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# Study of the Environmental Impacts of the Blow-in-Place Procedure of Various Explosives, Munitions and Charges

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**Defence R&D Canada – Valcartier**

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## **Abstract**

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A relatively large proportion of munitions used in live-fire exercises does not detonate as expected and generate unexploded ordnances (UXOs) in training areas. This percentage of non-functioning munitions can be evaluated to be between 3 and 10 % of the fired ammunition, while for some type of munitions, such as antitank weapons, this proportion can be as high as 50%. These UXOs might bury themselves or lie at the surface in the training areas. Once a year, military experts of the Explosive Ordnance Disposal Unit (EOD) perform a clearance level one (surface clearance) in all training areas to get rid of the surface UXOs. Because they are considered unsafe to move, UXOs are blown in place with a charge of C4. These critical activities are considered dangerous but needed for the safety problem that these UXOs represent. The environmental impact of this particular activity has not been highly documented and a systematic study was needed. DRDC Valcartier designed specific experiments in which various munitions and charges were detonated using either C4 in various quantities or shaped charges, both commercial and military, with ammunitions either fused or un-fused, to verify the relative environmental impacts of each event. An experimental set-up involving the use of witness plates and the collection of detonation residues for analysis of their energetic material contents was designed. Despite the presence of contamination in some trials, some generalizations could be made. The greatest concentrations, in the percent levels for TNT, RDX and HMX, came from low-order detonations. When high-order detonations were obtained, the largest concentration in TNT was  $324 \text{ mg/m}^2$  (1.0%), coming from a PMA-1A anti-personnel mine imitation. The greatest RDX deposited was  $47 \text{ mg/m}^2$  (0.6%) coming from a M67 grenade. Finally, for HMX, the greatest value obtained was  $4.8 \text{ mg/m}^2$  (0.5%) coming also from a M67 grenade. These indicate that TNT and Comp B-filled munitions are not always efficient at consuming all the main charge in blow-in-place conditions. The amount of residues collected after an event was influenced by the blow-in-place conditions. For example, the greatest residue recoveries were obtained when a linear shaped charge and a commercial 6.5-g RDX shaped charge were used. Moreover, the blow-in-place of various primer charges detonated alone showed that their potential contribution in explosive residues was low.

## **Résumé**

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Une proportion relativement grande de munitions utilisées lors des exercices de tir réel ne détone pas comme prévu et produit des munitions non détonées (UXO) dans les secteurs d'entraînement. Le pourcentage des munitions qui ne fonctionnent pas peut être évalué entre 3 et 10% de toutes les munitions mises à feu et même, pour certains types de munitions, telles que les armes anti-tank, cette proportion peut atteindre 50%. Ces UXO sont enterrés ou se retrouvent à la surface des secteurs d'entraînement. Une fois par an, des experts militaires de l'unité de disposition des explosifs effectuent un nettoyage de niveau un (nettoyage en surface) dans tous les secteurs d'entraînement pour se débarrasser des UXO en surface. Puisqu'ils sont considérés comme peu sûrs à déplacer, les UXO sont détonés sur place avec l'aide d'une charge de C4. Ces activités critiques sont considérées dangereuses mais nécessaires. Les impacts sur l'environnement de cette activité particulière n'ont pas été fortement documentés et une étude systématique était nécessaire. DRDC Valcartier a élaboré des expériences dans lesquelles diverses munitions et charges ont été détonées en utilisant soit du C4 en diverses quantités, soit des charges creuses commerciales ou militaires sur des munitions avec ou sans fusée, pour vérifier les incidences sur l'environnement de chaque événement. Une installation expérimentale impliquant l'utilisation de plaques témoins et la collection de résidus de détonation pour l'analyse de leur contenu en matériaux énergétiques a été conçue. En dépit de la présence de contamination dans quelques essais, quelques conclusions ont pu être tirées. Les plus grandes concentrations, de l'ordre du centième de la masse initiale, pour le TNT, le RDX et le HMX, proviennent des essais qui ont montré une faible détonation. Quand des détonations d'ordre élevé ont été obtenues, la plus grande concentration en TNT était de 324 mg/m<sup>2</sup> (1.0%), venant d'une imitation d'une mine antipersonnel PMA-1A. La plus grande quantité de RDX déposé était de 47 mg/m<sup>2</sup> (0.6%) provenant d'une grenade M67. Finalement, pour le HMX, la plus grande concentration obtenue était de 4.8 mg/m<sup>2</sup> (0.5%) provenant également d'une grenade M67. Ceci indique que les munitions remplies avec du TNT et de la Composition B ne sont pas toujours efficaces à consommer toute la charge d'explosif lors d'une détonation sur place. On a aussi constaté que la quantité de matériaux énergétiques récoltée après un événement était influencée par les conditions de détonation. Par exemple, les plus grandes quantités de résidus ont été obtenues quand des charges creuses linéaires et commerciales de 6.5-g de RDX ont été employées. De plus, la détonation sur place de diverses amorces a prouvé que leur contribution potentielle en explosifs était faible.

## Executive summary

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This study is part of a larger effort undertaken in the context of sustaining operational military activities. The Canadian Forces need to be informed about the potential environmental and human health impacts of activities such as live firing activities, detonation of unexploded ordnance (UXO) and detonation of surplus ammunition. To ensure that such activities can be conducted on a sustainable basis with minimum adverse environmental and health impacts, the way that the ranges are managed needs to be evaluated and, if necessary, improved. The complete destruction of energetic materials during a blow-in-place detonation depends on a variety of factors, such as the type of munitions, the confinement, the priming position, the position and orientation of the detonator, the quality and the quantity of the booster charge used and the weather conditions. To better understand the influence of these factors, blow-in-place detonation experiments need to be done in controlled conditions. The main objective of this work was, therefore, to evaluate the types and amounts of residues that can result from blow-in-place detonation and provide targeted recommendations to EOD personnel to minimize impact. In this work, blow-in-place detonations of 60- and 81-mm mortar rounds, M67 hand grenades, C4, PMA-1A land mines were performed using C4 and different shaped charges to establish a relationship between the amounts of residues dispersed in the surroundings and the effects of various factors (mentioned above). Residues were collected on witness plates that were thoroughly swabbed after each detonation. The samples were analyzed for explosives and their breakdown products.

The results showed that the greatest concentrations of explosives were coming from low-order detonation events that produced residues in the percent level. High-order detonations showed fewer residues in TNT, RDX and HMX, but the amount of residues varied in accordance with the blow-in-place conditions. The use of linear shaped charges and commercial 6.5-g RDX shaped charges showed a high incidence of low-order detonation. Moreover, the type of detonation of PMA-1A mines, but not for the M67 grenade, was dependent on the position of the detonator. For the mortar rounds, the order of detonation was more dependent on the quantity and type of primer (C4 or shaped charges) than on its position on the round; however, priming with C4 in the nose of the munition seems to lead to a larger dispersion of the residues than priming from the lateral position. Finally, in blow-in-place conditions, the presence of a fuse did not appear to influence the explosive residues recovery. The contribution of the primer charge, detonated alone, was also evaluated: the recovery of explosive residues was low for both C4 and commercial shaped charges. Finally, nitroglycerin was unexpectedly found in some post-detonation mortar residues. The use of witness plates as a collection medium brought experimental errors like contamination between trials. In addition, the area covered by the plume of the detonation could not be estimated, which caused the results to be underestimated. However, even with those problems, interesting and pertinent information was obtained that will help to draft future recommendations. Study results offer important information about the environment impact of detonation of explosives during range clearance operations and the critical detonation parameters that should be considered.

P. Dubé, S. Brochu, P. Brousseau, S. Thiboutot, G. Ampleman, J. Lewis, M. Bouchard, A. Gagnon, A. Marois, (2004), Study of the Environmental Impacts of the Blow-in-Place Procedure of Various Explosives, Munitions and Charges. DRDC TR 2003-370, Defence R&D Canada - Valcartier.

## Sommaire

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Cette étude fait partie d'un grand effort entrepris dans le contexte du développement durable des activités militaires opérationnelles. Les Forces canadiennes doivent être informées au sujet de l'impact potentiel sur l'environnement et la santé humaine des activités telles que le tir réel, la détonation des munitions non-détonées et la détonation des surplus de munitions. Pour s'assurer que de telles activités peuvent être menées sur une base durable avec des impacts minimes, la manière dont les champs de tirs sont gérés doit être évaluée et être améliorée, au besoin.

La destruction complète des matériaux énergiques pendant une détonation sur place dépend d'une variété de facteurs, tels que le type de munition détoné, le confinement, la position d'amorçage, la position et l'orientation du détonateur, la qualité du détonateur utilisée et les conditions atmosphériques. Pour mieux comprendre l'influence de ces facteurs, des expériences de détonation sur place ont été effectuées dans des conditions contrôlées. L'objectif principal de ce travail était d'évaluer les résidus de matériaux énergétiques qui pouvaient résulter de la détonation sur place et fournir des recommandations afin de réduire l'impact sur l'environnement et la santé au minimum. Dans ce travail, des détonations sur place de mortier de 60- et de 81-mm, de grenades M67, de C4, de mines PMA-1A ont été effectuées en utilisant du C4 et différentes charges creuses afin d'établir un rapport entre les quantités de résidus dispersés et les divers facteurs (mentionnés ci-dessus). Les résidus ont été recueillis à l'aide de plaques témoins qui ont été complètement essuyées après chaque détonation. Les échantillons ont été analysés afin de détecter les résidus de matériaux énergétiques.

Les résultats ont prouvé que les plus grandes concentrations en matériaux énergétiques provenaient des détonations d'ordre faible et les concentrations étaient de l'ordre du centième de la masse initiale détonée. Pour leur part, les détonations d'ordre élevé ont montré peu de résidus de TNT, de RDX et de HMX, mais la quantité de résidus variait selon les conditions utilisées. L'utilisation des charges creuses linéaires et commerciales, de 6.5-g de RDX, a montré une tendance à provoquer des détonations d'ordre faible. D'ailleurs, l'ordre de détonation de la mine PMA-1A, mais pas la grenade M67, dépendait de la position du détonateur. Pour les mortiers, l'ordre de la détonation dépendait plus de la quantité et du type d'amorce (C4 ou charges creuses) que de sa position sur le mortier. Cependant, l'amorçage avec le C4 sur le bout des munitions semblait mener à une plus grande quantité de résidus que l'amorçage latéral. En conclusion, dans des conditions de détonation sur place, la présence d'une fusée n'a pas semblé influencer la quantité d'explosif recueillie. La contribution de la charge d'amorçage, détonée seule, a également été évaluée: les résidus de matériaux énergétiques recueillis étaient faibles pour le C4 et pour les charges creuses commerciales. De plus, on a trouvé de la nitroglycérine dans quelques résidus de mortier.

L'utilisation des plaques témoins pour la cueillette des résidus peut occasionner des erreurs expérimentales comme la contamination des plaques entre les tests. De plus, la surface couverte par les résidus de détonation ne peut pas être estimée, ce qui a causé des résultats inférieurs aux estimations. Cependant, même avec ces problèmes, on a obtenu de l'information pertinente et intéressante afin de rédiger des recommandations. Les résultats de



l'étude fournissent des informations importantes sur l'impact environnemental de la détonation pendant des opérations de nettoyage des champs de tirs et sur les paramètres critiques de détonation qui devraient être utilisés.

P. Dubé, S. Brochu, P. Brousseau, S. Thiboutot, G. Ampleman, J. Lewis, M. Bouchard, A. Gagnon, A. Marois, (2004), Study of the Environmental Impacts of the Blow-in-Place Procedure of Various Explosives, Munitions and Charges. DRDC TR 2003-370, R et D pour la Défense Canada - Valcartier.

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# 1. Introduction

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The environmental impacts of particular activities such as routine military training and exercises involving munitions have recently brought increased awareness toward the potential build up of explosives residues in soil that may result in the contamination of groundwater [1]. Such a situation has been encountered at the Massachusetts Military Reservation (MMR) in the United States, where the establishment had to be closed because low RDX concentrations were found in the groundwater [2]. RDX and other high explosives have been identified as potential carcinogens by several environmental authorities [3]. In the case of MMR, the RDX could come from leaking or buried unexploded ordnance, residues from past ammunition disposal or from accumulated residues over the years.

In the context that military training ranges cannot be shut down because testing and training ranges are essential to maintain troop combat readiness, ways to sustain environmentally friendly military activities need to be found. One approach to address the problem is the identification and estimation of the explosive content that is dispersed to the surroundings after a detonation. This approach needed to be addressed because forensic analysis of post-blast residues has established the presence of explosives [4]. In this approach, two common techniques of detonation were evaluated. One of them is live-fire detonation, and the second one is blow-in-place techniques

Previous studies have revealed potential contamination after a detonation. Jenkins *et al.* [5] have determined the quantity of explosives residues produced by both detonation techniques of mortar rounds containing high explosives (HE). Experiments were conducted on snow-covered ranges to be able to estimate the area potentially contaminated using the soot produced by the detonation. The pattern of dispersion was heterogeneous requiring sampling of large areas to obtain representative results. The recovered amounts of explosives remained low, but varied from round to round. Some general trends could, however, be drawn. For instance, a higher percentage of TNT was consumed when the main charge was Composition B. Moreover, the RDX concentration was higher when C4 was used. Finally, nitroglycerin (NG) was unexpectedly found in post-detonation mortar residues.

A study related to on-snow detonation was also performed at DRDC-Valcartier [6]. Detonations of 60- and 81-mm mortars, hand grenades and PMA-2 mines imitation were evaluated. The blow-in-place detonation conditions were evaluated. The results showed that approximately 0.24% of the total explosive present prior to the detonation remained as residues following a blow-in-place detonation. Some trends were underlined in the study. The presence of C4 in the set-up of the detonation influences the RDX concentration in the residues. Also, the configuration is important for effective detonation of a charge.

A recent study related to detonation residues was performed by Hewitt *et al.* [7], where live-fire and blow-in-place detonation conditions were evaluated. Results showed that live-fire detonations of different types of munitions consumed an average of 99.997% or more of RDX and TNT. In blow-in-place, C4 contributed to the detonation residues and randomly dispersed the residues. Also, in blow-in-place, low-order detonations spread a non-negligible amount of explosive residues in the surroundings.

Finally, Brochu *et al.* [8] have performed an estimation of the quantity of explosive residues resulting from the blow-in-place detonation of unconfined explosive charges. Similar techniques, such as on-soil witness plate sampling, were used. The difference between the present study and Brochu *et al.* [8] was that unconfined explosives were evaluated instead of various common munitions and charges. The results showed that the detonation of unconfined explosives led to the dispersion of a small amount of explosives in the surroundings. Also, unconfined TNT charges with small diameters led to higher dispersion of unconsumed explosive because of the lack of confinement.

In the present work, the detonation trials were performed either over a soil-covered range or a concrete slab. Large polyethylene tarps were spread on the soil to eliminate the possible contamination from previous activities and to minimize the contamination of the range. Then, aluminum witness plates were spread on the tarps to collect post detonation residues. The witness plates were thoroughly swabbed after each detonation. Because this set-up offers higher potential of contamination compared to on-snow detonation, efforts were made to minimize this possibility. The advantages of using witness plates as a collection medium were numerous; more trials could be performed at the same place, less machinery was needed, the trials were not dependent of the amount of snow and the installation was fast and easy. The amount and the identification of explosive residue contamination resulting from blow-in-place detonations were assessed. This study was focused on the detonation of common Canadian Forces munitions 60- and 81-mm mortars rounds and M67 hand grenades. PMA-1A anti-personnel mine imitations were also tested because PMA-1A is heavily used in many areas around the globe. Finally, all munitions were detonated in controlled conditions while varying parameters such as the primer charge, the priming position and the orientation of the detonator. Moreover, because past studies have showed that C4 appeared to increase the amount of RDX contamination [6], different C4 primer charges were detonated alone to determine their contribution to explosive contamination.

