The ARDEC Gap Test for Small Grain Gun Propellants

Mr. Erik Wrobel*
Detonation Physics and Experimental Technologies Branch

Mr. Lucas R. Lopez
Propulsion Engineering Programs Branch

Mr. Chau Nguyen
Mr. Matthew Adelman
Munitions Safety and Hazard Classification Branch

U.S. Army Research, Development and Engineering Command
Picatinny Arsenal, NJ 07806

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Abstract

The United Nations (UN) gap test, Test 2(a) has undergone numerous revisions over the last several years. Historically, Test 2(a) was conducted at the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) to evaluate the shock sensitivity of energetic substances for the purpose of hazard classification. Originally envisaged as a one-size-fits-all energetic material characterization test, it presently does not adequately differentiate the hazards of propellants, pyrotechnics, and high explosives. The 2012 revisions to the TB 700-2 gap test procedures aimed to simplify the experimental setup but resulted in vague pass/fail criterion, complicating the local Interim Hazard Classification (IHC) assignment process. Modifications were made to this standard test to improve the quality and relevancy of the data collected while utilizing the same high explosive booster and sample tube.

The resulting ARDEC Gap Test measures the detonation velocity in an energetic substance as well as the dent depth produced in aluminum. The detonation velocity and dent depth metrics conclusively determine whether or not a sample material propagated a detonation in the UN gap test configuration. New assessment criteria were written for the test, allowing a better evaluation of the shock sensitivity hazard of a sample material. The ARDEC Gap Test has been conducted on numerous small-grain propellants, M9 flake propellant, and two high explosives. ARDEC is currently utilizing this test to support IHC assignment for small-grain propellant formulations.

Background

Department of Defense Ammunition and Explosives Hazard Classification Procedures (TB 700-2) underwent a revision dated 30 July 2012 which changed the shock sensitivity tests in order to harmonize with the UN standards. The revision changed both the test setup and assessment criteria for UN Tests 1(a) and 2(a).

Legacy UN Test 1(a) iii and 2(a) iii had three test criteria:

1. “A stable propagation velocity greater than the velocity of sound in the substance” (measured via resistive wire)
2. “A hole is punched through the witness plate”
3. “The sample tube is fragmented along its entire length”

If two of the three criteria above were met, the overall test result was considered positive (+).

Current UN Tests 1(a) and 2(a) have the following two criteria:

1. “A hole is punched through the witness plate”
2. “The sample tube is fragmented completely”

If either of the above criteria is met, the overall test result is considered positive (+).

TB 700-2 states that UN Test 1(a) is “intended to determine whether a solid or liquid substance will propagate a detonation in a confined state” and UN Test 2(a) is “intended to demonstrate whether a solid or liquid substance will propagate a detonation through a polymethyl methacrylate (PMMA) gap”. The current UN Test 2(a) evaluation criteria are not quantitative in nature. The sample tube fragmentation criterion does not specify the number of fragments or fragment sizes. The witness plate holing criterion can be ambiguous with regards to punctured or torn steel plates versus cleanly holed steel plates. These two criteria, as stated in the test standards, do not conclusively determine if the test sample detonated.

To evaluate these gap tests on inert materials, UN Tests 1(a) and 2(a) were conducted using water and on brown rice as the “energetic” substances. The sample tube loaded with brown rice in UN Test 1(a) was fragmented near the top and split in half. This could be considered a positive result. The top of the sample tube was also fragmented in the water-loaded UN Test 1(a), but since most of the tube was intact it would be assigned a negative result. No sample tube damage was observed in the inert Test 2(a) trials. The potential positive result in the brown rice UN Test 1(a) showed that the fragmentation criterion can be subjective and is not a conclusive discriminator for detonative vs. sub-detonative events. Photographs of the inert tests are shown following.

