ENVIRONMENTAL CHARACTERIZATION OF MILITARY TRAINING RANGES FOR MUNITIONS-RELATED CONTAMINANTS: UNDERSTANDING AND MINIMIZING THE ENVIRONMENTAL IMPACTS OF LIVE-FIRE TRAINING

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An important R&D effort was dedicated to the characterization of ranges and training areas and to the study of the environmental fate and the ecotoxicological impacts of munitions constituents in the last 20 years in Canada and the United States. Major environmental issues were identified, and the sources of munitions constituents in training ranges are better understood. Protocols were developed for collecting representative soil samples and their effective processing. In the last years, a large effort was dedicated to the measurement of the mass of munitions constituents deposited both at target impact areas and at firing positions, which led to a good estimation of source terms of contaminants. In Canadian ranges and training areas, efforts were also dedicated to characterize both surface and subsurface aquifers and geology, and detailed hydrogeological and geological mapping. All the data acquired over the last years have been used to build hazards and vulnerability maps, which can be combined to draw risk maps that represent great assets from a risk-management perspective. The next step is the development of environmentally sound solutions that will sustain military training and maintain force readiness. In order to achieve that goal, efforts are committed to the modification of actual live-firing activities to minimize their environmental adverse impacts. Finally, Canada is aiming at developing greener and insensitive munitions that will ease the environmental pressure. This paper is a summary of what has been done in North America toward understanding and minimizing the environmental footprint of munitions.

KEY WORDS: *characterization, munitions, unexploded ordnances, live fire, training ranges, environmental impact, deposition rate, munitions constituents, fate, ecotoxicology, hydrogeology, explosives, propellants*

1. INTRODUCTION

The readiness of the armed forces is predicated on well-trained troops and continuous enhancement of their munitions arsenal. Sustained live-fire training is critical to preparedness for missions abroad. Military live-fire training activities generate source zones of munitions constituents (MCs) in the environment, which threaten range sustainment. A source zone may be defined as an area where chemicals are deposited, usually on the surface soils, which poses a threat to ecological or human receptors. The Canadian Sustainable Training R&D program is aimed at maintaining both military readiness and environmentally friendly defense activities in order to ensure the long-term usage of military ranges and training areas (RTAs). In order to understand the various aspects related to the dispersion and fate of MCs, multidisciplinary collaborations were established with national and international research centers. In Canada, our main collaborators are the Institut National de la Recherche Scientifique-Centre Eau, Terre et Environnement (INRS-ETE) as well as the Biotechnology Research Institute of the National Research Council of Canada (BRI-NRC). In the United States, our collaborators are from the Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). Over the years, various aspects of research were supported by many stakeholders, including Defence R&D Canada (DRDC), R&D thrusts (Munitions and Firepower and Sustain thrusts), Director General Environment (DGE), Director Land Environment (DLE), and an U.S. peer-reviewed funding program, the Strategic Environmental Research and Development Program (SERDP, Arlington, VA). In order to better understand the extent of the problem, DRDC initiated a research program for the environmental assessment of the Army's RTAs. The RTA characterization work was conducted both in Canada and the United States and was done in collaboration with U.S. scientists from ERDC-CRREL to better understand the nature and extent of contamination.

Extensive surface soil characterization of most of the Canadian RTAs was done in conjunction with hydrogeological studies performed by INRS-ETE. Moreover, the study of the environmental fate of energetic materials (EMs) was conducted in close collaboration with BRI-NRC scientists. The strategy of sampling, sample treatment, and the analytical chemistry of soil and water samples and the RTA characterization work was done in collaboration with U.S. scientists from ERDC-CRREL (Ampleman et al., 1998, 2000, 2003a,b, 2004, 2008a, 2009; Brochu et al., 2008; Clausen et al., 2007; Dubé et al., 1999; Diaz et al., 2007; Jenkins et al., 1997a,b, 1998, 1999, 2001, 2004, 2005; Hewitt et al., 2003, 2007a,b, 2009; Thiboutot et al., 1997, 1998, 2000, 2001a,b, 2002, 2003a,b,c, 2004, 2008a; Marois et al., 2003, 2004; U.S. EPA, 2006; Walsh et al., 2002, 2004). Protocols were published both in Canada and the United States to effectively characterize the huge tracks of military live-fire lands (Hewitt et al., 2009; Jenkins et al., 2005a; Thiboutot et al., 2012). Through DRDC's participation in the North Atlantic Treaty Organization (NATO), the authors are aware that very few countries have published such

protocols up to now. The only country other than Canada or the United States that has reported a similar document is Norway (Voie et al., 2010). Figure 1 illustrates the numerous RTAs characterized for MCs deposition across North America by the DRDC and CRREL teams. The RTAs characterized over the years are spread out all over North America, which allowed the study of the effects of various geological formations and various climates.

The understanding and evaluation of the source terms for most weapons, both at impact areas and firing positions (FPs), were needed to better assess the actual source term of contaminants generated by the live-firing activities. Various trials were dedicated to estimating the deposition rates of most weapon platforms and characterizing the accumulation at target areas. In 2000, a six-year research project (SERDP ER-1155) was initiated by DRDC and CRREL, cosponsored by Canadian stakeholders and SERDP to study the deposition, accumulation, and fate of explosives at live-fire training ranges. SERDP project ER-1155 focused on impact areas where explosives such as hexahydro-1,3,5trinitro-1,3,5-triazine (RDX) were deposited, and where the potential for groundwater contamination was thus the highest. This project allowed the development of transport processes descriptors for the current explosives and their main transformation products and contributed to the understanding of the various sources of explosive contamination in target impacts areas (Jenkins et al., 2005a; Pennington et al., 2001, 2002, 2003, 2004, 2005, 2006a,b).



FIG. 1: RTAs characterized in North America.

Volume 11, Number 1, 2012

In 2006, SERDP project ER-1481 was initiated and cosponsored by SERDP and DLE to study the distribution, fate, and transport of propellant residues at firing points associated with live-fire training with munitions (Ampleman et al., 2008b, 2010; Jenkins et al., 2007, 2008; Poulin et al., 2008a,b; Poulin and Diaz, 2008; Quémerais et al., 2007a,b; Thiboutot et al., 2008b,c, 2009, 2010; Walsh et al., 2006, 2008, 2009). This allowed a better understanding of the contamination pattern at the firing positions. Several studies have also been performed on the wider fate of munitions constituents, mostly in collaboration with INRS-ETE and BRI-NRC (Bordeleau et al., 2007, 2008a,b; Halasz et al., 2002; Hawari et al., 2000a,b, 2001; Lewis et al., 2009; Mailloux et al., 2008a; Martel et al., 2007, 2009; Monteil-Rivera et al., 2004; Robertson et al., 2007; Zhao et al., 2004). A large effort was also dedicated in Canada on the study of the ecotoxicological impacts of MCs (Doddard et al., 2005; Lachance et al., 2008; Sarrazin et al., 2009; Robidoux et al., 2000, 2001, 2005; Rocheleau et al., 2008; Sunahara et al., 2009).

On the basis of these studies, environmental issues were identified and solutions to these problems are under development. Efforts are dedicated to modifying live-firing activities to minimize their environmental footprints. A few of the efforts presently conducted to minimize the deposition of MCs in Canadian RTAs will be presented. This paper describes the North American approach toward understanding and minimizing the environmental footprint of munitions in a live-fire context.

