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Cost and Performance Report

(ER-200406)

Passive Reactive Berm (PRBerm) to Provide Low Maintenance Lead Containment at Active Small Arms Firing Ranges

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TABLE OF CONTENTS

Page

1.0 EXECUTIVE SUMMARY 1
- 1.1 OBJECTIVES OF THE DEMONSTRATION 1
- 1.2 TECHNOLOGY DESCRIPTION 1
- 1.3 DEMONSTRATION RESULTS 1
- 1.4 IMPLEMENTATION ISSUES 2

2.0 INTRODUCTION 3
- 2.1 BACKGROUND 3
  - 2.1.1 Impact Berm Deceleration Media 5
  - 2.1.2 Phosphate Amendments 6
- 2.2 OBJECTIVES OF THE DEMONSTRATION 8
- 2.3 REGULATORY DRIVERS 8

3.0 TECHNOLOGY 9
- 3.1 TECHNOLOGY DESCRIPTION 9
- 3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 12

4.0 PERFORMANCE OBJECTIVES 15

5.0 SITE DESCRIPTION 17
- 5.1 SITE LOCATION AND HISTORY 17
- 5.2 SITE GEOLOGY/HYDROGEOLOGY 20
- 5.3 CONTAMINANT DISTRIBUTION 20

6.0 TEST DESIGN 21
- 6.1 CONCEPTUAL EXPERIMENTAL DESIGN 21
- 6.2 BASELINE CHARACTERIZATION 21
- 6.3 TREATABILITY STUDY RESULTS 21
- 6.4 FIELD TESTING 23
  - 6.4.1 Amendments 23
  - 6.4.2 Lysimeter Construction and Installation 25
  - 6.4.3 Metal Contamination per PRBerm™ 28
  - 6.4.4 Sampling Methods 29
  - 6.4.5 Sample Analysis 30
- 6.5 SAMPLING RESULTS 31
  - 6.5.1 Aqueous Samples 31
  - 6.5.2 Soil Samples 36

TABLE OF CONTENTS (continued)

Page

7.0 PERFORMANCE ASSESSMENT 41
7.1 QUANTITATIVE PERFORMANCE OBJECTIVES 41
7.1.1 Meet State Release Permit Requirements for Release of Munitions Metals in Runoff Water 41
7.1.2 Meet State Release Permit Requirements for pH of Discharge Water 41
7.2 QUALITATIVE PERFORMANCE ASSESSMENT 41
7.2.1 Reduce Transport of Munitions Metals from the Range 41
7.2.2 Reduce Range Operational Costs 42
7.2.3 Provide BAT for Range Operations 42

8.0 COST ASSESSMENT 43
8.1 COST MODEL 43
8.2 COST DRIVERS 44
8.3 COST ANALYSIS 44
8.3.1 Technology cost comparison 44
8.3.2 Life cycle costs of the PRberm™ 45
8.3.3 Life Cycle Costs of a Steel Bullet Trap 46

9.0 IMPLEMENTATION ISSUES 51
9.1 ENVIRONMENTAL CHECKLIST 51
9.2 REGULATORY ISSUES 51
9.3 END-USER ISSUES 51
9.4 MANAGEMENT COSTS 51
9.5 LESSONS LEARNED 51

