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Cost and Performance Report

(ER-0434)

Treatment of Explosives Residues From Range Activities

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ACRONYMS AND ABBREVIATIONS

bgs	below ground surface
C-4	Composition 4
CEC	cation exchange capacity
CIA	Central Impact Area
2,4-DNT	2,4- dinitrotoluene
2,6-DNT	2,6-dinitrotoluene
DNT	dinitrotoluene
DNX	hexahydro-1,3-dinitroso-5-nitro-1,3,5-triazine
DoD	Department of Defense
EOD	explosive ordnance disposal
ERDC-CRREL	Engineer Research and Development Center – Cold Regions Research and Engineering Laboratory
ESTCP	Environmental Security Technology Certification Program
FEP	fluorinated ethylene propylene
GR	Grenade Range
GRAS	generally recognized as safe
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
HPLC	high performance liquid chromatography
ID	inner diameter
MDL	method detection limit
MMR	Massachusetts Military Reservation
MNX	hexahydro-1-nitroso-3,5-dinitro-1,3,5-triazine
NC	nitrocellulose
NG	nitroglycerine
NPT	National Pipe Thread
OB/OD	open burn/open detonation
OD	outer diameter
PQL	practical quantitation limit
PMSO	peat moss plus crude soybean oil (the treatment material being evaluated)
PO1	PMSO with a 1:1 ratio of peat moss:soybean oil (w:w basis)
PO2	PMSO with a 1:2 ratio of peat moss:soybean oil (w:w basis)
PVC	polyvinyl chloride

RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
RED	Registration Eligibility Decision
RTLA	Range and Training Land Assessment
SERDP	Strategic Environmental Research and Development Program
SP1	Soil Plot 1
S.U.	standard units(s) (pH measurements)
TNT	2,4,6-trinitrotoluene
TNX	hexahydro-1,3,5-trinitroso-1,3,5-triazine
TOC	total organic carbon
USEPA	U.S. Environmental Protection Agency
UXO	unexploded ordnance

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1.0 EXECUTIVE SUMMARY

NOTE: This project was conducted as two parallel and different types of demonstrations. These two types of demonstrations were meant to address and evaluate very different aspects of the technology, and as such, they were very different in terms of scope. This Cost and Performance Report summarizes all the relevant information and results from both demonstrations.

1.1 BACKGROUND

Ranges and other areas used by the Department of Defense (DoD) for testing new ordnance and for training personnel are common sites for environmental contamination with explosives. The munitions used by DoD contain a number of different explosive compounds including 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) in the fuse. Residues from munitions are dispersed over the soil surface and then serve as point source for explosive compounds, which can migrate into the soil and eventually contaminate the underlying groundwater. Technologies are needed to reduce the impact of range activities involving munitions on environmental resources.

The technology being evaluated was a surface-applied material composed of peat moss plus crude soybean oil (PMSO) as a technology to prevent and mitigate near-surface soil contamination with explosive compounds, thereby protecting the subsurface and groundwater at active DoD ranges.

The technology was tested in two different types of demonstrations:

1.1.1 Soil Plot 1 (SP1) Demonstration

Nine aboveground plots containing native uncontaminated soil were established at the Massachusetts Military Reservation (MMR). Plots were instrumented for the collection of soil pore water and pore gases, as well as with soil moisture probes; a weather station was also set up to collect meteorological data. Three plots served as controls and received no PMSO; three received a 10 cm layer of PMSO (1:1 peat moss:crude soybean oil [PO1]); and the remaining three received a 10 cm layer of PMSO (1:2 peat moss:crude soybean oil [PO2]). Composition B detonation residues of approximately 1-mm size from an 81-mm mortar round were applied uniformly over the surface of each aboveground soil plot. Soil pore water samples, as well as drainage water samples, were collected over the course of 1.5 years and analyzed for explosive compounds. At the end of the demonstration, the plots were deconstructed and the concentration profile of residual explosives in the soil was determined. Results were used to calculate the explosive compound flux, and results from the different treatments were compared. Data was also used to refine the PMSO effectiveness model developed during the previous Strategic Environmental Research and Development Program (SERDP) project.

1.1.2 Grenade Range (GR) Demonstration

A 10 cm layer of PMSO (1:1 peat moss:crude soybean oil, w:w) was then applied across the surface of a 10 m x 10 m area in a single bay. After the PMSO was applied, hand grenade

training continued. The redistribution of the PMSO was monitored and recorded using digital photography and image analysis.

1.2 OBJECTIVES

The primary quantitative objective was to assess the effectiveness of the PMSO technology with respect to reducing the flux of dissolved explosive compounds in soil emanating from surface deposited munition residues. This objective was examined during the SP1 Demonstration. The PMSO with the higher oil concentration exceeded all the performance objectives. RDX and the RDX breakdown product, hexahydro-1-nitroso-3.5-dinitro-1,3,5-triazine (MNX), were the primary explosive-related compounds detected. The PMSO reduced the pore water concentrations, fluxes, and residual soil concentrations of these compounds in the treatment plots by more than 50% relative to the values observed in the control (no PMSO) plots.

The primary qualitative objective was to assess the compatibility of the PMSO technology with DoD training activities at ranges. This objective was examined during the GR Demonstration. The PMSO was not directly affected by grenade detonations but was moved around by wind and grenade bay maintenance activities, indicating that alternative application methods would be more appropriate.

1.3 DEMONSTRATION RESULTS

The results from both the SP1 and GR demonstrations yielded the following conclusions:

- The PMSO material is very effective at reducing the migration of RDX into and through the soil when it is dissolving from surface applied Composition B residues. The RDX flux reduction ranged from 25- to 100-fold in the PMSO-treated plots (10 cm depth of 1:2 peat moss:soybean oil) versus control plots. MNX flux was also reduced 12- to 50-fold, depending on the depth. Dissolved TNT and HMX were not detected with enough frequency to allow calculation of fluxes of these compounds, but based on the previously developed model, the effectiveness for these compounds would be expected to be very high as well.

- It is expected that the PMSO would be effective at reducing the transport (flux) of other munition and propellant compounds, including 2.4-dinitrotoluene (2,4-DNT) and 2,6-dinitrotoluene (2,6-DNT), nitroglycerin, and nitroguanidine based on the physico-chemical properties of these compounds as well as some preliminary laboratory results.

- Surface applied PMSO would not likely be drastically affected by grenade (or other munition) detonations themselves, but it would be redistributed horizontally and mixed vertically into the soil in the treated area.

- Explosive ordnance disposal (EOD) activities that employ large quantities of Composition 4 (C4) could result in smoldering of a surface-applied layer of PMSO.

1.4 IMPLEMENTATION ISSUES

Based on current results and model predictions, the PMSO material would be effective as a barrier to reduced explosive compound transport (flux) if it were either 1) applied and buried under a layer of soil 30 to 60 cm (1 to 2 ft) depth of soil or 2) mixed into the top 15 to 30 cm (0.5 to 1 ft) of soil. This would avoid most of the issues involving smoldering and generation of excessive fugitive dust. The exact depth of burial or mixing would be dependent on the type of training area at which the PMSO was being applied. For a hand grenade range, cratering is usually less than 45 cm (1.5 ft) deep, so PMSO burial at 60 cm should be sufficient. At a mortar target area, deeper burial may be needed due to deeper cratering, while treatment at a mortar firing point to capture and treat propellant residues might require burial at only 15 cm (1 ft), depending on the amount of heavy equipment or track vehicles that would be expected to be moving across the treated zone (e.g., the PMSO would need to be buried deep enough to prevent the vehicle traffic from digging up and removing the PMSO layer).

The PMSO technology is most applicable for portions of the range where UXO is not of concern, such as open burn/open detonation (OB/OD) areas and EOD training areas, as well as grenade training areas and mortar firing points. PMSO would also be applicable for inclusion as a sustainable range management technology for use in areas that have been cleared of all past unexploded ordnance (UXO).

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2.0 INTRODUCTION

2.1 BACKGROUND

2.1.1 Environmental Problem

Impact ranges that are used by the DoD for testing new ordnance and for training personnel to use mortars, rockets, and other munitions are common sites for environmental contamination with explosives. The munitions that are tested at DoD impact ranges contain a number of different explosive compounds. For example, a 60-mm mortar round contains TNT in the primer, 2,4-DNT and 2,6-DNT in the propellant charge, TNT and RDX in the filler, and RDX and HMX in the fuse.

After full or partial detonation of a high explosive, residues of these materials can remain in the impact area. In addition, munitions that fail to detonate during training (i.e., UXO) are also a potential long-term source for the release of explosive compounds into soils. In sandy soils with little organic matter or clay content, such as those present at the MMR, transport of TNT, RDX, and HMX to the vadose zone and ultimately to groundwater is possible. Recent reports of groundwater contamination at MMR with RDX confirm this assumption. The contamination of groundwater underlying these facilities is particularly problematic because the explosive residues have the potential to adversely impact local drinking water supplies.

Explosive-related compounds have been observed to be recalcitrant in many environments, leading to the potential for long-term contamination at sites where they are released. However, under the proper conditions (i.e., low oxygen concentrations, presence of labile carbon sources), the ability of microorganisms to biotransform and biodegrade these compounds has been shown to be very widespread.

The challenges to effectively addressing the pollution issues associated with live fire range activities stem from several factors, which are summarized in Table 1. The proposed technology was developed to address and overcome all the listed challenges.

Table 1. Key factors and associated challenges that need consideration when addressing prevention of live fire range contamination with energetic compounds.

Factor	Resulting Challenge/Difficulty
Large size of impact areas	• Additives must be low cost • Additives must be effective in reasonable amounts • Additives should be available locally
Existence of UXO	• Surface application required (no tilling) • May require aerial application
Existing vegetation	• Additives must be compatible with vegetation • May require aerial application
Permeable soils (i.e., MMR)	• Rapid migration of contaminants and additives • Additives must be nontoxic
Low organic content soils (i.e., MMR)	• Rapid migration of contaminants • Aerobic conditions limit biodegradation • Low microbial populations

Table 1. Key factors and associated challenges that need consideration when addressing prevention of live fire range contamination with energetic compounds (continued)**.**

Factor	Resulting Challenge/Difficulty
Recalcitrant contaminants	• Low rates of biodegradation • Limited populations of natural degraders
Slow release of contaminants from UXO	• Requires long-term treatment/protection • Additives must be long-lived • May require repeated applications
Ongoing activities	• Application and additive must not impact operations • May require repeated applications

2.1.2 Technology Description

The technology that was tested is a soil amendment process designed to enhance the immobilization and biodegradation of explosives residues generated during live fire training, EOD and training activities, and OB/OD procedures. The basic components of the amendment are a long-lived, high-capacity sorbent (i.e., peat moss) and a slow-release microbial stimulant (i.e., soybean oil), combined to yield PMSO. These are natural materials that are nontoxic and environmentally benign. The materials are generally available and inexpensive, can be easily mixed, and are easily applied to large areas using readily available landscaping/agricultural equipment (i.e., mulch/bark blowers) or tilled into or buried under a layer of soil, as required.

The PMSO technology was developed and tested under laboratory conditions and yielded very promising results (Fuller et al., 2004; Fuller et al., 2005; Hatzinger et al., 2004; and Schaefer et al., 2005). TNT, RDX, and HMX all demonstrated strong sorption onto peat moss and several other materials compared to sorption onto native soil from MMR. The desorption of these compounds from peat moss demonstrated hysteresis, indicating that the explosives desorb more slowly than they adsorb. This contributes to the effectiveness of the proposed technology because it allows explosives residues generated during detonation to be quickly immobilized at the soil surface, followed by slow release from the sorbent, and ultimately biotransformed by microorganisms.

The results described above were used to develop a fate and transport model of energetic compounds in and through the PMSO. These results compared the effectiveness of various treatments in reducing the vadose zone pore water concentrations of TNT and RDX at a depth of 10 ft below ground surface (bgs). These simulation results indicated that TNT transport through the subsurface was significantly reduced by the addition of peat and soybean oil. This reduction was due primarily to TNT uptake into both the peat moss and soybean oil phases (i.e., short residence time and minimal mineralization of TNT was observed in the batch studies). Simulated RDX transport was also significantly reduced in the presence of the peat moss plus soybean oil mixture but was only marginally reduced in the presence of peat moss alone. This observation reflected the relatively low partitioning of RDX into peat or soybean oil, coupled with the relatively large biodegradation rate when soybean oil was added to the treatment. Transport of HMX was similar to but less than RDX. The modeling results justified the further field-scale evaluation of the PMSO technology that was undertaken during the SP1 and GR demonstrations.

2.1.3 Advantages of the Technology

The major advantages of this technology are that the components are relatively inexpensive, available in most areas, and environmentally benign. This technology is primarily focused on the prevention of subsurface contamination with energetic compounds, as opposed to the remediation of such. There are no current conventional technologies to which it can be easily compared. The only alternative technology that is currently being evaluated is topical lime application.

2.1.4 Demonstration Design

2.1.4.1 SP1 Demonstration

Nine aboveground plots containing native uncontaminated soil were established at the MMR. Plots were instrumented for the collection of soil pore water and pore gases, as well as with soil moisture probes; a weather station was also set up to collect meteorological data. Three plots served as controls and received no PMSO; three received a 10 cm layer of PMSO (1:1 peat moss:crude soybean oil, PO1); and the remaining three received a 10 cm layer of PMSO (1:2, PO2). Composition B detonation residues of approximately 1-mm size from an 81-mm mortar round were applied uniformly over the surface of each aboveground soil plot. Soil pore water samples, as well as drainage water samples, were collected over the course of 1.5 years and analyzed for explosive compounds. At the end of the demonstration, the plots were deconstructed and the concentration profile of residual explosives in the soil was determined. Results were used to calculate the explosive compound flux, and results from the different treatments were compared. Data was also used to refine the PMSO effectiveness model developed during the previous SERDP project.

2.1.4.2 GR Demonstration

A 10 cm layer of PMSO (1:1 peat moss:crude soybean oil, w:w) was then applied across the surface of a 10 m x 10 m area in a single bay. After the PMSO was applied, hand grenade training continued. The redistribution of the PMSO was monitored and recorded using digital photography and image analysis.

2.2 OBJECTIVES OF THE SP1 AND GR DEMONSTRATIONS

Table 2. Performance objectives for the SP1 Demonstration.

	Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
1	Quantitative	Effectiveness of treatment layer for new residues	>50% reduction in explosives leaching and/or explosive compound flux into soil in treatment plots compared to clean soil control plots	Yes; performance exceeded performance metric
2	Quantitative	Effectiveness of treatment layer for new residues	>50% reduction in total soil explosives concentrations at different depths in the treatment plots compared to control plots at the end of the demonstration	Yes; performance exceeded performance metric
1	Qualitative/semi-quantitative	Redistribution of treatment layer	Range maintains a continuous layer of the treatment material after multiple grenade detonations	Yes
2	Qualitative/semi-quantitative	Redistribution of treatment layer	Treatment material incorporated into soil profile	Yes/partial (qualitative assessment)
3	Qualitative/semi-quantitative	Long term fate of treatment material	Treatment material remains in the treated area with no significant losses due to wind or rainfall	Demonstration terminated early; unable to accurately assess
4	Semi-quantitative	Effectiveness of treatment layer	50% reduction in new explosives residues in soil with treatment compared to control (composite 0-30 cm depth)	Demonstration terminated early; unable to accurately assess
5	Semi-quantitative	Effectiveness of treatment layer	50% lower explosive residues at discrete depths with treatment compared to the control	Demonstration terminated early; unable to accurately assess
6	Quantitative	Effectiveness of treatment layer	Sorption capacity of treatment material varies less than 20% over 1-year time frame	Demonstration terminated early; unable to accurately assess

2.3 REGULATORY DRIVERS

The explosive compounds being examined during this project are currently or expected to be regulated. 2,4- and 2,6-DNT and RDX are currently on the U.S. Environmental Protection Agency's (USEPA) Unregulated Drinking Water Contaminants list (http://www.epa.gov/safewater/dw_unregcontaminants.html). Health advisory limits in the low part-per-billion range for the above three compounds, as well as RDX, HMX, TNT, nitroguanidine, and nitrocellulose have also been issued by the USEPA (http://www.epa.gov/waterscience/drinking/standards/dwstandards.pdf).