Figure 1: Brown Rice UN Test 1(a) Results

Figure 2: Water UN Test 1(a) Results

Initial Propellant Characterization

After the 2012 TB 700-2 revision, the first major program at ARDEC requiring IHC assignment involved a family of small-grain propellants with novel stabilizer compounds. The Army Energetic Materials Qualification Board (EMQB) considered the modifications to these propellants minor formulation changes since both stabilizers were inert and they comprise approximately

1% of the propellant by weight. Some of these modified propellants had already completed Final Hazard Classification (FHC) testing at a contractor facility and were assigned Hazard Division (HD) 1.3C. Per EMQB guidance, both the baseline and the modified propellants underwent testing in accordance with the 2012 TB-700-2 standard. All but one of the modified propellant formulations produced positive (+) results in the current UN gap test. The baseline HD 1.3C formulations also yielded positive results in the current gap test. Table 1, below, shows the results for the propellants evaluated using both the legacy and the current standards.

Table 1: UN Test 2(a) Small-Grain Propellant Results

Propellant	Legacy Test Result	Current Test Result
Sample 1	**Positive** TF, HP, No DV	**Positive** TF, HP
Sample 2	**Positive** TF, HP, No DV	**Positive** TF, HP
Sample 3	**Negative** TF, No HP, No DV	**Positive** TF, No HP
Sample 4	**Negative** TF, No HP, No DV	**Positive** TF, No HP
Sample 5	**Positive** TF, HP, No DV	**Positive** TF, No HP
Sample 6	**Negative** TF, No HP, No DV	**Positive** TF, No HP
Sample 7	No Data	No Data
Sample 8	No Data	**Negative** No TF, No HP

TF = Tube Fragmented, HP = Holed Plate, DV = Detonation Velocity

All of the substances tested in this initial characterization effort were double base propellants with minor variation in grain size distribution. The small-grain propellants were comprised of similar ingredients with different nitroglycerine (NG)/nitrocellulose (NC) ratios.

All of the small-grain propellants, except Sample 8, fragmented the UN gap test steel tubes down their entire lengths; generally into four to ten pieces. This resulted in a positive assessment per the 2012 TB 700-2. However, the fragments were not indicative of a detonation reaction. These large tube fragments, as seen in Figure 3, were 2 to 6 inches long and typical of deflagration reactions. The fragments from a detonation reaction, below in Figure 4, are typically much more numerous and smaller in size.

Figure 3: UN Test 2(a) Propellant Deflagration Fragments

Figure 4: Typical Detonation Fragments

Some of the witness plates from this test series were "holed" but the propellants did not appear to detonate. Detonation reactions, even with relatively low density granular materials, typically result in “cleanly holed” witness plates with hole diameters greater than the diameter of the sample tube. Since no clear guidance is provided in TB 700-2 to evaluate the quality of the holing, positive results were conservatively assigned. Figure 5 shows a holed plate from one of the propellant tests.

Figure 5: UN Test 2(a) Witness Plate (holed)

The results of the initial propellant characterization tests were presented to the Department of Defense Explosive Safety Board (DDESB) and the board's recommendation was to conduct the 70 card Naval Ordnance Laboratory (NOL) Large Scale Gap Test (LSGT) as an alternative to UN Test 2(a) for IHC assignment purposes. A 50% point greater than 0.7" of PMMA (70 cards) would result in the classification of a bulk substance as HD 1.1. This was a historic test standard that was no longer in the relevant procedural documents. The results for the NOL LSGT 70 card series are shown below in Table 2. Full NOL LSGT series were conducted on several of the test samples to acquire 50% GO/NO-GO values.

Table 2: NOL LSGT Results

Propellant	70 Card LSGT Results	NOL LSGT 50% Point (cards)
Sample 1	Go, Go, Go	125.0
Sample 2	Go, Go, Go	131.5
Sample 3	Go, Go, Go	No Data
Sample 4	Go, Go, Go	141.0
Sample 5	Go, Go, Go	No Data
Sample 6	Go, Go, Go	139.5
Sample 7	Go, Go, Go	No Data
Sample 8	Go, Go, Go	140.5

Clean holes in the witness plates were observed in all of the 70 card tests, indicating detonation. A photograph of a post-test witness plate is shown in Figure 6. Three shots were conducted at 0.700" PMMA attenuation for each material to ensure the repeatability of energetic response. The 50% points found from the full NOL Gap Test series ranged from 125 to 141 cards, which correspond to 48.8 and 44.0 kbar input shocks, respectively.