10.0 REFERENCES 53

APPENDIX A POINTS OF CONTACT A-1

LIST OF TABLES

Page

Table 1. Soil chemistry that promotes transport of Pb off-range in surface water and to groundwater via leachate. 4
Table 2. Performance objectives. 15
Table 3. Lysimeter leachate parameters from different ballistic sand and amendments. 22
Table 4. Live-fire lysimeter (LFL) leachate parameters from different ballistic sand and amendments. 24
Table 5. Results of TCLP analysis of post-live-fire lysimeter berm sand and amendments. 24
Table 6. Amendment composition in the three field demonstration lysimeters. 26
Table 7. Type and number of rounds fired into each lysimeter on the CAFB M–60 range during the 2009 field demonstration. 28
Table 8. Metal concentration in soil for both rounds. 29
Table 9. Analytical methods for sample analysis. 31
Table 10. Volume of effluent collected from the PRBerm™ lysimeters during the field demonstration. 32
Table 11. Comparison of TSS concentrations in leachate and runoff water collected during the PRBerm™ demonstration at the CAFB M–60 range. 33
Table 12. Average concentration of total (digested) metals in lysimeter leachate. 33
Table 13. Average concentration of total (digested) metals in lysimeter runoff water. 34
Table 14. Average concentration of soluble metals in lysimeter leachate. 34
Table 15. Average concentration of soluble metals in lysimeter runoff water. 35
Table 16. Calculated Pb concentration in lysimeters. 35
Table 17. Average concentration of total (digested) metals in bulk lysimeter soil post-firing. 36
Table 18. Averge TCLP metal concentration of post-firing bulk lysimeter soils. 37
Table 19. TCLP Pb, Total Pb, and the Pb leachability ratios (TCLP to total Pb) in lysimeters. 37
Table 20. Average metal concentrations for post-firing bulk lysimeter soil samples analyzed using the DDI S&S leaching procedure. 38
Table 21. Average metal concentrations for bulk lysimeter soil samples post-SPLP. 38
Table 22. Summary of Sb(III) and Sb(V) linear K_d data. 39
Table 23. Cost Model for a PRBerm™. 44
Table 24. Comparative cost and maintenance of the PRBerm™. 45
Table 25. Life-cycle cost factors for applying the PRBerm™ technology. 46
Table 26. Cost estimate for bullet trap purchase and installation. 46
Table 27. Estimate for concrete pad. 47
Table 28. Nonrecurring costs for a steel deceleration trap. 48
Table 29. Recurring costs for steel deceleration trap. 48
Table 30. Summary costs for steel deceleration trap. 49

LIST OF FIGURES

Page

Figure 1. Potential compliance issues on SAFRs. 4
Figure 2. Effect of PRBerm™ technology on regulatory compliance issues. 5
Figure 3. Schematic cross section of typical range berm with the PRBerm™ technology application. 9
Figure 4. Preconstruction view of the firing points and impact berm area at the CAFB M-60 range. 10
Figure 5. Preconstruction close up view through the pipe that forms the firing line looking toward the berm. 10
Figure 6. Designs for the implementation of the PRBerm™ technology at the CAFB, M-60 range. 11
Figure 7. Aerial view of the CAFB with the location of the M-60 range indicated within the red box. 18
Figure 8. Aerial view of the M-60 range at CAFB indicating possible bullet firing distances. 19
Figure 9. Surface Danger Zone (SDZ) analysis of proposed M–60 range PRBerm™ installation. 19
Figure 10. Completed field lysimeter prior to transport to the CAFB M–60 range. 25
Figure 11. Removal of the old impact berm composed of local soil from under the newly constructed protective eyebrow. 26
Figure 12. Placement of the three lysimeters in the impact berm in line with the three fixed firing positions. 27
Figure 13. Placement of the amended ballistic sand in the lysimeters. 27
Figure 14. The completed impact berm enclosing the three experimental treatment lysimeters on the M–60 range, CAFB. 28

ACRONYMS AND ABBREVIATIONS

AES	Atomic Emission Spectroscopy
AFB	Air Force Base
AFRC	Air Force Reserve Command
AMC	Air Mobility Command
As	arsenic
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
ATC	Aberdeen Test Center
BAT	best available technology
BOD	biological oxygen demand
Ca	calcium
CAFB	Charleston Air Force Base
Cd	cadmium
CEC	cation exchange capacity
COTS	commercial off-the-shelf
Cr	chromium
Cu	copper
DCU	dust collection unit
DDI	distilled deionized water
DOC	dissolved organic carbon
DoD	Department of Defense
DTIC	Defense Technical Information Center
ERDC	Engineer Research and Development Center
ERDC-EL	Engineer Research and Development Center - Environmental Laboratory
ESTCP	Environmental Security Technology Certification Program
Fe	iron
ICP	inductively coupled plasma
ISO	Industry Standard Object
LFL	live-fire lysimeter
LPDES	Louisiana Pollutant Discharge Elimination System
LTM	long-term monitoring
Mg	magnesium
NA	not applicable
ND	non-detect
NEPA	National Environmental Policy Act
Ni	nickel