2. CONTAMINANTS OF CONCERN

Accurately detecting the type and quantity of contamination from MCs and their breakdown products in water, soil, and sediments is vital for assessing the extent of contamination and ultimately the risk to human and ecological receptors. This paper focuses on specific munitions-related contaminants and methods specific to RTAs and unexploded ordnances (UXOs) contaminated sites. The contaminants of concern that might be dispersed in the environment following live-fire training are mainly EMs and metals. Conventional weapons for live-fire training use EMs in the form of propellants (propulsion) and main charge explosive (detonation).

The explosives that are most frequently detected in RTAs are: RDX, 2,4,6-trinitrotoluene (TNT) and its main degradation products 2-amino-4,6-dinitrotoluene (2-A-DNT) and 4-amino-2,6-dinitrotoluene (4-A-DNT), high-melting explosive or octrahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), and rarely 2,4,6-trinitro-phenylmethylnitramine (tetryl) (Jenkins et al, 2005a). Propellants include both rocket and gun propellants. Most rocket propellants consist of a rubbery binder filled with ammonium perchlorate (AP) oxidizer and may contain powdered aluminum as fuel. Propellants may also be based on nitrate esters, usually nitroglycerine (NG), nitrocellulose (NC), or a nitramine such as RDX or HMX. Gun propellants are usually referred to as single base (composed of NC), double base (composed of NC and NG), or triple base [composed of NC, NG and nitroguanidine (NQ)]. Single-base propellants may also contain 2,4-dinitrotoluene (2,4-DNT) with traces of 2,6-dinitrotoluene (2,6-DNT). The vast majority of gun propellant formulations in Canada are either single- or-double base propellants and include lead as a decoppering agent, which represents another adverse environmental contaminant. Propellant formulations contain several other minor components such as stabilizers, plasticizers, and burn rate modifiers, but they represent <2% by weight of the propellants and have never been detected as MCs in soil surfaces. The major classes of EM used by the Department of National Defence (DND) are presented in Fig. 2. Tables 1 and 2 present the most commonly used explosive and propellant formulations in North American RTAs. In summary, the main EMs of concern in RTAs are: RDX, HMX, TNT, 2-A-DNT, 4-A-DNT, 2,4-DNT, 2,6-DNT, NG, NQ, and AP. NC is not included in this list because it is a polymer of very low toxicity and bioavailability and complex to analyze in environmental matrixes.



FIG. 2: Major classes of explosives.

Military appellation	Usage	Ingredients
Composition P	Artillary morter granada	60% RDX (contains 10% HMX) 39%
Composition B	Artificity, mortar, grenaue	TNT (1% TNT isomers and DNT)
C-4	Demolition explosive	91% RDX and wax
Tritonal	Air force bombs	80% TNT, 20% aluminium
TNT	Artillery	TNT
Octol	Antitank rockets	70% HMX (contains 10% RDX),
Octor	Antitalik TOCKETS	30% TNT
A4	40-mm grenade	RDX (contains 10% HMX)

TABLE 1: Explosives formulations

TABLE 2: Propellant formulations

Military appellation	Usage	Main ingredients
Single base	Small arms to 155 mm	NC, 2,4-DNT
Double base	Antitank rockets	NC, NG
Triple base	Large caliber guns	NC, NG, NQ
Composite	Rockets and missiles	Polymeric binder, AP

Live firing of munitions also spreads inorganic contaminants in the environment. Metals are deposited onto range soils by a variety of processes. High-order detonations generally disperse very fine metal particles, with the exception of prefragmented rounds, which might produce large fragments even in high-order scenarios. Much larger fragments are generally produced by low-order detonations. Metals can be transformed in other metallic compounds not originally present in the munitions. This transformation can occur either during the detonation process or during weathering of the metallic particles deposited on the range. For example, during a detonation event, the temperatures and pressures reach extremely high values that exceed the melting temperatures of some of the metallic compounds present in the munitions. These molten species are then free to react with other compounds to form new alloys, metallic complexes, or salts, which will all have their own environmental fate. After dispersion in the surface soil, both chemical and physical weathering of the metallic particles of fragments will take place. All the metals originally present in munitions are dispersed in RTAs after detonation, either in their original state, or as other metallic compounds. The list of metal analytes of concern will be presented later on in this paper.

3. SOURCES OF MUNITIONS CONSTITUENTS IN RANGE AND TRAINING AREAS

An understanding of the source of MCs in RTAs will facilitate the delineation of the source zones of EMs and metals in RTAs. This will help in establishing the localization, size, and shape of the decision units (DUs), or areas where sampling should be conducted.

3.1 Sources of EMs

The study of the sources of EMs is divided into two main groups: the firing positions (FPs) and the target impact areas. In the case of the FPs, several environmental assessment studies have shown that residues coming from the incomplete combustion of gun propellant accumulate as solid fibrous particulates in front of the FPs of guns, from small arms to large calibers (Ampleman et al., 2008b, 2010; Jenkins et al., 2007, 2008; Poulin et al., 2008a,b; Poulin and Diaz, 2008; Quémerais et al., 2007a,b; Thiboutot et al., 2008b,c, 2009, 2010; Walsh et al., 2006, 2008, 2009). Figures 3 and 4 show trials conducted to measure the masses of propellant deposited from the live firing of artillery and tank munitions. Constituents of concern at FPs are mostly 2,4-DNT and NG. Concentrations up to 140 mg/kg were observed at the FPs of small arms ranges (Walsh et al., 2007a), while concentrations as high as 6100 mg/kg of NG were detected behind antitank firing positions (Thiboutot et al., 2004).

The measurements of the mass of propellant residues deposited from various platforms have resulted in a good estimation of the source term of each type of firing, and



FIG. 3: Major classes of explosives.



FIG. 4: Propellant deposition trial, 105 mm artillery.

global results obtained are presented in Table 3. This table represents the most comprehensive database on propellant accumulation at this time.

Accumulation of NG and 2,4-DNT in the environment is cumulative over the years, since the NC matrix protects MCs from degradation and dissolution processes. A study on the fate of propellant residues was conducted on a former antitank FP that had been inactive for more than 35 years (Thiboutot et al., 2010). This study demonstrated that

