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Environmental Security Technology Certification Program

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

ESTCP Project Number ER-0742

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Final report

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Abstract: A common disposal method for munitions stockpiles is Open Burn/Open Detonation (OBOD). These activities are necessary to destroy unserviceable, unstable, or unusable munitions and explosives. Due to the relatively small area of OD facilities, there is a high probability of explosives and heavy metal contamination in the soil. The objective of this demonstration was to evaluate a lime soil amendment management strategy to control active OD area contaminant mobility and promote contaminant degradation that is low cost and minimally resource intensive. A soil treatability study and baseline characterization evaluation were undertaken at the site—the OD area of Aberdeen Proving Grounds—prior to initiation of the field demonstration. The field demonstration involved adding hydrated lime to the OD area to transform explosive residues and stabilize metals at the site to prevent offsite migration. Lime was further dispersed on the site and mixed with the deeper soils by adding it to the hole dug for the waste munitions before the detonations. Seven amendment methods were evaluated. Effective dispersion was monitored by surface soil sampling after the detonation fallout had settled. The detonations all dispersed the lime along with the crater ejecta. 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 spanned the depth of the detonation crater. Air monitoring and the effect of lime on soil invertebrates was also conducted. Alkaline hydrolysis of the munitions residues in soil was confirmed. Transport of the residues off-range in surface water or towards groundwater was reduced below baseline levels and met regulatory requirements. Results of the Toxicity Characteristic Leaching Procedure (TCLP) and the Distilled Deionized Water Suspend and Settle (DDI S&S) analysis of OBOD area soil samples indicated that cadmium was leached from the soil by the DDI S&S procedure, although not detected in the TCLP extraction solutions. Aluminum and iron, two metals leached by both procedures, were detected at higher concentration by the DDI S&S procedure but were well within national background concentrations for soil. Alkaline hydrolysis through lime amendment of soil was successful at controlling off-range transport of munitions explosive residues and heavy metals without changes in soil characteristics or ecological impact.

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Preface

The work reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS and the Aberdeen portion of Aberdeen Proving Ground's operational range complex, Aberdeen Proving Ground, MD. Funding was provided by the Environmental Security Technology Certification Program (ESTCP). The project was designated as ESTCP Project ER-0742.

The work presented in this report was part of an effort to investigate the use of lime to immobilize metals and transform explosives on an active open detonation area. W. Andy Martin, Deborah R. Felt, and Dr. Steven L. Larson of the ERDC-Environmental Laboratory (EL), Vicksburg, MS; Catherine C. Nestler of Applied Research Associates, Inc., Vicksburg, MS; and Gene L. Fabian, Aberdeen Test Center, prepared this report. The report was reviewed by John Childs and Michelle Wynter of ERDC-EL. The authors gratefully acknowledge the technical assistance provided by Chris Griggs, ERDC-EL; Deborah Regan, SpecPro; and Catherine Thomas, Jackson State University. The authors also wish to acknowledge the gracious participation of both the U.S. Army Center for Health Promotion and Preventive Medicine and the Aberdeen Test Center UXO avoidance support team for their assistance throughout the duration of this project.

This study was conducted under the direct supervision of W. Andy Martin, Chief, Environmental Engineering Branch, EL; and Dr. Richard E. Price, Chief, Environmental Processes and Engineering Division, EL; and under the general supervision of Dr. M. John Cullinane, Technical Director, EL. Dr. Michael Passmore was Deputy Director, EL; and Dr. Beth Fleming was Director, EL.

COL Kevin J. Wilson was Commander of ERDC. Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
microns	1.0 E-06	meters
square feet	0.09290304	square meters
tons (2,000 pounds, mass)	907.1847	kilograms

Acronyms

ACGIH	American Conference of Government Industrial Hygienists
ASTM	American Society for Testing and Materials
APG	Aberdeen Proving Grounds
ATC	Aberdeen Test Center
bgs	below ground surface
CEC	Cation Exchange Capacity
CFR	Code of Federal Regulations
CHPPM	Center for Health Promotion and Preventive Medicine (U.S. Army)
cm	centimeter
cm^3	cubic centimeter
COPC	Chemicals of Potential Concern
D	Dissolved
DDI S&S	Distilled, Deionized Water Suspend and Settle
DOD	Department of Defense
DPS	Deployable Particulate Sampler
EOD	Explosive Ordnance Disposal
EPA	Environmental Protection Agency
ERDC-EL	Engineer Research and Development Center – Environmental Laboratory
ESTCP	Environmental Security Technology Certification Program
ft	foot
ft^3	cubic foot
g	gram
GPS	Global Positioning System
HELP	Hydrologic Evaluation of Landfill Performance
HGR	Hand Grenade Range
hr	hour
IH	Industrial Hygiene
kg	kilogram
L	liter

lb	pound
MCDA	multi-criteria decision analysis
mg	milligram
min	minutes
MEC	Munitions and Explosives of Concern
m^3	cubic meter
nd	non-detect
NEPA	National Environmental Policy Act
NEW	Net Explosive Weight
OBF	Old Bombing Field
OBOD	Open Burn / Open Detonation
PEL	Permissible Exposure Limit
PM_{10}	Particulate Matter 10 (thoracic fraction; $\leq$ 10 µm)
ppb	parts per billion
PPE	Personal Protective Equipment
pt	point
r	Correlation Coefficient
r^2	Coefficient of Determination
RAC	Risk Assessment Code
RCRA	Resource Conservation and Recovery Act
sec	second
S	"Soil" reference to samples taken and labeled from the field site
SERDP	Strategic Environmental Research and Development Program
SU	Standard Unit
SVOC	Semi-Volatile Organic Compounds
T	Total
TCLP	Toxicity Characteristic Leaching Procedure
TLV	Threshold Limit Value
TWA	Time Weighted Average
USACE	U.S. Army Corps of Engineers
UXO	Unexploded Ordnance
VOC	Volatile Organic Compounds

µg	microgram
µm	micrometer

VOC/SVOC compounds

DCE	1,2-dichloroethane
DNPA	di-nitrosodiphenylamine
PCE	tetrachloroethene
TCE	trichloroethene

Energetic Compounds

ADNT	2,4/2,6-amino-dinitrotoluene
DNB	1,3-dinitrobenzene
DNX	hexahydro-1,3-dinitroso-5-nitro-1,3,5-triazine
HMX	Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
MNX	Hexahydro-1-nitroso-3,5-dinitro-1,3,5-triazine
NB	Nitrobenzene
RDX	Hexahydro-1,3,5-trinitro-1,3,5-triazine
TNB	1,3,5-trinitrobenzene
TNT	2,4,6-trinitrotoluene
TNX	Hexahydro-1,3,5-trinitroso-1,3,5-triazine

Metals

Al	Aluminum
As	Arsenic
Ca	Calcium
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
Mo	Molybdenum

Ni	Nickel
Pb	Lead
Sb	Antimony
Se	Selenium
Tl	Thallium
V	Vanadium
W	Tungsten
Zn	Zinc

Other Compounds

$CaCO_3$	Calcium carbonate
$Ca(OH)_2$	Calcitic hydrated lime/Calcium hydroxide
$HCOO^-$	Formate
NaOH	Sodium hydroxide
NO_2^-	Nitrite
OH^-	Hydroxide ion

1 Introduction

1.1 Open Burn/Open Detonation (OBOD)

A common disposal method for munitions stockpiles is Open Burn or Open Detonation (OBOD). These activities are necessary to destroy unserviceable, unstable, or unusable munitions and explosives. Munitions must be demilitarized or destroyed depending on their lifespan and/or other requirements. There are commercial demilitarization options available. In an assessment of several technologies available for the disposal of explosive wastes, Duijm and Markert (2002) compared open burning and open detonation, closed detonation, fluidized bed combustion, rotary kiln incineration and mobile furnace incineration. They used multi-criteria decision analysis (MCDA) to evaluate these technologies and concluded that the environmental impact of traditional OBOD activities could be greatly reduced using controlled incineration techniques in combination with high-pressure water washout of the burning areas. Their results are supported by the life-cycle analysis provided by Alverbro et al. (2009). Disadvantages to all these solutions is that they require great amounts of energy, making them very costly, and generally produce a secondary contaminated waste stream, again adding to the cost. In addition, the study by Alverbro et al. (2009) was based on the use of one hundred 40-mm grenades and underestimates the quantity, the specific requirements, and the safety risks involved in the variation and quantity of munitions destruction that can occur at an OBOD range. Therefore, commercial demilitarization methods can be both costly and inflexible.

OBOD operations are generally conducted in pans or unlined pits as a part of training activities and as a means of safely destroying munitions. Compliance with existing state and federal environmental regulations is an important factor in conducting OBOD activities. The Department of Defense (DoD) operates about a hundred OBOD 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 OD areas cover, there is a high probability of explosives contamination in the surrounding soil. The explosives present in the site area soil can be quite heterogeneous. Very large explosives concentrations in small soil volumes are possible when incomplete combustion results in the soil deposition of free product explosives. Measurable explosive levels have been observed in OD area soils at levels in the low parts per billion (ppb) up to percent levels in soils (Checkai et al. 1993; Pennington et al. 2003; Hewitt et al. 2005; Taylor et al. 2006). Off-site migration of explosives from OBOD area soils is possible through horizontal transport in surface water and vertical leachate water transport (Checkai et al. 1993; U.S. Environmental Protection Agency (USEPA) 2000; Clausen et al. 2004). Although these results have been disputed by the results of Ampleman et al. (1998), these pathways could provide a means by which limitations to OBOD activities could occur through enforcement of state and federal environmental regulations.

1.2 Alkaline hydrolysis

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 Wiesmann (1996), which resulted in complete transformation and partial mineralization. Hydrated lime was shown to break down TNT in soil with an application of 1 percent (%) $Ca(OH)_2$.

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 hydroxide to solution and soils containing TNT and RDX result in breakdown products such as nitrate and nitrite (Emmrich 1999, 2001).

Heilman et al. (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 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 Strategic Environmental Research and Development Program (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.

For the OD field demonstration, the hydrated lime will be topically applied and mixed into the surface six inches (in.) of the soil over the entire nine-acre site. Normal earth-moving activities related to OD area operational preparation activities will continue to mix this hydrated lime with the soil. Once the management area is established, hydrated lime additions will be incorporated into normal OD operations. Lime can be added before and after detonation activity to maintain the amended soil's pH in the desired range.

Lime application is a proven technology in treating organics such as TNT and RDX. SERDP project CU-1230 completed in FY 03 investigated the general base hydrolysis of explosives in soils (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 byproducts. For instance, after alkaline hydrolysis, the byproducts of RDX ring cleavage include formate ($HCOO^-$) and nitrite (NO_2^-) in bench scale tests. In addition, these by-products can be readily degraded biologically (aerobically and anaerobically) in native soils following alkaline hydrolysis (Figure 1). 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 C^{14} labeled study after a few weeks, and (b) less than 2% mineralization for RDX without alkaline hydrolysis.

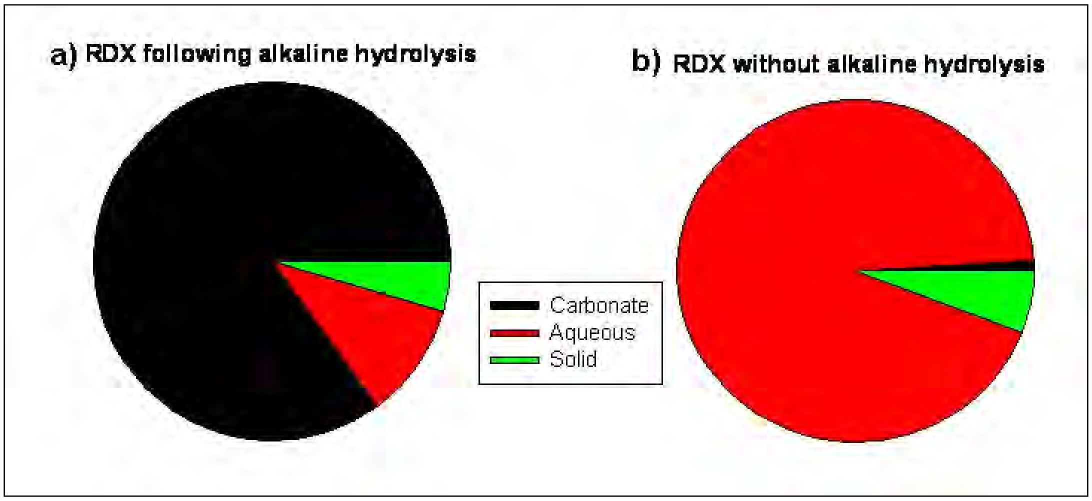

Figure 1. Degradation of RDX.

A field demonstration at the Fort Jackson, SC, hand grenade range (HGR) (Larson et al. 2008) explored the use of the base hydrolysis reaction to manage impact areas for hand grenade ranges 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 also react with soluble metals and stabilize them within the soil matrix as has been reported in Larson et al. (2008). 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 munitions constituents off-range.

In collaboration with the U.S./German Data Exchange Agreement, information on a recently reconstructed German ordnance detonation site was exchanged. Erosion control measures, a retention basin, and a wetland area were constructed to control the munitions constituents 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; rather, it treats the runoff from the soil associated with their detonation area.

In previous testing of this technology, a laboratory study was conducted with soil collected from two active hand grenade ranges (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 has also been 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 munitions constituents. The destruction of explosive residues requires a pH of 11.5, soil dependent, but generally achieved through an application of 0.5% lime by soil mass being treated.

1.3 Regulatory drivers

The EPA Office of Water Lifetime Health Advisory for RDX is 2-µg/L (USEPA 2006). In the future, this advisory level may become an EPA regulation for aqueous media.

A Resource Conservation and Recovery Act (RCRA) permit is required for continued operation of many of the Army Depot OBOD ranges. Active OBOD facilities used for disposal of waste munitions in the U.S. will also be required to have an RCRA permit in the near future.

1.4 Objectives

Currently, there is no in situ or remote alternative for management of soils on OBOD 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 OBOD areas acting as source zones for mobile contaminants using existing, ex situ remediation technologies will far exceed resources available for facility or range management budgets and is currently not practiced. 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) (Davis et al. 2007b, 2007c) in the soil, while stabilizing many munitions associated metals (Larson et al. 2008).

