

ESTCP Cost and Performance Report

(ER-200742)



Open Burn/Open Detonation (OBOD) Area Management Using Lime for Explosives Transformation and Metals Immobilization

October 2011



ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

*Form Approved
OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE OCT 2011	2. REPORT TYPE N/A	3. DATES COVERED -			
4. TITLE AND SUBTITLE ESTCP Cost and Performance Report (ER-200742) Open Burn/Open Detonation (OBOD) Area Management Using Lime for Explosives Transformation and Metals Immobilization		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ESTCP U.S. Department of Defense		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 79	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

COST & PERFORMANCE REPORT

Project: ER-200742

TABLE OF CONTENTS

	Page
1.0 EXECUTIVE SUMMARY	1
1.1 OBJECTIVES OF THE DEMONSTRATION.....	1
1.2 TECHNOLOGY DESCRIPTION	1
1.3 DEMONSTRATION RESULTS.....	2
1.4 IMPLEMENTATION ISSUES	3
2.0 INTRODUCTION	5
2.1 BACKGROUND	5
2.2 OBJECTIVES OF THE DEMONSTRATION.....	8
2.3 REGULATORY DRIVERS	8
3.0 TECHNOLOGY	11
3.1 TECHNOLOGY DESCRIPTION	11
3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY.....	13
4.0 PERFORMANCE OBJECTIVES	15
5.0 SITE DESCRIPTION	17
5.1 SITE LOCATION.....	17
5.2 SITE GEOLOGY/HYDROGEOLOGY	17
5.3 CONTAMINANT DISTRIBUTION.....	18
6.0 TEST DESIGN	21
6.1 CONCEPTUAL EXPERIMENTAL DESIGN.....	21
6.2 BASELINE CHARACTERIZATION.....	22
6.2.1 Surface Soil.....	22
6.2.2 Subsurface Soil	25
6.2.3 Pore Water	27
6.2.4 Groundwater	28
6.2.5 Surface Water.....	30
6.2.6 Air Monitoring.....	30
6.2.7 Soil invertebrate sampling	32
6.2.8 Hydrologic Evaluation of Landfill Performance (HELP) Model	32
6.3 TREATABILITY STUDY RESULTS	34
6.3.1 Lime Dosing Study	34
6.3.2 Column Study	35
6.4 FIELD TESTING.....	36
6.4.1 Initial Topical Application of Lime	36
6.4.2 Lime Application in and around Detonation Craters	37
6.5 SAMPLING METHODS.....	38

TABLE OF CONTENTS (continued)

	Page
6.6	SAMPLING RESULTS..... 40
6.6.1	Lime Application Methods 40
6.6.2	Effect of Lime on Soil Quality..... 40
6.6.3	Surface, Subsurface, and Ejected Soil 41
6.6.4	Pore Water, Surface Water, and Groundwater..... 44
6.6.5	pH Control in Soil and Aqueous Media..... 47
6.6.6	Air Monitoring 47
6.6.7	Soil Invertebrates 50
7.0	PERFORMANCE ASSESSMENT 51
7.1	QUANTITATIVE PERFORMANCE OBJECTIVES..... 51
7.2	QUALITATIVE PERFORMANCE ASSESSMENT 52
7.2.1	Evaluate Ease of Use 52
7.2.2	Evaluate Human Health Risk to the Range Personnel..... 52
7.2.3	Evaluate Potential Ecological Effects or Risks to Soil Invertebrates 53
7.2.4	Assess Lime Effects on General Water Quality Parameters of Groundwater and Soil Pore Water. Assess the Lime Effects on Percolation and Soil Drainage Characteristics..... 53
7.2.5	Evaluate OD Facility Management Costs..... 53
8.0	COST ASSESSMENT 55
8.1	COST MODEL 55
8.2	COST DRIVERS 57
8.3	COST ANALYSIS..... 58
8.3.1	Life-Cycle Costs 58
8.3.2	Technology Cost Comparison..... 59
9.0	IMPLEMENTATION ISSUES 61
9.1	ENVIRONMENTAL CHECKLIST 61
9.2	REGULATORY ISSUES 61
9.3	END-USER ISSUES 61
9.4	MANAGEMENT COSTS 62
9.5	LESSONS LEARNED..... 62
10.0	REFERENCES 65
APPENDIX A	POINTS OF CONTACT..... A-1

LIST OF TABLES

		Page
Table 1.	Performance objectives.....	15
Table 2.	Baseline characterization sampling plan.....	23
Table 3.	Concentrations of metals detected in pore water, surface water, and groundwater samples during baseline characterization of the APG OD site.....	29
Table 4.	Characteristics of soil layers used to calculate surface runoff and vertical transport of water on the APG OD area.....	33
Table 5.	Runoff water and leachate estimations as calculated by the HELP model for 1 yr, 2 yr, and 50 yr on the APG OB/OD area.....	33
Table 6.	Calculations to establish lime loading rate for topical application at the APG OD site.	34
Table 7.	Calculations to determine the quantity of lime added to the detonation area to account for soil dispersion.	35
Table 8.	Results of the column treatability study.....	35
Table 9.	Total number and types of samples collected during demonstration monitoring.....	39
Table 10.	Analytical methods for sample analysis.	40
Table 11.	Concentration of metals in TCLP extraction solution from post-liming soil.	44
Table 12.	Concentration of metals in DDI S&S extraction solution from post-liming soil.....	44
Table 13.	Concentrations of explosives detected in soil pore water pre- and post-lime application.....	45
Table 14.	Concentrations of explosives detected in surface water pre- and post-lime application.....	45
Table 15.	Concentrations of explosives in groundwater pre- and post-lime application.....	45
Table 16.	Concentrations of metals in surface water pre- and post-lime application.....	46
Table 17.	Change in pH of aqueous media post-liming of the APG OD area.	47
Table 18.	Personnel air sampler results from lime spreading activity during topical application.....	47
Table 19.	Personnel air sample results for detonation lime application method.	48
Table 20.	Perimeter air sample results.....	49
Table 21.	Concentrations of explosives detected in soil pore water pre- and post-lime application.....	51
Table 22.	Concentrations of explosives detected in surface water pre- and post-lime application.....	51
Table 23.	Concentrations of explosives in groundwater pre- and post-lime application.....	52
Table 24.	Cost model for application of lime to an OD facility.	56
Table 25.	Cost model for detonation lime application.....	57
Table 26.	Life-cycle cost factors for alkaline hydrolysis of soil on an OB/OD facility.	59

LIST OF FIGURES

		Page
Figure 1.	Degradation of RDX by alkaline hydrolysis demonstrating increase in mineralization.	7
Figure 2.	Schematic of the process of alkaline hydrolysis in a field demonstration.	13
Figure 3.	Location map of APG OBF-OD area.	17
Figure 4.	Study area showing depth to groundwater and locations of permanent monitoring wells.	18
Figure 5.	Field demonstration monitoring area.	19
Figure 6.	Concentration of metals in surface soil detected during baseline sampling at the APG OD site.	24
Figure 7.	Concentration of energetic compounds in surface soil during baseline characterization of the APG OD site.	24
Figure 8.	Concentrations of metals in the subsurface soil by depth.	26
Figure 9.	Concentration of metals in ejected soil at increasing distance from the detonation crater.	27
Figure 10.	Concentrations of explosives in soil pore water during baseline characterization of the APG OD site.	28
Figure 11.	Baseline concentrations of explosives in surface water on the APG OD site.	30
Figure 12.	Topical application of the hydrated lime.	36
Figure 13.	Illustration of lime application used in conjunction with detonations.	38
Figure 14.	Average surface soil concentrations of energetic COPCs	41
Figure 15.	Average concentration of energetic COPC in soil ejected from the detonation pit in distance from the pit center.	42
Figure 16.	Average surface soil concentrations of metals pre- and post-liming.	43
Figure 17.	Concentration of dissolved and total metals of concern in groundwater pre- and post-lime application.	46

ACRONYMS AND ABBREVIATIONS

ACGIH	American Conference of Government Industrial Hygienists
ADNT	2,4/2,6-amino-dinitrotoluene
AERTA	Army Environmental Requirements and Technology Assessments
Al	aluminum
APG	Aberdeen Proving Ground
As	arsenic
ASCE	American Society of Civil Engineers
ATSM	American Society for Testing and Materials
ATC	Aberdeen Test Center
bgs	below ground surface
BMP	best management practices
Ca	calcium
Ca(OH) ₂	hydrated lime or calcium hydroxide
Cd	cadmium
CEC	cation exchange capacity
CFR	Code of Federal Regulations
CHPPM	Center for Health Promotion and Preventive Medicine
Co	cobalt
CO ₂	carbon dioxide
COPC	contaminant of potential concern
Cr	chromium
Cu	copper
cis-DCE	cis-1,2-dichloroethene
DDI	deionized water
DNB	1,3-dinitrobenzene
DNX	hexahydro-1,3-dinitroso-5-nitro-1,3,5-triazine
DoD	Department of Defense
DPS [®]	SKC Deployable Particulate Sampler [®]
DTIC	Defense Technical Information Center
ERDC	Engineer Research and Development Center
EL	Environmental Laboratory
EOD	explosives ordnance disposal
ESTCP	Environmental Security Technology Certification Program
Fe	iron
GPS	global positioning system
HCHO	formaldehyde
HCOO ⁻	formate
HCOOH	formic acid

ACRONYMS AND ABBREVIATIONS (continued)

HELP	Hydrologic Evaluation of Landfill Performance
HGR	Hand Grenade Range
HMX	1,3,5,7-tetranitro-1,3,5,7-tetrazocane
IH	industrial hygiene
L/min	litres per minute
µg/L	micrograms per liter
MC	munitions constituents
MEC	munitions and explosives of concern
meq	milliequivalents
mg/kg	milligrams per kilogram
Mn	manganese
MNX	hexahydro-1-nitroso-3,5-dinitro-1,3,5-triazine
Mo	molybdenum
MOA	memorandum of agreement
N ₂	nitrogen
N ₂ O	nitrous oxide
NaOH	sodium hydroxide
NB	nitrobenzene
NEPA	National Environmental Policy Act
NEW	net explosive weight
NH ₃	ammonia
Ni	nickel
NO ₂	nitrite
OB	open burn
OBF	Old Bombing Field
OD	open detonation
Pb	lead
PCE	tetrachloroethene
PEL	permissible exposure limit
PM10	particulate matter 10
ppb	parts per billion
PPE	personal protective equipment
RAC	risk assessment code
RCRA	Resource Conservation and Recovery Act
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine

ACRONYMS AND ABBREVIATIONS (continued)

S&S	suspend and settle
Sb	antimony
Se	selenium
SERDP	Strategic Environmental Research and Development Program
SU	standard unit
SVOC	semi-volatile organic compound
TCE	trichloroethene
TCLP	Toxicity Characteristic Leaching Procedure
Tl	thallium
TLV	threshold limit value
TNB	1,3,5-trinitrobenzene
TNT	2,4,6-trinitrotoluene
TNX	hexahydro-1,3,5-trinitroso-1,3,5-triazine
TOC	total organic compound
TSS	Training Support System
TWA	time-weighted average
USEPA	U.S. Environmental Protection Agency
UXO	unexploded ordnance
V	vanadium
VOC	volatile organic compound
W	tungsten
Zn	zinc

This page left blank intentionally.

ACKNOWLEDGEMENTS

Financial support for this project was provided by the Environmental Security Technology Certification Program (ESTCP).

The authors would like to, specifically, recognize Dr. Andrea Leeson and Dr. Jeff Marqusee of ESTCP; Dr. Rajat Ghosh of Alcoa; and Ms. Deanne Rider, Ms. Cara Patton, Ms. Brittany Wills, and Ms. Katie O'Toole of HydroGeoLogic, Inc., for their technical and logistical support throughout the course of the project.

*Technical material contained in this report has been approved for public release.
Mention of trade names or commercial products in this report is for informational purposes only;
no endorsement or recommendation is implied.*

This page left blank intentionally.

1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

Open burn (OB)/open detonation (OD) activities are necessary to destroy unserviceable, unstable, or unusable munitions and explosives. Munitions must be demilitarized or destroyed depending on their lifespan and other requirements. There are commercial demilitarization options available, but most of these cannot sustain the volume and sometimes the specific requirements for munitions destruction. Therefore, commercial demilitarization can be costly and inflexible.

The Department of Defense (DoD) operates about a hundred OB/OD areas. These areas are usually located at fixed locations on installations. These locations may be limited to one type of operation (i.e., burning of propellants during training activities), or they may be used for multiple operations (i.e., to destroy many types of explosives, pyrotechnics, and propellants). Due to the relatively small area that OB/OD areas cover, there is a high probability of explosives contamination in the soil.

Currently there is no in situ or remote alternative for management of soils on OB/OD areas. Addressing the problem of OB/OD areas acting as source zones for mobile contaminants using existing, ex situ remediation technologies will far exceed resources available for facility or range management and is currently not practiced.

The objective of this demonstration was to evaluate and develop a management technology to control active OD area contaminant mobility and promote contaminant degradation that is low cost and minimally resource intensive. The demonstration identified and implemented lime amendment methods for explosives transformation and metals stabilization. The results from this study will improve OB/OD area design and operations and may result in sustainable management practices. The application of the proposed technology could supersede the need for intensive characterization and result in relatively short-term degradation of explosives (hexahydro-1,3,5-trinitro-1,3,5-triazine [RDX], 1,3,5,7-tetranitro-1,3,5,7-tetrazocane [HMX], 2,4,6-trinitrotoluene [TNT], and associated compounds) in the soil, while stabilizing many munitions associated metals. The technology will reduce munitions constituents (MC) migrating into the environment by adding lime to the soil for alkaline hydrolysis of explosives and hydroxide metals stabilization.

1.2 TECHNOLOGY DESCRIPTION

The technology is based on the alkaline hydrolysis reaction of nitroaromatic and nitramine compounds at high pH (>10.5). The reaction occurs in the soil pore water where the explosive residues are rapidly degraded into smaller molecular weight compounds or byproducts. These end products, including formate and nitrite, are readily degraded by indigenous soil bacteria using both anaerobic and aerobic degradation pathways.

Topical application of hydrated lime, which is mixed into the surface layers of the soil (about 6 inches) has been demonstrated in the confined space of a hand grenade range (HGR) (Environmental Security Technology Certification Program [ESTCP] project, ER-200216). The

increased pH of the soil destroys energetic compounds even through the continuous loading of training activities on the range. In addition, the lime amendment provides hydroxides to the soil that can react with soluble metals and stabilize them within the soil matrix.

The field demonstration was conducted on the Aberdeen Proving Ground (APG) OD site. It involved adding hydrated lime to the OD area to transform explosive residues and stabilize metals at the site to prevent off-site migration. Aberdeen Test Center (ATC) tills the OD site approximately once a year to prevent vegetation growth and brush fires. Lime addition was coordinated with the discing to manage explosives in the shallow surface soil layer. Lime was dispersed on the site and mixed with the deeper soils by adding it to the hole dug for the waste munitions before the detonations. The detonations dispersed the lime along with the crater ejecta. Effective dispersion was monitored by surface soil sampling after the detonation fallout had settled. Once surface soil sampling was complete, additional lime was placed in the bottom of the crater prior to pushing the dispersed soil back into the crater. The mechanical movement of the soil back into the crater served to further mix the dispersed lime into the soil. The end result was a reactive zone of elevated pH that spans the depth of the detonation crater. This dispersion method would be the typical application technique for sites that are dudded (contain unexploded ordnance [UXO]) or not regularly tilled as a standard maintenance practice.

1.3 DEMONSTRATION RESULTS

A laboratory treatability study determined the amount of lime to be added to the initial 9-acre OD site, the detonation pit, and the backfill operation. A lime loading rate of 0.5% (w:w) to the APG soil was determined to be optimal to raise the soil pH to the required level of 11.5 for alkaline hydrolysis. A laboratory column study, also using the APG soil, was performed to study the depth of pH change that could be expected if the limed soil was overcovered by unlimed soil (as in ejecta from a detonation) compared to limed soil covering unlimed soil. When the lime amendment was well-mixed and covered the untreated soil, there was an increase in soil pH of <1 standard unit (SU) over the untreated control soil (study average). There was an insignificant change in leachate pH from Day 1 to Day 9 showing that, while the increase was stable, the lime transport, as indicated by pH change, was minimal.

The objectives of the field study dealing with explosives in soil pore water, groundwater, and source zone soil were all deemed successful. There was >90% reduction in RDX in soil pore water compared to the baseline, and the concentration of RDX was <2 parts per billion (ppb). Additional explosive compounds in the pore water were also reduced below baseline levels (to non-detect concentrations). The concentrations of all explosives compounds in the groundwater were also reduced to non-detect values. Soil explosives concentrations were less than baseline values even though the site experienced continued loading of explosives constituents. The pH changes in the soil were maintained >10.5 in the source area but decreased to <9.0 outside the source area. When comparing the metals (total and dissolved concentrations) in groundwater and soil pore water to baseline values, aluminum (Al) values were generally slightly higher following the lime treatment. This is hypothesized to be due to the high clay content of the APG soil and the subsequent high natural concentration of Al in the soil.

The technology had no, or minimal, impact on the range downtime and no health risk for personnel following standard health and safety guidelines. In an evaluation of the potential

ecological effects of the liming, there was found to be minimal impact. The impact of the detonations and earth-moving activities were great enough that they masked any potential contribution from the lime.

1.4 IMPLEMENTATION ISSUES

This in situ lime technology does not involve the use of any toxic or hazardous chemicals. The only chemical used as the amendment is hydrated lime [Ca(OH)₂], which is not regulated for addition to soil. Potential regulatory concerns associated with the use of the lime amendments on OD ranges include the potential for runoff with elevated pH. The elevated pH may be detrimental to biota or surface water quality. However, in neither ESTCP-200912 (HGR) nor ESTCP-0742 (OD site) was the pH of surface water runoff affected for more than a few feet downstream of the source zone.

Technology transition efforts planned for the current and next fiscal year (10/11) include presentation at the Training Support System (TSS) Workshop, Army Science Conference, a poster at Strategic Environmental Research and Development Program (SERDP)/ESTCP Conference, publication in an American Society of Civil Engineers (ASCE) Journal, and publications in trade journals for range managers. The completed, approved reports will also be forwarded to the Defense Technical Information Center (DTIC).

This page left blank intentionally.

2.0 INTRODUCTION

2.1 BACKGROUND

OB/OD activities are necessary to destroy unserviceable, unstable, or unusable munitions and explosives. Munitions must be demilitarized or destroyed, depending on their lifespan and other requirements. There are commercial demilitarization options available, but most of these cannot sustain the volume and sometimes the specific requirements for munitions destruction. Therefore, commercial demilitarization can be costly and not very flexible. DoD operates about a hundred OB/OD areas, which are usually located at fixed locations on installations. These locations may be limited to one type of operation (i.e., burning of propellants during training activities), or they may be used for multiple operations (i.e., to destroy many types of explosives, pyrotechnics, and propellants).

Due to the relatively small area that OB/OD areas cover, there is a high probability of explosives contamination in the soil. Measurable explosive levels have been observed in OB/OD area soils at levels in the low parts per billion up to percent levels in soils. Off-site migration of explosives from OB/OD area soils have occurred through horizontal transport in surface water and vertical leachate water transport. These pathways provide a means by which limitations to OB/OD activities could occur through enforcement of state and federal environmental regulations.

Currently there is no in situ or remote alternative for management of soils on OB/OD areas. Some methods (i.e., phytoremediation, reactive barriers, etc.) exist for treatment after the explosive constituents have entered the groundwater or surface water. However, no methods exist to treat the soil from these areas while in use. Addressing the problem of OB/OD areas acting as source zones for mobile contaminants using existing, ex situ remediation technologies will far exceed resources available for facility or range management and is currently not practiced.