Several DoD sites, most notably MMR, have already come under regulatory pressure to stop activities that may result in contamination of groundwater with these compounds, as well as to

begin remediating contaminated groundwater and overlying soil. This PMSO technology is designed to help DoD meet these challenges.

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3.0 TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

The technology that was tested is a soil amendment process designed to enhance the immobilization and biodegradation of explosives residues generated during live fire training, EOD and training activities, and OB/OD procedures. The basic components of the amendment are a long-lived, high-capacity sorbent (i.e., peat moss) and a slow-release microbial stimulant (i.e., soybean oil), combined to yield PMSO. These are natural materials that are nontoxic and environmentally benign. The materials are generally available and inexpensive, can be easily mixed, and are easily applied to large areas using readily available landscaping/agricultural equipment (i.e., mulch/bark blowers) or tilled into or buried under a layer of soil, as required.

3.1.1 Prior Technology Development

Over 3 years of development and evaluation of the proposed technology under laboratory conditions has resulted in very promising results. TNT, RDX, and HMX all demonstrated strong sorption onto peat moss compared to sorption onto native soil from MMR. The desorption of these compounds from peat moss demonstrated hysteresis, indicating that the explosives desorb more slowly than they adsorb. This contributes to the effectiveness of the proposed technology because it allows explosives residues generated during detonation to be quickly immobilized at the soil surface, followed by slow release from the sorbent, and ultimately biotransformed by microorganisms.

Our research also examined how to stimulate native soil microorganisms to biodegrade TNT, RDX, and HMX. Experiments using soil slurry microcosms and unsaturated soil amended with microbial stimulants (cosubstrates) indicated that explosives were transformed and/or mineralized (converted to H_2O, CO_2 and other innocuous products) to a much greater extent in amended soil than in unamended soil. The results indicated that crude soybean oil promoted the biotransformation and/or mineralization of TNT, RDX, and, to some extent, HMX.

Model simulation results are shown in Figure 1. These results compared the effectiveness of various treatments in reducing the vadose zone pore water concentrations of TNT and RDX at a depth of 10 ft bgs. These simulations were performed using a combination of data obtained during the batch microcosm studies (to determine contaminant mineralization rates) and column studies (to determine mass transfer rates of contaminants in to the various sorbents). Since mineralization rates were used, these simulations likely underestimate the biological component of explosive residue attenuation because significant biotransformation can occur without mineralization. Aqueous concentrations of TNT and RDX entering the treatment layer were assigned values of 54 and 1.5 mg/L, respectively, which are quite reasonable based on published dissolution rates and our empirical data from our laboratory experiments. A rainfall rate of 120 cm/year was used in the simulation (corresponding to the annual rainfall total at MMR).

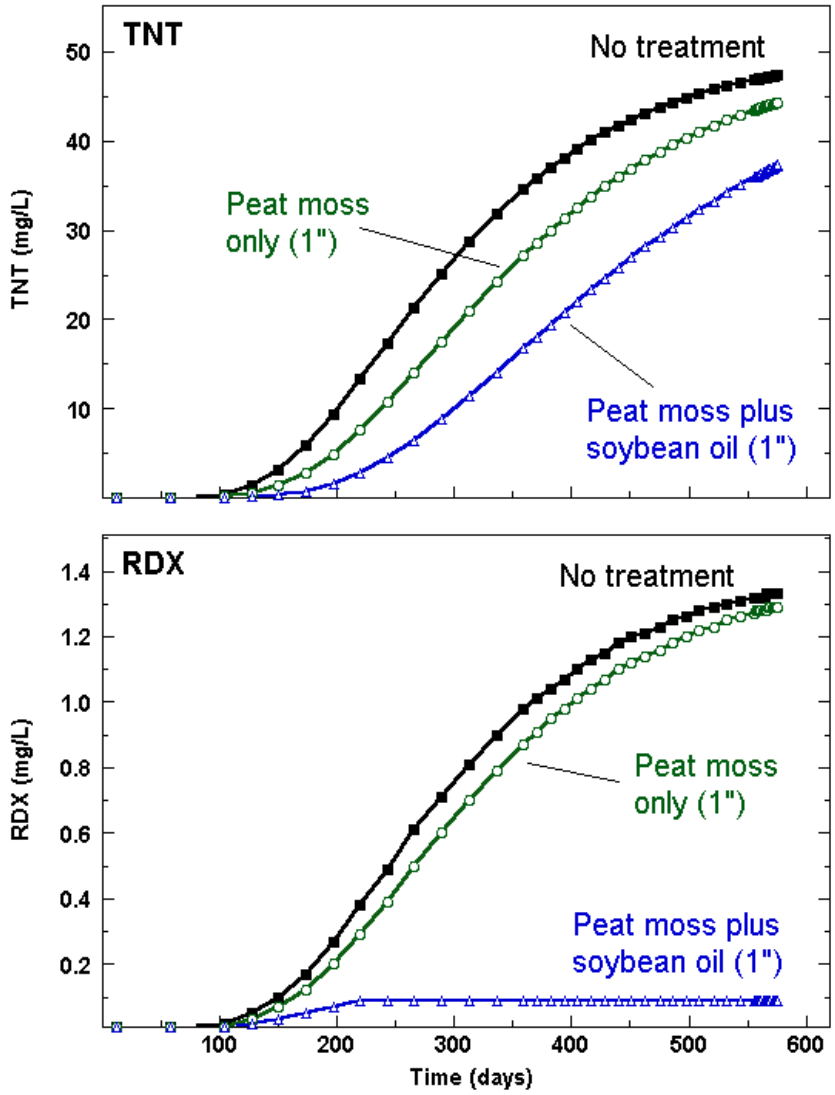

Figure 1. Modeling of treatment material effectiveness.
The results illustrate the predicted reduction in vadose zone pore water concentrations of TNT and RDX at a depth of 10 ft bgs with no in-place treatment, a 1-inch layer of peat moss, or a 1-inch layer of peat moss plus soybean oil.

These simulation results indicated that TNT transport through the subsurface was significantly reduced by addition of peat and soybean oil. This reduction was due primarily to TNT uptake into both the peat moss and soybean oil phases (i.e., short residence time and minimal mineralization of TNT was observed in the batch studies). Simulated RDX transport was also significantly reduced in the presence of the peat moss plus soybean oil mixture but was only marginally reduced in the presence of peat moss alone. This observation reflected the relatively low partitioning of RDX into peat or soybean oil, coupled with the relatively large biodegradation rate when soybean oil was added to the treatment. Transport of HMX was similar to but less than RDX.

Additional studies have evaluated mass transfer and biological processes as a function of rainfall rate, including the effects of intermittent rainfall on overall contaminant transport. Immobile pore water in the peat moss plus soybean oil layer between intermittent rain events tended to increase the residence time of the contaminants, allowing time for biological processes to further reduce dissolved concentrations.

3.1.2 ESTCP Technology Development

The results described above laid the foundation for these ESTCP field demonstrations. During the ESTCP demonstration, the following additional development of the PMSO technology was performed:

- The resistance of the PMSO to be ignited was tested under laboratory conditions. Neither red-hot metal probes nor open flames resulted in ignition or smoldering.

- Methods to efficiently mix and apply the PMSO were investigated. For the scale of demonstration performed during this project, mixing was easily done with a tow-behind cement mixer and hand raking to spread the material over the soil surface.

3.1.3 Expected Technology Applications

The PMSO technology would be most effective at areas ranging from a few hundred to a few thousand square meters. Sites that would be most likely to benefit from deployment of the PMSO technology include:

- Hand grenade training area
- OB/OD facilities
- Mortar and rocket firing points
- EOD training areas
- Small arms firing points (where there is a concern about nitrocellulose [NC]/nitroglycerine [NG]/dinitrotoluene [DNT] residues)

The data clearly indicated that the PMSO technology would be better either tilled into or emplaced beneath a layer of soil.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The major advantages of this technology are that the components are relatively inexpensive, available in most areas, and environmentally benign. This technology would have the same potential limitations as any of the other technologies being developed for surface application at live fire ranges. The largest currently unknown parameter is how well the technology will perform once it is dispersed, redistributed, and mixed into the soil by detonations. This was one of the main parameters to be assessed during the field demonstrations.

The main factors affecting the cost of the technology are the size of the area to be treated, the availability and cost of bulk quantities of the treatment components (peat moss, soybean oil), and the need for multiple treatment applications over a given period of time. Additionally, the environmental variables at a given site (rainfall, temperature) may also affect the cost and performance by increasing or decreasing both the dissolution and transport of the explosives and the biodegradation rates. Some of these factors began to be assessed during this project in terms of the PMSO effectiveness over periods longer than have been possible to study in the laboratory.

The only alternative technology for the PMSO is topical applied lime to promote the alkaline hydrolysis of energetic compounds. This technology is currently being evaluated under ESTCP Project ER-0216.

4.0 PERFORMANCE OBJECTIVES

The SP1 demonstration was focused on the evaluation of the effectiveness of the PMSO technology with respect to reducing the flux of dissolved explosive compounds in soil emanating from surface-deposited munition residues, while the GR demonstration was focused on the compatibility of the PMSO technology with range activities. The specific performance objectives for the two demonstrations are listed in Tables 3 and 4.

NOTE: Due to the early termination of the GR demonstration, Objectives 3 to 6 could not be fully assessed.

Table 3. Performance objectives for the SP1 Demonstration.

Type of Performance Objective		Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
1	Quantitative	Effectiveness of treatment layer for new residues	>50% reduction in explosives leaching and/or explosive compound flux into soil in treatment plots compared to clean soil control plots	Yes; performance exceeded performance metric
2	Quantitative	Effectiveness of treatment layer for new residues	>50% reduction in total soil explosives concentrations at different depths in the treatment plots compared to control plots at the end of the demonstration	Yes; performance exceeded performance metric

Table 4. Performance objectives for the GR Demonstration.

Type of Performance Objective		Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
1	Qualitative/ semi-quantitative	Redistribution of treatment layer	Range maintains a continuous layer of the treatment material after multiple grenade detonations	Yes
2	Qualitative/ semi-quantitative	Redistribution of treatment layer	Treatment material incorporated into soil profile	Yes
3	Qualitative/ semi-quantitative	Long-term fate of treatment material	Treatment material remains in the treated area with no significant losses due to wind or rainfall	Demonstration terminated early; unable to accurately assess
4	Semi-quantitative	Effectiveness of treatment layer	50% reduction in new explosives residues in soil with treatment compared to control (composite 0-30 cm depth)	Demonstration terminated early; unable to accurately assess
5	Semi-quantitative	Effectiveness of treatment layer	50% lower explosive residues at discrete depths with treatment compared to the control	Demonstration terminated early; unable to accurately assess
6	Quantitative	Effectiveness of treatment layer	Sorption capacity of treatment material varies less than 20% over 1-year time frame	Demonstration terminated early; unable to accurately assess

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5.0 SITE DESCRIPTION

The following sections summarize the sites where the SP1 and GR demonstrations were performed. Please see the full Final Report for more details.

5.1 SITE LOCATION

5.1.1 SP1 Demonstration

The MMR, a 22,000 acre (30 square miles) military training facility, is located on the upper western portion of Cape Cod, immediately south of the Cape Cod Canal in Barnstable County, MA. The SP1 demonstration was performed within the Central Impact Area (CIA), but outside the exclusion zone, in an area that did not have a history of soil contamination or UXO (Figure 2).

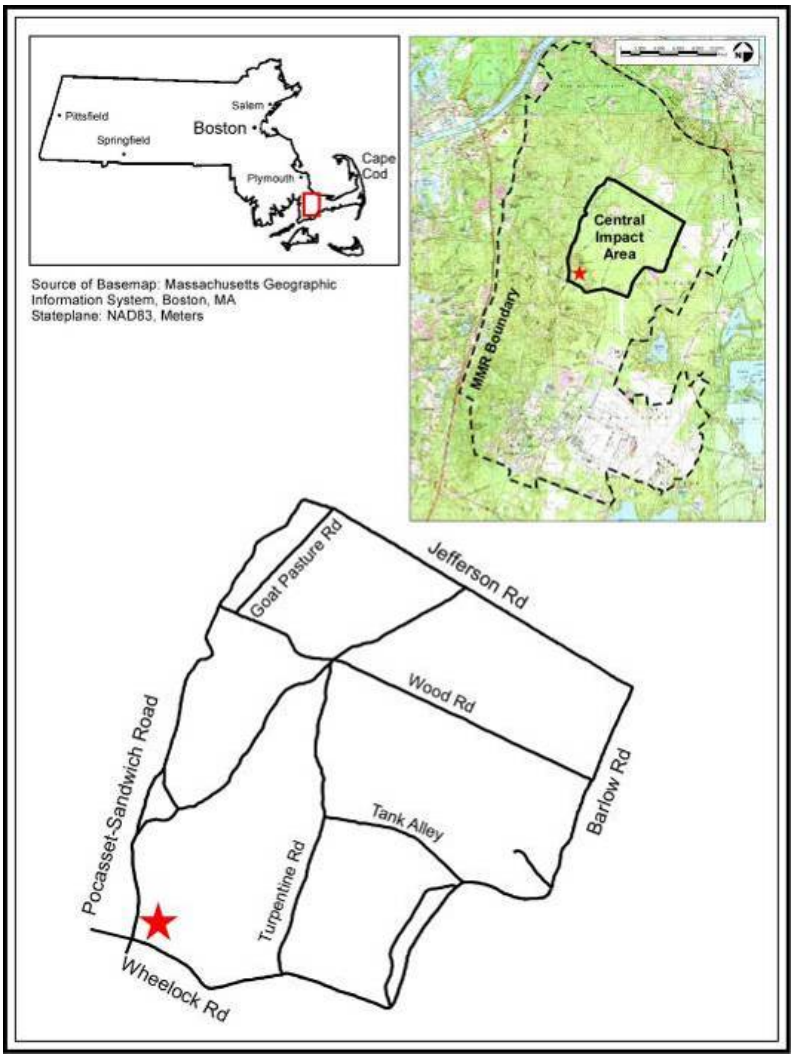

Figure 2. Map of Massachusetts, MMR, and the area within the CIA designated as the demonstration site.

5.1.2 GR Demonstration

Fort Jackson is a 21,000 hectare (52,000 acre) installation located in central SC, situated northeast of the state capital, Columbia. The GR demonstration was conducted at Remagen Range at Fort Jackson (see map Figure 3). Remagen Range is a Grenade Familiarization Range – Live (FCC 17883). The primary munitions used are live fragmentation hand grenades. Remagen range receives heavy annual use, with approximately 33,000 live hand grenades thrown each year.

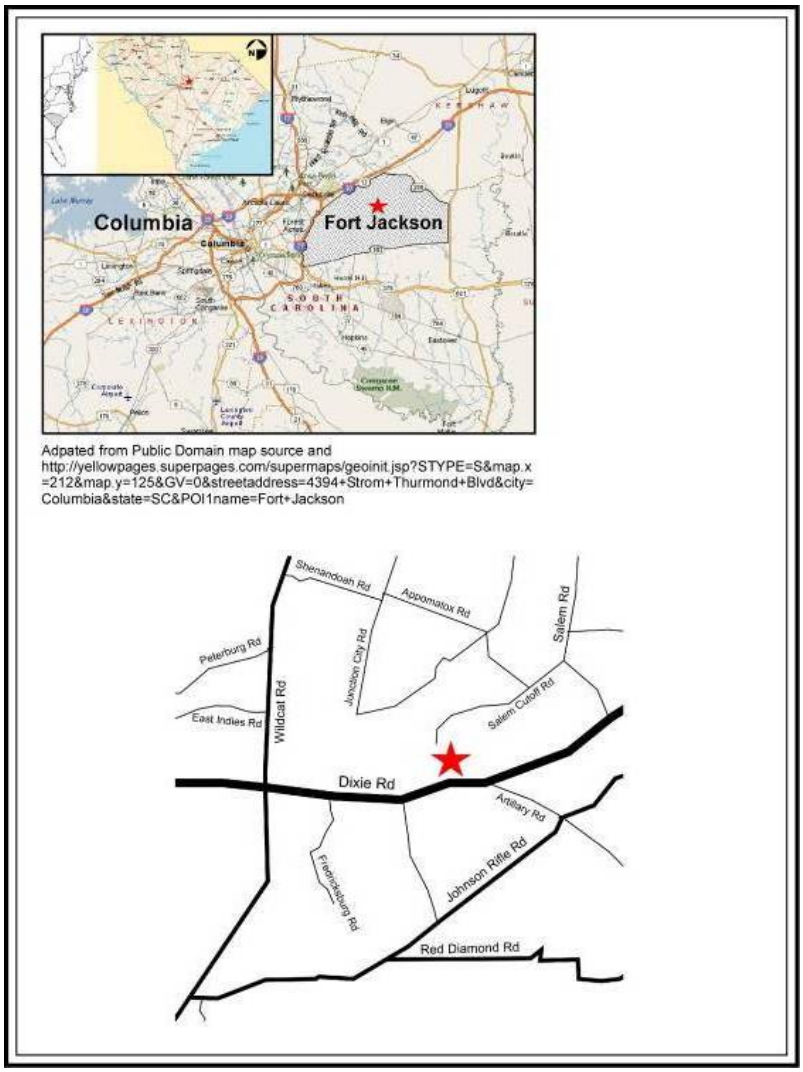

Figure 3. Maps of Fort Jackson, SC and the surrounding area.