O&M	operation and maintenance
OSHA	Occupational Safety and Health Administration
P	phosphorus
Pb	lead
PCMS	Project Configuration Management System
pH	potential hydrogen
PI	principal investigator
PRBerm™	Passive Reactive Berm
QA/QC	quality assurance/quality control
REC	Record of Environmental Consideration
S	sulfur
S&S	suspend and settle
SACON	shock-absorbing concrete
SAFR	small arms firing range
Sb	antimony
SDZ	surface danger zone
SPLP	Synthetic Precipitation Leaching Procedure
STDEV	standard deviation
TCLP	Toxicity Characteristic Leachate Procedure
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
TTF	thermally treated fish bones
USEPA	U.S. Environmental Protection Agency
Zn	zinc

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

The objectives of this technology demonstration are to assess the environmental benefits, feasibility, and cost of using sand as a deceleration medium in small arms firing range (SAFR) berms in conjunction with amendments designed to retard the migration of lead (Pb) into the surrounding environment. The amendments provide for reduction of Pb solubility through potential hydrogen (pH) buffering of pore fluids within the SAFR berm, as well as the sequestration of Pb through surface adsorption and the precipitation of insoluble Pb salts. This technology application is known as a Passive Reactive Berm (PRBerm™). The purpose of the technology demonstration is to provide range operators with an economical means of controlling the off-site migration of Pb, while maintaining the benefits of sand as a deceleration medium. The PRBerm™ technology is applicable to new and existing ranges. In particular, this technology is designed to address sites where the native soils available for SAFR berm construction either lack the characteristics necessary to retard the migration of soluble Pb (e.g., acidic soils) or are susceptible to erosion and off-site transport of Pb as a result of their high clay content.

1.2 TECHNOLOGY DESCRIPTION

Replacement of easily suspended, clay-rich soil in the primary impact area with a material that has high hydraulic conductivity and a low potential for producing suspended solids is expected to drastically reduce the amount of the Pb currently leaving the site. By amending the berms with buffer and Pb immobilization amendments such as the TRAPPS™ amendment and the thermally treated fish bones (TTF), the amount of soluble and colloidal Pb in the surface water and the leachate water leaving the new berm will also be reduced (Larson et al., 2007a). Both TRAPPS™ and the TTF have been used for Pb stabilization in analogous systems.

Treatability studies conducted at the Engineer Research and Development Center (ERDC) Vicksburg determined that an amendment ratio of 5% (weight/weight) to sand was sufficient to contain >90% of soluble Pb within the berm material. The technology was field tested on the SAFR (M-60 range) at Charleston Air Force Base (CAFB) in Charleston, SC. The CAFB PRBerm™ tested a 5% TRAPPS™ amendment (a granular, apatite-based material), alone and in combination with 5% TTF Apatite™. During the CAFB PRBerm™ field demonstration, storm water runoff and leachate water samples were collected and analyzed for metals, total suspended solids (TSS), and pH. At the conclusion of the study, the amended impact soils were analyzed for total and dissolved metals and metal leaching.

1.3 DEMONSTRATION RESULTS

Our results indicate that variation in the amount and type of rounds fired into berms has an effect on the Pb concentrations contained in leachate and runoff. The control lysimeter had the least amount of rounds fired into the impact area, which caused it to have the lowest Pb concentration. The lysimeter that was amended with 5% TRAPPS™ had the highest total Pb concentrations in both leachate and runoff. However, the inset lysimeter containing 5% TTF passed the regulatory limits for Pb, chromium (Cr), nickel (Ni), Arsenic (As), and antimony (Sb), which means that the

soil could be disposed of in a nonhazardous waste landfill. Nonhazardous waste provides a low-cost disposal option as compared to hazardous waste. For the Toxicity Characteristic Leaching Procedure (TCLP) tests, there was a decrease seen in the concentration of Pb for the amended lysimeters when compared to the unamended lysimeter. Even though both amendments decrease Pb concentrations, the 5% TTF performed the best.