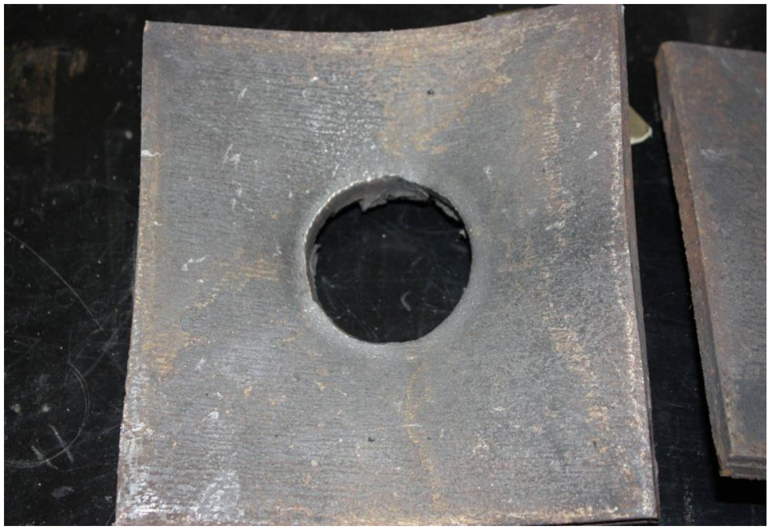
Figure 6: NOL LSGT Witness Plate from Propellant Testing

Both the NOL LSGT and UN Test 2(a) determine the shock sensitivity of a test sample exposed to a standard shock stimulus. The sample tubes for the NOL LSGT and the UN gap test have the same diameter and wall thickness but UN gap test’s sample tube is approximately 3 times longer, providing additional run distance for either detonation build-up or failure. The major difference between these two tests is the input stimulus. While both tests use the same 2” x 2” Pentolite (PETN/TNT) donor charge, the shock input with 200 card PMMA attenuation in UN Test 2(a) is 20.7 kbar versus the 69.8 kbar input from the 70 card NOL LSGT. Additionally, the witness plate in the NOL LSGT is three times thicker at 0.375 inches. Table 3 shows the configurations of the two shock sensitivity tests.

Table 3: Gap Test Configurations

	NOL LSGT 70 Card Test	UN Test 2(a)
Detonator	RP-502 or equivalent	RP-502 or equivalent
Booster	2" x 2" Pentolite	2" x 2" Pentolite
PMMA Thickness	70 cards	200 cards
Shock Input	69.8 kbar	20.7 kbar
Steel Tube	1.44" ID, 1.875" OD, 5.5" L	1.44" ID, 1.875" OD, 16" L
Witness Plate	0.375" thick	0.125" thick

The data generated in this study demonstrated that UN Test 2(a), given the current instrumentation and assessment criteria, is not suitable to ascertain if an energetic substance propagated a detonation. While NOL LSGT is more effective at determining whether or not a detonation occurred, there is no added instrumentation, the assessment criteria is a holed witness plate (qualitative in nature), and the sample tube provides limited reaction run distance. To improve the data gathered for the hazard classifiers, an alternative test was designed to quantitatively evaluate the shock sensitivity of energetic materials.

The ARDEC Gap Test

The ARDEC Gap Test is a modified variant of UN Test 2(a) with added instrumentation and a different test methodology. It utilizes the same steel tube as the UN gap test and the same booster and shock attenuation; maintaining the transmitted shock of 20.7 kbar. To confirm that the sample materials were detonable in this configuration, baseline tests without PMMA shock attenuation were conducted for each material. If a stable shock velocity was measured, eliminating critical diameter concerns, attenuated tests were performed.