This demonstration focused on the control of contaminant migration caused by OD activities and seeks to develop source control. If successful, results from this study will improve OB/OD area design and operations and may result in sustainable management practices. The application of the proposed technology could supersede the need for intensive characterization and result in relatively short-term degradation of explosives (RDX, HMX, TNT, and associated compounds) in the soil, while stabilizing many munitions associated metals. The proposed technology will reduce MCs migrating into the environment by adding lime to the soil for alkaline hydrolysis of explosives and hydroxide metals stabilization.

The topical application of lime for the destruction of explosives residues in soil and aqueous media is based on the alkaline hydrolysis chemical reaction. Alkaline hydrolysis of TNT was established by Janowsky (1891). More recent studies have determined that a variety of explosive and energetic compounds can be transformed by alkaline hydrolysis. Flask experiments were conducted on TNT under high pH conditions by Saupe and Wiesman (1996), which resulted in complete transformation and partial mineralization. Hydrated lime was shown to break down TNT in soil with an application of 1% Ca(OH)₂.

Studies on RDX by Hoffsommer et al. (1977) indicated that intermediates formed by ring cleavage of the nitramine also reacted with the hydroxide ions under aqueous alkaline conditions. Additional studies have shown that the application of calcium (Ca) hydroxide to solution and soils containing TNT and RDX result in breakdown products such as nitrate and nitrite (Emmrich, 1999 and 2001). Heilman (1996) found that subjecting RDX and HMX to pH ranges of 10 to 12 could be an effective remediation technology. Balakrishnan et al. (2003) examined the degradation intermediates and end products produced by alkaline hydrolysis of RDX and HMX in solution at a pH greater than or equal to 10. They determined that the initial step in alkaline hydrolysis is denitration of the ring, which causes ring cleavage, followed by spontaneous decomposition. The nontoxic degradation break down products of RDX, HMX, and hexahydro-1-nitroso-3,5-dinitro-1,3,5-triazine (MNX) were nitrite (NO_2^-), nitrous oxides (N_2O), nitrogen (N_2), ammonia (NH_3), formaldehyde (HCHO), formic acid (HCOOH) and carbon dioxide (CO_2).

Balakrishnan et al. (2003) showed that the degradation rate of HMX is slower than RDX, but the rate increases as the pH is raised. The rate of base hydrolysis explosives transformation in a specific soil is dependent on temperature, pH of soil pore water, soil moisture content, and contaminant type. Using the rate of explosives transformation and the hydraulic permeability of the amended soil, the thickness of the in situ management area required for transforming explosives deposited on the OD area can be determined. Transport of the hydroxide ion is also affected by soil geochemical parameters, such as pH, cation exchange capacity (CEC), and the base saturation. Results from the SERDP project suggest that topical application of alkaline material for remediation of RDX at depth and in soil with a high CEC and clay or metals content may not be effective.

Lime application is a proven technology in treating organics such as TNT and RDX. SERDP project ER-1230, completed in FY03, investigated the general base hydrolysis of explosives in soils (Brooks et al., 2003; Davis et al., 2006, 2007a). With the addition of lime into a system, the pH is elevated and alkaline hydrolysis of the TNT and RDX rapidly degrades the compound into smaller molecular weight compounds or by-products. For instance, in bench-scale tests, after alkaline hydrolysis, the by-products of RDX ring cleavage include formate (HCOO^-) and nitrite (NO_2^-) (Davis et al. 2007b). In addition, these by-products can be readily degraded biologically (aerobically and anaerobically) by native soils following alkaline hydrolysis (Figure 1) (Felt et al., 2007). Degradation of RDX base induced transformation products continues via both anaerobic and aerobic degradation: a) greater than 75% aerobic mineralization following alkaline hydrolysis obtained in ^{14}C labeled study after a few weeks and b) less than 2% mineralization for RDX without alkaline hydrolysis (Felt et al. 2007). For the OD field demonstration site, the $\text{Ca}(\text{OH})_2$ was topically applied to the surface of the soil and disced into the soil to a depth of 6 inches. Normal earth moving activities related to OD area operational preparation activities served to further mix this hydrated lime with the soil. Once the management area was established, $\text{Ca}(\text{OH})_2$ additions were incorporated into existing earth movement practices or OD activities to maintain the amended soil's pH in the desired range.

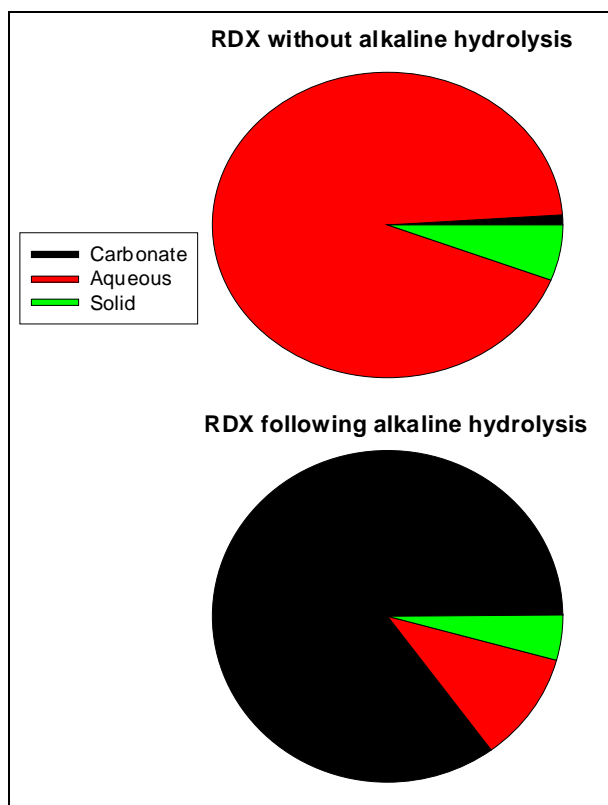


Figure 1. Degradation of RDX by alkaline hydrolysis, demonstrating increase in mineralization.

ESTCP project, ER-200216, completed field demonstration at the Fort Jackson, SC, HGR in FY07. The ESTCP research explored the use of the base hydrolysis reaction to manage impact areas for HGRs where the contaminant deposition and alkaline hydrolysis occurs primarily within the top 6 inches of the soil. The addition of lime provides hydroxides to the soil that can react with soluble metals and stabilize them within the soil matrix, as has been observed in ESTCP Project ER-200216. Erosion control measures have been shown to reduce the amount of total suspended solids released in surface water transport. Suspended solids can have high concentrations of metals and other contaminants associated with them. Therefore, the reduction of suspended solids in surface water runoff can be critical to reducing migration of MCs off range.

In collaboration with the U.S./German Data Exchange Agreement, information was exchanged on a recently reconstructed German ordnance detonation site. Erosion control measures, a retention basin, and a wetland area were constructed to control the MCs released from the range as storm water runoff. Molasses and wetlands were used to create reducing conditions for the RDX in the runoff waters and have achieved RDX levels below 20 ppb in water released from the basin/wetlands system. The German system does not treat the soil, but rather treats the runoff from the soil associated with their detonation area. The proposed technology for the OD area will combine the aspects of these existing technologies to set the conditions for alkaline hydrolysis in the range soil to reduce migration of the MCs from the range.

A laboratory study was conducted with soil collected from two active HGRs (Larson et al., 2007). The soil was treated with $\text{Ca}(\text{OH})_2$ and was placed in large laboratory lysimeters. Rainfall was simulated over the lysimeters with a sprinkler system and runoff water and leachate samples were collected. RDX concentrations in surface water and leachate samples were reduced by more than 90% in the treated soil.

Lime application as a range management technology was demonstrated at an active hand grenade training range (Larson et al., 2008). The field demonstration results indicated that, for an active range used on a regular basis, a quarterly application of lime would be sufficient as a range management tool to significantly reduce the migration of MCs. Lime dosage batch tests were performed on the APG OD range soil to determine the optimal lime dosage. It was determined that 0.5% of $\text{Ca}(\text{OH})_2$, would be required to raise the pH of the top 6 inches of soil to get the soil pH in the range of 11 to 11.5.

The sequence of events that occurred during the field demonstration was:

1. Baseline characterization
2. Soil treatability study and determination of the site-specific lime loading rate
3. Topical application of lime to 9 acres, mixed to a depth of 6-inches
4. Lime addition to the detonation pit
5. Detonation
6. Post-detonation sampling
7. Backfill crater with lime and soil
8. Repeat using a different method to fill detonation pit
9. Particulate matter 10 (PM10) air sampling throughout the demonstration (conducted by personnel from Center for Health Promotion and Preventive Medicine [CHPPM]).

2.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this demonstration was to develop and evaluate a management technology to control active OD area MC mobility and promote the degradation of energetic materials that is low cost and minimally resource intensive. The demonstration was used to identify and implement lime amendment methods for explosives transformation and metals stabilization.

2.3 REGULATORY DRIVERS

The U.S. Environmental Protection Agency (USEPA) Office of Water Lifetime Health Advisory for RDX is 2 micrograms per liter ($\mu\text{g}/\text{L}$). In the future, this advisory level may become a USEPA regulation for aqueous media.

A Resource Conservation and Recovery Act (RCRA) permit is required for continued operation of the APG and Anniston Army Depot OB/OD ranges. Active OB/OD ranges used for disposal

of waste munitions in the United States will also be required to have an RCRA permit in the near future.

The OB/OD area management technology addresses the following Army Environmental Requirements and Technology Assessments (AERTA):

- (2.5.e) for Sustainable Army Live-Fire Range Design and Maintenance. This is a high priority user need for the Army (ranked sixth in the compliance pillar).
- (1.2.a) for Enhanced Alternative and In-situ Treatment Technologies for Explosives and Organics in Groundwater (ranked second in restoration pillar).
- (1.6.f) for Remediation of Distributed Source Unexploded Ordnance-Related Contamination (UXO[C]) on Army Ranges (ranked fourth in restoration pillar).

This page left blank intentionally.

3.0 TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

The transformation of TNT in basic solutions was established by Janowsky (1891). More recent studies have determined that a variety of explosive and energetic compounds can be transformed by alkaline hydrolysis. Flask experiments were conducted on TNT under high pH conditions by Saupe and Wiesman (1996), which resulted in complete transformation and partial mineralization. Hydrated lime was shown to break down TNT in soil with an application of 1% $\text{Ca}(\text{OH})_2$.

Studies on RDX by Hoffsommer et al. (1977) indicated that intermediates formed by ring cleavage of the nitramine also reacted with the hydroxide ions under aqueous alkaline conditions. Additional studies have shown that the application of Ca hydroxide to solution and soils containing TNT and RDX result in breakdown products such as nitrate and NO_2 (Emmrich, 1999 and 2001). Heilman (1996) found that subjecting RDX and HMX to pH ranges of 10 to 12 could be an effective remediation technology. Balakrishnan et al. (2003) examined the degradation intermediates and end products produced by alkaline hydrolysis of RDX and HMX in solution at a pH greater than or equal to 10. They determined that the initial step in alkaline hydrolysis is denitration of the ring, which causes ring cleavage, followed by spontaneous decomposition. The nontoxic degradation breakdown products of RDX, HMX, and MNX were NO_2 , N_2O , N_2 , NH_3 , HCHO , HCOOH , and CO_2 .

Balakrishnan et al. (2003) showed that the degradation rate of HMX is slower than RDX, but the rate increases as the pH is raised. The rate of base hydrolysis explosives transformation in a specific soil is dependent on temperature, pH of soil pore water, soil moisture content and contaminant type. Using the rate of explosives transformation and the hydraulic permeability of the amended soil, the thickness of the in situ management area required for transforming explosives deposited on the OD area can be determined. Transport of the hydroxide ion is also affected by soil geochemical parameters, such as pH, CEC, and the base saturation. Results from the SERDP project suggest that topical application of alkaline material for remediation of RDX at depth and in soil with a high CEC and clay/metals content may not be effective.

Lime application is a proven technology in treating organics such as TNT and RDX. SERDP project ER-1230, completed in FY03, investigated the general base hydrolysis of explosives in soils (Brooks et al., 2003; Davis et al., 2006, 2007a). With the addition of lime into a system, the pH is elevated and alkaline hydrolysis of the TNT and RDX rapidly degrades the compound into smaller molecular weight compounds or by-products. For instance, in bench-scale tests, after alkaline hydrolysis, the by-products of RDX ring cleavage include HCOO^- and NO_2^- (Davis et al., 2007b). In addition, these by-products can be readily degraded biologically (aerobically and anaerobically) by native soils following alkaline hydrolysis as shown previously in Figure 1 (Felt et al., 2007). Degradation of RDX base induced transformation products continues via both anaerobic and aerobic degradation: a) greater than 75% aerobic mineralization following alkaline hydrolysis obtained in 14-C labeled study after a few weeks; and b) less than 2% mineralization for RDX without alkaline hydrolysis (Felt et al., 2007).

ESTCP project, ER-200216, completed field demonstration at the Fort Jackson, SC, HGR in FY07. The ESTCP research explored the use of the base hydrolysis reaction to manage impact areas for HGRs where the contaminant deposition and alkaline hydrolysis occurs primarily within the top six inches of the soil. The addition of lime provides hydroxides to the soil that can react with soluble metals and stabilize them within the soil matrix as has been observed in ESTCP project ER-200216. Erosion control measures have been shown to reduce the amount of total suspended solids released in surface water transport. Suspended solids can have high concentrations of metals and other contaminants associated with them. Therefore, the reduction of suspended solids in surface water runoff can be critical to reducing migration of MCs off range.

A laboratory study was conducted with soil collected from two active HGRs (Larson et al., 2007). The soil was treated with hydrated lime and was placed in large laboratory lysimeters. Rainfall was simulated over the lysimeters with a sprinkler system and runoff water and leachate samples were collected. RDX concentrations in surface water and leachate samples were reduced by more than 90% in the treated soil.

Lime application as a range management technology was demonstrated at an active hand grenade training range (Larson et al., 2008). The field demonstration results indicated that, for an active range used on a regular basis, a quarterly application of lime would be sufficient as a range management tool to significantly reduce the migration of MCs. Lime dosage batch tests were performed on the APG OD range soil to determine the optimal lime dosage. It was determined that 0.5% of $\text{Ca}(\text{OH})_2$ would be required to raise the pH of the top 6 inches of soil to get the soil pH in the range of 11 to 11.5. A schematic illustrating the application of this technology in the field is provided in Figure 2. For the OD field demonstration site, the hydrated lime was topically applied to the surface of the soil and disced into the soil to a depth of 6 inches. Normal earth moving activities related to OD area operational preparation activities served to further mix this hydrated lime with the soil. Once the management area was established, hydrated lime additions were incorporated into existing earth movement practices or OD activities to maintain the amended soil's pH in the desired range.

This technology can be applied on military or civilian range areas where soil conditions, site hydrology, and weather conditions improve the possibility of transport of munitions residues off range.

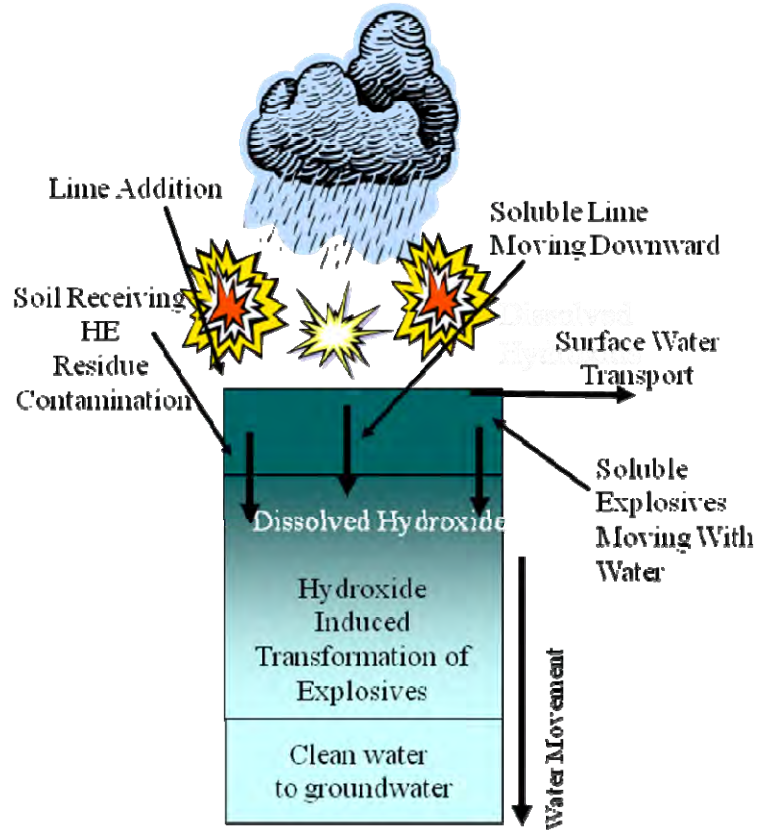


Figure 2. Schematic of the process of alkaline hydrolysis in a field demonstration.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages of this technology are:

- Low cost.
- The treatment does not involve addition of toxic chemicals to the soil and no toxic residues or secondary wastestreams are produced.
- In situ treatment encompasses soil, surface, and groundwater.
- Low level of interference with normal OB/OD facility operations.
- Once in place, the treatment is not affected by weather.

Limitations of this technology are:

- Weather (wind) affects emplacement of the technology due to atmospheric spreading of lime dust.
- Sufficient soil pore water is necessary to dissolve and mix the hydroxide and soluble explosive compounds.

- If the soil buffering capacity is high (high clay concentration), a larger amount of lime is required to achieve and maintain the ideal pH.
- Sufficient mixing of the soil is necessary to enhance contact of explosives with hydroxide ions in solution.
- Potential for solubilization of hydroxide and transport of hydroxide off the treated area in storm water which could have deleterious effects on off-site vegetation. This requires monitoring of storm water runoff.

Currently there are no in situ or remote alternatives for management of explosives residues in soils on OB/OD areas.

4.0 PERFORMANCE OBJECTIVES

The performance objectives for the field demonstration of the alkaline hydrolysis technology at the APG OD site are presented in Table 1.

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria*	Results
Quantitative Performance Objectives			
Reduce RDX concentrations in soil pore water.	Pre- and post-treatment contaminant concentrations in soil pore water	90% reduction compared to baseline. Goal is (RDX) <2 ppb.	90% reduction compared to baseline. Goal is (RDX) <2 ppb. Success
Reduce overall explosive constituents in soil pore water.	Pre- and post-treatment contaminant concentrations in soil pore water	Explosives concentrations <baseline levels	Explosives concentrations <baseline levels. Success
Reduce overall explosive constituents in groundwater.	Pre- and post-treatment contaminant concentrations in groundwater	Explosives concentrations <baseline levels	Explosives concentrations <baseline levels. Success
Reduce metals concentrations in groundwater.	Analysis of total and dissolved metals concentrations in baseline and test groundwater samples	Total and dissolved phase metals concentrations <baseline levels	Al was higher
Reduce metals concentrations in soil pore water.	Analysis of total and dissolved metals concentrations in baseline and test groundwater samples	Total and dissolved phase metals concentrations <baseline levels	Al was higher
Maintain control of soil pH levels.	pH measurements of soil samples collected on site and in the runoff pathways from the site	Soil pH >10.5 in the source area; pH=9.0 outside of source area	Success
Reduce explosive concentrations in the soil within the source area.	Soil samples collected within the source area*	Soil explosives concentrations < baseline levels	Success* . Continued success depends on the use and implementation of the best management practices (BMPs).
Determine permanency of hydroxide stabilization based on local soils and precipitation.	Comparison of pH concentrations in baseline and test soil samples	Soil pH is similar to baseline levels	Success* . Continued success depends on the use and implementation of the BMPs.

