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Grenade Range Management Using Lime for Metals Immobilization and Explosives Transformation

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ACRONYMS AND ABBREVIATIONS

ARA	Applied Research Associates, Inc.
ARDEC	Armament Research, Development and Engineering Center
ASTM	American Society for Testing and Materials
ATC	Aberdeen Test Center
ATV	all-terrain vehicle
bgs	below ground surface
BRM	Basic Rifle Marksmanship
Ca	calcium
Cd	cadmium
CEC	cation exchange capacity
CO ₂	carbon dioxide
Cr	chromium
Cu	copper
DENIX	Defense Environmental Network and Information Exchange
DO	dissolved oxygen
EOD	Explosive Ordnance Disposal
EPA	Environmental Protection Agency
EQT	Environmental Quality Technology
ERDC-EL	Engineer Research and Development Center–Environmental Laboratory
ESTCP	Environmental Security Technology Certification Program
Fe	iron
FRTR	Federal Remediation Technology Roundtable
HA	health advisory
HASP	Health and Safety Plan
HGR	hand grenade range
kg	Kilogram
ICP	inductively coupled plasma
µg	microgram
mg	milligram
Mn	manganese
N ₂	nitrogen
N ₂ O	nitrous oxides
NCHO	formaldehyde
HCOOH	formic acid
NH ₃	ammonia

ACRONYMS AND ABBREVIATIONS (continued)

Ni	nickel
NIOSH	National Institute for Occupational Safety and Health
NO ₂	nitrite
O&M	operations and maintenance
Pb	lead
PI	Principal Investigator
PM	Project Manager
ppb	parts per billion
PPE	personal protective equipment
ppm	parts per million
RDX	Royal Demolition Explosive, hexahydro-1,3,5-trinitro-1,3,5-triazine
SOP	standard operating procedure
SPE	solid phase extraction
SU	standard unit
TNT	2,4,6-trinitrotoluene
TOC	total organic carbon
TSS	total suspended solids
EPA	United States Environmental Protection Agency
UXO	Unexploded Ordnance
V	vanadium
Zn	zinc

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The work presented in this report was part of an effort to investigate the use of lime to immobilize metals and transform explosives on active hand grenade ranges. Dr. Steven L. Larson, Dr. Jeffery L. Davis, Mr. W. Andy Martin, and Ms. Deborah R. Felt of the ERDC-Environmental Laboratory (EL), Vicksburg, Mississippi, and Ms. Catherine C. Nestler of Applied Research Associates, Inc. (ARA), Vicksburg, Mississippi, prepared this report. Mr. Gene Fabian and Mr. Greg Zynda, Aberdeen Test Center (ATC), Aberdeen Proving Grounds, Maryland; Mr. Greg O'Connor, Armament Research, Development and Engineering Center (ARDEC), and Ms. Beth-Anee Johnson of the ITAM office at Fort Jackson, South Carolina, assisted in the execution of this project. We gratefully acknowledge the technical assistance provided by Mr. Karl Konecny, Mr. Chris Griggs, and Mr. Jared Johnson (ERDC-EL); Mr. Milton Beverly (Environmental Research and Development, Inc.); Ms. Michelle Thompson (ARA); Ms. LeeAnn Riggs and Ms. Deborah Regan (SpecPro); Mr. Casey Trest (Mississippi State University); and Ms. Tarmiko Graham (Alcorn State University). We also wish to acknowledge the gracious participation of the Fort Jackson, South Carolina, range control personnel for their assistance and support throughout the duration of this project.

This study was conducted under the direct supervision of Dr. Victor F. Medina, Acting Branch Chief (EP-E); Dr. Richard E. Price, Division Chief (EP); and under the general supervision of Dr. M. John Cullinane, Technical Director (EL).

At the time of publication of this report, Dr. Beth Fleming was the EL Director; COL Richard B. Jenkins was Commander and Executive Director of ERDC; and Dr. James R. Houston was Director.

Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

The Department of Defense (DoD) operates numerous hand grenade ranges (HGR) for training purposes. Live-fire training creates a potential source zone for munitions constituents such as metals and explosives. Fragmentation grenades, typically containing Composition B (60% Royal Demolition Explosive, hexahydro-1,3,5-trinitro-1,3,5-triazine [RDX], 39% 2,4,6-trinitrotoluene [TNT], 1% wax binder) within a steel shell casing constitute the majority of hand grenades used at fixed-position ranges. Explosives have been detected in HGR soils at levels from the low parts per billion (ppb) (microgram [μg]/kilogram [kg]) up to percent levels. RDX has been detected in leachate waters below live-fire hand grenade ranges and in surface waters leaving range impact areas (Jenkins et al., 2001; Pennington et al., 2001, 2002). The migration of metals and explosives, in both soluble and particulate forms, from the impact areas of the ranges occurs through a variety of mechanisms, including transport in surface water following rain and storm events, transport with soil particulates following rain and storm events, and leaching through the subsurface towards groundwater. Effective management of metals and explosives on HGRs requires an understanding of the natural and engineered processes controlling their fate and transport at these sites.

This project is based on the premise that increased alkalinity, caused by lime addition to soil, will result in (1) base-catalyzed transformation of explosives that will eliminate migration of RDX- and TNT-based explosives from the range area and (2) significantly decreased water solubility of heavy metals present in the soils. In addition, the demonstrated technology meets the criteria for active range management in that it would be inexpensive; easily applied in remote locations; effective on heterogeneous contaminant distributions; effective over large areas; effective on multiple compounds; nonintrusive, to the extent possible; and able to be incorporated into normal range maintenance operations.

Hydrated lime, $\text{Ca}(\text{OH})_2$, was chosen as the soil amendment for its ability to increase soil pH into the range necessary to transform explosives to environmentally friendly end products and its ability to stabilize metals. The munitions constituents of concern to this study were RDX and metals, particularly zinc (Zn). During the course of the 20-month demonstration, soil, pore water, surface water, and air samples were collected, along with meteorological data, to determine the effectiveness of lime as a management approach to reduce migration of munitions constituents from the range.

The application of hydrated lime to an HGR to provide a mechanism for both metals immobilization and explosives transformation was demonstrated at the Fort Jackson, South Carolina, Remagen HGR. It was determined during the treatability study that an application of 1% lime (w:w) was needed to elevate the Fort Jackson HGR soil above the desired pH of 11.5. This equated to approximately 1 ton of lime, which was added to the test bay (785 yd^3 soil) and mixed to a depth of 15.24 cm (6-in.).

Several techniques were used to apply the lime in the bays. These varied from simply opening bags on the range by hand and raking to give a uniform color distribution to using a drop-seed spreader. A hydroseeder was used during the final lime application to evaluate the effect of concurrent liming and watering. In order to mix the lime into the HGR soil to the required depth,

several techniques were evaluated, including a garden rotor tiller, a small disc, a cultivator, and a rake.

Prior to the demonstration, suction lysimeters were placed in the test bay and the control bay to monitor changes in pore water with lime treatment. Both HGRs had surface water samplers placed at the edge of the bays to collect surface water as it flowed from the impact area into the surrounding range. The surface water samplers were triggered by water levels in the storm water runoff path. Air monitors at the Fort Jackson HGR were placed in front of the throwing pits in Bays 2 and 4 for a total of six typical training days (24 hours). Six air samples were collected over several months and analyzed for calcium (Ca). Ca was used as a tracer for the hydrated lime $\text{Ca}[\text{OH}_2]$ in the dust associated with the hand grenade detonations. Meteorological data was collected at Fort Jackson for 20 months. The temperature and rainfall directly affect the percent moisture in the HGR soil, which controls the efficiency of the alkaline hydrolysis reaction responsible for transforming the explosives and stabilizing the metals.

The results indicate that application of lime can reduce the migration of munitions constituents from the HGRs. RDX was transformed by the alkaline hydrolysis reaction in the soil and soil concentrations were reduced by more than 90%. In addition, the metals were stabilized in the soil, with reduced concentrations of both iron (Fe) and Zn leaving the range via surface water and leachate.

There was concern over the possibility of negative impacts on groundwater and receiving surface waters from lime treatment of the soil. The impact area of the treated bay had to be maintained at a pH >10.5 to accomplish the alkaline hydrolysis of the RDX. However, while not a regulatory requirement, it was determined that the water leaving the source zone should have a pH <9.5. It was determined that for the soil, climate, and range use conditions at the Fort Jackson HGR, the bay would have to be limed on a quarterly basis to maintain the pH above 10.5. There was no statistical difference between the pore water leaving the treated and untreated bays, indicating that the hydroxide ion was completely neutralized before the leachate from the bay could impact the groundwater. The pH of the surface water runoff collected from the limed bay remained at approximately 6.3. The surface soil pH in the offsite area collecting this water averaged 7.4, approximately 1 standard unit (SU) above the control bay. Therefore, there was no evidence of impact from the lime outside the treated area.

The air monitoring results indicated that the Ca (used as a tracer for the hydroxide) levels in the air samples from the limed bay were similar to, if not the same as, the Ca levels in the air samples from the control bay. Application of the lime in the HGR bays requires only Level D personal protective equipment (PPE), modified by the addition of a particulate respiratory mask and, possibly, the substitution of goggles as protective eyewear.

The cost of the technology is approximately \$400 per lime application, depending on the source of the lime and transportation costs. The time investment is measured in hours, and no specialized equipment or operator training are required. This technology demonstrated that application of lime is a low-cost treatment that can be incorporated into normal range management operations and practices.