The objectives of this demonstration were to develop and evaluate a management technology to control active OD area contaminant mobility and to 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 following performance criteria were monitored at field scale:

1. Reduce RDX concentrations below baseline concentrations in soil
2. Reduce RDX concentrations below the EPA Lifetime Health Advisory of 2-µg/L in the pore water leaching from the source area
3. Reduce RDX concentrations by 80% in any storm water found ponding in the source area
4. Assess the overall effectiveness and potential side effects of the lime technology, including the following:
    a. Evaluate reduction of explosives in soil, soil pore water, and surface storm water, stabilization of metals in soil, and reduction of metals in pore water and surface water. Compare results from the baseline and test (post-lime)
    b. Maintain or reduce explosives concentrations in soil at the source area (Since continuous loading of explosives will occur, maintaining explosives concentrations in soil below baseline levels will be an appropriate objective.)
    c. Determine ability to maintain pH above 10.5 at the source area and below 9.0 outside the source area
    d. Evaluate ease of use. Identify problems, if any, with amendment and maintenance of the lime treated area. Determine the mixing efficiency required, estimate the concentration of lime amendment required to achieve the desired pH for explosives treatment, frequency of lime reapplication, and evaluate/project pH effect dissipation with respect to time and potential effects to soil drainage characteristics. Identify factors other than site use that may affect the maintenance frequency
    e. Evaluate the human health risks, including occupational risks associated with technology installation, site use and site maintenance using air monitoring and soil/groundwater characterization data. Consider potential impacts and/or risks to local ecological receptors (e.g., invertebrates)
    f. Determine transport characteristics by using calcium from the dissolution of lime as a tracer in pore water, surface water, and soils

5. Quantify costs:
    a. Estimate capital costs
    b. Estimate operation and maintenance costs
    c. Identify site characteristics that affect constituent management costs

2 Experimental Design

The steps of the test design were to:

- conduct a site soil treatability study
- conduct a site baseline characterization
- perform topical application of lime to 9 acres, mixed to a depth of 6-in.
- perform lime addition to the detonation pit
- perform the detonation
- perform post-detonation sampling
- backfill detonation crater with lime and soil
- repeat using a different method to fill detonation pit
- perform particulate matter (PM_{10}) air sampling throughout the demonstration (conducted by personnel from the Center for Health Promotion and Preventive Medicine (CHPPM).

Six months of baseline monitoring was performed prior to the initial lime application. The lime was applied and mixed into the soil of the entire 9–acre site over a period of 3 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. Soil, air, groundwater, and surface water sampling was performed for the 18-month monitoring period.

2.1 Demonstration site

An objective site screening and selection process was undertaken in selecting the demonstration site location at the Old Bombing Field (OBF) – OD site at Aberdeen Proving Ground, MD. The site features that made the Aberdeen Proving Ground's (APG) OD range an ideal demonstration site include the following:

1. The range is active, therefore, continuous explosives loading and soil mixing will occur.
2. The range is generally accessible year round.
3. There are sufficient explosives concentrations in soil.
4. Shallow depth to groundwater presents a potential subsurface contaminant transport issue.

5. The Aberdeen Test Center (ATC) provided unexploded ordnance (UXO) avoidance support at the site, as needed, to support monitoring equipment installation and sub-surface sampling activities.
6. There are only limited environmental drivers that limit the technology use at the selected site.
7. The operator of the site is ATC, one of the organizations implementing the technology with ERDC.

The OBF-OD range is located within the Aberdeen portion of APG's operational range complex, approximately 1,400 ft southeast of OBF-OB unit near the south central portion of the Aberdeen Area (Figure 2). Access is restricted by Range Control. The range consists of 18 acres and is a level, lowland area and contains a large flat non-grassy portion of consistent topography upon 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.

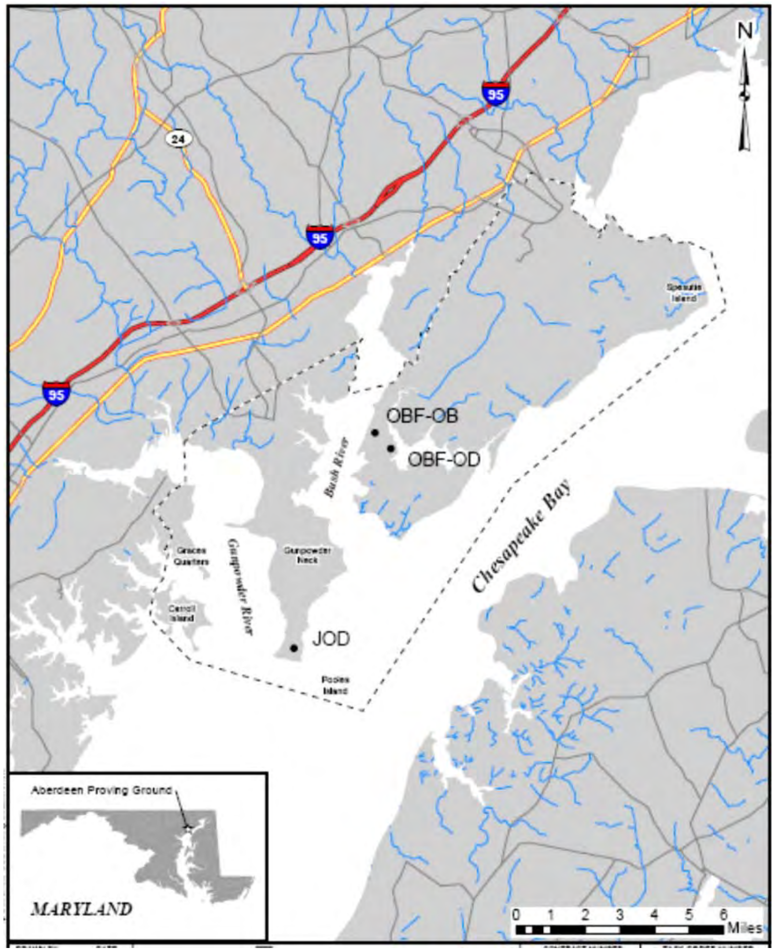

Figure 2. Location map of APG OBF-OD area.

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 Corps of Engineers (USACE) 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 excavation and backfilling activities as is consistent with current practices on the OD range.

Currently, [waste] military munitions are destroyed at the 18-acre APG OBF-OD site. The munitions include research and test munitions, as well as excess or degraded munitions periodically culled from long-term munitions storage. Typically, up to 500 pounds (lb) net explosive weight (NEW) of waste munitions are placed in a shallow pit. A donor charge is added at a 1:1 ratio with the waste munitions NEW and covered with soil. The detonation of these munitions results in munitions constituent residue dispersion on the range. In addition to waste munitions destruction, occasionally the detonation of UXO found on the test ranges is conducted in the OD area. UXO are placed on the ground surface and detonated using a donor charge. The munitions detonations can form craters up to 14 ft deep and are backfilled immediately with heavy equipment. The site is tilled annually to prevent vegetation growth and potential brush fires. The site is operated in a manner to minimize the potential for UXO accumulation, but it is controlled as a dudded area for safety reasons. A site characterization study was performed to assess potential contaminants of concern in surface soil, groundwater, and nearby surface water. The results of the study are being used for directing the baseline site characterization. As part of the RCRA permit renewal for the site, APG augmented and repaired the existing earthen berm along the down-gradient portions of the site to prevent flooding and to control surface water runoff and erosion into the adjacent water body, Romney Creek.

The field demonstration was focused on the Northwest (4.5 acres) and Southwest (4.5 acres) quadrants of the OD range (9 acres total) farthest from Romney Creek (Figure 3). Topical lime application and most of the detonations were conducted in this area during the demonstration. A reduced area was used because:

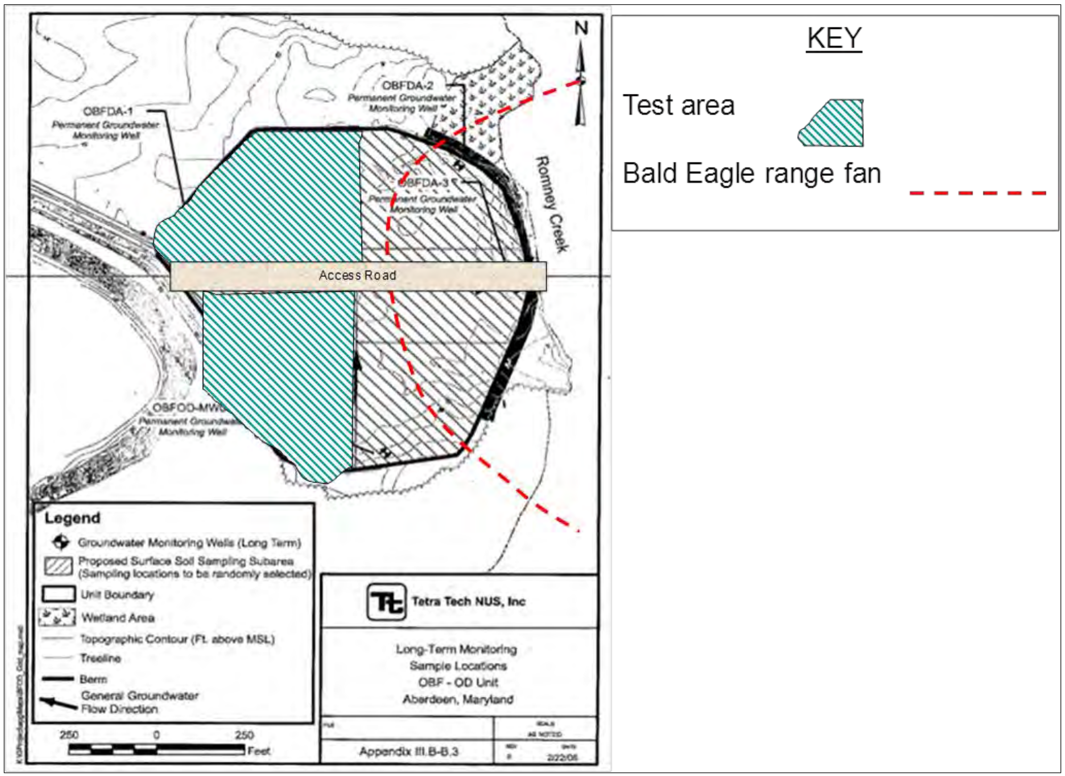

Figure 3. Field demonstration monitoring area.

- most detonations were being conducted on those quadrants—or the half of the range farthest from Romney Creek—to minimize potential airborne transport and deposition of crater ejecta on recently installed stormwater sediment traps in the eastern portion of the detonation field and in Romney Creek itself;
- the half of the OD area closest to Romney Creek falls within an exclusion area that is enforced when bald eagles are nesting (15 January thru 15 June) in a nest located on a tower in Romney Creek; and
- concentrating the monitoring in a controlled area on the OD range minimized monitoring costs and maximized the ability to detect trends in contaminant mobility or reduction.

There are three up-gradient (OBFDA-1, OBFDA-2, and OBFOD-MW01) and one down-gradient (OBFDA-3) monitoring wells at the site (Figure 4). Groundwater at the site can be as shallow as 4 to 9 ft bgs. A groundwater elevation map for the site is shown in Figure 5.

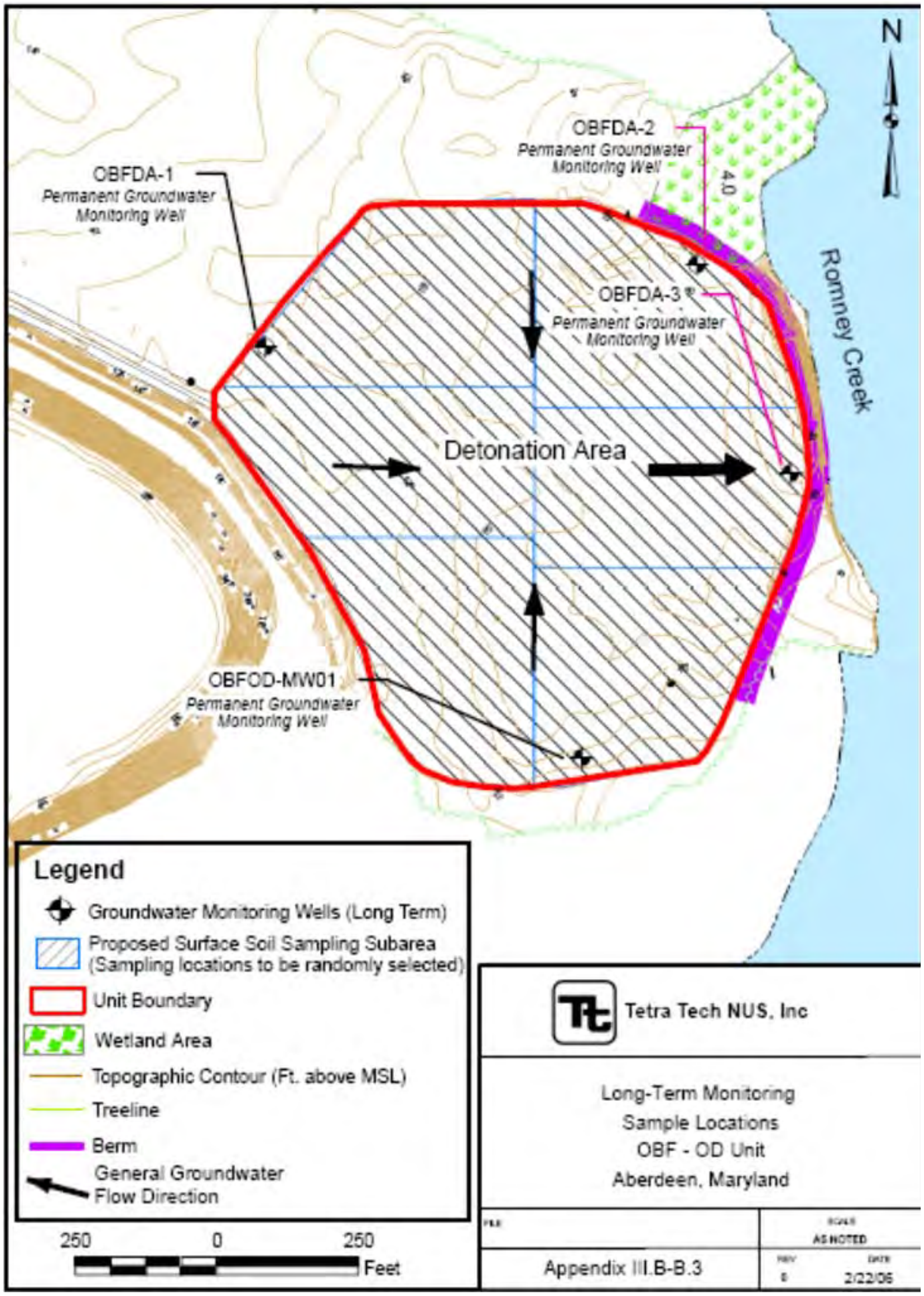

Figure 4. Location of permanent groundwater monitoring wells: OBFDA-1, OBFDA-2, OBFDA-3, and OBFOD-MW01.

