utilized. This paper summarizes recent efforts, both computational and experimental, to mitigate munition response to Fragment Impact (FI). FI tests represent operational and logistical threats that a munition may be subjected to. When a fragment traveling at high velocities impacts a munition, the explosive within can react violently, resulting in serious loss of life and significant impact to operational capability. Historically, a lot of attention has been devoted to improving munitions response to various IM threats. Methods for reducing AAW sensitivity to impact threats include Particle Impact Mitigation Sleeves (PIMS) and careful selection of energetic compositions among numerous others. PIMS work to reduce system response by acting as a physical barrier and reducing shock loading on the High Explosive (HE) fill [1]. HE driven sensitivity reduction is traditionally achieved by using less energetic formulations with lower metal-driving performance than their high energy analogues. Recent formulations have shown some promise to reduce sensitivity while maintaining performance via a more optimized energetic particle size distribution [2]. While energetic materials are the primary aspect that drive a munition's reaction violence, an integration of multiple technologies is required to reduce the system response to acceptable levels while still achieving required operational performance.

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IMPACT SENSITIVITY TESTING METHODS

Explosive sensitivity is the reaction of a formulation, however violently, to a consistent and quantifiable stimulus in the form of pressure, heat, or shock. The ability to characterize and compare sensitivity between systems and their energetic components is critical in ensuring the safety of personnel and resources during materiel transportation, storage, and general handling. To provide accurate assessments of IM performance, further studies are needed to verify and improve upon existing test methodologies.

Sensitivity reductions and comparisons, particularly to rapid and severe loading, are frequently demonstrated through explosive gap tests at the sub-scale level and FI tests at the munition level. Gap tests, such as Large Scale Gap Test (LSGT), measure sensitivity by the amount of some spacer "gap" material required to prevent a fixed size and composition (donor) charge from initiating a sample of the development formulation (receptor) charge [3]. In *Baker et al.*, 2018, a recent study presented engineering correlations relating LSGT results to explosive characteristics such as critical diameter, Held's criteria, and percent Theoretical Maximum Density (%TMD) can be used to help guide development of IM threat mitigation schemes [4]. HE sensitivity can also be characterized by conducting FI tests of a given test item configuration [5]. Often, results from both procedures are used in conjunction to isolate relative contributions of warhead geometry, material properties, and HE chemistry on overall system response to impact stimulus.

In terms of how sensitivity is gauged, violence of reaction is binned into one of five qualitative groups. Type V reactions are burning reactions. Type IV and III reactions represent a deflagration and explosion, respectively. Type II and I reactions, the most severe responses, represent a partial detonation and detonation, respectively. While these general categories are used qualitatively to compare the overall responsiveness of various energetic systems, related data in the form of blast overpressures, fragment spread, fragment recovery, witness plate damage, etc. may also be used to further delineate differences in response.

TESTING LIMITATIONS

Gap and fragment impact tests each have unique phenomena that make system level response characterization difficult. In gap tests, shock transmitted in short pulse widths and planar profiles is non-representative of the longer duration, curved shocks expected during actual impact events. In the fragment impact tests, gun issues causing velocity variability and aerodynamic instability of the test fragment leads to both non-replicability and inaccuracy in test conditions [6]. Often, because of the variable nature of test results, judgements are made on probabilistic bases using empirical values such as the Hugh-James criteria [7].

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ORGANIZATION

The present paper is split into three sub-studies. First, three series of fragment impact tests and one baseline case allow observation of the effect of AAW geometry on the suitability of a standard energetic material, PBXN-9 (92% HMX, 8% DOA/HYTEMP). A fourth accompanying FI series yields insights into an alternative HE, LX-14 composed of HMX and an estane binder. 80% of the HMX used in LX-14 was composed of Fluid Energetic Milled (FEM) HMX and the remainder was a standard distribution of particle sizes commonly used in that formulation. Standard and FEM variants of PBXN-9 and LX-14 were then compared in LSGT trials to determine whether sub-scale experimental results matched AAW FI data. Lastly, standard and FEM variants of PBXN-9 and FEM LX-14 were evaluated in the relatively new Small Scale Fragment Attack (SSFA) test set up to explore whether or not a correlation might exist between it, LSGT, and AAW FI test.