Changes to UN Test 2(a):

1. Replaced the current 0.125” thick steel witness plate with a 2” thick aluminum dent plate. Measuring and comparing dent depth in a thick metal plate is a well-established technique in the explosives community for detonation evaluation.

Transitioning to a dent plate eliminates the subjectivity in interpreting holing. While steel is the typical dent plate material, aluminum was chosen for this application due to the somewhat lower output of the selected propellant formulations compared to typical high explosive (HE) formulations. Aluminum allowed for a larger magnitude dents, reducing measurement precision concerns.

2. Added time of arrival (TOA) transducers for shock wave propagation measurement. A steady shock wave velocity is the most conclusive indication of a detonation reaction. The method of measuring shock velocity may vary; small holes may be drilled into the tube for fiber optics or piezoelectric/ionization TOA pins. Alternatively, piezoelectric TOA pins could be located on the outside of the sample tube. Fiber optics drilled into the tube were used for the following test series.

3. Evaluated the reaction via the dent depth and detonation velocity instead of plate holing and tube fragmentation.

Figure 7 shows a notional schematic of the proposed test and Figure 8 shows the test setup at ARDEC.

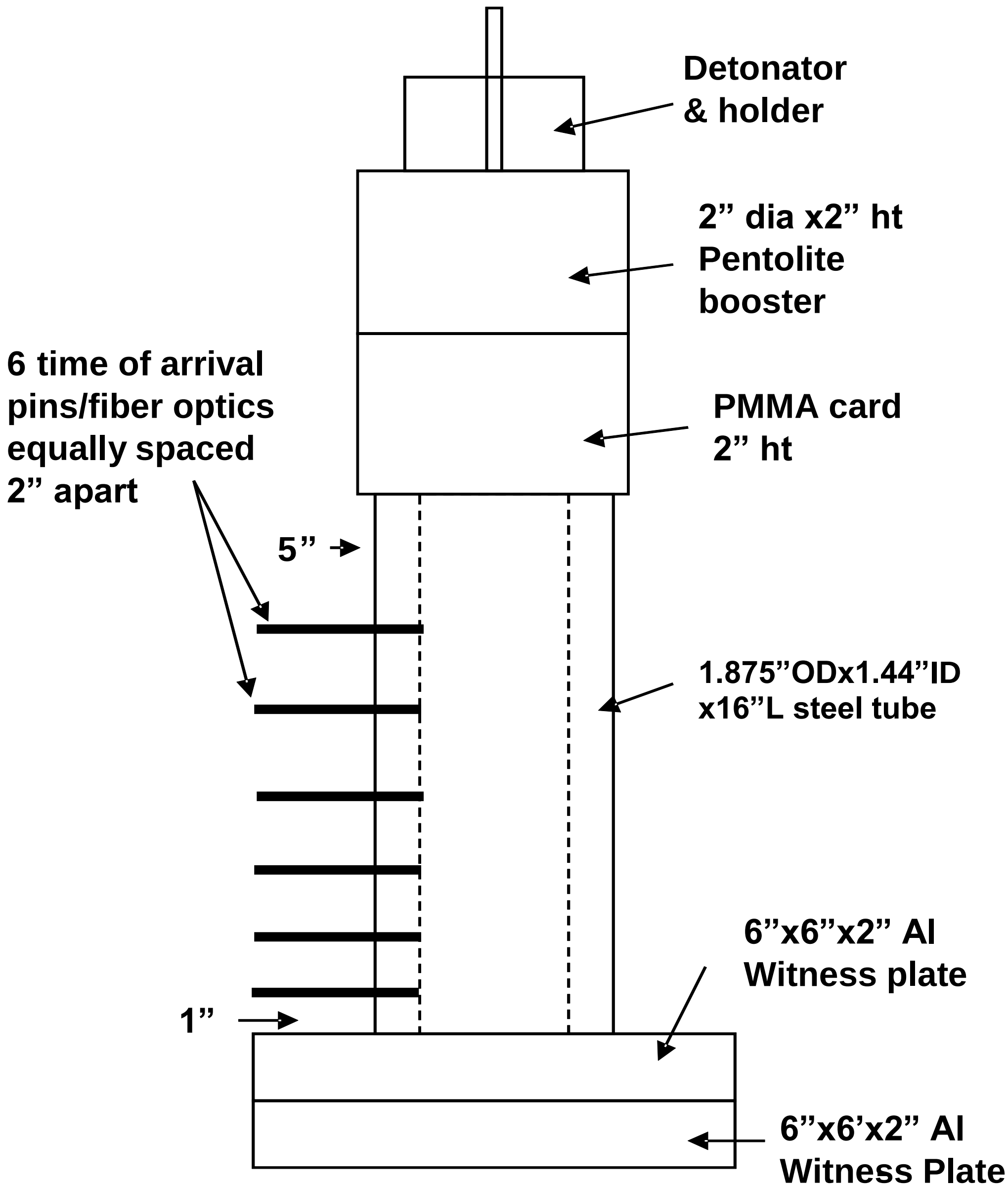

Figure 7: Notional Drawing of Proposed ARDEC Gap Test

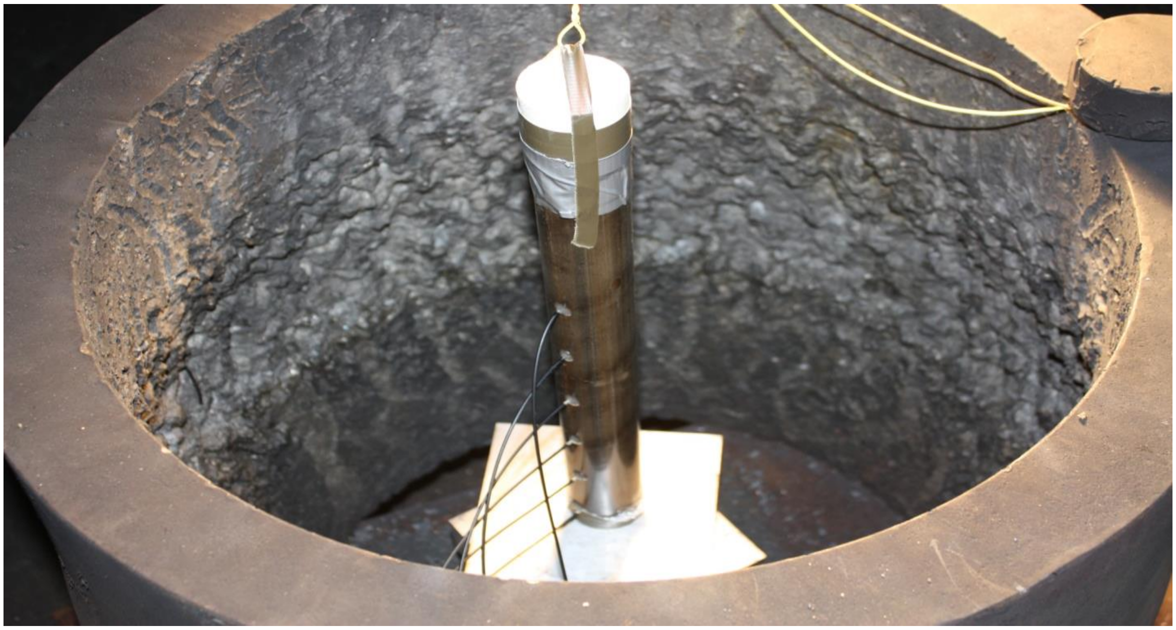

Figure 8: In-Chamber Test Setup

Test Methodology

Three trials were conducted on each sample material, detailed below.