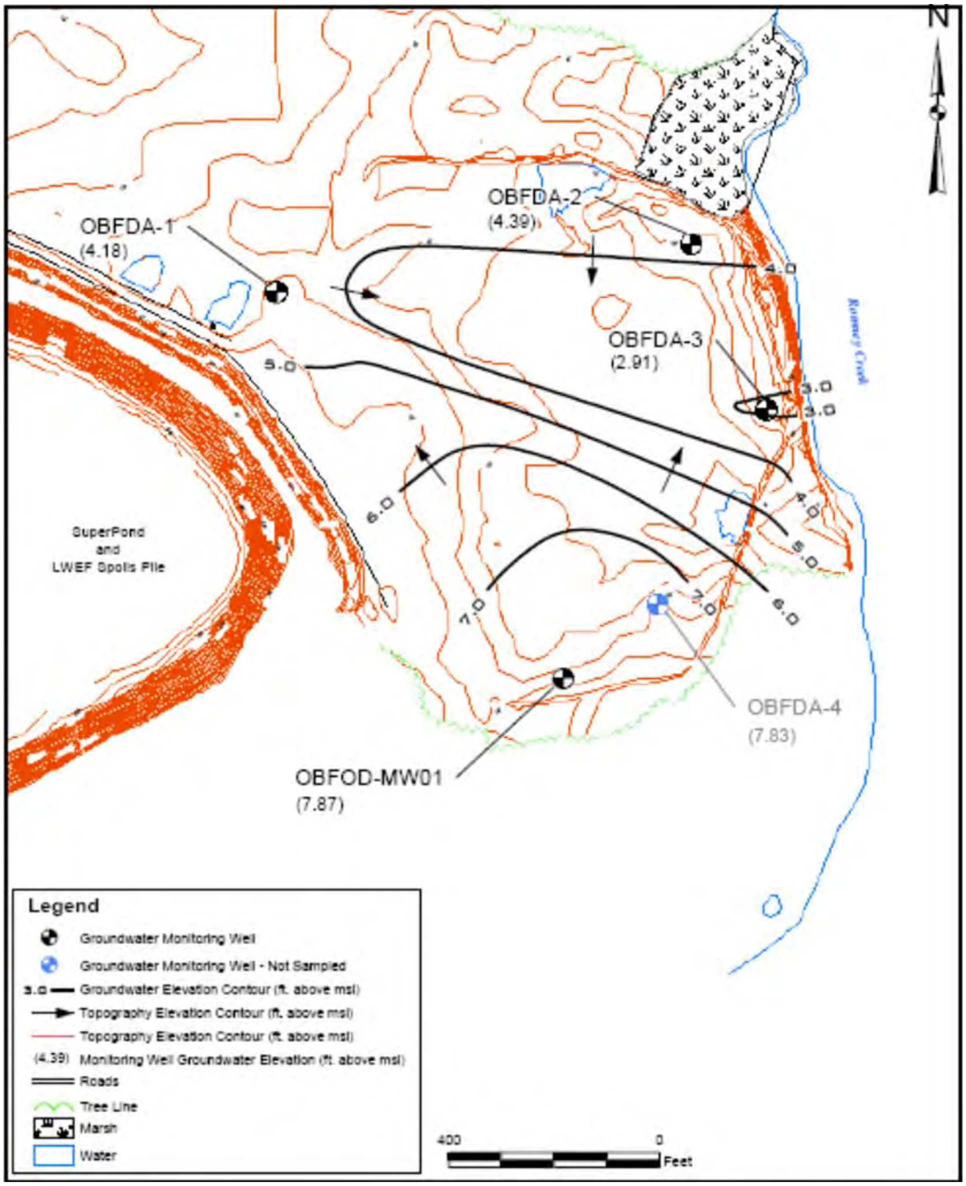

Figure 5. Water elevation map (September 24, 2003).

2.2 Treatability study

A treatability study was performed prior to the field demonstration to determine the lime dosing rate for the APG soil and to establish longevity of the treatment and depth of the reactive pH zone (Larson et al. 2007). A 10-gallon soil sample was collected from the OD area in July 2007 for lab testing at ERDC-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. These factors include 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 (COPC) properties expected following amendment application.

2.3 Baseline characterization

The sampling design for the site is shown in Figure 6 illustrating the collection points for soil and water samples. Baseline characterization included a count of invertebrate types and quantities, analysis of surface and sub-surface soil and pore/ground and surface water samples to determine concentrations of explosives and metals, and pH. Perchlorates, volatile organic compounds (VOCs) and semi-volatile compounds (SVOCs) were also analyzed for some samples. Baseline air samples were collected for calcium and particulates.

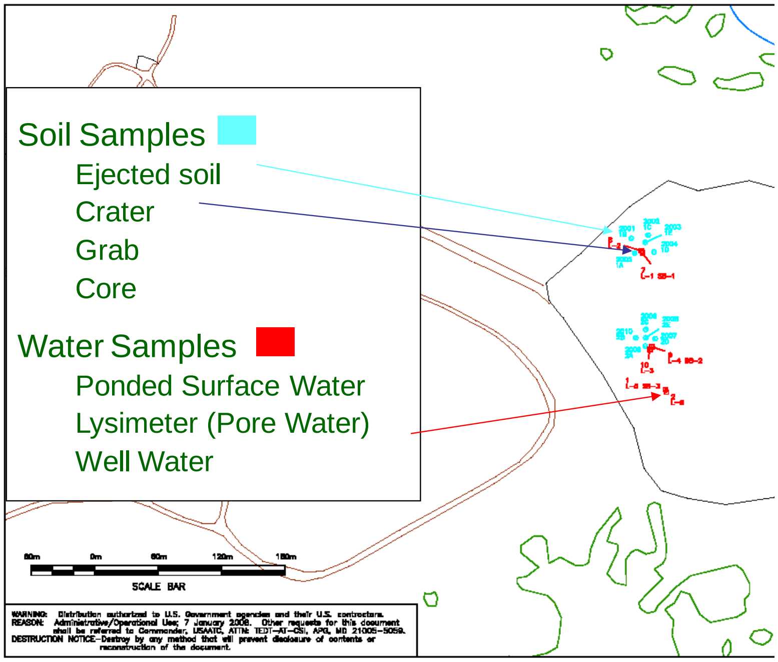

Figure 6. Test area sampling locations.

The Hydrologic Evaluation of Landfill Performance (HELP) model (ver.3.07, November 1997) was used to estimate both runoff water and vertical migration of moisture on the APG OD facility. Soluble products from the degradation of energetic compounds in soil should follow the flow of water. Two estimates were prepared; results after two (2) years, and after fifty (50) years. The HELP model analyses were prepared by ERDC-EL, Water Quality Modeling Branch.

2.4 Lime application methods

The field demonstration involved adding hydrated lime to the OD area to transform explosive residues and stabilize metals at the site. This would prevent off-site migration by both classes of soil contaminants. The APG discs the OD site once a year to prevent vegetation growth that may promote brush fires on the range. Lime addition was coordinated with the regular discing to manage explosives in the shallow surface soil layer. Lime was spread on the site with a drop spreader and then it was disced 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 munitions before the detonations. Seven amendment methods were evaluated. 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.

3 Materials and Methods

3.1 Treatability study

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 the liming dosage rates that would elevate the soil to the desired pH. Initial lime dosage rates were determined using ASTM Method D6276-99a (ASTM 1999) as described in Davis et al. (2007c).

Column study

A second treatability study was undertaken to answer questions concerning the longevity of the treatment and the depth of the reactive pH zone. This was designed as a column study using lime-amended site soil and the unamended site soil (Figure 7). Two treatment variations were considered:

1. Amended soil on top of the unamended soil (as shown in Figure 7), and
2. Unamended soil covering the lime-amended soil (as might happen during soil ejection from the detonation crater).

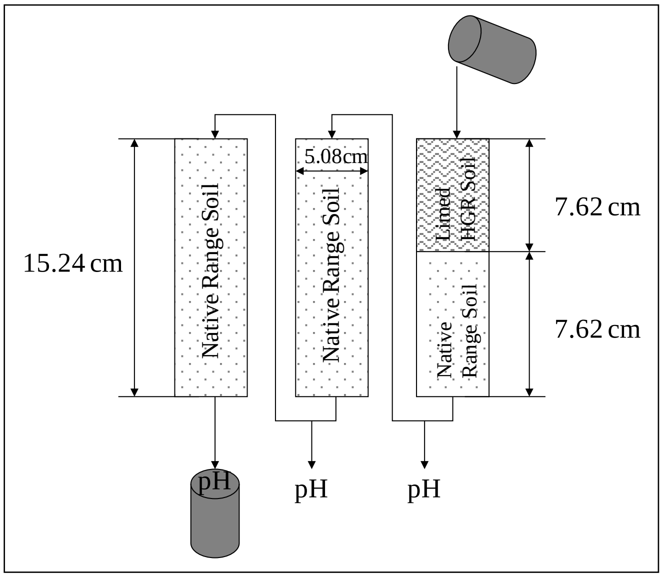

Figure 7. The column study used to test treatment options and longevity by tracking pH in the leachate from the APG OD soil.

3.2 Baseline site characterization

Baseline surface/sub-surface soil, pore water, groundwater and surface water samples were collected. A baseline survey of soil invertebrates was performed in the top 6 in. 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.

Aberdeen Test Center personnel collected the samples and shipped them to ERDC-EL for analysis. The baseline characterization sampling plan is summarized in Table 1.

Surface soil

Explosives (1,3-dinitrobenzene and nitrobenzene), perchlorate, and inorganics (arsenic, copper, nickel, selenium and zinc) were detected in previous surface soil samples collected from the OBF-OD area. These analytes are considered COPCs in surface soil at the site (USACE 2005). Additional surface soil samples were collected to determine concentrations of these and other parameters relevant to this demonstration.

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-pt composite soil sample was collected from each quadrant from a depth of 0 to 6 in. 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. The baseline results served as a comparison with sample results collected after the addition of lime to the site. Soil samples were collected with a clean stainless steel bowl and spoon. Each soil composite was placed in a stainless steel bowl, homogenized, and then transferred to the sample bottles.

Table 1. Baseline characterization sampling plan.

Media	No. of Sample Locations	Sample Type (Grab or Composite)	Depth Interval	Location	Sampling Method	Rounds	Frequency	Analysis
Surface Soil	4 (1 per quadrant)	30-point composite	0–6 in. bgs	Composites collected in grid pattern	Bowl and spoon	2	Quarterly	Explosives, perchlorate, metals, pH
Sub-surface 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- to 8-hr composite	NA	Perimeter of site	Portable Air Sampler	Minimum of 2 rounds	1 no site activity & 1 detonation	Calcium, PM_{10}
Air	1	4- to 8-hr composite	NA	Personnel	Personnel Air Sampler	Minimum of 2 rounds	Detonations	Calcium Hydroxide, PM_{10}
Ecological Survey	NA	NA	0–6 in. bgs	OD Range Source Area	Survey	1	Once	Soil invertebrate types and count

Notes:

Dissolved metals samples were field filtered.

Field parameters for water samples were collected in the field and included temperature, pH, conductivity and turbidity.

PM_{10} = particulate matter 10: measures particles suspended in the air which have a size range of 10 micrometers or less.

bgs = below ground surface.

NA = not available.

Sub-surface soil

Explosives (2,4-dinitrotoluene, nitrobenzene and RDX), VOCs (1,2-dichloroethane, tetrachloroethene and di-nitrosodiphenylamine), perchlorate, and inorganics (arsenic, cadmium, copper, nickel, thallium and zinc) were detected in previous subsurface soil samples collected from the OBF-OD unit. These analytes are considered COPCs in subsurface soil at the site (USACE 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-foot (ft) depth intervals (0–2 ft bgs, 2–4 ft bgs, etc.) to the top of the water table. 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.

Ejected soil from non-limed detonation craters was also sampled. Typical ejected soil from a detonation is shown in Figure 8. Samples were collected at increasing distances from the point of detonation.

Figure 8. Example of a detonation crater showing the spread of ejected soil.

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 content.

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 co-located 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. A total of 16 lysimeters were installed. 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 hours (hr) to attempt to fill the lysimeter with pore water. 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.

Groundwater

An explosive compound (e.g., RDX), VOCs (1,1-dichloroethene, trichloroethene and tetrachloroethene), perchlorate, bis(2-ethylhexyl)phthlate, and inorganics (aluminum, cobalt and nickel) were detected in previous groundwater samples collected from the OBF-OD unit. These analytes are considered COPCs in groundwater at the site (USACE 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 monitoring wells (OBFDA-1, OBFDA-2, and OBFOD-MW01) and one down-gradient monitoring well (OBFDA-3) at the site (Figures 4 and 5). Groundwater at the site can be as shallow as 4 to 9 ft bgs. A groundwater elevation map for the site is shown in Figure 5, but may not reflect the latest elevations due to range maintenance activity.

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 (Figure 9). 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.

Surface water

Since there are no defined surface water pathways from the OD area, water samples were collected from ponded water that accumulated 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 in the laboratory for explosives, total metals and dissolved metals.

Figure 9. Groundwater sample collection.

Air monitoring

Lime dust could potentially be an irritant to personnel working with the lime and to personnel outside the site perimeter. Air samples were collected during baseline characterization and analyzed for calcium and particulate matter (PM_{10}) during detonations without lime. PM_{10} analyzes for particles suspended in air that are 10 micrometers (µm) or less and can sufficiently penetrate into the human lungs. Two rounds of samples were collected for baseline analysis. Four samplers were located along the perimeter of the site during detonations. One person involved with the set up of the detonation materials and lime spreading 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 L per minute (L/min) was used to conduct the air sampling for ambient levels of calcium 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 PM_{10}, to facilitate recovery of the collected particulate matter. The PM_{10} size fraction was chosen given its high mobility properties in ambient air, therefore giving it a high potential for reaching the boundary limits of the OBF-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 calcium (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 the Ca 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 PM_{10}. 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 PM_{10} collected, of which lime was a small fraction.