Finally, the total mass of explosive residues was calculated from the information obtained from the laboratory analyses. The area of soot was not calculated during the trials because no visual identification of the soot was available after the blasts. Hence, the results do not reflect any area calculation. The total mass of the explosive residues found on the witness plates was determined. Then, a percentage of unconsumed explosive was calculated. At the end, a concentration ( $\text{mg}/\text{m}^2$ ) was determined taking into account the use of different numbers of witness plates during the trials. The experimental work was conducted in the spring of 2001 and in the fall of 2002 on the DRDC-Valcartier testing range located in the Valcartier Garrison. The work was conducted under the Weapons and Firepower thrust as part of the work breakdown element 12ny01 on the study of sustainable training.



## 2. Experimental

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### 2.1 Munitions and explosives tested

The munitions and explosives and the ways they were tested are described in Tables 1 and 2. Different kinds of munitions and charges were detonated under blow-in-place conditions. The following is a brief description of the munitions and charges tested.

The 60-mm mortar round is 37.7 cm long and has a main charge of 0.3 kg TNT [9]. This 60-mm mortar differs from the US version, which uses Composition B as its main charge. In all trials, the propellant ignition cartridge and bags were removed because the propellant is completely used up during launch; it would thus not be present in either UXOs or normally detonating rounds. Since NG was detected in some trials involving 60-mm mortars, it is important to mention here that NG is only present in the ignition cartridge (1.68-g). For their part, the fuses may contain RDX, HMX, lead azide and various other primers, but the masses were not considered in our results because they are negligible.

The 81-mm mortar round is very similar to the 60-mm mortar; however, the main charge is 857-g of Composition B [10] (59.5% RDX, 39.5% TNT and 1% wax). The mortar is 52.9 cm long. For the same reasons as for the 60-mm mortar tests, the propellant was removed prior to testing. Since NG was also detected in some trials involving 81-mm mortars, it is important to know that NG is present in the propellant of the ignition cartridge only (4.15-g). Standard Canadian Forces M67 grenades were also detonated. The grenade is quite small, measuring 6.8 cm diameter, and is roughly spherical in shape [11]. The main charge is 185-g of Composition B. The fuse was removed for safety reasons.

Mock-ups PMA-1A anti-personnel mines were tested. The explosive charge included in the mine is 200-g of TNT. The mine is mass-produced by several countries including the Czech Republic and China. The mine is very simple in design, and is made to detonate when pressure (3 kg) is applied to its top surface. The dimensions are 31 mm of height, 140 mm of length and 68 mm of width. The case is made of plastic [12]. For blow-in-place detonations, a booster charge was needed. The booster charge used for the majority of munitions was C4, a plastic explosive composed of 91% RDX [13]. The quantity used varied between 4 and 150-g. As another booster charge, FIXOR™ explosive was also tested [14]. FIXOR™ is a Canadian-developed explosive based on two components, a flammable liquid and an inert powder, which become a high explosive when mixed together. It has been tested to possibly replace C4 and TNT blocks for traditional disposal of UXO explosive charges [14]. FIXOR™ has significant advantages over conventional explosives for use in blow-in-place EOD operations. These include non-suitability for terrorist use in mass-detonation devices, because the mixture becomes harmless after a couple hours of settling. Its transportation is also easier than that of traditional explosives, because it is classified as a flammable liquid. FIXOR™ is also less expensive and more readily available than C4. FIXOR™ performance equivalency is around 85% of TNT by weight (as determined by air-blast tests) and as a detonation velocity of 4300 m/s compare to 6900 m/s for TNT [14].

Along with the booster charge, shaped charges were used in some cases. Shaped charges intend, by design, to focus all of their energy on a single line or point, making shaped charges very accurate and controllable. They are used to cut or perforate metal and armour. Different designs of shaped charges are used in UXO destruction. During the trials the standard military C4 linear M7 shaped charge (LSC) and the commercial shaped charges (SC) coming from Prime Perforating Systems Limited [15] were evaluated. These last are multi-purpose perforating charges used in a variety of tasks, mostly for well perforation in the oil and gas industry. The efficiency of these shaped charges in the destruction of UXOs was evaluated.

In some trials (see Tables 1 and 2), the fuse was kept on the munition for the detonation, but the fuses were usually removed from munitions for safety reasons.

The explosives included in those munitions and charges were C4, TNT and Composition B (Comp B). Comp B was of Type I flakes, Grade A [16]. TNT generally contains up to 1% impurities made of a mixture of isomers of TNT and dinitrotoluenes (DNT), especially 2,4-DNT, 1,3-dinitrobenzene and 1,3,5-trinitrobenzene [17]. Military-grade RDX is generally contaminated with 10 to 15% HMX [18]. In this project, 12% of HMX impurity was used for the calculations. Different priming positions were tried during the trials. Figures 1 and 2 illustrate the lateral priming position and the nose priming position. For the C4 charges detonated alone two detonator positions were assessed. First, the detonator laid parallel to the ground surface; this orientation was designated as horizontal in Tables 1 and 2. When the detonator was perpendicular to the ground surface; this orientation was designated as vertical. Finally, ammunition specialists were responsible for the preparation of the rounds and the initiation of the explosives to ensure that all trials were conducted safely and according to standard procedures.

**Table 1.** Description of the explosive samples and the detonation conditions used for each trial of spring 2001

Trial number	Blown-in-place charge	Description	Priming charge	Primer mass	Priming Position	Fuse	Number of witness plates
A1	81-mm	857-g Comp B	C4	75-g	Nose	N	22
A2	81-mm	857-g Comp B	C4	150-g	Lateral	N	22
A3	81-mm	857-g Comp B	FIXOR™	2 bottles	1 bottle each side	Y	22
A4	81-mm	857-g Comp B	C4	75-g	Nose	N	22
A5	81-mm	857-g Comp B	C4	75-g	Nose	N	20
A6	81-mm	857-g Comp B	C4	100-g	Lateral	N	18
B1	60-mm	351-g TNT	FIXOR™	2 bottles	1 bottle each side	N	18
B2	60-mm	351-g TNT	C4	150-g	Lateral	Y	18
B3	60-mm	351-g TNT	C4	150-g	Lateral	N	18
B4	60-mm	351-g TNT	C4	100-g	Lateral	Y	18
B5	60-mm	351-g TNT	C4	100-g	Lateral	N	18
B6	60-mm	351-g TNT	C4 Linear Shaped Charge	75-g	Lateral	N	18
C1	M67 Grenade	185-g Comp B	Direct in Comp B	0-g	Detonator inside grenade	N	12
C2	M67 Grenade	185-g Comp B	C4	145-g	Lateral	N	12
C3	M67 Grenade	185-g Comp B	FIXOR™	2 bottles	1 bottle each side	N	12
C4	M67 Grenade	185-g Comp B	Direct in Comp B	0-g	Detonator inside grenade	N	12
C5	M67 Grenade	185-g Comp B	C4	100-g	Lateral	N	12
D1	PMA-1A	200-g TNT	C4	25-g	No hole, charge lying on mine	N	6
D2	PMA-1A	200-g TNT	C4	30-g	From lateral hole (5-g in hole)	N	6
D3	PMA-1A	200-g TNT	C4	4-g	From lateral hole (4-g in hole)	N	6
D4	PMA-1A	200-g TNT	C4	20-g	Top center hole	N	6
D5	PMA-1A	200-g TNT	C4	20-g	Top center hole	N	6
D6	PMA-1A	200-g TNT	C4 Linear Shaped Charge	20-g	No hole, charge lying on mine	N	6
D7	PMA-1A	200-g TNT	C4	4-g	From lateral hole (4-g in hole)	N	8
D8	PMA-1A	200-g TNT	FIXOR™	1 bottle	Bottle lying on mine	N	12
F1	C4	20-g 91% RDX	None	NA	Vertical position with Det Holder	N	6
F2	C4	50-g 91% RDX	None	NA	Horizontal position with Det Holder	N	6
F3	C4	75-g 91% RDX	None	NA	Detonator in the vertical position	N	6
F4	C4	100-g 91% RDX	None	NA	Detonator in the vertical position	N	6
F5	C4	100-g 91% RDX	None	NA	Detonator in the horizontal position	N	8
F6	C4	20-g 91% RDX	None	NA	Vertical position with Det Holder	N	8
F7	C4	50-g 91% RDX	None	NA	Detonator in the vertical position	N	8
F8	C4	75-g 91% RDX	None	NA	Detonator in the vertical position	N	8

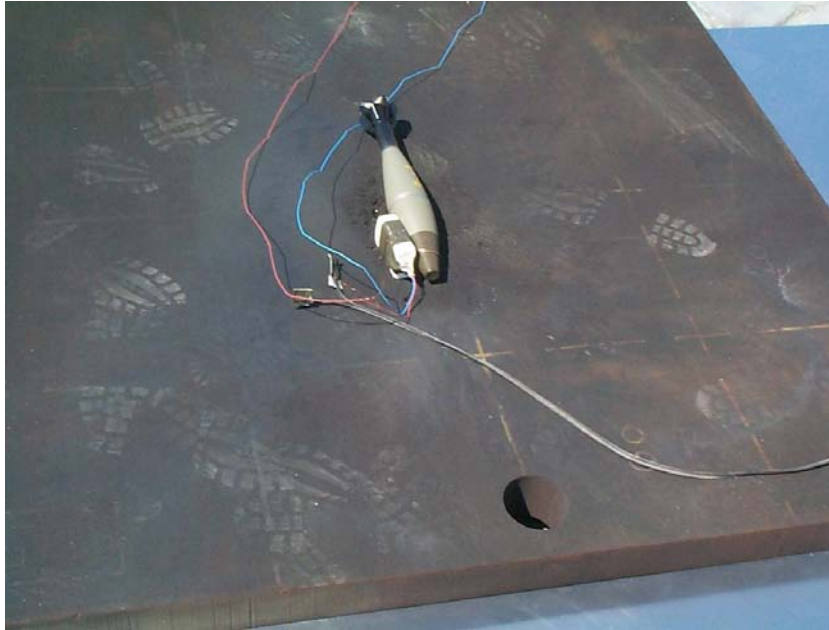
Det Holder: Support made of polypropylene use to hold the detonator

NA: Not applicable

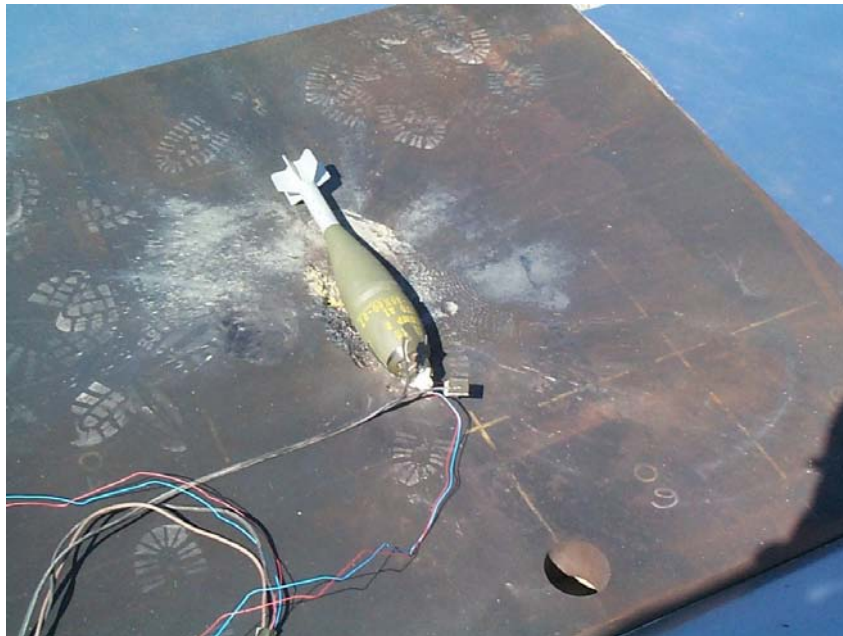
**Table 2.** Description of the explosive samples and the detonation conditions used for each trial of autumn 2002

Trial number	Blown-in-place charge	Explosive composition	Priming charge	Primer mass	Priming Position	Fuse	Number of witness plates
6-1	60-mm	351-g TNT	C4	150-g	Lateral	Y	18
6-2	60-mm	351-g TNT	C4	50-g	Nose	N	18
6-3B	60-mm	351-g TNT	C4	100-g	Lateral	N	18
6-4	60-mm	351-g TNT	C4 Linear shaped charge	75-g	Lateral	N	18
6-5	60-mm	351-g TNT	FIXOR™	2 bottles	Each side by the bottles bottoms	Y	18
6-6	60-mm	351-g TNT	RDX Shaped Charge	36-g	Lateral	Y	18
6-7	60-mm	351-g TNT	RDX Shaped Charge	6.5-g	Lateral	N	18
6-8	60-mm	351-g TNT	RDX Shaped Charge	16.5-g	Lateral	N	18
6-9	81-mm	857-g Comp B	C4	150-g	Lateral	Y	24
6-10	81-mm	857-g Comp B	C4	75-g	Nose	N	24
6-11	81-mm	857-g Comp B	C4	100-g	Lateral	N	24
6-12	81-mm	857-g Comp B	C4 Linear Shaped charge	75-g	Lateral	N	24
6-13	81-mm	857-g Comp B	FIXOR™	2 bottles	Each side by the bottles bottoms	Y	24
6-14	81-mm	857-g Comp B	RDX Shaped Charge	36-g	Lateral	Y	24
6-15	81-mm	857-g Comp B	RDX Shaped Charge	6.5-g	Lateral	N	24
6-16	81-mm	857-g Comp B	RDX Shaped Charge	16.5-g	Lateral	N	24
6-17	M67 Grenade	185-g Comp B	C4	100-g	Lateral	Y	8
6-18	M67 Grenade	185-g Comp B	Direct in Comp B	0-g	In Comp B	N	12
6-18B	M67 Grenade	185-g Comp B	Direct in Comp B	0-g	In Comp B	N	12
6-19	M67 Grenade	185-g Comp B	C4	20-g	Lateral	NA	12
6-21	M67 Grenade	185-g Comp B	FIXOR™	2 bottles	Each side by the bottles sides	Y	12
6-22	M67 Grenade	185-g Comp B	RDX Shaped Charge	36-g	Lateral	N	12
6-23	M67 Grenade	185-g Comp B	RDX Shaped Charge	6.5-g	Lateral	N	12
6-24	M67 Grenade	185-g Comp B	RDX Shaped Charge	16.5-g	Lateral	N	12
6-25	Shaped Charge 6.5-g	6.5-g RDX	None	None	NA	N	8
6-26	Shaped Charge 16.5-g	16.5-g RDX	None	None	NA	N	8
6-27	Shaped Charge 36-g	36-g RDX	None	None	NA	N	8
6-28	FIXOR™	None	None	2 bottles	NA	N	8

NA: Not available



**Figure 1.** 60-mm mortar and 150-g of C4 using a lateral priming position



**Figure 2.** 81-mm mortar and 75-g of C4 using a nose priming position

## 2.2 Site set-up

Two sets of experiments were performed at the demolition range of Garrison Valcartier: the first one was conducted in May 2001, and the second one in September 2002. The major requirements for the site were to have proper weather because high winds and heavy rain were considered inappropriate for sampling. Each explosive was placed in the middle of a heavy steel plate 1.34 x 1.77 x 0.1 m. To prevent contamination by residues from prior detonations, the heavy steel plate was raised 0.3 m from the ground as shown in Figure 3. Six polyethylene tarps 3.7 x 5.5 m were spread on the soil to avoid contamination from previous demolition activities. Aluminum witness plates, 6 to 24, 1 m x 1 m x 3 mm (Figure 4) were placed on the tarps around the steel plate to collect the residues. The distance between the witness plates was 50 cm. To help with sampling, these witness plates were gently bent diagonally, from corner to corner, which created a slightly concave surface. Short aluminum feet were welded at each corner (Figure 5). These kept the sampling surface off the ground. Figure 6 illustrates the way the witness plates were oriented around the heavy steel plate in accordance with the number of them. The tarps had to be changed regularly, because sometimes they did not resist the heat produced by the fireball and the fragments generated by the detonations. However, the elevated platform preserved the tarp as much as possible from the fireball and avoided flipping of the plates during a detonation.