The primary end user for this innovative in situ technology will be active hand grenade training ranges. Technology transfer efforts include the Marine Corps, the U.S.-German Data Exchange Agreement; the Environmental Quality Technology (EQT) Program—Distributed Sources Program; Armament Research, Development and Engineering Center (ARDEC)—Environmental Technology Division; and the Huntsville Center of Expertise for Range Design.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

2.1.1 Technology Background, Development, Function, and Intended Use

Most hand grenades used at fixed position ranges are fragmentation grenades composed of Composition B explosive, a mixture of hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and TNT. Measurable explosive levels have been observed in hand grenade range (HGR) soils at levels in the low ppb or $\mu\text{g/kg}$ up to percent levels (Pennington et al., 2006). Hand grenade training results in the deposition on the range floor of residual Composition B and any metals used in hand grenade manufacture (such as Fe, Zn, cadmium [Cd], chromium [Cr], copper [Cu]). Two potential mechanisms for off-site migration of metals and explosives from HGR soil are horizontal transport in surface water and vertical pore water transport in leachate. Simple, innovative, and cost-effective technologies are needed that can quickly break down potential contaminants, eliminating potential source zone contamination at the training sites and preventing contamination from migrating to local surface water and groundwater supplies.

Currently, there is no in situ or remote alternative for management of munitions constituents in soils on HGRs. This demonstration project focused on the control of contaminant migration resulting from grenade live-fire training activities and sought to develop source control via lime-amended impact areas established at a demonstration range. Results from this study will improve new grenade range designs and result in sustainable range management practices for currently active grenade ranges.

2.1.2 Applicable Systems

The U.S. Army currently has 583 sites with confirmed explosives-contaminated groundwater at 82 installations nationwide. At 22 other installations, 88 additional sites are suspected of groundwater contamination with explosives and organics (Defense Environmental Network and Information Exchange [DENIX], 2003 [<http://www.denix.osd.mil>]).

Design and construction of new HGRs also provides an opportunity to consider cost-effective pollution prevention opportunities. In some cases, local soil might have a basic pH high enough (>10.5) to hydrolyze explosives prior to migration of contaminants off site without further intervention. In most cases, however, native soil pH levels are below the pH level required for explosives to be transformed by base hydrolysis. Amendment of impact areas with $\text{Ca}(\text{OH})_2$ or other low-cost hydroxide sources can transform existing grenade impact areas into managed systems for in situ explosives transformation. Similarly, introduction of a hydroxide source into the impact area soil during range construction may prevent long-term costs resulting from explosives or metals migration to surface water or groundwater.

2.1.3 Target Contaminants

The target contaminants for the lime amendment technology are the energetic compounds RDX and TNT and the metals Fe and Zn. The major toxicological effects of exposure to RDX are nausea, irritability, convulsions, unconsciousness, and amnesia. RDX has also been associated

with systemic poisoning usually affecting bone marrow and the liver (ATSDR, 1995a). Symptoms of exposure to TNT include sneezing, coughing, sore throat, jaundice, muscular pain, dermatitis, and kidney and liver damage. Acute and chronic exposure to TNT causes a reduction of red blood cell count and hemoglobin content; leukocytosis (change in white blood cell count) may also occur (Agency for Toxic Substances and Disease Registry [ATSDR], 1995b). Exposure to Fe and Zn can result in various health symptoms depending on the metal, the exposure type, and the concentration. These symptoms include kidney damage, blood disorders, stomach pains, nausea, and anemia. Drinking water concentrations of metals are also regulated. Due to these effects shown in humans, the United States Environmental Protection Agency (EPA) has established a drinking water health advisory (HA) of 2 µg/L exposure for both RDX and TNT and 2 parts per million (ppm) or milligram (mg)/L for exposure to Zn (EPA, 2004).

2.1.4 Theory of Operation

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 degraded by alkaline destruction (Karasch et al., 2002). Application of Ca hydroxide to solution and soils containing TNT and RDX results in break-down products such as nitrate and nitrite (Emmrich, 1999; 2001). 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 indicated that the initial step in alkaline hydrolysis is denitration of the ring, which causes ring cleavage, followed by spontaneous decomposition. The degradation breakdown products of RDX, HMX, and MNX were nitrite (NO₂), nitrous oxides (N₂O), nitrogen (N₂), ammonia (NH₃), formaldehyde (HCHO), formic acid (HCOOH) and carbon dioxide (CO₂).

In a recent test, two grenades were detonated and the residues from these detonations collected and analyzed (Larson et al., 2007b). Samples of the residues, treated in slurry at a pH of 12 for 72 hours, resulted in a 99.9% reduction of RDX and TNT concentrations.

A bench scale simulation using TNT-laden soil was performed to study the explosives transformation under typical soil moisture conditions (Hansen et al., 2003). The soil was placed in a pan, dry lime was applied to the soil at 5% of the dry soil weight, and then water was added to the surface to adjust the soil moisture to 31.5%. Concentrations were reduced from 55 ppm to 10 ppm in 10 days. Soils from many army ammunition plants and firing ranges were tested at bench-scale with the addition of 5% lime and water. RDX exhibited 74% removal in 21 days (Davis et al., 2006).

A mesoscale lysimeter study was performed on site soils from Fort Jackson in order to set design parameters for the field demonstration (Larson et al., 2007a). The lysimeter study involved the addition of lime to site soil and simulated one year of typical rainfall. A schematic cross section of the lysimeter cell is shown in Figure 1. Parameters such as pH, RDX, and TNT concentrations; metals concentrations; Ca concentration; and total suspended solids (TSS) were monitored to determine the effectiveness of the technology. In addition, factors such as the soil cation exchange capacity (CEC) and soil buffering capacity were reviewed to determine optimal lime dosages for the field demonstration.

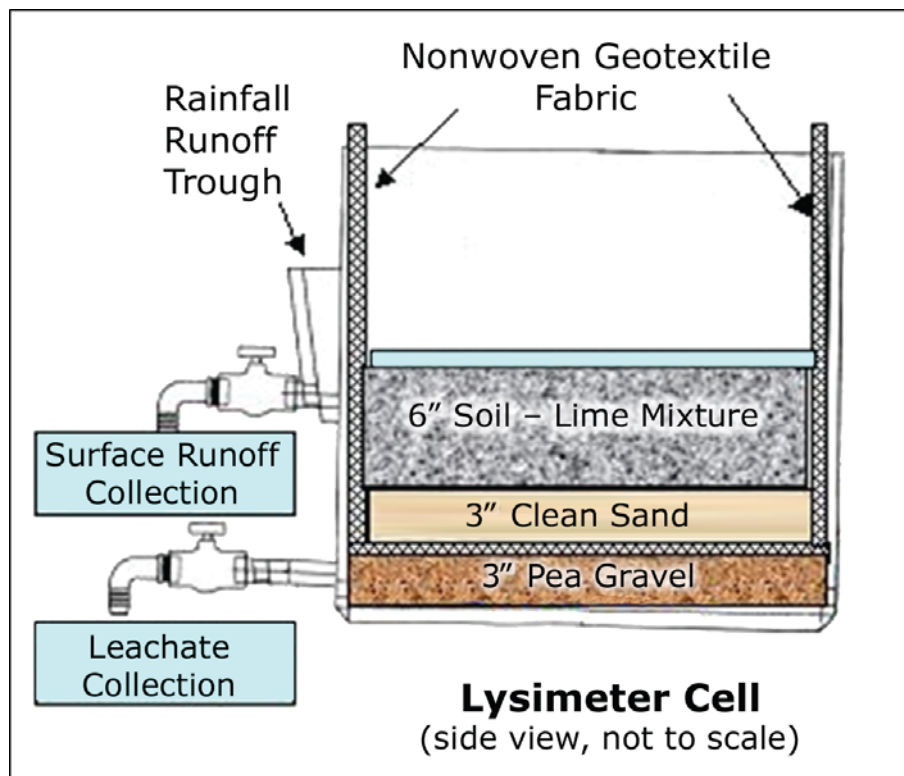


Figure 1. Cross Section of the Laboratory Lysimeter Cells Used to Evaluate Leachate and Runoff Water Conditions Using Simulated Rain Events.

2.2 PROCESS DESCRIPTION

2.2.1 Mobilization, Installation, and Operational Requirements

Explosive Ordnance Disposal (EOD) support was coordinated with Fort Jackson prior to conducting range activities. Sumps, lysimeters, surface water runoff collectors, and air monitoring equipment were installed 2 months prior to start-up in order to collect baseline data on the site. For details, see Section 3.4 of this report, the Engineer Research and Development Center-Environmental Laboratory (ERDC-EL) technical report (Larson et al., 2007c), and the Environmental Security Technology Certification Program (ESTCP) Final Report (Larson et al., 2007d).

2.2.2 Design Criteria

Based on results from the lysimeter study, the ideal lime dosage was 0.5% of the dry Fort Jackson soil weight to be mixed into the top six inches of soil. An approximately 600-m³ area (785-yd³ or 21,186-ft³) on Bay 4 of Remagen Range was amended with Ca(OH)₂. The treated area encompassed the primary impact area near the targets and the area immediately in front of and to the sides of the primary impact area. No residual materials were expected to be generated from the energetic compounds, and metals were stabilized in place.