Trial 1: Baseline test, no PMMA attenuation

Measured the dent depth and the detonation velocity when the Pentolite booster was in direct contact with the sample. This verified that the test was being conducted above the confined critical diameter for the sample material and established a baseline dent depth and detonation velocity for comparative purposes.

Trial 2: Attenuated test, 2" PMMA gap

Measured the resulting aluminum dent depth and the shock velocity and compared those values to the baseline.

Trial 3: Repeat of trial 2, 2" PMMA gap

Measured the resulting aluminum dent depth and the shock velocity and compared those values to the baseline.

Evaluation criteria

If the dent depth from either trial 2 or 3 was greater than 50% of the trial 1 (baseline) dent depth, OR if there was a stable shock velocity observed in trial 2 or 3, the test sample detonated and was assigned a positive result.

Results

Eight small-grain propellants, M9 flake propellant, and two HE formulations were tested in the ARDEC Gap Test configuration. The results are shown in the following tables.

Table 4: ARDEC Gap Test Results for Small-Grain Propellants

Propellant	Trial #	PMMA gap (in.)	Det. Vel. (mm/us)	Dent (in.)
Sample 1	1	None	5.077	0.597
	2	2	Not used	0.043
	3	2	No Trace	0.039
Sample 2	1	None	5.190	0.595
	2	2	Not used	0.053
	3	2	No Trace	0.049
Sample 3	1	None	5.322	0.764
	2	2	Not used	0.024
	3	2	No Trace	0.025
Sample 4	1	None	5.364	0.746
	2	2	Not used	0.037
	3	2	No Trace	0.035
Sample 5	1	None	5.437	0.697
	2	2	Not used	0.053
	3	2	No Trace	0.049
Sample 6	1	None	5.435	0.736
	2	2	Not used	0.039
	3	2	No Trace	0.040
Sample 7	1	None	5.081	0.582
	2	2	Not used	0.002
	3	2	No Trace	0.002
Sample 8	1	None	4.899	0.581
	2	2	Not used	0.013
	3	2	No Trace	0.018

A steady shock velocity was recorded for all baseline shots, which indicated that the samples were above their confined critical diameter. In the baseline configuration (trial 1), the propellant samples generated detonation velocities of approximately 5.0-5.5 km/s and dent depths of about 0.600-0.750". When attenuated in trials 2 and 3 (20.7 kbar input), none of the propellants detonated. Trial 2 and 3 dent depths were all less than 10% of the baseline dent depths and no measureable shock velocities were observed with the 20.7 kbar shock input. Based on the ARDEC Gap Test evaluation method, all of the propellants would be assigned a negative result. The following figures contain photographs of the aluminum dent blocks from the propellant test series.

Figure 11: Propellant Trial 2/3 Dent

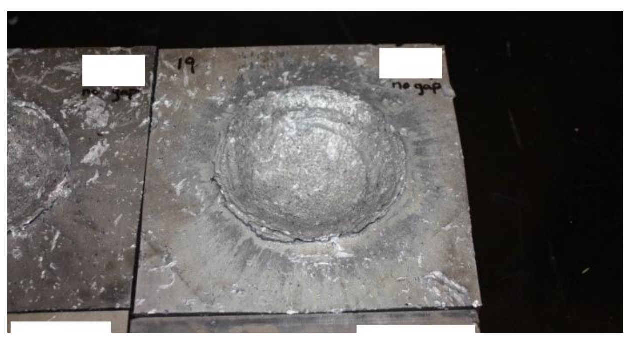

Figure 12: Propellant Trial 1 Dent

M9 Propellant Test Results

In an effort to demonstrate the validity of the ARDEC Gap Test, flake M9 propellant was tested following same methodology and in the same configuration as the small-grain propellant test series. M9 is a double base propellant with 40% NG content and is one of the most detonable granular propellants in DoD inventory.