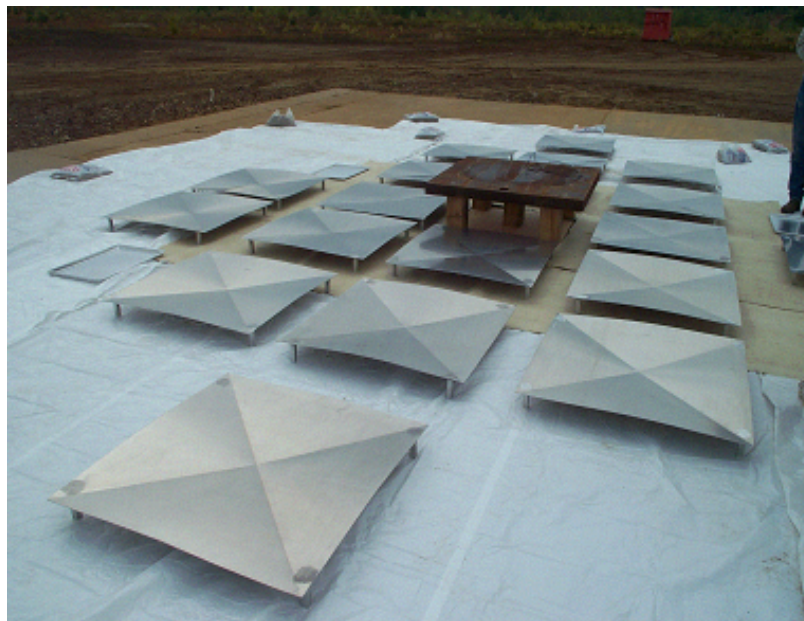
The air-blast pressure created by each detonation was recorded using PCB 113B51 sensors (Figure 3). Two sensors were used for each trial, and these were installed at 5- and 10-m distances for the smaller munitions, or 10- and 15-m for the larger munitions. These sensors were powered using ports 1 and 2 of a PCB Model 481 current source, and the output was monitored through ports 1 and 2 of a Nicolet Model 440 oscilloscope. The acquisition frequency of the oscilloscope was maintained at 500 kHz for all trials.

No meteorological station was used during the trial of spring 2001, but the temperature and the weather conditions were noted. Weather conditions and temperatures are listed in Annex D. A meteorological station was used in autumn 2002. The equipment used was a Weather Monitor II from Davis Instruments. Atmospheric pressure, temperature, wind direction, and minimum and maximum wind speed were registered.

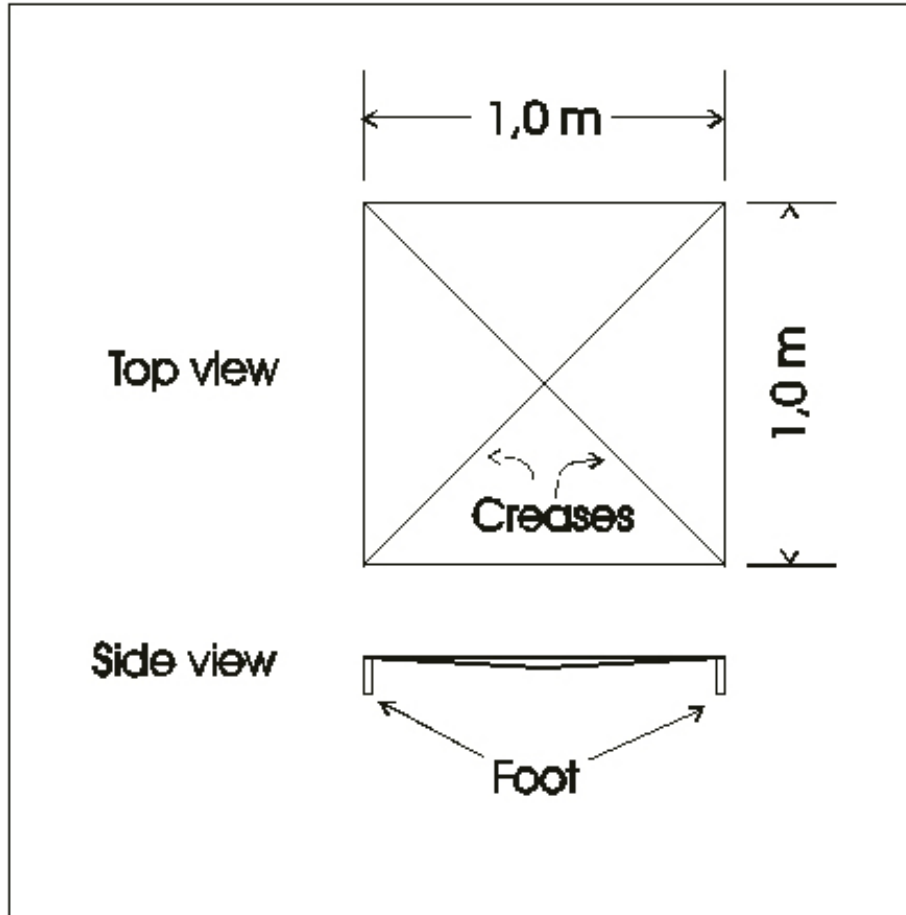
A Kodak CR2000 and a Sony Betacam camera operating at 1000 and 30 images per second, respectively, were used to record each trial. The Kodak camera was located at about 18 m from the detonation plate and secured in a photo shack, while the Sony was on the roof of the bunker.



**Figure 3.** EOD staff installing a detonator on a 60-mm mortar and location of the 5-m pressure sensor

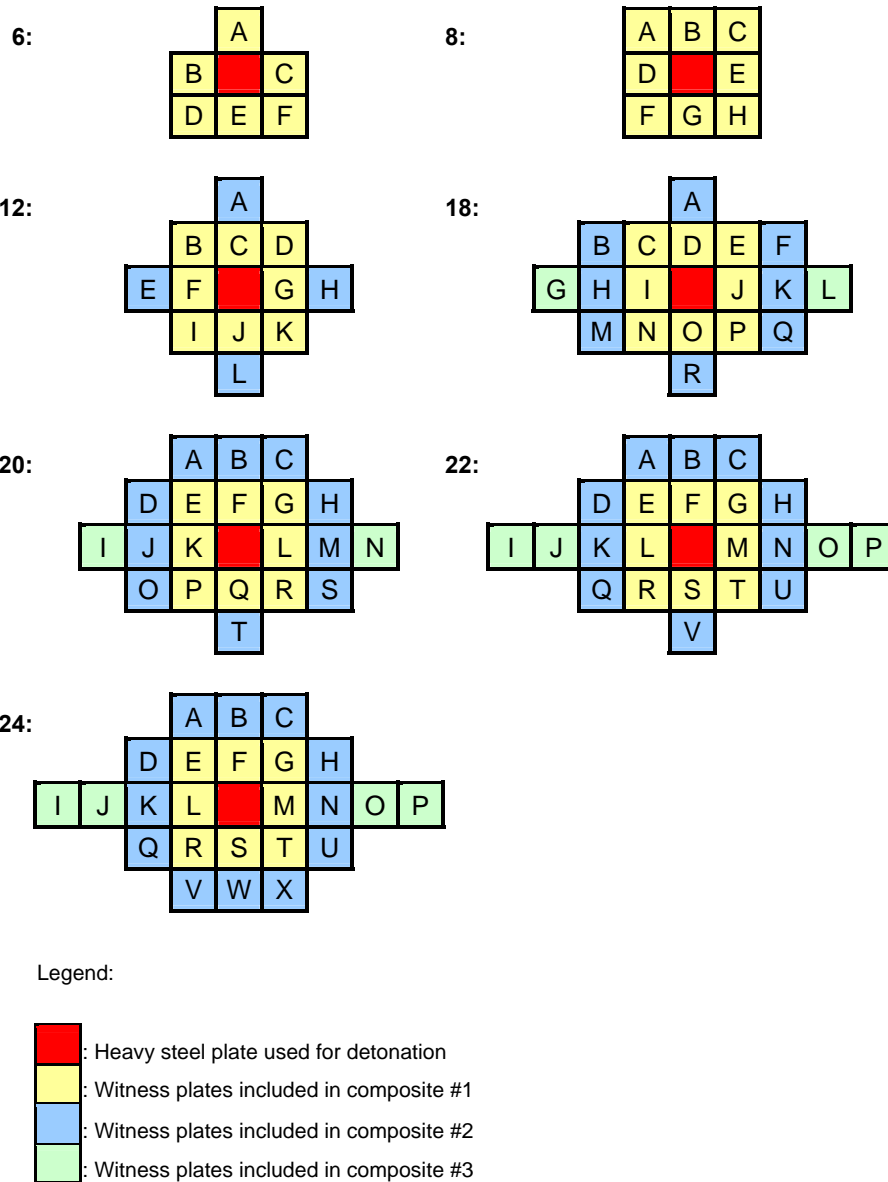


**Figure 4.** Witness plates layout around the heavy steel plate



**Figure 5.** Diagram of an aluminium witness plate used during the trials





**Figure 6.** Layout of the witness plates in accordance with their numbers, and witness plates included in the different composites (Note: the distance between each witness plates is 50 cm)

## 2.3 Sampling

After each detonation, to avoid the degradation of the explosives residues, the plates were sampled as soon as possible. The sampling began approximately 15 min. after the detonation to allow inspection of the site by the EOD specialist to insure that the site was secure after the detonation. The solid residues, if any, that were projected onto the aluminum plates were first transferred to a 250-mL amber sample bottle with a clean swab. Swabs were 4-ply rayon polyester of 10.2 x 10.2 cm. Each plate was then thoroughly wiped with acetone-soaked swabs that were put in a 250-mL amber sample bottle together with the sand already collected (Figure 7). The samples were immediately put in an icebox and kept from direct sunlight. At the end of the day, the samples were transferred in a conditioning chamber and kept at -20 °C until the extraction.

After the sampling, the plates were thoroughly sprayed with acetone and distilled water to remove any residual explosives that may still stick to the plates (Figure 8). They were then put back in place for another detonation.



**Figure 7.** Sampling of a witness plate after an event



**Figure 8.** Washing of a witness plate after sampling

## 2.4 Extraction and Analysis

Into every 250-mL amber sample bottle, about 100 mL of acetonitrile were added, enough to cover the wipes and allow a freestanding solution. Then, the sample bottles were placed on a wrist action shaker table for 18 hrs, after which they were transferred to an ultrasonic bath for 1 hour. The samples were grouped together because the number of HPLC analyses had to be minimized. The composite pattern is color-illustrated in Figure 6. Then, 10 mL of solvent coming from each sample bottle was withdrawn with a pipette and mixed in one container to form a composite solution. For example, the extracts coming from the witness plates represented by the same color in Figure 6 were combined in one sole extract. Prior to mixing, the 10-mL extract was filtered with a 0.45- $\mu$ m filter.

Finally, a precise quantity of the final solution (between 700-800  $\mu$ L) was transferred with an Eppendorf pipet in a 3-mL Luer-Lok syringe fitted with a 0.45- $\mu$ m filter. Water was added in different proportions, and the resulting solution was filtered into a 2-mL HPLC amber bottle.

Spring 2001 samples were extracted and analyzed by DRDC-Valcartier using reversed-phase HPLC. Analyses were performed on a HPLC equipped with a UV diode array detector monitoring at 210, 220 and 254 nm. The column used was a Supelcosil LC-8 column 25 cm x 3 mm x 5  $\mu$ m eluted with 15:85 isopropanol/water

(v/v) at a flow rate of 0.75 mL/min. Standards and solvents were diluted 1:2, acetonitrile to water.

Autumn 2002 samples were extracted and analyzed by CRREL using reversed-phase HPLC. Analyses were performed on a modular system consisting of a P1000 isocratic pump, a UV2000 dual wavelength absorbance detector set at 210 and 254 nm and an AS3000 autosampler. Analyte separations were performed using the 15 cm x 3.9 mm NovaPac C-8 column eluted with 15:85 isopropanol/water (v/v), 1.4 mL/min. Standards and solvents were diluted 1:3, acetonitrile to water.

The accuracy of the extraction and the analysis method has been tested. At DRDC-Valcartier, swabs were previously spiked with a standard solution of 25 mg/L and analyzed three times over 10 days. Mean recovery percentages were satisfactory: HMX =  $96 \pm 2.5\%$ , TNT =  $96 \pm 2.5\%$  and RDX =  $95 \pm 2.7\%$ . At CRREL, comparable instruments and the same extraction method was used. Similar mean recovery percentages were obtained: HMX = 97.9%, TNT = 98.7% and RDX = 95.5%. CRREL obtained better recovery percentages when swabs were dried before spiking.

The values detected by the RP-HPLC (Annex A) represented the explosive concentrations of the composites. When the concentration was multiplied by the amount of solvent used for the composites extraction, the results equaled the mass of explosive residues found in a composite. These results must be interpreted carefully because they do not represent the total mass of explosive residues formed by the munition or charge, since only a certain area was sampled. Hence, the results are underestimated.

### 3. Results and discussion

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HPLC results obtained after the extraction and analysis of the swipes are reported in Annex A for both trials. The values in Annex A are presented by composite using the pattern described in Figure 6. In addition, in Annex A the mass (mg) and the surface concentration ( $\text{mg}/\text{m}^2$ ) for TNT, RDX and HMX were added to allow a better comparison. Values for TNT, RDX, and HMX were numerically transformed. The TNT manufacturing impurity, 2,4-DNT, and the TNT products, 2-ADNT and 4-ADNT, were proportional to the TNT concentration; therefore, values for these compounds were not numerically transformed. Finally, the transformations of the values were performed using the calculations described in Annex B.

The values presented in this work are underestimated, because they have not been corrected to take into account the full area covered by the blast. Only the residues found on the aluminum plates were included in the calculation. However, the same approach was taken for all the detonation trials. Therefore, the comparison of the results can still lead to the identification of general trends and provide a good idea of the order of magnitude of the contamination.