2.2.3 Site Operation Schematics

The sampling locations in and around the test HGR bay (Bay 4) and the untreated control bay (Bay 2) are illustrated in Figure 2.

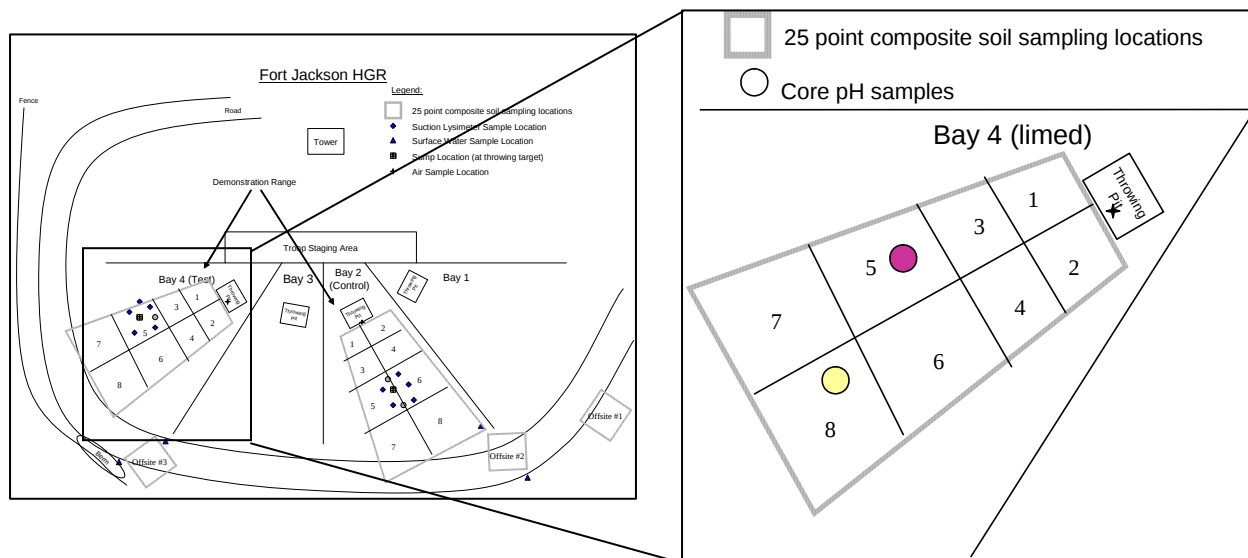


Figure 2. Baseline and Long-Term Monitoring Sample Locations.

2.2.4 Performance Summary

RDX was transformed by the alkaline hydrolysis reaction, and soil concentrations were reduced by more than 90%. In addition, the metals were stabilized in the soil, with reduction in the concentrations of both Fe and Zn leaving the range via surface water and leachate. The reactive impact area of the bay was maintained at a pH over 10.5; however, the soil pore water and the surface water runoff remained near neutral pH. The air monitoring results indicated that the Ca (used as a tracer for the hydroxide) levels in the air samples from the limed bay were similar to if not the same as the Ca levels in the air samples from the control bay.

2.2.5 Target Regulatory Standards

Currently, the Remagen Hand Grenade Range at Fort Jackson is under no regulatory drivers for reducing storm water runoff and leachate contaminant concentrations. Their incentive for participating in the field demonstration is to help develop a low-cost, low-maintenance range technology that will control contaminant migration at the source zone and mitigate future cleanup costs and potential environmental problems.

2.2.6 Personnel/Training Requirements

Limited specialized personnel, equipment, or training is required to initiate or maintain this technology, except for a general understanding of the site soil conditions.

2.2.7 Health and Safety Requirements

This in situ lime technology does not involve the use of any toxic or hazardous chemicals. The only chemical used as the amendment is Ca(OH)_2 , commonly used in engineering applications as a soil stabilizer. Hydrated lime is not regulated for addition to soil. No lime residuals are produced by the technology. Although not specifically required by health regulations, it is recommended that field personnel wear a particulate respirator (dust mask). Level D protective clothing is also recommended, as is protective eyewear. Washing skin and changing clothes at the completion of the lime application are encouraged.

2.2.8 Ease of Operation

The application of the lime can be accomplished within a few hours with a limited number of people.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The anticipated advantages of the lime technology are: low operating costs, low capital costs, mass reduction of source zone explosives, elimination of contaminant (explosives and metals) mobility, elimination or reduction of soil and groundwater remediation following range closure, reduction of liability, and enhancement of public perception. The technology will be limited by site-specific geochemistry and climate.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The objective of the lime technology demonstration was to validate at a field site that lime amendment of range soil could reduce or eliminate RDX, TNT, and degradation product concentrations in soil; stabilize metals at the source area; and significantly reduce migration of explosives and metals in solution (Larson et al., 2007c; 2007d). Fort Jackson is an active range so there is constant loading of explosives to the soil. Specifying explosives reductions in soil could be an impractical objective. Therefore, reducing mobility in the aqueous phase was the focus of this demonstration project. Greater than 90% reduction in explosives concentrations in leachate water and surface water runoff, as compared to the baseline and control range concentrations, was established as the metric of technology success. Greater than 90% reduction of metals concentrations in pore water and storm water runoff, or no significant increase in metals concentrations, was the primary objective for metals constituents. Performance objectives are summarized in Table 1.

Through this technology demonstration, issues such as ease of implementation, cost-effectiveness, and constituent management efficiency were studied. It also provided site-specific information about these issues, which could not be addressed in bench-scale treatability studies such as constant explosives and metals loading and the constant detonation mixing effects on the lime treatment technology. Other concerns addressed by this field-scale demonstration were validating the treatability study predictions and determining if lime was an effective and economical range management technology for metals- and explosives-contaminated soil.

3.2 SELECTING TEST SITE

Fort Jackson was selected as the test site for the lime demonstration project. Several factors made Fort Jackson an ideal test location, including: the range is active so continuous explosives loading and soil mixing will occur; the range is generally accessible between October through March; the size was appropriate for both a treated and control area; there were sufficient explosives concentrations in soil; there was the potential for contaminant mobility in surface water runoff; the depth to groundwater presented a potential subsurface contaminant transport issue; and Fort Jackson agreed to provide unexploded ordnance (UXO) clearance and support at the site.

3.3 TEST SITE DESCRIPTION

3.3.1 Fort Jackson and the Remagen Range

Fort Jackson was established in 1917 as an infantry training center. After World War I, Fort Jackson was demobilized as a full-time training site, and the post was state-controlled as a training area for troops of the South Carolina National Guard. The installation was returned to Federal control in 1940 for U.S. Army infantry training for World War II (WWII). During WWII, the fort was expanded to approximately its present size. Following WWII, the fort was used to station various U.S. Army Divisions. The fort has been an active U.S. Army Basic Training Center since 1973 (Parsons, 1999).

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Primary or Secondary
Quantitative	1. Reduce RDX and TNT concentrations in runoff water	Greater than 90% reduction compared to baseline and control	Primary
	2. Reduce RDX and TNT concentrations in soil pore water	Greater than 90% reduction compared to baseline and control	Primary
	3. Reduce metals concentrations in runoff water	Total and dissolved phase metals concentrations < control level	Primary
	4. Reduce metals concentration in soil pore water	Dissolved phase metals concentrations < control levels	Primary
	5. Maintain control of soil pH levels	pH > 10.5 in source area; pH < 12.5 outside of source area	Primary
	6. Reduce explosive concentrations in the soil within the source area	Explosives concentrations < baseline and control levels	Secondary
Qualitative	7. Reduce overall explosive constituents in runoff water	Explosives concentrations < control level	Secondary
	8. Reduce overall explosive constituents in soil pore water	Explosives concentrations < control level	Secondary
	9. Evaluate ease of use	Amendment application method, frequency, and range downtime	Secondary
	10. Evaluate human health risk to range user	No health risk or inhalation, eye, or skin irritation allowed	Primary
	11. Assess lime effects on general water quality parameters of runoff and soil pore water	pH, hardness, TSS (runoff only), alkalinity, etc. meet state water quality parameters	Secondary
	12. Evaluate grenade range management costs	Develop annual cost to maintain the Fort Jackson range and other ranges	Secondary

Remagen Range is a Grenade Familiarization Range used to train and test soldiers in the use of live fragmentation hand grenades. Remagen range consists of four bays with berms and walls separating each bay. Each bay has one throwing pit and a group of approximately five silhouette targets placed 30 m down range. The grenades generally land within a 10-m diameter area that encompasses, and extends slightly in front of, the targets. This area is characterized by generally loose soil that contains impact craters as deep as 2 ft. Typical maintenance conducted by the installation includes periodic grading of this area to fill in the craters and replenish the soil that may have been transported away from the range by storm water runoff. Remagen range receives heavy annual use, with approximately 55,000 live hand grenades thrown each year. Its soil is a clay and sand mixture that has a low to moderate soil permeability. The impact area around the

targets on the range presents a potential source zone for explosives in groundwater and surface water.

3.3.2 Fort Jackson Geology and Hydrogeology

Fort Jackson is located in central South Carolina, occupying approximately 52,000 acres adjacent to and east of Columbia, South Carolina. This area is located in the upper Atlantic Coastal Plain geologic province of South Carolina, characterized by low elevation and rolling, sandy hills. The installation is predominantly covered with pine forests except in the low-lying areas and flood plains surrounding streams where more deciduous trees and marsh vegetation occur.