Three sampling sites were strategically located to triangulate the areas where detonations were to occur:

- At the intersection of the range and the exit road or the west end of the range

- At the far left site near the left side boundary of the range when facing the water or the north side
- At 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 feet of each detonation. The ambient weather conditions during sampling events are provided in Appendix B.

A 24-hr zero background sample (when no detonations were occurring) was collected in July of 2008 to determine background levels of Ca. 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 very low, thereby contributing little to the total Ca.

The USEPA Method 6010B (1999) was used to analyze for the metal Ca in ambient air. For the stabilization of heavy metals it is important that the biopolymer cross-links around the adsorbed metal and soil particle to reduce the mobility of the soil particle in water and the transport of the heavy metal. No other acceptable laboratory methods for ambient air levels of $Ca(OH)_2$ 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/molarmass/$Ca(OH)_2$. Therefore, the total weight of the collected lime equals the Ca weight divided by 0.54092.

Soil invertebrates

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 in.) 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.

Hydrologic Evaluation of Landfill Performance (HELP model)

The shallow aquifer underlying the OBOD area consists primarily of interbedded, unconsolidated sediment with relatively low permeability. The general direction of groundwater flow is from the OBOD units to nearby surface water discharge areas such as Romney Creek and the Bush River. 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 OBOD units. Migration of groundwater contaminants identified during the site characterization study is limited to the immediate vicinity of the OBOD unit with discharge to local surface water bodies.

The HELP model (ver. 3.07) was initially developed by the ERDC-EL for the USEPA Risk Reduction Engineering Laboratory. The runoff water curves were computed using as a soil base soil texture #14 with a good stand of grass, a surface slope of 1.0% and a slope length of 1,200 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 2 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.

3.3 Field demonstration

Demonstration monitoring was performed for 18 months. During the 18-month monitoring period, no site maintenance—aside from the addition of lime to the detonations—was performed.

Table 2. 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

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

The lime application by detonations occurred with the routine munitions waste disposal detonations the first 12 months of the 18-month monitoring period. Lime (between 2 and 4 cubic yards) was mixed into the detonation area soil by seven amendment methods tested from December 2008 to December 2009. The detonations dispersed the lime along with the crater ejecta. Effective dispersion was monitored by surface soil sampling after the detonation fallout settled. The methods of lime application during a detonation event are discussed in Section 2.4 of this report and ranged from no additional lime in the detonation area, to lime buried with the detonation material. Common elements of the application method variations were:

- the initial lime application over the nine-acre site; and
- backfilling the detonation crater with 0.625 tons (1,250 lb, ½ of a pallet) of lime.

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 spanned the depth of the detonation crater. As more lime-amended detonations occurred, the deep treatment zones were promulgated throughout the OD range. This dispersion method would be the typical application technique for sites that are dudded (contain UXO) or at facilities that do not regularly till the site as a standard maintenance practice.

The lime application was curtailed after the first twelve months to monitor pH effect dissipation with respect to time. This information will provide insight into the application frequency required to effectively manage the munitions COPC in the soil.

Initial topical lime application

The entire nine 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 six inches as shown in Figure 10. The first addition of lime was performed in October 2008 using a drop spreader and then discing the lime into the soil. Once the lime was mixed into soil, its presence was not obvious.

Figure 10. 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 PPE. B. The lime is then disced into the soil to a depth of 6 in. using a tractor and disc attachment. C. The completed site. Minimal lime is exposed on the soil surface.

The initial liming was performed to destroy munitions constituents in the top 6-in. soil profile, since the OD range was an active range and there had been measureable concentrations of munitions constituents present in the soil prior to the studies' baseline sampling. In essence, the liming event provided low levels of munitions constituents in the surface soil (i.e., the top 6 in.) for the field demonstration.

Lime application in and around detonation craters

The normal setup for detonating explosives is to:

1. dig a 3- to 4-ft deep pit;
2. place waste explosives and donor charge in the pit; and
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) was formed over the pit. This basic configuration was used for all detonations conducted during the test except for Methods 1 and 2. Each of the methods 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 nine acre site; and
- backfilling the detonation crater with 0.625 tons (1,250 lb, ½ of a pallet) of lime.

Method 1 – Placed bags of lime directly on top of the explosives prior to backfilling the pit. Soil (1–3 ft) was 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 11). Another 1.25 tons of lime was mixed in the post-detonation pit during backfilling.

Figure 11. Illustration of Test Method 6 in which the detonation pit was filled with soil covering the explosives and mounded approximately 8-ft high. Intact bags of lime surrounded the mound on three sides.

Method 6a – The same as Method 6 except that more lime—2.5 tons—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.

These methods allowed the detonation to disperse the lime where it was mixed with the ejected soil. Effective dispersion was monitored by surface soil sampling after the detonation fallout settled. Once surface soil sampling was complete, up to 1 cubic yard of 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.

Sampling methods

Soil and aqueous samples were taken and analyzed for explosives and metals as described during "Baseline Characterization."

Assess the effects of liming on soil drainage and metal leaching

Metal leaching

The leaching of metals from limed soil was evaluated at the conclusion of the demonstration using the Toxicity Characteristic Leaching Procedure (TCLP), USEPA SW-846 Method 1311 (1999) and the Distilled, Deionized Water Suspend and Settle (DDI S&S) leaching procedure.

Hydraulic conductivity

Hydraulic conductivity testing was performed pre- and post-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.

3.4 Sample analysis

Soil and aqueous samples were analyzed according to the methods shown in Table 3. The data obtained from the lime demonstration project is presented as explosives removal as a function of time. Changes in concentrations of metals, other explosives, and pH in soil and aqueous media were also evaluated. The test data were compared to the baseline data and established regulatory levels or guidance, where available, to evaluate the lime technology performance.

Table 3. Analysis methods.

Analysis	Method
Soils	
Explosives	SW-846 8330 / 8095/8330 B
Metals	SW-846 6010
pH	SW-846 9045
Aqueous	
Explosives	SW-846 8330 / 8095
Total metals	SW-846 6020
Dissolved metals	SW-846 6020
pH	EPA 150.1
Hardness (total as $CaCO_3$)	EPA 130.2
Perchlorate	EPA 314
VOCs	EPA 8260
SVOCs	EPA 8270
Air	
Calcium	NIOSH Method 7020
PM_{10}	Gravimetric

The experimental control was the baseline sampling that was performed at the site prior to the addition of lime to establish contaminant and chemistry concentrations that are pertinent to the evaluation of the explosives transformation study.

Several weather parameters can affect the performance of the technology, including precipitation amounts and frequency, and the interval between rain events. These variables, as well as temperature and humidity, can affect soil moisture, which is pertinent to this technology. Wind speed and direction could also affect the atmospheric transport of lime. The APG operates a weather station located at the OBOD area. Data from the weather was retrieved, including rainfall amounts, temperature, wind speed, wind direction, and humidity (this data is available on CD by request).

4 Results and Discussion

4.1 Treatability study

Lime dosing study

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 nine acre site. During the initial topical application and discing, approximately 26 cubic yards of lime were added to the soil to raise the pH to 11 (Table 4). After initial treatment, lime was incorporated into the pit with the explosives prior to the detonations. The incorporated lime treated 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 cubic yards of lime was added to each detonation and approximately the same amount was spread in the crater after the detonation (Table 5).

Column study

Results from the column study are shown in Table 6. Soil pH was affected to the greatest extent when unlimed soil was placed over the lime-amended soil. This could indicate simply that the pH experienced less soil buffering over the shorter distance to the sample port. 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. The 6-in. tilling depth would be sufficient to raise the pH to the reactive level in the surface soils but the pH change would not be readily transported to groundwater.

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 munitions pre-detonation in several different ways.
- Lime was mixed with the backfill soil and used to fill the detonation crater following each detonation event.

Table 4. Calculations to establish lime loading rate for topical application at the APG OD site.[1]

Area	9 acres = 392,040 sq ft
Depth	0.5 ft
Soil Volume	196,020 cubic ft
Soil Density (estimated)	1.6 g/cm^3 = 100 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 g/cm^3 = 140 lb/ft^3
Lime Volume Required	26 cubic yards

[1] Initial loading rate determined using ASTM Method D6276-99a (ASTM 1999).

Table 5. Calculations to determine the quantity of lime added to the detonation area to account for soil dispersion.

Crater Volume[1]	3,600 cubic 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	1,800 lb = 0.9 tons
Lime Density	2.24 g/cm^3 = 140 lb/ft^3
Lime Volume Required (minimum)	0.5 cubic yard
Recommended lime quantity added to each detonation. (Accounts for dispersion loss outside of crater fill collection area[2])	4 to 8 times the minimum lime volume (2 to 4 cubic yards)

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

[2] 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.

Table 6. Results of the column treatability study.

	Leachate pH			
Column Treatment	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

4.2 Baseline site characterization

As discussed in Section 2.1, the OD facility on the Aberdeen Proving Ground is in continuous use with over 12 detonations per year, accounting for over 500 lb of NEW munitions per detonation. A donor charge (C4) is added at a 1:1 ratio with the waste munitions NEW. This rate and type of use continued throughout the field demonstration continuously adding munition residues to the soil. The initial liming of the site destroyed the majority of the background residues, permitting effective comparison of the lime treatment to the background concentrations.

Soil samples

Surface soil

Surface soil pH ranged from 4.8 to 5.3.

Explosives

The results of baseline sampling of surface soil and analysis for explosives are shown in Figure 12. 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 DNX increased over the same time period. TNX was detected from all three sampling events. There was a single detection of HMX.

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

Metals

The frequency of occurrence and concentration of metal contaminants of potential concern (CPOC) in the surface soil are shown in Figure 13. Copper and zinc were routinely detected at concentrations ranging from 14 mg/kg to 32 mg/kg. Nickel was detected only during the three earliest (2008) sampling events. Calcium concentrations were stable at approximately 2,600 mg/kg. Aluminum ranged from 4,200 to 6,500 mg/kg. The soil from APG had a high percentage of clay in the fines. Aluminum 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). Neither selenium nor arsenic was detected in the surface soil during the baseline characterization of the APG OD site.

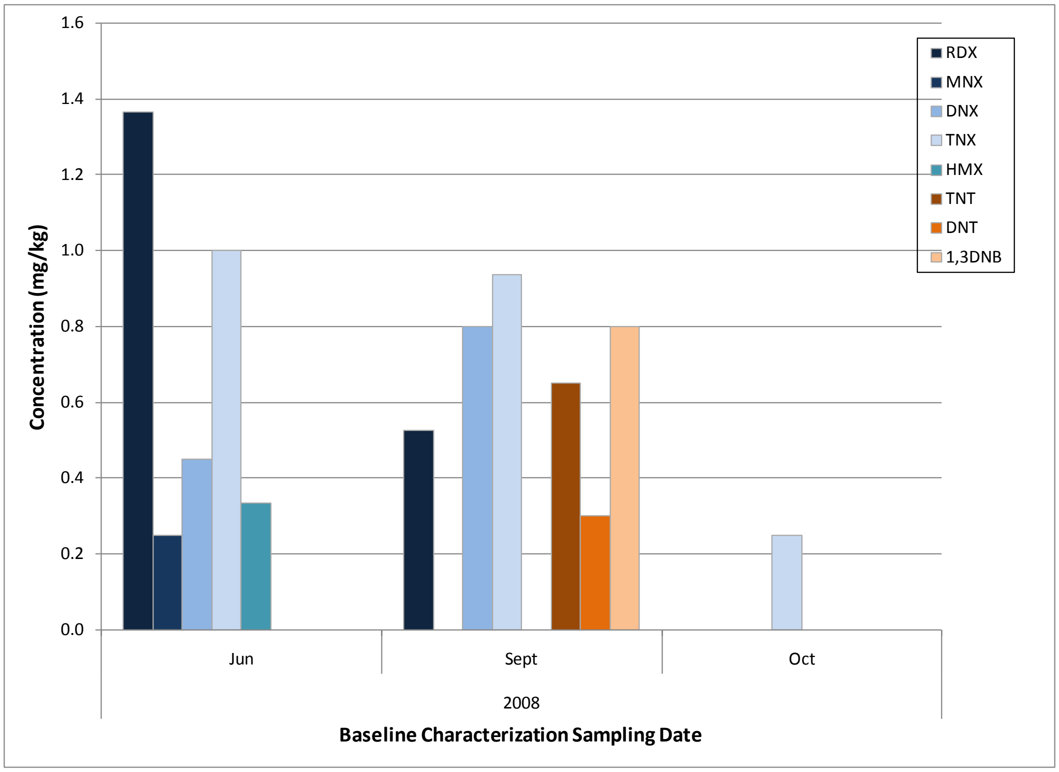

Figure 12. Average concentration of energetic compounds in surface soil during baseline characterization of the APG OD site.

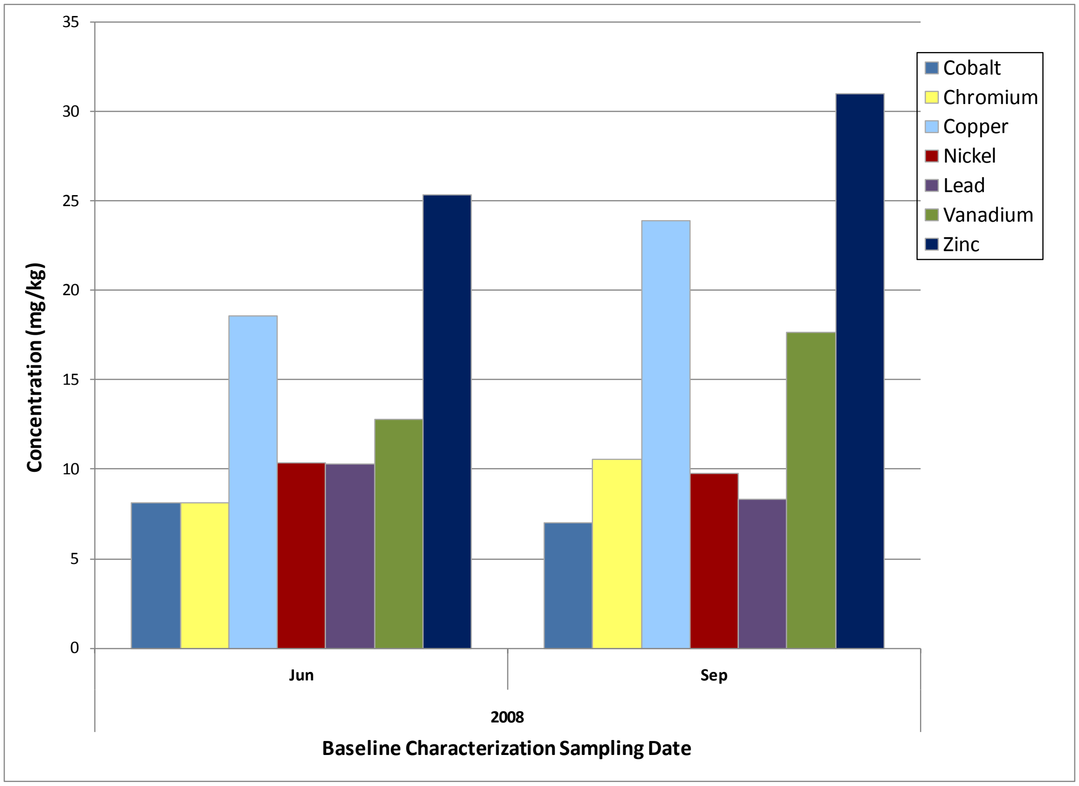

Figure 13. Average concentration of metal COPC in samples from the surface soil (n=4).

