High and low velocity detonation in a highly insensitive explosive

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Abstract. Low-velocity detonation (LVD) in a solid explosive from input shocks below the threshold for high-velocity detonation (HVD) had been previously reported for PBXN-109 in two gap tests with sample diameters of 36.5 and 73.0 mm. Similar phenomenon has now been observed for the highly insensitive PBXIH-140, whose critical diameter of ~100 mm required an even larger gap test with a sample diameter of 178 mm. When just exceeding the critical gap for HVD, LVD propagated at similar velocities as in PBXN-109 and would punch clean holes in a witness plate like HVD. For somewhat greater gaps, there was enough shock reaction to drive LVD at constant but reduced velocities as the input shock decreased to ~ ½ of critical. With a different formulation now exhibiting LVD, it may be more prevalent than previously realized. It is speculated to occur in various confinements when small percentages of easily detonable ingredients fail to initiate the remainder of less shock sensitive ingredients.

1. Introduction

The sensitivity of energetic materials to detonate from a shock is measured by attenuating the output from an explosive donor with a gap whose thickness is varied until achieving a threshold for initiation. The size of the test depends upon the critical diameter for propagating detonation in the sample, and ranges from the small-scale gap test for explosive leads to the super large-scale gap test (SLSGT) for insensitive bomb fills [1]. The sample is confined by a metallic tube, which together are referred to as an acceptor. The diameters of the explosive donor, gap, and acceptor are often the same or nearly so for each test. The reduction in shock strength as gap thickness increases is calibrated or at least scalable [2] so that threshold (critical) pressure for initiation can be related from different tests on the same energetic material. A plate or block at the end of the acceptor witnesses whether or not initiation was achieved. It was believed that shock reaction either failed or transited to detonation after propagating a distance of less than one diameter, as observed in unconfined samples. Since acceptors for the most common tests have a sample length to diameter ratio (L/D) of ~4, for ideal explosives there is clear distinction between no witness deformation for failed reaction versus a cleanly punched plate or deep dent from transiting to high-velocity detonation (HVD). There was, however, for the insensitive explosive PBXN-109 some witness deformation for gaps greater than critical from low-velocity detonation (LVD) in both the NOL (NSWC, White Oak) large scale gap test (LSGT) and the expanded large scale gap test (ELSGT) [3]. Similar phenomena have now been observed for an even less sensitive explosive, PBXIH-140, in a larger test appropriate for its critical diameter of ~100 mm. The large critical diameter and shock insensitivity of PBXIH-140 are due to the primary ingredient being 3-nitro-1,2,4-triazol-5-one (NTO) versus trimethylenetrinitramine (RDX) in PBXN-109.

2. SLSGT arrangement

An 8-inch diameter gap test [4] developed at Eglin AFB evolved into the SLSGT [5]. Figure 1 is a schematic of the arrangement used in this study and is probably the most widely accepted version. The 203.2-mm diameter by 203.2-mm high donor of cast Composition B is initiated by a 50.8-mm diameter by 50.8-mm high booster. That booster in the current tests and in the NATO specifications is Composition A-5 for direct initiation by a detonator. In early versions of the test, its calibration [5], and the arrangement in Fig. 5-31 of TB 700-2 [6], the booster is cast Composition B, which requires a small sub-booster of Composition A-5. This combination was replaced in a hydrocode calculation by a LSGT donor with no discernible effect on the calibration.

The polymethyl methacrylate (PMMA) gap and acceptor tube are the same diameter as the donor. The most common acceptor tube is mild steel with a sample L/D of only 2.3. TB 700-2 specifies a longer 812.8-mm tube for propellants with an L/D of 4.6. SLSGTs usually include piezoelectric pins inserted through the acceptor tube wall at 50.8-mm intervals. Current tests had pins spiraling around the tube to avoid a loss of confinement by longitudinal cracks between pin holes. One end of the acceptor tube has a steel closure plate for sample casting that is removed before testing. Otherwise, impact of this closure plate on the witness plate makes determination of a detonation very difficult.