The range consists of four open bays consisting of a throwing pit and a group of approximately five upright targets placed 30 m (~100 ft) from the pit. Grenade impacts are concentrated in a 10 m (~30 ft) diameter area in front of the targets. This area was characterized by impact craters as deep as 60 cm (2 ft) of generally uncompacted soil. The soil was a clay sand mix with low to moderate soil permeability. The area was nonvegetated. A photograph of one of the bays is presented in Figure 4.2-2 of the Soil Plot Final Report.

5.2 SITE GEOLOGY/HYDROLOGY

5.2.1 SP1 Demonstration

The surface soils of MMR are defined by glacial deposition of loose material, resulting in porous, sandy soils. The low carbon, high sand soils allow rapid recharge of groundwater, which also allows contaminants to enter the aquifer quite easily. A single, unconfined aquifer called the Sagamore Lens underlies MMR, and the water table is at approximately 50 ft bgs. The Sagamore Lens is the sole-source aquifer supplying drinking water for the western part of Cape Cod (known as the Upper Cape). The Sagamore Lens is a large, 300-ft-thick layer of groundwater with rapid groundwater movement (1 to 2 ft/day). The aquifer is fed by recharge resulting from precipitation. Of the 40 to 47 inches of precipitation received by the Western Cape each year, an estimated 18 to 22 inches recharges the aquifer. The average low temperatures are around -3°C (27°F), and average high temperatures are around 22°C (72°F).

5.2.2 GR Demonstration

Due to the limited extent of the project, no extensive investigation was performed regarding the site geology and/or hydrogeology of the Remagen range. A more complete description of Fort Jackson's hydrogeologic setting was presented in the Field Demonstration Plan for ESTCP Project ER-0216, "Grenade Range Management Using Lime for Dual Role of Metals Immobilization and Explosives Transformation," compiled by Dr. Steve Larson.

5.3 CONTAMINANT DISTRIBUTION

5.3.1 SP1 Demonstration

This demonstration used clean MMR soils, which were then experimentally contaminated with Composition B detonation residues. Therefore an extensive discussion of existing contaminant distribution is not relevant for this demonstration report.

5.3.2 GR Demonstration

The contamination at the Remagen range was limited to the grenade training bays. A preliminary assessment was performed and presented by Dr. Steve Larson during ESTCP Project ER-0216, "Grenade Range Management Using Lime for Dual Role of Metals Immobilization and Explosives Transformation." Contamination consisted mainly of explosive residues (RDX) and some metals (Fe, Zn). Based on other work characterizing contaminants hand grenade training ranges, it was expected that the concentrations were highest in the middle of each training bay where the majority of the grenades detonate, and likely extended to depths of up to 60 cm. However, the hard clay soils at Fort Jackson probably limited the movement of particulate residues into depths greater than 15-30 cm.

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6.0 TEST DESIGN

The following sections summarize the test design for both the SP1 and the GR demonstrations. For clarity, the individual sections describing each demonstration have been grouped under the demonstration names. More details are provided in the Final Report.

6.1 SP1 DEMONSTRATION

6.1.1 CONCEPTUAL EXPERIMENTAL DESIGN (SP1)

The SP1 demonstration was performed under field conditions. Clean soil from the demonstration site was loaded into instrumented plastic tanks (called "soil plots"). Nine replicate soil plots were established. Six of the soil plots received a layer of PMSO and three did not receive the layer and served as controls. Explosive residues from actual munition detonations were applied to the surface of each soil plot (i.e., directly to the soil surface in the control plots and on top of the PMSO layer in the treatment plots. Samples of soil pore water were collected from two different depths in each soil plot and analyzed for explosives concentrations. Pore water total organic carbon (TOC), soil gases, soil moisture content, pH, etc., were also monitored. At the end of the demonstration, the soil plots were deconstructed and the profile of explosive concentrations in the soil of each soil plot was determined. The results were analyzed, specifically looking at differences between the treatment and control soil plots with respect to soil pore water and final soil concentrations of the explosive compounds.

6.1.2 BASELINE CHARACTERIZATION (SP1)

Characterization was done on the uncontaminated soil to be used in the plots. This soil was excavated from a 1 m x 2 m x 0.3 m shallow pit from an area that was immediately adjacent to the area where the soil plots were established. Sufficient soil to fill all the soil plots (approximately 1.5 m^2 [2 cubic yards]) from this area was excavated, screened to remove large rocks (2.5 cm/1-inch mesh opening), and homogenized with shovels. Composite samples from throughout the soil pile were to be removed (Procedure No. SOP-TFS-106, Appendix B) for confirmatory explosive compound analyses. Additional soil parameters (texture, pH, cation exchange capacity [CEC], TOC) were also measured to assure that the selected soil was comparable to other areas within the Central Impact Area of MMR that have been contaminated by range activities. The soil pile was then covered until the soil was used to load the soil pots. A summary of the soil characteristics is presented in Table 5.2-1 of the Soil Plot Final Report.

The soil was classified as a sandy loam. No HMX, RDX, or TNT (the components of Composition B), nor any of the potential breakdown products, were detected above the analytical detection limit of 120 µg/kg.

6.1.3 TREATABILITY OR LABORATORY STUDY RESULTS (SP1)

The main laboratory treatability results were presented in a previous report submitted to ESTCP in December 2006 titled "Treatment of Explosives Residues from Range Activities (ER-0434) - Treatability Study Report." The results of the Treatability Study Report relevant to the SP1 demonstration were as follows: 1) The materials used to construct the soil plots that were not

metal needed to be teflon or polypropylene to prevent sorption and/or degradation of the three main explosives (HMX, RDX, and TNT) being monitored. However, a limited amount of polyvinyl chloride (PVC) would be allowable for less critical elements of the plots due to ease of use and availability, 2) A wick drainage system constructed from a heavy fiberglass rope material was shown to be effective for draining and maintaining soil in an unsaturated state for the field demonstration apparatus. The wick needed to be washed thoroughly several times to remove the organic material that is applied to the fibers during manufacture, 3) The PMSO material was expected to maintain its ability to sorb and promote the degradation of the three main explosive compounds even after 1 year of outside incubation.

6.1.4 FIELD TESTING (SP1)

6.1.4.1 Soil Plot Construction

A schematic diagram and photographs of the test apparatus ("soil plots") is presented in Figure 5.4-1 of the Soil Plot Final Report. The base tank was straight-walled polypropylene, 0.45 m in diameter and 1.2 m high, with a 0.6 cm wall thickness (Chem-Tainer Industries, West Babylon, NY, USA; P/N: TC1840AB) and modified with the following: 1) capillary wick drainage system consisting of a 150 cm length fiberglass rope material (Amatex/Norfab Corp., Norristown, PA, USA; medium density fiberglass rope P/N: 10-863KR-08, 2.5 cm diameter) threaded through a PVC bulkhead fitting (2.5 cm slip x 2.5 cm female National Pipe Thread [NPT]) at the bottom of the tank and into a 1.2 m length of PVC tubing (2.5 cm inner diameter [ID] x 3.1 cm outer diameter [OD], 0.3 cm wall), which terminated at a 20 L plastic bucket with a teflon liner; 2) soil pore water samplers at depths of 15 and 45 cm below the soil surface, consisting of porous ceramic cups (Soilmoisture Equipment Corp., Santa Barbara, CA, USA; P/N: 1911) attached to sampling ports outside the tank via fluorinated ethylene propylent [FEP] teflon tubing; 3) soil pore water samplers at depths of 15 and 45 cm below the soil surface, consisting of a small, screened cut-off syringe attached to sampling ports outside the tank via FEP teflon tubing; and 4) soil volumetric moisture probes placed at depths of 15 and 45 cm below the soil surface, consisting of SMA Soil Moisture Smart Sensors (P/N: S-SMA-M005) attached via cables to two HOBO® Weather Station Data Loggers (P/N: H21-001, Onset Computer Corporation, Pocasset, MA, USA).

6.1.4.2 Soil Loading

Each tank was loaded with clean MMR soil to a depth of 75 cm, packed to a bulk density of 1.5 g/cm^3. Soil was loaded in 2.5 to 5 cm layers and manually compressed to assure uniformity between the plots. Gravimetric soil moisture at the time of packing was approximately 4% (kg H_2O/kg dry soil). Once loaded, the plots were anchored to 0.9 m x 0.9 m plastic shipping pallets with tie-down straps, and the pallets were then placed on elevated pallet racks using a forklift (Figure 5.4-1 of Soil Plot Final Report).

6.1.4.3 PMSO Application

Two ratios of peat moss:crude soybean oil were evaluated, 1:1 and 1:2 (w:w), based on the air dry weight of the peat moss. Three plots received the 1:1 PMSO (designated PO1; 2.5 kg peat moss (dry wt.) plus 2.5 kg crude soybean oil) and three received the 1:2 PMSO (designated PO2;

2.5 kg peat moss (dry wt.) plus 5 kg crude soybean oil), while three plots served as controls and received no PMSO (designated CON). PMSO was prepared by thoroughly mixing the required weight of crude soybean oil into the peat moss. PMSO was added to the plots to achieve a 10 cm depth on top of the soil surface in the treatment plots.

6.1.4.4 Composition B Residue Application

Each soil plot received a total of 10 g of detonation residues, consisting of approximately 5.6 g RDX, 3.4 g TNT, 0.03 g HMX, and 0.9 g acetonitrile-insoluble matter. Residues were mixed with 90 g of clean sand as a carrier to assure safe transport and aid with distribution. Residue-sand mixtures were applied evenly over the entire surface of the soil plots, on top of the PMSO layers in the treatment plots, and directly at the soil surface in the control plots.

6.1.5 SAMPLING METHODS (SP1)

6.1.5.1 Sampling

Sampling was performed roughly biweekly to monthly throughout the field evaluation, except for two "standby" periods during the winter seasons: from December 20, 2006, to April 26, 2007, and again from December 20, 2007, to March 24, 2008. During standby, the plots were covered with lids and tarps to prevent snow and ice from building up, which could have damaged the sensors and sampling ports.

Soil pore gas readings were made using a CheckPoint O_2/CO_2 Analyzer (PBI Dansensor, Topac, Inc., Cohasset MA, USA) attached to the gas sampling ports. Measurements of the ambient gases also were recorded. Soil pore water samples were collected using disposable polypropylene syringes by applying suction to the porous ceramic cups. At each sampling point, a 10-15 ml "purge" volume was collected, followed by a 10 to 20 ml "sample" volume (if the soil would yield both based on the prevailing moisture content). Both purge and sample volumes were analyzed as described below. The volume of drainage water collected was recorded at each sampling event and samples were collected for analysis. Soil moisture readings were collected every 10 minutes and recorded using the dataloggers. Weather parameters were collected continuously using a WatchDog Weather Station coupled with a datalogger (Spectrum Technologies, Inc., Plainfield, IL, USA). Data was offloaded from the soil moisture and weather station dataloggers using data shuttles, which were shipped to the laboratory for analysis and then archived.

At the termination of the field evaluation, the soil in the plots was extensively sampled and analyzed for residual explosive compounds. The topmost layers of soil in the CON plots were removed in 1.25 cm lifts. The PMSO in the PO1 and PO2 plots was collected in two portions: the top 2.5 cm and the remainder down to the soil surface. The topmost soil in the PO1 and PO2 plots was collected in 2.5 cm lifts. After the PMSO was removed and the soil lifts were collected, eight replicate cores from each soil plot were collected using a hand geoprobe device. Soil layers and PMSO were air dried then sieved into size fractions of >2 mm, 0.5 to 2 mm, and <0.5 mm to facilitate handling during extraction. The different size fractions of the top layers of soil and PMSO were extracted en toto, while well-homogenized triplicate subsamples of each depth interval of the soil cores were extracted. Extraction was performed in glass jars with

technical grade acetone with vigorous shaking (150 rpm) for 18 hours at room temperature. Aliquots of the extracts were passed through glass microfiber filters (0.45 µm) prior to analysis by high performance liquid chromatography (HPLC), as described below.

6.1.5.2 Analytical

The concentrations of the explosives and their breakdown products were monitored during incubation using HPLC according to a modified USEPA Method 8330 using a Dionex 3000 Ultimate HPLC with an Explosives E1 column, variable wavelength detector (reading at 230 nm), and a photodiode array detector collecting peak spectral data. The mobile phase was 43:57 methanol:water at a flow rate of 0.95 ml/minute. The column temperature was 32°C. The practical quantitation limit (PQL) was approximately 10 µg/L for the main USEPA Method 8330 analytes and 25 µg/L for the RDX breakdown products (MNX; hexahydro-1,3-dinitroso-5-nitro-1,3,5-triazine [DNX]; and hexahydro-1,3,5-trinitroso-1,3,5-triazine [TNX]). Method detection limits (MDL) were 5.2 and 5.9 µg/L for the main USEPA Method 8330 analytes and the RDX breakdown products, respectively. Samples that were reported as below detection were assigned a value of one-half of the MDL for graphing and data analysis purposes. Aqueous samples were also analyzed for pH (using a pH electrode) and TOC (USEPA Method 415.1).

6.1.5.3 Data Analysis

RDX and MNX concentration comparisons across treatments, and mass and flux calculations, were only performed on data collected after the Composition B residues had been applied to the plots. Dissolved explosive flux through the soil plots at 30 cm (averaged between the 15 and 45 cm sampling locations) was estimated for discrete time points as follows:

$$J_i = \frac{\Delta S C_i}{a \Delta t} \qquad \text{Eq. 1}$$

where J_i is the dissolved flux for explosive compound i (mg/cm^2/day), ΔS is the change in water storage (cm^3), C_i is the dissolved concentration of energetic compound i (mg/cm^3), *a* is the cross-sectional area of the tank (cm^2), and Δt is the time interval over which the flux was evaluated (day). The change in storage at 30 cm was calculated based on the measured moisture contents at z=15 cm and z=45 cm below the soil surface as follows (Fares and Alva, 2000):

$$\Delta S = \int_{z=15}^{z=45} \theta(z, t_1)\,dz - \int_{z=15}^{z=45} \theta(z, t_2)\,dz \qquad \text{Eq. 2}$$

where θ is the volumetric water content (cm^3/cm^3), and t1 and t2 represent the time interval for the discrete flux measurements (day). Dissolved explosive flux at the tank effluent (75 cm) was calculated in a similar fashion, except that ΔS was directly measured as the volume collected in the drainage tank over the sampling time interval (Δt). Mass eluted through z=30 cm or z=75 cm was calculated by multiplying the flux by the cross-section area (*a*) and the time interval.

6.1.6 SAMPLING RESULTS (SP1)

The soil plots were prepared on 18 August 2006. PMSO was added to the treatment plots on October 13, 2006 (Day 59), and Composition B detonation residues were applied on June 11, 2007 (Day 302). The evaluation was terminated on September 23, 2008 (Day 770). Data analysis and presentation is focused on the time period after the Composition B residues were applied as a source of explosive compounds.