To correctly analyze the results, the effectiveness of the detonation had to be determined. Only results for high-order detonations can be compared between them, because low-order detonations are characterized by very random results. A low-order detonation is either an incomplete detonation or a complete detonation occurring at lower than its maximum velocity. Low-order detonations may be caused by any one or a combination of these factors: initiator of inadequate power, deterioration of the explosive, poor contact between the initiator and the explosive, and lack of continuity in the explosive, like holes or cracks. To determine the order of the detonation, a comparison was made using the Conwep software [19]. Conwep predicts the pressure of a high-order detonation. The experimental pressure values were compared with the theoretical Conwep values (Annex C) to establish the order of the detonation. When both pressures were similar, the reaction was considered of high-order. However, when the experimental values were below 60% of the theoretical Conwep values and in agreement with visual observations made during the trial, a decision was made to consider the detonation low-order. Because the Conwep software does not offer the possibility to calculate the exact theoretical pressure for complete munitions and charges, the theoretical values were calculated as if the munitions or charges were bare HE. This assumption results in theoretical pressures slightly higher than experimental pressures, since energy is lost to break the casing of the munitions. Finally, when a low-order detonation had occurred for a specific trial, the corresponding results, highlighted in yellow in the Tables, were not compared with high-order detonation trials.

The surface concentration values ( $\text{mg}/\text{m}^2$ ) were observed to vary between the composites of the same trial (Annex A). Usually, the concentrations tend to decrease from composite 1 to 3, with increasing distance from the central plate. But for the larger charges like the 60- and 81-mm mortars, the highest concentrations were sometimes obtained for composite 2. The pattern of dispersion was, therefore, heterogeneous. However, the explosive residues were projected farther for larger charges, which is logical.

Trace amounts of TNT, RDX and HMX residues were found in some of the six blank samples, but no TNT manufacturing impurities or transformation products were detected. The average amounts were 0.33-mg for TNT, 0.005 mg for RDX, and 0.006-mg for HMX. Blank samples were taken randomly on washed witness plates. Numerous possibilities can explain the presence of background residues; residues from past detonations, particles carried by the wind, and also improper washing of the plates. Sand samples taken around the set-up were analyzed to evaluate the potential contribution of the surroundings to the contamination of the plates. Two sand samples showed an average concentration of 1.12 mg/kg of HMX, but no other explosives were detected. Results presented in this paper were not corrected for background residues.

The results of Annex A indicate that contamination was found in some trials. In trial 6-5, detonation of a 60-mm mortar with FIXOR™ produced high concentration of RDX and HMX when none was contained in the charge nor in the primer. This result is attributed to FIXOR™ producing sufficiently high blast pressure to project a large quantity of contaminated surrounding sand onto the aluminum plates. This is particularly true considering that FIXOR™ produced a huge fireball that completely burned the tarps around the detonation plate. The trials with FIXOR™ (B1, C3, 6-5, 6-13 and 6-21) have been highlighted in light green in Tables 3 to 6. Contamination was also found in some C4 charges detonated alone (Samples F5 to F8). All showed a significant TNT concentration, but none was supposed to be found because C4 does not contain TNT. This TNT contamination may come from prior detonations, because the plates were particularly difficult to wash before trial F5 due to the great contamination by the proceeding low-order detonations (B6, D7 and A6). This suggests that the washing was not adequate to remove all residues from the plates. Thus, because of the possibility of contamination, the results for trials done after a low-order detonation should be considered with caution. The chronological order of the trials was added in Tables 3 to 6 to point out those following low-order detonations. They were highlighted in blue in the Tables. Concerning the washing, the use of clean acetone-soaked rags or clean acetone baths should be considered for future trials.

The mass of explosive found after a detonation was compared with the initial quantities of explosive present in the total charge before the detonation events, giving a percentage of unconsumed explosive (Tables 3 and 4). The amount of explosive in the primer charge was taken into consideration in all cases. In addition, the residual 12% of HMX that comes from the synthesis of RDX was taken into account in the calculations (Annex B). Then, Tables 5 and 6, constructed using the results of Tables 3 and 4, present the explosive concentration per unit area ( $\text{mg}/\text{m}^2$ ) after an event. Those values are useful to compare the results of similar trials when different numbers of aluminum plates were used. Theoretically, when more aluminum plates were used, the area covered was larger, and the proportion recovered should be larger.

The results in Tables 5 and 6 show that the greatest concentrations came from low-order detonations, in agreement with results reported elsewhere. The contamination in TNT, RDX and HMX reached as much as 4.98% (D6, PMA-1A with LSC), 2.64% (D7, PMA-1A with 4-g C4 in a lateral hole) and 1.59% (6-12, 81-mm with LSC), respectively. For high-order detonations, the highest TNT concentration was of  $324 \text{ mg}/\text{m}^2$  (1.0%) from a PMA-1A mine detonated with 20-g C4 in the top hole. For RDX the greatest concentration deposited was  $47 \text{ mg}/\text{m}^2$  (0.6%) for an M67 grenade detonated with FIXOR™. And finally, for HMX, the

greatest value obtained was 4.8 mg/m<sup>2</sup> (0.5%) for an M67 grenade detonated with FIXOR™. Knowing that these concentrations are underestimated, these findings indicate that the blow-in-place of TNT- and Comp B-filled munitions is not always efficient at consuming all the main charge in certain detonation configurations. The results show that the highest contamination comes from PMA-1A anti-personnel mine imitations. However, some differences exist between real and imitation mines. The plastic casing used in the imitation might not have offered the same confinement as a real mine casing. A lack of continuity in the explosive, which is common to homemade munitions, is also possible. Moreover, the geometry of the mine and the critical diameter of TNT may have caused this situation. The use of more C4 might have given better results; however, the quantities used (4-g to 30-g) were those recommended by the EOD personnel for the destruction of PMA-1A mines.

Interestingly, all of the detonations of M67 grenades were high-order. The percentage of unconsumed TNT was generally below 0.05%. Four trials gave much higher results: C3 (FIXOR™, 0.29%), 6-17 (100-g of C4, 0.37%), 6-22 (36-g SC, 0.42%) and 6-23 (6.5-g SC, 0.66%). FIXOR™ was later discovered to have been used in an incorrect configuration for C3 (see below). Tests 6-17 and 6-23 followed, low-order detonations, and, thus, could be contaminated. That leaves only 1 trial with an inexplicably high concentration of TNT. With the exception of C3 (wrong FIXOR™ configuration), the highest RDX concentration was 0.035% for 6-18 (grenade with detonator in Comp B). HMX concentrations were much lower, below 0.02%; again, with the exception of C3, the highest concentration was found for 6-18.

For 60-mm mortars, 6 low-order detonations in 14 trials were obtained (B4, B5, B6, 6-3B, 6-4 and 6-7). Therefore, the efficient destruction of a 60-mm mortar cannot be done with less than 100-g of C4 sticking to the casing, or by a linear shaped charge (LSC), or with a 6.5-g shaped charge (SC); at least 150-g C4 or a SC of 16.5-g are necessary for this operation. With the exception of B1 (wrong FIXOR™ configuration, see below), the worst contaminating trials for TNT were 6-2 (50-g C4 in nose 0.18% TNT) and 6-6 (36-g SC, 0.14% TNT). This result is surprising for trial 6-2, but it follows a low-order detonation. Besides this, the TNT concentration is below 0.1%. RDX concentration is generally below 0.01%, the highest value being for sample 6-2. HMX is usually much lower or undetectable, except for sample B3, which was detonated with 150-g of C4 on the side of the casing.

For 81-mm mortars, 4 low-order detonations over 14 trials were obtained; these were observed for samples A4 (75-g of C4 in nose), A6 (100-g of C4 lateral), 6-12 LSC and 6-15 (6.5-g SC). The occurrence of a low-order detonation for A4 is strange because 3 other similar trials (A1, A5, 6-10) gave high-order detonations. TNT concentrations as high as 0.4% were obtained for A1 (75-g of C4 in nose) and A2 (150-g of C4 lateral). RDX concentrations were generally below 0.1%, except for A5 (75-g of C4 in nose, 0.214%), which followed a low-order detonation. RDX, 0.096%, was obtained for the 16.5g SC. HMX was usually undetectable, except for A5, which was possibly contaminated.

Differences were noted according to the primer charges used during the trials. When linear shaped charges were used, in four trials, only low-order detonations were obtained. This result is not surprising because LSC are specially designed to give low-order detonations. This kind of detonation is generally characterized by heavy contamination, and the two cases reported here are no exceptions. Commercial shaped charges, namely the 6.5g RDX SC, also

showed a high proportion of low-order detonation: two trials out of three gave low-order detonations, and the third showed a particularly high level of TNT contamination (see trials 6-7, 6-15 and 6-23). The destruction of munitions using C4 was more effective when a sufficient amount was used. The required quantity of C4 depends on the type of munition to be destroyed. High-order detonations with low levels of contamination were only obtained with the use of at least 150-g of C4 on the side of the munition for the 60- and 81-mm, but for the grenades 20-g were enough.

Extracting information concerning the proper primer position from the results obtained in this work is difficult. The detonation of M67 grenades generally gave high-order detonations and low levels of contamination, regardless of the position of the detonator. The blow-in-place of mortar rounds was more influenced by the quantity and type of primer than by the position of the primer. Of the 5 trials that were done with 150-g of C4 (A2, B2, B3, 6-1 and 6-9), all gave high-order detonations and mostly low levels of contamination. The only exception was sample A2 for which higher levels of TNT were found; however, trial A2 follows a low-order detonation. Five trials (A1, A4, A5, 6-2, 6-10) were also done with 50 to 75-g of C4 in the nose of the mortar. One of them (A4) produced a low-order detonation and the other ones seem to lead to higher levels of contamination than mortars detonated laterally. However, 3 of these 4 high-order detonations followed a low-order detonation and could be contaminated. For the PMA-1A anti-personnel mine imitation, the cleanest trials came from detonations done with 4 to 30-g of primer in a lateral hole (D2, D3 and D7). Still, more data are needed because one of these trials gave a low-order detonation. The worst contaminating trials came from mines that were detonated with C4 introduced in the top center hole (D4 and D5). This could indicate that the geometry of the mine hinders the propagation of the shock wave when the detonation is initiated by the middle part of the TNT block. Unexpectedly, low levels of contamination were obtained for the mine without holes (D1) for which C4 was only deposited on the casing without any direct contact with the explosive. We would have thought that close contact between the explosive and the primer was necessary to obtain clean detonations. Maybe the absence of holes in the plastic casing increased the degree of confinement and led to a better detonation. More results are needed to confirm those findings.

The presence of a fuse does not seem to influence the type of detonation and the level of contamination, at least for the 60-mm mortars. Indeed, high-order detonations and comparable amount of residues were obtained for trials B2 to B5, which were detonated under similar conditions, but with and without fuses.

Primer charges were also tested alone to evaluate their potential contribution to the explosive residues. Commercial RDX SC, and C4 blocks were thus detonated. The amount of explosives residues recovered after each detonation was small and similar for SC and C4, around 0.001-0.006% for RDX. The greatest recovery was 0.02% of RDX for a 20-g block of C4. The percentage of unconsumed HMX in C4 was generally below 0.01%, except for the 20-g block of C4, for which as much as 0.015% of the initial amount of HMX was recovered. TNT contamination occurred for all C4 and SC charges. For FIXOR™ detonated alone, no data were available, because the detonation was only conducted to generate a reference blast pressure.

When FIXOR™ was used as a primer charge, contamination of RDX and HMX was observed in three trials of rounds containing only TNT: B1 (60-mm), D8 (PMA-1A), 6-5 (60-mm). No



conclusion can be made for the moment. The contamination may come from the high blast pressure of FIXOR™ that might have sprayed residues from the surrounding onto the aluminum plates and from the huge fireball that completely destroyed the tarps around the detonation plate for spring 2001 samples, hence increasing the amount of explosives recovered. Nevertheless, two interesting facts were observed. First, only high order detonations were logged with FIXOR™ in 8 trials. This is an important observation considering that high-order detonations seldom show high levels of contamination. The second interesting observation about FIXOR™ concerns the way this initiating charge was used for the destruction of munitions. The amounts of TNT recovered after each detonation in the fall 2002 trial were always lower than those of spring 2001. This may be due to a better positioning of the bottles of FIXOR™ around the munitions; in the first trial they were placed vertically beside the munition, while in autumn 2002 they were laid down with their bottoms touching the munitions, following the manufacturer's advice. But the possibility of contamination by the surrounding sand in the spring 2001 samples cannot be ruled out. Indeed, the protecting tarps of autumn 2002 around the detonation plate were fire retardant, contrary to those of spring 2001. They were thus not systematically burned by the fireball. Therefore, there is a larger potential for contamination of spring 2001 samples than for those of autumn 2002. On the other hand, the HMX and RDX concentrations did not follow the same trend as TNT. More experiments would thus be needed before drawing final conclusions.

High concentrations of NG were surprisingly found in trials A and B (60- and 81-mm mortars) of spring 2001. Since NG was not detected in sand samples, but present only for 60- and 81-mm mortars, it probably comes from the propellant bags and the ignition cartridges, which are the only components of this kind of mortar containing NG. For trial B1 for example, a total of 71.2 mg of NG was found. None was detected in autumn 2002 trials because NG analysis was not targeted. The EOD personnel prior to the experiments removed the propellant bags. The ignition cartridge was also supposed to have been removed, but it is hard to verify because these cartridges are inside the mortars. The presence of NG could also come from contamination introduced during the manufacturing or the handling of the munitions [20]. The 71.2 mg found in trial B1 strongly suggest that the ignition cartridge was present during some trials. If the presence of the ignition cartridge is assumed, it represents 4100 mg of double-based propellant, which corresponds to 1640 mg of NG (40% w/w) present prior to detonation. The 71.2 mg of trial B7 corresponds thus to 4.34% of unconsumed NG. In view of this result, apparently NG was less consumed than TNT and RDX.

Sources of errors are numerous in these kinds of trials. The first is the heterogeneous dispersion of the residues. The area covered by the detonation could not be estimated. Other sources of error include the contamination and the adsorption of explosives on soot, which makes extraction of explosives difficult. Brochu *et al.* [8] has addressed this problem. However, soot was not present after all events; it was found mostly after low-order detonation and when FIXOR™ was used.

The variations in weather conditions, such as the wind speed and direction, might also have caused errors. Hot weather has been mentioned as particularly hard to deal with because the witness plates become very hot, which may degrade the explosives faster. Also, in hot weather the plates are difficult to sample and wash with acetone and methanol because of the

fast evaporation of the solvent. Considering that the trial of spring 2001 was done in very hot and humid conditions, the results may be more uncertain. Measuring the impacts of the wind speed and direction was impossible, since we used composites for the analysis. Furthermore, no relationship could be found between the temperature at the time of the detonation or the atmospheric pressure and the amount of dispersed residues (Annex D).