Groundwater is generally plentiful at Fort Jackson. The Tuscaloosa Formation, of Upper Cretaceous age, underlies Fort Jackson and is the primary source of groundwater in the area. The Tuscaloosa Formation is at the surface over most of Fort Jackson. This formation lies unconformably on a peneplained surface of older, crystalline rocks. Groundwater occurs under water table conditions in the upper part of the zone of saturation. At a depth of about 99–251 ft, permeable sand zones are frequently overlain by less permeable clay zones, and the groundwater exists under artesian conditions (Parsons, 1999).

The grenade range at Fort Jackson, Remagen Range, lies within the Colonels Creek watershed. A wetland area is the nearest open water resource down gradient of Remagen Range. The shortest distance between the range and this wetland area is approximately 450 m. Visual observations in the field indicate that surface runoff water from the range area travels a maximum of 200 m from the range. Within this distance, the runoff water will pond and infiltrate into the subsurface. No direct discharge into the wetland area was evident from the flow paths observed during preliminary sampling events. The water that infiltrates into the soil on the range and in the runoff flow paths exiting the grenade range provides part of the base flow to this wetland area.

3.4 SITE PREPARATION, TECHNOLOGY INSTALLATION, AND OPERATION

The field demonstration was conducted in Bays 2 and 4 of Remagen Range at Fort Jackson. The lime amendments were applied to Bay 4. Bay 2 did not have lime amendments added to the soil and was monitored as a control. Bay usage was evenly dispersed among all 4 bays of the range, and soil and runoff characteristics were equivalent between Bays 2 and 4. Each of the four bays at the HGR is separated by a berm, which prevented spreading of the lime or grenade fragments to the other bays. Bays 2 and 4 storm water runoff flow paths are naturally separated and eventually join downrange of the HGR. Prior to baseline sampling and lime amendment application, the cratered surface areas of Bays 2 and 4 were graded to begin the demonstration with a smooth surface.

Five suction lysimeters were placed approximately 1.52 m (5 ft) below ground surface (bgs) under the main impact area for each test bay. In addition, one sump was placed under the main impact areas of each test bay. Two surface water samplers were placed in the main runoff flow areas of Bays 2 and 4. Sumps and lysimeters were placed three months prior to actual liming in order to obtain baseline data for explosives and metals in pore water and surface waters. A weather station was placed near the range control tower, and air samplers were emplaced near

the throwing pits of Bays 2 and 4. Based on results from the lysimeter study, the ideal lime dosage was 0.5% of the dry soil weight to be mixed in the top six inches of soil. This equated to approximately 1 ton of lime. An approximately 600-m² (785-yd³ or 21,186-ft³) area on Bay 4 of Remagen Range was amended with lime. This encompassed the primary impact area near the targets and the area immediately in front of and to the sides of the primary impact area. The initial liming event occurred in December 2005. Several techniques were used to apply the lime in the bay. These varied from simply opening bags on the range by hand and raking to give a uniform color distribution to using a drop seed spreader. A hydroseeder was used after the final lime application in order to evaluate the effect of concurrent liming and watering. The lime amendment was mixed into the soil to a depth of approximately 6 inches. Several mixing techniques were evaluated, including a garden rotor tiller, a small disc, a cultivator, and a rake. The application was monitored to ensure a uniform distribution of the lime.

Sampling was scheduled monthly during the first quarter of the project, and then quarterly to coincide with quarterly liming events. Demonstration monitoring was performed for a total of 20 months from December 2005 to June 2007. This period included 3 months of baseline monitoring and 17 months of monitoring following the lime applications.

3.5 SAMPLING/MONITORING PROCEDURES

Soil and water samples were collected from the Fort Jackson HGR demonstration site and shipped to ERDC-EL in Vicksburg, Mississippi, for analysis. The sampling locations are illustrated in Figure 2. The samples collected, after lime application, are shown in Table 2. The post-liming samples were taken 24 hours after the liming event. The same sample types, quantities, and analyses were performed at the demonstration bay (Bay 4) and the control bay (Bay 2) during the baseline and monitoring sampling. In addition to the samples and data identified above, a weather station was installed near the Remagen Range to collect daily precipitation, wind, temperature, and humidity data.

Based on the field experience of Dr. T.F. Jenkins (personal communication) and Mr. J. Johnson (personal communication), 25-point composite soil samples were collected from eight sampling areas (numbered 1 to 8) within each bay (Figure 2), homogenized, extracted, and analyzed. Twenty-five point composite soil samples were also collected from three sample areas located on the range but off-site from the main impact area of the bays, numbered 1 to 3 (Figure 2). All samples were labeled and tightly sealed to avoid cross-contamination during storage and shipment. Samples were shipped to the ERDC-EL laboratory in Vicksburg via overnight delivery.

The logs of direct real-time readings such as temperature, conductivity, E_h, pH, and dissolved oxygen (DO) were kept in a field logbook. These readings were recorded by Aberdeen Test Center (ATC) field personnel or locally contracted support. A copy of these readings was sent to the ERDC-EL principal investigator (PI) and/or Co-PI at the end of each sampling event. Daily weather data was downloaded from the on-site weather station by ATC personnel or locally contracted support twice per month and transmitted electronically to ATC and ERDC-EL. Range usage data collected by range control or the Basic Rifle Marksmanship (BRM) Range Officer was collated quarterly and stored in an Excel spreadsheet format. The data was reduced by ATC and transmitted electronically to ERDC-EL.

Table 2. Monitoring Samples and Analyses.

Media	Number of Sample Locations/Bays	Sample Type	Frequency	Sampling Method	Location	Depth (bgs)	Analysis
Soil	5 to 8	25-point composites	Quarterly ³	Scoop	Source area	0-6 inches	Explosives, metals, pH
Soil	5 to 8	25-point composites	Quarterly ³	Scoop	Outside source area	0-6 inches	
Soil/sediment	3	25-point composites	Quarterly ³	Scoop	Down-gradient	0-6 inches	
Pore water (leachate)	5	Grab or composite	Monthly	Suction lysimeter	Source area	3	Explosives, total metals, dissolved metals ¹ , pH, alkalinity, hardness, field parameters ²
Pore water (leachate)	1	Grab	Monthly	Sump with suction lysimeter, pump, or tubing	Source area	3	
Surface water	1	Grab	Up to 12 rain events	Automatic storm water sampler	Down-gradient	0	
Surface water	1	Grab	Up to 12 rain events	Automatic storm water sampler	Down-gradient	0	
Air	1	Training day (~12 hours)	Five events after liming during training	Air monitor	Throwing pit	4 ft above ground surface	Calcium
Meteorological data	1	Composite	Daily	Monitoring station and fort records as backup	Near HGR		Temperature, humidity, wind

¹ Dissolved metals samples will be field filtered.

² Field parameters = temperature, pH, conductivity, turbidity, dissolved oxygen, and redox

³ Soil samples may be collected monthly during the first quarter at ERDC-EL discretion.

bgs = below ground surface

3.6 ANALYTICAL PROCEDURES

Samples were analyzed using the methods detailed in Appendix A and Appendix B of the ESTCP Project ER-0216 Final Report (Larson et al., 2007d) and summarized here in Table 3. The analysis methods are standard methods approved by EPA or the American Society for Testing and Materials (ASTM). The analyte list for each sample method is included with the lab standard operating procedures (SOP). Explosives analysis was generally performed using Method 8330 for higher concentrations. However, Method 8095, which has lower detection limits, was used as needed to provide meaningful explosives data. Soil and aqueous samples were screened by inductively coupled plasma (ICP) to quantify metals. Metals analysis for soil was performed using Method 6010. For aqueous samples, Method 6020 was used since it can achieve much lower detection limits.

Table 3. Summary of Analytical Methods.

Analysis	Method
Solids	
Explosives	SW-846 8330 / 8095
Metals	SW-846 6010
pH	SW-846 9045
Alkalinity as CaCO ₃	SW-846 310.1
Total organic carbon (TOC)	SW-846 9060
Grain size	
Inorganic anions	EPA ¹ M 300.0
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
Air	
Calcium	NIOSH ² Method 7020

¹ Environmental Protection Agency

² National Institute for Occupational Safety and Health

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA AND OBJECTIVES

The lime technology performance in the field demonstration was assessed by the criteria identified in Table 4.

Table 4. Performance Objectives and Criteria.

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Primary or Secondary
Quantitative	1. Reduce RDX and TNT concentrations in runoff water	Greater than 90% reduction compared to baseline and control values	Primary
	2. Reduce RDX and TNT concentrations in soil pore water	Greater than 90% reduction compared to baseline and control values	Primary
	3. Reduce metals concentrations in runoff water	Total and dissolved phase metals concentrations < control values	Primary
	4. Reduce metals concentration in soil pore water	Dissolved phase metals concentrations < control values	Primary
	5. Maintain control of soil pH values	pH > 10.5 in source area; pH < 12.5 outside of source area	Primary
	6. Reduce explosive concentrations in the soil within the source area	Explosives concentrations < baseline and control value	Secondary
Qualitative	7. Reduce overall explosive constituents in runoff water	Explosives concentrations < control value	Secondary
	8. Reduce overall explosive constituents in soil pore water	Explosives concentrations < control value	Secondary
	9. Evaluate ease of use	Amendment application method, frequency, and range downtime	Secondary
	10. Evaluate human health risk to range user	No health risk or inhalation, eye, or skin irritation allowed	Primary
	11. Assess lime effects on general water quality parameters of runoff and soil pore water	pH, hardness, TSS (runoff only), alkalinity, etc. meet state water quality parameters	Secondary
	12. Evaluate grenade range management costs	Develop annual cost to maintain the Fort Jackson range and other ranges	Secondary

4.2 PERFORMANCE DATA

Selected data obtained from the lime demonstration project is presented in terms of removal as a function of time. Changes in concentrations of metals, explosives, and pH were evaluated for

soil and aqueous media. Complete data is available in the ESTCP Project ER-0216 Final Report and the ERDC/EL technical report.