Volume 11, Number 1, 2012

FABLE 3: Deposition	of propellant residu	tes from live firing of	f various	s platforms	
Weapon system	Weapon size	Munition tested	EM	Residues / round (mg)	Deposition rates (%)
Small cal. (U.S.)	9 mm pistol	M882	ŊĠ	2.1	5.32
	5.56 mm rifle	M855	NG	1.8	1.10
	5.56 mm MG	M27	ŊĊ	1.3	0.71
	7.62 mm MG	M80	ŊĊ	1.5	0.56
			DNT	0.0018	0.05
	12.7 mm MG	9M	NG	11	0.74
Curoll on Counda	9 mm pistol	MK1 Ball	NG	0.74	1.39
Small cal. Canada	9 mm pistol	Frangible	ŊĠ	0.95	1.97
	9 mm pistol	115 FMJ Ball	NG	2.03	3.90
	5.56 mm C7 rifle	Frangible	ŊĊ	1.06	0.62
	5.56 mm C7 rifle	C77 ball clip	NG	0.30	0.19
	5.56 mm C7 rifle	C79A1 blank clip	NG	0.02	0.05
	5.56 mm C8 AC	C77 ball clip	NG	0.07	0.04
	5.56 mm C8 AC	C79A1 blank clip	ŊĠ	0.02	0.06
	5.56 mm C9 MG	C77/C78 link	ŊĊ	0.05	0.03
	5.56 mm C9 MG	C79A1 blank clip	ŊĊ	0.01	0.01
	7.62 mm C6 MG	C21/C19 ball link	NG	0.98	1.36
	7.62 mm C6 MG	C24 blank	NG	0.16	na
	0.338 Cal rifle	Match B406	NG	0.03	0.001
	0.5 Cal MG	M2/M17 link	NG	0.25	0.02
	0.5 Cal rifle	AAA750	NG	0.27	0.02
Med cal.	40 mm	Mk281 Mod 0	NG	2.2	0.59
		M430	ŊŊ	76	8.44

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International Journal of Energetic Materials and Chemical Propulsion

Thiboutot et al.

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TABLE 3: Continu	led				
Weapon system	Weapon size	Munition tested	EM	Residues / round (mg)	Deposition rates (%)
Mortars	60 mm	M888 / M702	NG	0.088	0.0065
	81 mm	M301A3 / M185	NG	1,000	3.3
	120 mm	M933 / M230	NG	350	1.4
Rockets	84 mm	M136 (AT4)	NG	95,000	73
	84 mm	Carl Gustav	NG	20,000	14
	66 mm	M72 LAW	NG	42	0.19
	204 mm	GMLRS	AP	< 1.6	< 0.000003
	203 mm	MK-58 AIM-7	AP	2.000	0.000000425
Howitzers	105 mm	M1 / M67	DNT	34	0.081
	105 mm	M1 charge 5	DNT	29	0.050
	105 mm	M1 charge 4	DNT	135	0.290
	105 mm	M1 charge 6	DNT	193	0.230
	155 mm	M107 / M3	DNT	1.2	0.0000480
British L131	155 mm	L8 charge 3	NQ	0.066	0.00000870
		L8 charge 5	NQ	0.857	0.0000442
		L10 charge 8	NQ	0.415	0.000062
		L8 charge 3	NG	0.015	0.00000579
		L8 charge 5	NG	0.200	0.0000304
		L10 charge 8	NG	0	0
Tank	105 mm	C109A1(Canada)	DNT	7.9	0.00263

levels as high as 4000 mg/kg of NG are still detected in the surface soils, showing that the residence time of propellant residues was long, consistent with work conducted by Dontsova et al. (2009a). Using Table 3 and data from range firing logbooks, it is now possible to estimate the quantity of propellant residues that is deposited over a determined period at a specific range. As an example, if 100 rounds of 84 mm Carl Gustav are fired on a range, it means that around 200 g of NG will be deposited behind the firing position. A comprehensive review paper on propellant deposition rates for various munitions has been presented at a NATO RTO symposium (Ampleman et al., 2011).

Another source of propellant residues identified in RTAs comes from the burning of excess artillery propellant charges. Artillery guns use a propelling charge system composed of multiple charge bags to fire projectiles at required distances. Following a gun firing operation, discarded propelling charge increments were open burned near the gun position on the soil surface or on snow/ice in the winter (Figs. 5 and 6). Sampling of the surface soils demonstrated that burning residues built up and represented a threat to the environment and human health. A recent fate study conducted by INRS-ETE demonstrated that 500 g of burning residues spread over 1 m² of surface soil may lead to the contamination of more than 7.5 million liters of groundwater in the first infiltration (Martel et al., 2010). Contrary to the particles deposited at the gun mouth, which led to a very slow dissolution rate of 2,4-DNT or NG, open burning led to a highly leachable fraction of 2,4-DNT, which is rapidly brought to the groundwater (Martel et al., 2010). This situation mandated the development of a safe and environmental alternative destruction methods.

Overall, the following areas can be considered potentially contaminated by propellant residues in RTAs' FP:



FIG. 5: Field expedient burning of excess artillery propellants.

International Journal of Energetic Materials and Chemical Propulsion



FIG. 6: Leftover residues after burning on snow.

- In front of gun FPs, from small arms to 155 mm calibers
- Behind and in front of antitank rocket FPs
- At former excess propellant field expedient burning sites

At the other end of the range, target areas were highly suspected of being contaminated by explosive residues. Many trials were dedicated to better understanding the deposition pattern of explosive residues from various scenarios (Jenkins et al., 2005a; Pennington et al., 2001, 2002, 2003, 2004, 2005, 2006a,b, 2008a,b; Walsh et al., 2005b). The conclusions drawn from this work are presented in this subsection. The following sources of explosives have been studied: high-order detonations, low-order detonations, UXO blow in place (BIP), UXO shell cracking, and UXO corrosion.

High-order detonations are defined as detonations that reach the desired pressure and detonation velocity. The evaluation of explosives deposition following high-order detonations is not a simple task. The detonation process involves high pressure and temperature, and the deposition pattern can be very complex to assess. Various trials were conducted and led to the development of a setup involving detonation on pristine snow cover, which allowed an easier delineation of the deposition plume (Jenkins et al., 2002; Walsh et al., 2007b). Table 4 presents representative high-order results obtained with mortars, hand grenades, and artillery rounds. As illustrated in Table 4, the quantities of explosive deposited from high-order detonations are very small, almost at forensic

Weapons system	Explosive	Number of rounds fired	Percent of un- burned explosive deposited (%)	Mass de- posited per round (µg)
Mortar 60 mm	RDX	11	$3 imes 10^{-5}$	94
Mortar 81 mm	RDX	5	$2 imes 10^{-3}$	8500
Mortar 81 mm	TNT	5	$3 imes 10^{-4}$	1100
M67 Hand grenade	RDX	7	$2 imes 10^{-5}$	25
Howitzer 105 mm	RDX	9	$7 imes 10^{-6}$	95
Howitzer 105 mm	TNT	9	$2 imes 10^{-5}$	170
Howitzer 155 mm	RDX	7	$5 imes 10^{-6}$	310

TABLE 4: Mass of explosive deposited from high-order detonations

levels. The quantities are spread over large areas, and do not lead to the buildup of concentrations of concern of explosives. Low-order detonations might happen in various scenarios in live-firing events. A large percentage of the fired munitions function as designed and generate high-order detonations. A fraction varying from 1 to 50% of rounds might generate low-order detonations or UXO. The failure rate of munitions depends on the type of round, and in general, artillery rounds have a malfunctioning rate around 1–5%, whereas antitank rockets have a malfunction rate as high as 50%. A low-order detonation is defined as a detonation that does not reach the maximum detonation pressure and temperature, and is sometimes referred to as a deflagration. Low-order detonations were achieved on purpose by using a weak detonation trigger (Pennington et al., 2001, 2002, 2003, 2004, 2008a,b), and it was found that while high-order detonations deposit micrograms of fine explosive dust, low-order detonations deposit gram quantities of explosives from fine dust to large chunks. Table 5 presents deposition results measured from low-order detonations of mortar and artillery shells. When sampling RTAs, loworder detonation sites were encountered where the presence of high concentrations of explosives was always detected. Figure 7 presents a representative low-order detonation crater sampled in Canadian Force Base (CFB) Cold Lake RTA (Ampleman et al., 2004). The reddish color of the pond indicated the presence of TNT photodegradation by-products.