PROCEDURE

FI Test

Four series of fragment impact tests were conducted to analyze the effect of warhead geometry and HE on warhead sensitivity. The aim-point for these tests is through the largest cross-sectional area of explosive. Series 1 compared an arbitrary AAW against a second variant, labeled warhead A and warhead B respectively. Warhead A has a characteristic length of 115 mm and the case is made of a hardened steel labeled as steel 1. Warhead B has a characteristic length of 99 mm and its case is made of a softer, more malleable steel labeled as steel 2. Each warhead also has different materials for the liner section, labeled liner 1 and liner 2 for warhead A and B, respectively. It is noted that there are additional differences between the two warheads, namely the liner geometry, positioning of the wave-shaper and liner, and the case thickness. The series 1 tests for warhead A and B listed in Table I involve an isolated warhead with sections of packaging added in the shot-line. It is also important to note that while both warheads A and B employed PBXN-9 as their energetic material, the source of supply for the different lots of PBXN-9 were different.

Previously, the program office conducted baseline FI testing against warhead A in the logistical configuration, which resulted in a detonation (Type I) response. The packaging is composed of a High Density Polyethylene (HDPE) tube that protects against environmental intrusion.

Series 2 reduced the geometrical complexity of warhead A down to a right circular cylinder fabricated with two different steels, steels 1 and 2 (Figure 1). The purpose of this test series was to isolate any effect that case material might have on impact sensitivity.

Series 3 re-introduces the configuration of warhead A with an added variation in shaped charge liner material. The liner cavity is either left empty or filled with one of two possible liner materials, the aforementioned liners 1 and 2. Additionally, a third warhead C was tested with standard LX-14.

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Figure 1. FI surrogate warhead example.

TABLE 1 Summary of FI series and test cases

Series	Condition	Explosive	# of Trials
Baseline	Warhead A – Logistical	PBXN-9	1
1	Warhead A	PBXN-9	1
1	Warhead B	PBXN-9	2
2	Surrogate Warhead A – steel 1	PBXN-9	3
2	Surrogate Warhead A - steel 2	PBXN-9	3
3	Warhead A - No Liner	PBXN-9	2
3	Warhead A - Liner 1	PBXN-9	3
3	Warhead A - Liner 2	PBXN-9	2
4	Surrogate Warhead A – steel 1	80% FEM LX-14	1
3	Warhead C	Std LX-14	1
4	Warhead C	80% FEM LX-14	1

Series 4 utilized the same geometry as the simplified warhead A in series 2 and the warhead C geometry from series 3, but substituted LX-14 comprised of 80% FEM HMX in lieu of PBXN-9 and standard LX-14, respectively. The single set of variables used in series 4 was compared to the PBXN-9 tested in series 2 and standard LX-14 tested in series 3, with energetic material as a control variable.

Nominal impact speed of the fragment was the mean velocity of 8300 ft/s (2530 m/s) for all scenarios. A summary of the above series with their test matrices is shown in Table 1.

LSGT Tests

LSGT tests are conducted by loading prefabricated explosive pellets into a vertical steel tube on top of which acrylic gap cards act as buffers against a well characterized pressure. Pressure is delivered via detonation of a pentolite donor charge. Shock sensitivity is measured by the gap over which detonation is determined to occur with 50% probability. PBXN-9 and LX-14, both standard and FEM variants, were subjected

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to LSGT to evaluate explosive sensitivity and to gather general material properties. The PBXN-9 pellet specimens were fabricated from each of the lots used in series 1 through 3 of the FI tests and tested via the LSGT fixtures. LX-14 pellet specimens were fabricated from two lots of 80% FEM HMX.

TABLE 2. Test matrix and results for LSGT tests

HE	FI Series	HE Pressed Density	Card Gap
		[g/cc]	
Standard PBXN-9	1	1.73	175
Standard PBXN-9	2	1.73	169
Standard PBXN-9	3	1.73	179
Standard LX-14	--	--	236
LX-14 with 80% FEM HMX	4	1.81	166.5
LX-14 with 80% FEM HMX	--	1.80	177

Previously, LSGT testing of LX-14 with standard HMX was also conducted [2]. These LSGT tests, along with corresponding results, are given in Table 2. Note that all LSGT testing, with the exception of standard LX-14, was conducted at Picatinny Arsenal.

SSFA Tests

An alternative to LSGT is explored in the form of Small Scale Fragment Attack (SSFA) test to address potential deficiencies in LSGT. The test setup is based on previous works which utilizes a reduced scale test apparatus [8, 9]. In general, a small, well characterized and consistent EFP is fired through a variable thickness cover plate before impacting a confined acceptor HE sample. Presently, the range of acceptor materials includes two lots of PBXN-9, one lot of standard LX-14, and one lot of 80% FEM LX-14. In general, cover plate thicknesses vary from 1/8 in. (3.18mm) to 1/2 in (12.7 mm). Overall response is anticipated to be more benign with increasing thickness of cover plate.