Sub-surface/ejected soil

Explosives

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.

In the ejected soil, the major explosive detected at all distances was RDX. Prior to lime addition (October 2008) explosives detected nearest to the detonation area were RDX, MNX, and the ADNTs.

Metals

Concentrations of metals in the subsurface soil are illustrated in Figure 14 for Cu, Ni, and Zn. There was no detection of arsenic, cadmium, or thallium. Copper, Ni and Zn were detected at concentrations that were consistent across the depth profile of the soil, as was Fe and Pb. Calcium 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 the soil at 9,200 mg/kg (Sposito 2008). Cobalt was only detected in the upper 4 ft of the soil. The source of the Co was probably destroyed munitons. Vanadium was also detected at low concentrations (16 to 23 mg/kg) at all soil depths and is also probably from destroyed munitions.

Copper, Ni, and Zn were also detected in the ejected soil (Figure 15). Copper 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), Pb (10 to 26 mg/kg), and V (9 to 19 mg/kg). Nickel 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.

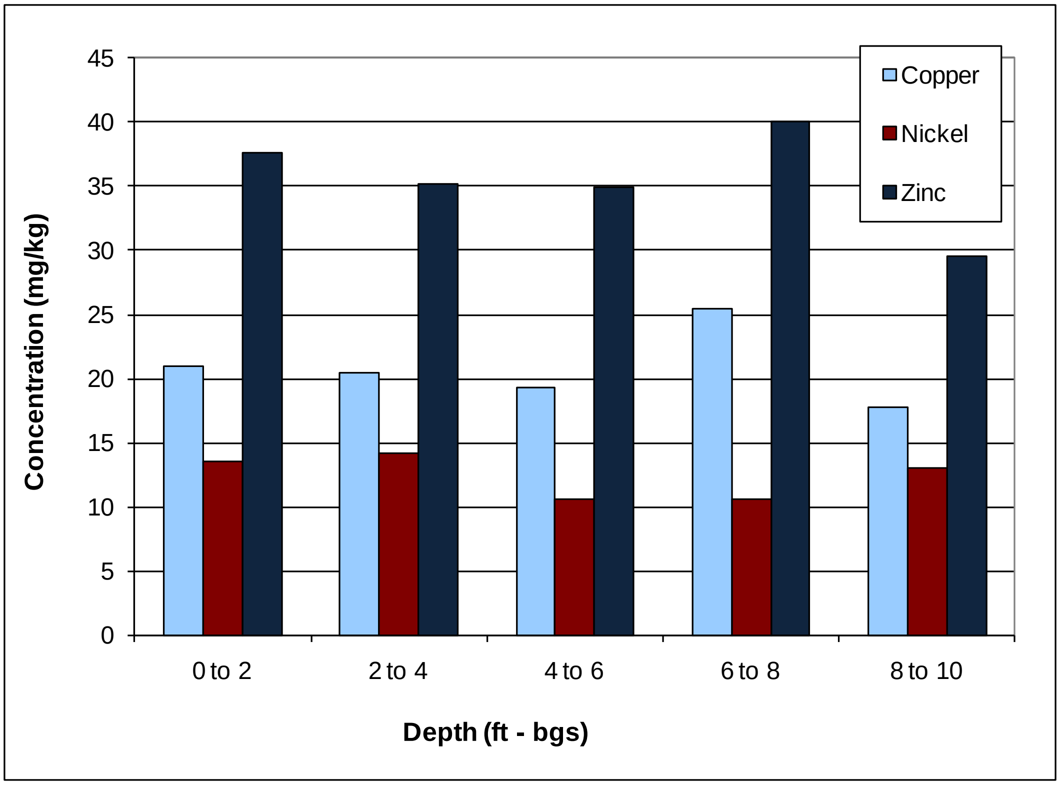

Figure 14. Concentrations of metals in the sub-surface soil by depth during baseline characterization studies of the APG OD area.

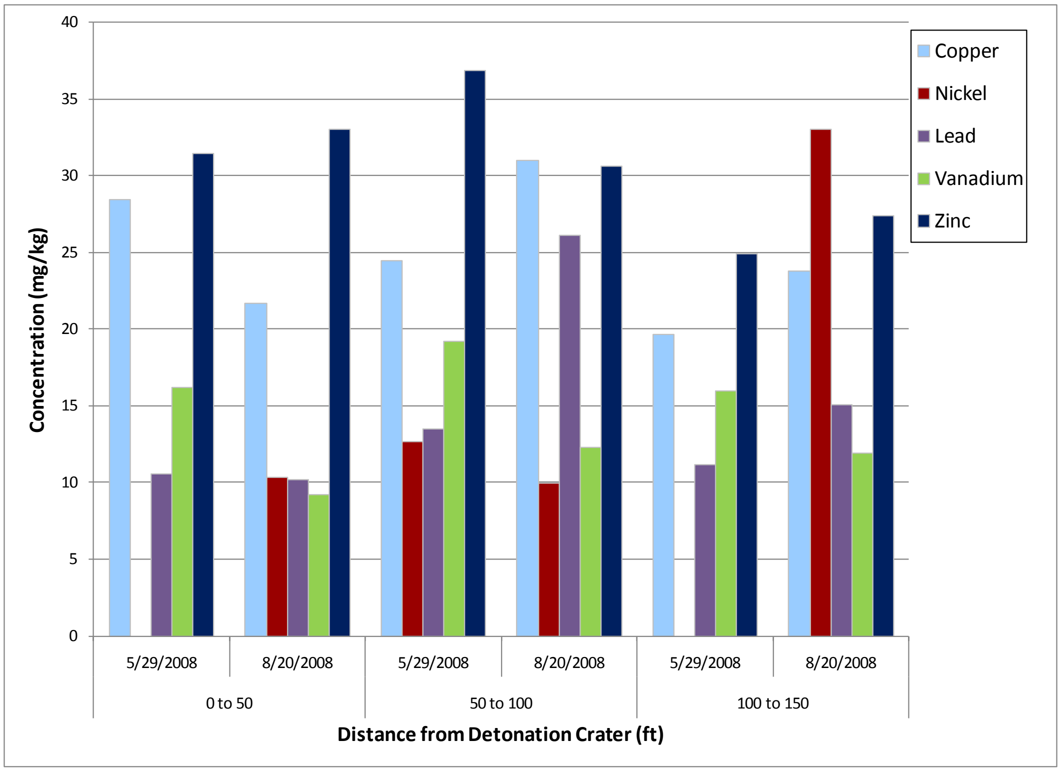

Figure 15. Concentration of metals in ejected soil at increasing distance from the detonation crater.

Aluminum and Fe were also detected in the ejected soil, although not shown in Figure 15. Aluminum concentrations ranged from 2,600 mg/kg in the outermost ring to 6,600 in the innermost ring, well within the mean concentration typically found in soils (Sposito 2008). The concentrations detected following the second detonation event were 1/3 those of the first event and may be due to differences in munition formulations. Iron was present at each sampling distance from the crater with maximum concentrations detected from the center sampling ring. Overall concentrations ranged from 6,000 mg/kg to 9,400 mg/kg. Background calcium concentration in the ejected soils ranged from 700 mg/kg to 1,200 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 generally 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.

Aqueous samples

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. Sampling was performed twice, July and September of 2008, prior to the addition of lime to the soil.

Explosives

Concentrations of explosives in the soil pore water are shown in Figure 16. The lysimeters are shown by depth bgs. No MNX was detected following either sampling event. In July, RDX ranged from non-detect up to 0.75 mg/L and up to 0.25 µg/L in September. DNX and TNX were only detected in July at concentrations up to 0.69 µg/L (DNX) and 0.45 µg/L (TNX).

Metals

Results of the metals analysis of pore water samples taken during the baseline characterization studies are shown in Table 7, where they are compared with metal concentrations in other aqueous media.

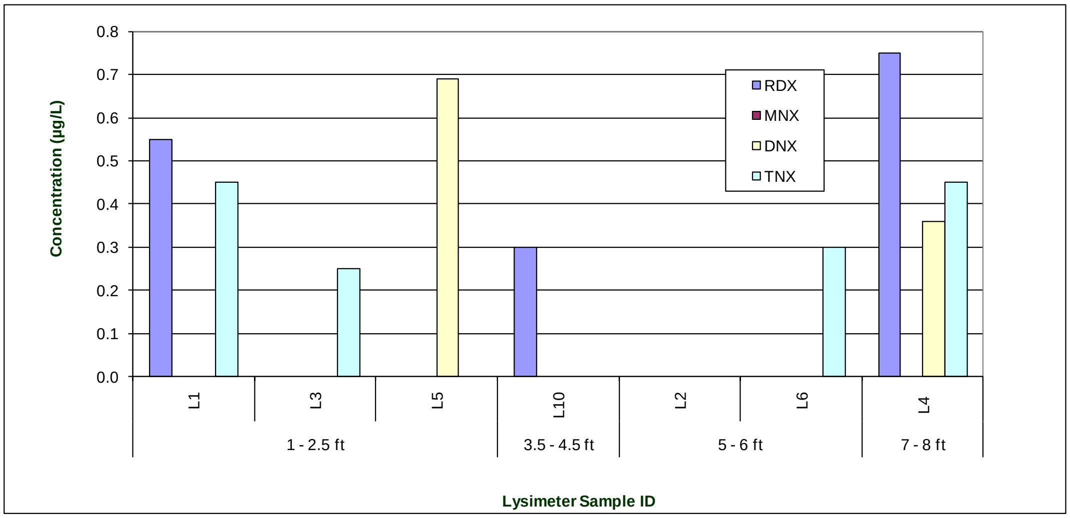

Figure 16. Concentrations of explosives (mg/L) in soil pore water during baseline characterization of the APG OD site.

Table 7. Concentrations of metals detected in pore water, surface water and groundwater samples during baseline characterization of the APG OD site.

	Concentration (mg/L)					
	Surface Water		Pore Water		Groundwater	
Metal	Max	Min	Max	Min	Max	Min
Aluminum	0.50	0.23	nd	nd	0.20	nd
Calcium	98.12	21.56	nd	nd	34.50	5.71
Cadmium	nd	nd	399.16	11.60	nd	nd
Cobalt	0.32	nd	nd	nd	nd	nd
Chromium	nd	nd	0.19	nd	nd	nd
Copper	nd	nd	nd	nd	nd	nd
Iron	0.89	0.29	9.92	nd	0.38	nd
Manganese	8.74	0.07	17.63	0.15	0.19	0.08
Nickel	0.49	nd	0.79	0.14	0.07	nd
Lead	nd	nd	nd	nd	nd	nd
Thallium	0.15	nd	nd	nd	0.81	nd
Vanadium	nd	nd	nd	nd	nd	nd
Zinc	0.42	nd	0.08	nd	nd	nd

nd = non-detect (below the laboratory detection limit of 0.025 mg/L).

Groundwater

A minimum of one round of baseline groundwater samples were collected from the four monitoring wells located at the OD area. The pH of the groundwater samples ranged from 5.0 to 5.6. Trace VOCs included TCE (5.0 µg/L), PCE (0.006 µg/L), and *cis*-1,2-DCE (0.014 µg/L). No SVOCs were detected in the groundwater samples.

Explosives

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. The laboratory detection limit for explosives in groundwater was 0.05 µg/L. Perchlorate was below detection limits for all samples (<0.2 µg/L).

Metals

The results of the metals analysis of groundwater samples taken during the baseline characterization studies are shown in Table 7.

Surface water

Surface water samples were collected from ponded water that accumulated 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 pH of the surface water samples ranged from 4.3 to 6.7.

Explosives

Each of the four surface water 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 17).

Metals

The results of the metals analysis of surface water, pore water and groundwater samples taken during the baseline characterization studies are shown in Table 7.

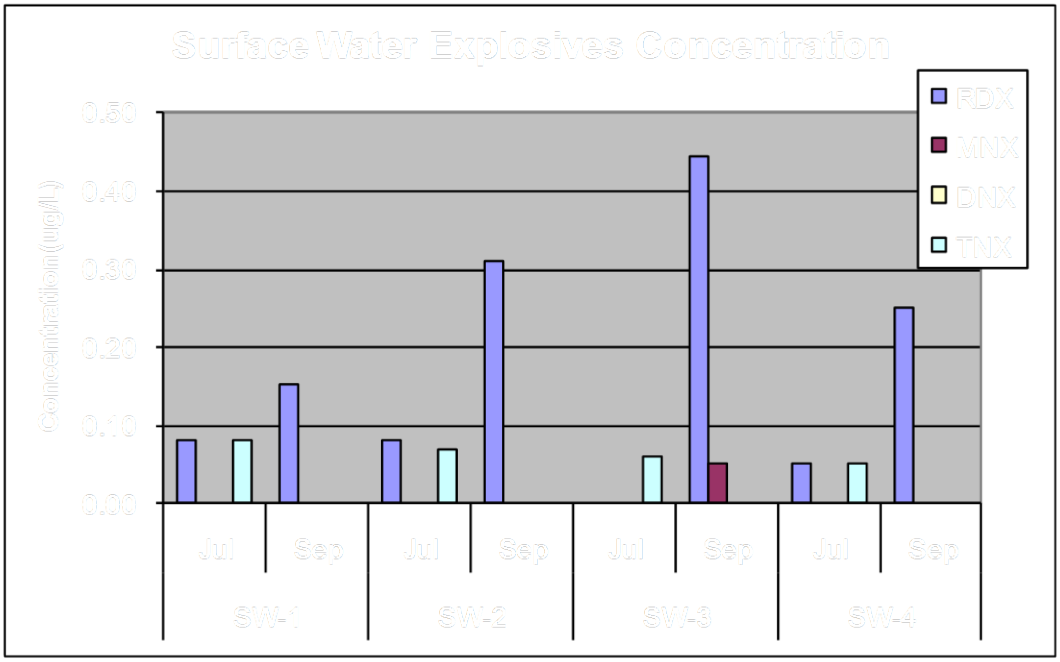

Figure 17. Baseline concentrations of explosives in surface water on the APG OD site.