Item	Explosive fill	Percent of unburned explosive deposited (%)	Mass deposited (g)
Mortar 60 mm	Composition B	35	67
Mortar 81 mm	Composition B	42	300
Howitzer 105 mm	Composition B	27	620
Howitzer 155 mm	TNT	29	2000

TABLE 5: Mass of explosive deposited from low-order detonations

International Journal of Energetic Materials and Chemical Propulsion



FIG. 7: Low-order detonation crater in Cold Lake RTA.

In order to solve the safety risk that a surface UXO represents in our RTAs, explosive ordnances disposal (EOD) teams regularly proceed to an UXO BIP operation that consists of detonating C-4 blocks nearby the UXO (without moving it). The impacts of disposal operations conducted on RTAs when encountering UXO by detonating them with C-4 is now better understood. The use of unconfined C-4 blocks generates the dispersion of RDX in the surrounding of the detonation point (Pennington et al., 2002, 2003, 2004, 2005, 2006,a,b, 2008,a,b). Moreover, the probability of leading to low-order detonations when doing BIP is higher than in a live-firing context, since the UXO can be partially buried or in a configuration that does not allow a high-order event when initiating it with C-4. Therefore, locations where intense BIP has been conducted might present measurable concentrations of RDX from the C-4 and also of other explosives from the UXOs.

Finally, an important source of explosive in RTAs was identified through the quest for understanding the explosive contamination pattern. Surface UXOs in impact areas are susceptible of being hit by razor sharp flying fragments from close-proximity highorder detonations. Designed experiments using 81 mm mortar shells demonstrated that this phenomenon is very easy to achieve and led to gram to kilogram quantities of explosives in the surrounding environment (Lewis et al., 2009; Walsh et al., 2011a). This indicates that the surface to near-surface UXOs that are exposed to other rounds that explode nearby represent an important source of explosive in the surface soils. The broken shells can release as much as the totality of their explosive content in the environment. This source of explosive residues stresses the importance for regular clearance of surface UXOs in RTAs. EOD teams normally take care of the UXOs by BIP as soon as they identify one. The regular elimination of surface UXOs from highly used impact areas such as an artillery impact central area might not be always feasible and, therefore, cracked UXOs shall be looked for when sampling for explosive residues in target impact areas, and the surrounding area must be sampled. If feasible, remains of the cracked UXO shall be eliminated either by detonation or else by collecting the large chunks of explosives that may remain on site. A detailed review paper on explosive deposition rates for various munitions has been presented at a NATO RTO symposium (Walsh et al., 2011a).

On a longer-term perspective, corrosion of the munitions casings also represents a source of explosives in the environment and a related risk to the underlying groundwater. The corrosion rate is a complex phenomenon, which depends on soil conditions, on heating/cooling and wet/dry cycles, on soil physicochemical characteristics, and many other parameters. It is assumed that corrosion represents a long-term source term that is still undefined and that most of the risk is not related to surface soils but to groundwater.

The major conclusions from RTAs characterization and explosive deposition studies are as follows:

- A forensic amount of explosives is deposited when a round is functioning as designed.
- BIP detonations deposit a greater percentage of residues than live-fire high order and deposit RDX from the C-4 donor charge.
- By far, the largest explosive residues deposition is from low-order detonations and particles deposited that range from micrometers to centimeters in diameter.
- As a rule of thumb: it takes 10,000 to 100,000 high-order detonations to deposit the same amount of explosive as one low-order detonation.
- Surface UXO cracking may expose as much as 100% of the explosive filler to the environment and also represents an important source of contamination.

3.2 Sources of Metals

The precise knowledge of the metallic composition of munitions is generally unknown, because this kind of information is proprietary to the manufacturer. Nevertheless, the following subsection provides an overview of the main known sources of metals in RTAs as well as their deposition processes.

As for EMs, the studies of metal deposition in RTAs are divided in two parts: the metals at the FP and at the impact areas. In the case of the FP, metals generally come from the detonation of the primer, from the combustion of the gun propellant, from the erosion of munitions or weapon during the firing event, or from large metallic parts ejected from the weapon during the firing, such as small arms cartridge cases. The metals that could be expected would mostly be copper, zinc, lead, and mercury. Firing positions are generally small areas on which contaminants could potentially accumulate very fast.

However, metallic species are seldom detected at firing positions in concentrations above guidelines. Large metallic parts, such as casings, are recovered by the users after the training activity. The screening for metals at an FP is therefore not mandatory.

In the case of impact areas, the metals come from the projectiles. In general, mediumand large-caliber munitions projectiles are made of steel [an alloy of iron (Fe) and carbon (C)] or aluminum (Al). Small-caliber bullets mainly contain lead (Pb), antimony (Sb), arsenic (As), copper (Cu), and zinc (Zn), and grenade bodies are generally made of brass, a Cu-Zn alloy. Fe and Al are ubiquitous in the environment and of little concern, but Pb, Sb, Cu, and Zn are regulated in Canada. In addition, a wide variety of metals are also present in the other parts of the munitions (e.g., fuse, booster and primer cups, cartridge, tail, stabilizing fins, primer tube, connecting elements, percussion pin, etc.), albeit in smaller quantities. For example, the 60 mm mortar contains Fe in the shell, aluminum, Zn, magnesium (Mg), and Cu in the tail and the stabilizing fins, and Al, Cu, bismuth (Bi), and Pb in the cartridge. Primary explosives also constitute another source, albeit small, of heavy metals such as Pb or mercury (Hg). A comprehensive guide has been published by ITRC (2005) and includes the list of contaminants targeted for analysis in small arms ranges, as shown in Table 6. Most of the metallic debris deposited in the impact areas of RTAs come from the munitions' casings and are located in the vicinity of targets. However, an important source of metals in RTAs that is often overlooked is the target itself (e.g., old tanks, cars, trucks, etc.) that can be partly disintegrated by the detonation of munitions into metallic debris of various particle size and compositions. This metallic debris also has an environmental impact and should not be neglected when performing an environmental risk assessment.