1.4 IMPLEMENTATION ISSUES

The PRBerm™ technology does not involve the use of any toxic or hazardous chemicals. The TRAPPS™ amendment is not regulated and is approved for addition to soils. The TTF also are not regulated.

The potential for off-range migration of munitons metals 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.

The primary end user for this innovative in situ technology will be managers of active small arms ranges. The technology is expected to stabilize munitions metals within the impact berm before they can migrate to surface water or storm water discharge areas.

Technology transition efforts planned include presentation to range managers at the next TSS Workshop, publication in an American Society of Civil Engineers (ASCE) journal, and publication in trade journals for range managers. The completed, approved reports will also be forwarded to Defense Technical Information Center (DTIC).

2.0 INTRODUCTION

2.1 BACKGROUND

The Department of Defense (DoD) operates more than 3000 SAFRs. Live-fire training exercises are necessary to maintain mission readiness for our nations' warfighters. Compliance with existing state and federal environmental regulations is an important factor in training range availability. Traditional small-arms rounds consist of copper-jacketed Pb-alloy projectiles. Training exercises result in the deposition of Pb alloys in berm soils as particles ranging in size from microscopic dust to whole projectiles. Metals present in SAFR soils can migrate off-site into sensitive environmental receptors (e.g., wetlands, surface-water bodies, groundwater supplies) through surface water transport (runoff) or by vertical migration (leaching) of metals into groundwater. The resulting environmental contamination can result in state or federal regulatory action, which may ultimately impose constraints on critical training activities at SAFRs (Figure 1).

The use of earthen backstops (berms) composed of native soil can present environmental and regulatory challenges for installations that contain SAFRs, depending on the physical and chemical properties of the soil, and the proximity of the berm to sensitive environmental receptors. All Pb entering a berm on a firing range initially is present as metallic Pb. As the metallic Pb ages within the SAFR berm, it undergoes corrosion processes that can result in the release of dissolved Pb cations. Depending on the environment within the berm, the fate of dissolved Pb can range from transport to groundwater as soluble Pb, transport to surface water as soluble Pb, sorption onto electronegative particle surfaces (e.g., clays, organic matter, iron or manganese oxide), precipitation of Pb salts (e.g., carbonates, sulfates, sulfides, and phosphates).

Generally, the mobility of dissolved Pb is controlled by pH conditions, adsorption/desorption of Pb with soil particles, and advective processes such as groundwater or surface-water flow. When conditions are not optimal, the range may face regulatory issues, with Pb or other heavy metals being transported off range (Figure 1). Low pH soil (acidic soils) generally enhances Pb solubility, while neutral to basic pH conditions tend to favor the precipitation of Pb salts. Soils rich in clay and (or) organic matter typically exhibit high soil/water distribution coefficients (K_d values) for Pb and may thus be effective in retarding the Pb migration to the surrounding environment. However, the erosion and transport of Pb contaminated soils by surface runoff (especially those soils containing a high proportion of silt and clay) can result in the redistribution of Pb over relatively large distances.

Soils that are characterized by either high acidity (low pH), high alkalinity (high pH), high permeability, and (or) low soil/water K_d values for Pb may be ineffective in retarding the migration of soluble Pb into nearby groundwater or surface water bodies (Figure 1). Conversely, soils characterized by neutral to slightly basic pH conditions, relatively low permeability, and (or) those that exhibit a high K_d value for Pb may be effective in limiting the mobility of soluble Pb to the surrounding environment (Figure 2). However, mechanical erosion and transport of such soils (especially clay-rich soils) can lead to offsite transport of Pb in surface water runoff (Table 1).