It was determined that one of the three control soil plots (CON-2) was not behaving the same as the other two control plots based on a careful assessment of several parameters, including higher volumetric moisture content over the duration of the study, substantially elevated concentrations of TOC in soil pore water relative to the other controls, and the presence of an algal slime layer on the soil surface at the end of demonstration (no algal slime layer was observed in the other soil plots). The concentrations of RDX detected in the soil pore water collected at 45 cm depth and in the drainage water from CON-2, and the residual RDX in the soil profile at the end of the field test, also were substantially different from the other two control plots. The data from CON-2 was therefore excluded when comparisons between the control and treatments were being performed.

Water flow through the plots was comparable for all the plots, varying by about a factor of only 1.5 to 2. Some of the lower water flows were observed in the treatment plots, which can be attributed to retention in and evaporation from the PMSO layer of received precipitation before it infiltrated the soil column. There was good agreement (generally within 20%) between the water flow values calculated based on drainage water collected and from integration of the soil volumetric moisture probe curves.

Soil pore water samples at all depths in the plots had a pH of 6.0 ±0.2 standard units (S.U.), only slightly higher than the pH of the incident precipitation (5.3 ± 0.4 S.U.). Pore water TOC values markedly increased in the treatment plots compared to the control plots after application of the PMSO material. The TOC values were highest at the 15 cm sampling depth, with progressively lower values at the 45 cm depth and in the drainage water. The maximum average TOC values in the PO1 and PO2 plots at the 15 cm depth were 220 and 1700 mg/L, respectively, compared to a maximum of 22 mg/L in the CON plots. Soil pore gases indicated that the soil remained essentially aerobic throughout the demonstration, although oxygen concentrations in the PO1 and PO2 plots trended about 1% to 2% below the concentrations observed in the CON plots at corresponding depths.

With the exceptions of RDX and the RDX breakdown product MNX, all other explosive-related compounds were not detected in aqueous samples above the detection limit with enough frequency to allow robust comparisons between the control and the treatments. Of 423 aqueous samples analyzed after the Composition residues were applied (from all plots and depths), there were only five detections of TNT and 11 detections of HMX, compared to 189 detections of RDX. Similarly, there were only 22 and 25 detections of TNX and DNX, respectively, compared to 120 detections of MNX. The two main TNT breakdown products, 2-amino-4,6-DNT and 4-amino-2,6-DNT, were detected 4 and 6 times, respectively. However, based on all the previous development work (summarized in Section 3), we would expect that the in field performance of the PMSO technology for TNT and its breakdown products would meet or

exceed that observed for RDX, and that the performance for HMX would be similar to that observed for RDX.

The average concentrations of RDX in pore water and drainage from the CON, PO1, and PO2 soil plots, are presented in Figure 4. The PO2 plots consistently had the lowest concentrations of RDX at all sample depths, with only a few exceptions. The PO1 plots had concentrations roughly between the PO2 and CON plots in the 15 cm and drainage samples, but had concentrations that were either greater than or within one standard deviation of the CON plots for much of the evaluation at the 45 cm samples. Over the interval from when the Composition B residues were applied to the end of the evaluation, the RDX concentrations detected at depths of 15 cm, 45 cm, and in the drainage for the PO2 were on average 4000-, 760-, and 1030-fold lower, respectively, than the concentrations at the corresponding depths of the CON plots. For the PO1 plots, the average concentrations of RDX were 10- and 780-fold lower than the CON plots at 15 cm and in the drainage but approximately the same as the CON plots at 45 cm. It is not readily apparent why the PO1 plots performed so poorly with respect to RDX at the 45 cm depth, especially compared to the PO2 plots. The lower amount of crude soybean oil in the PMSO in the PO1 plots provided less biostimulative nutrients for RDX biodegradation, and at the deeper soil depths, it was not as effective as the PO2 (also reflected in the overall lower TOC values in the pore water). Also, it should be noted that two of the PO1 plots performed substantially better than the third PO1 plot. This poorer performance of this third PO1 plot made performance evaluation of the average values indicate that the PO1 was not very effective.

Corresponding concentrations of MNX at the three sampling depths are presented in Figure 5. A pattern similar to the RDX concentration data was observed with respect to MNX concentrations. While concentrations of MNX were similar in the PO1 and PO2 plots compared to the CON plots for most of the evaluation, by the latter timepoints the PO2 plots were approximately 50- to 100-fold lower than the CON plots at corresponding depths. PO1 plots were less effective at reducing MNX concentrations, but at the end of the evaluation, the MNX was between 5- and 10-fold lower than observed at the corresponding depths of the CON plots.

The presence of measurable MNX in the CON plots indicates that degradation of RDX was occurring even in native MMR soil, without the addition of any amendments. The mode of degradation may have been abiotic or biological, although significant biotic RDX would not be expected given the prevailing aerobic conditions and low organic carbon levels. A previous study with MMR soil examined under unsaturated (and unamended) conditions did report sporadic detections of MNX (as well as DNX and TNX) (Fuller et al., 2005), although production of MNX in another unsaturated soil was not reported even when RDX was degraded (Ringelberg et al., 2003). MNX has been confirmed as a product from RDX photolysis (Peyton et al., 1999), so some of the observed MNX may have arisen from sunlight interactions with the particulate Composition B at the soil surface. It should also be noted that the lack of detection of MNX in any samples from the PO2 plots (all values were at or below the detection limit) likely reflects binding and further degradation of MNX in the PMSO material as opposed to lack of RDX degradation.

The average cumulative mass and flux of RDX in the control and treatments calculated at depths of 30 cm and 75 cm are presented in Figure 6 and Figure 7, respectively. Corresponding data for

MNX are presented in Figure 8 and Figure 9. For RDX, the cumulative mass is approximately 60-fold and 120-fold higher in the CON plots compared to the PO2 plots at depths of 30 cm and 75 cm, respectively. The cumulative RDX mass at 30 cm in the PO1 was approximately 50% of that observed in the CON plots, but was at least 100-fold lower than the CON plots at a depth of 75 cm. Evaluation of explosive flux among the soil plots provided an assessment on the potential impacts of the PMSO treatments on transient pore water quality during precipitation events. The estimated RDX fluxes were 1000- and 100-fold lower at depths of 30 cm and 75 cm, respectively, in the PO2 plots compared to the CON plots. RDX fluxes in the PO1 plots were similar to the CON plots at 30 cm (generally less than 10-fold difference), but were on the order of 10,000-fold lower at 75 cm. Comparison of the explosive flux data to the rain flux data indicate that explosive flux was positively correlated to the rain flux, and that the PO2 treatment is effective at reducing explosive flux at both high and low rain flux conditions. Cumulative masses and fluxes of MNX paralleled the RDX results, although the absolute cumulative mass values were 30- to 100-fold lower.

For solid phase samples, only RDX was detected with enough frequency for valid comparisons. The final soil profiles of RDX in the plots is shown in Figure 10. Due to compaction during the geoprobe coring process, the recovered core lengths averaged about 40 cm, and any losses were assumed to be at the deeper depths (e.g., at the bottom of the cores). Soil RDX concentrations at the surface were approximately two orders of magnitude lower in both the PO1 and PO2 plots compared to the CON plots. Soil concentrations decreased much more quickly as a function of depth in the PO2 than in the PO1 plots. Soil concentrations in the CON plots dropped 100-fold within the top 5 cm of soil, then only slowly decreased for the remainder of the sample depths. These soil results are consistent with the aqueous results, indicating that the PMSO treatment inhibited the dissolved flux of explosive compounds through the soil plots. For the PO1 and PO2 plots, average RDX concentrations of 2329 ± 855 and 995 ± 497 mg/kg were measured in the top 2.5 cm of PMSO, respectively. Average RDX in the remaining 7.5 cm of the PMSO layer was 458 ± 155 and 454 ± 103 mg/kg for the PO1 and PO2 plots, respectively.

The highest RDX and other compound concentrations in the surface soil and the PMSO layer at the end of the evaluation were observed in the 0.5 to 2 mm size fraction, with significant concentrations also detected in the <0.5 mm fraction. These results are consistent with the size of the Composition B residues applied (~1 mm), and also with the likelihood that the 1 mm particles decreased in size during the evaluation. These trends were observed to a depth of 3.75 cm below the soil surface in the CON plots, indicating that particulate Composition B likely migrated into the soil. These data are also indicative that any RDX and TNT that dissolved from the particulate Composition B partitioned onto the smaller clays in the CON plots and the clay-sized peat moss in the treatment plots, the latter being consistent with previous research regarding changes in explosive compound Kd values as a function of peat moss size fractions.

Migration of RDX and TNT through 10 cm of the PO2 treatment and 15 cm of soil were evaluated using a previously developed model. Although the experimental soil plot data was not intended to provide a field-scale validation of the model, the observed consistency between the simulations and experimental results provides confirmation and insight regarding the processes that mitigate explosive transport (e.g., sorption and biodegradation) in the PMSO treatments. For purposes of a screening-level evaluation, steady water flow of 50 cm/year (average flow

through the soil plots) was assumed in the model. Model simulations also assume that no depletion of the crude soybean oil occurred. TNT simulation results showed approximately 2.5 years would be needed before TNT concentrations were detectable at the 15 cm depth with no PMSO treatment and that no TNT detections would ever be expected at this depth with PMSO treatment. RDX simulation results showed that concentrations would reach steady values (i.e., equal to the dissolved concentration of RDX percolating through the emplaced explosive residues, with a maximum of 30 mg/L) at a depth of 15 cm at approximately 370 days. This simulation time appears generally consistent with the RDX data shown in Figure 10. For RDX in the PO2 plots, the model indicated that no measurable RDX would be expected to ever migrate 10 cm into the soil column, primarily due to PMSO-enhanced biodegradation of RDX. Similar simulation results were obtained for RDX using PO1 treatment. Based on these simulation results, the observed migration of RDX in the PO1 treatments is likely due to a reduced level of RDX biodegradation relative to the PO2 treatment, resulting from a depletion of the soybean oil substrate in the PO1 field plot. This suggests that the elevated oil dosage used in the PO2 treatment was more effective for sustaining optimum RDX biodegradation rates.

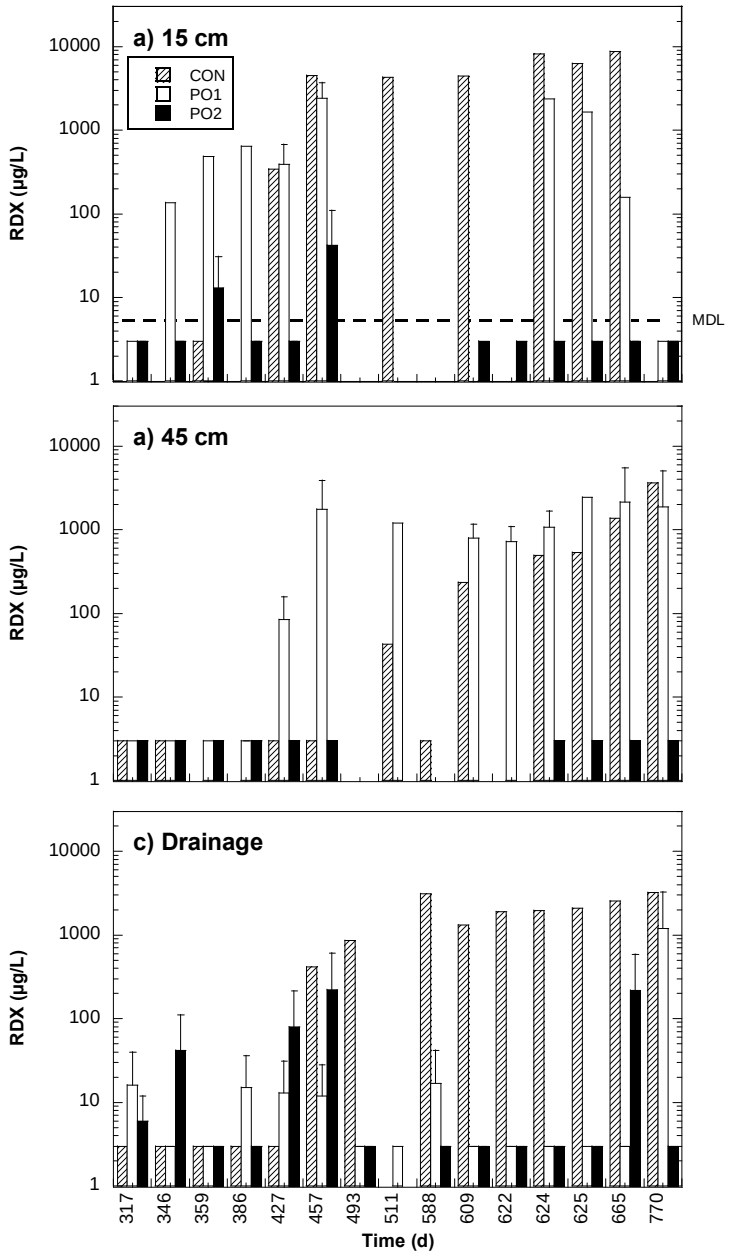


Figure 4. Concentrations of RDX in pore water at different depths in the soil plots. Data are average concentrations in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable. The dashed horizontal line represents the MDL for RDX. Missing columns indicate that no data was available for a given treatment at given timepoint. Datapoints measured as below the reporting limit were set to one-half the MDL.

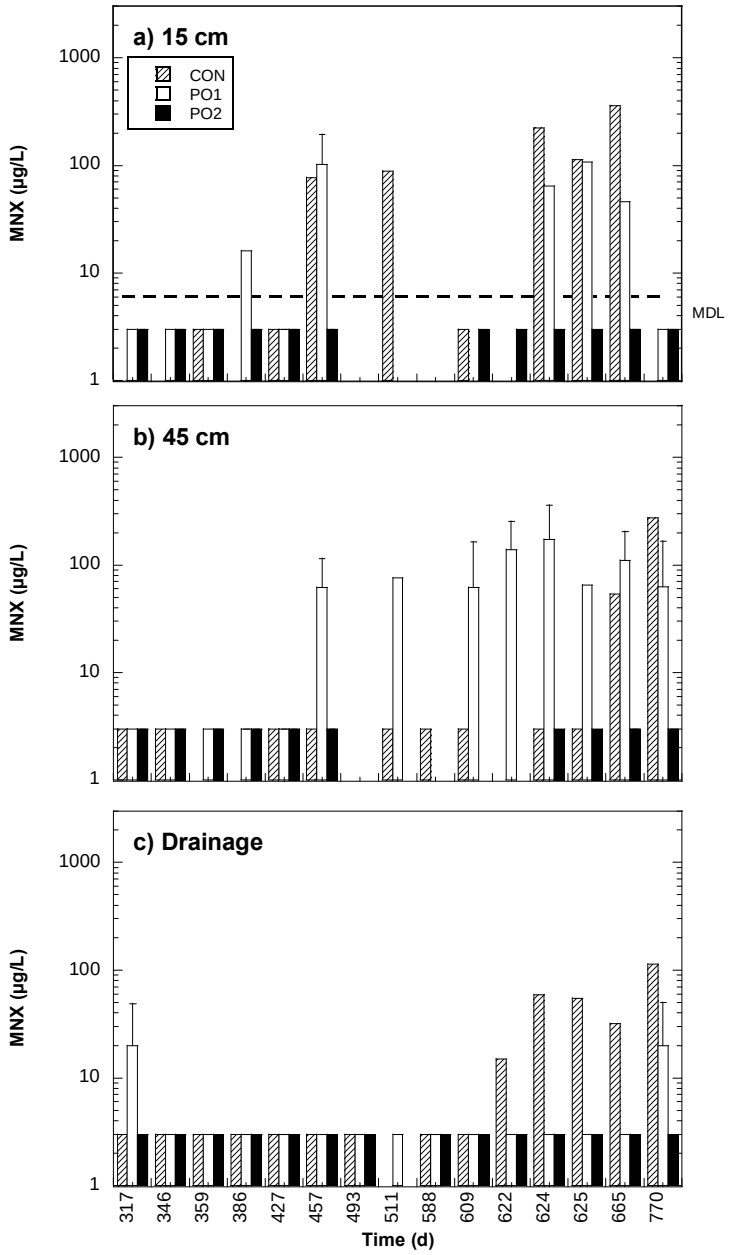


Figure 5. Concentrations of MNX in pore water at different depths in the soil plots. Data are average concentrations in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable. The dashed horizontal line represents the MDL for MNX. Missing columns indicate that no data was available for a given treatment at given timepoint. Datapoints measured as below the reporting limit were set to one-half the MDL.