4. SAMPLING STRATEGY FOR MUNITIONS CONSTITUENTS IN SURFACE SOILS

The primary objectives in RTAs characterization are as follows:

- To measure the surface soil contaminants that may pose a threat to the health of military users that may come in contact with the contaminants (human exposure)
- To measure the surface soil contaminants that may further be dissolved and brought to the surface water bodies
- To measure the surface soil contaminants that may further be dissolved and reach the groundwater
- To measure the surface soil concentrations that may pose a threat to local ecological receptors (ecotoxicity)
- A combination of some or all of the above

Volume 11, Number 1, 2012

Constituent	Symbol	Source
Lead	Pb	Primary constituent of most projectiles
Lead styphnate/lead azide		Primary constituent of most primers
Antimony	Sb	Hardening agent
Antimony Sulfide		From 5% to 30% is used in most primer compounds
Arsenic	As	Lead shot constituent (used in the produc- tion of small shot since it increases the sur- face tension of dropped lead, thereby im- proving lead shot roundness)
Copper	Cu	 Sometimes a primary alloy in center-fire ammunition and some small-caliber rifle bullets also used in frangible pistol ammunition Jacket alloy metal (Increases hardness)
Bismuth	Bi	Lead shot replacement
Tin	Sn	Primary metal for center-fire ammunition and shot (increases hardness)
Zinc	Zn	Jacket alloy metal
Iron	Fe	Iron tips on penetrator rounds and steel shot (has been used successfully to remediate high levels of lead and arsenic in some soils)
Tungsten	W	Alternative projectile material to lead (re- cent research indicates there may be some adverse environmental and human health concerns regarding tungsten)
Nickel	Ni	Coating to improve shot performance
Cobalt and chromium	Co and Cr	Alloys in some ammunition rounds

TABLE 6: Constituents of small arms munitions

There are numerous challenges in obtaining representative results of the level of contamination by MCs over military live-firing ranges that cover many square kilometers and where a multitude of activities involving munitions are conducted. First of all, the nature of explosive and propellant dispersion comprises both compositional and distributional heterogeneity. The compositional heterogeneity is due to the intrinsic nature of the explosives and propellants: the formulations are complex and are inhomogeneous in nature from their conceptions. In other words, compositional heterogeneity is described as the variability of contaminant concentrations between the particles that make the population, which leads to a fundamental error. The fundamental error is managed by collecting and analyzing sufficient sample mass to address the compositional heterogeneity. There is also a very high distributional heterogeneity in the dispersion of MCs. Taylor et al. (2006) and Jenkins et al. (1999, 2004, 2005b), have studied extensively the high heterogeneous pattern associated with explosive and propellant distribution. Solid particles may vary from very fine dust to large chunks of explosives, up to centimeter size. This heterogeneity results in a segregation error. In order to minimize the fundamental error and compensate for compositional heterogeneity, a greater sample mass must be collected, and in order to minimize the segregation error and compensate for the distributional heterogeneity, multiple subsamples must be collected. To achieve that, it is recommended to use a composite sampling strategy with a judgmental systematic random sampling design to characterize the average concentration of MCs within a chosen area or DU.

This approach is different from the collection of discrete samples and the commonly used practice of field splitting or laboratory subsampling by removing only a portion of the sample received from the field for further processing. Composite sampling is not a new concept and has been well documented (Esbensen, 2004; Hathaway, 2005; Jent et al., 2006; Keith, 1991). While composite sampling was not new, there was a very high resistance in the United States from the U.S. Environmental Protection Agency (EPA) to accept the application of compositing in RTAs characterization. The assumption was that this led to sample dilution and that discrete sampling was more appropriate. Composite sampling is done by collecting a minimum of 50 small increments of soil from a specified DU and combining these into a single sample. A DU can be defined as an area where a decision is to be made regarding the extent and magnitude of contamination with respect to the potential environmental or human health hazards posed by the exposure to munitions contaminants. Table 7 presents a general guidance as to the minimum number of increments to use, depending on the size of the DU. A minimum of 50 subsamples is recommended to form a sample that weights between 1 and 2 kg. The size and location of the DUs is planned using knowledge sufficient to delineate areas that are likely to be contaminated. The DU is walked in a serpentine manner and increments are collected at each three to four steps, in the same area of the subunit. When all the surface of the DU is covered, the same process is repeated after a rotation of the sampling path by 90 deg, as illustrated in Fig. 8. Where practical, a rectangular shape DU is recommended for ease of sampling. DUs of 100 to 200 m^2 and larger have successfully been used to map

Size of the DU	Number of increments
$0-10 \text{ m}^2$	50
$10-50 \text{ m}^2$	75
50–100 m ²	100

TABLE 7: Minimum number of increments recommended in function of the size of the DU



FIG. 8: Systematic sampling approach in a square DU.

explosive residues on active ranges. For larger DUs, the sample mass collected needs to be larger than 2 kg, such as up to 5–7 kg.

Using composite sampling, reliable estimates of mean concentrations for the specified area of virtually any size are obtained. Properly collected replicate samples should lead to a relative standard deviation lower than 30% between replicates.

Sampling in RTAs represents a high safety risk since the RTAs are in general heavily impacted with UXOs. All the personnel involved in the sampling campaign need a mandatory safety briefing given by the range control office. When entering a UXO contaminated range, the sampling team must always be accompanied by an experienced EOD specialist, who will indicate the safe path for walking and driving. In very high– density UXO areas or in antitank impact areas where piezoelectric fuses might be triggered only by the shadow of a person, access might be either denied or restricted to the EOD specialist only, who could perform the sampling after precise sampling instructions.

With the exception of ranges where the surface is regularly physically moved, the highest concentrations of MCs are always present in the top 2.5 cm of surface soil. A variety of sampling tools are available to collect soil samples. They range from a spade to hydraulic powered coring equipment. Representative soil samples can best be obtained by using a core-sampling tool. Indeed, CRREL has developed a coring device that is handy and most helpful in RTAs. It involves a soil plunger, which can be adapted to vary the sampling depth, and the corer diameter can also be varied, depending on the sampling goals. The choice of collection tools often depends on the cohesiveness, coarseness, and moisture content of the soil. Scoops and spoons are necessary for non-cohesive soils and heavily cobbled surfaces. Coring tools are recommended for cohesive surface soils

with and without vegetation. Samples should be stored in a polyethylene bag, tightly closed. Splitting the sample in the field to reduce the volume sent for laboratory analysis is not recommended. The whole samples are stored in the cold and dark and sent to the laboratory for homogenization and analysis.

5. SAMPLE PROCESSING

Sample processing is as important as the sampling itself because it will ensure whole sample representativeness. The heterogeneous nature of MC mandates that care be taken in the careful homogenization of the sample. Air drying of the soil samples must be conducted in the dark to avoid the alteration of the contaminants of concern. Once the samples are dried, they need to be homogenized to ensure that the subsample is representative of the whole sample. There are two methods for homogenizing: the acetone slurry method, and the mechanical grinding method. The first method uses acetone to dissolve the EM compounds and redistribute them evenly on the soil particles, while the second method relies on mechanical grinding to reduce the size of the EM particles and fibers to the same size as the soil particles to ensure uniform dispersion (EPA SW846 Method 8330b). The two methods for sample homogenization will not be described in detail in this paper, but can be found in Thiboutot et al. (2012). After thorough homogenization, a 10 g sample is extracted with acetonitrile and analyzed following the EPA 8330b method (U.S. EPA, 2006).

Energetic-spiked samples are not recommended on a routine basis, because 1-2 kg samples would need a relatively large amount of standard. However, a 10 g subsample after homogenization should be fortified with a known concentration of nitroaromatics and nitramines for every batch of samples collected in a specific geological formation. Background samples (10% of the total number of samples) need to be collected at a site of the same representative geology as the DU samples. Table 8 highlights the EMs that were most frequently encountered in specific ranges.