4.2.1 Soil pH

The results of a direct comparison of field pH (using pH paper) and the laboratory-verified pH (using a pH electrode) for the first year of the field study are shown in Table 5. The pH paper is subject to interpretation by the user so there is some difference in the pH range from the paper to the probe. However, with experience, the soil pH can be determined using pH paper and can provide an inexpensive and rapid soil evaluation for the reapplication of lime. The soil pH for Bay 4 varied depending on the time since the last application of lime, whereas the pH for Bay 2 soil remained relatively constant, around pH 7, throughout the demonstration. The limed bay, Bay 4, had high average pH at the post-liming sampling events in January and April 2006 and January 2007. The effect of liming on the soil pH was apparent at the post-liming sampling which took place 24 hours after lime application. The soil pH then gradually declined until the next liming event (Figure 3). Based on this pH profile of decrease over time, to achieve the desired pH of greater than 10.5 to induce alkaline hydrolysis, a quarterly application rate of lime should be, and was, used.

Table 5. Comparison of Field and Laboratory Measured Soil pH.

Date		Bay 2 (Control)		Bay 4 (Limed)	
		pH Probe ^a	pH Paper	pH Probe ^a	pH Paper
2006	Jan	6.5	6.0	10.3 ^c	12.0 ^c
	Mar	6.5	6.5	8.4 ^b	10.5 ^b
	Apr	6.9	5.5	11.9 ^c	12.5 ^c
	Jul	6.6	6.5	7.8	9.0
2007	Jan	6.4	6.3	8.0 ^b	6.8 ^b
				12.1 ^c	12.3 ^c

^a Measurement taken from the homogenized 25-pt composite sample

^b Sample taken pre-liming

^c Sample taken post-liming

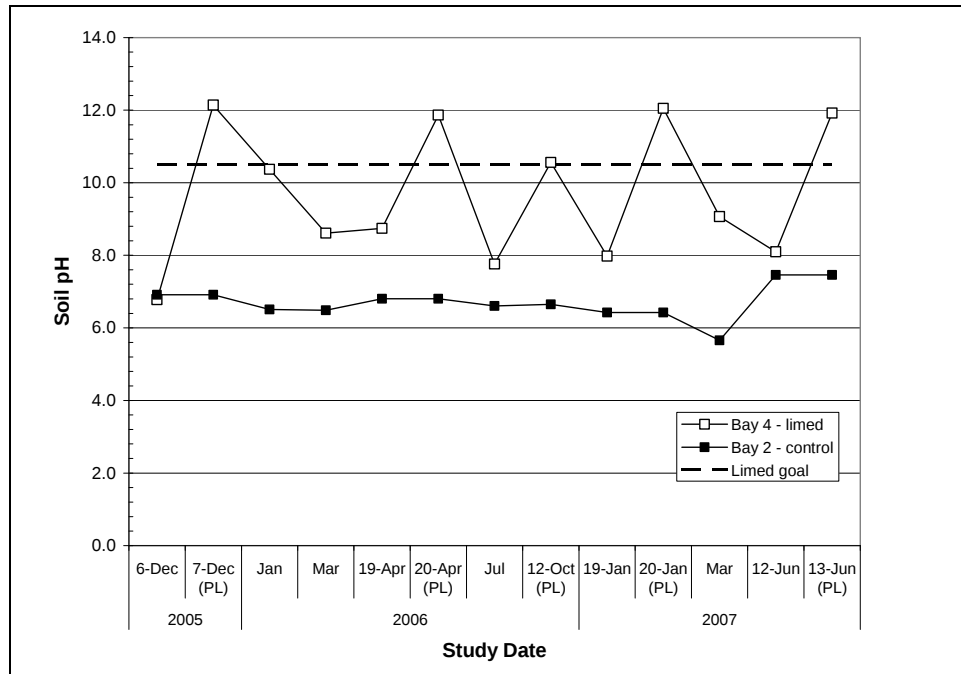


Figure 3. Soil pH Profile for Fort Jackson, Bays 2 and 4, During the Field Demonstration (n=3) (PL = post lime, 24 hours post application).

4.2.2 Soil Metals

The hand grenade shell consists primarily of Fe, Zn, and other trace metals such as vanadium (V), manganese (Mn), nickel (Ni), Cr, and lead (Pb). The average concentrations of the metals in the two bays, and the results of an analysis of treatment significance are presented in Table 6. The metals concentrations obtained from both the treated and untreated bays were analyzed statistically by *t*-test ($P=0.001$) and, when normality failed, by the Mann-Whitney Rank Sum test. All the metals analyzed demonstrated either a significant decrease in concentration (Fe, Cr, Mn, and V) or no change in concentration (Zn, Pb, and Ni) when measured in soil treated with hydrated lime and compared to untreated range soil. The change in solubility that was exhibited by these metals across the pH range of this study is consistent with their known solubility data (Hazardous Waste Site Soil Remediation 1994) with the exception of Cr. According to solubility data available for Cr, “no change” in solubility would have been anticipated instead of a decrease. The discrepancy could be due to sample variability.

Table 6. Comparison of Average Metal Concentrations in HGR Soil from Bay 2 (Untreated Control) and Bay 4 (Lime Amended), Fort Jackson.

Metal	Bay 2		Bay 4		Significance
	Avg (n=8)	Stdev	Avg (n=10)	Stdev	
Fe	9750.63	1085.58	5642.11	718.92	D
Zn	1379.66	1648.81	1155.80	651.49	NC
Cr	16.68	1.41	11.13	0.75	D
Pb	23.17	0.84	20.73	1.38	NC
Ni	13.12	0.80	12.42	0.68	NC
Mn	19.35	2.97	14.82	2.22	D
V	19.07	1.45	14.28	2.23	D

D = significant decrease with treatment

NC = no significant difference with treatment

4.2.3 Soil Explosives

The average (n=5) initial Fort Jackson HGR grab soil concentrations of RDX from the four throwing bays ranged from 1.04 to 3.78 mg/kg, confirming the values reported for the treatability study (Larson et al., 2007). Although TNT makes up 39% of the high explosive in each grenade thrown, very little to no detectable TNT was found in the range soil from Fort Jackson. A measurable concentration was detected only in two out of three replicates from one of the five grab samples from Fort Jackson's Bay 2 (2.83±3.04 mg/kg). No TNT was detected in Bay 4 or in the off-site background samples.

The average soil RDX concentration per bay throughout the field demonstration is presented in Figure 4, which compares the RDX concentration in soil from Bay 2 (control) with the RDX concentration in soil from Bay 4, pre-liming, and 24 hours later, at the post-liming sampling. There were low concentrations of RDX in the surface soil during the month of January 2006 and prior to the July 2006 sampling event due to range maintenance operations that placed additional topsoil in the bays. The topsoil was applied to fill in divots generated by grenade explosions and to adjust the surface water flow for Bay 2 (prior to July 2006). This addition of topsoil places relatively clean soil on top of the treatment area, resulting in a reduction of the soil pH in that area and, therefore, a reduction in the alkaline hydrolysis transformation of the explosive.

The standard deviation is particularly high for the soil samples from Bay 2 when compared to Bay 4. The lower sample variability from Bay 4 is due to the increased soil homogenization associated with the lime amendment as well as the alkaline hydrolysis reaction.

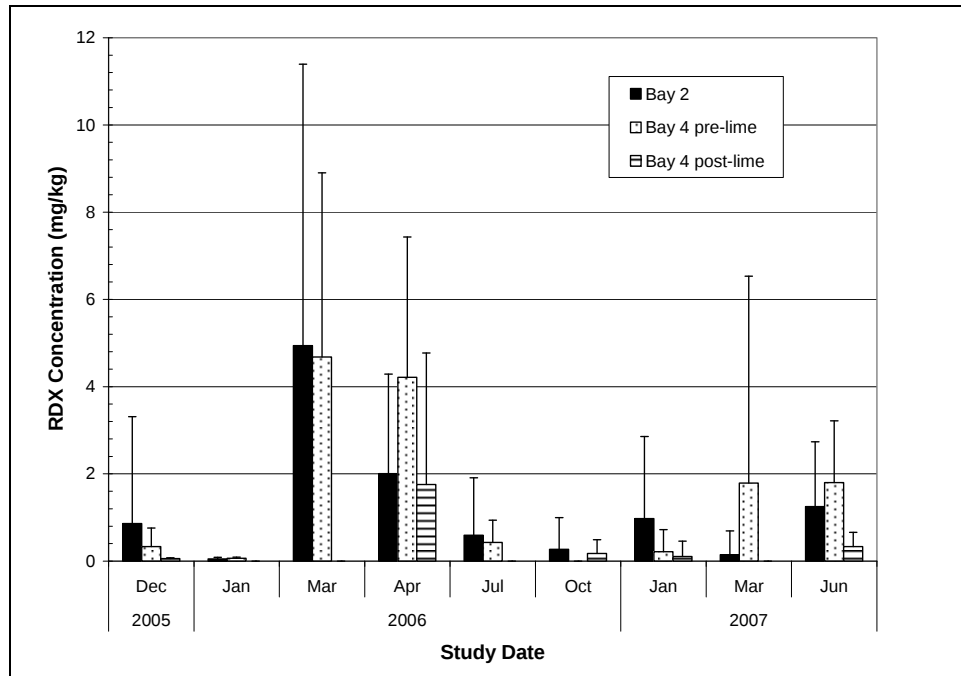


Figure 4. Average Soil RDX Concentration by Bay During the Field Demonstration.