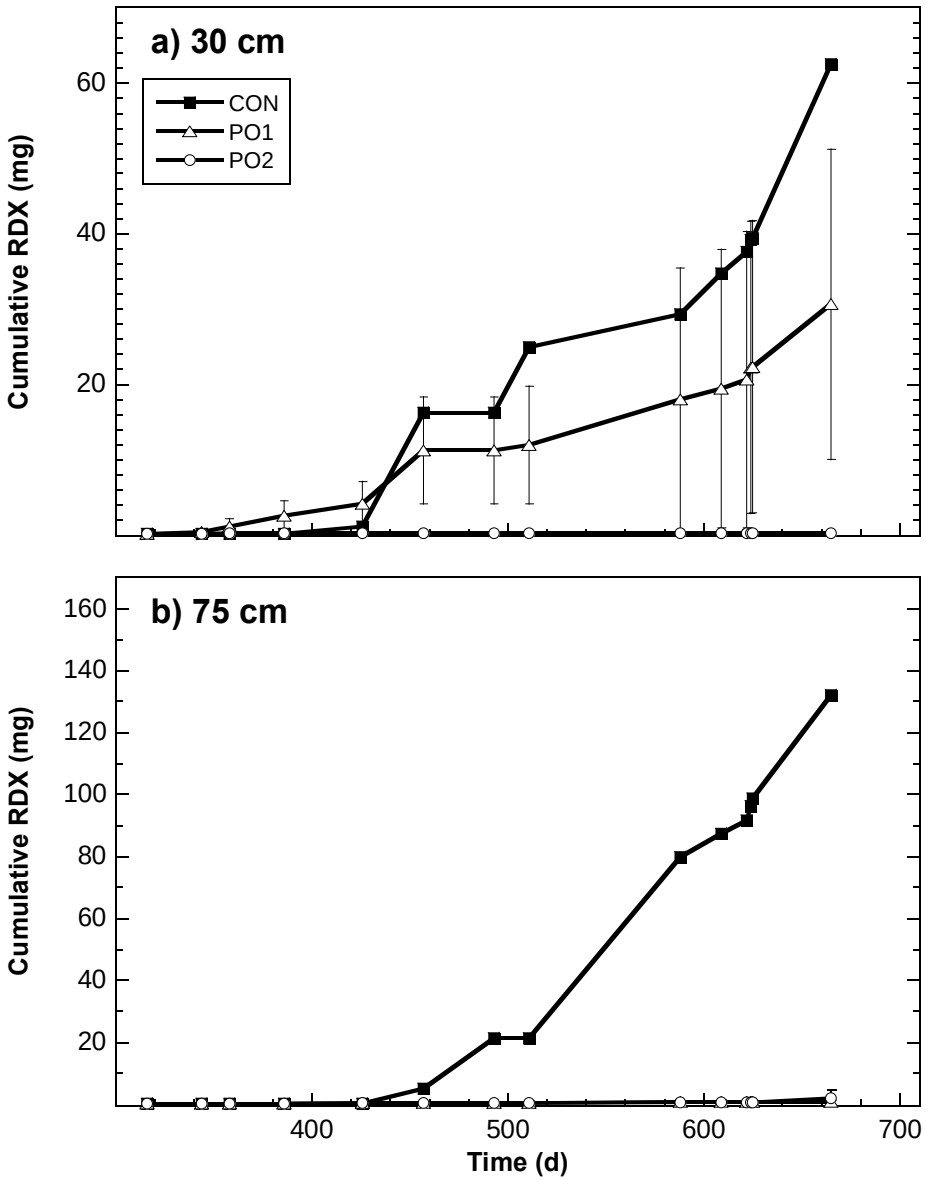


Figure 6. Mass of RDX passing through two different depths in the soil plots. Data are average masses in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable.

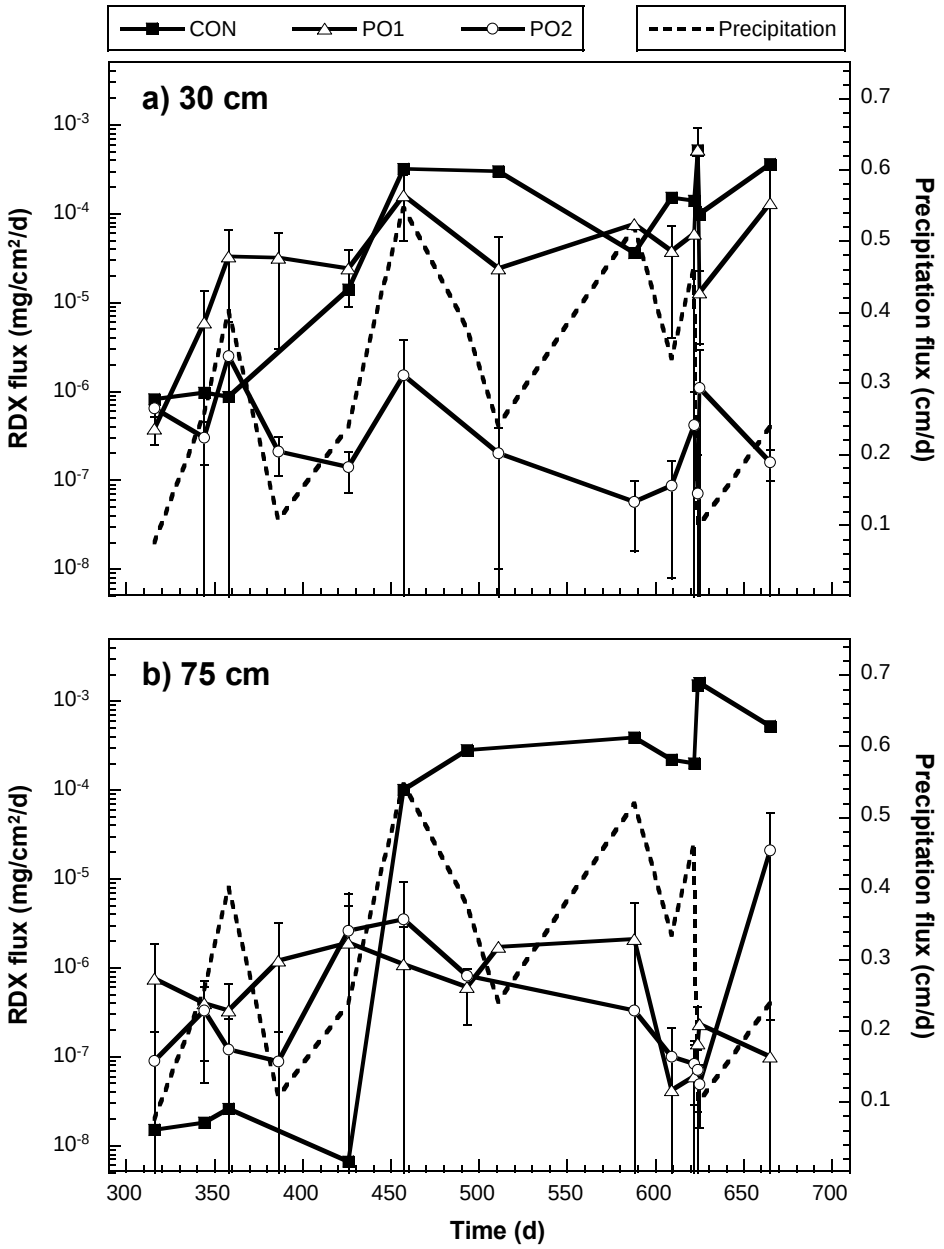


Figure 7. Flux of RDX passing through two different depths in the soil plots. Data are average fluxes in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable. The dashed line represents the flux of precipitation falling onto the plots.

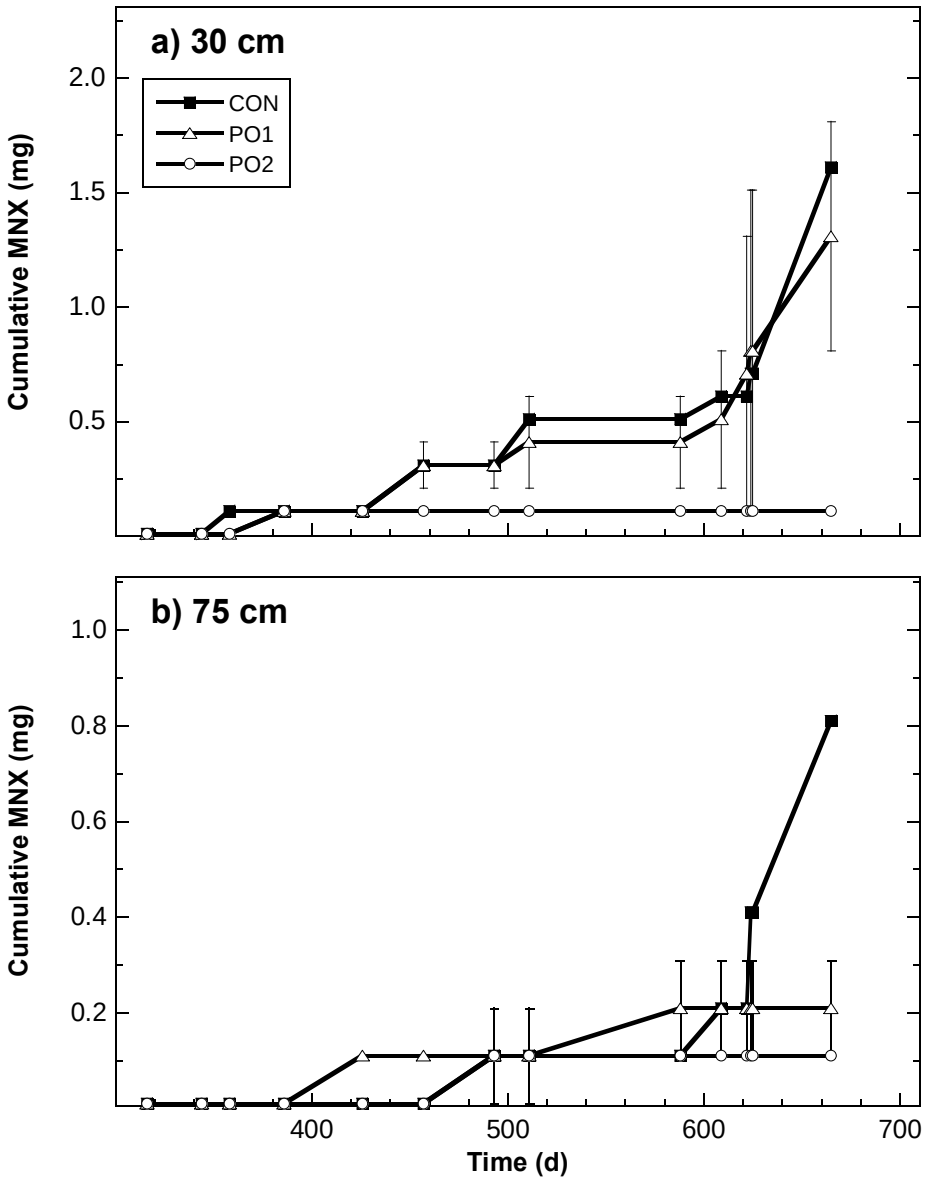


Figure 8. Mass of MNX passing through two different depths in the soil plots. Data are average masses in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable.

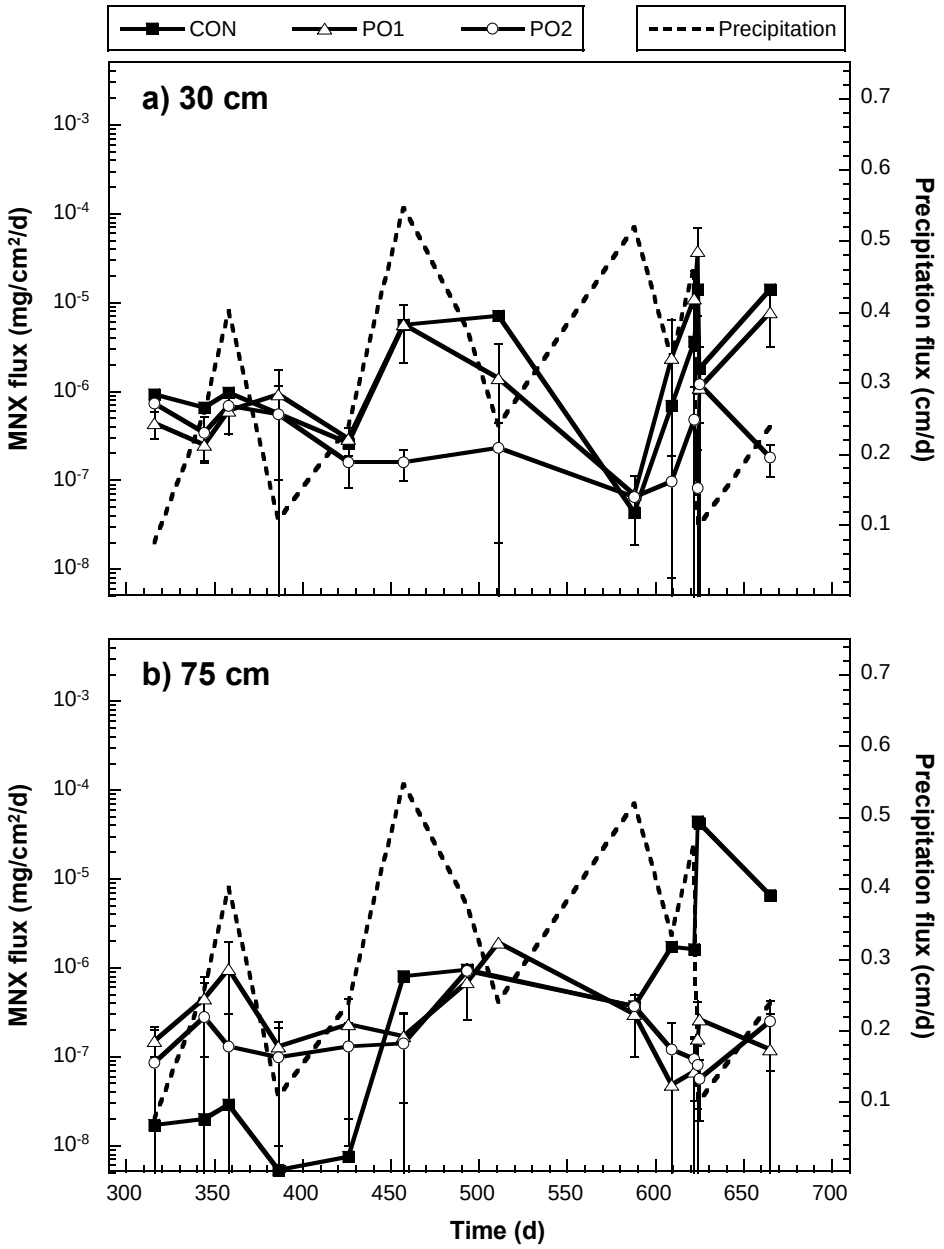


Figure 9. Flux of MNX passing through two different depths in the soil plots. Data are average fluxes in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable. The dashed line represents the flux of precipitation falling onto the plots.