**Table 3.** Correlation between mass before event and mass after event for trials of spring 2001. Area sampled and detonation orders are also presented

Trial order	Trial number	Blow-in-place charge	Initiating charge	Total mass before event (g)			Total mass after event (g)			Area (m <sup>2</sup> )	% of unconsumed explosive			Detonation type
				TNT	RDX	HMX	TNT	RDX	HMX		TNT	RDX	HMX	
21	A1	81-mm	75-g C4	338.5	508.8	69.4	1.358	0.001	ND	22	0.401	0.000	ND	High-order
22	A2	81-mm	150-g C4	338.5	568.8	77.6	1.312	0.001	ND	22	0.388	0.000	ND	High-order
23	A3	81-mm	2 bottles FIXOR™	338.5	448.7	61.2	0.282	0.000	0.000	22	0.083	0.000	0.000	High-order
24	A4	81-mm	75-g C4	338.5	508.8	69.4	1.719	3.136	0.204	22	0.508	0.616	0.294	Low-order
25	A5	81-mm	75-g C4	338.5	508.8	69.4	0.664	1.087	0.068	20	0.196	0.214	0.098	High-order
26	A6	81-mm	100-g C4	338.5	528.8	72.1	0.794	1.375	0.092	18	0.235	0.260	0.127	Low-order
16	B1	60-mm	2 bottles FIXOR™	351.0	0.0	0.0	1.500	0.000	0.002	18	0.427	C	C	High-order
17	B2	60-mm	150-g C4	351.0	120.1	16.4	0.093	0.001	ND	18	0.027	0.001	ND	High-order
18	B3	60-mm	150-g C4	351.0	120.1	16.4	0.026	ND	0.058	18	0.007	ND	0.354	High-order
19	B4	60-mm	100-g C4	351.0	80.1	10.9	8.680	0.001	0.000	18	2.473	0.002	0.000	Low-order
20	B5	60-mm	100-g C4	351.0	80.1	10.9	9.489	0.004	0.001	18	2.703	0.005	0.008	Low-order
27	B6	60-mm	75-g C4	351.0	60.1	8.2	9.250	0.136	0.011	18	2.635	0.227	0.133	Low-order
7	C1	M67 Grenade	Direct in Comp B	73.1	96.9	12.2	0.035	ND	ND	12	0.047	ND	ND	High-order
8	C2	M67 Grenade	145-g C4	73.1	213.0	28.0	0.025	0.007	0.002	12	0.034	0.003	0.007	High-order
9	C3	M67 Grenade	2 bottles FIXOR™	73.1	96.9	12.2	0.211	0.565	0.058	12	0.288	0.583	0.471	High-order
10	C4	M67 Grenade	Direct in Comp B	73.1	96.9	12.2	0.003	0.004	0.001	12	0.005	0.004	0.005	High-order
11	C5	M67 Grenade	100-g C4	73.1	176.9	23.1	0.002	0.001	0.000	12	0.003	0.000	0.001	High-order
1	D1	PMA-1A	25-g C4	200.0	20.0	2.7	0.282	0.001	0.000	6	0.141	0.005	0.000	NA
2	D2	PMA-1A	30-g C4	200.0	24.0	3.3	0.017	ND	0.000	6	0.009	ND	0.005	High-order
3	D3	PMA-1A	4-g C4	200.0	3.2	0.4	0.236	ND	ND	6	0.118	ND	ND	High-order
4	D4	PMA-1A	20-g C4	200.0	16.0	2.2	3.118	0.007	0.000	6	1.559	0.046	0.000	NA
5	D5	PMA-1A	20-g C4	200.0	16.0	2.2	1.946	0.000	0.000	6	0.973	0.000	0.000	High-order
6	D6	PMA-1A	20-g C4	200.0	16.0	2.2	9.965	0.000	0.000	6	4.982	0.000	0.000	Low-order
28	D7	PMA-1A	4-g C4	200.0	3.2	0.4	6.901	0.085	0.006	8	3.450	2.643	1.406	Low-order
33	D8	PMA-1A	1 bottle FIXOR™	200.0	0.0	0.0	1.404	0.015	0.002	12	0.702	C	C	High-order
12	F1	C4	20-g C4	0.0	16.0	2.2	0.002	0.000	0.000	6	C	0.002	0.006	High-order
13	F2	C4	50-g C4	0.0	40.0	5.5	0.001	0.001	0.000	6	C	0.002	0.003	High-order
14	F3	C4	75-g C4	0.0	60.1	8.2	0.001	0.002	0.000	6	C	0.003	0.002	High-order
15	F4	C4	100-g C4	0.0	80.1	10.9	0.001	0.000	ND	6	C	0.001	ND	High-order
29	F5	C4	100-g C4	0.0	80.1	10.9	0.547	0.012	0.001	8	C	0.015	0.008	High-order
30	F6	C4	20-g C4	0.0	16.0	2.2	0.335	0.004	0.000	8	C	0.023	0.015	High-order
31	F7	C4	50-g C4	0.0	40.0	5.5	0.207	0.005	0.000	8	C	0.014	0.009	High-order
32	F8	C4	75-g C4	0.0	60.1	8.2	0.095	0.003	0.000	8	C	0.006	0.004	High-order

SC: Shaped Charge ND: Not detected NA: Not available C: Contamination  : Low-order detonation  : Performed after a low-order  : Possible contamination

**Table 4.** Correlation between mass before event and mass after event for trials of autumn 2002. Area sampled and detonation orders are also presented

Trial order	Trial number	Blow-in-place charge	Initiating charge	Total mass before event (g)			Total mass after event (g)			% of unconsumed explosive			Area (m <sup>2</sup> )	Detonation type
				TNT	RDX	HMX	TNT*	RDX	HMX	TNT	RDX	HMX		
1	6-1	60-mm	150-g C4	351.0	120.1	16.4	0.020	0.001	ND	0.006	0.001	0.000	18	High-order
4	6-2	60-mm	50-g C4	351.0	40.0	5.5	0.633	0.004	ND	0.180	0.010	0.000	18	High-order
23	6-3B	60-mm	100-g C4	351.0	80.1	10.9	9.023	0.019	ND	2.571	0.024	0.000	18	Low-order
3	6-4	60-mm	75-g C4 LSC	351.0	60.1	8.2	4.752	0.002	ND	1.354	0.004	0.000	18	Low-order
18	6-5	60-mm	FIXOR™	351.0	0.0	0.0	0.252	0.237	0.013	0.072	C	C	18	High-order
5	6-6	60-mm	36-g RDX SC	351.0	31.7	4.3	0.484	0.001	ND	0.138	0.003	0.000	18	High-order
7	6-7	60-mm	6.5-g RDX SC	351.0	5.7	0.8	4.720	0.008	ND	1.345	0.135	0.000	18	Low-order
6	6-8	60-mm	16.5-g RDX SC	351.0	14.5	2.0	0.564	0.001	ND	0.161	0.004	0.000	18	High-order
9	6-9	81-mm	150-g C4	338.5	568.8	77.6	0.054	0.003	ND	0.016	0.000	0.000	24	High-order
10	6-10	81-mm	75-g C4	338.5	508.8	69.4	0.077	0.001	ND	0.023	0.000	0.000	24	High-order
11	6-11	81-mm	100-g C4	338.5	528.8	72.1	0.023	0.000	ND	0.007	0.000	0.000	24	High-order
12	6-12	81-mm	75-g C4 LSC	338.5	508.8	69.4	12.159	18.130	1.105	3.592	3.563	1.592	24	Low-order
19	6-13	81-mm	FIXOR™	338.5	448.7	61.2	0.089	0.141	0.009	0.026	0.031	0.015	24	High-order
15	6-14	81-mm	36-g RDX SC	338.5	480.4	65.5	0.076	0.073	0.004	0.022	0.015	0.006	24	High-order
16	6-15	81-mm	6.5-g RDX SC	338.5	454.4	62.0	0.392	0.670	0.054	0.116	0.147	0.088	24	Low-order
13	6-16	81-mm	16.5-g RDX SC	338.5	463.2	63.2	0.264	0.445	0.027	0.078	0.096	0.043	24	High-order
8	6-17	M67 Grenade	100-g C4	73.1	176.9	23.1	0.267	0.000	ND	0.366	0.000	0.000	8	High-order
14	6-18	M67 Grenade	Direct in Comp B	73.1	96.9	12.2	0.017	0.034	0.002	0.024	0.035	0.018	12	High-order
21	6-18B	M67 Grenade	Direct in Comp B	73.1	96.9	12.2	0.011	0.017	0.001	0.015	0.017	0.009	12	High-order
17	6-19	M67 Grenade	20-g C4	73.1	112.9	14.4	0.008	0.015	0.001	0.011	0.013	0.007	12	High-order
20	6-21	M67 Grenade	FIXOR™	73.1	96.9	12.2	0.010	0.023	0.002	0.014	0.023	0.013	12	High-order
25	6-22	M67 Grenade	36-g RDX SC	73.1	128.5	16.5	0.306	0.012	ND	0.418	0.009	0.000	12	High-order
24	6-23	M67 Grenade	6.5-g RDX SC	73.1	102.6	13.0	0.485	0.011	ND	0.663	0.010	0.000	12	High-order
22	6-24	M67 Grenade	16.5-g RDX SC	73.1	111.4	14.2	0.012	0.017	0.001	0.017	0.015	0.008	12	High-order
26	6-25	SC 6.5-g RDX	None	0.0	5.7	0.8	0.004	0.000	ND	C	0.005	0.000	8	High-order
27	6-26	SC 16.5-g RDX	None	0.0	14.5	2.0	0.001	0.000	ND	C	0.001	0.000	8	High-order
28	6-27	SC 36-g RDX	None	0.0	31.7	4.3	0.008	0.001	ND	C	0.002	0.000	8	High-order
29	6-28	FIXOR™	None	0.0	0.0	0.0	NA	NA	NA	NA	NA	NA	8	High-order

SC: Shaped Charge

ND: Not detected NA: Not available

C: Contamination

Low-order detonation

Performed after a low-order

Possible contamination

**Table 5.** Mean surface concentration (mg/m<sup>2</sup>) after event for trials of spring 2001

Trial order	Trial number	Blow-in-place charge	Initiating charge	Mean concentration after events (mg/m <sup>2</sup> )			Area (m <sup>2</sup> )	Detonation Type
				TNT	RDX	HMX		
				21	A1	81-mm		
22	A2	81-mm	150-g C4	59.7	0.0	ND	22	High-order
23	A3	81-mm	2 bottles FIXOR™	12.8	0.0	0.0	22	High-order
24	A4	81-mm	75-g C4	78.2	142.5	9.3	22	Low-order
25	A5	81-mm	75-g C4	33.2	54.4	3.4	20	High-order
26	A6	81-mm	100-g C4	44.1	76.4	5.1	18	Low-order
16	B1	60-mm	2 bottles FIXOR™	83.3	0.0*	0.1*	18	High-order
17	B2	60-mm	150-g C4	5.2	0.0	ND	18	High-order
18	B3	60-mm	150-g C4	1.4	ND	3.2	18	High-order
19	B4	60-mm	100-g C4	482.2	0.1	0.0	18	Low-order
20	B5	60-mm	100-g C4	527.2	0.2	0.1	18	Low-order
27	B6	60-mm	75-g C4	513.9	7.6	0.6	18	Low-order
7	C1	M67 Grenade	None	2.9	ND	ND	12	High-order
8	C2	M67 Grenade	145-g C4	2.1	0.6	0.2	12	High-order
9	C3	M67 Grenade	2 bottles FIXOR™	17.6	47.1	4.8	12	High-order
10	C4	M67 Grenade	None	0.3	0.3	0.1	12	High-order
11	C5	M67 Grenade	100-g C4	0.2	0.1	0.0	12	High-order
1	D1	PMA-1A	25-g C4	46.9	0.2	0.0	6	NA
2	D2	PMA-1A	30-g C4	2.8	ND	0.0	6	High-order
3	D3	PMA-1A	4-g C4	39.3	ND	ND	6	High-order
4	D4	PMA-1A	20-g C4	519.6	1.2	0.0	6	NA
5	D5	PMA-1A	20-g C4	324.4	0.0	0.0	6	High-order
6	D6	PMA-1A	20-g C4	1660.8	0.0	0.0	6	Low-order
28	D7	PMA-1A	4-g C4	862.6	10.6	0.8	8	Low-order
33	D8	PMA-1A	1 bottle FIXOR™	117.0	1.2*	0.1*	12	High-order
12	F1	C4	20-g C4	0.3*	0.0	0.0	6	High-order
13	F2	C4	50-g C4	0.2*	0.1	0.0	6	High-order
14	F3	C4	75-g C4	0.2*	0.3	0.0	6	High-order
15	F4	C4	100-g C4	0.2*	0.1	ND	6	High-order
29	F5	C4	100-g C4	68.3*	1.5	0.1	8	High-order
30	F6	C4	20-g C4	41.8*	0.5	0.0	8	High-order
31	F7	C4	50-g C4	25.8*	0.7	0.1	8	High-order
32	F8	C4	75-g C4	11.9*	0.4	0.0	8	High-order

NA: Not available

ND: Not detected

\*: Contamination

☐: Low-order detonation

☐: Performed after a low-order

☐: Possible contamination

**Table 6.** Mean surface concentration (mg/m<sup>2</sup>) after event for trials of autumn 2002

Trial order	Trial number	Blow-in-place charge	Initiating charge	Mean concentration after events (mg/m <sup>2</sup> )			Area (m <sup>2</sup> )	Detonation type
				TNT	RDX	HMX		
1	6-1	60-mm	150-g C4	1.1	0.0	ND	18	High-order
4	6-2	60-mm	50-g C4	35.2	0.2	ND	18	High-order
23	6-3B	60-mm	100-g C4	501.3	1.1	ND	18	Low-order
3	6-4	60-mm	75-g C4 LSC	264.0	0.1	ND	18	Low-order
18	6-5	60-mm	FIXOR™	14.0	13.2*	0.7*	18	High-order
5	6-6	60-mm	36-g RDX SC	26.9	0.1	ND	18	High-order
7	6-7	60-mm	6.5-g RDX SC	262.2	0.4	ND	18	Low-order
6	6-8	60-mm	16.5-g RDX SC	31.4	0.0	ND	18	High-order
9	6-9	81-mm	150-g C4	2.3	0.1	ND	24	High-order
10	6-10	81-mm	75-g C4	3.2	0.1	ND	24	High-order
11	6-11	81-mm	100-g C4	1.0	0.0	ND	24	High-order
12	6-12	81-mm	75-g C4 LSC	506.6	755.4	46.0	24	Low-order
19	6-13	81-mm	FIXOR™	3.7	5.9	0.4	24	High-order
15	6-14	81-mm	36-g RDX SC	3.2	3.0	0.2	24	High-order
16	6-15	81-mm	6.5-g RDX SC	16.3	27.9	2.3	24	Low-order
13	6-16	81-mm	16.5-g RDX SC	11.0	18.6	1.1	24	High-order
8	6-17	M67 Grenade	100-g C4	33.4	0.0	ND	8	High-order
14	6-18	M67 Grenade	Direct in Comp B	1.4	2.8	0.2	12	High-order
21	6-18B	M67 Grenade	Direct in Comp B	0.9	1.4	0.1	12	High-order
17	6-19	M67 Grenade	20g C4	0.7	1.2	0.1	12	High-order
20	6-21	M67 Grenade	FIXOR™	0.8	1.9	0.1	12	High-order
25	6-22	M67 Grenade	36-g RDX SC	25.5	1.0	ND	12	High-order
24	6-23	M67 Grenade	6.5-g RDX SC	40.4	0.9	ND	12	High-order
22	6-24	M67 Grenade	16.5-g RDX SC	1.0	1.4	0.1	12	High-order
26	6-25	SC 6.5-g RDX	None	0.5*	0.0	ND	8	High-order
27	6-26	SC 16.5-g RDX	None	0.1*	0.0	ND	8	High-order
28	6-27	SC 36-g RDX	None	1.1*	0.1	ND	8	High-order
29	6-28	FIXOR™	None	NA	NA	NA	8	High-order

NA: Not available

ND: Not detected

\*: Contamination

■: Low-order detonation

■: Performed after a low-order

■: Possible contamination

## 4. Conclusion

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The first objective of this study was the estimation of the quantities and types of residues resulting from the blow-in-place detonation of various munitions. The detonation of munitions using blow-in-place conditions was not always efficient at consuming all of the main charge. For low-order detonations, more residues (up to a few percents) were recovered independently of the configuration. High-order detonations were characterized by much lower contamination; the maximum values found were 1.0%, 0.6% and 0.5% for TNT, RDX and HMX, respectively. However, typical levels of contamination were often around 0.05 to 0.4% for TNT, 0.035 to 0.1% for RDX and undetectable to 0.02% for HMX. To ensure high-order detonations with 60- and 81-mm mortars, 150-g of C4 on the side of the casing should be employed. FIXOR™ and the commercial shaped charges of 16.5-g and 36-g could also be used. For grenades, all of the configurations tested gave high-order detonations. For the PMA-1A, 4 to 30-g of C4 in a lateral hole or the use of FIXOR™ can lead to high-order detonations. The commercial shaped charges could probably give similar results, but they have not been tested with the mines.

