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Physical Simulation of Live-Fire Detonations using Command-Detonation Fuzing

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Abstract: Testing of munitions for environmental impact is required in many countries as part of the life cycle assessment process. Although the post-detonation mass and composition of metallic species are known, energetics residues from the detonation process are difficult to estimate. Past methods using detonation chamber testing and modeling have been shown to be problematic, especially with newer generation energetic materials. This paper describes a method of field-testing munitions using command detonation systems for static rounds that simulate live-fire high order detonations. Research demonstrates that results from command detonated high explosive rounds are similar to residues from rounds fired onto an ice-covered impact area. The ability to substitute command detonations for live fire will enable the assessment of the environmental impact new munitions will have on training ranges prior to full development and certification. Data may also be used to assess detonation efficiencies for explosive formulations as well as for energetic components in those formulations.

Keywords: Munitions · Command Detonation · Live Fire · Physical Simulation · Energetics

1 Introduction

Live fire training with military munitions is a critical component of maintaining the readiness of combat forces worldwide. This training will result in the deposition of energetics on ranges [1, 2, 3, 4, 5]. Some of these energetic materials will have adverse effects on human health and the environment if found in sufficient concentrations. Live-fire testing of munitions from military inventories has been conducted by the US and Canada to quantify energetics residues from combat training. Recently, we have been investigating detonation residues from the new generation of insensitive munitions that have not been certified for firing [6, 7, 8].

To obtain empirical data on high-order detonations, rounds that cannot be fired need to be statically detonated using a command detonation system. There are several methods that have been used in the past, such as applying a donor charge to the exterior of the munition being tested, using a shaped charge or an explosively-formed projectile on the munition, or removing the fuze from the nose of the projectile and stuffing the fuze cavity with a plastic explosive such as Composition C4 (C4) and initiating the round with a blasting cap. None of these methods simulate a high-order detonation of a fired round. Externally initiated rounds are essentially blow-in-place operations, which have been shown not to be effective at initiating a high-order detonation [9]. Placing C4 in the nose of the round comes closer to simulating a live-fire detonation, but the open nose of the round decreases the detonation efficiency, likely because the open nose does not confine the initiation within the munition [10]. A method for better simulating a live fire detonation of an intact round has been developed and is described in this paper. One test series comparing live-fire with command-detonation results is given.

2 Experimental Section

Artillery fuzes employ a series of explosives that result in progressively greater detonations. This progression is called the explosive train [11]. The final energetic section of a fuze is called the booster pellet, usually composed of grams to tens of grams of an explosive formulation containing an energetic compound such as Octogen (HMX) or Hexogen (RDX). In some projectiles, a removable supplemental explosive charge is used to ensure better detonation initiation or to fill a fuze well that is machined into the round's explosive filler to accommodate longer fuzes, such as a proximity fuze.

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To simulate a live-fire detonation, the explosive train of a fuze normally assigned to that round needs to be replicated as closely as possible. Two characteristics initially stand out as needing replication: Having a fuzing system consisting of metal parts that closely matched those of a typical fuze and having a device that confines, as much as possible, the explosive train within the fuze and projectile. The simulation fuze needs to be dimensionally close to fuzes issued for the rounds being tested, and the detonation performance of the booster pellet needs to be the same as or very close to the original fuze pellet to ensure the explosive filler of the round initiates properly.

The fuze simulator system that was developed by the US Army Cold Regions Research and Engineering Laboratory (CRREL) for detonation research is an aluminum "plug" machined to fit the threads in the nose of the rounds being tested. The plug incorporates a pocket at the bottom that holds the booster material, similar to the booster cup for the booster pellet on a projectile fuze. In the nose of the device, a central hole is dilled through to the pocket that is just large enough in diameter to insert a standard blasting cap into the booster material (Figure 1). The dimensions of the CRREL Fuze Simulator (CFS) are dictated by both the standard issue fuze dimensions and the dimensions of the blasting cap used for initiation.

Figure 1. The CRREL Fuzing System: Inserting CFS with C4 booster in 81-mm round (L) and blasting cap in CFS prior to initiation (R).