As in the LSGT and ELSGT, there are air gaps above and below the witness plate to assist with punching a clean hole when the sample detonates. The 12.7-mm air gap above the witness plate in figure 1 is specified in Figure 5-31 of reference [6] as only 1.6 mm, the same as in the LSGT. This should make little difference in punching a clean hole. In the current tests, the air gap above the witness plate was from two strips of plywood and that below was from 76-mm thick foam blocks.

Witness plate dimensions in figure 1 scale with those plates in the LSGT and ELSGT. Larger plates of the same thickness are less likely to fracture, making it easier to recover and determine whether or not there was HVD (GO) or failure (NOGO). With HVD there is a clean hole somewhat larger than the outer diameter of the acceptor tube with little bowing of the plate. Even a slightly smaller hole or bending near the hole to form a funnel is evidence of LVD or a failing detonation.

A photograph in figure 2 of the set-up for Shot 2 is for a 203-mm gap (white in appearance), consisting of four 50.8-mm thick pieces. The wires approaching the left side of the acceptor connect to the piezoelectric pins.
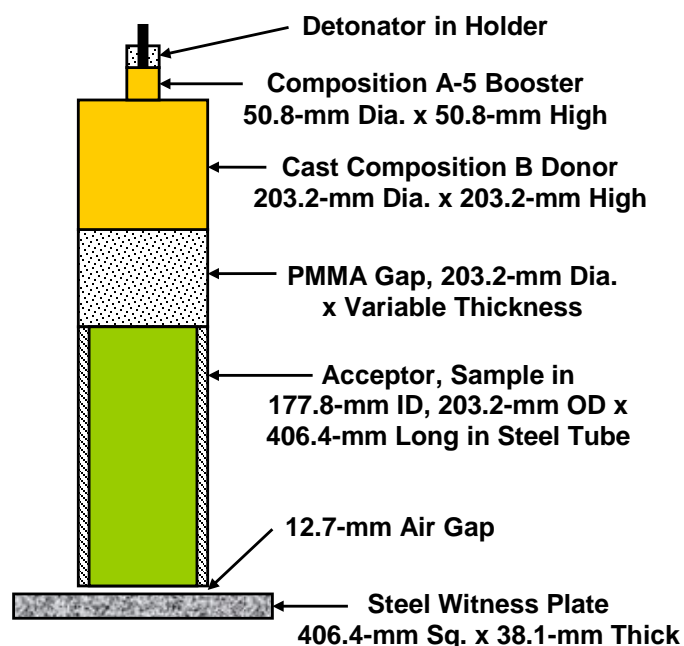

Figure 1. SLSGT for explosive samples.

Figure 2. SLSGT setup for Shot 2.

3. SLSGT results

Twelve PBXIH-140 shots are summarized in table 1 in order of increasing gap, where shock pressure at the end of the gap (P_G) is from the calibration [5]. Shot 1 had no gap to assure a GO. The witness plate (figure 3) had a clean hole, about 10% larger than the acceptor, and was fractured because of a relatively large hole exposed to detonation products. Witness plates were similar for GOs from longer gaps in Shots 3, 4, and 12, even when pins indicated a transition to HVD near the witness. The GO at the longest gap of 152 mm in Shot 4 was with the only sample without voids because of being vacuum cast. With casting voids, the critical gap was between 146 mm for the GO in Shot 12 and 149 mm for the NOGO in Shot 11. Witness plates when just beyond the critical gap in Shots 10 (figure 4) and 11 had clean but smaller holes about the diameter of the acceptor and didn't fracture. With larger gaps there was a small, rough hole in the witness plate, as shown in figure 5 for Shot 2 with the largest gap of 203 mm. A partial hole in the witness plate for Shot 8 (figure 6) probably resulted from weakening of the acceptor tube by a second set of pin holes longitudinally displaced 25 mm from the other set.

Table 1. Summary of SLSGTs on PBXIH-140.