RESULTS

FI tests

Reaction types for the four aforementioned FI series as well as the baseline tests are summarized in Table 3. For most trials, reactions followed non-detonation regimes. Exceptions occur in baseline and series 1, warhead A loaded with PBXN-9 and series 4, 80% FEM HMX LX-14. Witness plates for these reactions are depicted in Figure 2.

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TABLE 3. Fragment Impact Results

Series	Test Condition	Explosive	Reaction Type
Baseline	Warhead A - Logistical	PBXN-9	I
1	Warhead A	PBXN-9	(I)
1	Warhead B	PBXN-9	(III)
1	Warhead B	PBXN-9	(III)
2	Surrogate Warhead A – steel 1	PBXN-9	(IV)
2	Surrogate Warhead A – steel 1	PBXN-9	(V)
2	Surrogate Warhead A – steel 1	PBXN-9	(V)
2	Surrogate Warhead A – steel 2	PBXN-9	(IV)
2	Surrogate Warhead A – steel 2	PBXN-9	(IV)
2	Surrogate Warhead A – steel 2	PBXN-9	(V)
3	Warhead A - No Liner	PBXN-9	(IV)
3	Warhead A - No Liner	PBXN-9	(IV)
3	Warhead A - Liner 1	PBXN-9	(IV)
3	Warhead A - Liner 1	PBXN-9	(V)
3	Warhead A - Liner 1	PBXN-9	(IV)
3	Warhead A - Liner 2	PBXN-9	(V)
3	Warhead A - Liner 2	PBXN-9	(IV)
3	Warhead C	Std LX-14	(I)
4	Surrogate Warhead A – steel 1	80% FEM LX-14	(I)
4	Warhead C	80% FEM LX-14	(I)

a. b. c. d.

Figure 2. FI witness plates for detonative trials (a) Baseline, (b) Series 1, Warhead A, (c) Series 3, Warhead C, (d) Series 4

LSGT Test

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Card gap values for the LSGT tests are presented in Table II. For PBXN-9, the maximum and minimum are found to vary no more than 3.5% from the mean of 175 cards. Standard LX-14 is notably more sensitive than PBXN-9 with a recorded gap value of 236. This value drops by 27% when considering the mean of the 80% FEM mix, 171.75, which is more comparable to LSGT values for PBXN-9.

SSFA Test

Violence of reaction for the aforementioned materials is shown in Table 4. The two lots of PBXN-9 are similar, with minor inter-lot variation at lower pressure initiation events (thicker cover plate). Between lots of LX-14, results indicate that the FEM variant of LX-14 is less sensitive than standard LX-14 variant. Compared to both LX-14 variants, PBXN-9 is consistently less sensitive and has an inversely proportional dependence on cover plate thickness with regards to reaction violence. In Figure 3, it also appears that LX-14 increases in sub-detonative reaction intensity with increasing plate thickness, as evidenced by the increased damage to the test apparatus. Further testing with additional instrumentation is needed to verify that this is indeed the case. It should be noted that unreacted HE was recovered in the ½" test for standard LX-14, whereas no HE was recovered in the other tests for LX-14.

TABLE 4. Reaction types across SSFA samples and cover plate thicknesses

Material	Cover plate thickness [in.]				
	1/8	1/4	5/16	3/8	1/2
PBXN-9 - Lot A	I	IV	--	V	--
PBXN-9 - Lot B	I	IV	--	VI	--
LX-14	--	III	III	III	III
LX-14 (80% FEM)	--	III	--	IV	IV

a. b. c.

Figure 3. Post SSFA test apparatus of standard LX-14 for cover plates of thicknesses at (a.) ¼ in (6.35 mm), (b.) 5/16 in. (7.94 mm), and (c.) 3/8 in. (9.53 mm)

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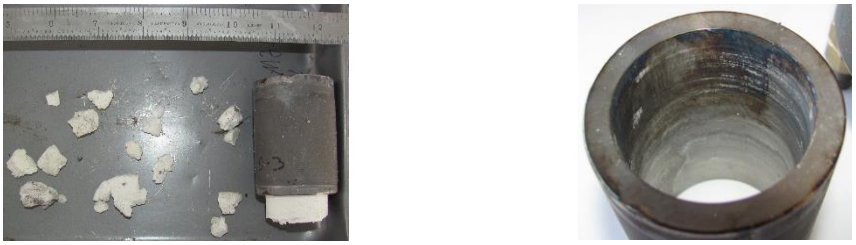
a. b.

Figure 4. Post SSFA test apparatus of 80% FEM HMX LX-14 for cover plates of thicknesses at (a.) ¼ in (6.35 mm), (b.) 3/8 in. (9.53 mm)



a. b.