Table 1. Performance objectives (continued)

Performance Objective	Data Requirements	Success Criteria*	Results
Qualitative Performance Objectives			
Ease of use.	Amendment application method, frequency, and range downtime	Amendment application requires no or minimal downtime of the range	Success
Evaluate human health risk to range user.	Air monitoring of PM10 concentrations	No health risk or inhalation, eye, or skin irritation allowed	Success
Evaluate potential ecological effects or risks to soil invertebrates.	Pre- and post-treatment measurements of species variety and count	Maintain the same types and quantities of soil invertebrates compared to baseline levels.	Success
Assess lime effects on soil drainage characteristics and general water quality parameters of groundwater. Estimate length of pH effects after curtailment of liming operations.	Pre- and post-treatment measurements taken from soil samples and groundwater monitoring stations	Hardness, alkalinity and pH meet state and federal water quality parameters in groundwater. Pore water collected down gradient of the amended soil <baseline levels. Same perc test results as baseline results.	Success
Evaluate OD range management costs.	Amendment application method, frequency, and downtime	Develop annual cost to maintain the APG range and other ranges.	Success

* Since use of the OB/OD site will result in continued loading of explosives constituents during the demonstration, an assessment of the reduction of explosives concentrations within the source area is compared to baseline concentrations.

5.0 SITE DESCRIPTION

5.1 SITE LOCATION

The Old Bombing Field (OBF) OD range is located within the Aberdeen portion of APG's operational range complex, approximately 1400 ft southeast of OBF-OB unit near the south central portion of the Aberdeen Area (Figure 3). Access is restricted by Range Control. The range consists of 18 acres and is a level, lowland area. It contains a large, flat, non-grassy portion of consistent topography on which the munitions are treated. The site is gently sloped to the east and southeast where surface water is captured by a runoff control berm that runs along the eastern boundary of the unit.

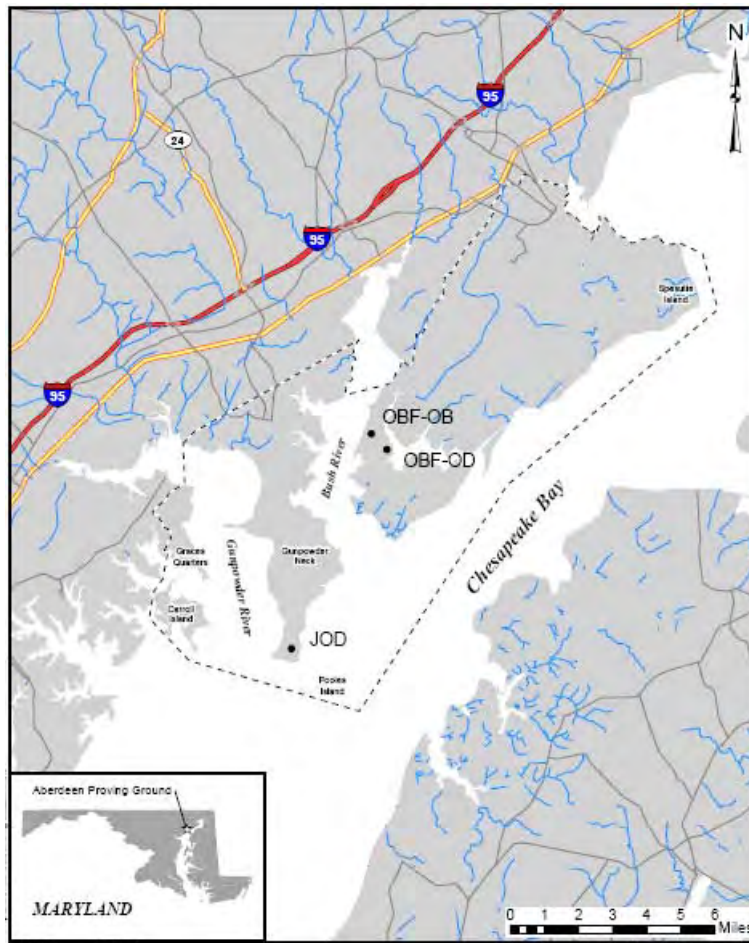


Figure 3. Location map of APG OBF-OD area.

5.2 SITE GEOLOGY/HYDROGEOLOGY

The soils along the northern portions of the OBF-OD range are silty clay to clay from the surface to depths of 9 to 12 ft below ground surface (bgs) (U.S. Army, 2005). Beneath this range, there are medium to coarse-grained sands to at least 16 ft bgs. In the western and central portions of the site, there is sandy clay from the surface to 3 ft bgs. This range is underlain by sand to sand interbedded with a clay layer that grades into a medium to coarse-grained sand unit. There are

localized lenses of clay in the medium to coarse-grained sand unit. Soil borings completed in areas of former detonation trenches indicated previous excavation and backfilling activities.

The shallow depth to groundwater (3 to 8 ft) suggests the potential for subsurface transport of contaminants (Figure 4).

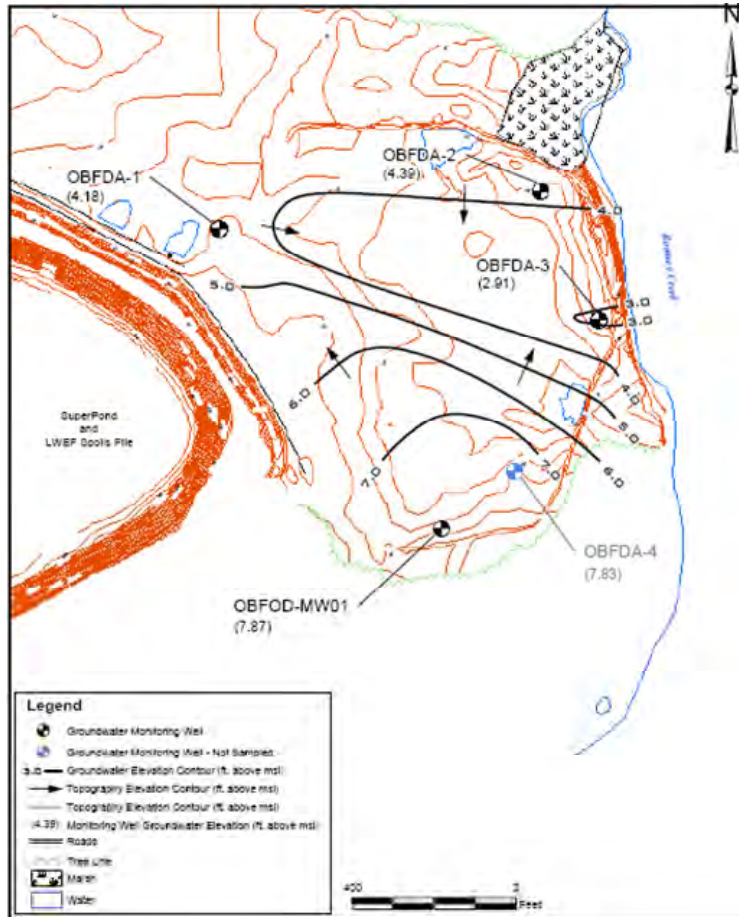


Figure 4. Study area showing depth to groundwater and locations of permanent monitoring wells.

5.3 CONTAMINANT DISTRIBUTION

The field demonstration was focused on the Northwest and Southwest quadrants of the OD range (9 acres) farthest from Romney Creek (Figure 5). Topical lime application and most of the detonations were conducted in this area during the demonstration. The western portion of the OD facility was used for the technology demonstration because:

- Most detonations were conducted on the half of the range farthest from Romney Creek (i.e., the western portion) to minimize potential airborne transport and deposition of crater ejecta on recently installed storm water sediment traps in the eastern portion of the detonation field and on Romney Creek itself.

- The half of the OD range closest to Romney Creek falls within an exclusion area that is enforced when bald eagles are nesting (January 15 through June 15) in a nest located on a tower in Romney Creek.
- Concentrating the monitoring in a relatively smaller area minimized monitoring costs and maximized the ability to detect trends in contaminant mobility or reduction.

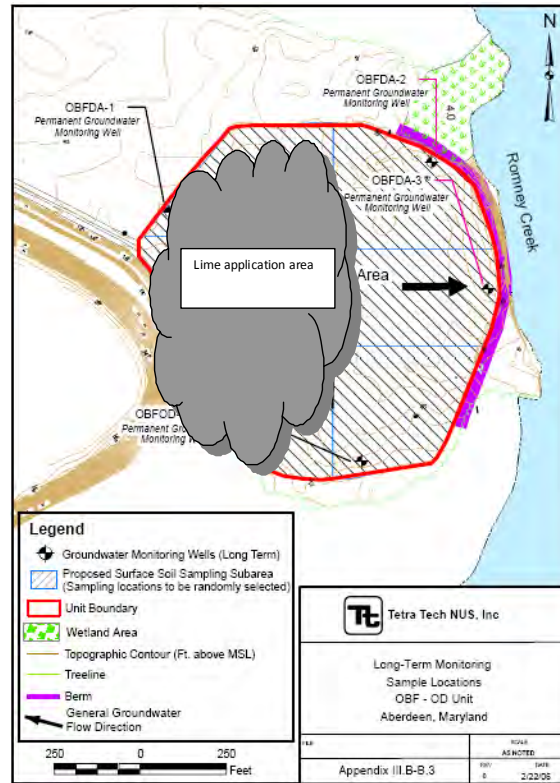


Figure 5. Field demonstration monitoring area.
The established surface water runoff control berm and groundwater monitoring wells are indicated.

A 10-gal soil sample was collected from this area in July 2007 for lab testing at Engineer Research and Development Center (ERDC)-Environmental Laboratory (EL). This soil sample was collected from the surface in and around the area where a munitions disposal detonation had recently been performed. The lab tests were designed to determine the critical design factors for the field demonstration. These factors included the amount of amendment required to elevate the soil pH to the point where explosives transformation occurs at a rapid rate compared to contaminant loading and migration, and the changes in the soil and chemicals of potential concern properties that could be expected following amendment application. ERDC-EL lab tests resulted in a recommended lime application concentration of 0.5% of the soil volume in the targeted soil layer.

Samples were also collected from the APG OD site to determine baseline concentrations of contaminant of potential concern (COPC) and a baseline count of invertebrate types and quantities before the lime technology was tested in the field. Baseline explosives, metals, and

pH levels were determined from surface soil, subsurface soil, pore water, groundwater, and surface water samples. Perchlorates, volatile organic compounds (VOC) and semi-volatile organic compounds (SVOC) were also analyzed for some samples. Baseline air samples were collected for Ca and particulates. Baseline sampling began in April 2008 and continued through September 2008.

6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

A memorandum of agreement (MOA) with APG details the scope of work performed at the OB/OD area. UXO avoidance support was provided via the ATC to support monitoring equipment installation and subsurface sampling activities. The APG OD facility is an active area with regular detonation activity, and the introduction of MCs has occurred for the duration of the facility's lifetime, thus the energetic material in the soil is not from just one detonation, but multiple detonations throughout many years.

The field demonstration involved adding hydrated lime to the OD area to transform explosive residues and stabilize metals at the site to prevent off-site migration. ATC tills the OD site approximately once a year to prevent vegetation growth and brush fires. Lime addition was coordinated with the discing to manage explosives in the shallow surface soil layer. Lime was first spread on the site with a drop spreader and then disced it into the soil. Afterwards, lime was dispersed on the site and mixed with the deeper soils by adding it to the hole dug for the waste munitions before the detonations. The detonations dispersed the lime along with the crater ejecta. Effective dispersion was monitored by surface soil sampling after the detonation fallout had settled.

Once surface soil sampling was complete, additional lime was placed in the bottom of the crater prior to pushing the dispersed soil back into the crater. The mechanical movement of the soil back into the crater served to further mix the dispersed lime into the soil. The end result was a reactive zone of elevated pH that spans the depth of the detonation crater. As more lime-amended detonations occur, the deep treatment zones will promulgate throughout the OD range. This dispersion method would be the typical application technique for sites that are dudded (contain UXO) or do not regularly till the site as a standard maintenance practice.

Demonstration monitoring was performed for 18 months. In addition, 6 months of baseline monitoring was performed prior to the initial lime application and 18-month monitoring period. The lime was applied and mixed into the soil over a period of 1 to 2 days. The lime application by detonations occurred with the routine munitions waste disposal detonations for the first 12 months of the 18-month monitoring period. The lime application was curtailed after the first 12 months to monitor pH effect dissipation with respect to time. This information provided insight into the application frequency required to effectively manage the munitions COPCs in the soil.

The steps of the Test Design were:

1. Soil treatability study
2. Baseline characterization
3. Topical application of lime to 9 acres, mixed to a depth of 6 inches
4. Lime addition to the detonation pit
5. Detonation

6. Post-detonation sampling
7. Backfill crater with lime and soil
8. Repeat using a different method to fill detonation pit
9. PM10 air sampling throughout the demonstration (conducted by personnel from CHPPM).

6.2 BASELINE CHARACTERIZATION

Baseline soil, pore water, groundwater, and surface water samples were collected. A baseline survey of soil invertebrates was performed in the top 6 inches of soil in the source area. The baseline data was reviewed prior to the lime application to assure that the data obtained and the sample locations and depths were appropriate to monitor the field study. ATC personnel collected the samples and shipped them to ERDC-EL for analysis. The baseline characterization sampling plan is summarized in Table 2.

6.2.1 Surface Soil

Residues of explosives (1,3-dinitrobenzene and nitrobenzene), perchlorate, and inorganics (arsenic [As], copper [Cu], nickel [Ni], selenium [Se], and zinc [Zn]) were detected in previous surface soil samples collected from the OBF-OD range. These analytes are considered COPCs in surface soil at the site (U.S. Army, 2005).

Five baseline sampling events gathered soil samples from the non-limed detonation crater, surface areas, and subsurface areas, as well as soil ejected from the detonation crater before lime was applied to the site. The site was divided into four quadrants; one 30-point composite soil sample was collected from each quadrant from a depth of 0-6 inches bgs. Each point of the composite sample was collected in a grid pattern within each cell. Ejected soil from non-limed detonation craters was also sampled. Each surface soil sample was analyzed for explosives, perchlorate, metals, and pH.

No As or Se was detected in the surface soil samples. Concentrations of other metals are shown in Figure 6. Cu concentrations ranged from 19 to 24 milligrams per kilogram (mg/kg). Zn concentrations ranged from 25 to 31 mg/kg. Ni only ranged from 10 to 12 mg/kg. Ca concentrations were stable at approximately 2600 mg/kg. Al ranged from 4200 to 6500 mg/kg. The soil from APG had a high percentage of clay in the fines. Al is a common component of soils and clays, with a mean concentration of 79,600 mg/kg in the earth's crust and 47,000 mg/kg in the soil (Sposito, 2008).

Surface soil pH ranged from 4.8 to 5.3.

Table 2. Baseline characterization sampling plan.

Media	No. of Sample Locations	Grab or Comp.	Depth Interval	Location	Sampling Method	Rounds	Frequency	Analysis
Surface soil	4 (1 per quadrant)	30 point comp.	0-6 inches bgs	Composites collected in grid pattern	Bowl and spoon	2	Quarterly	Explosives, perchlorate, metals, pH
Subsurface soil	2 craters (1 per crater)	Grab	Collect in 2-ft intervals to top of water table.	From sides of detonation craters	Bowl and spoon	(1 per crater)	Detonations	Explosives, perchlorate, metals, pH
Pore water	2 craters (2 locations per crater); 4 total lysimeters	Grab	1-3 ft bgs; 4-6 ft bgs	Install in sides of detonation craters (or augered next to crater)	Lysimeter	2	Every 2 months	Explosives, total metals, dissolved metals
Groundwater	4	Grab	Wells screened across water table	Upgradient: OBFDA-1, OBFDA-2, OBFOD-MW01 Downgradient: OBFDA-3	Monitoring well: submersible or peristaltic pump	2	Quarterly	Explosives, total metals, dissolved metals, perchlorate, (VOCs and SVOCs for at least 1 round)
Surface / ponded water	4	Grab	NA	Ground surface	Peristaltic pump or scoop	2	Rainfall events	Explosives, total metals, dissolved metals
Air	4	4-8 hr comp.	NA	Perimeter of site	Portable air sampler	Minimum of 2 rounds	1 no site activity & 1 detonation	Ca, PM10
Air	1	4-8 hr comp.	NA	Personnel	Personnel air sampler	Minimum of 2 rounds	Detonations	Ca hydroxide, PM10
Ecological survey	NA	NA	0-6 inches	OD range source area	Survey	1	Once	Soil invertebrate types and count

Notes:

1. Dissolved metals samples were field filtered.
2. Field parameters for water samples were collected in the field and included temperature, pH, conductivity, and turbidity.
3. PM10 = particulate matter 10: measures particles suspended in the air which have a size range of 10 micrometers or less.
4. bgs = below ground surface.

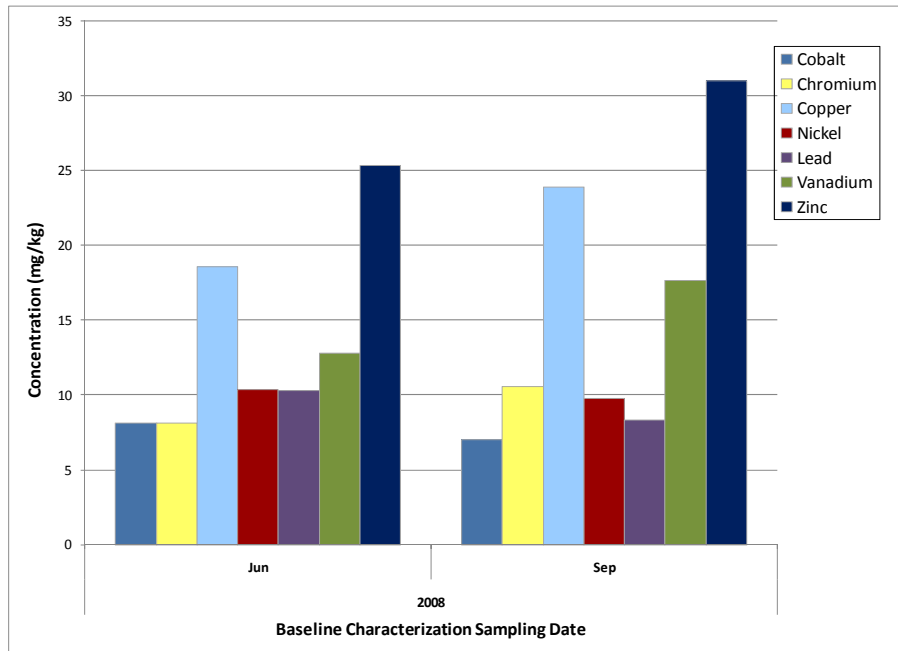


Figure 6. Concentration of metals in surface soil detected during baseline sampling at the APG OD site.

The results of baseline sampling and analysis for explosives in surface soil are shown in Figure 7. As expected, because the detonating charge used is C4, the nitramine compounds are most prevalent. Concentrations of RDX decreased from June to September, but the concentration of hexahydro-1,3-dinitroso-5-nitro-1,3,5-triazine (DNX) increased over the same time period. Hexahydro-1,3,5-trinitroso-1,3,5-triazine (TNX) was detected from all three sampling events. There was a single detection of HMX.

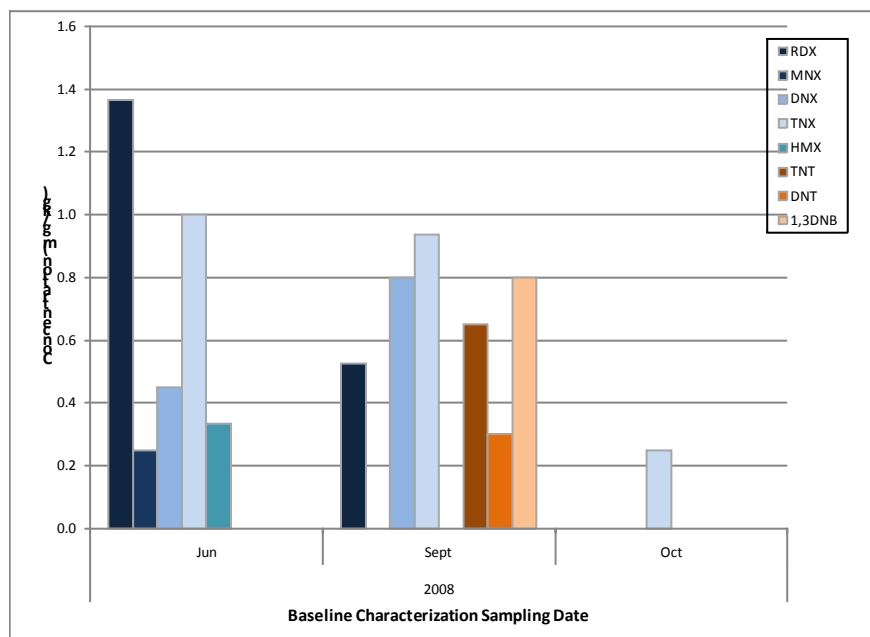


Figure 7. Concentration of energetic compounds in surface soil during baseline characterization of the APG OD site.