Shot	Gap (mm)	P_G (GPa)	GO/ NOGO*	Casting Void Dia. at each End (mm)	
				Gap	Witness
1	0	20.9	GO	10	>25
3	102	6.68	GO	16	<6
12	146	4.04	GO	13	10
11	149	3.87	NOGO[1]	10	10
4	152	3.72	GO	None	None
10	152	3.72	NOGO[1]	13	10
9	154	3.64	NOGO[2]	13	>13
8[#]	156	3.57	NOGO[3]	>25	<6
7	159	3.42	NOGO[2]	<6	<6
6	165	3.15	NOGO[2]	10	19
5	178	2.67	NOGO[2]	8	<6
2	203	1.95	NOGO[2]	>25	19

[#]Acceptor tube had a second set of probe holes
*NOGO witness plates: 1 = Small clean hole, 2 = Small rough hole, 3 = Partial hole

Figure 3. Witness plate from GO in Shot 1.

Figure 4. Witness plate from NOGO in Shot 10.

Figure 5. Witness plate from NOGO in Shot 2.

Figure 6. Witness plate from NOGO in Shot 8.

The pin data in figure 7 exhibit slower initial velocities as gap thickness increases, as was observed in ELSGTs on PBXN-109 [3]. There was HVD at 7.44 mm/μs for the entire sample with no gap (Shot 1); transition to HVD about half way down the sample with a 102-mm gap (Shot 3); and transition near the end of a sample with casting voids for a 146-mm gap (Shot 12), and in a sample without casting voids for a 152-mm gap (Shot 4). The higher velocities shown in figure 7 following transitions near the witness, especially the 8.47 mm/μs for the last two pins in Shot 4, are possibly a phase effect from central initiation proceeding both radially and axially. For a 149-mm gap (Shot 11) that is just beyond the critical gap for samples with casting voids, the initial velocity was 3.55 mm/μs for the first half of the tube before transiting to a LVD of 5.23 mm/μs that punched a clean hole in the witness plate, although at reduced diameter. The response for a 152-mm gap in Shot 10 was similar. For greater gaps there was steady LVD, decreasing from 3.52 mm/μs for a 154-mm gap to 3.06 mm/μs for a 203-mm gap, with small rough holes in witness plates.
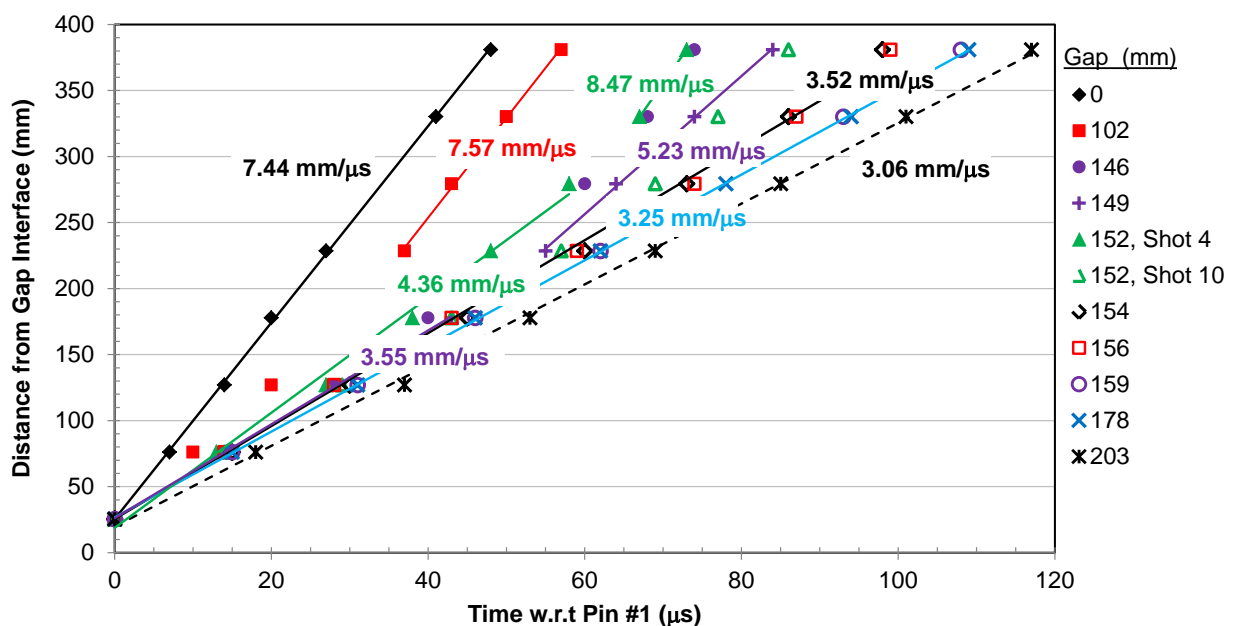

Figure 7. Pin responses.