4.2.4 Leachate and Surface Water pH

Five pore water suction lysimeters were placed approximately 1.52 m bgs in each HGR bay. During the field demonstration sampling, the pH of the pore water ranged from 5.7 to 7.6 for the lysimeters in the treated bay, Bay 4, and from 5.5 to 7.7 for the lysimeters in the control bay, Bay 2 (Table 7). The surface water samplers were placed in the direct surface water flow path from each bay. During the field demonstration, the pH of the surface water collected from the Bay 4 samplers 1 and 2 ranged from 4.9 to 7.8. The pH for the surface water collected from the control Bay 2 surface water samplers 3 and 4 ranged from 5.4 to 6.6. Complete surface water pH data is available in Appendix A of the ERDC-EL technical report. This data meets the criteria in which the overall effectiveness of the treatment would be assessed based on keeping the pH outside the source zone below 12.5.

Table 7. Pore Water pH from the Suction Lysimeters.

Bay	Lysimeter ID	Average pH
4	1	6.9
	2	6.9
	3	7.0
	4	6.9
	5	6.6
2	6	7.1
	7	7.1
	8	7.1
	9	6.9
	10	7.0

4.2.5 Leachate and Surface Water Metals

The soluble metal concentrations were determined for the soil pore water collected by the lysimeters in each bay. The ratio of metals concentration in the pore water from the untreated bay to that in the treated bay is shown in Table 8 for each sampling event. When the value for the metal was greater than 1, the concentration was greater in the untreated bay (i.e., lower concentrations are found in the leachate of the treated [limed] bay). When the value was less than 1, the concentration was less in the untreated bay and higher in the treated (limed) bay. The shaded averages indicate metals for which the leachate concentrations were decreased by lime treatment (Fe, Ni, molybdenum [Mo]). Ca, used as a treatment tracer, was present in leachate from treated and untreated soil at 3.90 and 2.49 mg/L, respectively, values that are not statistically different ($p=0.05$). Zn demonstrated no effect from the lime treatment. Mn concentration was slightly increased by the lime treatment. The results of the comparison indicate that primary Objective 4, to reduce metals concentrations by greater than 90% or demonstrate no significant increase in metals migration in the pore water leaching from the source area, was met.

Table 8. Ratio of Metals Concentration in the Pore Water Between the Untreated Control Bay 2 and the Lime-Amended Bay 4.

Metal	Ratio of Metal Concentrations (Untreated/Treated) in the Lysimeter Pore Water by Sampling Event											
	1	2	3	4	5	6	7	8	9	10	11	Average
Fe	1.00	1.00	1.00	1.00	1.10 ^a	0.15 ^b	0.79	43.02 ^c	3.29	2.41	1.16	3.29
Ni	2.25	0.63	1.38	2.65	2.01	2.25	2.05	2.06	0.82	0.87	0.56	1.55
Zn	0.21	0.18	2.77	1.81	3.40	2.57	0.47	0.90	1.10	0.35	0.19	1.00
Mn	0.56	0.83	1.06	2.01	1.87	1.65	1.54	0.79	0.75	0.80	0.70	0.87
Mo	0.41	1.52	1.06	1.22	1.19	1.91	1.39	4.45	0.96	2.01	1.47	1.54
Ca	ns	1.10	1.10	1.55	ns	2.18	1.72	2.10	1.85	1.89	1.22	1.45

^a Value greater than 1, concentration was greater in the untreated bay

^b Value less than 1, concentration was less in the untreated bay

^c Heavy rain preceded collection of the lysimeter samples

4.2.6 Leachate and Surface Water Explosives

Based on the average pore water concentration in the treated and untreated bays over the demonstration period, there was a 77% reduction in RDX concentration in pore water from the treated bay. The average pore water RDX concentration was consistently less in the limed Bay 4 than the control, Bay 2, throughout the duration of the field demonstration (Figure 5), with a statistically significant difference between the untreated and the limed bays. Figure 5 also shows the average, the high, and the low concentrations that were detected in each lysimeter during the field demonstration, illustrating the low variability between samples from the treated bay versus the untreated bay. The RDX concentrations by date for each lysimeter can be found in Appendix A of the ERDC-EL technical report.

The total mass of RDX collected by each lysimeter is significantly less in the lime-treated bay than for those in the untreated bay (Figure 6). Stacked by sampling date, the larger RDX losses present in both sets of lysimeters in January 2006 are clear. The results shown in Figure 6 represent the mass of RDX in milligrams present in the volume of leachate water removed from

each of the 10 lysimeters. Following some rain events, large volumes of water were extracted using the suction lysimeters. Following periods of low rainfall, smaller volumes of water are collected and the resulting mass of RDX present in the leachates collected is low. The volume of water collected by each lysimeter during each month of the field demonstration is also recorded in Appendix A of the ERDC-EL technical report.

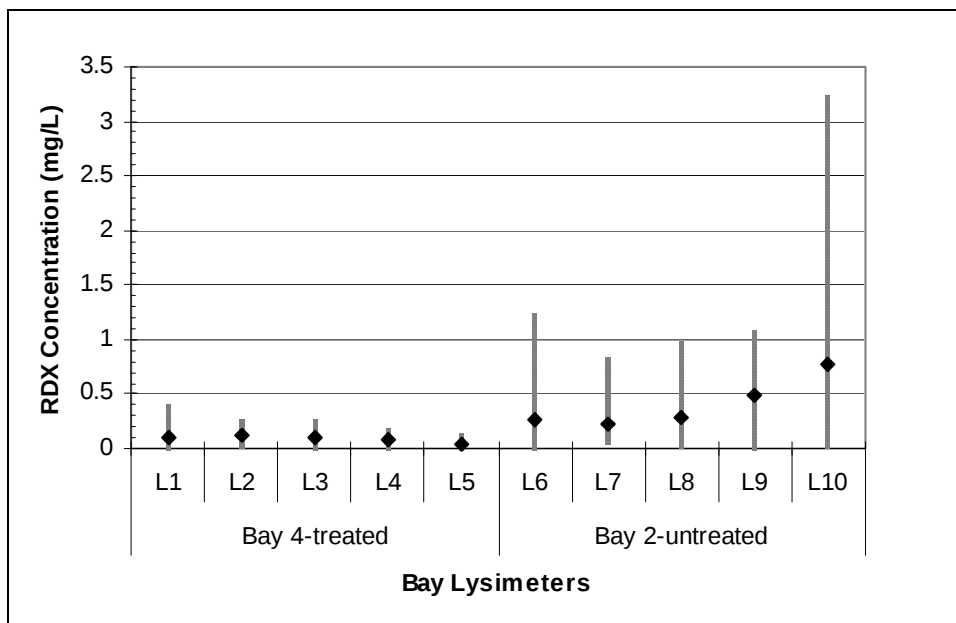


Figure 5. Pore Water RDX Concentration by Bay and Lysimeter with High and Low Concentration Profiles. (Average—sample size varies from 7 to 10.)

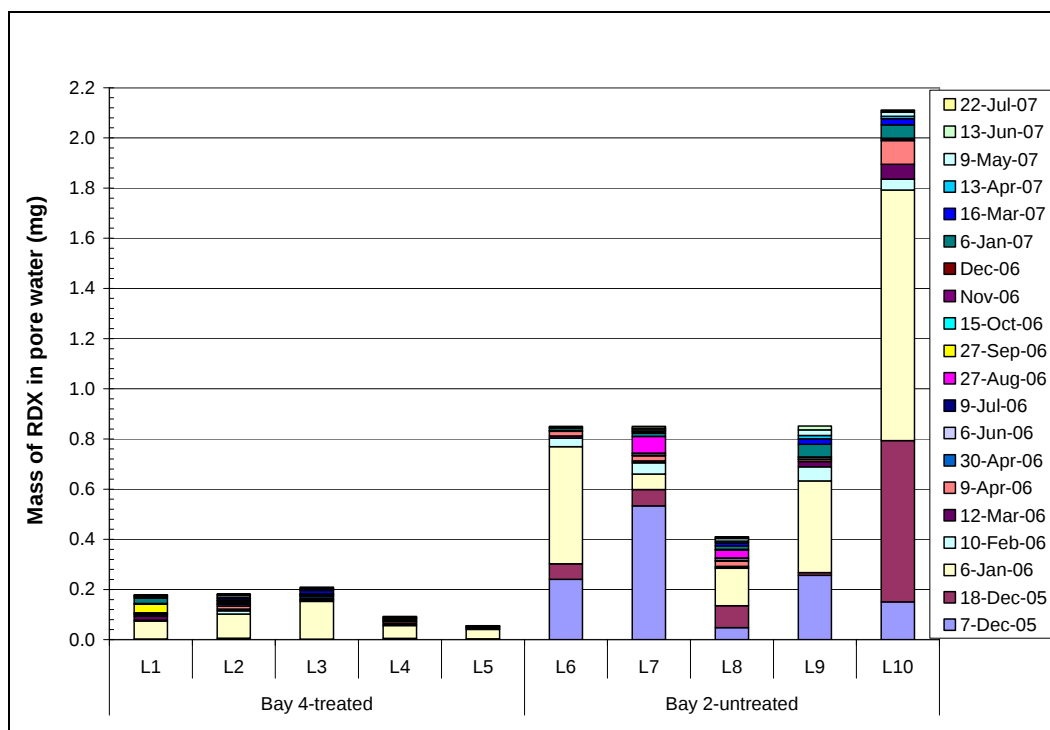


Figure 6. Mass of RDX per Suction Lysimeter During the Field Demonstration.