Nitroaromatic energetics were detected only at the second sampling event (September) and are possibly due to the particular formulation of the munitions destroyed at that time.

6.2.2 Subsurface Soil

Explosives (2,4-dinitrotoluene, nitrobenzene, and RDX), VOCs (1,2-dichloroethane, tetrachloroethene, and ni-nitrosodiphenylamine), perchlorate, and inorganics (As, cadmium [cd], Cu, Ni, thallium [Tl], and Zn) were detected in previous subsurface soil samples collected from the OBF-OD unit. These analytes are considered COPCs in subsurface soil at the site (U.S. Army, 2005). Additional subsurface soil samples were collected to determine current concentrations of these and other parameters relevant to this demonstration.

Subsurface soil samples were collected from two locations before lime was applied to the site. The soil cores were collected at 2 ft depth intervals (0-2 ft bgs, 2-4 ft bgs, etc.) to the top of the water table. Ejected soil from non-limed detonation craters was also sampled. Each subsurface soil sample was analyzed for explosives, perchlorate, metals, and pH. The baseline results were compared with sample results collected from the same locations at the completion of the field demonstration. Each soil composite was placed in a stainless steel bowl, homogenized, and then transferred to the sample bottles.

In general, RDX concentrations in the subsurface soils ranged from 0.25 up to 0.62 mg/kg, with the lowest concentrations appearing in the middle depths. The highest concentration was at the deepest depth. There were comparable concentrations of DNX and TNX throughout the soil depth. These ranged from 0.25 to 1.8 mg/kg. MNX was detected at 8-10 ft bgs, at 0.95 mg/kg. HMX was detected at a uniform concentration of 0.25 mg/kg from 2 to 10 ft bgs. There were no detections of the nitroaromatic compounds, 1,3-dinitrobenzene (DNB), 1,3,5-trinitrobenzene (TNB), 2,4/2,6-amino-dinitrotoluene (ADNT) or nitrobenzene (NB). TNT was detected one time (0.15 mg/kg) at 6 to 8 ft bgs.

Concentrations of metals in the subsurface soil are illustrated in Figure 8 for Cu, Ni, and Zn. The mean concentrations of Cu, Ni, and Zn in earth's crust have been reported at 25 mg/kg, 56 mg/kg, and 65 mg/kg, respectively (Sposito 2008). Cu, Ni and Zn were detected at concentrations that were consistent across the depth profile of the soil, as was iron (Fe) and lead. There was no detection of As, Cd, or Tl. Ca concentrations decreased with depth from 845 mg/kg to 496 mg/kg; the mean concentration of Ca has been reported in the earth's crust at 38,500 mg/kg and in the soil at 9200 mg/kg (Sposito, 2008). Cobalt (Co) was detected only in the upper 4 ft of the soil. The source of the Co was probably destroyed munitions. Vanadium (V) was also detected at low concentrations (16 to 23 mg/kg) at all soil depths and the source is also probably from destroyed munitions.

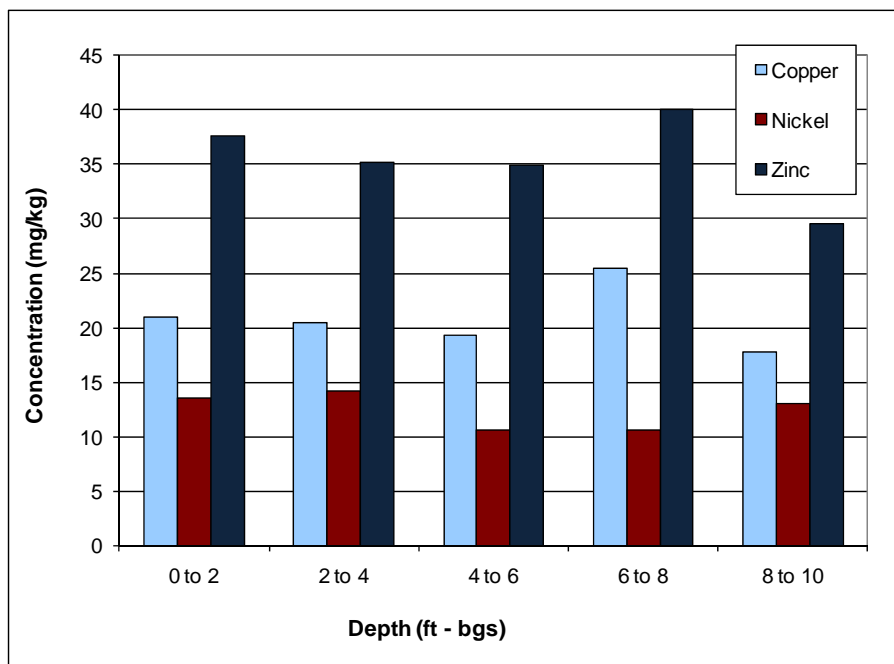


Figure 8. Concentrations of metals in the subsurface soil by depth

Cu, Ni, and Zn were also detected in the ejected soil (Figure 9). Cu was detected at all distances from each detonation event in concentrations from 20 to 31 mg/kg, as was Zn (25 to 37 mg/kg), lead (10 to 26 mg/kg), and V (9 to 19 mg/kg). Ni was not detected after each detonation in the inner ring closest to the detonation crater. The other metals were detected in higher concentrations in the middle ring, 50 to 100 ft from the crater. Metal formulations in the munitions being destroyed have an effect on the concentrations of the metals detected.

Al and Fe were also detected in the ejected soil, although not shown in Figure 9. Al concentrations ranged from 2600 mg/kg in the outermost ring to 6600 mg/kg in the innermost ring, well within the mean concentration typically found in soils (Sposito, 2008). The concentrations detected following the second detonation event were one-third those of the first event and may be due to differences in munition formulations. Fe was present at each sampling distance from the crater with maximum concentrations detected from the center sampling ring. Overall concentrations ranged from 6000 mg/kg to 9400 mg/kg. Background Ca concentration in the ejected soils ranged from 700 mg/kg to 1200 mg/kg with little variation between detonation event and distance from the crater, indicating that its distribution is fairly homogeneous and well below the mean concentration typically found in soils (Sposito, 2008).

Soil samples taken from the detonation pit, in general, followed the detections of metals in the ejected soil with the exception of the presence of chromium following the first detonation. Chromium was detected at 12 and 13 mg/kg.

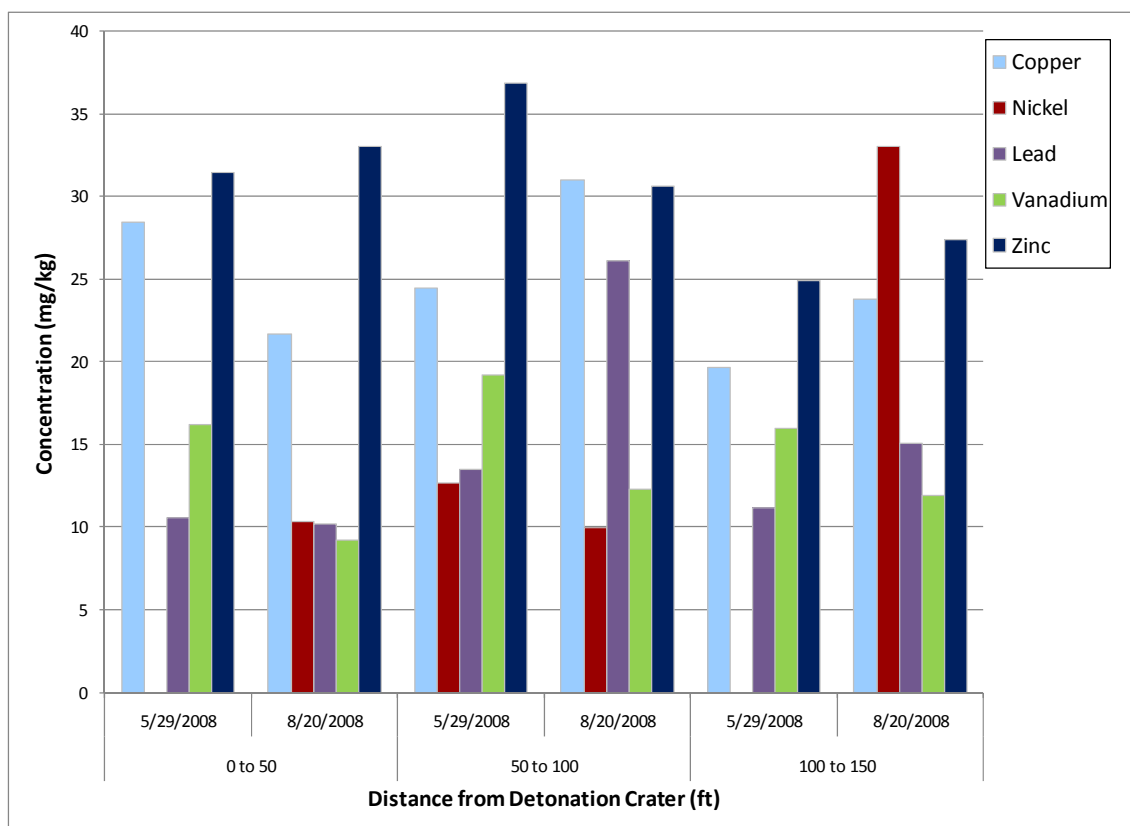


Figure 9. Concentration of metals in ejected soil at increasing distance from the detonation crater.

6.2.3 Pore Water

Pore water samples were collected from the soil above the water table to determine baseline concentrations of explosives, metals, and pH at the site. Pore water samples were not previously collected in subsurface soil above the water table at the site. Two rounds of baseline pore water samples were collected prior to lime addition to the soil. Sample collection was dependent on sufficient soil moisture and the survival of the pore water samplers after detonation activities.

The pore water samples were collected from suction lysimeters that were installed in the subsurface and connected to tubing running to the ground surface. The lysimeters are constructed from porous stainless steel that allows soil moisture to enter the lysimeter into a storage chamber when a vacuum is applied from a pump. The pore water is then brought to the surface by applying vacuum or pressure. The lysimeters are most suitable in moist soil and can also be used below the water table.

The lysimeters were installed in seven locations colocated with two baseline craters and six lime-amended craters. The lysimeters were installed in nested pairs at different depths. The target depths at each location were 1-2.5 ft bgs, 3.5-4.5 ft bgs, 5-6 ft bgs, and 7-8 ft bgs. The deep lysimeters were placed so that they were just above the water table for all or most of the year. Each suction lysimeter was installed in an augured borehole. Silica flour was placed around the lysimeter, and the borehole was backfilled to the surface using native soil and bentonite. The

bentonite was added to prevent preferential flow of surface water down the borehole. Sample tubing was attached to the samplers and run to the ground surface. The tubing was also placed in steel pipe to protect the tubing from site activities. A map of the buried lysimeter locations was sketched in the logbook along with Global Positioning System (GPS) coordinates in the event the tubing became completely buried or was destroyed during detonation activities.

Sampling was performed twice, July and September of 2008. During pore water sampling, a vacuum was applied to the suction lysimeter using a battery powered pump for approximately 1 to 24 hr to attempt to fill the lysimeter with pore water. A pressure was then applied to the lysimeter to bring the pore water to the surface, and the appropriate sample bottles were filled. Not all lysimeters provided adequate sample for analysis at each of the sampling events.

Pore water concentrations of explosives are shown in Figure 10. The lysimeters are shown by depth bgs. No MNX was detected following either sampling event. In July 2008, RDX ranged from non-detect up to 0.75 $\mu\text{g/L}$ and up to 0.25 $\mu\text{g/L}$ in September 2008. DNX and TNX were only detected in July at concentrations up to 0.69 $\mu\text{g/L}$ (DNX) and 0.45 $\mu\text{g/L}$ (TNX).

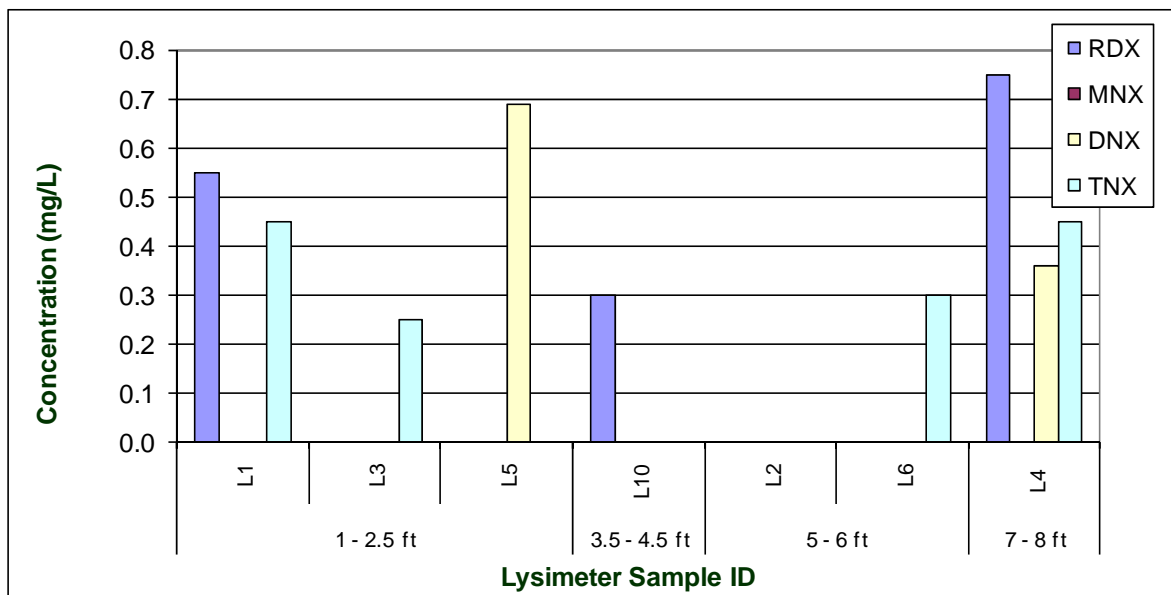


Figure 10. Concentrations of explosives in soil pore water during baseline characterization of the APG OD site.

Results of the metals analysis of pore water samples taken during the baseline characterization studies are shown in Table 4.

6.2.4 Groundwater

An explosive compound (RDX), VOCs (1,1-dichloroethene, trichloroethene, and tetrachloroethene), perchlorate, bis(2-ethylhexyl)phthalate, and inorganics (Al, Co and Ni) were detected in previous groundwater samples collected from the OBF-OD unit. These analytes are considered COPCs in groundwater at the site (U.S. Army, 2005). Additional groundwater

samples were collected to determine current concentrations of these and other parameters relevant to this demonstration.

A minimum of one round of baseline groundwater samples were collected from the four monitoring wells located at the OD area to supplement the current database. There are three up-gradient (OBFDA-1, OBFDA-2, and OBFOD-MW01) and one downgradient (OBFDA-3) monitoring wells at the site. Groundwater at the site can be as shallow as 4 to 9 feet bgs.

During each round of groundwater sampling, a minimum of one well volume of water was purged from each well, or until water quality parameters such as pH, temperature, conductivity, and turbidity stabilized before sampling. The samples were analyzed for explosives, perchlorates, total metals, and dissolved metals. VOCs and SVOCs were also analyzed for at least one round sampling. Field parameters included pH, turbidity, and temperature.

Explosives analysis of the groundwater samples obtained during baseline characterization of the APG OD site detected RDX in concentrations that ranged from 0.25 µg/L to 0.55 µg/L. Concentrations of TNX ranged from 0.40 µg/L to 0.50 µg/L. No MNX or DNX was detected in these samples. Perchlorate was below detection limits for all samples (<0.2 mg/L).

Results of the metals analysis of groundwater samples taken during the baseline characterization studies are shown in Table 3.

Table 3. Concentrations of metals detected in pore water, surface water, and groundwater samples during baseline characterization of the APG OD site.

Metal	Concentration (mg/L)					
	Surface Water		Pore Water		Groundwater	
	Max	Min	Max	Min	Max	Min
Al	0.50	0.23	nd	nd	0.20	nd
Ca	98.12	21.56	nd	nd	34.50	5.71
Cd	nd	nd	399.16	11.60	nd	nd
Co	0.32	nd	nd	nd	nd	nd
Chromium	nd	nd	0.19	nd	nd	nd
Cu	nd	nd	nd	nd	nd	nd
Fe	0.89	0.29	9.92	nd	0.38	nd
Manganese (Mn)	8.74	0.07	17.63	0.15	0.19	0.08
Ni	0.49	nd	0.79	0.14	0.07	nd
Lead	nd	nd	nd	nd	nd	nd
Tl	0.15	nd	nd	nd	0.81	nd
V	nd	nd	nd	nd	nd	nd
Zn	0.42	nd	0.08	nd	nd	nd

nd – non-detect (below the laboratory detection limit for this metal)

The pH of the groundwater samples ranged from 5.0 to 5.6.

Trace VOCs included trichloroethene (TCE) (5.0 µg/L), tetrachloroethene (PCE) (0.006 µg/L), and cis-1,2-dichloroethene (cis-DCE) (0.014 µg/L). No SVOCs were detected in the groundwater samples.

6.2.5 Surface Water

Since there are no defined surface water pathways from the OD area, baseline water samples were collected from ponded water that accumulates after significant rainfall events. Two rounds of samples were collected from four locations at the site. Field parameters analyzed included pH, turbidity, and temperature. The samples were analyzed for explosives, total metals, and dissolved metals.

The pH of the surface water samples ranged from 4.3 to 6.7.

Each of the four sampling sites showed concentrations of RDX and TNX. The RDX concentrations ranged from <0.1 µg/L to 4.5 µg/L. All TNX concentrations were <0.1 µg/L (Figure 11). MNX was detected at one sampling event from one location. DNX was not detected at any time or location.

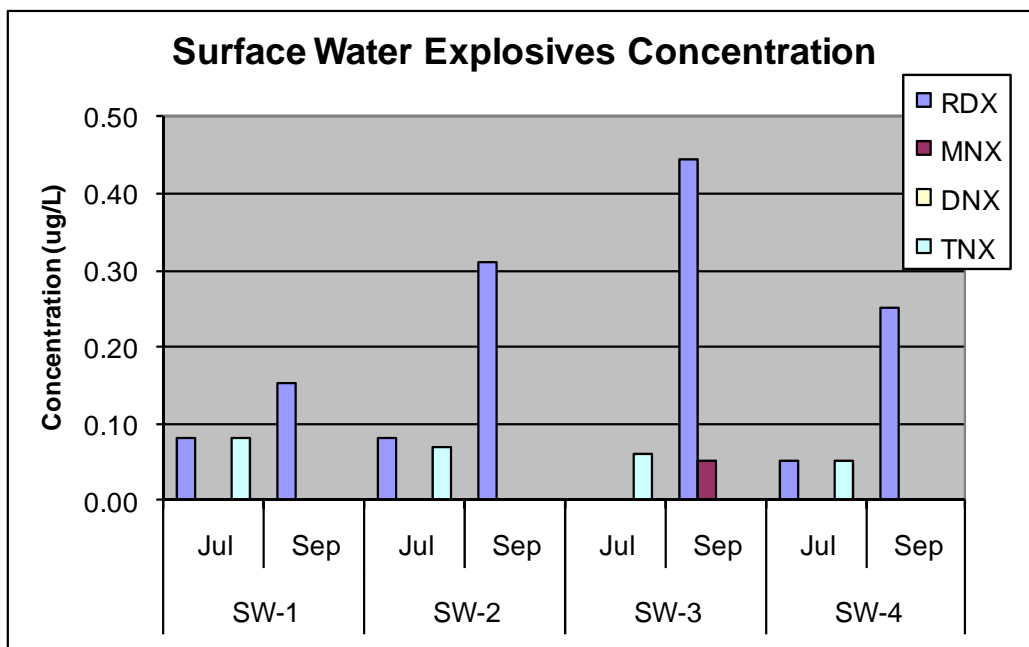


Figure 11. Baseline concentrations of explosives in surface water on the APG OD site.