Figure 5. Post SSFA test apparatus of PBXN-9 for cover plates of thicknesses at (a.) 1/4 in. (6.35 mm), and (b.) 3/8 in. (9.53 mm)

DISCUSSION

Series 3 FI test results are significantly benign when compared to those of series 1 and baseline, which detonated using a similar configuration (warhead A). This may be due to a potential lot-to-lot variability in the PBXN-9 material, which results in the varied response to impact stimulus. Lot-to-lot variability in impact response has been observed in prior tests using LX-14 [9, 10]. Another source of uncertainty may be due to the difficulty of fragment flight control noted in section 1.1.2.

FI tests between warhead A and B show an increased sensitivity of the former warhead, which suggests a better suitability of the latter warhead configuration for situations where impact survivability is paramount**.**

Comparing FI test results of similar configurations of PBXN-9 (series 2, surrogate warhead A) and FEM LX-14 (series 4, surrogate warhead A), detonation of only the latter indicates that LSGT tests should yield a higher card gap value for the FEM LX-14. However, PBXN-9 and 80% FEM LX-14 have similar card gap values. The mechanism for this is unclear in the present study, but contributing factors could include shear concentration in the considerably stiffer FEM LX-14 binder, which would be exacerbated by shock-front curvature in an FI test.

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Also, contrary to LSGT data, SSFA results align more closely with FI data, and suggest greater impact sensitivity of 80% FEM LX-14 over PBXN-9. The differences in response are likely due to binder material stiffness, total nitramine loading content, and crystal shear. FEM LX-14 contains smaller crystals that reduce average void size, and therefore reduce the response under adiabatic compression in the short duration, planar LSGT environment. Crystal size and binder stiffness can contrarily also explain the increased sensitivity under FI test, with shear concentration leading to initiation rather than void collapse.

With regards to the SSFA procedure, additional instrumentation control is desired. While results for PBXN-9 agree with previous studies and follow the expected trend of decreased sensitivity with increasing cover plate thickness, those for LX-14 are more ambiguous. Without better resolution of test conditions and measurement, all LX-14 reactions were deemed to be type III despite increasing in violence with cover plate thickness. Repeating the experiment with additional resources may help clarify the observed trend.

The trends observed in the gap test experiments diverge from those observed in the impact tests. This behavior is not altogether unexpected. Phenomenological models, such as the Hugh James criteria, predict initiation based on a set of threshold metrics [11, 12]. The James criteria is a hyperbolic relationship between a critical energy fluence and a critical specific energy term. Gap tests approach the asymptote of the Energy Fluence with high amplitude, short duration shock events. Impact tests approach the Specific Energy asymptote, with lot amplitude, long duration events that impart more particle velocity to the HE.

CONCLUSION

Both the LSGT and SSFA tests have some degree of usefulness as screening tests for the prediction of full scale, system level FI reaction violence. The LSGT has a large body of historical data to compare to, is inexpensive to conduct, and is conducted at a number of facilities throughout the United States. Although there is some evidence that suggests that what is actually occurring in the LSGT is more complicated than we have historically believed, and that our ability to accurately model these tests might in fact be limited, the test still has value as an agreed upon standard methodology useful for measuring shock pressures required to induce shock initiation of explosives [10]. This is most applicable to prompt shock to detonation transition (SDT) scenarios. One must be careful not to extrapolate too far outside of its range of applicability of this test however, as a munitions response to an actual fragment impact test appears to depend upon a number of additional factors such as fragment tile, yaw, miss distance, curvature, shear initiation and damage. None of these phenomena are captured by the LSGT. In contrast, the SSFA test, although not built on the historical body of data that LSGT is, does at least give an unquantified indication of shock, damage, and penetration phenomena as well as a gross, relatively inexpensive, qualitative assessment of a munition's response. Again, care must be exercised to interpret the results within a somewhat limited range of the mass, velocity, and geometric profile of the EFP as all of these, save velocity, are appreciably different from what would result from the standard NATO fragment impact experiment. SSFA will, however, require further study to

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gauge robustness for additional explosive systems and to improve upon the original procedure. It is recommended that as resources permit, additional tests should be conducted (LSGT, SSFA, and FI) in order to produce a statistically relevant set of data with which to measure HE sensitivity. Additionally, procedures undergoing updating and any emerging test methods should seek to place an emphasis on test repeatability.

The results discussed in this paper indicate some disagreement between trends observed in the LSGT data and those observed in impact tests. This disagreement serves to discourage the notion of either set of data being adequate as a single-value metric of explosive sensitivity. The divergence of the two experimental techniques is not altogether unexpected, as phenomenological models such as the Hugh James criteria treat initiability as a hyperbolic function of both short pulse, high amplitude (explosive, e.g., LSGT) events and longer acting, lower amplitude (impact, e.g., FI) events.

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