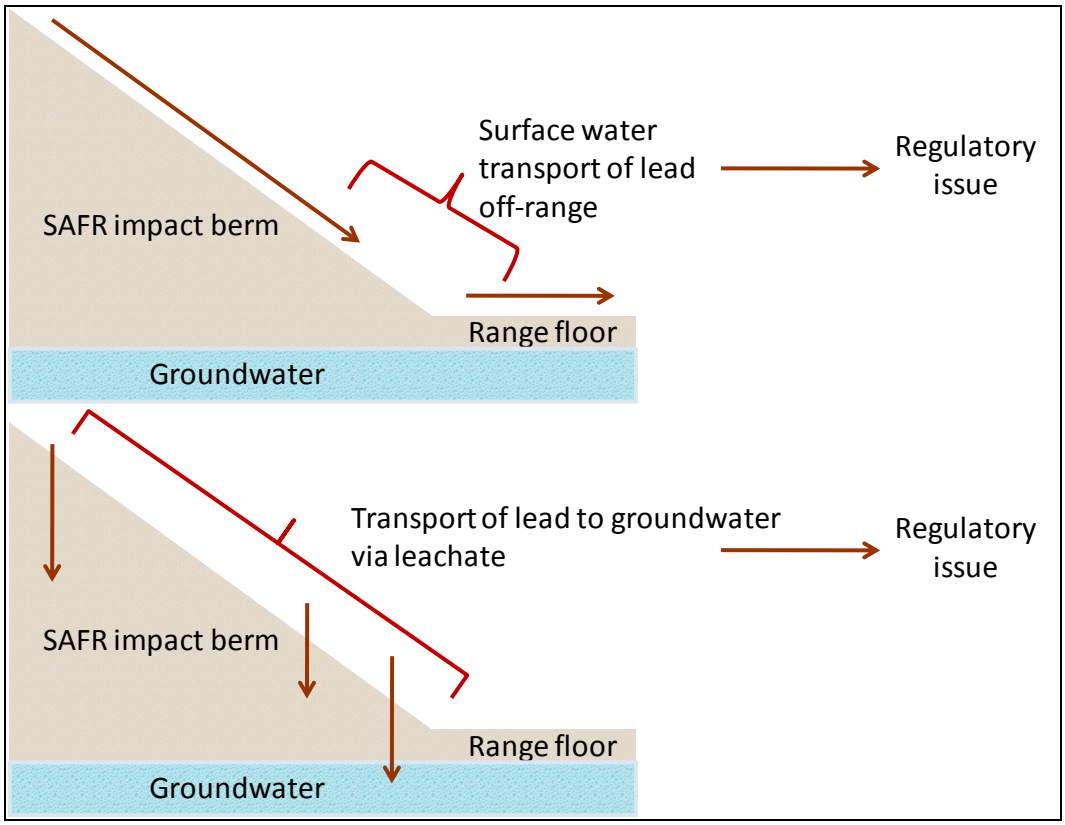

Figure 1. Potential compliance issues on SAFRs.

Table 1. Soil chemistry that promotes transport of Pb off-range in surface water and to groundwater via leachate.

Surface Water Transport	Leachate Transport
High CEC*	Low CEC
High percentage of fines (small particle size)	Lower percentage of fines
Extreme pH (acid or alkaline)	Extreme pH (acid or alkaline)
Low permeability	High permeability
High sorption capacity (high K_d)	Low sorption capacity (low K_d)
Potential problem soil types: silt, clay soils	Potential problem soil types: sandy soils
Regulatory Issue	**Regulatory Issue**