When metals are the analytes of interest, it is also essential to process the soil samples before their analysis. The purpose of sample treatment is to produce a smaller, dry and manageable sample suitable for laboratory-scale analysis while at the same time

Type of Range	RDX	HMX	TNT	2,4-DNT	4ADNT	2ADNT	NG
Hand grenade	\checkmark	\checkmark	\checkmark		\checkmark	\checkmark	
Antitank rocket range	\checkmark						
Artillery range	\checkmark	\checkmark	\checkmark	\checkmark			\checkmark
Bombing range	\checkmark		\checkmark				
Demolition range	\checkmark	\checkmark		\checkmark			\checkmark
Small arms ranges							\checkmark

TABLE 8: EM commonly observed by range type

ensuring that the prepared sample is homogeneous and fully representative of the original field material. First, the samples should be dried at temperatures of $<40^{\circ}$ C to avoid the potential loss of volatile compounds, such as antimony, arsenic, and mercury, and to avoid the oxidation of some heavy metal compounds, especially sulfides. The whole sample should then be sieved using stainless steel screens to remove pebbles, sticks, and bullet fragments larger than 2 mm, and then be ground using a ring pulverizer to decrease the particle size of $<75 \ \mu$ m. Care should be exercised to choose a ring pulverizer that will not contaminate the sample with the analytes of interest. Accredited laboratories shall provide detailed information about this operation and the associated contamination. In doubt, a clean sand sample obtained from a local supplier could be sent to the laboratory for analysis with and without the pulverization step.

The analysis of metals should be done using inductively coupled plasma-mass spectrometry (ICP-MS) or inductively coupled plasma-atomic emission spectrometry (ICP-AES) following the general guidelines of EPA methods 6020A or 6010C, respectively (U.S. EPA, 1994, 2007). Generally, ICP-MS is used to determine concentration levels in parts per billion and below while the ICP-AES is used to determine levels in parts per million and higher. Table 9 illustrates the metals commonly detected in concentrations above guidelines in soils of specific ranges.

Field sampling reproducibility of composite sampling should be subject to quality assurance and quality control requirements similar to those traditionally required to demonstrate laboratory analytical reproducibility. Field replicates provide a measure of the total error or variability of the data set. The sampling plan must provide for enough replicate QC sampling to obtain the required precision. As a general rule, it is recommended to collect triplicate composite sampling for at least 10% of all the DUs. Whenever possible, the triplicates should be collected by three teams to validate the absence of bias.

6. FATE AND TRANSPORT OF MC

This section will briefly present the general mechanisms that govern the fate and transport of MCs. In general, explosives and propellants have low vapor pressure. Therefore,

Type of Range	Pb	Cu	Zn	Sb	Cr	Ni	Cd
Hand grenade		\checkmark	\checkmark				\checkmark
Antitank rocket range	\checkmark	\checkmark	\checkmark		\checkmark	\checkmark	
Artillery range	\checkmark	\checkmark	\checkmark				
Bombing range	\checkmark	\checkmark		\checkmark			\checkmark
Demolition range		\checkmark	\checkmark		\checkmark		
Small arms range berms	\checkmark	\checkmark	\checkmark	\checkmark			

TABLE 9: Metals commonly observed by range type

International Journal of Energetic Materials and Chemical Propulsion

their fate is driven by dissolution/leaching, transformation, and mineralization. NG and 2,4-DNT have higher vapor pressure, but when dispersed in a NC matrix, volatilization is highly limited. The fate and the risk associated with a contaminant are closely related, as illustrated in the conceptual model presented in Fig. 9. The risk is associated to the effect of each MC, their metabolites, and their fate. Their fate is driven through transport and degradation.

Propellant residues have a long-term environmental residence time since they are embedded in a NC matrix that protects them from dissolution and further biotic or abiotic processes (Hewitt and Bigl, 2005; Thiboutot et al., 2010). Therefore, the risk to the groundwater is low and most of the MCs remain at the soil surface in the first 2.5 cm of soil for many years, even decades. One exception is 2,4-DNT liberated by field expedient burning of excess artillery propellants. In this case, there is a fraction of highly leachable 2,4-DNT that is available to dissolution and degradation processes (Martel et al., 2012b). The remaining fraction is embedded in NC and will remain at the soil surface for years and will be immobile except for the nitrate that can leach out from the degradation of NG (Martel et al., 2012b). Composite rocket propellants may lead to the dispersion of AP in the environment. It has been demonstrated that when normal functioning occurs, the combustion in the rocket is very effective and AP is not dispersed in RTA (Jenkins et al., 2007; Thiboutot et al., 2008b). Ammonium perchlorate is also included in a few other weapons such as M72 antitank rocket propellants or smoke formulations.

The explosives mostly used in Canadian munitions are TNT, RDX, and HMX based and many efforts were dedicated to better understand their complex fate and transport mechanisms (Halasz et al., 2002; Hawari et al., 2000a,b, 2001; Lewis et al., 2009; Mailloux et al., 2008; Martel et al., 2007, 2009; Monteil-Rivera et al., 2004; Robertson et al., 2007; Zhao et al., 2004). Overviews of the main process descriptors for explosives has been published by Brannon and Pennington (2002), Halsaz et al. (2002), and more



FIG. 9: Conceptual model for the environmental fate of MC.

recently by Monteil-Rivera (2004) and Kaldersi (2011). The environmental fate of explosives can be attributed mostly to their molecular structure and related water solubility, their adsorption to soil particles, and the production of metabolites through biotic and abiotic routes. In other terms, the main processes that control their fate are: solubility and dissolution, adsorption, transformation, biodegradation, photolysis, and volatilization. For instance, TNT is a nitroaromatic and tends to degrade by photolysis, while nitramines such as RDX and HMX can be photodegraded but to a much lower extent. Some photodegradation by-products of TNT are well known, while other species are still to be determined. TNT is also more soluble and dissolves more rapidly in water than RDX or HMX (HMX being the least soluble). TNT can degrade into more than 20 different metabolites with various solubilities and toxicities. For example, the aminodinitrotoluenes (ADNTs) that result from the photolysis or biodegradation of TNT are much more soluble than the parent compound, but they can easily covalently bind to humic acid. Therefore, these metabolites are stabilized by the formation of an amide with the organic content of the soil. Moreover, in soils that contain clay minerals, sorption mechanisms are stronger with TNT and its metabolites than for RDX and HMX (Dontsova, 2009b). Therefore, the relative rates of soil leaching of these three explosives can be explained in terms of the relative water solubilities and adsorption strengths. RDX leaches out faster than TNT, which in turn leaches out faster than HMX. TNT and its metabolites are more soluble than RDX, but their migration is inhibited by strong bonding interactions with soil constituents. On the other hand, HMX has a tendency to remain at the surface of the soil, because it is much less soluble in water. Interactions with the soil are an important factor when characterizing explosives in terms of bioavailability and extractability. TNT is particularly difficult to characterize because it is easily reduced to amino degradation products, namely, 2- and 4-amino-dinitrotoluene (2-and 4-ADNT), 2,4- and 2,6-diamino-nitrotoluene (DANT), and, under anaerobic conditions, 2,4,6-triaminotoluene. All data acquired up to now tend to indicate that most TNT metabolites are rapidly strongly sorbed to soil humic acid, if not irreversibly, which greatly limits their bioavailability. Therefore, even if TNT and its metabolites are considered toxic, they are not readily available for receptors.