The sporadic nature of the surface water samples supports only a qualitative examination of the data; however, initial samples of surface water from areas unaffected by the lime treatment indicate an RDX concentration of approximately 0.0095-mg/L (sample concentrations determined by solid phase extraction [SPE]). Following the first liming event in December of 2005, RDX concentrations in the surface water collection areas servicing Bay 4 decreased to 0.001-0.003 mg/L. These concentrations were maintained until April at which time the pre-liming samples of surface water from Bay 4 had increased to initial RDX concentrations. Lime treatment of Bay 4 resulted in greater decreases in the RDX concentrations in the surface water, a condition which, again, persisted for 3 to 4 months. The final samples indicated a reduction in surface water RDX concentration from the control of >96%, which meets the criteria outlined in Table 4.

4.2.7 Air Monitoring

As required in the criteria listed in Table 4, the health risks associated with the lime amendment technology were evaluated. As in soil and water samples, Ca was used as a tracer for the presence of lime in the dust collected by air monitoring samplers. The air monitoring samples were collected during training on six separate occasions. Although individual sample days produced some differences in Ca concentration, as seen in Figure 7 and confirmed statistically, there was no significant difference in Ca concentrations between the air of the control bay and the limed bay.

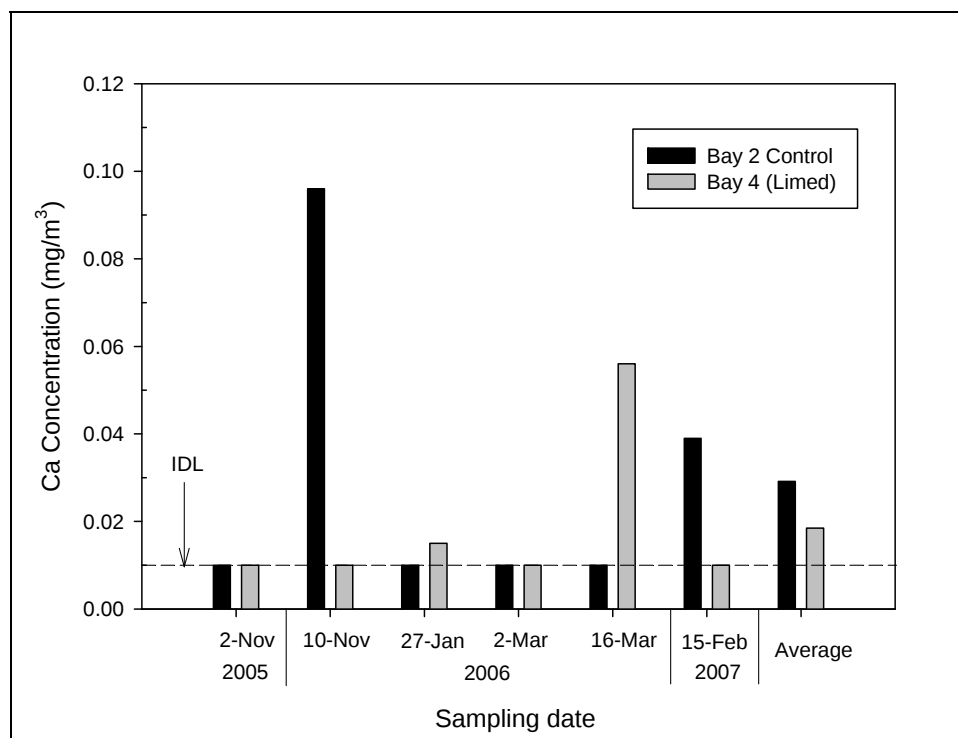
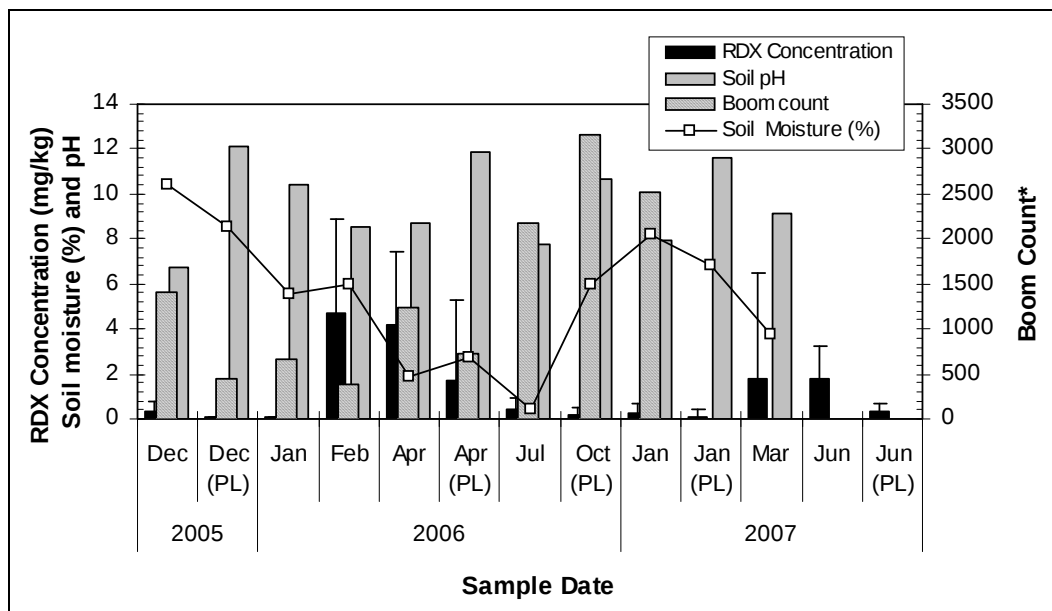


Figure 7. Comparison of the Calcium Concentrations in Air (mg/m³) from Treated and Untreated Bays During the Field Demonstration Study. (IDL=instrument detection limit.)

4.3 DATA ASSESSMENT

There are many factors that influence the concentration of RDX in soil and the effectiveness of lime amendment. These include the number of grenades thrown on the range (boom count), as well as soil properties such as the pH, precipitation at the site, and the soil moisture content. The trends for Bay 4 are represented graphically in Figure 8.

In general, for alkaline hydrolysis to perform effectively, the soil pH must be elevated above 10.5 and there must be sufficient moisture content (or precipitation) for the RDX and hydroxide to react. Months of poor performance (February and April 2006 and March 2007) have several factors in common. First, range maintenance operations were conducted in January of each year and included filling divots with clean topsoil. This action decreases the pH of the entire topsoil cover and also creates areas of much lower pH. Second, the decreased rainfall in these months resulted in lower soil moisture, which adversely impacts the efficiency of the process. Third, high usage rates in the months immediately preceding the sampling, as determined by the boom count, increases the concentrations of RDX even though transformation is occurring, as evidenced by the low concentrations of RDX in the lysimeter pore water. The zone of high pH seen in the soil cores between 6 and 12 inches bgs is also evidence that RDX transformation can continue even when the surface pH decreases below optimal levels.



*The boom counts are added together for the months that were not sampled.

Figure 8. Bay 4 (limed) RDX Soil Concentration with Soil pH and Moisture and Boom Count.

There were no regulatory standards to meet, and no special training is required for technology implementation. The complete Health and Safety Plan (HASP) can be found as Appendix C of the ESTCP ER-0216 Final Report, and a Soldier/Range Cadre Risk Analysis makes up Appendix C of the ERDC-EL technical report. Application of the lime in the HGR bays requires only Level D PPE, modified by the addition of a particulate respiratory mask and, possibly, the

substitution of goggles as protective eyewear. Range maintenance will require only Level D protection as the lime is incorporated into the soil at that point.

4.4 TECHNOLOGY COMPARISON

The data obtained from the lime demonstration project are presented as explosives removal as a function of time. Changes in concentrations of metals, other explosives, and pH have also been evaluated for soil and aqueous media. The test data are compared to the baseline data and control site data to evaluate the lime technology performance, as there is no comparable technology available for performance comparison.