Air monitoring

A 24-hr zero background sample (when no detonations were occurring) was collected in July of 2008 to determine background levels of Ca. 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 very low, thereby contributing little to the total Ca.

Soil invertebrates

No macroinvertebrates were found in any of the soil samples taken for baseline characterization of the APG OD range. There are several reasons why this is not an unexpected occurrence:

1. APG tills the OB-OD range which is not good for the micro/ macroinvertebrates in the soil, such as earthworms. The act of tilling alone can influence the lack of species in the area (Kladivko 1993).
2. Active earthwork and explosions affect the soil and disturb micro/ macroinvertebrates; therefore, they have a tendency to not live in those areas.

3. The range is physically cut off from the surrounding area with berms and roads that disrupt the movement of micro/macroinvertebrates into the OB/OD area, making it an isolated island-type environment.

There may be some affect on the micro/macroinvertebrate populations due to munitions constituents on the range, but this may also be due to other factors affecting the range, such as tillage, earthwork, and the physical structure of the site.

Hydrologic Evaluation of Landfill Performance (HELP model)

The HELP model (ver. 3.07) was initially developed by the ERDC-EL for the USEPA Risk Reduction Engineering Laboratory. The runoff water curves were computed using as a soil base of soil texture #14 with a good stand of grass, a surface slope of 1.0% and a slope length of 1,200 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 results of the model runs are compared in Table 8 for Year 1, Year 2, and Year 50. The complete model output results are available in Appendix D.

Table 8. Runoff water and leachate estimations as calculated by the HELP model for 1-year, 2-years, and 50-years on the APG OBOD area.

	Year 1		Year 2		Year 50	
Parameter Measured	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 the course of 50 years, the peak value for percolation through the barrier layer of soil (layer 4) was predicted to be 0.22 in. The predicted peak value for hydraulic head on layer 4 was 0.10. The highest value for runoff water was 2.54 in. Based on the predicted results from the HELP model over the 50-year 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.

Hydraulic conductivity testing was performed 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/sec (for unamended soil) to 3.0×10^{-3} cm/sec (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.

4.3 Field demonstration

The objective of the lime technology demonstration was to confirm at a large, relatively unconfined field site 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.

Lime application methods

As outlined in Section 3.3, 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 of 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. Soil was moist to very moist with some ponded surface water evident on the site. Winds were not significant.

Method 6a: The same as Method 6 except that more lime was added to the detonation (2.5 tons instead of 1.25 tons).

Soil samples

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

Surface soil

Explosives

As seen in Figure 18, 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.

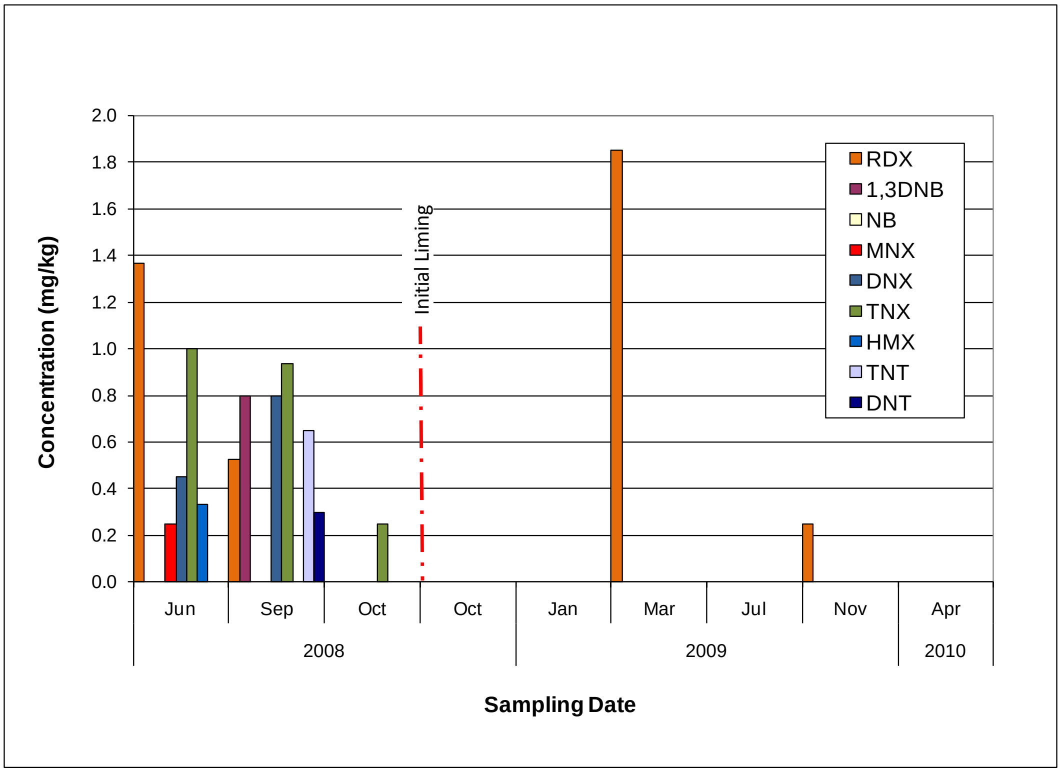

Figure 18. Average surface soil concentrations of energetic COPCs (mg/kg).

Metals

Pre- and post-liming concentrations of metals of potential concern are shown in Figure 19. 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 hand grenade range liming field study, that the increase in pH stabilizes the majority of metals in the soil.

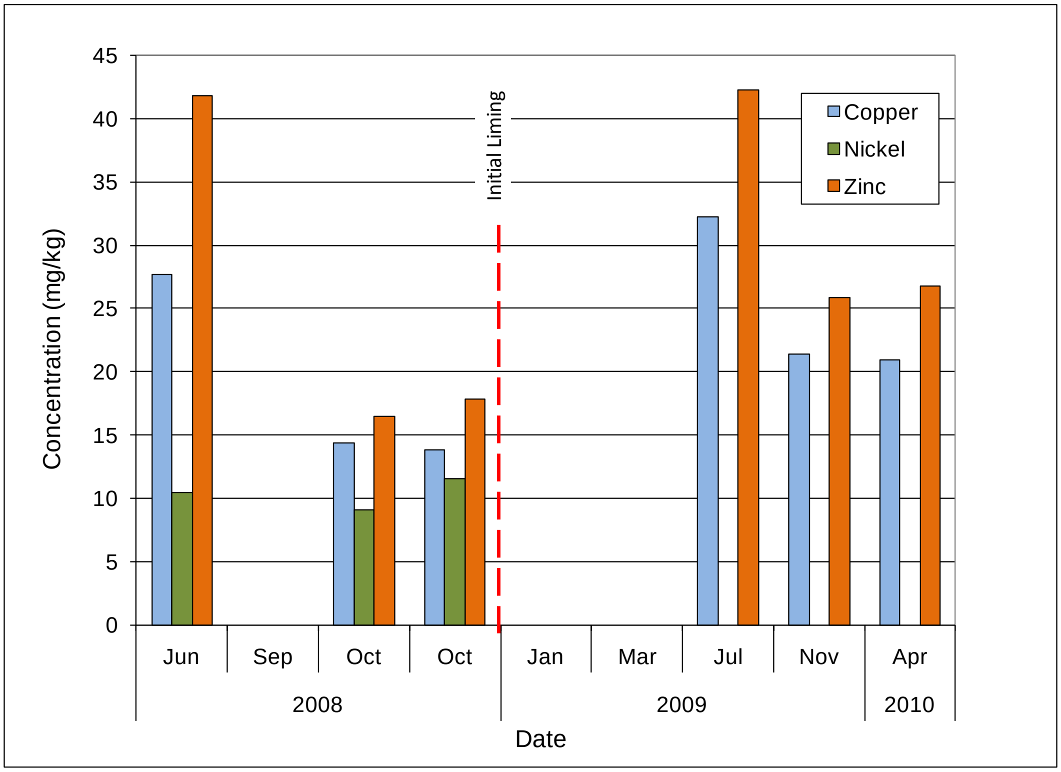

Figure 19. Average surface soil concentrations of metals pre- and post-liming (mg/kg).

Leaching of metals

At the conclusion of the field demonstration, four samples of the surface soil were taken and subjected to two separate leaching tests, the TCLP and DDI 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 hr. 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-µm 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 9. Of the COPC on the APG OD site, TCLP limits have only been established for arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and selenium (Se) (40 CFR §261.24). Metals not leached by the TCLP, and not included in the table, were Sb, As, Cd, Co, Cr, Mo, Tl, and V. Lead 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 (2) surface soil samples but only one replicate each. It is therefore presumed to have originated with destroyed munitions.

Table 9. Concentration of metals in TCLP extraction solution from post-liming soil.

	Concentration (µg/L) and Standard Deviation				
Metal	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[1]	nd	nd	nd	0.04[1]
Fe	0.01 ± 0.10	nd	0.05 ± 0.01	0.04[1]	0.06 ± 0.03
Pb	0.18 ± 0.21	0.14 ± 0.08	0.11 ± 0.02	0.05[1]	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[1]	nd	nd	nd
Zn	0.05 ± 0.02	0.09[1]	0.05 ± 0.02	0.04[1]	0.03 ± 0.00

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

[1] Single detection, no statistical analysis possible.

The results of the DDI S&S analysis are shown in Table 10. Metals not leached from the soil by the DDI S&S procedure were Sb, As, Co, Cr, Cu, Mo, Ni, Se, Tl, and V. Tungsten (W) was noted in one (1) surface soil sample at an average concentration of 0.03 ± 0.00 µg/L. The W is presumed to have originated with destroyed munitions. The metals Pb

(0.03 ± 0.01 µg/L) and Zn (0.04 ± 0.00 µg/L) were also only detected in one surface soil sample. Cadmium was leached from the soil by the DDI S&S procedure, although not detected in the TCLP extraction solutions. Aluminum and Fe, two metals leached by both procedures, were detected at higher concentration by the DDI S&S procedure.

Table 10. 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[1]	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[1]	0.03[1]	nd	nd

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

[1] Single detection, no statistical analysis possible.

Sub-surface/ejected soil

Explosives

The concentrations of energetic COPCs in soil ejected from the detonation crater are shown in Figure 20. 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 only detected 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.

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.

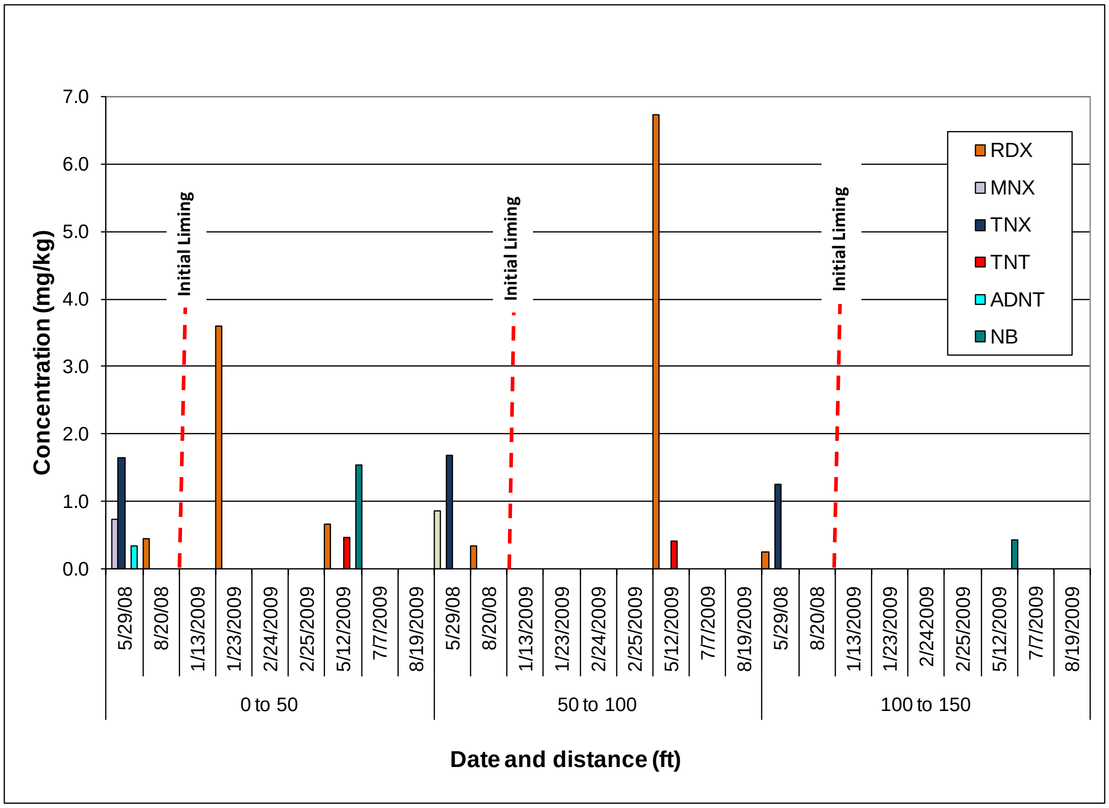

Figure 20. Average concentration of energetic COPC in soil ejected from the detonation pit in distance from the pit center (mg/kg).

Minimal change in pH was measured in soil pore water, groundwater and surface water following liming as shown in Table 11. 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 11. Change in pH of aqueous media post-liming of the APG OD area.

	pH	
Media	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

Aqueous samples

Pore water

Explosives

The performance metric 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 application are summarized in Table 12. 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 12. Concentrations of explosives detected in soil pore water pre- and post-lime application (µg/L).