The fate and transport of heavy metals in the environment will depend strongly on their solubility in water (which depends of the metal speciation and on the water pH and Eh) and their capacity to bind to the soil constituents. A metal compound with a high solubility and a low binding capacity has a higher mobility and presents a larger potential for leaching in groundwater and/or travel far away from the range. However, a compound having a low solubility will most probably stay on the surface of the soil, and a compound with strong binding affinities will most probably stay either on the surface or in the subsurface, where a specific bonding agent is encountered. In addition, small particles tend to be more mobile, either in solution or as colloids.

The water solubility of heavy metals in their elemental state is generally low. However, heavy metals do not generally remain in their elemental form when they are exposed to weathering and water. They are easily oxidized in their ionic form and will form various salts with soil constituents, all having a different solubility and bioavail-ability. As a general rule, nitrates, chlorides, bromides, and acetates are readily soluble in water, and sulphides are considered to be insoluble. However, the solubility of hydroxides, sulphates, phosphates, and carbonates will vary depending on the heavy metal counterpart, and on the pH of the water. The lowest solubilities are generally observed in neutral pH water (6.5-7.5). Acidic water (pH < 6.5) tends to increase the solubility of most metals salts, while basic water (pH > 7.5) will either induce the precipitation and immobilization of an insoluble heavy metal compound, or increase its solubility, depending on the heavy metal. Thus, extreme caution must be exercised when trying to decrease the leaching of soils containing multiple heavy metals by controlling the pH of the soil, because the solubility of some heavy metal compounds may increase when exposed to basic pH.

Key parameters governing the bioavailability of a given heavy metal compound are the composition (organic matter, metallic constituents) and pH of the soil, the particle size distribution, and the contact time between water and the heavy metal compound. These parameters in turn govern measurable, macroscopic parameters, such as the type of soil (sand, silt, clay, etc.), the cation exchange capacity (CEC), and the reductionoxidation (redox). The binding capacity tends to increase with the decrease of soil particles size. For example, absorption in clay is much higher than in sand, because the groundwater movement in clay is slower, and also because the surface area of soil particles to which a heavy metal compound can bind is higher. In consequence, sandy soils present the highest leaching potential. The contact time between water and the heavy metal compounds is controlled by the amount of annual precipitation, the rainfall intensity, and the hydraulic conductivity of the soils. The absorption of several heavy metal compounds to soil components also tends to increase with the CEC. The redox potential will affect the type of heavy metal compound that is stable in a given area. The mobility of heavy metals is also affected by external physical factors, such as the topographic slope and the intensity of wind.

7. HYDROGEOLOGICAL CHARACTERIZATION OF RTAS

The potential for MCs to travel to water bodies in RTAs varies from quite low probability for NC embedded propellant residues to very high probability for RDX and AP. Therefore, it is imperative to monitor both surface and subsurface water bodies' quality. In Canada, a large effort was dedicated to the hydrogeological characterization of major RTAs. This approach is carried out as part of a collaborative effort with INRS-ETE. Hydrogeology typically provides detailed information on the quality and flow direction of surface water and groundwater, on the water table depth, and on the various types of soil on which the ranges are built. In Canada, detailed hydrogeological characterization of six Army RTAs has been conducted up to now. The approach is stepwise and, in general, the work is accomplished in sequential phases over a period of three to four years. The number of wells installed per phase is approximately between 15 and 20 and is combined with a detailed surficial and 3D geological survey. This stepwise approach allows the better localization of wells and optimizes the process.

7.1 Well Installation

The major concern for the installation of wells in UXO-contaminated ranges is the possibility of encountering buried UXO during well installation. Another concern is that the wells will be destroyed as gunners use them for target practice. The installation of flush-mounted wells has eliminated this issue, and these types of wells have been installed within impact ranges across Canada (Bordeleau et al., 2008b; Martel et al., 2009). Before any drilling is to be conducted within an area that could have buried UXO present, UXO avoidance activities must have been completed. Qualified personnel (EOD or UXO technicians) will clear pathways to proposed sampling locations, usually done using magnetometers. The pathways must be wide enough for safe passage of drilling equipment and personnel and, in general, a sufficiently large area will be cleared at the sampling location to allow the drilling equipment to maneuver properly. At all drilling locations, down-hole avoidance techniques are required. Each 0.5 m interval needs to be cleared using a magnetometer prior to further advancement of the drilling equipment to insure the safety of the drilling crew.

Mailloux et al. (2008) used a hollow-stem auger to drill wells at the Arnhem antitank rocket range at CFB Valcartier in Canada. In a few wells, split spoon can be used to sample the soil at depth to determine the stratigraphy of the formation. The stratigraphy refers to the layering of the soil strata, and it is important when trying to understand the hydraulic properties of the soil profile. It is critical that wells be installed within the proper aquifer to assess questions of offsite migration. Direct push wells can sometimes be used for groundwater monitoring, depending on the geology and stratigraphy of a given location. More details on well installation can be found in Martel et al. (2012a).

7.2 Water Sampling and Analysis

The collection of groundwater must be representative of the conditions at the site. For groundwater, samples are collected to investigate the water in the aquifer that is migrating through the formation. Installing a well can modify the aquifer's structure and environment near the well screen, and this may affect the stability of various chemicals in the well and in its vicinity. To minimize this, common practice is to purge three to five well volumes prior to collection of a groundwater sample from the well. This removes the stagnant water that is present in the casing above and below the well screen and water near the screen that might have been affected by the conditions within the well. Studies have shown that explosives are not as readily sorbed by the materials used to sample (Parker et al., 1990; Parker and Ranney, 1994, 1997, 1998). There are several sample collection methods that are commonly used for groundwater sampling. These include the use of bailers, low-flow pumping with a peristaltic pump or a bladder pump, or passive diffusion samplers. The Canadian approach used a low-flow sampling technique with a dedicated system made of a 6 mm Teflon tubing connected to a flexible Viton tubing via a Teflon connector to avoid any cross contamination. The groundwater sample is taken when the groundwater quality parameters are stabilized. Groundwater samples are to be collected in a 1 L amber glass bottle to prevent photodegradation, cooled to 4°C, and shipped by overnight carrier. The stability of energetic compounds can be extended if the water is acidified to pH 2 with sodium bisulfate after collection (Jenkins et al., 1995). Sample analysis is conducted as described in SW846 Method 8330B (U.S. EPA, 2006). Water samples are generally preconcentrated using solid phase extraction to provide adequate detection capability. Most analyses have been conducted using reverse phase high-pressure liquid chromatography (HPLC) using an ultraviolet (UV) detector.

7.3 Thematic Maps

The hydrogeological data collected led to the preparation of several thematic maps such as hydraulic head and surficial geology, as illustrated in Figs. 10 and 11. The following step is the groundwater flow and contaminant transport modeling. This is generally performed using a numerical model such as FEFLOW, which needs to be fed with input



FIG. 10: Piezometric map.