Table 5: ARDEC Gap Test Results for M9 Flake

Propellant	Trial #	PMMA gap (In.)	Det. Vel. (mm/us)	Dent (in.)
M9	1	None	No Trace	0.276
	2	2	No Trace	0.292
	3	2	No Trace	0.275
	4	2	No Trace	0.286

All M9 trials, un-attenuated and attenuated, fragmented the sample tube completely. The size and number of fragments were similar to those of the un-attenuated shock input fragments produced by the other small-grain propellant formulations. However, the dents were significantly shallower. This was due to lower packing density of the M9 flake material. The attenuated shock input dent depths were approximately equal to the baseline dent depth.

No detonation velocity traces were recorded for the M9 flake testing. It is presently not known why the fiber optic method did not observe light pulses for a shock velocity analysis. The failure may have been due to the low packing density of the M9 flake, resulting in a reduction in the brightness of the ionized air shocks. Based on the dent depth analysis, the material was detonating. Piezoelectric TOA pins have been used successfully in recent test series.

Based on the ARDEC Gap Test evaluation criteria the overall test result for M9 was positive.

Figure 13: M9 Flake Tube Fragmentation

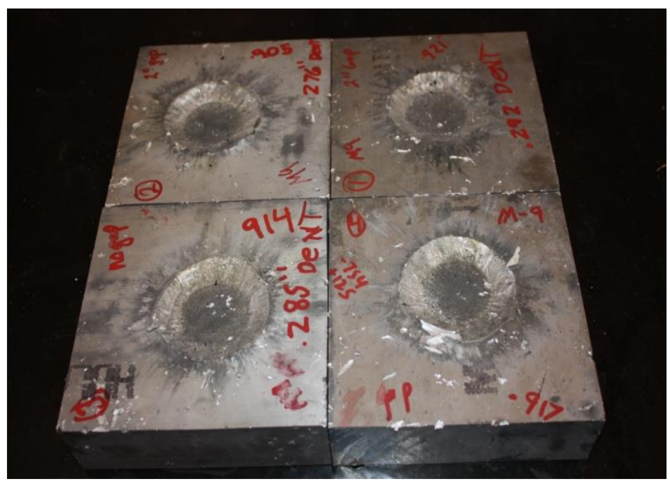

Figure 14: M9 Flake Dent Depths

High Explosive Test Results

Though the ARDEC Gap Test was primarily designed for small-grain propellants, two common explosives, Octol 70/30 and TNT, were tested. The results are shown below in Table 6.

Table 6: ARDEC Gap Test Results on High Explosives

Explosive	Trial #	Density (g/cc)	NOL 50% Point (cards)	PMMA gap (In.)	Det. Vel. (mm/us)	Dent (in.)
Octol 70/30 (cast)	1	1.8	>220	None	8.274	1.078
	2	1.8		2	Not used	1.081
	3	1.8		2	8.239	1.119
TNT (cast)	1	1.56	~150	None	6.583	0.826
	2	1.56		2	Not used	0
	3	1.56		2	No Trace	0

Both explosives detonated in the baseline trial and detonation velocities were recorded. The results of the attenuated trials differed greatly between the two explosives. Octol detonated in trials 2 and 3 and produced dent depths almost identical to the baseline trial, resulting in a positive response. TNT did not produce a dent and no detonation velocity was recorded in trials 2 and 3, resulting in a negative response. A photograph of the witness plates from the high explosive testing follow.