5.0 COST ASSESSMENT

5.1 COST REPORTING

As requested in the ESTCP preparation guide, the Federal Remediation Technology Roundtable (FRTR) *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* was used as a guide for tracking and estimating grenade range management costs using the lime amendment technology. The cost elements that influence the use of lime amendments to manage munitions constituents on grenade ranges include initial treatability testing required to determine the appropriate lime application rate for the range soil; cost of the lime; rental equipment (spreader and disc with small tractor) to apply the lime if these items are not available on the base; 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. The actual demonstration cost, which includes experimental sampling and analysis of soil, pore water, surface water runoff, and air monitoring, is detailed in Table 9. Implementation costs of the technology for a hand grenade range are detailed in Table 10, where the unit is a single hand grenade range bay. In Table 10, costs are compared for renting the lime application equipment against buying the equipment and amortizing the cost over 6 years. The costs are based on 2008 retail prices. The cost of treatability testing remains the same over all 6 years as does the cost of operations and maintenance (O&M). Within the O&M cost category, the cost of lime doesn't fluctuate a great deal so it was kept steady over the 6 years. Fuel for the all-terrain vehicle (ATV) was also held constant since that cost is currently fluctuating so widely it is difficult to predict 6-year changes. With these stipulations, based on renting equipment yearly for lime application, the technology cost becomes \$20/yd³ of contaminated soil. Six years after purchasing the equipment, the cost drops to approximately \$15/yd³.

Because a hand grenade range bay is the full-scale operation, another table is deemed redundant. The cost would simply be multiplied by the number of bays treated, a factor which is site-specific.

5.2 COST ANALYSIS

The primary cost drivers for HGR management using lime amendment are material cost of the lime and equipment rental 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. At some active sites, lime may need to be reapplied more or less frequently dependent on the soil buffering and physical characteristics and local weather characteristics. A pH test of the soil would likely be recommended quarterly at each site until the lime requirement has been established.

If UXO is present, then EOD support may become an additional cost driver in the application of the technology. We found that monitoring the technology immediately following regular range clearance by EOD personnel greatly reduced cost and time to the project.

If equipment is available on the base, then the equipment cost becomes zero.

Table 9. HGR Demonstration Project Cost Summary.

Type of Cost	Technology Cost (\$)	Quantity Treated
1. Capital Cost for Demonstration Project		
Mobilization/demobilization Planning/preparation (labor)	319,000	
Equipment	18,500	
Other—treatability testing for lime requirement	2,000	
Total Capital Costs	339,500	
2. O&M for Demonstration Project		
Labor (ERDC ¹)	201,360	
Labor (contractor)	273,000	
Labor (ARDEC ²)	35,000	
Labor (ATC ³)	163,000	
Materials (lime)	1,600	
Travel to site	77,500	
Performance testing and analysis	385,260	
Total O&M Costs	1,136,720	
3. Other Technology-Specific Costs	N/A	
4. Other Project Costs	44,700	
Total Technology Cost	1,520,920	
Quantity Treated		600 m ³ soil (per bay) (785 yd ³)
Calculated Unit Cost	\$2,535 per m ³ soil \$1,937 per yd ³ soil	

¹Engineer Research and Development Center

²Armament Research, Development and Research Center

³Aberdeen Test Center

Table 10. HGR Management Implementation Cost Summary.

Type of Cost	Technology Cost \$ (on a per year basis per HGR bay, with equipment rented by the base)	Technology Cost \$ (for year one per HGR bay, with equipment purchased by the base)	Technology Cost \$ (for Years 2-5 per HGR bay, with equipment purchased by the base)	Technology Cost \$ (for Year 6 per HGR bay, with equipment purchased by the base)
1. Capital Cost				
Equipment for lime				
- ATV (5% interest for 5 years)	1,000	1,134	1,134	0
- Disc plow	125	300	0	0
- Dropseed spreader	150	325	0	0
- Hydroseeder (5% interest)	2,000	2,520	2,520	0
Other				
- Treatability testing for lime requirement	2,000	2,000	2,000	2,000
Total Capital Cost	5,275	6,279	5,654	2,000
2. O&M for Lime Amendment (performed quarterly, x4)				
Labor – with UXO clearance provided by base	8,000	8,000	8,000	8,000
Materials(lime)	1,600	1,600	1,600	1,600
Utilities/fuel	200	200	200	200
Performance testing and analysis (soil pH testing)	75	75	75	75
Other (e.g., PPE ¹)	200	200	200	200
Total O&M Cost	10,075	10,075	10,075	10,075
Total technology cost (per year):	15,350	16,354	15,729	12,075
Quantity treated:	600 m³ soil (785 yd³)	600 m³ soil (785 yd³)	600 m³ soil (785 yd³)	600 m³ soil (785 yd³)
Unit Cost per m³ soil per year:	\$25.58	\$27.26	\$26.22	\$20.13
Unit Cost per yd³ soil per year:	\$19.55	\$20.83	\$20.04	\$15.38

¹personal protective equipment

The cost of hydrated lime (per ton) doesn't vary greatly across the country. Shipping over long distances will increase the material cost; therefore, a local distributor is the least expensive option.

5.3 COST COMPARISON

Based on the technology matrix supplied by the FRTR web site, there is no comparable technology to the lime amendment for in situ transformation of explosive compounds and simultaneous immobilization of the metals. The technology closest for comparison purposes would be an ex situ treatment train (1) removes the soil from the site, (2) degrades the energetic compounds, and (3) follows up with chemical treatment to immobilize the metals (Table 11). Treatments that result in degradation of the explosives to intermediates and/or complete mineralization include composting, landfarming, and thermal treatment (such as incineration or open burning/open detonation). Compared to alkaline hydrolysis and thermal treatments, composting and landfarming require much more time to complete. They often do not achieve complete mineralization of the energetic compounds, leaving behind recalcitrant and toxic intermediates, that require specialized training in these technologies to set up and monitor progress. In comparison with these available technologies, the lime amendment requires only a simple soil-lime requirement test based on ASTM Method D6276, as outlined in Appendix D of Davis et al. (2007), not a complicated microbiological or hydrogeological workup. There are no requirements for roads and such beyond those already on the base; large areas of the base do not need to be set aside as treatment areas; excavation equipment and transportation of the soil is not required; and no fire protection is needed. There are no wastes or residuals to dispose of, and, in the case of Fort Jackson, no permits to acquire or hazardous exposure to mitigate. Based on its speed, we chose to compare alkaline hydrolysis with thermal degradation technologies. If treatment speed not an issue, then a biological method could be tested.

Table 11. Cost Comparison Between Lime Amendment and Thermal Treatment/Chemical Immobilization for Explosives Destruction and Metals Immobilization.

Cost Areas	Lime Amendment	Thermal Decomposition	Chemical Immobilization
Capital	\$2,000 for determination of lime requirement	- Initial excavation and transportation off-site - Re-application of topsoil to the HGR bay	
O&M	- Lime = \$0.67/m³ soil - Quarterly application = \$2.67 m³ soil per year - soil pH testing = \$75 per year	\$1,047/m³ for incineration - Cost not available for open burn/open detonation	\$216/m ³ soil for a small site, easily treated
Total Cost	Lime amendment of soil = \$19 to \$54/m ³ of soil to be treated per year (\$25 to \$71/yd ³).	\$1,047/m ³ (\$1,369/yd ³) plus excavation/shipping costs Thermal decomposition of explosives followed by chemical stabilization of the metals = \$1,263/m ³ (\$1,652/yd ³) of soil.	\$216/m ³ (\$283/yd ³) plus excavation/shipping costs

Assuming 100 hand grenade ranges with four bays per range and each bay with 600 m³ (785 yd³) of soil to be treated (2400 m³ or 3,139 yd³), then the cost of the lime treatment becomes \$456,000 to \$1,296,000. The other technologies range from \$518,000 to \$2,512,800, plus excavation/shipping charges.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The key factor affecting project costs is equipment rental. This becomes unnecessary when equipment is already on base and available for use. Site-specific issues that will affect cost are rainfall amount and soil type. If rainfall is inadequate, watering may become necessary after the application of the lime. If the soil is highly buffered, more lime will be required to elevate soil pH into the reactive range.

There are limited areas for future cost reduction. One possibility would be the bulk purchase of hydrated lime.

6.2 PERFORMANCE OBJECTIVES

The results of this study indicate that hydrated lime amendment to HGR soils was effective in achieving the project goals, as outlined in Table 4. The primary factor that caused deviation from the objectives was the weather. Extensive drought resulted in low surface water collection volumes and silting of the sump pumps in the bays. Drought also resulted in several periods of low explosives transformation as the reaction requires soil pore water. Measures that could be used to address this are watering following lime application and quarterly soil testing for pH to ensure that the lime remains in the reactive pH zone.

6.3 SCALE-UP

The demonstration project was a full-scale representation of the technology. Moving to a larger scale would only involve treating the remaining bays of the hand grenade range in the same manner. The major cost increase would be from increased labor for application time and increase in lime amount used.

6.4 OTHER SIGNIFICANT OBSERVATIONS

There are no major factors that can affect implementation of the technology beyond those discussed in the previous sections.

For help in implementing this technology, the range manager should contact one of the project PIs listed in Section 8.

The primary end user for this innovative in situ technology will be active hand grenade training ranges. The technology is expected to break down explosives contaminants and stabilize metals at the source zone 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 safely be implemented in these areas.

6.5 LESSONS LEARNED

Lessons learned from the demonstration of this technology include:

- A chief benefit is ease of use.
- The cost is low.
- Installations have most, if not all, the needed equipment available.
- Lime application is best performed in conjunction with range maintenance activities.
- Lime application rates will vary depending on the soil chemistry and site conditions.

6.6 END-USER ISSUES

A usage guide to implementation of this technology at other HGRs is in preparation (Martin et al., 2007).

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

There were no regulatory drivers at the Fort Jackson HGR site, and no permits were required to implement this technology. Based on our experience at this site, no permits will be required for surface water runoff or soil pore water at other sites.

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APPENDIX A

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