Unfortunately, the identification of general trends is difficult because of the heterogeneous dispersion of the residues and because of the presence of contamination in some samples. This contamination may come from the improper washing of the witness plates or from the high-pressure blasts that may have sprayed explosive residues onto the witness plates. Moreover, all values are underestimated because the area covered by the plume could not be estimated; only the witness plates were sampled. Conclusions had to be drawn with caution.

Contamination by TNT tended to be higher than contamination by RDX, while HMX was less often found. The cleanest detonations were generally obtained from grenades, while the use of PMA-1A anti-personnel mine imitations released major quantities of explosive residues. As already mentioned, the use of imitation offers a different configuration from real mines, which may explain these results. The geometry and the critical diameter of TNT may also have caused this situation. Concerning the type of primer charge, cleaner detonations were obtained with at least 150-g of C4 for the 60- and 81-mm, but 4 to 20-g were enough for the grenades. The linear shaped charges and the 6.5-g SC gave mostly low-order detonations, and, consequently, a high dispersion of explosive residues. The commercial RDX SC of 16.5-g and 36-g were less of a problem, but more replicates are needed to determine their effectiveness in the field. FIXOR™ gave interesting results only when strictly following the manufacturer's advice.

The priming position influenced the dispersion of residues for PMA-1A mine imitations. Indeed, the cleanest trials came from detonations done with C4 introduced in a lateral hole and from mines without holes that were detonated with C4 in the middle of the mine, while the most contaminating ones were initiated with C4 in the top center hole. For the mortar rounds, the priming by the nose with 75-g C4 was more contaminating than priming by the lateral position with 150-g C4. However, whether this was due to differences between the priming positions or the quantities of C4 is unclear. The detonations of M67 grenades were not influenced by the position of the detonator. Finally, the blow-in-place of munitions were not affected by the presence of the fuse.

The presence of NG in post detonation residues of mortar rounds was unexpected, since no NG was supposed to be included in the detonation set-ups. However, the ignition cartridge may not have been removed as requested, and may thus have contributed to the dispersion of NG. More data are needed to confirm the poor NG consumption during live-fire detonations in order to make recommendations on potential for NG contamination of the environment.

The second objective of this work was to determine the contribution to the dispersion of explosive residues of many primer charges detonated alone. Past studies have shown that detonation of C4 appeared to increase the amount of RDX contamination [6]. Thus, C4 charges were tested, along with commercial RDX shaped charges, to determine the potential contribution of the primers. The detonation of various weights of C4 and of commercial RDX SC showed that their contribution was small, the use of C4 leading to the dispersion of less than 0.02% of RDX and HMX. The performance of commercial SC was even better, with only 0.005% RDX dispersed; no HMX was detected.

In general, this study showed that a certain proportion of explosives during a blow-in-place detonation could be sprayed into the environment. The study also demonstrated that the distributions are heterogeneous, and that the amount of explosive residues collected after a detonation strongly depends on the order of detonation. The configuration of the blow-in-place detonation also influences the level of contamination. For future work, at least 6 replicates of the same detonation are recommended to be able to generate statistically valid results. Nevertheless, this study has allowed the identification of some problematic cases and some general trends that can be used to make the following recommendations to the EOD personnel:

- In blow-in-place conditions, the conditions leading to low-order detonations should be avoided whenever possible.
- Linear shaped charges and commercial 6.5-g RDX shaped charges should not be used for blow-in-place detonations, charges of 16.5-g and 36-g are more required.
- To minimize contamination, 150-g of C4 should be used for blow-in-place of 60- and 81-mm mortars.
- The blow-in-place of PMA-1A mine imitations lead to high dispersion of explosive into the environment.
- The blow-in-place of PMA-1A mine imitations is highly dependent on the position of the primer.

The following suggestions are specifically addressed to scientists who perform similar trials:

- Washing of the aluminum witness plates is critical to prevent cross contamination. The use of clean acetone soaked rags or clean acetone baths are suggested.
- The efficiency of FIXOR™ should be further evaluated in conditions minimizing contamination from the surroundings.



-The analysis of NG in post-detonation residues should be done whenever NG is present in the munition to be tested.

-Whenever possible, the area covered by the plume should be evaluated to calculate the total contamination.

In conclusion, this study demonstrated that blow-in-place operations could spread explosives into the environment, but that the processes involved in controlling a detonation are extremely difficult and complex. More work will be needed to completely understand all the parameters involved in such experiments and to produce applicable solutions to this important activity.

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## 6. Annex A - Analytical results

**Table A1.** HPLC results, volume used for extraction, and mass of detonation residues by composite for spring 2001 trials

Sample and Composite #	(mg/L) corrected for dilution							Volume (L)	Mass (mg)			Mass (mg/m <sup>2</sup> )			# plates
	HMX	RDX	TNT	NG	2,4-DNT	2-ADNT	4-ADNT		TNT	RDX	HMX	TNT	RDX	HMX	
A1-1	ND	0.3	592.7	27.1	0.8	0.4	ND	0.80	474.2	0.2	ND	59.3	0.0	ND	8
A1-2	ND	0.7	794.5	26.1	1.0	ND	ND	1.00	794.5	0.7	ND	79.4	0.1	ND	10
A1-3	ND	0.6	222.6	ND	0.3	ND	ND	0.40	89.0	0.2	ND	22.3	0.1	ND	4
A2-1	ND	0.4	429.3	3.5	0.5	0.4	0.6	0.85	364.9	0.3	ND	45.6	0.0	ND	8
A2-2	ND	0.5	938.7	10.9	1.2	ND	ND	1.00	938.7	0.5	ND	93.9	0.0	ND	10
A2-3	ND	0.0	22.0	1.8	ND	ND	ND	0.40	8.8	0.0	ND	2.2	0.0	ND	4
A3-1	0.3	0.2	91.9	6.9	ND	ND	ND	0.85	78.1	0.2	0.3	9.8	0.0	0.0	8
A3-2	ND	0.2	174.3	7.9	0.2	ND	0.2	1.05	183.0	0.2	ND	18.3	0.0	ND	10
A3-3	ND	ND	52.6	0.5	ND	ND	ND	0.40	21.1	ND	ND	5.3	ND	ND	4
A4-1	124.8	1939.8	1013.5	ND	1.7	ND	ND	0.90	912.2	1745.9	112.4	114.0	218.2	14.0	8
A4-2	74.7	1130.2	653.9	ND	1.1	ND	ND	1.15	752.0	1299.7	85.9	75.2	130.0	8.6	10
A4-3	27.5	452.0	276.0	8.7	0.5	ND	ND	0.20	55.2	90.4	5.5	13.8	22.6	1.4	4
A5-1	35.4	563.6	340.8	ND	ND	ND	ND	0.85	289.7	479.1	30.1	36.2	59.9	3.8	8
A5-2	37.4	604.4	372.5	ND	ND	ND	ND	1.00	372.5	604.4	37.4	37.2	60.4	3.7	10
A5-3	1.28	19.5	11.6	ND	ND	ND	ND	0.20	2.3	3.9	0.2	1.2	1.9	0.1	2
A6-1	52.9	768.3	413.2	ND	0.8	ND	ND	0.95	392.6	729.9	50.2	49.1	91.2	6.3	8
A6-2	45.9	715.8	451.2	2.9	0.7	ND	ND	0.80	361.0	572.7	36.7	45.1	71.6	4.6	8
A6-3	25.0	360.3	202.6	2.2	ND	ND	ND	0.20	40.5	72.1	5.0	20.3	36.0	2.5	2
B1-1	1.3	ND	969.2	25.7	1.5	ND	ND	1.05	1017.7	ND	1.4	127.2	ND	0.2	8
B1-2	ND	0.5	432.7	33.9	0.6	ND	ND	0.95	411.1	0.5	ND	51.4	0.1	ND	8
B1-3	0.8	ND	353.8	59.8	0.5	ND	ND	0.20	70.8	ND	0.2	35.4	ND	0.1	2
B2-1	ND	0.5	37.7	25.4	ND	ND	ND	0.85	32.0	0.5	ND	4.0	0.1	ND	8
B2-2	ND	0.3	63.1	24.0	ND	ND	ND	0.80	50.5	0.2	ND	6.3	0.0	ND	8
B2-3	ND	0.6	53.2	45.3	ND	ND	ND	0.20	10.6	0.1	ND	5.3	0.1	ND	2
B3-1	ND	ND	14.7	6.1	ND	ND	ND	0.80	11.8	ND	ND	1.5	ND	ND	8
B3-2	72.5	ND	16.0	5.6	ND	ND	ND	0.80	12.8	ND	58.0	1.6	ND	7.2	8
B3-3	ND	ND	4.9	4.5	ND	ND	ND	0.20	1.0	ND	ND	0.5	ND	ND	2
B4-1	ND	1.3	7124.8	0.4	0.5	ND	ND	0.95	6768.6	1.3	ND	846.1	0.2	ND	8
B4-2	ND	ND	2125.2	1.0	ND	ND	ND	0.85	1806.4	ND	ND	225.8	ND	ND	8
B4-3	ND	ND	524.8	0.6	ND	ND	ND	0.20	105.0	ND	ND	52.5	ND	ND	2

Sample and Composite #	(mg/L) corrected for dilution							Volume (L)	Mass (mg)			Mass (mg/m <sup>2</sup> )			# plates
	HMX	RDX	TNT	NG	2,4-DNT	2-ADNT	4-ADNT		TNT	RDX	HMX	TNT	RDX	HMX	
B5-1	0.8	1.3	6205.2	ND	6.8	ND	ND	0.85	5274.4	1.1	0.7	659.3	0.1	0.1	8
B5-2	0.3	2.6	4746.4	ND	2.5	ND	ND	0.85	4034.4	2.2	0.2	504.3	0.3	0.0	8
B5-3	ND	2.2	899.9	ND	1.4	ND	ND	0.20	180.0	0.5	ND	90.0	0.2	ND	2
B6-1	8.9	111.4	16781.4	ND	33.3	ND	ND	0.95	15942.4	105.8	8.5	1992.8	13.2	1.1	8
B6-2	2.5	31.5	9405.7	ND	15.3	ND	ND	0.90	8465.2	28.3	2.2	1058.1	3.5	0.3	8
B6-3	0.9	11.8	3923.5	ND	6.8	ND	ND	0.20	784.7	2.4	0.2	392.4	1.2	0.1	2
C1-1	ND	ND	35.2	ND	ND	ND	ND	0.80	28.2	ND	ND	3.5	ND	ND	8
C1-2	ND	ND	16.0	ND	ND	ND	ND	0.40	6.4	ND	ND	1.6	ND	ND	4
C2-1	ND	0.3	19.8	ND	ND	ND	ND	0.80	15.8	0.2	ND	2.0	0.0	ND	8
C2-2	5.1	17.4	22.3	ND	ND	ND	ND	0.40	8.9	7.0	2.0	2.2	1.7	0.5	4
C3-1	39.4	389.3	136.0	ND	ND	ND	ND	1.05	142.8	408.8	41.4	17.9	51.1	5.2	8
C3-2	40.3	389.8	170.0	ND	ND	ND	ND	0.40	68.0	155.9	16.1	17.0	39.0	4.0	4
C4-1	0.6	3.0	3.4	ND	ND	ND	ND	0.80	2.7	2.4	0.5	0.3	0.3	0.1	8
C4-2	0.5	2.9	1.6	ND	ND	ND	ND	0.40	0.6	1.2	0.2	0.2	0.3	0.0	4
C5-1	0.2	0.7	2.0	ND	ND	ND	ND	0.80	1.6	0.6	0.2	0.2	0.1	0.0	8
C5-2	ND	0.5	0.8	ND	ND	ND	ND	0.40	0.3	0.2	ND	0.1	0.0	ND	4
D1	0.0	1.6	469.5	ND	ND	ND	ND	0.60	281.7	1.0	0.0	46.9	0.2	0.0	6
D2	0.2	ND	24.3	ND	ND	ND	ND	0.70	17.0	ND	0.2	2.8	ND	0.0	6
D3	ND	ND	393.5	ND	ND	ND	ND	0.60	236.1	ND	ND	39.3	ND	ND	6
D4	ND	12.2	5196.2	ND	ND	ND	ND	0.60	3117.7	7.3	ND	519.6	1.2	ND	6
D5	ND	ND	3243.6	ND	ND	ND	ND	0.60	1946.1	ND	ND	324.4	ND	ND	6
D6	ND	ND	13286.4	ND	ND	ND	ND	0.75	9964.8	ND	ND	1660.8	ND	ND	6
D7	6.8	94.1	7667.4	ND	ND	ND	ND	0.90	6900.7	84.7	6.1	1150.1	14.1	1.0	6
D8-1	1.1	14.8	981.2	ND	0.7	ND	ND	0.90	883.1	13.3	1.0	110.4	1.7	0.1	8
D8-2	1.3	3.3	1041.0	ND	0.8	ND	ND	0.50	520.5	1.7	0.6	130.1	0.4	0.2	4
F1	0.2	0.4	2.8	ND	ND	ND	ND	0.60	1.7	0.3	0.1	0.3	0.0	0.0	6
F2	0.3	1.5	1.7	ND	ND	ND	ND	0.60	1.0	0.9	0.2	0.2	0.1	0.0	6
F3	0.3	2.8	2.4	ND	ND	ND	ND	0.60	1.4	1.7	0.2	0.2	0.3	0.0	6
F4	ND	0.8	2.0	ND	ND	ND	ND	0.65	1.3	0.5	ND	0.2	0.1	ND	6
F5	1.1	14.5	643.0	ND	0.8	ND	ND	0.85	546.6	12.3	0.9	68.3	1.5	0.1	8
F6	0.4	4.7	418.1	ND	0.5	ND	ND	0.80	334.5	3.8	0.3	41.8	0.5	0.0	8
F7	0.6	6.9	258.2	ND	0.3	ND	ND	0.80	206.5	5.5	0.5	25.8	0.7	0.1	8
F8	0.4	4.3	118.6	ND	ND	ND	ND	0.80	94.9	3.4	0.3	11.9	0.4	0.0	8