Results of the metals analysis of surface water, pore water, and ground water samples taken during the baseline characterization studies are shown in Table 3.

6.2.6 Air Monitoring

Lime dust could potentially be an irritant to personnel working with the lime and to personnel outside the site perimeter. Baseline air samples were collected and analyzed for Ca and PM10 during detonations without lime. PM10 analyzes for particles suspended in air that are 10

micrometers or less and can penetrate into the human lungs. Two rounds of samples were collected for baseline analysis. Three samplers were located along the perimeter of the site during detonations. One person involved with the setup of the detonation materials and lime spreading also wore a personnel air sampler during site activities.

The samplers worn by personnel were used to determine levels of lime dust for industrial hygiene (IH) purposes. The samplers were used to measure the amount of lime dust to which personnel may be exposed during site activities involving handling of lime. Each sampler was attached to the shoulder area to collect air samples within the breathing zone. The portable SKC Deployable Particulate Sampler[®] (DPS[®]) operating at a calibrated flow rate of 10 litres per minute (L/min) was used to conduct the air sampling for ambient levels of Ca hydroxide (Ca(OH)₂), or hydrated lime, near the boundary of the APG OD range. The DPS[®] is able to maintain a continuous set flow rate throughout a sampling period of up to 24 hr using an internal thermometer, barometer, and a mass flow controller. Teflon[®] filters were used to collect the particulate matter with an aerodynamic diameter of 10 micrometers (1 micrometer=1 μm=1×10⁻⁶ m) and smaller, commonly referred to as PM10, to facilitate recovery of the collected particulate matter. The PM10 size fraction was chosen given its high mobility properties in ambient air, giving it a high potential for reaching the boundary limits of the APG OD range. Particulate collected on quartz fiber filters is embedded within the structure of a filter and difficult to recover without digesting the filter, thereby introducing Ca as a spiked background. In the case of a Teflon filter, the particulate is simply rinsed from the surface of the filter and collected for Ca metal analysis.

Prior to each sampling event, the DPSs[®] were calibrated against a certified transfer flow standard device to ensure accurate flow rates of 10.0 L/min throughout the sampling event. Samplers were manually turned on immediately prior to a detonation (no programming was used), and manually turned off after a detonation when the area had cleared of visible ambient dust. Rain hats were used to protect the delicate filters from detonation debris and are specifically designed not to interfere with collection of PM10. Perimeter air samples were collected by placing each air sampler behind a thick metal barricade to protect the samplers during the detonation blasts. The samplers were placed on stands about 5 ft above the ground. The sampler inlet was mounted on a foldable tripod and placed just behind and below the roofline of the blast booth. Large rocks and clumps of dirt thrown from the detonation had the potential to severely damage the sampling equipment without the use of a blast booth.

All Teflon[®] filters were preconditioned in a weighing chamber prior to obtaining their pre-weights, and sample filters were preconditioned after each event prior to obtaining final weights. The difference between the pre- and post-weights equaled the total mass of PM10 collected, of which lime was a small fraction.

Three sampling sites were strategically located to triangulate about the areas where detonations were to occur: (1) intersection of the range and the exit road or the west end of the range, (2) the far left site near the left side boundary of the range when facing the water or the north side, and (3) the far right site near the boundary of the range or the south side. These samples were used to determine the amount of lime dust blowing off the site near ground level during the spreading and detonation activities. The positions of the sites were able to roughly account for variability

in wind direction, and at least one site was always within a few hundred ft of each detonation. The ambient weather conditions during sampling events are provided in Appendix D of the ESTCP ER-200742 Final Report.

A 24-hr background sample (when no detonations were occurring) was collected in July of 2008 to determine background levels of Ca when no detonations were occurring. A small quantity of Ca was found at the Intersection Site where crushed limestone rock had been piled, which likely skewed the results. The limestone rocks had been used to construct soil stabilization areas on the far north side of the range where no detonations that were sampled had occurred. Natural, ambient background levels of Ca in the air were expected to be very low, thereby contributing little to the total Ca.

USEPA Analysis Method 6010B was used to analyze for the metal Ca in ambient air. No other acceptable laboratory methods for ambient air levels of $\text{Ca}(\text{OH})_2$ were available to meet the low detection limit of 20 micrograms (1×10^{-6} g) per filter. To determine the quantity of lime on a filter, all Ca is assumed to be from the hydrated lime, of which Ca is 54.092% of the molecular weight, according to [http://www.convertunits.com/molar mass/Ca\(OH\)₂](http://www.convertunits.com/molar mass/Ca(OH)2). Therefore, the total weight of the collected lime equals the Ca weight divided by 0.540.

6.2.7 Soil invertebrate sampling

The abundance and diversity of invertebrates was monitored by extracting soil cores. Without removing the plant cover, a bucket auger was pressed down into the soil to collect samples from the top 15 cm (6 inches) of soil. Soil cores were then extracted and bagged to prevent desiccation and animal escape. All material from funnels and trays was sieved onto a screen cloth and organisms poured into a Petri dish. Specimens were examined under a stereoscopic microscope, counted, and classified to the lowest possible taxonomic level. Identification was performed using keys and illustrations.

No macro-invertebrate species were detected during baseline characterization, which could be related to multiple range operational procedures and not the liming, since the lack of invertebrates was observed prior to liming. For instance, the constant movement of soil during the OD operations could preclude the establishment of an acceptable habitat for terrestrial invertebrates to exist. In addition, the constant bi-annual tilling of the range soil is not conducive to the establishment of such invertebrates as the common earthworm; the tilling action destroys their burrows and underground habitat.

6.2.8 Hydrologic Evaluation of Landfill Performance (HELP) Model

The shallow aquifer underlying the OB/OD unit consists primarily of interbedded, unconsolidated sediment with relatively low permeability. The general direction of groundwater flow is from the OB/OD units to nearby surface water discharge areas such as Romney Creek and the Bush River, as shown in Figure 2. The shallow aquifer is not used for groundwater supply in the range areas. Existing groundwater supply wells at APG and the region are screened at depths well below the shallow aquifer and are not within the influence of groundwater movement at the OB/OD units. Migration of groundwater contaminants identified

during the site characterization study is limited to the immediate vicinity of the OB/OD unit with discharge to local surface water bodies.

The HELP model (ver. 3.07) was initially developed by ERDC-EL for the USEPA Risk Reduction Engineering Laboratory. The runoff water curves were computed using base soil texture #14 with a good stand of grass, a surface slope of 1.0% and a slope length of 1200.00 ft. The horizontal plane was equal to 18.4 acres and 100% of the area was assumed to allow runoff. The evapotranspiration and weather data were obtained from Baltimore, MD.

The characteristics of the four soil layers used in the calculations for leachate transport are described in Table 4, based on soil cores from the APG facility. The HELP computer model was run to predict leaching and runoff totals for 50 years using the information listed above. The totals for the first year (Year 1) and the fiftieth year (Year 50) are compared in Table 5. The complete results of this model are listed in Appendix C of the Final Report.

Table 4. Characteristics of soil layers used to calculate surface runoff and vertical transport of water on the APG OD area.

Soil Characteristic	Layer 1	Layer 2	Layer 3	Layer 4
Description	Vertical Percolation Layer	Vertical Percolation Layer	Vertical Percolation Layer	Barrier Soil Layer
Material texture number	14	14	6	15
Thickness (in)	12	96	96	36
Porosity (vol/vol)	0.479	0.479	0.453	0.475
Field capacity (vol/vol)	0.371	0.371	0.190	0.378
Wilting point (vol/vol)	0.251	0.251	0.085	0.265
Initial soil water content (vol/vol)	0.352	0.436	0.231	0.475
Effective saturated hydraulic conductivity ¹	0.245×10^{-4} cm/sec	0.245×10^{-4} cm/sec	0.720×10^{-3} cm/sec	0.170×10^{-4} cm/sec

¹Saturated hydraulic conductivity is multiplied by 3.0 for root channels in the top half of the evaporative zone.

Table 5. Runoff water and leachate estimations as calculated by the HELP model for 1 yr, 2 yr, and 50 yr on the APG OB/OD area.

Parameter Measured	Year 1		Year 2		Year 50	
	Inches	%	Inches	%	Inches	%
Precipitation	41.53	100	40.98	100	41.79	100
Runoff	1.29	3.11	6.850	16.71	3.66	8.77
Evapotranspiration	30.02	72.27	27.38	66.81	29.93	71.61
Percolation/leakage through soil layer 4	9.15	22.04	12.04	29.38	8.28	19.80
Avg. head on top of soil layer 4	0.0119		0.0155		0.010	

Over 50 years, the peak value for percolation through the barrier layer of soil (layer 4) was 0.22 inches. The peak value for hydraulic head on layer 4 was 0.10. The highest value for runoff water was 2.54 inches. Based on the results from the HELP model over the 50 yr run, from

19.80% to 29.38% of the total water budget will percolate or leach through the soil layer 4. The results indicate that less than 30% of the water will leach into the local groundwater.

In addition, there was no evidence of soil crusting after the lime application. Also, hydraulic conductivity testing was performed after lime application using a mini disk infiltrometer manufactured by Decagon Devices. The infiltrometer determined hydraulic conductivity by measuring the rate of water flow from a cylinder into the soil. Time and water volume measurements were used to calculate hydraulic conductivity. The hydraulic conductivity measurements ranged from 5.0×10^{-4} cm/s (for unamended soil) to 3.0×10^{-3} cm/s (post-lime application). These values are all within one order of magnitude; thus, there was no significant difference in water infiltration rates observed due to liming of the soil.

6.3 TREATABILITY STUDY RESULTS

6.3.1 Lime Dosing Study

Soil samples were collected from the APG OD demonstration site and shipped to ERDC-EL in Vicksburg, MS. A treatability study was performed using the site soil to establish appropriate liming dosage rates that would elevate the soil to the desired pH. Initial lime dosage rates were determined using American Society for Testing and Materials (ASTM) Method D6276-99a (ASTM, 1999) as described in Davis et al. (2007c). The lime loading rate was determined to be 0.5% of the dry soil weight to be mixed into the top six inches of the soil on the 9-acre site. During the initial topical application and discing, approximately 26 cu yd of lime were required to raise the pH to 11 in the shallow soil (Table 6). After initial treatment, lime was incorporated into the pit with the explosives prior to the detonations to treat the explosive residue in the crater ejecta contributed from each blast. Additional lime was applied in the detonation crater before backfilling of the crater to create a deep subsurface reactive zone to degrade explosives. Approximately 1 to 2 cu yd of lime was added to each detonation and approximately the same amount was spread in the crater after the detonation (Table 7).

Table 6. Calculations to establish lime loading rate for topical application at the APG OD site.*

Area	9 acres = 392,040 sq ft
Depth	0.5 ft
Soil volume	196,020 cu ft
Soil density (estimated)	$1.6 \text{ g/cm}^3 = 100 \text{ lb/ft}^3$
Quantity of lime	Soil volume * Soil density * Lime rate (0.5%)
Total quantity of lime	98,000 lb = 49 tons
Lime density	$2.24 \text{ g/cm}^3 = 140 \text{ lb/ft}^3$
Lime volume required	26 cu yd

*Initial loading rate determined using ASTM Method D6276-99a (ASTM, 1999)

Table 7. Calculations to determine the quantity of lime added to the detonation area to account for soil dispersion.

Area*	3600 cu ft
Soil density (estimated)	1.6 g/cm ³ = 100 lb/ft ³
Quantity of lime	Soil volume * Soil density * Lime rate (0.5%)
Quantity of lime for ejecta volume	1800 lb = 0.9 tons
Lime density	2.24 g/cm ³ = 140 lb/ft ³
Lime volume required (minimum)	0.5 cu yd
Recommended lime quantity added to each detonation (Accounts for dispersion loss outside of crater fill collection area^{**})	4 to 8 times the minimum lime volume (2 to 4 cu yd)

*Estimated average crater size is 16 ft diameter and 14 ft deep. A rectangular volume of 16ft×16ft×14ft was used as a conservative estimate.

**Assumes half of the crater ejecta lands within 100 ft of the crater. The lime dispersion is proportional to the soil in the ejecta, and only soil within 100 ft of the crater is pushed back in the crater. A multiplication factor of 4 to 8 times the lime quantity was used to both maintain pH within the 100 ft radius of the crater and to adequately lower the pH of the soil pushed back into the crater. Movement of the bulldozer over the surrounding soil served to mix the additional lime into the soil. Actual lime volume added to detonations varied based on the size of the crater.

6.3.2 Column Study

A second treatability study was undertaken to answer questions concerning the longevity of the treatment and depth of the reactive pH zone. This was designed as a column study using lime-amended site soil and the unamended site soil. Two treatment variations were considered:

1. Amended soil on top of the unamended soil
2. Unamended soil covering the lime-amended soil (as might happen during soil ejection from the detonation crater).

Results from the column study are shown in Table 8. Soil pH was affected to the greatest extent when unlimed soil was placed over the lime-amended soil. When the lime amendment was well-mixed and covered the untreated soil, there was an increase in soil pH of <1 SU over the untreated control soil (study average). There was an insignificant change in leachate pH from Day 1 to Day 9 showing that, while the increase was stable, the lime transport, as indicated by pH change, was minimal.

Table 8. Results of the column treatability study.

Column Treatment	Leachate pH			
	Day 1	Day 5	Day 9	Study Average
Control	6.90	6.93	6.88	6.99
Control	6.74	6.88	7.03	6.96
Limed soil over unlimed soil 1	7.32	7.15	7.39	7.29
Limed soil over unlimed soil 2	7.01	6.79	7.27	7.10
Unlimed soil over limed soil 1	8.37	8.12	8.40	8.35
Unlimed soil over limed soil 2	8.43	7.96	8.38	8.34

The lime application plan was modified to reflect the findings of the treatability study:

- The entire 9-acre site was amended with lime.
- With prior approval of APG OD personnel, lime was applied to the waste munitions predetonation in several different ways.
- Lime was mixed with the backfill soil and used to fill the detonation crater following each detonation event.

6.4 FIELD TESTING

6.4.1 Initial Topical Application of Lime

The entire 9-acre demonstration site was treated by applying hydrated lime to the surface of the soil and discing it into the soil to a depth of 6 inches, as shown in Figure 12. The initial liming was performed to destroy MCs in the top 6-inch soil profile, since the OD range was an active range and there had been measureable concentrations of MCs present in the soil prior to the study's baseline sampling. In essence, the liming event provided low levels of MCs in the surface soil (i.e., the top 6 inches) for the field demonstration.



Figure 12. Topical application of the hydrated lime.

(A.) Applying the hydrated lime using a tractor and drop spreader to ensure even distribution of the lime. Note personnel in personal protective equipment (PPE). (B.) The lime was then disced into the soil to a depth of 6 inches using a tractor and disc attachment. (C.) The completed site. Minimal lime is exposed on the soil surface.

6.4.2 Lime Application in and around Detonation Craters

The typical operational procedure for detonating explosives is to:

1. Dig a 3 – 6 ft deep pit.
2. Place waste explosives and the donor charge in the pit.
3. Backfill the pit with soil while maintaining access to the explosive via a 1 ft diameter cardboard tube through which the detonating charge is applied.

When backfilling the pit with soil, a mound of soil (approximately 5 ft high) is typically formed over the pit. This basic configuration was used for all detonations conducted during the field demonstration tests except for Methods 1 and 2. Each method described below describes how the lime (in intact 50 lb bags) was placed relative to the soil mound described above. Seven amendment methods were tested during the field demonstration period from December, 2008 to April 2009. Common elements of the application method variations were:

- The initial lime application over the 9-acre site
- Backfilling the detonation crater with 0.625 tons (1250 lb, one-half of a pallet) of lime.

The lime was mixed into the soil by both detonation and tilling. The technology was therefore tested for sites that allow tilling and for sites that do not. The APG OD site is a non-dudded area and tilling is routinely performed to prevent vegetation from growing, which reduces the risk of brush fires.

Method 1 – Placed bags of lime directly on top of the explosives prior to backfilling the pit. A few feet of soil placed on top of lime. Twenty-five bags of lime (0.625 tons) were incorporated into the detonation. Another 0.625 tons of lime was mixed in the post-detonation pit during backfilling.

Method 2 – The explosives were covered with about 2 ft of soil and the ground was leveled to grade with a bulldozer. Fifty bags of lime (1.25 tons) were placed intact in a 5 ft radius around the detonation tube. Another 0.625 tons of lime was mixed in the post-detonation pit during backfilling.

Method 3 – The explosives were covered with about 2 ft of soil and the ground was leveled to grade with a bulldozer. One hundred bags of lime (2.5 tons) were placed intact in a 5 ft radius around the detonation tube. The lime was covered by another 2 ft of soil. Another 0.625 tons of lime was mixed in the post-detonation pit during backfilling.

Method 4 – The explosives were buried under a soil mound per normal open detonation procedures. Fifty bags of lime (1.25 tons) were placed intact on the soil mound. Another 1.25 tons of lime was mixed in the post-detonation pit during backfilling.

Method 5 – The explosives were buried under a soil mound per normal open detonation procedures. Fifty bags of lime (1.25 tons) were placed intact around the soil mound, 10 ft from

the toe of the mound. Another 2.5 tons of lime was mixed in the post-detonation pit during backfilling.

Method 6 – The explosives were buried under a soil mound per normal open detonation procedures. Fifty bags of lime (1.25 tons) were placed intact around the soil mound, 2 ft from the toe of the mound (Figure 13). Another 1.25 tons of lime was mixed in the post-detonation pit during backfilling.



Figure 13. Illustration of lime application used in conjunction with detonations.
Intact lime surrounding the mound is visible as white bags.

Method 6a – The same as Method 6, only 2.5 tons of lime was added to the detonation instead of 1.25 tons.

Method 7 – No lime was used in the detonation; 0.625 tons of lime was mixed in the post-detonation pit during backfilling.

6.5 SAMPLING METHODS

ATC personnel collected samples during the field demonstration according to the schedule outlined in Table 9. Sampling methods for each environmental matrix are described in Section 6.2, Baseline Characterization. All samples were stored on ice and shipped overnight to ERDC-EL for analysis. Standard methods were used in sample analysis (Table 10).

Table 9. Total number and types of samples collected during demonstration monitoring.

Component	Matrix	Number of Samples	Analyte	Location
Technology performance sampling	Surface soil	20	Explosives, metals—total and dissolved—pH	Each quadrant of the test area
	Subsurface soil	2	Explosives, metals—total and dissolved—pH	Detonation pit walls
	Ejected soil	21	Explosives, metals—total and dissolved—pH	50 ft, 100 ft, and 150 ft from detonation pit
	Soil pore water	50	Explosives, metals—total and dissolved—pH, temperature, turbidity, conductivity	Lysimeters
	Runoff water	22	Explosives, metals—total and dissolved—pH	Ponded surface water on site
	Groundwater	22	Explosives, metals—total and dissolved— pH, temperature, turbidity, conductivity	Monitoring wells surrounding the OD area
	Air monitoring	12	Ca, PM10	Three monitoring stations surrounding the OD area
Post-demonstration sampling	Surface soil	10	Explosives, metals—total and dissolved—pH	Each quadrant of the test area
	Soil pore water	27	Explosives, metals—total and dissolved—pH, temperature, turbidity, conductivity	Lysimeter
	Runoff water	10	Explosives, metals—total and dissolved—pH	Ponded surface water on site
	Groundwater	10	Explosives, metals—total and dissolved—pH, temperature, turbidity, conductivity	Monitoring wells surrounding the OD area

Table 10. Analytical methods for sample analysis.