The CFS was first tested on the Fort Richardson, Alaska, Demolition Range 3 (Demo 3) in March of 2010 [12]. For this research, we were investigating the effect of a detonation of a round in close proximity to an unexploded ordnance (UXO) item. For these tests, 81-mm high-explosive mortar rounds (M374A2) containing 950 g of Composition B (Comp B) explosive were used for both the detonating rounds and the UXO. To determine the performance of the CFS, three rounds were set up without UXO present and command detonated on the snow-covered range (Table 1, Test 2). Residues were collected from the snow surface using the multi-increment sampling (MIS) method [13].

Table 1. Munitions tested using the fuze simulators.

Test	Round	Fuze	Booster Material	Booster Mass (g)	Explosive Filler	Filler Mass (g)
1	81-mm[a]	PD[c]	A5	23	Comp B	950
2	81-mm[a]	CFS	C4	23	Comp B	950
3	60-mm[a]	CFS	C4	12.6	PAX-21	360
4a	60-mm[a]	CFS	C4	12	IMX-104	340
4b	81-mm[a]	CFS	C4	12	IMX-104	810
5a	81-mm[a]	CFS	C4	18	IMX-104	810
5b	155-mm[a]	CFS	C4	50	IMX-101	1100
6	81-mm[a]	CFS	C4	18	IMX-104	810
7a	60-mm[a]	AFS	PBX	9	IMX-104	340
7b	81-mm[a]	AFS	PBX	9	IMX-104	810
7c	155-mm[b]	AFS	PBX	9	IMX-101	1100
8	81-mm[a]	CFS	C4	12	Comp B	1100

[a] Mortar round. [b] Howitzer round. [c] Standard point-detonating fuze (live-fire test).

The samples were processed at a field lab in Alaska and at CRREL in New Hampshire prior to analysis for RDX, HMX, and 2,4,6-trinitrotoluene (TNT) [14]. Results were compared to live-fire residues estimates from testing of the same type of rounds in Alaska in 2002 [1].

A second SERDP-sponsored research project involved investigating post-detonation residues from a new generation of US insensitive munitions containing PAX and IMX explosives. Most of these munitions had not attained certification at the time of this research, so command detonations had to be conducted. Four types of rounds were tested between 2012 and 2017 (Table 1, Tests 3–6). Rounds were set up vertically on the snow-covered ice of the Eagle River Flats (ERF) impact range on Joint Base Elmendorf- Richardson for Tests 3–5 and on a clean ice surface for Test 6. MIS was used to collect the residues samples on snow. Samples on ice were collected by sweeping up the visible residues. Most rounds contained supplemental charges, which were left in the rounds. As no live-fire detonation tests for explosive residues had been conducted on this family of rounds, the C4 booster charge mass in the CFS was varied to determine its effect on the detonation efficiency (consumption of the explosive filler).

The use of C4 as a substitute for the fuze booster pellet will not fully replicate the standard booster pellet performance. To more closely match the performance of the explosive train for the rounds tested by CRREL, the US Armament Research, Development, and Engineering Center (ARDEC) at Picatinny Arsenal designed a fuze simulator based on a modified standard issue fuze, the ARDEC Fuze Simulator (AFS). The AFS incorporates the complete explosive train, including the booster pellet, of the standard fuze. The AFS was used on the rounds during the tests conducted on the ERF impact range in Alaska in 2017 (Table 1, Tests 7a–c). Rounds tested were filled with IMX-104 (60- and 81-mm) and IMX-101 (155-mm). Again, the supplemental charges were left in the rounds. The IMX-104 rounds were tested on snow-covered ice, the IMX-101 rounds on a swept ice surface. Individual detonations were sampled for the IMX-104 tests. The 155-mm rounds were detonated in groups of one, three, and three rounds. The overlapping 3-round shots were sampled by sweeping all the residues up and treating the samples as one three-shot sample, as has been done successfully with overlapping live-fire detonations in the past [15].