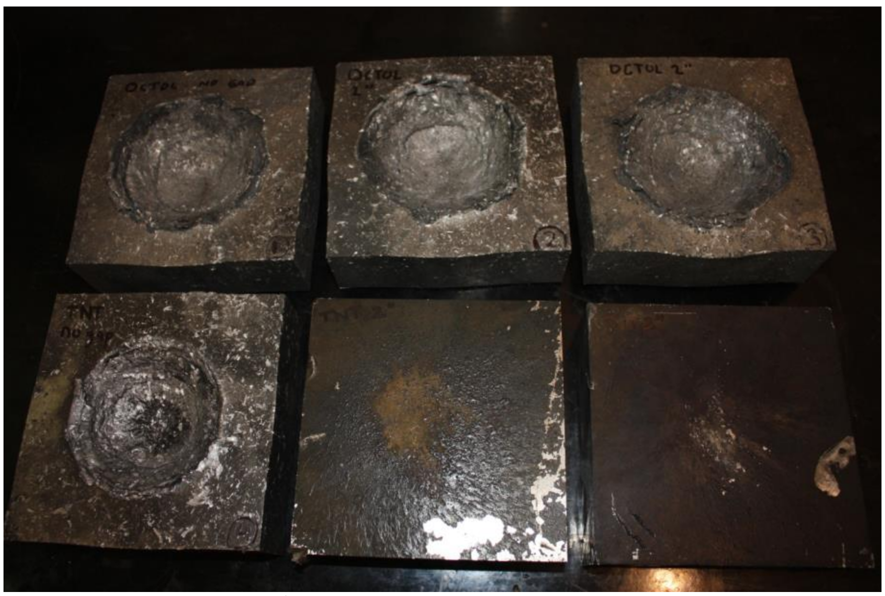

Figure 15: Dent plates from HE testing – Octol Trials 1,2,3 Top, TNT 4,5,6 Bottom

Conclusions

There are challenges associated with conducting gap tests on any propellants other than small grain, densely-packed propellants. Repeatability is a major issue with shock sensitivity testing on larger grain propellants due to arbitrary packing. Grain packing and uneven interfaces pose challenges for all of the existing shock sensitivity tests. Numerous experimenters have investigated the effects of grain orientation on both the input and output ends of acceptor materials in gap tests. There is more work to be done to determine the experimental best practices for quantifying the shock sensitivity and output of propellants.

The ARDEC Gap Test is an improvement over UN Test 2(a) for investigating the shock sensitivity of energetic materials. The addition of a shock TOA metric and the use of a dent plate instead of a thin witness plate allows for a more quantitative evaluation of detonation properties. All of the small-grain propellants tested as part of this effort detonated in the baseline configuration; when the propellant was directly in contact with the Pentolite booster. None of the propellants detonated when subjected to the 20.7 kbar attenuated shock. Detonation velocity and dent depths were measured, but there was no clear trend between shock sensitivity or performance with NG content or particle size. ARDEC hazard classifiers have been using this gap test as part of their local test matrix to assign IHCs for small-grain propellants.

Limitations and Future Work

There are still concerns regarding the choice of attenuator thickness. The 2" PMMA attenuator standard has existed for decades. However, given the emphasis on developing Insensitive Munitions (IM) fills, many new high explosive formulations would also receive negative results from 20.7 kbar input gap tests based on NOL LSGT and E-LSGT 50% points. Many of the IM explosives have large failure diameters and would not be detonable in the 1.44" inner diameter steel tube configuration. When 0.7" PMMA attenuators (69.8 kbar output) were used in the NOL LSGT configuration on the small grain propellants, all 8 samples consistently detonated. Full NOL LSGT series were conducted on several of the test materials, resulting in 50% points ranging from 125 to 141 cards. Certain gun propellants have been observed to have 50% points of 200 cards or more, indicating greater shock sensitivity than many legacy high-performance explosives. Determining and reporting a 50% point shock initiation pressure would be more valuable information for hazard classifiers and users.

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References

1. Department of Defensive Ammunition and Explosives Hazard Classification Procedures (TB 700-2). Various editions.
2. Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria. Various revisions.
3. P. Lu, *ARDEC Solid Gun Propellant Shock Initiation Sensitivity Test*, Minutes 26th DDESB Seminar, August 1994.
4. B. Fuchs, A. Wilson, M9 Accident Investigation Testing, ARDEC Technical Report, March 2007.
5. *Qualification of Small-grain propellant**, Army EMQB Qualification Memorandum, July 2011.