Analyte Class	Individual Analytes	Method
Metals	Al, As, Cd, Co, Se, Tl, lead, Cu, Fe, Zn, Ca, Ni, Mn, molybdenum (Mo), V, chromium	USEPA Methods SW-846-3051 SW-846-3010 SW 846 6010B
Explosives	HMX, RDX, TNT, 2,4/2,6-dinitrotoluene, 2-/4-amino-dinitrotoluene, NB, 1,3-dinitrobenzene, 1,3,5-trinitrobenzene, MNX, DNX, TNX	USEPA Method SW-846-8330
VOCs	1,2-dichloroethane, tetrachloroethene, n-nitrosodiphenylamine, 1,1-dichloroethene, TCE	USEPA Method 8260B
SVOCs	Bis(2-ethylhexyl)phthalate	USEPA Method 8270C

6.6 SAMPLING RESULTS

The objective of the lime technology demonstration was to confirm at a large, relatively unconfined field site used for open detonation destruction of munitions that lime-amended soil can reduce or eliminate RDX, TNT, and degradation product concentrations in soil at the source area, thus reducing migration of explosives in solution.

6.6.1 Lime Application Methods

As outlined above, several different methods were employed when the lime was added in and around the detonation pits. Methods 6 and 6a provided the best lime dispersion performance. The other methods generally resulted in dispersion of lime outside the OD area or ineffective lime dispersion in the OD area.

Method 6: The explosives were buried under a soil mound per normal open detonation procedures. Fifty bags of lime (1.25 tons) were placed intact around the soil mound, 2 ft from the toe of the mound. Another 1.25 tons of lime was mixed in the post-detonation pit during backfilling.

Method 6a: The same as Method 6 only 2.5 tons of lime was added to the detonation instead of 1.25 tons.

6.6.2 Effect of Lime on Soil Quality

The liming did not produce soil surface crusting.

Hydraulic conductivity testing was performed after lime application using a mini disk infiltrometer manufactured by Decagon Devices. The infiltrometer determined hydraulic conductivity by measuring the rate of water flow from a cylinder into the soil. Time and water volume measurements were used to calculate hydraulic conductivity. The hydraulic conductivity measurements ranged from 5.0×10^{-4} cm/s (for unamended soil) to 3.0×10^{-3} cm/s (post-lime application). These values are all within one order of magnitude; thus, there was no significant difference in water infiltration rates observed due to liming of the soil.

6.6.3 Surface, Subsurface, and Ejected Soil

The performance metric for this objective was to achieve explosives concentrations that were less than the concentrations observed during baseline characterization in surface and subsurface soil and in ejected soil.

As seen in Figure 14, this objective was successful at degrading all compounds except RDX. Since the OD range is an active range and detonations occur at a minimum on a monthly basis, the detections of RDX in March and November 2009 are most likely particulates that were broken apart from the donor charge or in subsequent detonations. While there is evidence that the initial liming removed detectable concentrations of energetic compounds from the surface soil, there is also evidence that subsequent and additional liming is necessary to provide a sustainable range management approach.

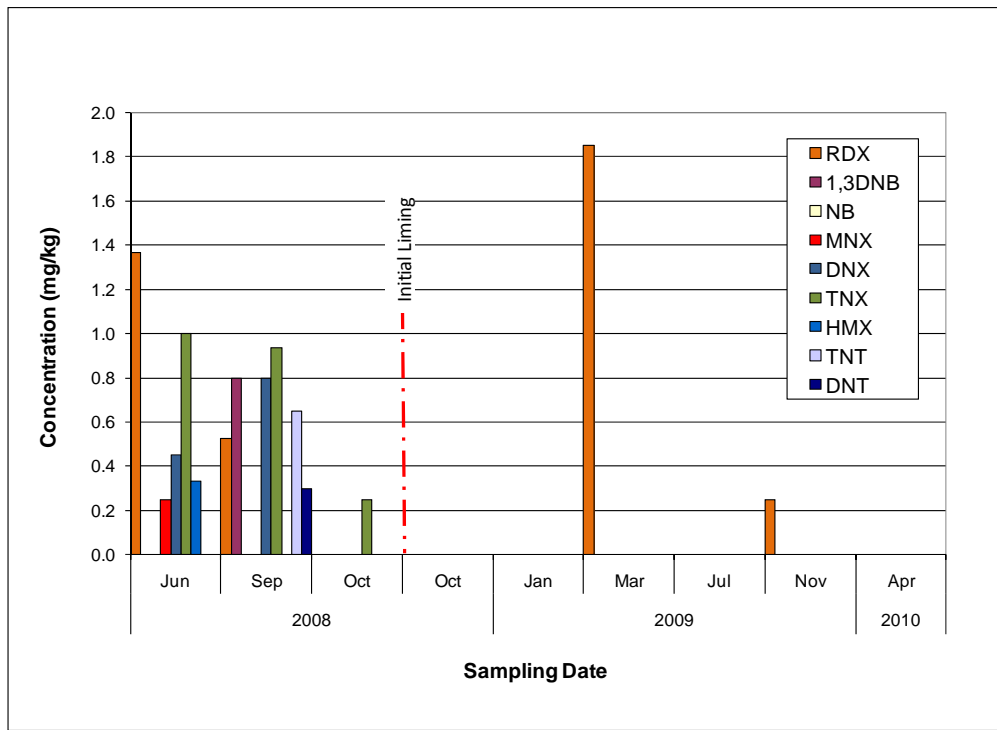


Figure 14. Average surface soil concentrations of energetic COPCs (mg/kg).

The concentrations of energetic COPCs in soil ejected from the detonation crater are shown in Figure 15. RDX was detected the greatest number of times. The detections of RDX in March and November 2009 are likely particulates that were broken apart from the donor charge or in subsequent detonations. From the middle sampling area, 50 to 100 ft from the detonation, following lime addition, RDX and TNT were detected only at a single sampling event. This detection is probably due to particulates from munitions or the donor charge. The performance metric was met as these compounds were not detected at subsequent sampling events. At the greatest distance from the detonation, 100 to 150 ft, after liming, there was a single detection of NB.

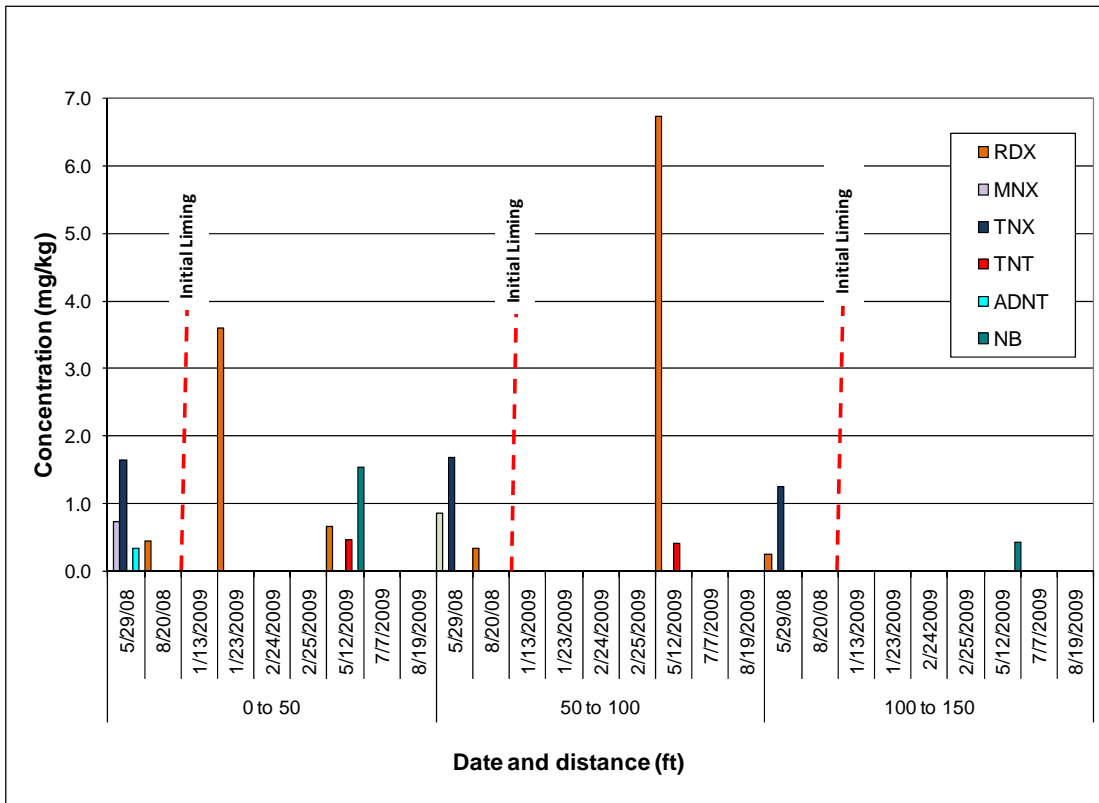


Figure 15. Average concentration of energetic COPC in soil ejected from the detonation pit in distance from the pit center (mg/kg).

Pre- and post-liming concentrations of metals of potential concern are shown in Figure 16. The only metals detected in the surface soil, post-liming, were Cu and Zn. This supports the metals stabilization hypothesis proposed by Larson et al. (2008), suggested by data from the HGR liming field study, that the increase in pH stabilizes the majority of metals in the soil.

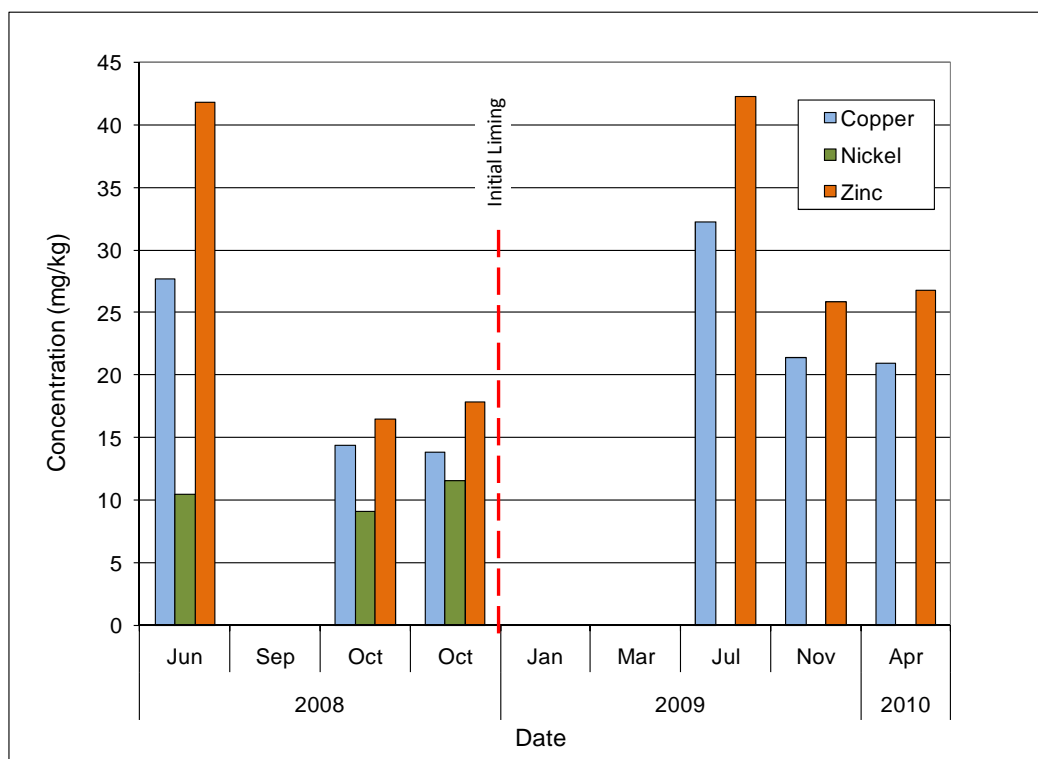


Figure 16. Average surface soil concentrations of metals pre- and post-liming (mg/kg).

At the conclusion of the field demonstration, four samples of the surface soil were taken and subjected to two separate leaching tests, the Toxicity Characteristic Leaching Procedure (TCLP) and deionized water (DDI) suspend and settle (S&S). The TCLP, although originally designed to evaluate landfill leachate, is often used to establish compliance with state and federal environmental regulations. The aggressive, acidic leaching solutions are effective at mobilizing lead from soil. Unlike the TCLP, the DDI S&S leaching procedure is a water-based leaching test that simulates the effect of rainwater on leaching metals from soil.

The TCLP was performed according to USEPA SW 846 Method 1311 (USEPA, 1999). A 1:20 (w:v) soil-to-extraction fluid ratio was used. Triplicate samples were placed on a tumbler for 18 ± 2 hrs. After tumbling, an aliquot of the sample was removed and centrifuged. Approximately 60 mL of the supernatant was removed and filtered through a 0.45 μ m syringe filter and analyzed for metals. The DDI S&S is a water-leaching test, a modification of the TCLP. An amended-soil-to-DDI water ratio of 1:20 (w:v) was maintained, similar to the TCLP. The samples were placed on a shaker table for 1 hr, then allowed to settle for 18 ± 2 hr. After settling, aliquot samples were removed, syringe filtered, and analyzed for metals.

The results of the TCLP analysis are shown in Table 11. Of the COPC on the APG OD site, TCLP limits have only been established for As, Cd, chromium (Cr), lead (Pb), and Se (40 Code of Federal Regulations [CFR] §261.24). Metals not leached by the TCLP, and not included in the table, were antimony (Sb), As, Cd, Co, Cr, Mo, Tl, and V. Pb and Se were well below the TCLP regulatory limits of 5.0 mg/L and 1.0 mg/L, respectively. Tungsten (W) was noted in two

surface soil samples but only one replicate each. It is therefore presumed to have originated with destroyed munitions.

Table 11. Concentration of metals in TCLP extraction solution from post-liming soil.

Metal	Concentration (µg/L) and Standard Deviation				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Al	0.14±0.01	0.16±0.03	0.17±0.02	0.15±0.02	0.17±0.02
Cu	0.08*	nd	nd	nd	0.04*
Fe	0.01±0.10	nd	0.05±0.01	0.04*	0.06±0.03
Pb	0.18±0.21	0.14±0.08	0.11±0.02	0.05*	0.13±0.03
Mn	0.93±0.05	0.79±0.02	0.73±0.02	0.58±0.04	0.70±0.08
Ni	Nd	0.03±0.00	nd	0.04±0.01	0.04±0.00
Se	0.08±0.04	0.05*	nd	nd	nd
Zn	0.05±0.02	0.09*	0.05±0.02	0.04*	0.03±0.00

nd – non-detect (below the laboratory reporting limit of 0.025 µg/L)

*single detection, no statistical analysis possible

The results of the DDI S&S analysis are shown in Table 12. Metals not leached from the soil by the DDI S&S procedure were Sb, As, Co, Cr, Cu, Mo, Ni, Se, Tl, and V. W was noted in one surface soil sample at an average concentration of 0.03±0.00 µg/L. The W is presumed to have originated with destroyed munitions. Also detected only in one surface soil sample were the metals Pb (0.03±0.01 µg/L) and Zn (0.04±0.00 µg/L). Cd was leached from the soil by the DDI S&S procedure although not detected in the TCLP extraction solutions. Al and Fe, two metals leached by both procedures, were detected at higher concentration by the DDI S&S procedure.

Table 12. Concentration of metals in DDI S&S extraction solution from post-liming soil.

Metal	Concentration (µg/L) and standard deviation				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Al	1.28±0.01	1.15±0.01	2.86±0.01	1.23±0.24	0.58±0.01
Cd	0.46*	0.68 ±0.23	0.14±0.06	1.04±0.84	0.92±0.19
Fe	0.87±0.01	0.69±0.01	1.79±0.01	0.86±0.04	0.35±0.00
Mn	0.07±0.01	0.04*	0.03*	nd	nd

nd – non-detect (below laboratory detection limit of 0.025 µg/L)

*single detection, no statistical analysis possible

6.6.4 Pore Water, Surface Water, and Groundwater

The performance metric for explosives treatment was to achieve RDX concentrations less than the concentrations observed during baseline characterization. The goal was to observe RDX concentrations that were below 2 µg/L. The results of soil pore water analysis for explosives both pre- and post-lime applications are summarized in Table 13. TNX was detected at high concentrations at both the 1-2 ft and 7-8 ft depth (bgs). This objective is considered to be successful because post-liming concentrations of MNX, DNX, and TNX were all non-detect, and RDX was below the goal of 2 µg/L for post-liming sample events.

Table 13. Concentrations of explosives detected in soil pore water pre- and post-lime application (µg/L).

Sample Date	Explosives Concentrations (µg/L)			
	RDX	MNX	DNX	TNX
Pre-Lime				
7/17/08 (n=9)	0.53 ^a	<0.05	0.53 ^b	0.36 ^{a,b}
9/18/08 (n=9)	0.12 ^b	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

^aHigh concentration detected at 7-8 ft bgs

^bHigh concentration detected at 1-2 ft bgs

Surface water samples were taken from ponding areas that formed on the range following heavy precipitation. Concentrations of explosives detected in surface water samples pre- and post-liming are summarized in Table 14. This objective is considered successful as the explosives concentrations post-liming were non-detect.

Table 14. Concentrations of explosives detected in surface water pre- and post-lime application (µg/L).

Sample Date	Explosives Concentrations (µg/L)			
	RDX	MNX	DNX	TNX
Pre-Lime				
7/17/08 (n=4)	0.07	<0.05	<0.05	0.07
9/18/08 (n=5)	0.29	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

The concentrations of explosives detected in groundwater pre- and post-lime application are shown in Table 15. Concentrations of RDX, MNX, DNX, and TNX were all non-detect in groundwater following lime application.

Table 15. Concentrations of explosives in groundwater pre- and post-lime application (µg/L).

Sample Date	Explosives Concentration (µg/L)			
	RDX	MNX	DNX	TNX
Pre-Lime				
7/17/08	0.25	<0.25	<0.25	0.40
7/17/08	<0.05	<0.05	<0.05	<0.05
9/16/08	<0.05	<0.05	<0.05	<0.05
9/16/08	<0.05	<0.05	<0.05	<0.05
9/16/08	<0.05	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

Concentrations of metals, total and dissolved, in surface water, pre- and post-lime application, are summarized in Table 16. Only total TI increased in the post-lime sampling.

Table 16. Concentrations of metals in surface water pre- and post-lime application.

Metal	Concentration (mg/L)		
	Pre-Lime		Post-Lime
	7/17/08 (n=4)	9/18/08 (n=5)	(n=17)
Al (T)	0.32	0.28	1.36
Al (D)	0.09	0.12	0.21
Ca (T)	91.04	10.22	25.07
Ca (D)	97.03	12.45	44.15
Co (T)	0.20	0.08	nd
Co (D)	0.21	0.09	nd
Fe (T)	0.60	0.44	1.85
Fe (D)	0.06	nd	0.32
Mn (T)	3.06	0.77	1.36
Mn (D)	3.21	0.60	0.14
Ni (T)	0.30	1.03	0.16
Ni (D)	0.32	0.09	nd
Tl (T)	nd	0.09	0.34
Tl (D)	nd	0.09	nd

T=total concentration

D=dissolved concentration

nd=non-detect: below laboratory detection limit of 0.025 mg/L

The metals of concern in the groundwater were Al, Co, and Ni. The effect of lime application on metals immobilization is shown in Figure 17 for the dissolved and total metals. Co, not shown, was detected only once, at 0.04 mg/L. Concentrations of metals were unchanged by liming, except for Al, which appeared to increase post-liming.