During the tests conducted with the AFS, six 81-mm Comp B rounds were tested with the CFS (Table 1, Test 8). This test was conducted to provide back-up data for the original CFS tests and to tie prior command detonation tests to the 2017 tests to determine if test conditions had an influence on the results. The rounds were different from the previous tests, M889A2 rather than M734A2, so direct comparison to previous data was not possible. We therefore compared the overall detonation efficiencies to determine consistency of test results. The fuze booster load was 12 g of C4 in the CFS. The mass of the explosive filler in the round was slightly higher, 1.06 kg vs. 0.95 kg. All other variables remained the same.

3 Results

Test 1

A total of fourteen 81-mm mortar rounds were fired and detonated on the ERF impact area. One detonation had no residues overlap with any other detonations (Round 1). The other 13 rounds had overlapping residues deposition areas (RDAs) and were sampled as one unit. Results are depicted in Table 2.

Table 2. Test 1 Results of live-fire detonation residues sampling, 81-mm Comp-B rounds.

Round	Deposition Area (m^2)[a]	Mass of RDX (mg)	Mass of TNT (mg)
1	230	5.4	2.2
2-14[b]	120	8.7	1.0
All[c]	130	8.5	1.1

[a] Determined visually. [b] Means of the 13 rounds. [c] Means of the 14 rounds.

Test 2

Three 81-mm rounds were detonated using the CFS on a snow-covered demolitions training range. The booster for the CFS was 23 g of C4 (91 % RDX/HMX). The detonations penetrated the snow in one case, Round 1, causing mixture of soil with the sample and elevated residues recovery (Table 3). Quality assurance samples taken outside the RDAs (ODAs) contained no energetics. Overlap of data occurred for both analyte results between Test 2 and Test 1.

Table 3. Test 2 Results of first test of CFS, 81-mm Comp-B rounds.

Round	Deposition Area (m^2)	RDX Mass (mg)	TNT Mass (mg)
1[a]	260	1.8	<0.6
2	220	<1.7	<0.01
3	200	0.7	<0.01
All[b]	230	<1.4	<0.6

[a] Detonation penetrated to ground. One replicate not included in mass calculations. [b] Means of the 3 rounds.

Test 3

Seven 60-mm rounds filled with PAX-21 explosive (RDX, 2,4-dinitroanisole (DNAN), and ammonium perchlorate (AP)) were detonated on the ice and snow covered ERF impact range using the CRREL fuzing system with a 12.6-g C4 booster charge [6]. The detonations did not penetrate the ice cover, and none of the RDAs overlapped with adjacent rounds. Results are depicted in Table 4. In the table, perchlorate (ClO_4) is reported rather than AP. Quality assurance samples taken outside the RDA contained less than 0.15 % of the total deposited mass of energetics residues.

Table 4. Test 3 Results for 60-mm PAX-21 mortar rounds with CFS.

	Deposition Area (m^2)	RDX Mass (mg)	DNAN Mass (mg)	ClO_4 Mass[a] (mg)
Means[b]	330	7.1	9.2	14,000
Ranges		0.34–40	1.3–18	7500–18,000

[a] ClO_4 (perchlorate) from the AP. [b] Analyte means of 7 rounds.

Both RDX and DNAN were consumed at rates averaging >99.99 % per round, indicating high-order detonations. The elevated estimated mass of ClO_4 recovered in the residues was a phenomenon not seen before with conventional (Comp B, TNT, octol) explosive formulations. Variability for RDX and DNAN was caused by the low mass recovery rates, at or below instrument reporting limits, for those compounds. Data for ClO_4 was normally distributed.

Test 4

For Test 4, seven 60-mm and seven 81-mm mortar rounds filled with IMX-104 explosive (RDX, DNAN, nitrotriazolone (NTO)) were detonated on the ice and snow covered ERF impact range using the CRREL fuzing system with a 12-g C4 booster charge **[8]**. The detonations did not penetrate the ice cover, and none of the RDAs overlapped with adjacent rounds. Estimated residues mass means and data variability are depicted in Table 5. Quality assurance samples taken outside the RDAs and below the increment locations sampled to determine if the depth of sampling was sufficient. Less than 0.1% of the total estimated residues were found below the original sampling depth. No residues were detected outside the RDAs for the 60-mm rounds. Residues were recovered (>3% of the total residues) outside the demarcated areas for three of the seven 81-mm detonations. The ODA residues were added to the RDA residues to calculate the total residues estimates for those detonations.