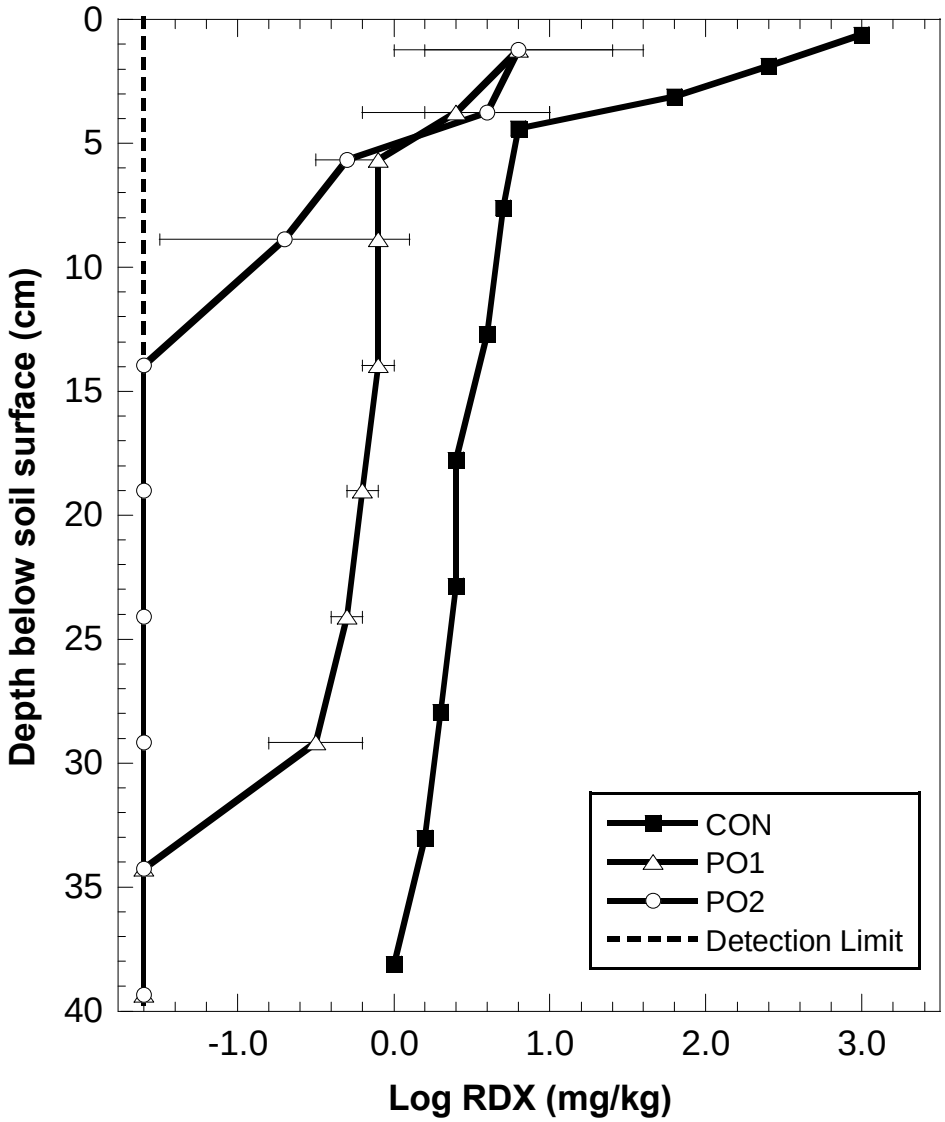


Figure 10. Profile of total soil RDX concentrations in the plots as a function of depth. Data are average concentrations in control plots (n = 2) and treatment plots (n = 3), and standard deviations are shown when applicable. The detection limit is represented by the dashed line.

6.2 GR DEMONSTRATION

6.2.1 CONCEPTUAL EXPERIMENTAL DESIGN (GR)

6.2.1.1 Demonstration Design for GR Demonstration

The GR demonstration was performed under field conditions at the Remagen Grenade Training Range at Fort Jackson, SC. An area in one of the training bays that corresponded to the location where the majority of grenade detonations occur received a layer of PMSO. The corresponding area in another training bay did not receive any treatment materials and served as a control. Grenade training activities resumed, and digital photographs of the treated area were collected. The photos underwent image analysis to determine the percent area coverage and horizontal movement of the PMSO in response to grenade detonations. The results were analyzed, specifically looking at how well the integrity of the treatment layer was maintained during training activities.

An additional effort was focused on how the PMSO material became vertically redistributed through the soil profile. However, due to early termination, post-application sampling and data analyses were not able to be performed. These sampling and analytical details are therefore not reported here. Please see the full Final Report for more information.

6.2.2 BASELINE CHARACTERIZATION (GR)

Soil samples from the two training bays to be used in this demonstration were obtained prior to the application of the treatment materials. Both composite and soil core samples were collected and analyzed for explosive concentrations and total organic carbon to establish a baseline for qualitative/semi-quantitative comparison with samples collected over the duration of the demonstration. No post-application samples were able to be collected, so these data were not analyzed further.

6.3 TREATABILITY OR LABORATORY STUDY RESULTS (GR)

The main laboratory treatability results were presented in a previous report submitted to ESTCP in December 2006 titled "Treatment of Explosives Residues from Range Activities (ER-0434) - Treatability Study Report." A question regarding the potential for the PMSO igniting and burning due to grenade detonations was raised during the preparation of the Field Demonstration Plan. To address this concern, additional laboratory testing was performed.

Briefly, the ignitability of peat moss, peat moss plus soybean oil, and soybean oil was tested under laboratory conditions. Testing was done with the peat moss or peat moss plus soybean oil in a very dry and in a moderately wet state. Both an open flame (butane-type lighter used for lighting candles, barbecues, etc.) and a hot metal wire (steel wire heated till it was glowing orange in a bunsen burner) were used as sources of ignition. These sources were meant to represent the fireball during grenade detonations and the hot metal grenade fragments. The ignition sources were held near or directly touched the test materials, and the results were filmed.

Although there was some smoldering observed, it was markedly less with the combined peat moss plus soybean oil than with the peat moss, and it quickly self-extinguished. No open flames were ever observed. Based on this information, it was deemed that under normal grenade training activities that the PMSO material would not burn.

6.3.1 FIELD TESTING (GR)

The site was graded fully immediately before PMSO application in order to level the ground surface. Horticulture grade sphagnum peat moss was obtained from a local home and garden center (85 x 2.2 ft^3 bags (compressed) = 10 m^3). The peat moss was used bag "wet," but all calculations were performed using the peat dry weight basis. A total of 1200 lbs of crude soybean oil was purchased from Grain States Soya, Inc. (West Point, NE, USA) and shipped to the site in three 55 gal plastic drums.

6.3.1.1 <u>Treatment Layer Preparation</u>

The PMSO mixture was prepared in a ratio of peat moss and crude soybean oil of 1:1 (w:w). The PMSO was prepared in batches using a small tow-behind plastic drum gas cement mixer (9 cu. ft capacity). Peat moss bags were weighed, and then emptied into the drum. The amount of oil required was then weighed out into a bucket and dumped into the drum. An average "recipe" consisted of two bags of peat moss plus one 5 gal bucket of soybean oil, although each batch was mixed specifically to achieve the 1:1 (w:w) ratio based on the weights of each bag of peat moss added to the mixer. The peat and oil was then mixed until it was judged that the oil had thoroughly combined with the peat moss. Photographs of the PMSO preparation are presented in Figure 11.

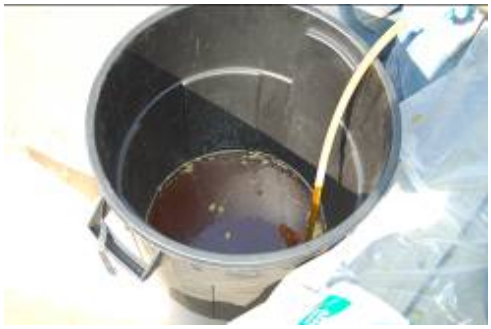
6.3.1.2 <u>Treatment Layer Application</u>

The bays at Remagen that were used for the demonstration were Bay 1, Treatment applied and Bay 3, Control. According to the Cadre, these two bays are used to a comparable degree by "short" throwers, and hence experience a similar number of grenade detonations over a given period of time.

The treatment materials were applied to achieve a uniform 10 cm (4-inch) thick layer across a 10 x 10 m (~33 x 33 ft) area centered in the area of Bay 1 where most of the detonations occur (based on the distribution of cratering). PMSO was applied by dumping the contents of the cement mixer, moving the mixer forward/backward/sideways, and repeating the process until the entire area was covered. A plumb line and grid system on the outside of the area allowed the PMSO to be roughly applied at the appropriate depth and location. Areas of excess or deficit in the layer were later manually redistributed using a rake. The area covered with the treatment material was approximately 100 m^2 (~1000 ft^2). Photographs of the PMSO application process are presented in Figure 12. PMSO was applied on May 22, 2007.

Peat staged around test area

Transfer of oil from drum to small vessel



Adding peat to cement mixer

Batch of PMSO mixing

Figure 11. Photographs depicting preparation of the PMSO material.

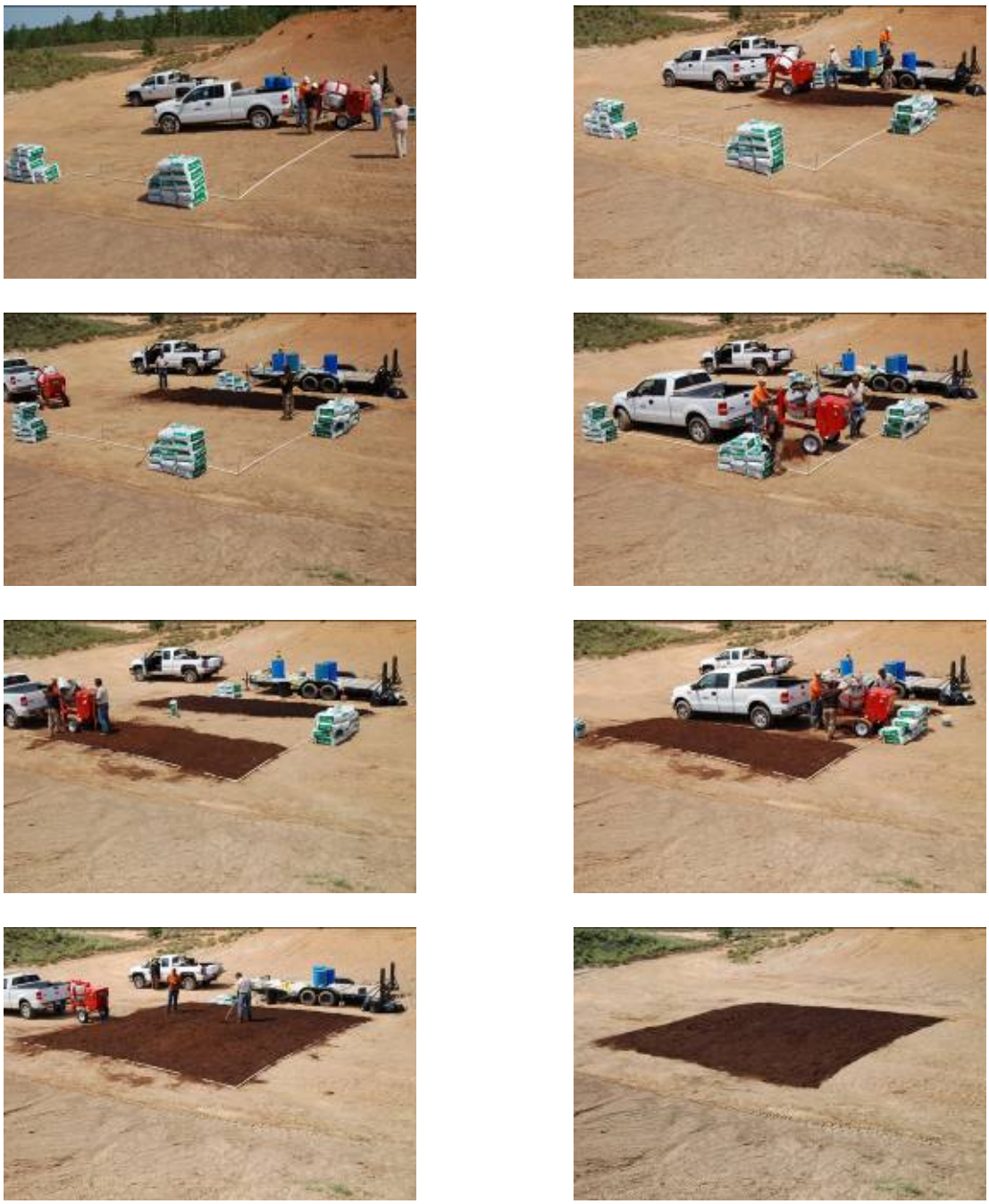


Figure 12. Photographs showing application of the PMSO material to Bay 1.

6.3.2 SAMPLING METHODS (GR)

Hand grenade training activities began again on 23 May 2007. Photographs of the PMSO interactions with some of the grenades is presented in Figure 13.

Digital images of the training bay that received the treatment material were collected from the same vantage point after three successive days of training. Photographs were taken that included objects of known size (cardboard boxes painted bright orange) to allow determination of scale during later processing. White paper sheets were also included so that white balance differences due to changes in solar illumination (cloudy versus direct sun) could be corrected for later on. Images were collected pre- and post-training within a time frame that minimized the potential of nontraining impacts on the movement and transport of the treatment material (i.e., wind, precipitation).

Figure 13. Photographs showing a grenade detonation on the PMSO layer in Bay 1.

6.3.2.1 <u>Data Analysis</u>

Images of the PMSO layer pre- and post-training were processed using the program ImageJ (v1.35p, National Institutes of Health; public domain). Given the light color of the soil at the

Fort Jackson grenade range and the relatively dark color of the peat moss plus soybean oil treatment materials, the contrast between covered and uncovered areas was robust. The changes of the PMSO in response to grenade detonations were calculated as percentages of areal coverage.

6.3.3 SAMPLING RESULTS (GR)

A series of images of the PMSO layer in Bay 1 taken pre- and post-hand-grenade training sessions are presented in Figure 14. These photographs were taken from the number of grenades detonated in Bay 1; the percent coverage, based on image analysis, is also given.

Time: Pre-Training 1

Date: 23 May

Grenades: 0

Coverage: 100%

Time: Post-Training 1

Date: 23 May

Grenades: 32

Coverage: 95%

Figure 14. Photographs of PMSO treatment layer in Bay 1.

Time: Pre-Training 2 (same as Post-Training 1)

Date: 23 May

Grenades: 32

Coverage: 95%

Time: Post-Training 2

Date: 24 May

Grenades: 70

Coverage: 83%

Figure 14. Photographs of PMSO treatment layer in Bay 1 (continued).

Time: Pre-Training 3
(same as Post-Training 2)

Date: 25 May

Grenades: 70

Coverage: 83%

Time: Post-Training 3

Date: 25 May

Grenades: 128

Coverage: 88%

Figure 14. Photographs of PMSO treatment layer in Bay 1 (continued).

The image analysis indicated that the PMSO layer coverage was not immediately and drastically reduced by the grenade detonations. While PMSO material was removed from some areas, it was redistributed to others. This is the likely reason that the areal coverage slightly increased between the second and third training sessions, as PMSO that had been removed and/or piled up in some areas during training event 2 was moved back during the latter grenade training event 3. It was apparent from these images that the PMSO layer's coverage was not significantly decreased by the detonations, as the treatment materials were observed to fall back and fill in the craters during subsequent detonations. Also, the total area covered actually increased as the PMSO was moved beyond it original boundaries. (NOTE: This spreading was not included in the image analysis; only the initial 10 m x 10 m area was analyzed.)

Figure 15 shows an additional photograph of Bay 1 after 4 months of grenade training. A total of 2500 grenades had been detonated, and eight grading events conducted. This image was not able to be used for image analysis due to the different vantage point. However, it was quite obvious that the grenade detonations and grading activities had basically buried the PMSO under the soil in the Bay.

Pre-training

Dashed line represents approximate area where PMSO had been applied.