Sample Date	Explosives Concentrations (µg/L)			
Pre-Lime	RDX	MNX	DNX	TNX
7/17/08 (n=9)	0.53[1]	<0.05	0.53[2]	0.36[1,2]
9/18/08 (n=9)	0.12[2]	<0.05	<0.05	<0.05
Post-Lime	All concentrations were below the laboratory detection limit of 0.05 µg/L			

[1] High concentration detected at 7–8 ft bgs.

[2] High concentration detected at 1–2 ft bgs.

Surface water

Explosives

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 13. This objective is considered successful as the explosives concentrations post-liming were non-detect.

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

Sample Date	Explosives Concentrations (µg/L)			
Pre-Lime	RDX	MNX	DNX	TNX
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			

Metals

Concentrations of metals, total and dissolved, in surface water pre- and post-lime application are summarized in Table 14. Only total Tl increased in the post-lime sampling.

Table 14. Concentrations of metals in surface water pre- and post lime application.

	Concentration (mg/L)		
	Pre-Lime		Post-Lime
Metal	7/17/08 (n=4)	9/18/08 (n=5)	(n=17)
Aluminum (T)	0.32	0.28	1.36
Aluminum (D)	0.09	0.12	0.21
Calcium (T)	91.04	10.22	25.07
Calcium (D)	97.03	12.45	44.15
Cobalt (T)	0.20	0.08	nd
Cobalt (D)	0.21	0.09	nd
Iron (T)	0.60	0.44	1.85
Iron (D)	0.06	nd	0.32
Manganese (T)	3.06	0.77	1.36
Manganese (D)	3.21	0.60	0.14
Nickel (T)	0.30	1.03	0.16
Nickel (D)	0.32	0.09	nd
Thallium (T)	nd	0.09	0.34
Thallium (D)	nd	0.09	nd

T = total concentration.

D = dissolved concentration.

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

Groundwater

Explosives

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)			
Pre-Lime	RDX	MNX	DNX	TNX
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			

Metals

The metals of concern in the groundwater were Al, Co, and Ni. The effect of lime application on metals immobilization is shown in Figure 21 for the dissolved and total metals. Cobalt, not shown, was only detected once, at 0.04 mg/L.

Concentrations of metals were unchanged by liming, except for Al, which appeared to increase post-liming.

Air monitoring

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 16). During the lime spreading, personnel wore the samplers while each carried a 50-lb bag of lime. They cut the bags open with a razor knife, and then dumped the bags into a spreader. The personnel wore air-purifying respirators, disposable coverall suits and gloves. Conditions were extremely dusty during this operation.

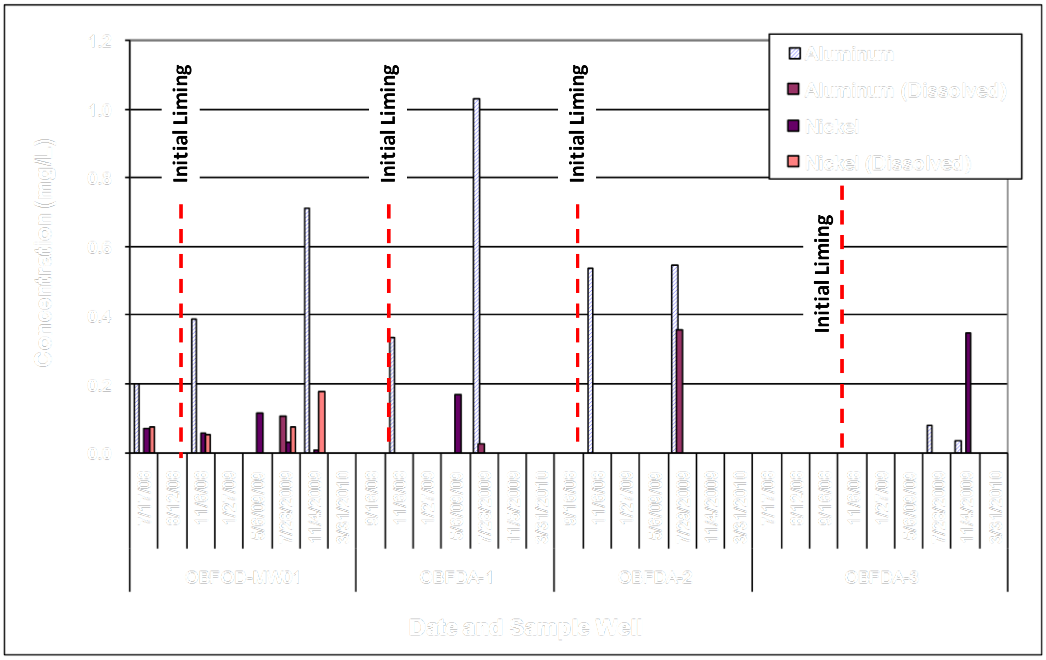

Figure 21. Concentration of dissolved and total metals of concern in groundwater pre- and post-lime application (mg/L).

Table 16. Personnel air sampler results from lime spreading activity during topical application.

Sample Date	Sample Duration (min)	Chemical Monitored	Results (mg/m³ 8-hr TWA)	PEL TLV (mg/m³)	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	Calcium hydroxide	6.26	5	Yes

TWA = time-weighted average.

PEL = permissible exposure limit.

TLV = threshold limit value.

NaOH = sodium hydroxide.

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

Detonation lime application method

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/m^3 (Table 17). This result was well below the PEL of 15 mg/m^3 (Code of Federal Regulations (CFR) 2008) action limit. The 8-hr TWA air sampling result for $Ca(OH)_2$ was 0.06 mg/m^3 and was well below the PEL of 5 mg/m^3 (American Conference of Government Industrial Hygienists (ACGIH) 2008).

Table 17. 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	Calcium 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 personal protective equipment. 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.

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 disking 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. 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 $\mu g/cm^3$ during the 24-hr zero background and between non-detect and 18 $\mu g/cm^3$ in the background detonation with no lime (Table 18). During one of the days on which lime was topically spread, $Ca(OH)_2$ concentrations at the perimeter of the OD site were between 2.3 and 38 $\mu g/cm^3$.

Table 18. Perimeter air sample results.

Sample Date	Sample Location	$Ca(OH)_2$ ($\mu g/cm^3$)
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 ton of Lime Spreading and Disking		
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 $\mu g/cm^3$. 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.

Soil invertebrates

The performance metric for this objective was to observe no effect/ 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:

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

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

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/sec (for unamended soil) to 3.0×10^{-3} cm/sec (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.

5 Cost Assessment

The cost of using lime to manage the accumulation and mobility of munitions and constituents of explosives of concern associated with OBOD activities is dependent upon 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 munitions detonations, were field tested on the ATC open detonation area. The cost models and benefits of each application method are discussed below.

5.1 Cost models

The cost elements that influence the use of lime amendments to manage munitions constituents 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 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 19). 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 open burning operations and for an initial broad area management of surface residues on the open detonation area.

Table 19. Cost model for application of lime to an OD facility.

Cost Element	Data Tracked During the Demonstration	Costs	
Treatability study	Personnel and labor required	Project engineer, 3 h	$300
	Materials	Materials (test kits)	$100
	Analytical laboratory costs	Analytical laboratory	NA
Baseline characterization	Standard soil and groundwater monitoring, no cost tracking	NA	
Material cost	Unit: $ per acre for lime material Data requirements:	Material cost/application/acre:	
	Application rate: 5 tons of lime per acre based on soil buffering capacity	Lime ($225/ton)	$1,125
	Reapplication: dependent upon use and potential MEC residue accumulation	PPE	$50
Installation	Unit: $ per acre Data requirements:	3 Technicians, 3 h/each	$675
	Equipment rental (tractor+implements) Time required (3 technicians, 3 h/acre)	Equipment rental/day/acre	$550
Waste disposal	Standard solid waste disposal, no cost tracking	NA	
Long-term monitoring	For the project, standard soil and groundwater monitoring, no cost tracking	NA	
	As a part of facility operations, quarterly monitoring of soil, ground and surface water is recommended	Materials (test kits): $100	
Total project cost		**$2,400/acre + $500 treatability study and monitoring costs**	

NA = not applicable.

Depending upon the size of the OBOD 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 nine acres on the ATC open detonation area at a soil concentration of 0.5% in the top 6-in. layer of soil during this field demonstration. The relevant costs documented in Table 19 reflect a per acre cost ($2,400/acre) to apply and disc the lime in the open detonation 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 OBOD 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 hours 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 personnel protection equipment (PPE) (i.e., Tyvek® clothing and respirator particulate cartridges) for the personnel handling the lime.

The majority of the costs associated with lime application are material cost and labor regardless of the application method. Generally, a baseline characterization should not be needed because these areas have already been characterized to support Resource Conservation and Recovery Act (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 wastes (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 the target pH range is achieved. Standard long-term monitoring practices for OBOD waste facility operations should provide data on munitions 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 20). During each detonation, the open detonation 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 open detonation 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 was already on-site to support waste munitions transport so no additional equipment was needed and actual equipment costs were not collected.

Table 20. Cost model for detonation lime application.

Cost Element	**Data Tracked During the Demonstration**	**Costs**	
Treatability study	Personnel and labor required	Project engineer, 3 h	$300
	Materials	Materials (test kits)	$100
	Analytical laboratory costs	Analytical laboratory	NA
Baseline characterization	Standard soil and groundwater monitoring, no cost tracking	NA	
Material cost	Unit: $ per detonation for lime material Data requirements:	Material cost/application/acre:	
	Application rate: Up to 2.5 tons of lime per detonation depending on the volume of soil ejecta	Lime ($225/ton)	$562
Installation	Unit: $ per detonation Data requirements: Time required (5 technicians, 1 h/detonation)	5 Demolition Technicians, 1 h/each	$750
Waste disposal	Standard solid waste disposal, no cost tracking	NA	
Operation and maintenance costs	No unique requirements recorded	NA	
Long-term monitoring	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		**$1,312/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 it with a spreader, and was easily incorporated into open detonation activities.

The cost to perform the lime spreading with the detonation after startup costs is approximately $1,312 for each detonation. After performing several detonations, the lime setup activities became fairly routine and added approximately 1 hr to the typical five-man crew's normal detonation activities.

5.2 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 unexploded ordnance (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 that 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.

5.3 Cost analysis

OBOD areas are generally open fields on which waste munitions destruction is performed. The area affected by the OBOD operations is dependent upon the amount of NEW allowed in the detonations and the detonation practices used on the site. The cost of managing munition residues on the OBOD area is related to the frequency of lime re-application. At the ATC open detonation area, lime was initially topically applied to the 9 acre area where detonations were conducted at a cost of $21,600 ($2,400 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 $1,200 per detonation. Waste munitions open detonations 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 OBOD areas are permitted waste treatment facilities, off-site transport of contaminants may trigger fines or restrict operations of the facilities until controls are implemented.

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.

Technology cost comparison

There are currently no in situ munitions treatments for open detonation areas.

6 Implementation Issues

6.1 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 hydrated lime [$Ca(OH)_2$], which is not regulated for addition to soil. However, 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 (elevated pH) 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-0216 at a Fort Jackson HGR did not indicate a significant increase in runoff pH. Liming of the soil on the OD facility did not affect the pH of the pore water and groundwater.

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

- 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. 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 munitions constituents 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.
- 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.

- Management goals: To meet more stringent management goals, larger quantities of lime, more efficient soil mixing, or maintaining appropriate soil moisture may be necessary.
- 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.

6.2 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 hand grenade range, 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 0216) were evaluated with regards 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 contaminants of potential concern (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 hand grenade range 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.

6.3 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.

6.4 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 costs 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; and
- Management Goals: More stringent management goals may require additional monitoring to verify that ideal pH levels are maintained.

7 Conclusions and Recommendations

Methods 6 and 6a provided the best lime dispersion performance from the detonation activity.

- **Method 6**: The explosives were buried under a soil mound per normal open detonation procedures. Fifty (50) 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. Soil was moist to very moist with some ponded surface water evident on the site. Winds were not significant.
- **Method 6a**: The same as Method 6 only 2.5 tons of lime was added to the detonation instead of 1.25 tons.

Alkaline hydrolysis of the muntions residues in soil was confirmed. Transport of the residues off-range in surface water or towards groundwater was reduced below baseline levels and met regulatory requirements. Concentrations in aqueous media were non-detect following liming of the OD area and the detonation pits.

It is not clear if alkaline hydrolysis was responsible for the increase in aluminum observed following lime application, but the Al soil concentrations remained well within the national soil concentration averages.

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.

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, and lime application is commonly used in agricultural practices as a soil amendment.

Potential regulatory concerns associated with the use of the lime amendments on OD facilities 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 hand grenade range (Larson et al. 2008), 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 lime the pH was increased to an average of 7.4, with a pH range of 4.3 to 10.4. 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 majority of the costs associated with lime application on an OD site are material cost and labor, regardless of the application method. The materials cost of the lime is dependent upon a number of site factors that may influence the concentration of lime to be added to the soil and the frequency of lime application. The initial topical application of the lime was $2,400/acre. Generally, these costs will scale linearly with increasing acreage for areas with similar soil buffering capacities. Lime application by detonation was $1,200/detonation. The life cycle costs specifically associated with the lime technology are related to the frequency of lime re-application. Currently, there are no other in situ technologies with which to compare treatment costs.

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Appendix A: Lime Dose Calculations

Based on preliminary results from a batch test study using site soil, the ideal lime dosage was calculated to be 0.5% of the dry soil weight to be mixed in the top six inches of soil on the 9-acre site. During the initial topical application and discing, approximately 26 cubic yards of lime were required to raise the pH to 11 in the shallow soil (Table A1). 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. A portion of the lime was applied to the craters after the detonations because scorched soil that possibly contains explosive residue is often observed on the sides of the craters. Lime application to the detonation crater before backfilling of the crater creates a deep subsurface reactive zone to degrade explosives. Approximately 1 to 2 cubic yards of lime were added to each detonation and approximately the same amount was spread in the crater after the detonation (Table A2). This was performed over an approximately one year period (up to 24 detonations). Lime application rates were adjusted, based on the monitoring results, in order to keep the pH of the soil above 10.5.

Table A1. Lime topical application quantity.