Table 5. Test 4 Results for IMX-104 mortar rounds with CFS.

Round	Deposition Area (m^2)	RDX Mass (mg)	DNAN Mass (mg)	NTO Mass (mg)
60-mm	250	1.0[a]	2.6[a]	17,000[a]
(Range)		1.0–18[b]	3.0–6.0[b]	13,000–28,000[b]
81-mm	350	16	27	1900
(Range)		0.6–47	2.1–71	900–2800

[a] Mean mass depositions of the 7 rounds. [b] Data range.

Both RDX and DNAN were consumed at rates averaging at least 99.99% per round, indicating high-order detonations occurred for all rounds. The mass of NTO recovered in the residues indicates lower detonation efficiency of this compound, similar to what was seen for the perchlorate in the PAX-21 tests. Low analyte concentrations again affected the range of residues estimates for RDX and DNAN. Data for NTO was normally distributed.

Test 5

For Test 5, we reran the 81-mm IMX-104 tests with a larger booster load in the CFS (18 g vs. 12 g) to determine if a fully efficient detonation could be initiated using more C4 in the fuze. We also tested a new munition, the M1122 155-mm howitzer practice round, which contains an IMX-101 explosive charge (DNAN, NTO, nitroguanadine (NQ)) in the nose of the round. The CFS booster mass for the 155-mm rounds was varied to determine residues mass with respect to booster mass for this very insensitive munition. The detonations did not penetrate the ice cover, and none of the RDAs overlapped with adjacent rounds. Results are depicted in Table 6.

Quality assurance samples were taken outside the RDAs and also below the increment locations sampled to determine if the depth of sampling was sufficient. Less than 0.8% of the total estimated residues were found below the original sampling depth and in the ODAs. These residues were added to the RDAs to calculate the total residues estimates for those detonations.

Both RDX and DNAN were consumed at rates averaging >99.99% per round, indicating high-order detonations occurred for the 81-mm rounds. The mass of NTO recovered indicates a higher detonation efficiency with the larger fuze booster mass, demonstrating the ability to vary detonation efficiency with fuze simulator booster mass. Low analyte concentrations again affected the range of residues estimates for RDX and DNAN. Performance of the three IMX-104 energetic compounds is similar relative to Test 4, with NTO residues higher than DNAN and RDX residues, which are similar to each other.

The results for the 155-mm round indicate a high-order detonation did not occur. None of the nine detonations reached the 99.99% filler consumption we use for determining a high-order detonation. Detonation consumption of the three energetic compounds increased with increased booster load, but little improvement occurred between the 50-g load and 60-g load, indicating a leveling off of efficiency. The supplemental charge in the 155-mm round contained RDX, the consumption of which exceeded 99.99% for all 155-mm tests, indicating that the supplemental charge functioned properly.

Test 6

Test 6 was a confirmation test for the 81-mm IMX-104 rounds of Test 5. All initiation systems used the CFS with 18 g of C4 in the booster. For rounds 1 and 2, the deto-

Table 6. Test 5 Results for IMX-104 and IMX-101 rounds with CFS.

Round	Deposition Area (m^2)	RDX Mass (mg)	DNAN Mass (mg)	NTO Mass (mg)	NQ Mass (mg)
81-mm	670	8.0[a]	8.0[a]	540[a]	–
(Range)		>1.0–15[b]	<2.0–23	370–700	–
155-mm	280[c]	–	5,900	40,000	170,000
	320[d]	–	2,400	15,000	130,000
(Range)		–	120–4800[b]	6800–27,000	86000–180,000
	670[e]	–	660	14,000	120,000

[a] Mean mass depositions. [b] Data range. [c] 40-g booster mass/one round. [d] 50-g booster mass/7 rounds. [e] 60-g booster mass/one round.

Table 7. Test 6 Results for 81-mm IMX-104 mortar rounds with CFS.