ND: Not detected

**Table A2.** HPLC results, volume used for extraction, mass of detonation residues and mass of detonation residues by composite for autumn 2002 trials

Sample and Composite #	(mg/L) corrected for dilution							Volume (L)	Mass (mg)			Mass (mg/m <sup>2</sup> )			# plates
	HMX	RDX	TNT	NG	2,4-DNT	2-ADNT	4-ADNT		TNT	RDX	HMX	TNT	RDX	HMX	
6-1-1	ND	1.1	21.8	ND	0.0	0.1	0.4	0.49	10.7	0.5	ND	1.3	0.1	ND	8
6-1-2	ND	0.8	17.6	ND	0.0	0.0	0.2	0.50	8.8	0.4	ND	1.1	0.0	ND	8
6-1-3	ND	0.0	3.0	ND	ND	ND	ND	0.13	0.4	0.0	ND	0.2	0.0	ND	2
6-2-1	ND	6.0	502	ND	0.5	ND	ND	0.50	252.0	3.0	ND	31.5	0.4	ND	8
6-2-2	ND	2.0	698	ND	0.6	ND	ND	0.50	349.7	1.0	ND	43.7	0.1	ND	8
6-2-3	ND	0.2	259	ND	0.2	ND	ND	0.12	31.6	0.0	ND	15.8	0.0	ND	2
6-3B-1	<1	25.2	7980	ND	2.7	<1	<1	0.51	4069.8	12.9	ND	508.7	1.6	ND	8
6-3B-2	<1	11.4	8270	ND	3.0	<1	<1	0.51	4201.2	5.8	ND	525.1	0.7	ND	8
6-3B-3	<1	4.7	5970	ND	2.2	<1	<1	0.13	752.2	0.6	ND	376.1	0.3	ND	2
6-4-1	<1	1.7	1770	ND	<1	<1	<1	1.43	2534.6	2.4	ND	316.8	0.3	ND	8
6-4-2	<1	<1	1420	ND	<1	<1	<1	1.37	1945.4	ND	ND	243.2	ND	ND	8
6-4-3	<1	<1	1080	ND	<1	<1	<1	0.25	272.2	ND	ND	136.1	ND	ND	2
6-5-1	15.4	275.0	288.0	ND	ND	ND	ND	0.69	197.3	188.4	10.5	24.7	23.5	1.3	8
6-5-2	4.7	80.9	89.2	ND	ND	ND	ND	0.57	50.7	46.0	2.7	6.3	5.7	0.3	8
6-5-3	1.5	23.8	30.3	ND	ND	ND	ND	0.13	3.8	3.0	0.2	1.9	1.5	0.1	2
6-6-1	ND	0.9	280	ND	0.2	ND	ND	0.80	224.0	0.7	ND	28.0	0.1	ND	8
6-6-2	ND	0.3	245	ND	0.2	ND	ND	0.80	196.0	0.2	ND	24.5	0.0	ND	8
6-6-3	ND	0.2	318	ND	0.2	ND	ND	0.20	63.6	0.0	ND	31.8	0.0	ND	2
6-7-1	<1	9.0	2680	ND	1.9	<1	<1	0.85	2278.0	7.7	ND	284.8	1.0	ND	8
6-7-2	<1	<1	2740	ND	1.9	<1	<1	0.80	2192.0	ND	ND	274.0	ND	ND	8
6-7-3	<1	<1	1250	ND	<1	<1	<1	0.20	250.0	ND	ND	125.0	ND	ND	2
6-8-1	ND	0.5	354	ND	0.2	ND	ND	0.80	283.2	0.4	ND	35.4	0.0	ND	8
6-8-2	ND	0.2	225	ND	ND	ND	ND	0.80	180.0	0.2	ND	22.5	0.0	ND	8
6-8-3	ND	0.1	506	ND	0.2	ND	ND	0.20	101.2	0.0	ND	50.6	0.0	ND	2
6-9-1	ND	0.8	30.2	ND	ND	ND	ND	0.80	24.2	0.6	ND	3.0	0.1	ND	8
6-9-2	ND	1.6	22.0	ND	ND	ND	ND	1.20	26.4	1.9	ND	2.2	0.2	ND	12
6-9-3	ND	0.1	9.3	ND	ND	ND	ND	0.40	3.7	0.0	ND	0.9	0.0	ND	4
6-10-1	ND	0.6	37.4	ND	ND	ND	ND	0.85	31.8	0.5	ND	4.0	0.1	ND	8
6-10-2	ND	0.7	34.4	ND	ND	ND	ND	1.20	41.3	0.8	ND	3.4	0.1	ND	12
6-10-3	ND	0.2	8.8	ND	ND	ND	ND	0.40	3.5	0.1	ND	0.9	0.0	ND	4
6-11-1	ND	0.1	6.2	ND	ND	0.0	0.0	0.80	4.9	0.1	ND	0.6	0.0	ND	8
6-11-2	ND	0.2	11.4	ND	ND	0.0	0.0	1.20	13.7	0.2	ND	1.1	0.0	ND	12
6-11-3	ND	0.1	11.1	ND	ND	0.0	0.0	0.40	4.4	0.0	ND	1.1	0.0	ND	4

Sample and Composite #	(mg/L) corrected for dilution							Volume (L)	Mass (mg)			Mass (mg/m <sup>2</sup> )			# plates
	HMX	RDX	TNT	NG	2,4-DNT	2-ADNT	4-ADNT		TNT	RDX	HMX	TNT	RDX	HMX	
6-12-1	651	10700	7270	ND	<10	<10	<10	0.90	6543.0	9630	586	817.9	1203.8	73.2	8
6-12-2	317	5190	3440	ND	<10	<10	<10	1.25	4300.0	6488	396	358.3	540.6	33.0	12
6-12-3	307	5030	3290	ND	<10	<10	<10	0.40	1316.0	2012	123	329.0	503.0	30.7	4
6-13-1	4.0	65.8	38.2	ND	0.0	0.1	0.3	0.90	34.4	59.2	3.6	4.3	7.4	0.4	8
6-13-2	3.4	51.9	35.2	ND	0.0	0.0	0.1	1.20	42.2	62.3	4.1	3.5	5.2	0.3	12
6-13-3	3.4	49.5	31.1	ND	0.0	0.0	0.0	0.40	12.4	19.8	1.3	3.1	5.0	0.3	4
6-14-1	1.4	23.7	24.4	ND	ND	ND	ND	0.80	19.5	19.0	1.1	2.4	2.4	0.1	8
6-14-2	2.2	41.6	43.9	ND	ND	ND	ND	1.20	52.7	49.9	2.7	4.4	4.2	0.2	12
6-14-3	0.6	9.6	8.7	ND	ND	ND	ND	0.40	3.5	3.8	0.2	0.9	1.0	0.1	4
6-15-1	18.7	212	130	ND	<1	<1	<1	0.80	104.0	169.6	15.0	13.0	21.2	1.9	8
6-15-2	22.3	280	168	ND	<1	<1	<1	1.29	216.7	361.2	28.8	18.1	30.1	2.4	12
6-15-3	21.1	279	142	ND	<1	<1	<1	0.50	71.0	139.5	10.6	17.8	34.9	2.6	4
6-16-1	11.9	198.0	104.0	ND	ND	ND	ND	0.80	83.2	158.4	9.5	10.4	19.8	1.2	8
6-16-2	13.0	214.0	136.0	ND	0.2	ND	ND	1.20	163.2	256.8	15.6	13.6	21.4	1.3	12
6-16-3	4.6	75.7	43.3	ND	ND	ND	ND	0.40	17.3	30.3	1.8	4.3	7.6	0.5	4
6-17-1	ND	0.4	334.0	ND	ND	ND	ND	0.80	267.2	0.3	ND	33.4	0.0	ND	8
6-18-1	1.8	28.7	15.2	ND	ND	ND	ND	0.90	13.7	25.8	1.7	1.7	3.2	0.2	8
6-18-2	1.4	20.4	9.1	ND	ND	ND	ND	0.40	3.6	8.2	0.6	0.9	2.0	0.1	4
6-18-1'	1.2	18.8	12.8	ND	ND	ND	ND	0.80	10.2	15.0	0.9	1.3	1.9	0.1	8
6-18-2'	0.4	3.7	2.6	ND	ND	ND	ND	0.40	1.1	1.5	0.2	0.3	0.4	0.0	4
6-19-1	1.0	13.7	8.8	ND	ND	ND	ND	0.80	7.1	11.0	0.8	0.9	1.4	0.1	8
6-19-2	0.7	8.9	3.1	ND	ND	ND	ND	0.40	1.2	3.6	0.3	0.3	0.9	0.1	4
6-21-1	1.2	17.8	7.5	ND	ND	ND	ND	0.85	6.4	15.1	1.1	0.8	1.9	0.1	8
6-21-2	1.3	18.9	9.3	ND	ND	ND	ND	0.40	3.7	7.6	0.5	0.9	1.9	0.1	4
6-22-1	<1	12.5	314.0	ND	<1	<1	<1	0.80	251.2	10.0	ND	31.4	1.3	ND	8
6-22-2	<1	4.9	136.0	ND	<1	<1	<1	0.40	54.4	2.0	ND	13.6	0.5	ND	4
6-23-1	<1	9.9	449.0	ND	<1	<1	<1	0.80	359.2	7.9	ND	44.9	1.0	ND	8
6-23-2	<1	6.8	314.0	ND	<1	<1	<1	0.40	125.6	2.7	ND	31.4	0.7	ND	4
6-24-1	1.1	15.0	10.3	ND	ND	ND	ND	0.80	8.2	12.0	0.9	1.0	1.5	0.1	8
6-24-2	0.8	12.7	9.9	ND	ND	ND	ND	0.40	3.9	5.1	0.3	1.0	1.3	0.1	4
6-25-1	ND	0.3	5.1	ND	ND	ND	ND	0.80	4.1	0.3	ND	0.5	0.0	ND	8
6-26-1	ND	0.2	1.4	ND	ND	ND	ND	0.80	1.1	0.1	ND	0.1	0.0	ND	8
6-27-1	ND	0.7	10.5	ND	ND	ND	ND	0.80	8.4	0.6	ND	1.1	0.1	ND	8
6-28-1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	ND	8

ND: Not detected

NA: Not available

## 7. Annex B - Calculations

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1-Calculate the amount of explosive residues in each composite as follows:

For each composite an amount of explosive residue was calculated. The value was based on the HPLC values previously corrected for dilution and on the total volume of solvent used for extraction. Only TNT, RDX and HMX values were calculated to simplify the results.

For example, in trial 6-1 composite 6-1-1: TNT = 21.8 mg/L and 0.489 L of solvent was used, for a total of 10.9453 mg, which is rounded to one significant figure: 10.9 mg

This value is listed in Annex A under mass. It corresponds to the total amount of unconsumed explosive residue found in one composite.

2-Calculate the total amount released after event

All the composites of a same trial were added together to represent the total mass released for a specific event. For example, 6-1-1 + 6-1-2 + 6-1-3 = total mass for 6-1. The values were reported in Tables 3 and 4 under total mass after event.

3-Calculate the total mass before event (Tables 3 and 4)

The total explosive weights for the Canadian Forces munitions were obtained from the relevant Canadian Forces Technical Order (CFTO) and from other relevant specifications. The 60-mm mortar and the PMA-1A did not require further calculations, as they are both 100% TNT. The 81-mm mortar HE round and M67 grenade were both filled with Composition B, a mixture of 59.5% RDX and 39.5% TNT with the remaining 1 percent in wax.

For their part, the C4 demolition blocks are composed of 91% of RDX. The mass of RDX in the commercial shaped charge explosives is indicated on the product. RDX contains however between 10-15% of HMX. No CFTO governs the amount of HMX allowable in RDX (if anything, the presence of HMX increases the explosive effectiveness). Therefore, for the purpose of calculation, an average of 12% was used. Here are some examples:

For 150-g C4:

$$((150\text{-g}) \times 0.91) \times 0.12 = 16.38\text{-g HMX}$$

$$((150\text{-g}) \times 0.91) \times 0.88 = 120.12\text{-g RDX}$$

For 81-mm mortar (857-g Comp B)

$$857\text{-g} \times 0.395 = 338.5\text{-g of TNT}$$



$$(857\text{-g} \times 0.595) \times 0.12 = 61.19\text{-g of HMX}$$

$$(857\text{-g} \times 0.595) \times 0.88 = 448.73\text{-g of RDX}$$

4-Calculate the percent explosive remaining after detonation (Tables 3 and 4)

The percentage in Tables 3 and 4 is simply the amount of residues found after an event divided by the amount of explosives before the event multiplied by 100.

For example, for trial 6-1, 0.020262g of TNT was found after the event and 351-g of TNT was present before the event.

$$0.020262\text{-g} / 351\text{-g} \times 100 = 0.0058\%$$

The values were reported as “% of unconsumed explosive” in Tables 3 and 4

5-Calculate the concentration of explosive

The concentration of explosive residues by area was calculated from the amounts of residues recovered divided by the number of plates used. Since every aluminum plate was 1 m<sup>2</sup>, then the results gave the concentration in mg/m<sup>2</sup>.