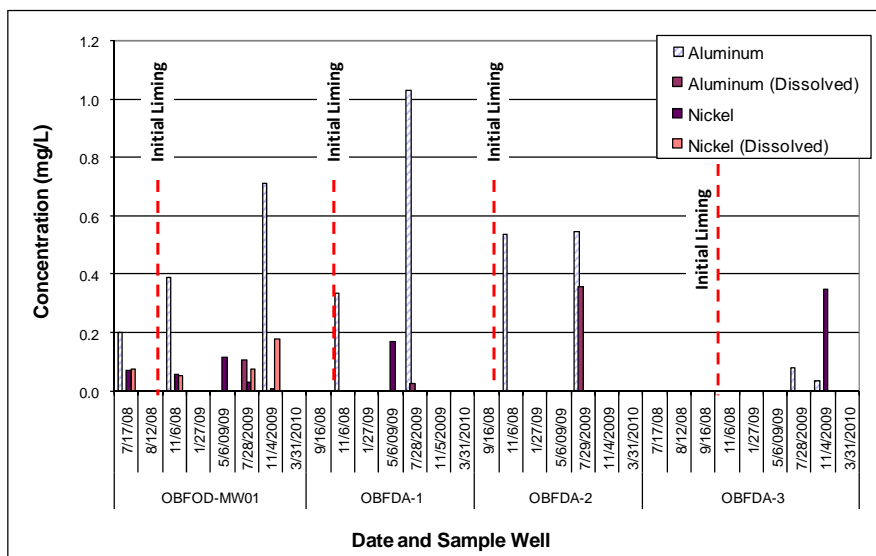


Figure 17. Concentration of dissolved and total metals of concern in groundwater pre- and post-lime application (mg/L).

6.6.5 pH Control in Soil and Aqueous Media

The performance metric for this objective was to maintain a pH >10.5 in the soil within the source area and a pH <9.0 in the soil outside the source area. This objective was achieved.

Minimal change in pH was measured in soil pore water, groundwater and surface water following liming as shown in Table 17. The greatest change from pre-liming pH was seen in the surface water; however, the average pH of the surface water samples was 7.4. No change was seen in groundwater or pore water pH.

Table 17. Change in pH of aqueous media post-liming of the APG OD area.

Media	pH	
	Range	Avg
Surface water (n=10)	10.4 – 4.3	7.4±1.6
Groundwater (n=10)	5.6 – 4.7	5.0±0.2
Pore water (n=27)	7.0 – 2.9	4.9±1.4

6.6.6 Air Monitoring

Under the topical lime application method, three air samples were collected from samplers worn by personnel during two days of lime spreading on the 21st and 22nd of October, 2008 (Table 18). During the lime spreading, personnel wore the samplers while carrying each 50 lb bag of lime, cutting the bags open with a razor knife, and then dumping the bags into a spreader. The personnel wore air-purifying respirators, disposable coverall suits, and gloves. Conditions were extremely dusty during this operation.

Table 18. Personnel air sampler results from lime spreading activity during topical application.

Sample Date	Sample Duration (min)	Chemical Monitored	Results (mg/m ³ -8-hr TWA)	PEL TLV (mg/m ³)	Action Level Exceeded?
10/21/08	142	Respirable dust	0.87	5	No
10/21/08	120	Alkaline dust as NaOH	0.85	2	No
10/22/08	155	Total dust	12.15	15	No
10/22/08	155	Ca hydroxide	6.26	5	Yes

TWA – time-weighted average
 PEL – permissible exposure limit
 TLV – threshold limit value
 NaOH – sodium hydroxide

Based on these results, IH regulations recommend a health risk assessment code (RAC) of 3 for this operation (Appendix B of the Final Report). A RAC of 3 indicates a moderate health risk to the personnel performing this operation. Personnel should wear the proper PPE.

Under the detonation method of lime application, one IH air sample was collected during detonation activities in which 1.25 tons of lime was incorporated and during placement of 1.25 tons of lime during backfilling of the crater on 13 January, 2009. The personnel wore air-purifying respirators, disposable coverall suits, and chemical resistant gloves. The bags were not cut open during the detonation and backfilling setup activities, so there was only a limited amount of dust created during this operation.

One personnel air sample was collected and analyzed for total dust and Ca(OH)₂. The 8 hr TWA air sampling result for total dust was 0.27 mg/m³ (Table 19). This result was well below the PEL of 15 mg/m³ (CFR, 2008) action limit. The 8 hr TWA air sampling result for Ca(OH)₂ was 0.06 mg/m³ and was well below the PEL of 5 mg/m³ (American Conference of Government Industrial Hygienists [ACGIH], 2008).

Table 19. Personnel air sample results for detonation lime application method.

Sample Date	Sample Duration	Chemical Monitored	Results (mg/m ³ 8-hr TWA)	PEL TLV (mg/m ³)	Action Level Exceeded?
01/13/09	157	Total dust	0.27	15	No
01/13/09	157	Ca hydroxide	0.06	5	No

TWA – time-weighted average
 PEL – permissible exposure limit
 TLV – threshold limit value

IH recommendations are that personnel applying Ca(OH)₂ during detonation activities should wear the proper PPE. A health RAC of 4 has been assigned to applying lime during detonation operations. A RAC of 4 indicates a minor health risk to the personnel performing this operation.

Under perimeter air monitoring, air samples were collected from two samplers (north and west) during the 24 hr background sampling event and from three samplers (north, south, and west) for the five other sampling events. These included one detonation with no lime, the spreading and diking of 50 tons of lime, 1.25 tons of lime on a detonation, 1.25 tons of lime 10 ft from a detonation, and 2.5 tons of lime immediately around a detonation. The prevailing wind direction, wind speed, and wind gusts are available on CD by request as stated in Appendix C of the Final Report. For the purpose of calculating the lime concentrations, it was assumed that all of the detected Ca in the air samples was Ca(OH)₂.

The concentrations of Ca(OH)₂ were between non-detect and 5.3 µg/cm³ during the 24 hr zero background and between non-detect and 18 µg/cm³ in the background detonation with no lime (Table 20). During one of the days in which lime was topically spread, Ca(OH)₂ concentrations at the perimeter of the OD site were between 2.3 and 38 µg/cm³.

Table 20. Perimeter air sample results.

Sample Date	Sample Location	Ca(OH) ₂ (µg/cm ³)
24 hr Zero Background		
7/30/08 – 7/31/08	North	nd
7/30/08 – 7/31/08	West	5.3
Background Detonation		
8/20/08	North	nd
8/20/08	South	nd
8/20/08	West	18.0
50 Tons of Lime Spreading and Discing		
10/21/08	North	2.3
10/21/08	South	17.7
10/21/08	West	38.0
1.25 Tons of Lime on Soil Mound during Detonation		
1/13/09	North	nd
1/13/09	South	nd
1/13/09	West	nd
1.25 Tons of Lime 10-ft from Soil Mound during Detonation		
6/08/09	North	nd
6/08/09	South	nd
6/08/09	West	nd
2.5 Tons of Lime Immediately around Soil Mound during Detonation		
8/18/09	North	80.8
8/18/09	South	308
8/18/09	West	49.9

nd – non-detect

During the two detonations with 1.25 tons of lime, Ca(OH)₂ was not detected in either of the air samples. Through direct observation and the review of captured video, it appeared that much of the lime, which was placed on top of the detonation pile soil mound, was directed up in the air during the first detonation causing the lime to apparently transport off-site at elevations above the intake of the air sampler. During the second detonation, the lime bags were placed too far away from the detonation to disperse the lime effectively. Many lime bags did not rupture and those that did deposited the lime in the immediate area adjacent to the bag location. No significant amounts of dust were created.

During the detonation with 2.5 tons of lime, Ca(OH)₂ was detected at concentrations between 49.9 and 308 µg/cm³. The high concentrations of lime detected in the detonation with 2.5 tons of lime were due to the lime placement next to the detonation pile soil mound. The detonation forced the lime sideways (laterally) on the site and limited the amount of lime that was forced up in the air. Better dispersion on the OD area ground surface was achieved but more Ca(OH)₂ was

detected at the site perimeter. Significant airborne transport at higher elevations was not visually observed using this application method.

6.6.7 Soil Invertebrates

The performance metric for this objective was to observe no effect and minimal effects on soil invertebrates due to the change in pH of the soil. No invertebrates were observed during baseline sampling and no invertebrates were observed at the conclusion of the field demonstration. The lack of communities of soil invertebrates can be attributed to several factors:

- APG tills the OB/OD range yearly which inhibits the growth and expansion of soil micro- and macro-invertebrate communities (Kladivko, 1993).
- The range is physically cut off from the surrounding area by berms and roads that disrupt the movement of micro- and macro-invertebrate into the OB/OD area, making it into an isolated island-type environment.

While there may be some effect of MCs on the soil micro- and macro-invertebrate communities, these will be masked due to the greater effects of the tilling and earthwork.

7.0 PERFORMANCE ASSESSMENT

7.1 QUANTITATIVE PERFORMANCE OBJECTIVES

The performance objectives required that RDX concentrations in soil pore water be reduced by 90% compared to baseline measurements. The goal was to observe RDX concentrations that were below 2 µg/L. The results of soil pore water analysis for explosives both pre- and post-lime application is summarized in Table 21. This objective is considered to be successful because post-liming concentrations of RDX, MNX, DNX, and TNX were all non-detect.

Table 21. Concentrations of explosives detected in soil pore water pre- and post-lime application (µg/L).

Sample Date	Explosives Concentrations (µg/L)			
	RDX	MNX	DNX	TNX
Pre-Lime				
7/17/08 (n=9)	0.53 ^a	<0.05	0.53 ^b	0.36 ^{a,b}
9/18/08 (n=9)	0.12 ^b	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

^aHighest concentration detected at 7-8 ft bgs

^bHighest concentration detected at 1-2 ft bgs

Surface water samples were taken from ponding areas that formed on the range following heavy precipitation. Concentrations of explosives detected in surface water samples pre- and post-liming are summarized in Table 22. This objective is considered successful as the concentrations post-liming were non-detect.

Table 22. Concentrations of explosives detected in surface water pre- and post-lime application (µg/L).

Sample Date	Explosives Concentrations (µg/L)			
	RDX	MNX	DNX	TNX
Pre-Lime				
7/17/08 (n=4)	0.07	<0.05	<0.05	0.07
9/18/08 (n=5)	0.29	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

The performance metric for groundwater explosives was to achieve RDX concentrations that were less than the concentrations observed during baseline characterization. The success of this objective is shown in Table 23. Concentrations of RDX, MNX, DNX, and TNX were all non-detect in groundwater following lime application.

Table 23. Concentrations of explosives in groundwater pre- and post-lime application (µg/L).

Sample Date	Explosives Concentration (µg/L)			
	RDX	MNX	DNX	TNX
Pre-Lime				
7/17/08	0.25	<0.25	<0.25	0.40
7/17/08	<0.05	<0.05	<0.05	<0.05
9/16/08	<0.05	<0.05	<0.05	<0.05
9/16/08	<0.05	<0.05	<0.05	<0.05
9/16/08	<0.05	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

The quantitative performance metrics for explosives in surface and ejected soils were to reduce concentrations of RDX and other explosives residues below baseline concentrations. This objective was successful (Figures 14 and 15).

The quantitative performance metrics for metals in surface and groundwater were to not show any increases over baseline concentrations. Concentrations of metals were unchanged by liming, except for Al, which appeared to increase post-liming (Table 17 and Figure 17).

7.2 QUALITATIVE PERFORMANCE ASSESSMENT

7.2.1 Evaluate Ease of Use

The performance metric for this objective takes into account amendment application factors, application frequency, and range downtime. Using the equipment available, topical application of lime to the entire 9-acre site required three technicians, each working for 3 days. Application of lime to the detonation area required the services of five demolition technicians, each for one hour.

7.2.2 Evaluate Human Health Risk to the Range Personnel

The performance metric for this objective considers the occurrence of any skin or eye irritation that occurs even though the user is wearing correct PPE. Air particulates were monitored during lime detonations and compared to un-limed detonations and background air samples.

IH regulations recommend a health RAC of 3 during topical application of lime. A RAC of 3 indicates a moderate health risk to the personnel performing this operation. Personnel should wear the proper PPE (ATC, 2010).

IH recommendations are that personnel applying Ca(OH)₂ during detonation activities should wear the proper PPE. A health RAC of 4 has been assigned to applying lime during detonation operations. A RAC of 4 indicates a minor health risk to the personnel performing this operation.

7.2.3 Evaluate Potential Ecological Effects or Risks to Soil Invertebrates

The performance metric for this objective was to observe no effect and minimal effects on soil invertebrates due to the change in pH of the soil. While there may be some effect of MCs on the soil micro- and macro-invertebrate communities, these were masked due to the greater effects of the tilling and earthwork.

7.2.4 Assess Lime Effects on General Water Quality Parameters of Groundwater and Soil Pore Water. Assess the Lime Effects on Percolation and Soil Drainage Characteristics.

The performance metric for this objective required that observed water quality parameters (pH, hardness, alkalinity, etc.) in pore water and groundwater be maintained at values less than or equal to those observed during baseline characterization. This objective was achieved.

Based on the results from the HELP model over the 50-yr run, from 19.80% to 29.38% of the total water budget will percolate or leach through the soil layer 4. The results indicate that less than 30% of the water will leach into the local groundwater. In addition, there was no evidence of soil crusting after the lime application. Also, hydraulic conductivity testing was performed after lime application using a mini disk infiltrometer manufactured by Decagon Devices. The infiltrometer determined hydraulic conductivity by measuring the rate of water flow from a cylinder into the soil. Time and water volume measurements were used to calculate hydraulic conductivity. The hydraulic conductivity measurements ranged from 5.0×10^{-4} cm/s (for unamended soil) to 3.0×10^{-3} cm/s (post-lime application). These values are all within one order of magnitude; thus, there was no significant difference in water infiltration rates observed due to liming of the soil.

7.2.5 Evaluate OD Facility Management Costs

The performance objective of this metric is to develop an annual cost estimate to manage MCs on the APG OD range and compare the costs to the cleanup costs required to maintain the range compliance. This is detailed in Section 7 of this report.

This page left blank intentionally.

8.0 COST ASSESSMENT

The cost of using lime to manage the accumulation and mobility of munitions and explosives of concern (MEC) constituents associated with OB/OD activities depends on the method of application as well as a number of site factors that may influence the concentration of lime to be added to the soil and the frequency of lime application. Two methods of lime application—topical application and incorporation in waste munitions detonations—were field tested on the ATC OD area. The cost models and benefits of each application method are discussed in the following subsections.

8.1 COST MODEL

The cost elements that influence the use of lime amendments to manage MCs on OD ranges include initial treatability testing required to determine the appropriate lime application rate for the range soil, cost of the lime, rental equipment (tractor with spreader and disc) to apply the lime, labor required to coordinate and apply the lime, and labor and analysis costs to periodically check soil pH to determine when re-application will be necessary. No permitting or environmental reporting costs were incurred other than the initial filing of appropriate National Environmental Policy Act (NEPA) documentation prior to the first application of the amendment to the range.

Two cost models for lime application are presented to document the costs associated with each lime application method used during the field demonstration. The first application method involved spreading bulk lime with a drop spreader and discing the lime into the top 6 inches of the soil (Table 24). Both the drop spreader and discs were towed by a tractor. The major equipment required to support this activity was already available from ATC's maintenance equipment inventory so actual equipment costs were not collected. Their rental costs were estimated in the cost model. At installations where spreading and discing equipment are not available, equipment rental or purchase costs may vary significantly with location. This application method will typically be used to manage residues deposited around burn pans from OB operations and for an initial broad area management of surface residues on the OD area. Depending upon the size of the OB/OD areas and the burning containment or detonation practices used, the application area size may range from 1 to 20 acres, or more.

Lime was topically applied to a 9-acre area on the ATC OD area at a soil concentration of 0.5% in the top 6-inch layer of soil during this field demonstration. The relevant costs documented in Table 24 reflect a per acre cost (\$2400/acre) to apply and disc the lime in the OD area. Generally, these costs will scale linearly with increasing acreage for areas with similar soil buffering capacities. Labor costs may be able to be reduced depending upon the size and application rates of the available equipment and the lime storage capabilities available at the installation. Note that ATC used lime in 50 lb bags because storage facilities capable of handling bulk lime were not available near the OB/OD areas. As a result, the drop spreader had to be manually loaded, which increased the labor cost for the operation. With the available equipment and manual loading of the drop spreader, approximately 3 hr was required to spread and disc approximately 5 tons of lime in the soil per acre. Three technicians were required to support this activity. Material costs were primarily the lime and PPE (i.e., Tyvek® clothing and respirator particulate cartridges) for the personnel handling the lime.

Table 24. Cost model for application of lime to an OD facility.

Cost Element	Data Tracked During the Demonstration	Costs	
Treatability study	<ul style="list-style-type: none"> Personnel and labor required Materials Analytical laboratory costs 	Project engineer, 3 hr	\$300
		Materials (test kits)	\$100
		Analytical laboratory	NA
Baseline characterization	<ul style="list-style-type: none"> Standard soil and groundwater monitoring, no cost tracking 	NA	
Material cost	Unit: \$ per acre for lime material Data requirements: <ul style="list-style-type: none"> Application rate: 5 tons of lime per acre based on soil buffering capacity Reapplication: dependent upon use and potential MEC residue accumulation 	Material cost/application/acre:	
		Lime (\$225/ton)	\$1125
		PPE	\$50
Installation	Unit: \$ per acre Data requirements: <ul style="list-style-type: none"> Equipment rental (tractor+implements) Time required (3 technicians, 3 hr/acre) 	3 Technicians, 3 hr/each	\$675
		Equipment rental/day/acre	\$550
Waste disposal	Standard solid waste disposal, no cost tracking	NA	
Long-term monitoring	<ul style="list-style-type: none"> For the project, standard soil and groundwater monitoring, no cost tracking As a part of facility operations, quarterly monitoring of soil, groundwater and surface water is recommended 	NA Materials (test kits): \$100	
Total project cost		\$2400/acre + \$500 treatability study and monitoring costs	

NA – not applicable

The majority of the costs associated with lime application are material cost and labor regardless of the application method. Baseline characterization should not be needed because these areas generally have already been characterized to support RCRA waste disposal facility permit applications or as ongoing monitoring required for permitted facilities. Minor treatability costs are incurred prior to the first application to determine soil pH and buffering capacity to establish the appropriate lime application concentrations. ERDC-EL has established implementation guidance to determine lime application concentrations using readily available field test kits for soil pH and buffering capacity. No waste disposal costs were incurred. Solid waste (lime bags and Tyvek® clothing) were placed in the installations general waste containers. No long-term monitoring is necessary other than checks of soil pH after lime application to ensure that the target pH range is achieved. Standard long-term monitoring practices for OB/OD waste facility operations should provide data on MEC residue levels to further track lime performance and are not a cost factor for technology implementation.

The second lime application method that was tested involved spreading the lime with the waste munitions detonations (Table 25). During each detonation, the OD setup activities were completed as normal by the demolition crew. After the soil cover was placed on the detonation material, up to 1.25 tons of lime was transported by forklift to the OD site. Personnel placed each 50 lb bag around the soil mound by hand. After the detonation, another 1.25 tons of lime was placed around the detonation crater and the lime was pushed into the crater during backfilling. PPE is not required because the bags of lime are not opened by the personnel. The

detonation and backfilling activities disperse the lime without risk of personnel exposure. The forklift required to transport the lime was already on-site to support waste munitions transport so no additional equipment was needed and actual equipment costs were not collected.

Table 25. Cost model for detonation lime application.