Area	9 acres = 392,040 sq ft
Depth	0.5 ft
Soil Volume	196,020 cubic ft
Soil Density (estimated)	1.6 g/cm^3 = 100 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 g/cm^3 = 140 lb/ft^3
Lime Volume Required	26 cubic yards

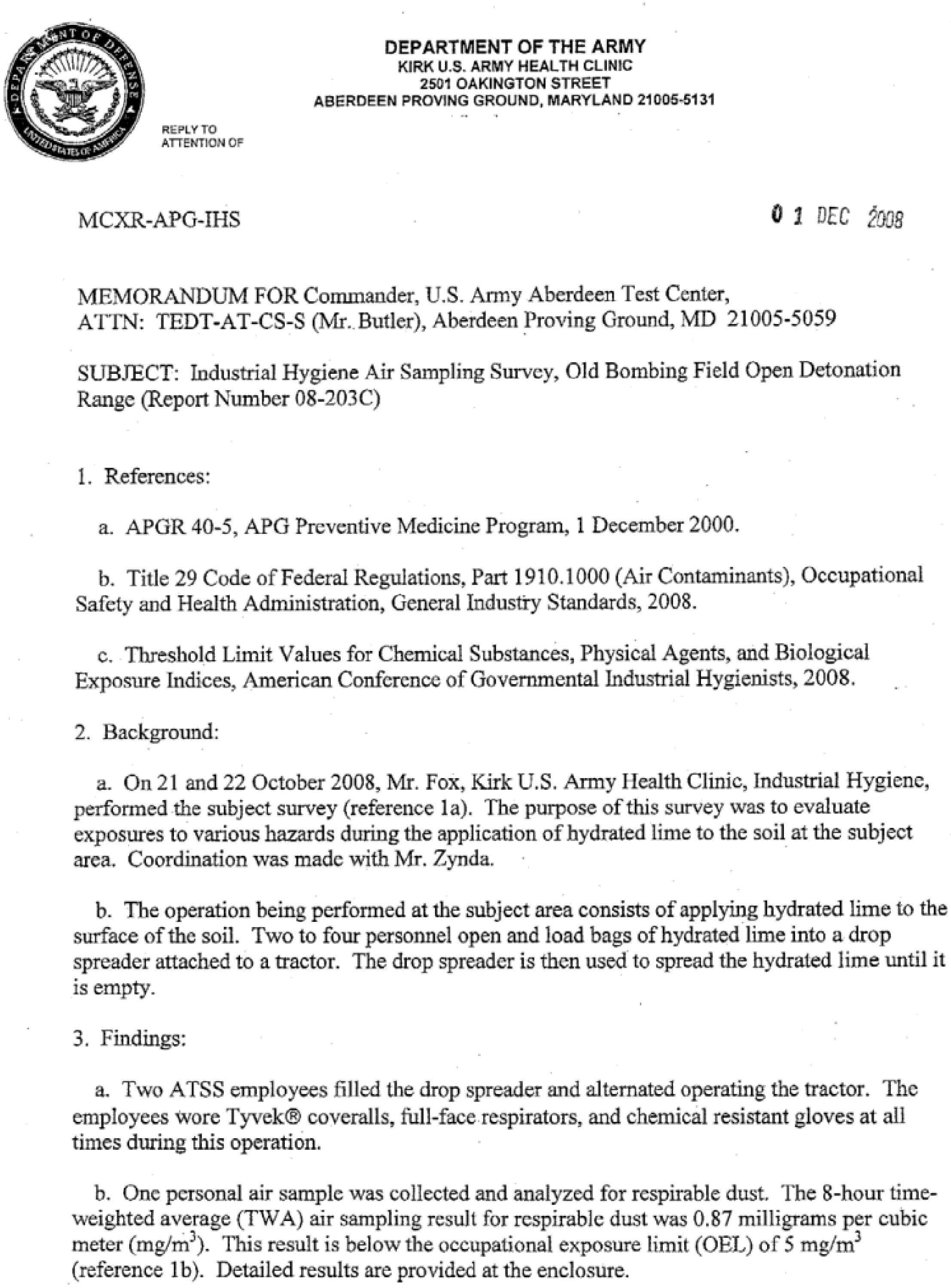
Table A2. Lime detonation dispersion quantity.

Crater Volume[1]	3,600 cubic 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	1,800 lb = 0.9 tons
Lime Density	2.24 g/cm^3 = 140 lb/ft^3
Lime volume required (minimum)	0.5 cubic yard
Recommended lime quantity added to each detonation. (Accounts for dispersion loss outside of crater fill collection area[2])	4 to 8 times the minimum lime volume (2 to 4 cubic yards)

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

[2] The calculations assume that 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 will be 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 will serve to mix the additional lime into the soil. Actual lime volume added to detonations will vary based on the size of the crater.

Appendix B. Air Monitoring Data



DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA

DEPARTMENT OF THE ARMY
KIRK U.S. ARMY HEALTH CLINIC
2501 OAKINGTON STREET
ABERDEEN PROVING GROUND, MARYLAND 21005-5131

REPLY TO
ATTENTION OF

MCXR-APG-IHS

01 DEC 2008

MEMORANDUM FOR Commander, U.S. Army Aberdeen Test Center,
ATTN: TEDT-AT-CS-S (Mr. Butler), Aberdeen Proving Ground, MD 21005-5059

SUBJECT: Industrial Hygiene Air Sampling Survey, Old Bombing Field Open Detonation Range (Report Number 08-203C)

1. References:

a. APGR 40-5, APG Preventive Medicine Program, 1 December 2000.

b. Title 29 Code of Federal Regulations, Part 1910.1000 (Air Contaminants), Occupational Safety and Health Administration, General Industry Standards, 2008.

c. Threshold Limit Values for Chemical Substances, Physical Agents, and Biological Exposure Indices, American Conference of Governmental Industrial Hygienists, 2008.

2. Background:

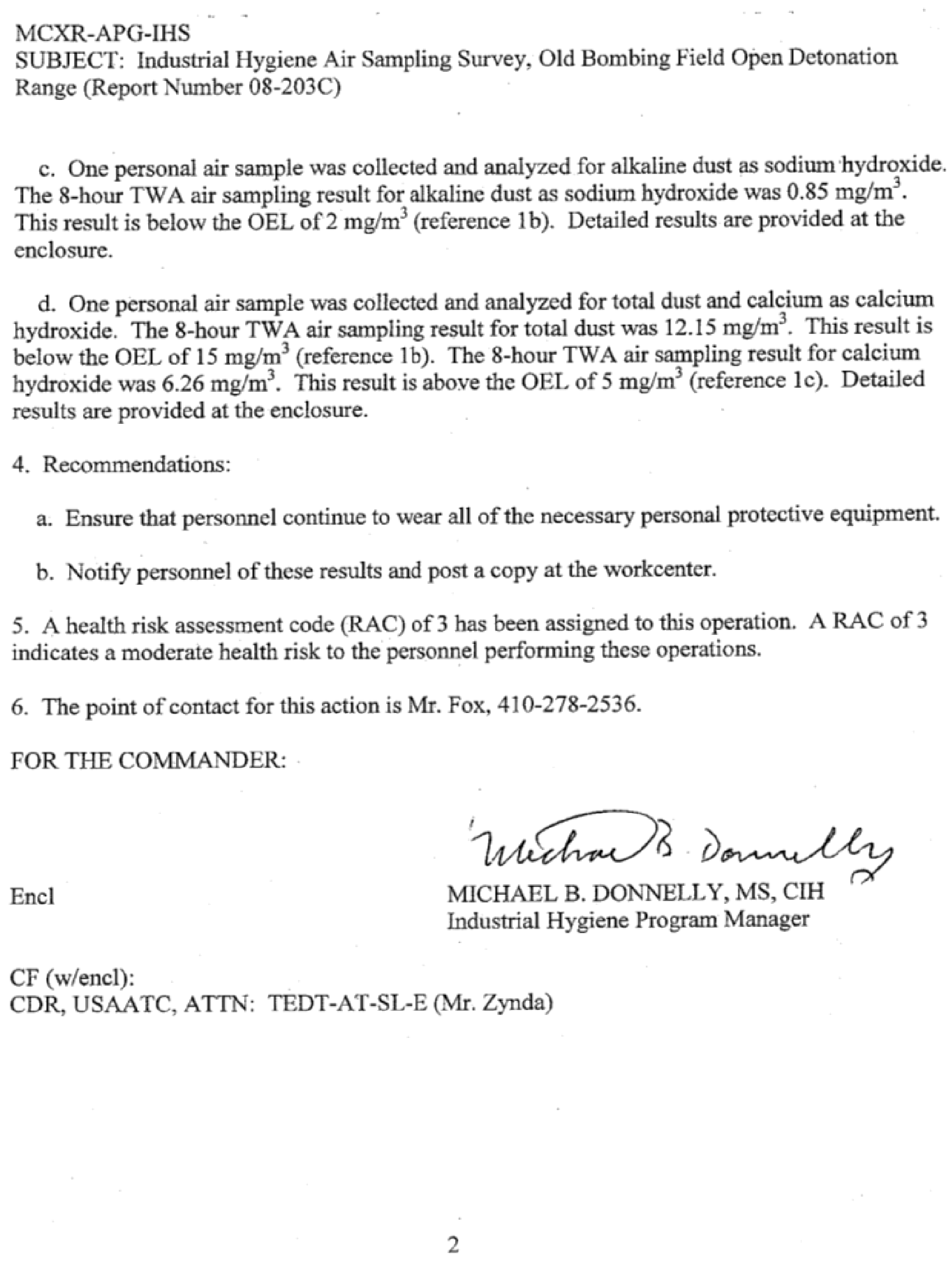
a. On 21 and 22 October 2008, Mr. Fox, Kirk U.S. Army Health Clinic, Industrial Hygiene, performed the subject survey (reference 1a). The purpose of this survey was to evaluate exposures to various hazards during the application of hydrated lime to the soil at the subject area. Coordination was made with Mr. Zynda.

b. The operation being performed at the subject area consists of applying hydrated lime to the surface of the soil. Two to four personnel open and load bags of hydrated lime into a drop spreader attached to a tractor. The drop spreader is then used to spread the hydrated lime until it is empty.

3. Findings:

a. Two ATSS employees filled the drop spreader and alternated operating the tractor. The employees wore Tyvek® coveralls, full-face respirators, and chemical resistant gloves at all times during this operation.

b. One personal air sample was collected and analyzed for respirable dust. The 8-hour time-weighted average (TWA) air sampling result for respirable dust was 0.87 milligrams per cubic meter (mg/m^3). This result is below the occupational exposure limit (OEL) of 5 mg/m^3 (reference 1b). Detailed results are provided at the enclosure.



MCXR-APG-IHS
SUBJECT: Industrial Hygiene Air Sampling Survey, Old Bombing Field Open Detonation Range (Report Number 08-203C)

c. One personal air sample was collected and analyzed for alkaline dust as sodium hydroxide. The 8-hour TWA air sampling result for alkaline dust as sodium hydroxide was 0.85 mg/m^3. This result is below the OEL of 2 mg/m^3 (reference 1b). Detailed results are provided at the enclosure.

d. One personal air sample was collected and analyzed for total dust and calcium as calcium hydroxide. The 8-hour TWA air sampling result for total dust was 12.15 mg/m^3. This result is below the OEL of 15 mg/m^3 (reference 1b). The 8-hour TWA air sampling result for calcium hydroxide was 6.26 mg/m^3. This result is above the OEL of 5 mg/m^3 (reference 1c). Detailed results are provided at the enclosure.

4. Recommendations:

a. Ensure that personnel continue to wear all of the necessary personal protective equipment.

b. Notify personnel of these results and post a copy at the workcenter.

5. A health risk assessment code (RAC) of 3 has been assigned to this operation. A RAC of 3 indicates a moderate health risk to the personnel performing these operations.

6. The point of contact for this action is Mr. Fox, 410-278-2536.

FOR THE COMMANDER:

Michael B. Donnelly

Encl

MICHAEL B. DONNELLY, MS, CIH
Industrial Hygiene Program Manager

CF (w/encl):
CDR, USAATC, ATTN: TEDT-AT-SL-E (Mr. Zynda)

Appendix C: Meterological Data

Data will be supplied on CD by request to the authors.

REPORT DOCUMENTATION PAGE

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September 2011

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

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ESTCP ER-0742

5e. TASK NUMBER

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14. ABSTRACT

A common disposal method for munitions stockpiles is Open Burn/Open Detonation (OBOD). These activities are necessary to destroy unserviceable, unstable, or unusable munitions and explosives. Due to the relatively small area of OD facilities, there is a high probability of explosives and heavy metal contamination in the soil. The objective of this demonstration was to evaluate a lime soil amendment management strategy to control active OD area contaminant mobility and promote contaminant degradation that is low cost and minimally resource intensive. A soil treatability study and baseline characterization evaluation were undertaken at the site—the OD area of Aberdeen Proving Grounds—prior to initiation of the field demonstration. The field demonstration involved adding hydrated lime to the OD area to transform explosive residues and stabilize metals at the site to prevent offsite migration. Lime was further dispersed on the site and mixed with the deeper soils by adding it to the hole dug for the waste munitions before the detonations. Seven amendment methods were evaluated. Effective dispersion was monitored by surface soil sampling after the detonation fallout had settled. The detonations all dispersed the lime along with the crater ejecta. 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

(Continued)

15. SUBJECT TERMS

Alkaline hydrolysis	Explosives transformation	Metals immobilization
ESTCP	Lime soil amendment strategy	OBOD area management

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		89	

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Applied Research Associates, Inc., Southern Division
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14. ABSTRACT (Concluded)

dispersed lime into the soil. The end result was a reactive zone of elevated pH that spanned the depth of the detonation crater. Air monitoring and the effect of lime on soil invertebrates was also conducted. Alkaline hydrolysis of the munitions residues in soil was confirmed. Transport of the residues off-range in surface water or towards groundwater was reduced below baseline levels and met regulatory requirements. Results of the Toxicity Characteristic Leaching Procedure (TCLP) and the Distilled Deionized Water Suspend and Settle (DDI S&S) analysis of OBOD area soil samples indicated that cadmium was leached from the soil by the DDI S&S procedure, although not detected in the TCLP extraction solutions. Aluminum and iron, two metals leached by both procedures, were detected at higher concentration by the DDI S&S procedure but were well within national background concentrations for soil. Alkaline hydrolysis through lime amendment of soil was successful at controlling off-range transport of munitions explosive residues and heavy metals without changes in soil characteristics or ecological impact.