## 8. Annex C - Pressure data

**Table C1.** Pressure sensors results for blow-in-place detonation trials of spring 2001 with theoretical Conwep values

Trial order and number		Blow-in-place Charge	Sensor # 1			Sensor # 2		
			Distance	Pressure (kPa)		Distance	Pressure (kPa)	
		m		Theoretical	Experimental		m	Theoretical
21	A1	81-mm	15	8.6	8.91	10	14.8	12.10
22	A2	81-mm	15	9.0	6.90	10	15.4	9.28
23	A3	81-mm	15	10.8	6.57	10	18.8	12.56
24	A4	81-mm	15	8.6	4.73	10	14.8	6.22
25	A5	81-mm	15	8.6	8.09	10	14.8	12.83
26	A6	81-mm	15	8.8	5.53	10	15.0	7.34
16	B1	60-mm	10	15.6	9.51	5	46.1	38.82
17	B2	60-mm	10	11.3	9.51	5	30.7	29.79
18	B3	60-mm	10	11.3	10.07	5	30.7	28.94
19	B4	60-mm	10	10.7	5.33	5	28.7	20.20
20	B5	60-mm	10	10.7	6.40	5	28.7	19.50
27	B6	60-mm	10	10.4	6.03	5	27.7	14.99
7	C1	M67 Grenade	10	7.1	6.18	5	17.2	12.44
8	C2	M67 Grenade	10	9.3	9.83	5	24.2	24.26
9	C3	M67 Grenade	10	14.5	9.93	5	42.1	34.08
10	C4	M67 Grenade	10	7.1	9.53	5	17.2	23.54
11	C5	M67 Grenade	10	9.0	9.02	5	23.3	20.96
1	D1	PMA-1A	10	7.9	NA	5	19.8	NA
2	D2	PMA-1A	10	8.0	9.62	5	20.0	NA
3	D3	PMA-1A	10	7.5	5.78	5	18.7	15.21
4	D4	PMA-1A	10	7.8	NA	5	19.6	NA
5	D5	PMA-1A	10	7.8	6.40	5	19.6	16.04
6	D6	PMA-1A	10	7.8	3.28	5	19.6	9.01
28	D7	PMA-1A	10	7.5	3.00	5	18.7	6.84
33	D8	PMA-1A	10	11.6	7.76	5	31.8	25.08
12	F1	20-g C4	10	3.0	NA	5	7.5	NA
13	F2	50-g C4	10	4.6	5.07	5	11.0	12.79
14	F3	75-g C4	10	5.4	5.14	5	13.1	15.87
15	F4	100-g C4	10	6.1	5.38	5	15.0	13.87
29	F5	100-g C4	10	6.1	5.35	5	15.0	16.20
30	F6	20-g C4	10	3.0	3.01	5	7.5	7.86
31	F7	50-g C4	10	4.6	4.38	5	11.0	8.54
32	F8	75-g C4	10	5.4	5.75	5	13.1	8.95

NA: Not available

**Table C2.** Pressure sensors results for blow-in-place detonation trials of autumn 2002 with theoretical Conwep values

Trial order and number		Blow-in-place Charge	Sensor # 1			Sensor # 2		
			Distance	Pressure (kPa)		Distance	Pressure (kPa)	
			m	Theoretical	Experimental	m	Theoretical	Experimental
1	6-1	60-mm	5	30.7	29.41	10	11.3	12.40
4	6-2	60-mm	5	26.2	NA	10	9.9	9.26
23	6-3B	60-mm	5	28.7	15.98	10	10.7	7.16
3	6-4	60-mm	5	27.7	12.02	10	10.4	7.09
18	6-5	60-mm	5	46.1	46.73	10	15.6	14.38
5	6-6	60-mm	5	25.8	16.16	10	9.8	10.26
7	6-7	60-mm	5	25.1	10.85	10	9.6	4.11
6	6-8	60-mm	5	24.7	15.40	10	9.4	8.48
9	6-9	81-mm	10	15.4	14.49	15	9.0	9.03
10	6-10	81-mm	10	14.8	13.62	15	8.6	12.56
11	6-11	81-mm	10	15.0	13.42	15	8.8	11.10
12	6-12	81-mm	10	14.8	6.64	15	8.6	4.60
19	6-13	81-mm	10	18.8	17.88	15	10.8	12.11
15	6-14	81-mm	10	14.5	12.17	15	8.6	9.23
16	6-15	81-mm	10	14.4	4.60	15	8.5	3.41
13	6-16	81-mm	10	14.3	10.58	15	8.4	8.89
8	6-17	M67 Grenade	5	23.3	23.41	10	9.0	10.14
14	6-18	M67 Grenade	5	17.2	12.82	10	7.1	6.77
21	6-18B	M67 Grenade	5	17.2	17.41	10	7.1	6.22
17	6-19	M67 Grenade	5	19.2	21.03	10	7.5	6.98
20	6-21	M67 Grenade	5	42.1	47.92	10	14.5	13.23
25	6-22	M67 Grenade	5	20.1	14.38	10	7.9	6.95
24	6-23	M67 Grenade	5	19.2	23.79	10	7.6	7.57
22	6-24	M67 Grenade	5	18.7	13.26	10	7.5	7.21
26	6-25	Shaped Charge 6.5-g	5	4.4	3.05	10	-	1.58
27	6-26	Shaped Charge 16.5-g	5	6.5	4.17	10	2.6	1.39
28	6-27	Shaped Charge 36-g	5	9.9	6.45	10	3.7	3.78
29	6-28	FIXORT™	5	37.4	49.86	10	13.1	14.29

NA: Not available      □: Low-order detonation

## 9. Annex D - Meteorological data

**Table D1.** Meteorological readings of blow-in-place detonation trials of spring 2001

<b>Trial</b>	<b>Date</b>	<b>Approximate Temperature (°C)</b>	<b>Comments</b>
A1	2001-05-08	25	Windy and sunny
A2	2001-05-08	25	Low wind and sunny
A3	2001-05-08	25	Windy and sunny
A4	2001-05-09	20	Low wind and sunny
A5	2001-05-09	20	Windy and sunny
A6	2001-05-09	20	Windy and sunny
B1	2001-05-07	20	Low wind and sunny
B2	2001-05-07	20	Windy and sunny
B3	2001-05-07	20	Windy and sunny
B4	2001-05-07	20	Windy and sunny
B5	2001-05-08	25	Low wind and sunny
B6	2001-05-09	20	Windy and sunny
C1	2001-05-02	25	Very Windy and sunny
C2	2001-05-03	25	Low wind and sunny
C3	2001-05-03	25	Windy and sunny
C4	2001-05-03	25	Very Windy and sunny
C5	2001-05-03	25	Very Windy and sunny
D1	2001-05-01	30	Windy and sunny
D2	2001-05-01	30	Windy and sunny
D3	2001-05-01	30	Windy and sunny
D4	2001-05-02	25	Low wind and sunny
D5	2001-05-02	25	Low wind and sunny
D6	2001-05-02	25	Low wind and sunny
D7	2001-05-10	20	Low wind and sunny
D8	2001-05-10	20	Windy and sunny
F1	2001-05-04	15	Windy and cloudy
F2	2001-05-04	15	Windy and cloudy
F3	2001-05-04	15	Windy and cloudy
F4	2001-05-04	15	Windy and cloudy
F5	2001-05-10	20	Low wind and sunny
F6	2001-05-10	20	Low wind and sunny
F7	2001-05-10	20	Windy and sunny
F8	2001-05-10	20	Windy and sunny

**Table D2.** Meteorological readings of blow-in-place detonation trials of autumn 2002

Trial	Date	Hour	Temperature (°C)	Barometric pressure Mb	Wind direction	Wind speed Km/h	Wind minimum Km/h	Wind maximum Km/h
# 6-1	2002-09-17	09:57:13	13.9	1011.4	205	7.2	5	10
		09:58:13	14.2	1011.4	211	6.1	5	8
		09:59:14	14.5	1011.4	215	6.7	3	10
# 6-2	2002-09-18	09:27:26	11.8	1017.8	88	5.3	3	6
		09:28:26	11.8	1017.8	113	5.7	3	8
		09:29:27	12.0	1017.8	117	5.2	3	8
# 6-3	2002-09-17	11:24:45	17.1	1011.4	254	10.2	6	14
		11:25:45	17.2	1011.3	248	11.9	10	16
		11:26:46	17.4	1011.3	242	13.2	8	18
# 6-3B	2002-09-25	09:29:25	13.0	1026.2	104	0.7	0	3
		09:30:25	13.0	1026.2	191	2.7	2	5
		09:31:24	13.1	1026.3	188	3.8	3	5
# 6-4	2002-09-17	13:43:34	19.4	1010.6	256	15.2	8	21
		13:44:35	19.3	1010.6	253	10.9	5	16
		13:45:35	19.2	1010.6	280	6.8	3	10
# 6-5	2002-09-24	10:10:53	13.8	1024.2	120	5.0	2	8
		10:11:53	14.0	1024.2	124	3.6	3	6
		10:12:54	14.1	1024.2	69	2.4	2	3
# 6-6	2002-09-18	10:48:51	14.1	1017.5	263	9.9	6	14
		10:49:51	14.6	1017.5	248	10.1	6	14
		10:50:51	15.1	1017.5	246	8.4	5	11
# 6-7	2002-09-18	14:01:49	17.7	1015.6	275	6.3	3	10
		14:02:50	17.6	1015.6	256	4.3	2	10
		14:03:50	17.6	1015.6	211	9.1	5	14
# 6-8	2002-09-18	12:55:29	16.7	1016.2	262	8.7	3	18
		12:56:29	16.9	1016.2	272	9.9	3	16
		12:57:30	16.8	1016.2	219	5.1	3	8
# 6-9	2002-09-19	10:00:40	16.8	1014.7	193	3.8	2	5
		10:01:40	16.8	1014.7	231	5.4	0	8
		10:02:40	16.9	1014.7	247	3.8	2	6
# 6-10	2002-09-19	10:51:56	18.9	1014.2	95	0.9	0	2
		10:52:56	18.8	1014.2	110	1.4	0	3
		10:53:56	18.9	1014.2	98	5.2	3	8
# 6-11	2002-09-19	12:48:31	21.3	1013.5	328	1.5	0	2
		12:49:32	21.4	1013.5	262	3.0	2	6
		12:50:31	21.6	1013.4	274	6.8	5	10
# 6-12	2002-09-19	13:35:46	23.2	1012.7	197	11.6	6	16
		13:36:46	23.2	1012.7	233	11.2	10	14
		13:37:46	23.5	1012.7	141	10.2	6	18
# 6-13	2002-09-24	11:22:15	15.5	1023.5	86	9.7	5	13
		11:23:15	15.7	1023.5	70	8.1	5	11
		11:24:16	15.8	1023.5	90	8.3	6	11
# 6-14	2002-09-23	11:04:03	16.7	1013.1	299	11.6	6	19
		11:05:03	16.3	1013.2	304	12.0	6	19
		11:06:03	16.4	1013.2	290	8.7	5	13
# 6-15	2002-09-23	13:17:51	17.9	1014.5	278	21.4	14	32
		13:18:52	17.9	1014.4	280	24.3	16	35
		13:19:52	17.6	1014.6	287	22.4	16	32
# 6-16	2002-09-20	09:44:05	18.9	1009.7	273	11.5	8	14
		09:45:05	19.0	1009.7	267	10.9	8	18
		09:46:04	19.0	1009.7	282	16.3	8	21

<b>Trial</b>	<b>Date</b>	<b>Hour</b>	<b>Temperature (°C)</b>	<b>Barometric pressure Mb</b>	<b>Wind direction</b>	<b>Wind speed Km/h</b>	<b>Wind minimum Km/h</b>	<b>Wind maximum Km/h</b>
# 6-17	2002-09-18	14:59:07	17.9	1015.2	283	4.8	2	11
		15:00:07	17.8	1015.2	274	3.7	2	6
		15:01:08	18.1	1015.1	245	10.4	3	18
# 6-18A	2002-09-20	10:59:27	19.3	1009.4	257	13.0	10	18
		11:00:28	19.3	1009.4	251	12.5	10	18
		11:01:27	19.3	1009.5	254	9.5	5	14
# 6-18B	2002-09-24	14:09:06	17.9	1022.0	148	8.2	3	13
		14:10:06	18.0	1022.0	107	2.8	2	5
		14:11:06	17.8	1022.0	124	4.6	2	8
# 6-19	2002-09-23	14:55:26	17.3	1015.3	269	18.8	11	23
		14:56:27	17.4	1015.3	272	17.7	11	24
		14:57:27	17.2	1015.3	277	14.9	10	21
# 6-21	2002-09-24	13:26:52	17.5	1022.2	89	4.5	3	6
		13:27:53	17.4	1022.1	202	5.0	2	11
		13:28:53	17.5	1022.2	191	12.3	5	19
# 6-22	2002-09-25	10:56:51	16.4	1026.1	104	3.5	2	6
		10:57:51	16.4	1026.1	117	5.1	2	8
		10:58:52	16.3	1026.1	129	4.0	2	8
# 6-23	2002-09-25	10:19:40	15.1	1026.3	153	2.9	0	5
		10:20:40	14.9	1026.2	150	3.1	0	6
		10:21:40	14.9	1026.2	132	3.5	2	6
# 6-24	2002-09-24	14:43:16	18.1	1021.7	149	8.1	3	11
		14:44:16	18.1	1021.7	96	9.8	6	13
		14:45:17	18.1	1021.7	111	9.0	5	13
# 6-25	2002-09-25	12:50:25	17.8	1024.9	104	4.6	2	6
		12:51:25	18.3	1024.8	185	6.2	2	11
		12:52:26	18.9	1024.8	201	6.5	5	10
# 6-26	2002-09-25	13:14:32	19.4	1024.7	233	6.2	2	11
		13:15:33	19.3	1024.7	247	10.1	6	14
		13:16:33	19.7	1024.6	244	12.6	8	16
# 6-27	2002-09-25	13:36:39	19.9	1024.6	248	10.7	6	14
		13:37:39	19.9	1024.6	260	10.3	8	11
		13:38:40	19.7	1024.6	246	8.4	3	18
# 6-28	2002-09-25	14:01:47	20.4	1024.4	208	7.4	6	11
		14:02:47	20.4	1024.4	187	7.6	3	14
		14:03:47	20.3	1024.4	204	8.9	5	19

## List of symbols/abbreviations/acronyms/initialisms

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2-ADNT	2-amino-4,6-dinitrotoluene
4-ADNT	4-amino-2,6-dinitrotoluene
CRREL	Cold Regions Research and Engineering Laboratory
2,4-DNT	2,4-dinitrotoluene
DGE	Director General Environment
DND	Department of National Defence
DRDC	Defence Research and Development Canada
EOD	Explosives Ordnance Disposal
EPA	Environmental Protection Agency
HE	High Explosive
LSC	Linear Shaped Charge
METC	Munitions Experimental Test Centre
MMR	Massachusetts Military Reservation
NB	Nitrobenzene
NG	Nitroglycerine
HMX	1,3,5,7-hexahydro-1,3,5,7-trinitro-1,3,5,7-tetrazocine
RDX	1,3,5-hexahydro-1,3,5-trinitro-1,3,5-triazine
RP-HPLC	Reversed-Phase High Performance Liquid Chromatography
SC	Shaped Charge
SERDP	Strategic Environmental Research and Development Program
1,3,5-TNB	1,3,5-trinitrobenzene
TNT	Trinitrotoluene

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A relatively large proportion of munitions used in live-fire exercises does not detonate as expected and generate unexploded ordnances (UXOs) in training areas. This percentage of non-functioning munitions can be evaluated to be between 3 and 10 % of the fired ammunition, while for some type of munitions, such as antitank weapons, this proportion can be as high as 50%. These UXOs might bury themselves or lie at the surface in the training areas. Once a year, military experts of the Explosive Ordnance Disposal Unit (EOD) perform a clearance level one (surface clearance) in all training areas to get rid of the surface UXOs. Because they are considered unsafe to move, UXOs are blown in place with a charge of C4. These critical activities are considered dangerous but needed for the safety problem that these UXOs represent. The environmental impact of this particular activity has not been highly documented and a systematic study was needed. DRDC Valcartier designed specific experiments in which various munitions and charges were detonated using either C4 in various quantities or shaped charges, both commercial and military, with ammunitions either fused or un-fused, to verify the relative environmental impacts of each event. An experimental set-up involving the use of witness plates and the collection of detonation residues for analysis of their energetic material contents was designed. Despite the presence of contamination in some trials, some generalizations could be made. The greatest concentrations, in the percent levels for TNT, RDX and HMX, came from low-order detonations. When high-order detonations were obtained, the largest concentration in TNT was 324 mg/m<sup>2</sup> (1.0%), coming from a PMA-1A anti-personnel mine imitation. The greatest RDX deposited was 47 mg/m<sup>2</sup> (0.6%) coming from a M67 grenade. Finally, for HMX, the greatest value obtained was 4.8 mg/m<sup>2</sup> (0.5%) coming also from a M67 grenade. These indicate that TNT and Comp B-filled munitions are not always efficient at consuming all the main charge in blow-in-place conditions. The amount of residues collected after an event was influenced by the blow-in-place conditions. For example, the greatest residue recoveries were obtained when a linear shaped charge and a commercial 6.5-g RDX shaped charge were used. Moreover, the blow-in-place of various primer charges detonated alone showed that their potential contribution in explosive residues was low.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Detonations, blow-in-place detonation, unexploded ordnances, explosive residus, NG, TNT, RDX, HMX, Training ranges, surface sampling, high-explosive projectiles

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