Cost Element	Data Tracked During the Demonstration	Costs	
Treatability study	<ul style="list-style-type: none"> Personnel and labor required Materials Analytical laboratory costs 	Project engineer, 3 hr	\$300
		Materials (test kits)	\$100
		Analytical laboratory	NA
Baseline characterization	<ul style="list-style-type: none"> Standard soil and groundwater monitoring, no cost tracking 	NA	
Material cost	Unit: \$ per detonation for lime material Data requirements: <ul style="list-style-type: none"> Application rate: Up to 2.5 tons of lime per detonation depending on the volume of soil ejecta 	Material cost/application/acre:	
		Lime (\$225/ton)	\$562
Installation	Unit: \$ per detonation Data requirements: <ul style="list-style-type: none"> Time required (5 technicians, 1 hr/detonation) 	5 Demolition Technicians, 1 hr/each	\$750
Waste disposal	<ul style="list-style-type: none"> Standard solid waste disposal, no cost tracking 	NA	
Operation and maintenance costs	<ul style="list-style-type: none"> No unique requirements recorded 	NA	
Long-term monitoring	<ul style="list-style-type: none"> For the project, standard soil and groundwater monitoring, no cost tracking As a part of facility operations, quarterly monitoring of soil, ground and surface water is recommended 	NA	
		Materials (test kits): \$100	
Total project cost (\$/acre)		\$1312/detonation + \$500 treatability and monitoring costs	

NA – not applicable

This spreading method reduces the amount of labor required to spread the lime, reduces potential lime exposure to personnel, immediately spreads the lime with the explosive residues for source control, and concentrates the lime where it is needed. This lime application method was easier than applying with a spreader and was easily incorporated into OD activities.

The cost to perform the lime spreading with the detonation after startup costs is approximately \$1200 for each detonation. After performing several detonations, the lime setup activities became fairly routine and added approximately 1 hr to the typical 5 man crew’s normal detonation activities.

8.2 COST DRIVERS

Cost drivers that should be considered when implementing the technology include site-specific soil and pore water geochemistry characteristics such as the presence of a high CEC, high buffering capacity, or low pH, which may require higher lime dosages or even preclude use of

liming technology. Application costs encompass the costs associated with lime, labor, and rental equipment for mixing the lime into the soil or spreading it on the surface. The quantity of lime used will depend on the initial pH and soil buffering capacity. Labor requirements are influenced by the type and capacity of the equipment available for spreading and mixing the lime into the soil. If UXO is present, then explosives ordnance disposal (EOD) support may become an additional cost in the application of the technology.

Management goals and regulatory permit monitoring requirements may require more frequent monitoring to verify that ideal pH levels are maintained or source zone contaminant levels are controlled in source or transport media. Periodic sampling to monitor pH levels and explosives and metals concentrations to meet these management or regulatory requirements may increase analytical costs.

8.3 COST ANALYSIS

OB/OD areas are generally open fields on which waste munitions destruction is performed. The area affected by the OB/OD operations depends on the amount of net explosive weight (NEW) allowed in the detonations and the detonation practices used on the site. The cost of managing MEC residues on the OB/OD area is related to the frequency of lime re-application. At the ATC OD area, lime was initially topically applied to the 9-acre area where detonations were conducted at a cost of \$21,600 (\$2400 per acre). After this initial treatment, pH conditions were maintained in the soils subjected to ongoing waste munitions destruction operations by incorporating the lime into each detonation at a cost of \$1200 per detonation. Waste munitions ODs were performed approximately 10 to 12 times per year in this area resulting in an ongoing annual liming cost of \$12,000 to \$14,400 per year. Topical re-application did not need to be performed because the detonation applications appeared to control any residues that may have been added by the detonations based on soil and groundwater monitoring samples collected throughout the field demonstration. At other active sites, lime may need to be reapplied more or less frequently depending upon dispersion characteristics of the detonations, frequency of detonations, soil buffering and physical characteristics, and local weather.

The major benefit of this technology is the potential cost avoidance for sites where explosives transport may be a factor. The cost of managing MEC residues in the source area will be significantly less than trying to capture and treat contaminated runoff or groundwater that may reach receptors. Also, because OB/OD areas are permitted waste treatment facilities, off-site transport of contaminants may trigger fines or restrict operations of the facilities until controls are implemented.

8.3.1 Life-Cycle Costs

The life-cycle costs specifically associated with the lime technology are related to the frequency of lime re-application. For the technology to work effectively, a pH of at least 10.5 must be maintained in the soil moisture. Based on the demonstration results for the lime application at the Fort Jackson HGR, two applications of lime each year should be sufficient for most sites (Larson et al., 2008). However, at other active sites, lime may need to be reapplied more or less frequently depending upon the soil buffering and physical characteristics and local weather. A pH test of the soil would likely be recommended at least yearly at each site.

The initial assumptions made when considering this technology are listed below. The initial assumptions are based on results of previous work with this technology as well as the results from the current application (Brooks et al., 2003; Davis et al., 2006, 2007a, 2007b; Felt et al., 2007; Johnson et al., 2010; Larson et al., 2007, 2008).

- Soil pH is between 4.5 and 8
- Soil structure is in the range of 87% sand and/or 99% fines with minimal gravel (<6%).
- Soil total organic compound (TOC) is $\leq 5\%$
- Soil CEC is between 4 and 30 milliequivalents (meq)/100g
- Rainfall average is 20 to 50-inches/year

The cost factors involved in successfully applying this technology on a site are listed in Table 26 along with site details that will affect those costs. Costs of this technology are highly dependent on site soil conditions and climate.

Table 26. Life-cycle cost factors for alkaline hydrolysis of soil on an OB/OD facility.

Cost Factor	Affected By
Lime	Acreage for topical application
	# of yearly detonations
Application	Rent or own equipment
Sampling/monitoring	If there is a potential for groundwater contamination, then wells should be monitored
	If there is a potential for surface water contamination, then receiving waters should be monitored
	Soil should be monitored for pH monthly
Re-application frequency	Soil properties
	Yearly precipitation

8.3.2 Technology Cost Comparison

There are no in situ munitions treatments for OD areas.

This page left blank intentionally.

9.0 IMPLEMENTATION ISSUES

9.1 ENVIRONMENTAL CHECKLIST

This in situ lime technology does not involve the use of any toxic or hazardous chemicals. The only chemical used as the amendment is $\text{Ca}(\text{OH})_2$, which is not regulated for addition to soil.

9.2 REGULATORY ISSUES

Munitions constituent migration potential should be investigated prior to implementing any management strategy. If migration potential is present and threatens nearby open water or groundwater resources, then Clean Water Act and/or Safe Drinking Water Act regulations may be of concern to ongoing range operations.

Potential regulatory concerns associated with the use of the lime amendments on OD areas include the potential for runoff water with elevated pH. The elevated pH may be detrimental to biota or surface water quality. Surface water runoff was monitored during this demonstration as well as previous demonstrations. On the HGR, the pH of the runoff water was neutralized to background levels before leaving the range. On the APG site, baseline characterization of the surface water indicated a pH range of 4.3 to 6.7. Following treatment of the site with the lime, the pH was increased to an average of 7.4 ± 1.6 , with a pH range of 10.4 to 4.3. This average increase still keeps the pH around neutral but the highest values indicate the surface water should be monitored in areas where runoff into wetlands or large permanent surface waters is possible.

The amphoteric solubility properties of some metals show increased solubility at both high and low pH. Elevation of the OD area pH to 12.5 may pose a risk of increased solubility of heavy metals on site. The HGR soils (ESTCP Project ER-200216) were evaluated with regard to increased metals leachability on hydrated lime amendment, release of heavy metals, hydroxide concentrations (pH) in leachate water, and surface water during both the lab studies and the ongoing field phase of the work. Increased metals mobility was not observed and the final results suggested that metals stabilization had occurred within the HGR soil that had been treated with lime.

Lab studies using the OD area soil indicated increased stability of the metal COPCs in the soil. Monitoring was conducted during the field phase of the OD management study to further evaluate metals stability. The only metals detected in the surface soil of the OD area, post-liming, were Cu and Zn. This supports the metals stabilization hypothesis proposed by Larson et al. (2008), suggested by data from the HGR liming field study, that the increase in pH stabilizes the majority of metals in the soil. Concentrations of metals leaching to groundwater were unchanged by liming, except for Al, which increased. However, the Al soil concentrations remained well within the national soil concentration averages. This is supported also by the fact that pH of the pore water and groundwater was unchanged by the liming of the soil.

9.3 END-USER ISSUES

The primary end user for this innovative in situ technology will be managers of active OD facilities. The technology is expected to break down explosives contaminants at the source

before they can migrate to surface water or groundwater. The lime amendment management technology may be capable of being applied to other active range areas where explosives constituents are being deposited in the shallow soil layer; however, further development is required to identify effective application methods that can be safely implemented in these areas.

9.4 MANAGEMENT COSTS

Several factors determine the constituent management costs. These include:

- **Analytical Costs:** Periodic sampling to monitor pH levels and explosives and metals concentrations in one or more of the following media: soil, surface water, pore water, and groundwater.
- **Operation Costs:** Operation cost will mainly encompass the costs associated with lime, labor, and rental equipment for mixing the lime into the soil or spreading it on the surface. The quantity of lime used will depend on the initial soil pH and soil buffering capacity.
- **Soil and Pore Water Geochemistry:** The presence of a high CEC, high buffering capacity, or low pH, may require higher lime dosages.
- **Management Goals:** More stringent management goals may require additional monitoring to verify that ideal pH levels are maintained.

9.5 LESSONS LEARNED

Lessons learned from this demonstration are: From air monitoring during the topical application and detonation application of lime to the OD area, the data suggests atmospheric transport of the lime to the boundaries of the range, but was highly dependent on prevailing wind directions; distance from the detonation to the boundary and the sampler; moisture content of the soil surrounding the detonated items; the quantities of the lime applied; and to some degree, the methods used to apply the lime. Possible mitigation techniques would likely involve adding moisture to the surrounding soil to reduce entrainment of lime (and soil dusts) into the ambient air as a result of the detonation.

Several environmental factors may affect the successful implementation and management of this technology at future sites. They include:

1. **Soil Moisture:** The alkaline hydrolysis reaction of the explosives breakdown occurs in the aqueous phase. Sufficient soil pore water is necessary to dissolve and mix the hydroxide and soluble explosive compounds.
2. **Soil Buffering Capacity:** If buffering capacity is high, a larger amount of lime is required to achieve and maintain the ideal pH. Generally, soils containing high clay or organic matter content typically have a high buffering capacity.
3. **Management Goals:** To meet more stringent management goals, larger quantities of lime, more efficient soil mixing, or maintaining appropriate soil moisture may be necessary.

4. ***Heterogeneity:*** Sufficient mixing of the soil is necessary to enhance contact of explosives with hydroxide ions in solution. The explosives distribution in soils is likely heterogeneous; therefore, sufficient mixing of lime into the soil is necessary. Otherwise, the lime may dissolve and be removed with surface runoff or leach through the ground in preferential pathways without reacting with the explosives.

A potential issue of concern in taking the technology from the lab to field-testing is the solubilization of hydroxide and transport of hydroxide off the treated area in storm water. High hydroxide concentrations can result in phytotoxic effects. Hydrated lime solubility is low and stops when a pH of approximately 12.5 is reached. Specific soil types have varying reactive capacity for neutralization of hydroxide. Field samples of storm water runoff from the ESTCP Project ER-200216 at a Fort Jackson HGR did not indicate a significant increase in runoff pH. Similar screening of the demonstration site soil was conducted to avoid off-site migration of elevated surface water pH from the OD area.

The amphoteric solubility properties of some metals show increased solubility at both high and low pH. Elevation of the OD area pH to 12.5 may pose a risk of increased solubility of heavy metals on site. The HGR soils (ESTCP Project 200216) were evaluated with regard to increased metals leachability upon hydrated lime amendment, release of heavy metals, hydroxide concentrations (pH) in leachate water and surface water during both the lab studies and the ongoing field phase of the work. Increased metals mobility was not observed and the final results suggested that metals stabilization had occurred within the HGR soil that had been treated with lime. Lab studies using the OD area soil indicated increased stability of the metal COPCs in the soil. Monitoring was conducted during the field phase of the OD management study to further evaluate metals stability.

Alkaline hydrolysis is moisture driven; the energetic materials (e.g., RDX and TNT) and hydroxide ions need to be in solution for the alkaline hydrolysis of the energetic materials to occur. Under low rainfall conditions, the lime application might need to be modified to mitigate excessive lime accumulation in the soil. If a drought or insufficient moisture exists to dissolve the MCs and lime, then they may build up in the soil until adequate rainfall does occur. Since this is a passive management process, watering or irrigating the area to activate the hydrolysis reaction is not recommended. The explosives, metals, and lime will be immobile without the rainfall to act as a transport mechanism. Once rainfall occurs and sufficiently moistens the ground, explosives and lime will dissolve into the pore water solution and react. If extended periods of drought occur, then guidance may be needed to ensure that the area is not overdosed with lime. The specifics of this guidance will be determined through lab and field study.

Since the lime dust could be an irritant to personnel in training and site maintenance personnel, air samples were collected and analyzed for PM₁₀ during the demonstration. PM₁₀ describes particles suspended in the air, which have a specific size range of 10 micrometers or less and can penetrate into human lungs.

This page left blank intentionally.

10.0 REFERENCES

- Aberdeen Test Center (ATC). 2010 Test Record: Open Burn Open Detonation Test Record No.: SL-51-09.
- American Conference of Government Industrial Hygienists (ACGIH). 2008. Threshold limit values for chemical substances, physical agents, and biological exposure indices.
- American Society for Testing and Materials (ASTM). 1999. Standard test method for using pH to estimate the soil-lime proportion requirement for soil stabilization. Report D-6276. West Conshocken, PA: ASTM International.
- Balakrishnan, V.K., A. Halasz, and J. Hawari. 2003. Alkaline hydrolysis of the cyclic nitramine explosives RDX, HMX, and CL-20: New insights into degradation pathways obtained by the observation of novel intermediates. *Environ. Sci. Technol.*, 37(9), 1838-1843.
- Brooks, M.C., J.L. Davis, S.L. Larson, D.R. Felt, and C.C. Nestler. 2003. Topical lime treatment for containment of source zone energetics contamination. ERDC/EL TR-03-19, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Code of Federal Regulations (CFR). 2008. Title 29, Part 1910.1000 (Air Contaminants), Occupational Safety and Health Administration, General Industry Standards.
- Davis, J.L., M.C. Brooks, S.L. Larson, C.C. Nestler, and D.R. Felt. 2006. Lime treatment of explosives-contaminated soil from munitions plants and firing ranges. *Soil & Sediment Contamination*, 15, 565-580.
- Davis, J.L., M.C. Brooks, S.L. Larson, C.C. Nestler, and D.R. Felt. 2007a. Lime treatment for containment of source zone energetics contamination: Mesocosm study. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 11, 11-19.
- Davis, J.L., S.L. Larson, D.R. Felt, C.C. Nestler, A.W. Martin, L. Riggs, E.J. Valente, and G.R. Bishop. 2007b. Engineering considerations for hydroxide treatment of training ranges. ERDC/EL TR-07-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Davis, J.L., C.C. Nestler, D.R. Felt, and S.L. Larson. 2007c. Effect of treatment pH on the end products of the alkaline hydrolysis of TNT and RDX. ERDC/EL TR-07-4, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Emmrich, M. 1999. "Kinetics of the alkaline hydrolysis of 2,4,6-trinitrotoluene in aqueous solution and highly contaminated soils," *Environ. Sci. Technol.* 33(21), 3802-3805.
- Emmrich, M. 2001. Kinetics of the alkaline hydrolysis of important nitroaromatic co-contaminants of 2,4,6-trinitrotoluene in highly contaminated soils. *Environ. Sci. Technol.* 35(5), 874-877.

- Felt, D.R., C.C. Nestler, J.L. Davis, and S.L. Larson. 2007. Potential for biodegradation of the alkaline hydrolysis end products of TNT and RDX. ERDC/EL TR-07-25, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Heilman, H.M., U. Wiesmann, and M.K. Stenstrom. 1996. Kinetics of the alkaline hydrolysis of high explosives RDX and HMX in aqueous solution and adsorbed to activated carbon. *Environ. Sci. Technol.* 30(5), 1485-1492.
- Hoffsommer, J.C., D.A. Kubose, and D.J. Glover. 1977. Kinetic isotope effects and intermediate formation for the aqueous alkaline homogeneous hydrolysis of 1,3,5-triaza-1,3,5-trinitrocyclohexane (RDX). *J. Phy. Chem.* 81(5), 380-385.
- Johnson, J.L., J.L. Davis, and C.C. Nestler. 2010. Topical Lime Application for the Management of Munitions Constituents Following Blow-In-Place Operations, ERDC/EL TR-10-10, Engineering Research and Development Center, Vicksburg, MS.
- Janowsky, J.V. 1891. Ueber eine reaction der dinitrokörper. *Berichte* 24, 971.
- Kladivko, E. 1993. Soil/Physical Condition: Earthworms and Crop Management. Report AY-279. Purdue University Cooperative Extension Service – Agronomy guide.
- Larson, S.L., J.L. Davis, W.A. Martin, D.R. Felt, C.C. Nestler, J.M. Brannon, G. Fabian, and G. O'Connor. 2007. Grenade Range Management Using Lime for the Dual Role of Metals Immobilization and Explosives Transformation; Treatability Study. ERDC/EL TR-07-5, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Larson, S.L., W.A. Martin, D.R. Felt, C.C. Nestler, J.M. Brannon, G. Fabian, and G. O'Connor. 2008. Grenade Range Management Using Lime for the Dual Role of Metals Immobilization and Explosives Transformation; Field Demonstration at Fort Jackson, SC. ERDC/EL TR-08-5, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Saupe, A., and U. Wiesmann. 1996. Degradation of nitroaromatic xenobiotics by ozonation and subsequent biological treatment. *Acta Hydrochimica et Hydrobiologica* 24, 118-126.
- Sposito, G. 2008. *The Chemistry of Soils*. 2nd Ed. New York: Oxford University Press.
- U.S. Army. 2005. OB/OD Preliminary Site Characterization Study. Aberdeen Proving Ground, Maryland. Contract No. DACA01-01-D-0016. Task Order No. 0037. Prepared for Aberdeen Proving Ground Directorate of Safety, Health and Environment Under Contract to U.S. Army Corps of Engineers Mobile District. January 2005.
- U.S. Environmental Protection Agency (USEPA). 1999. Test Methods for Evaluating Solid Waste: Physical/Chemical Methods, SW-846. Washington, DC.

APPENDIX A
POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
W. Andy Martin	U.S. Army ERDC- Environmental Lab 3909 Halls Ferry Road Vicksburg, MS 39180	Phone: (601) 634-3710 Fax: (601) 634-3851 E-mail: Andy.Martin@erdc.usace.army.mil	Co-Principal Investigator
Deborah Felt	U.S. Army ERDC- Environmental Lab 3909 Halls Ferry Road Vicksburg, MS 39180	Phone: (601) 634-3576 Fax: (601) 634-3851 E-mail: Deborah.Felt@erdc.usace.army.mil	Co-Principal Investigator
Steven L. Larson	U.S. Army ERDC- Environmental Lab 3909 Halls Ferry Road Vicksburg, MS 39180	Phone: (601) 634-3431 Fax: (601) 634-3581 E-mail: Steven.L.Larson@erdc.usace.army.mil	Co-Principal Investigator
Gene L. Fabian	Aberdeen Test Center 400 Collieran Road Aberdeen Proving Ground, MD 21005	Phone: (410) 278-7421 Fax: (410) 278-1598 E-mail: Gene.Fabian@us.army.mil	Co-Principal Investigator
Andrea Leeson	ESTCP Office 901 North Stuart Street Suite 303 Arlington, VA 22203	Phone: (703) 696-2118 Fax: (703) 696-2114 E-mail: Andrea.Leeson@osd.mil	Environmental Restoration Program Manager



ESTCP Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

E-mail: estcp@estcp.org
www.serdp-estcp.org