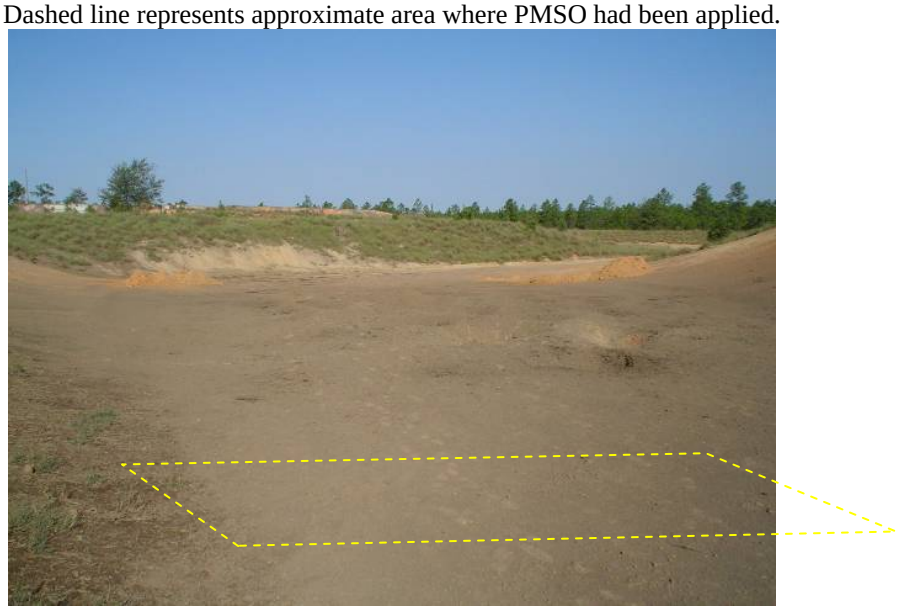


Figure 15. Photographs of Bay 1 before and after 4 months of training and grading activities.

7.0 PERFORMANCE ASSESSMENT

Tables 5 and 6 list the performance criteria by which the SP1 and GR demonstrations were assessed, the data used in the assessment, and the actual performance assessment results.

Table 5. Performance assessment for the SP1 Demonstration.

1 Effectiveness of Treatment Layer for New Residues >50% reduction in explosives leaching and/or explosive compound flux into soil in treatment plots compared to clean soil control plots.	
Explanation	This quantitative performance objective is the main criteria by which the S1 Demonstration was assessed. The question this performance objective was meant to answer was, "Does the PMSO material reduce the flux of explosive compounds going from new residues into the soil to a sufficient degree to warrant further development?" No technology is expected to reduce the flux of munitions-related compounds 100%, but based on current fate and transport modeling, even a moderate reduction of new residues entering the soil would greatly reduce the danger to groundwater resources. A metric of a greater than 50% reduction in explosives leaching and/or explosive compound flux into the soil (PMSO treated versus untreated) was chosen for this demonstration based on levels of reduction that were expected to be achievable as reflected in the previous empirical laboratory data, as well as the results from modeling efforts during the previous SERDP project.
Data collected	The data collected to allow assessment of this performance objective included: • Concentrations of soluble explosives in soil pore water. Soil pore water samples were collected at depths of 15 cm and 45 cm below the soil surface of each plot, as well as soil plot drainage water samples. Samples were collected biweekly to monthly throughout the project. The samples were analyzed for explosive compounds and relevant breakdown products according to a modified USEPA Method 8330 using HPLC. • Water flux through the soil plots. Soil volumetric moisture content was measured using capacitance-based soil moisture probes at depths of 15 and 45 cm. Soil plot drainage volumes were also measured, and precipitation data was collected using the weather station datalogger.
Data interpretation	The soluble pore water explosives concentration data were analyzed and interpreted in two ways. First, the absolute concentrations of dissolved explosives observed at each depth (15 cm, 45 cm, drainage) at a given timepoint in the PMSO-treated and control plots were compared. Comparisons were made for each plot individually, as well as the average of each set of three replicate plots. Second, the actual flux (in terms of mg of explosive compound) over time for each treatment was calculated.
Success criteria met?	Yes. The concentrations of dissolved RDX at a given depth in the PO2-treated plots were consistently <50% of those observed in the control (no PMSO) plots at each timepoint. Concentrations of RDX in the PO1-treated plots were more variable but on average met the performance criteria 60% of the time. The calculated flux of RDX was approximately 500-fold lower in PO2-treated plots than in the control plots at the end of the demonstration. Fluxes at the end of the demonstration were about 2-fold lower in the PO1-treated plots compared to the control plots. *NOTE: Concentrations of TNT and HMX, the other components present in the Composition B applied at the beginning of the demonstration, and their related breakdown products, were generally below the analytical detection limit or were detected too sporadically to generate enough data for a valid assessment in terms of this performance criteria.*

Table 5. Performance assessment for the SP1 Demonstration (continued)**.**

2 Effectiveness of Treatment Layer for New Residues >50% reduction in total soil explosives concentrations at different depths in the treatment plots compared to control plots at the end of the demonstration.	
Explanation	This quantitative performance objective was meant to be complimentary to Performance Objective #1 by looking at the total residual explosive concentrations in the soil as a function of depth. This performance objective was meant to provide an answer to the question, "Does the PMSO material reduce the loading of explosive compounds to the underlying soil?" Again, no technology is expected to completely eliminate munitions-related compounds from getting into the soil, but based on current fate and transport modeling, even a moderate reduction of new residues entering the soil would greatly reduce the danger to groundwater resources. A metric of greater than 50% reduction in total explosive concentrations in the soil profile (PMSO treated versus untreated) was chosen for this demonstration based on previous laboratory data.
Data collected	The data to allow assessment of this performance objective was all collected at the end of the demonstration as the soil plots were being deconstructed during demobilization. Data included: • Total explosives remaining in the soil. The surface soil in each plot was removed in several 1 to 2.5 cm layers. Soil was air dried, sieved to specific size fractions, and extracted according to established procedures. The extracts were analyzed for explosive compounds and relevant breakdown products according to a modified USEPA Method 8330 using HPLC. • Total explosives in the PMSO material. The topmost 2.5 cm of the PMSO was removed, air dried, sieved to specific size fractions, extracted, and analyzed for explosive compounds using HPLC. • Total explosives distributed throughout the soil profile. After the surface layers were removed, a hand geoprobe was used to drive a 30 cm corer into the soil. The soil cores were then subsampled at ~5 cm intervals, air dried, extracted, and analyzed for explosive compounds using HPLC.
Data interpretation	The data was analyzed by comparing the total soil explosive concentrations at each depth in the PMSO-treated versus the control (no PMSO) plots.
Success criteria met?	Yes. The average concentrations of RDX, TNT, and HMX (if detected) in the topmost 2.5 to 5 cm of the soil were close to 10- to 100-fold lower in the PMSO-treated plots compared to the control plots. This translated to residual soil RDX concentrations in the treated plots being <10% those observed in the control plots. Concentrations in treatment PO2 plots were less than in PO1 plots. Throughout the soil profile, the concentration of RDX was approximately 5- to 15-fold lower when comparing the average for all the PMSO-treated plots to the average for the control plots. This translates to residual concentrations of RDX at a given depth being between 7 to 20% of those observed at the same depth in the control plots. *NOTE: Concentrations of TNT and HMX, the other components present in the Composition B applied at the beginning of the demonstration, and their related breakdown products, were generally below the analytical detection limit or were detected too sporadically to generate enough data for a valid assessment in terms of this performance criteria.*

Table 6. Performance assessment for the GR Demonstration.

1 Redistribution of Treatment Layer Range maintains a continuous layer of the treatment material after multiple grenade detonations.	
Explanation	This qualitative/semi-quantitative performance objective was the main focus of this GR demonstration. In order for this technology to be effective at a given site, it needs to remain in place, either as a relatively even intact layer, or mixed into the soil profile within the treated area. The question this performance objective was attempting to answer was, "Will grenade detonations disrupt the PMSO layer to a large extent?"
Data collected	The primary data used to assess this performance objective were digital photographs. Photodocumentation was performed immediately after the 10 cm PMSO layer was emplaced in the 10 m x 10 m treated area and after each of three successive hand grenade training sessions. Photographs were taken from the same vantage points at each timepoint. Markers were included in the photographs to allow exact scales to be determined. Selected areas of the treated area were also photograph from other angles and with different levels of magnification (wide angle versus telephoto). After the initial 3 days of photodocumentation, visual reporting from site personnel were used to qualitatively assess the extent of the PMSO treatment layer coverage, accompanied by quarterly photodocumentation of the test area.
Data interpretation	Photographs were analyzed qualitatively by eye to assess PMSO coverage extents. The PMSO coverage in selected photographic series was measured by using image analysis software.
Success criteria met?	Yes. After three training sessions and 128 grenade detonations within or near the test area, approximately 88% coverage of the area by the PMSO remained. Although detonations were moving the PMSO around, it appeared that the PMSO was maintained close to the boundaries of the initial treated area.
2 Redistribution of Treatment Layer Treatment material incorporated into soil profile.	
Explanation	This qualitative/semi-quantitative performance objective was included to answer the question, "Will the PMSO be mixed into the soil due through grenade detonations creation of craters and other mixing effects?" This is important to determine as mixing of the PMSO into the soil profile would help to maintain the treatment materials in the designated area. Based on modeling efforts, it was assumed that the PMSO would be as effective at adsorbing and promoting the degradation of explosive residues if it were present as a single layer or if it were mixed into the soil matrix.
Data collected	Part of the data needed to assess this Performance Objective (digital photodocumentation) was the same as for Performance Objective #1. Additionally, 25 randomly placed soil cores were collected over an interval of 0 to 60 cm at the start of the demonstration. Had the demonstration not been terminated, additional cores would have been collected quarterly until the end of the demonstration. Cores were subsampled and analyzed for TOC concentrations (as a proxy for PMSO) as a function of depth. Soil cores were also collected from the bay, which did not receive PMSO (the control area), and analyzed for TOC.

Table 6. Performance assessment for the GR Demonstration (continued)**.**

2 Redistribution of Treatment Layer (continued) Treatment material incorporated into soil profile.	
Data interpretation	Photographs were analyzed qualitatively as described for Performance Objective #1. The soil core data would have been analyzed in terms of differences in TOC versus depth over time in the treatment area, as wells as differences in TOC versus depth at a given timepoint in the treated compared to the control area. Higher levels of TOC in the treated soil at various depths would be interpreted as evidence of incorporation of PMSO into the soil profile.
Success criteria met?	Yes. Qualitative assessment of the photographs clearly documented that the PMSO was being mixed into the soil profile by grenade detonations. Craters formed by one detonation would then have PMSO from the surrounding area fall into it when another grenade detonated nearby. A semi-quantitative assessment of this Performance Objective based on the TOC profiles in soil cores over time and, in the treated versus the control areas, was not possible due to the early termination of the demonstration.

Performance criteria were selected based on factors that would likely be considered when bringing the proposed technology to full-scale application. Primary criteria were linked directly to the project performance objectives, while secondary criteria included additional factors that could be used to assess overall project performance.

8.0 COST ASSESSMENT

8.1 COST MODEL

This section describes the cost performance criteria that were evaluated in completing the economic analysis of the PMSO technology for in situ remediation of explosives.

8.2 COST DRIVERS

The main cost drivers for use of this technology would be the cost of the materials (peat moss, crude soybean oil), and the labor required to perform the application. These costs, in turn are dependent on the ratio of peat moss to oil being used, the size of the area to be treated, the depth of material to be applied, and the period between required reapplications. The results of the SP1 and GR Demonstrations supplied data to provide general guidelines to allow determination of the depth of material to apply to achieve a given level of explosive residue immobilization (given estimates of residue loading, precipitation, etc.). Knowing this value, calculation of the amount of materials needed and the labor required to apply it would be easily calculated. It was also possible to estimate of the longevity of the treatment materials.

8.3 COST ANALYSIS

The cost analysis is based primarily on the GR demonstration due to its larger, more full-scale-relevant scope, but the majority of the quantitative performance data were derived from the SP1 demonstration to allow a more detailed and relevant cost estimate to be calculated.

The cost analysis was developed in conjunction with the technical protocol for implementing the technology, which was based on the use of the predictive model of treatment performance and the technical requirements for full-scale implementation. The cost analysis is presented for a typical site, assuming full-scale application. The cost analysis includes provisions and contingencies related to application of the technology to different size areas as well as different methods of application (surface versus buried PMSO layer) in light of the lessons learned.

8.3.1 Basic Site Description

The PMSO technology would be most effective at areas ranging from a few hundred to a few thousand square meters. Sites that would be most likely to benefit from deployment of the PMSO technology include:

- Hand grenade training area
- OB/OD facilities
- Mortar and rocket firing points
- EOD training areas
- Small arms firing points (where there is a concern about NC/NG/DNT residues).

The data obtained during the GR demonstration (Part II of this report) clearly indicated that the PMSO technology would be better either tilled into or emplaced beneath a layer of soil. The cost for tilled deployment is the baseline, but an option for burial is included.

8.3.2 Treatment Time Frame

The PMSO technology is designed to prevent contamination of subsurface and groundwater resources. As such, the treatment timeframe is defined here as the length of time before the PMSO's ability to sorb and enhance the degradation of dissolved explosive compounds is decreased, requiring that the material needs to be rejuvenated and/or replaced.

Based on the previous research and the data obtained during this project, the previously developed model of Schaefer et al. (2005) was used to estimate the effective reduction in the fluxes of TNT, RDX, and HMX over time. A 10 cm layer of PMSO having a composition of 1:2 peat moss:crude soybean oil (w:w) and an annual rainfall of 70 cm was assumed. Retardation factors for HMX, RDX, and TNT were based on a 1:2 PMSO material, but biodegradation rate constants were based on a 1:1 PMSO material, as this was the only dataset available. Biodegradation rates would likely be higher in the 1:2 PMSO material.

The model estimate is presented in Figure 16. The flux of TNT and RDX is reduced by >50% for more than 48 months, while that of HMX starts to increase above the 50% mark around 48 months. Therefore, for the cost analysis a baseline re-application rate of 48 months was selected (i.e., it would be advised that the PMSO be rejuvenated or replaced every 48 months).

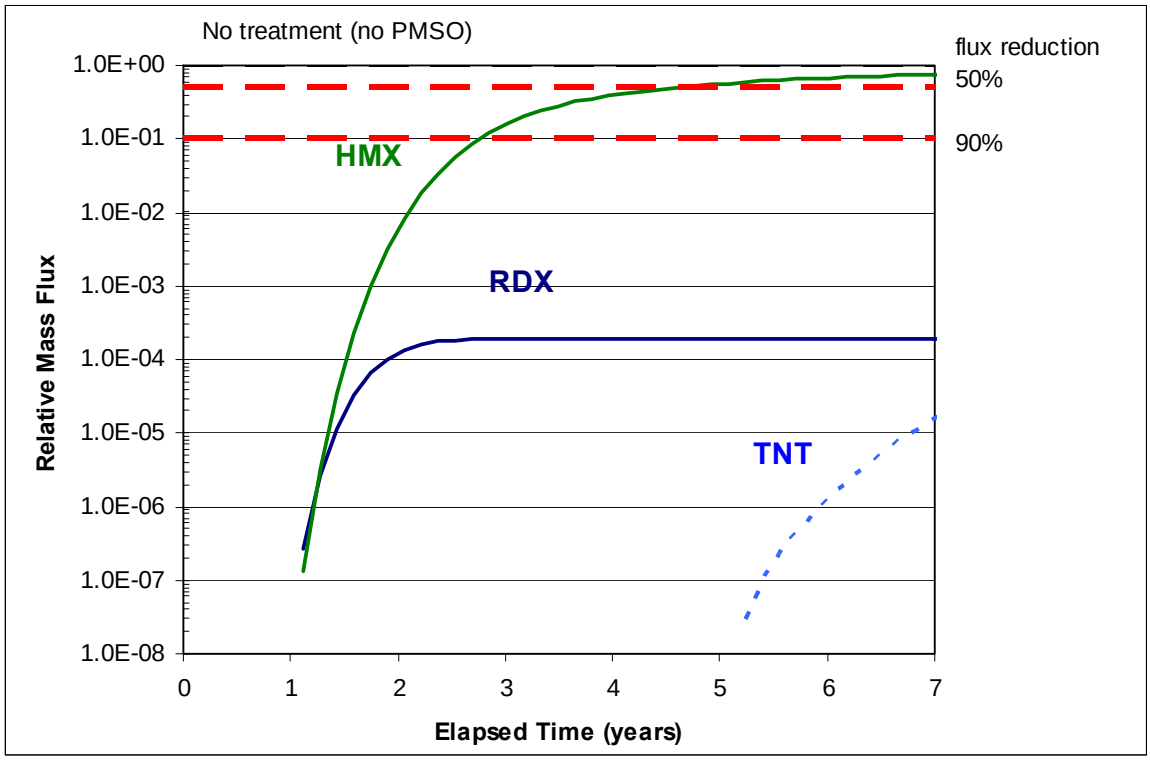


Figure 16. Model predictions of PMSO performance over time in terms of mass flux of TNT, RDX, and HMX relative to no PMSO application.
Assumptions: 10 cm of PMSO having a composition of 1:2 peat moss:crude soybean oil (w:w); annual rainfall of 70 cm. Mass flux measured at the bottom of the PMSO/top of the underlying soil boundary.