4. Discussion

Gap tests on ideal explosives typically result in either a cleanly punched witness plate from HVD or one that is undamaged or merely bent from a failing reaction. A non-ideal explosive can exhibit intermediate responses, referred to as LVD, with reduced damage to the witness (and confinement tube when its recovery is possible) than from HVD that correlates with steady or slightly accelerating front velocities less than HVD [3]. While most gap tests don't routinely utilize velocity probes, such probes will identify LVD and confirm the critical gap for HVD by providing the distance-to-detonation, which approaches the sample length at the threshold for HVD. When gap tests utilize a witness block, intermediate responses are manifested by reduced dent depth. Although a plate is the only practical witness in an arrangement as large as the SLSGT, the difference between HVD and LVD can still be assessed from overall damage and diameter of the punched hole.

In this study, as in other gap tests, there was no change in witness plate damage whether transiting to HVD near the gap or witness. The change from HVD to LVD just beyond the critical gap was recognized by smaller holes that didn't fracture the witness plates and an increasing front velocity less than HVD. There is the potential that the accelerating front would transit to HVD in a longer acceptor with an L/D of 4 versus the 2.3 for the SLSGT arrangement in figure 1. For gaps just ~5 mm more than critical, front velocity didn't accelerate but remained steady over the entire length of the acceptor and produced less damage to the witness plate; therefore, there was little potential for transiting to HVD in a longer acceptor. Other than a small change in critical gap, <5 mm in these tests, there is no advantage to a longer sample. This is consistent with PBXN-109 data obtained at both an L/D of 1.4 in a shortened version of the ELSGT and the ELSGT with an L/D of 3.8 [3].

Steady front velocity over the length of the samples persisted for gaps from 154 to 203 mm, the longest tested, with velocity decreasing for increasing gap thickness. Steady instead of failing fronts and witness plate damage were indicative of LVD. For the longest gap of 203-mm gap, P_G was about half of that at the critical gap for HVD but still a substantial 1.95 GPa for the long duration pulse in the SLSGT. LVD failed for P_G ~ ½ of critical in ELSGTs on PBXN-109 with insensitive RDX [3]. At some reduced P_G, the front will also fail in PBXIH-140 and not damage the witness plate. While the critical gap for HVD is the metric in gap testing, perhaps the threshold for LVD should also be considered because LVD increases the overall hazard.

When LVD velocities are in the range of 3 to 4 mm/µs, ~half of that for HVD and not that much greater than the longitudinal sound velocity, only a small portion of the explosive reacts in a timeframe that supports the front. Confinement also has an effect and reaction would probably extinguish without it. A second set of probe holes in the Shot 8 acceptor did not diminish front velocity but reduced damage to the witness plate. This suggests 1) earlier activation of fracture allowing radial rarefactions to reduce sample momentum towards the witness plate, and 2) that the compressive waves reinforcing LVD and maintaining its velocity came from reaction near the front before the tube fractured.

LVD may be characteristic of insensitive explosives formulated with a small percentage of an easily detonable ingredient that is intended to initiate the remainder in HVD but fails to do so in LVD. Even though RDX is the major ingredient in PBXN-109, the shock sensitivity of some crystals within a particle class will be more sensitive than others in addition to substantial differences between classes and even within a class from various manufacturers. By contrast, more ideal explosives have enough shock reaction at similar pressures for achieving shock-to-detonation transition to HVD.

5. Summary and conclusions

The SLSGT is more widely used as insensitive explosives are being developed with critical diameters exceeding the sample size in the ELSGT. LVD has now been observed in the SLSGT for a highly insensitive explosive with a critical diameter an order of magnitude larger than PBXN-109, which exhibited LVD in the LSGT and ELSGT. Interpretation of gap tests from witness plates requires attention to LVD, which may be more prevalent than previously realized. An uncertain interpretation

for HVD can be verified with velocity probes or, if practical, by replacing the witness plate with a block.

Acknowledgements

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