FIG. 11: Surficial geology map.

parameters such as the 3D geological model, the measured hydraulic heads, the measured hydraulic conductivity of the various hydrostratigraphic units, and the recharges. This model allows the reproduction of the behavior of groundwater at regional and local scales, and the prediction of the transport of contaminants, which is extremely important to perform risk analyses of the ecological and human receptors surrounding RTAs. A conceptual model is then built following the geological model and from the knowledge of the environmental fate of EMs. The risk analysis is completed by building hazard, aquifer vulnerability, and risks maps. The vulnerability map reflects the vulnerability of a given aquifer to surface contamination, of which an example is shown in Fig. 12. The hazard for a range is evaluated with an index system specifically developed and based on residue deposition frequency, on the environmental dangerousness of each type of explosive used, and on the surface area of the range where the munitions are used. The environmental dangerousness is based on five criteria, i.e., drinking water toxicity, solubility in water, natural biodegradation, photodegradation, and adsorption on the organic fraction of soil, and is evaluated for each possible EM released in a range. The surface area index is inversely proportional to the surface area of the training area or range. Firing positions have very small deposition areas (order of magnitude 100 m²) on, behind, or in front of them, whereas impact areas may extend to millions of square meters, which dilute the concentration at the surface and consequently have a lower surface area index. The frequency index, the environmental dangerousness index, and the surface area of

International Journal of Energetic Materials and Chemical Propulsion



FIG. 12: Vulnerability map.

deposition index are multiplied together to give the hazard value for each of the energetic materials used for a given range. The aquifer vulnerability map and the hazard map are combined to generate the risk map. For more details on aquifer vulnerability, hazard, and risk maps see Martel et al. (2011).

8. RISK MANAGEMENT: MITIGATION METHODS

All the work described above allowed a comprehensive and detailed knowledge of the source of MCs in RTAs. Work was subsequently undertaken to mitigate or eliminate the adverse impacts measured, or else to develop management tools. The vulnerability, hazard, and risk maps represent a good example of highly relevant range management tools. Based on these maps, various decisions, such as range relocation or closure, can be taken to minimize the adverse measured impacts such as reducing the potential for aquifer contamination.

In some instances, tools were developed to completely eliminate the MC from entering the environment. An example of this is the development of a burn table for the destruction of excess artillery and mortar propellants. Various table design iterations and trials have been conducted, and this led to the development of a Canadian table for the burning of the excess artillery and mortar propelling charges (Thiboutot et al., 2011), as illustrated in Fig. 13. Field expedient burning of charges on the surface soils is now



FIG. 13: Canadian burn table.

forbidden in Canada. The table allows the safe destruction of 200 kg of excess charge bags per burn and leads to a 99.5% mass reduction. The design ensures a safe process and burn residues can easily be collected and treated as hazardous materials. The gaseous emissions emitted have been predicted and monitored and are not of concern. The use of the burn table greatly reduces the environmental footprint of artillery live-fire training: the proven accumulation of 2,4-DNT and lead in the environment has been stopped. A standard operating procedure (SOP) for the destruction using the table as well as a procedure for the safe return of the excess charge bags to the ammunition stores have been provided to the military users. Finally, another option is also under study, which is the development of modular charges for 105 mm guns. This would eliminate the requirement for open burning and would increase the sustainability even more.

Another example of a tool under development to minimize MC surface soil deposition is the Canadian small arm bullet catcher. Our characterization work joined with various studies of the fate of metals involving lysimeters have stressed the need to move away from conventional sand backstop butts for small arms ranges. Many prototypes were constructed over the last few years, ending up with a suitable prototype. The new concept uses the slope of the former stop butts, a cell where the water will not penetrate, and a reservoir in case there would be leaks. The goal was to design a cost-efficient bullet trap that could be easily implemented in Canadian small arms training ranges.

Finally, the context of observed environmental impacts from UXO and the study of the energetic formulations from the past highlighted the desired properties to achieve greener munitions. In 2008, Canada initiated a technology demonstration program named RIGHTTRAC for revolutionary insensitive, green and healthier training technology with reduced adverse contamination, aiming at proving that greener and insensitive munitions (IMs) can decrease the environmental pressure on RTAs and minimize the health hazards the users without decreasing the performance of the munitions (Brochu et al., 2011). The goals of this five-year TDP are to reach a near-zero failure rate, and to eliminate the potential for RDX contamination and the use of toxic and carcinogenic compounds. This will be done by performing significant improvements to the fusing system, the main explosive charge, and the gun propellant.

9. CONCLUSION

The general approach to obtain representative results from the characterization of huge tracks of military RTAs was refined over the years to overcome numerous challenges, including the high compositional and distributional heterogeneity associated with MC dispersion. The research dedicated to munitions deposition and fate led to the development of a detailed protocol for the effective and safe characterization of range and training areas. The sample collection, treatment, and homogenization were carefully studied, and are presently the topic of intense international exchanges for standardization. A protocol covering the main contaminants of concern, i.e., propellants, explosives, and metals, was developed.

The large effort dedicated to the measurement of the deposition rate of MCs both at the target impact areas and at the FP led to a good estimation of the source terms of contaminants generated by various live-firing activities. The research conducted on impact areas demonstrated that normally functioning munitions only spread forensic amounts of their explosive content in the environment. Therefore, most of the contamination comes from UXOs that are cracked open by flying shrapnel coming from the detonation of an incoming round, by incomplete (low order) detonations, or by the BIP destruction of duds. Subsequently, the distribution, fate, and transport of propellant residues at firing points associated with live-fire training with munitions were studied. This allowed for a better understanding of the contamination pattern at the firing positions. The two major sources of propellant residues at the FPs were identified as the deposition of residues from incomplete combustion in the guns and field expedient burning of excess artillery and mortar propellants.

Several studies have also been performed on the fate and behavior of all MCs and their metabolites. This allowed the development of transport process descriptors for current explosives and propellants and their main transformation products. Moreover, the ecotoxicity of munitions constituents was also intensely studied, mostly in collaboration with BRI-NRC. The work conducted on the ecotoxicology of MCs led to international cooperation and publication of soil guidelines and textbook for ensuring military training sustainability.

Major environmental issues were identified and the sources of MCs in training ranges are now better understood. In Canadian Army RTAs, on top of RTAs' surface characterization, large efforts were dedicated to characterize the subsurface, and detailed hydrogeological and geological studies were conducted mainly by INRS-ETE. This led to the acquisition of a large database, and a better understanding of the complex dispersion and fate of munitions-related contaminants toward groundwater. The evaluation of the risk of aquifer contamination associated with military training activities was then allowed, and it produced practical range management tools.

On the basis of the knowledge acquired in the study of the environmental impact of the munitions, our efforts are presently dedicated to the development of environmentally sound solutions that will sustain military training and maintain force readiness. In order to achieve this goal, efforts are committed to the modification of actual livefiring activities. As an example, burn trays were developed and implemented in Canada, and field expedient open burning of excess propellant is now forbidden. Another example is the development of bullet catchers that will retain the heavy metals in enclosed units to avoid their environmental dissemination. In parallel, remediation of sites where levels of concern about munitions-related contaminants were identified will be undertaken.

One important conclusion of this project is that future munitions development must take into consideration the environmental aspects at a very early stage of the development process in order to avoid fielding munitions that would lead to high environmental and liability costs. It is within this context that Canada initiated a project in 2008 to develop greener, insensitive munitions that will ease the environmental pressure on RTAs without decreasing the performance. This represents a holistic approach toward the ultimate objective of totally sustainable military live-firing ranges.

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46

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