8.3.3 Life-Cycle Assessment

The following items were considered in the life-cycle cost estimate:

1. *Facility capital costs (deployment and reapplication).* The facility capital costs are expected to be minimal and may include the purchase of some commercially available equipment for mixing and application of the peat moss plus soybean oil treatment materials and basic soil manipulation. It is just as likely that this equipment would be rented or bought or that this activity would be subcontracted to a private vendor, so these options are included in the cost analysis.

2. *Maintenance costs.* As stated above, the results of previous model development and the SP1 and GR demonstrations indicated that the duration of PMSO effectiveness (>50% reduction in contaminant flux to the subsurface) was approximately 48 months. The costs for activities to rejuvenate the treatment layer by adding more treatment materials, or to replace the PMSO entirely, were estimated.

8.3.4 Cost Comparison

The results were compared to the only other competing technology, topically applied lime. ESTCP funded research on a topical applied lime technology that has a similar goal of reducing explosive residue leaching to groundwater (Project ER-0216). Efforts were made to make a parameter-relevant comparison between the peat moss plus soybean-oil-based technology and the lime-based technology. The Cost and Performance Report for ER-0216 was used as the source of the costs for the lime technology (specifically, Table 10, p. 29). The costs assume that soil is "treated" to an effective depth of 1 m (or 1 yard) under the area covered, so application of either lime or PMSO to 600 m^2 effectively treats 600 m^2. A cost comparison for a 4-year reapplication rate to achieve a >50% reduction in HMX and >99% reductions in RDX and TNT loadings is presented in Table 7. A cost comparison for a 2.5-year reapplication rate to achieve a >90% reduction in HMX, and >99% reductions in RDX and TNT loadings is presented in Table 8.

Table 7. Cost analysis for PMSO technology compared to topical lime (4-year life cycle).
4-year reapplication rate to achieve >50% reduction in flux of HMX and >99% reduction in the flux of RDX and TNT.

LIFE CYCLE	**4 Years**	**4 Years**	**4 Years**
APPLICATION METHOD	**Tilled**	**Tilled**	**Buried**
EQUIPMENT	**Rented**	**Rented**	**Rented**
	Lime	**PMSO**	**PMSO**
1. Capital Cost			
Application equipment			
-ATV (5% interest, 5 years)	4000	1000	0
-Disc plow	500	125	0
-Dropseed spreader	600	0	0
-Hydroseeder	8000	0	0
-Drum mixer (cement mixer)	0	200	200
-Road grader (140 HP)	0	0	1720

Table 7. Cost analysis for PMSO technology compared to topical lime (4-year life cycle) (continued).

4-year reapplication rate to achieve >50% reduction in flux of HMX and >99% reduction in the flux of RDX, and TNT.

LIFE CYCLE	4 Years	4 Years	4 Years
APPLICATION METHOD	Tilled	Tilled	Buried
EQUIPMENT	Rented	Rented	Rented
	Lime	PMSO	PMSO
-Vibratory roller (5 ton)	0	0	620
-Frontend loader (2.5 yd^3)	0	1070	1070
Other			
-Treatability testing for lime requirement	8000	0	0
Total Capital Cost	**21,100**	**2395**	**3610**
2. O&M			
Labor (UXO clearance by base)[a]	32,000	12,264	12,264
Materials[b]	6400	13,343	13,343
Fuel[c]	800	200	400
Soil testing	300	0	0
Other[d]	800	200	200
Total O&M Cost	**40,300**	**26,007**	**26,207**
Total Technology Cost	**61,400**	**28,402**	**29,817**
Quantity treated (m^3/yd^3)	600 / 785	600 / 785	600 / 785
Unit cost (per m^3/per yd^3)	**102.33 / 78.22**	**47.34 / 36.18**	**49.70 / 37.98**

Assumptions:

[a] Labor for lime technology estimated at $8000/yr for quarterly lime application. Labor for PMSO technology is based on the labor required at Fort Jackson grenade range demonstration to apply 100 m^2 PMSO ($2044, 4 field laborers x 8 hr x ~$64/hr burdened labor rate) then multiplying by six (6) for application of 600 m^2.

[b] Materials for lime technology included lime at $1600/year for quarterly lime application. Materials for PMSO technology included peat moss ($6885) and crude soybean oil ($5005), including shipping of oil as described in Section 8.3.4, Cost Comparison.

[c] Fuel for equipment listed in section 1 for each scenario. For lime technology, estimated as $200/year. For PMSO technology, estimated as $200 for tilling in PMSO once every 4 years, and $400 for burial of PMSO once every 4 years.

[d] Lime technology assumes costs of $200/yr for protective equipment for quarterly lime application. PMSO technology assumes a total of $200 for PMSO application once every 4 years for protective clothing and miscellaneous garden tools (shovels, rakes, etc.).

Table 8. Cost analysis for PMSO technology compared to topical lime (2.5-year life cycle).

2.5-year reapplication rate to achieve >90% reduction in flux of HMX and >99% reduction in the flux of RDX, and TNT.

LIFE CYCLE	2.5 Years	2.5 Years	2.5 Years
APPLICATION METHOD	Tilled	Tilled	Buried
EQUIPMENT	Rented	Rented	Rented
	Lime	PMSO	PMSO
1. Capital Cost			
Application Equipment			
-ATV (5% interest, 5 years)	2500	1000	0
-Disc plow	313	125	0
-Dropseed spreader	375	0	0
-Hydroseeder	5000	0	0
-Drum mixer (cement mixer)	0	200	200
-Road grader (140 HP)	0	0	1720
-Vibratory roller (5 ton)	0	0	620
-Frontend loader (2.5 yd^3)	0	1070	1070
Other			
-Treatability testing for lime requirement	5000	0	0

Table 8. Cost analysis for PMSO technology compared to topical lime (2.5-year life cycle) (continued).

2.5-year reapplication rate to achieve >90% reduction in flux of HMX and >99% reduction in the flux of RDX, and TNT.

LIFE CYCLE	2.5 Years	2.5 Years	2.5 Years
APPLICATION METHOD	Tilled	Tilled	Buried
EQUIPMENT	Rented	Rented	Rented
	Lime	PMSO	PMSO
Total Capital Cost	**13,188**	**2395**	**3610**
2. O&M			
Labor (UXO clearance by base)[a]	20,000	12,264	12,264
Materials[b]	4000	13,343	13,343
Fuel[c]	500	500	500
Soil testing	188	0	0
Other[d]	500	200	200
Total O&M Cost	**25,188**	**26,307**	**26,307**
Total Technology Cost	**38,375**	**28,702**	**29,917**
Quantity treated (m^3/yd^3)	600 / 785	600 / 785	600 / 785
Unit cost (per m^3/per yd^3)	**63.96 / 48.89**	**47.84 / 36.56**	**49.86 / 38.11**

Assumptions:

[a] Labor for lime technology estimated at $8000/yr for quarterly lime application. Labor for PMSO technology is based on the labor required at Fort Jackson grenade range demonstration to apply 100 m^2 PMSO ($2044, 4 field laborers x 8 hr x ~$64/hr burdened labor rate) then multiplying by 6 for application of 600 m^2.

[b] Materials for lime technology included lime at $1600/year for quarterly lime application. Materials for PMSO technology included peat moss ($6885) and crude soybean oil ($5005), including shipping of oil as described in Section 8.3.4, Cost Comparison.

[c] Fuel for equipment listed in section 1 for each scenario. For lime technology, estimated as $200/year. For PMSO technology, estimated as $200 for tilling in PMSO once every 4 years, and $400 for burial of PMSO once every 2.5 years.

[d] Lime technology assumes costs of $200/yr for protective equipment for quarterly lime application. PMSO technology assumes a total of $200 for PMSO application once every 2.5 years for protective clothing and miscellaneous garden tools (shovels, rakes, etc.).

Because the baseline re-application rate was assumed to be 48 months as opposed to every quarter for the lime technology, the cost comparison is presented only based on rental of the needed equipment. Rental periods of 1 week were assumed.

Costs for materials were based on:

Crude soybean oil

Amount: 14,400 lbs to cover 600 m^2 of 1:2 peat:oil PMSO, based on 1200 lbs for 100 m^2 at 1:1 peat:oil ratio.

Cost: Average $/lb of oil of $0.3476 based on April/May 2009 commodity data from Iowa, Illinois, Indiana-Ohio, and Minnesota, plus $0.0125/lb for the distributor's charge (amount charged when the oil for the GR demonstration was purchased). Shipping of oil was based on freight transport of 7200 lbs of oil from Iowa City, IA, to Columbia, SC, using a National Motor Freight Classification NMFC# 65, which is the classification for biodiesel.

Peat moss

Amount: 2250 ft^3 to cover 600 m^2, based on 373 ft^3 for 100 m^2 at 1:1 peat:oil ratio.

Cost: Average $/$ft^3$ of peat moss of $3.06, based on the actual purchase made for the GR demonstration. It is likely that with large bulk purchases of peat moss, the costs would decrease by around $3 to $5 per unit treated. Costs of around $1.50/$ft^3$ of peat moss were obtained for large "super bales" from one supplier.

8.3.5 Cost Comparison Summary

On a 4-year life cycle, the PMSO would be cheaper per unit of soil than the lime by about a factor of 2. On a 2.5-year life cycle, using the PMSO realizes an ~25% cost savings compared to the lime. There is not a great difference between the tilled and the buried application methods. These results indicate that the PMSO would be competitive with surface applied lime.

9.0 IMPLEMENTATION ISSUES

9.1 REGULATORY ISSUES

The soybean oil (CAS# 8001-22-7) used in the PMSO is classified as "generally recognized as safe" (GRAS) according to the USEPA document, "Registration Eligibility Decision (RED), Flower and Vegetable Oils. December 1993. USEPA# 738-R-93-031." http://www.ntis.gov/search/product.aspx?ABBR=PB94152048.

The peat moss (no CAS number) used in PMSO is categorized as "4A - Minimal Risk Inert Ingredients" on the USEPA's "List of Inert Pesticide Ingredients," which was updated in August 2004 (http://www.epa.gov/opprd001/inerts/inerts_list4Acas.pdf).

Based on this information, no permits were expected to be required for implementation of this technology at any site. The material is meant to be left in place once it is deployed, although additional peat moss or soybean oil might be added to rejuvenate the treatment. If the PMSO were to be permanently removed, some analyses for easily desorbed or leachable explosive residues should be performed prior to disposal.

9.2 END-USER ISSUES

The primary end users of this technology would likely be DoD site managers and DoD contractors responsible for protecting groundwater resources at military installations. The general concerns of these end users include the following: (1) technology applicability under local site conditions; (2) technology performance; (3) technology scale-up; and (4) technology cost.

This project, performed as two separate yet complimentary demonstrations, has provided information that can be used to address these concerns. General findings are presented below, with reference to the relevant sections of the report where details can be found.

- Technology applicability under local site conditions
  - The use of PMSO would be applicable.

- Technology performance
  - The PMSO material reduced the flux of RDX through the soil by approximately 500-fold compared to flux of RDX in the untreated control. See Sections 5.8.2 and 6.3 of the Soil Plot Final Report.
  - The PMSO material reduced the residual concentrations of explosive compounds as a function of depth compared to the explosive compound concentration profile observed in the untreated control. See Section 5.8.3 and 6.4 of the Soil Plot Final Report.

- Technology scale-up
  - The PMSO materials were relatively easy to handle and apply using readily available equipment. Scale-up of mixing and spreading the PMSO would likely actually be easier than the demonstration performed during

this project. As the peat moss part of the PMSO is routinely used for horticultural and landscaping purposes, handling at these larger scales would be readily feasible. See PART II, Section 5.5 of the Soil Plot Final Report.

- Technology cost
  - A cost estimate of $40-50 per 600 m3 of soil treated per 48 months (including material, labor, and equipment rental costs) was calculated based on data from both the SP1 and GR demonstrations. See Section 8, Cost Assessment.

9.3 PROCUREMENT ISSUES

The materials used in the PMSO are readily available in most areas. Peat moss and crude soybean oil can be obtained in bulk (or large unit sizes) from a number of suppliers. Contacts for some of the suppliers are presented in Table 9.

Table 9. Supplier contact information.

Company	Address	Phone/Fax
Peat moss suppliers		
Sun Gro Horticulture Distribution, Inc.	15831 N.E. 8th Street Suite 100 Bellevue, WA 98008	Phone: 801-244-0245 Fax: 801-406-0272 www.sungro.com
Waupaca Northwoods	P.O. Box 569 801 W. Fulton St. Waupaca, WI 54981	Phone: 715-256-4020 Fax: 715-256-4030 www.waupacasoilblenders.com
Crude soybean oil suppliers		
Grain States Soya Inc.	400 Johnson Road West Point, NE 68788	Phone: 402-372-2429 Fax: 402-372-3305 www.soybest.com
Cargill Industrial Oils & Lubricants	P.O. Box 5700, MS 66 Minneapolis, MN 55440	Phone: 800-842-3631 Fax: 952-742-6722 www.techoils.cargill.com
Zeeland Farm Services, Inc.	P.O. Box 290 2525 - 84th Avenue Zeeland, MI 49464	Phone: 800-748-0595 Fax: 616-772-7075 www.zfsinc.com

No claims regarding material quality or availability are made regarding these suppliers. They simply represent the suppliers that provided information about their product availability.

The equipment needed for applying the PMSO material would be dependent on the size of the area to be treated and the mode of emplacement. At a minimum, and as per the recommendations presented elsewhere in this report, it is expected that the following equipment would be required:

- Grader for soil removal and replacement
- Rotary type mixer for preparing the PMSO material (e.g., cement mixer)
- Forklift for moving drums of oil or bulk peat moss

- Bucket loader for moving loose peat moss and/or prepared PMSO.

Larger or smaller versions of this equipment would be needed, depending on the scale of the planned application. Additionally, the following types of equipment may be needed under some circumstances:

- Bark/straw blower for dispersing the PMSO across broad areas
- Tractor and tiller attachment for incorporation of the PMSO into the soil.

9.4 LESSONS LEARNED

Based on this entire project, including both the SP1 and GR Demonstrations, the recommendation for application of PMSO would be as follows.

- Plan to use PMSO with a ratio of 1:2 (peat moss:oil).
- After UXO/range clearance, remove the top layer of soil using a bulldozer or grader. The depth of soil to remove will vary depending on the type of training area being treated. Remove more soil in areas where deeper cratering is expected or where vehicle traffic might dig into the soil. For a hand grenade range, a depth of 60 cm (2 ft) would be recommended.
- Apply the PMSO as a continuous layer of between 10 and 15 cm (4 to 6 inches) within the excavated area.
- Re-apply the soil over the PMSO layer. Compact the soil if vehicle traffic is expected.
- As an ongoing preventative range management measure, apply a 10 cm (4-inch) layer of PMSO every 4 to 6 years and till (or otherwise mix) the material into the top 30 cm (1 ft) of the soil.

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Address	Phone/Fax/E-Mail	Role in Project
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Charles E. Schaefer	Shaw Environmental, Inc. 17 Princess Road Lawrenceville, NJ 08648	Phone: 609-895-5372 Fax: 609-895-1858 E-mail: charles.schaefer@shawgrp.com	Modeler
Robert J. Steffan	Shaw Environmental, Inc. 17 Princess Road Lawrenceville, NJ 08648	Phone: 609-895-5350 Fax: 609-895-1858 E-mail: rob.steffan@shawgrp.com	Fiscal Manager
Ben Gregson	Impact Area Groundwater Study Office 1803 West Outer Road Camp Edwards, MA 02542	Phone : 508-968-5821 Fax: 508-968-5286 E-mail: benjamin.p.gregson@us.army.mil	MMR Site Contact
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