Round	Test Surface	Deposition Area (m^2)	RDX Mass (mg)	DNAN Mass (mg)	NTO Mass (mg)
1 & 2	Snow	620[a]	7.6 (3.8)[b]	26 (13)[b]	2300 (1100)[b]
(Range)			6.7–9.3	22–30	1500–3000
3	Ice	460	7.8	32	720
4	Ice	450	0.4	1.2	730

[a] Moderate winds (3 m/s) caused an elongation of the deposition area. [b] Value in (parentheses) are average values per round.

Table 8. Test 7 Results for IMX-104 and IMX-101 rounds with AFS.

Round	Rounds	Deposition Area (m^2)	RDX Mass (g)	DNAN Mass (g)	NTO Mass (g)	NQ Mass (g)
60-mm	7	250	0.009	0.007	3.8	–
	Range[a]	190–450	0.001–0.048	0.003–0.014	2.6–5.2	
81-mm	7	770	0.011	0.047	1.7	–
	Range[a]	680–870	0.001–0.050	0.005–0.23	0.79–3.0	
155-mm	1	180	–	1.6	31	49
	2–4[b]	180	–	3.5	37	59
	5–7[b]	180	–	1.3	28	26
	Means	–	–	2.3	32	44

[a] Range of values for the 7 rounds, based on averages of the three replicates for each detonation. [b] Per round estimate.

nations were co-located and occurred on snow covered ice. Multi-increment snow samples, five replicates from the RDA, plus 2 replicate ODA samples were collected and analyzed. No residues were detected in the ODA samples (below detection limits). For rounds 3 and 4, detonations occurred on a clean, bare ice surface, which was swept to obtain the sample. RDAs were estimated based on the visible residues on the ice surface. Results are depicted in Table 7.

Both RDX and DNAN were consumed at rates averaging >99.99% per round, indicating a high-order detonation. Once again, NTO recoveries were elevated compared to the DNAN and RDX, indicating a differential consumption efficiency of that compound. Scatter in the data for RDX and DNAN is also consistent with previous data and is tied to the very low recovery concentrations. Overlap in the data from Test 5 and Test 6 indicates the results for these two tests are not significantly different. There is consistency between the three similar tests.

Test 7

The ARDEC Fuzing System was used to initiate the IMX-104 and IMX-101 rounds for Test 7. The booster material in the AFS is a polymer-bonded explosive (95% HMX). For the 60- and 81-mm rounds, detonations occurred on blocks of ice placed on snow-covered ice. Triplicate multi-increment snow samples from the RDA plus samples outside the RDA were collected and analyzed for each detonation. No residues were detected outside the RDAs. Chunks of IMX-101 were detected during a pre-test detonation of the 155-mm round, so the 155-mm test rounds were detonated on cleared ice to enable collection of all the residues. The seven rounds were detonated in three shots because the cleared ice area was limited. The shots were composed of one round, three rounds, and three rounds, with overlap between the round for the multi-round shots. Residues were collected between shots. The deposition area given is for the area swept for each of the shots. Samples were pre-processed at the on-site lab and sent to the CRREL analytical lab in Hanover, NH, for final processing and analyses. Results are depicted in Table 8. Note that the mass estimates are given in grams.

Again, both RDX and DNAN were consumed at rates averaging >99.99% per round for the 60- and 81-mm mortar rounds, indicating a high-order detonation of the IMX-104 explosive. NTO recovery was elevated, comparable to the mass estimates from Test 4. For the 155-mm rounds, the concrete filler material of the round that was liberated during the detonation and collected with the residues sample altered the pH of the samples when they were melted during processing. With a pH of 11 or higher, base hydrolysis of the DNAN and NQ occurred, resulting in lower apparent mass recovery rates for those compounds. Hydrolysis will be covered further in the Discussion section. NQ mass was similar to that estimated from Test 5 (See Table 6).

Test 8

Test 8 was a test of the CFS on a different Comp-B filled 81-mm mortar round. The original type mortar round (M734) was not available, so tests were conducted with a newer round (M889). The booster material in the CFS was 12 g of C4. Six rounds were detonated on snow-covered ice in two shots (1–3, 4–6) and sampled using triplicate MIS. No residues were detected in the ODAs (below detection limits). Results are depicted in Table 9.

Table 9. Test 8 Results for 81-mm Comp B rounds with CFS.

Round	Deposition Area (m^2)	RDX Mass (mg)	TNT Mass (mg)
1	300	<0.4	<0.4
2	240	<0.4	<0.4
3	370	<0.4	<0.4
4	410	<0.4	<0.4
5	590	0.64	<0.4
6	570	<0.4	<0.4
Means	460	<0.44	<0.4

4 Discussion

The simulation of live-fire detonations using a command-detonation fuzing system appears feasible, based on this study. Using two different fuzing systems and testing five different rounds of three calibers resulted in very consistent data. Testing of the 81-mm Comp-B rounds strongly indicates that command detonation of those rounds resulted in data consistent with live-fire residues mass data.

Testing of the insensitive munitions was of particular interest. The two fuzing systems, the CFS and the AFS, performed comparably, with the AFS results slightly but significantly higher than the CFS results for the mortar rounds, the only comparable data available for the two systems (Figure 2). Significance was determined using Student's t-Test (60-mm) and Fisher's Least-Significant Difference technique (81-mm). All datasets of six or more detonations were normal.

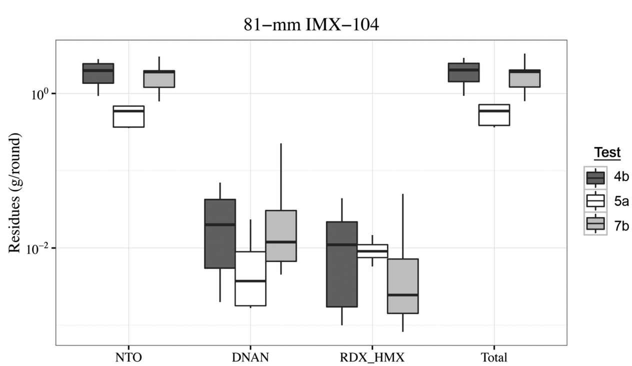

Figure 2. Box plots of 81-mm IMX-104 munitions tests.

The base hydrolysis of the DNAN and NQ that occurred during and following the melting of the samples for Test 7c disrupted the dataset for that test. Comparisons between Tests 5b and 7c are thus not directly possible, although the residual mass of NTO, which appeared unaffected for Test 7c, is quite similar to that found during Test 5b, with a factor of 2 difference for the 50- and 60-g booster charge and little difference with the 40-g booster mass. The type of round tested, a practice round with a 1-kg spotting charge, cannot be compared to previous 155-mm high-explosive rounds tested containing Comp-B and TNT.

The use of the AFS system is recommended because it more accurately mimics the explosive train of a live-fired round. The use of the AFS eliminates the need to estimate the C4 mass equivalent of the booster pellet in the CFS fuzing system. Both systems provide similar results when the C4 mass of the CFS is correctly estimated, and the CFS will allow experimentation of the effects of varying booster pellet load on munition efficiency. Both systems will also greatly improve post-detonation residues as reported in life-cycle assessments of munitions [16].

Although testing with both command-detonation fuze systems returned very valuable data, live-fire research on these munitions should also be conducted. We feel this is necessary to verify the results of our tests and to ensure that decisions made based on our testing are correct.

5 Conclusions

Two fuzing systems have been developed and tested for the command detonation of high-explosive artillery projectiles. The system developed by CRREL uses a blasting cap and C4 fuze booster charge to initiate detonation of the explosive filler of the munition. The system developed by ARDEC uses as a basis a modified standard-issue fuze for the round under test that retains the explosive train and thus more closely simulates the functioning of a live-fired round. Both systems gave consistent results compared to the other system, and results within each test were also consistent, with normally distributed data. The one test that included live-fire data indicated similar results between live-fire and command detonations. Based on our testing, the fuzing systems may be used to obtain preliminary performance data in the munition development process. The use of the ARDEC system is recommended as it reduces the number of test variables.

Further research needs to be conducted to assess the performance of both fuzing systems with actual live-fire detonation residues data. This research will verify whether or not command detonations can be used to simulate live fire. Using empirical data as derived from these tests will greatly improve the accuracy of life cycle environmental assessments of post-detonation energetics residues.

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