*CEC-cation exchange capacity

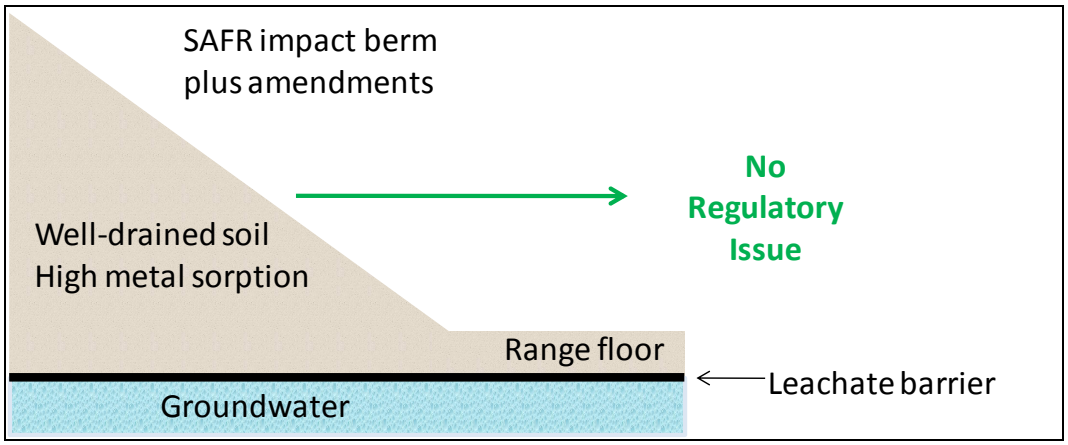

Figure 2. Effect of PRBerm™ technology on regulatory compliance issues.

2.1.1 Impact Berm Deceleration Media

The design and construction of new ranges and rehabilitation of older ranges should include consideration of pollution prevention opportunities. Moreover, operators of existing ranges may wish to consider implementing design changes that will reduce or eliminate migration of Pb into the surrounding environment. One critical design factor is the choice of material for impact berms. In many cases, the physical and chemical characteristics of the native soil will be adequate to retard the migration of Pb and thus prevent the contamination of nearby surface water or groundwater. In cases where the native soils have undesirable chemical properties for range purposes (e.g., high acidity or low pH, low K_d for Pb), or are easily eroded from berm surfaces, an alternative berm material may be utilized to minimize the risk of off-site transport, while still providing an economical alternative to enclosed steel bullet traps.

Washed construction sands that consist principally of silicate minerals (e.g., quartz), such as those commonly used in masonry and concrete manufacture, may provide a suitable medium for the construction or replacement of SAFR impact berms. Commercially available masonry or concrete sands are relatively low cost materials and are widely available due to their extensive use in construction. From an operational standpoint, sand has numerous beneficial properties as a deceleration medium at firing ranges and is generally the material of choice for this purpose. Impact berms made from sand are effective in decelerating fired projectiles safely with minimal fragmentation, a low risk of ricochet, and relatively little dust generation. The chemical inertness of silicate sands minimizes berm cementation and hardening, thus ensuring proper deceleration of projectiles. Further, the granularity, low bulk density, and non-cohesive nature of sand facilitate the separation of spent bullet fragments during range maintenance or clearance activities (e.g., by soil screening). Finally, the refractory and nonflammable nature of sand provides additional benefits in ranges where tracer rounds may be used.

From an environmental perspective, the use of silicate mineral sand offers three principal benefits: (1) washed sand typically contains a low proportion of silt and clay-sized particles, which reduces the potential for Pb transport by storm water runoff; (2) the relatively high hydraulic conductivity of sand minimizes the amount surface runoff down the berm face; and (3) the drainage characteristics (combination of the high permeability and low specific retention)

of sand tend to limit the contact time between water and Pb particles, thus inhibiting the in situ corrosion (weathering) of Pb.

However, from an environmental standpoint, there are a number of disadvantages associated with the use of sand in SAFR berms: (1) Most silicate mineral sands have a negligible pH buffering capacity. The lack of an adequate buffering capacity could lead to a reduction of soil pH to levels where both the rate of Pb corrosion and extent of Pb solubility in water are significantly increased. For this reason, Pb present in an unamended sand berm would be susceptible to leaching by acid precipitation (acid rain). (2) Commercially available washed construction sands typically contain relatively low proportions of clay, silt, and organic (humic) material and are thus characterized by relatively low K_d values. (3) Further, unamended silicate sands generally contain minimal amounts of carbonates, iron and manganese oxides, sulfides, organic matter, and phosphate compounds and are generally ineffective in retarding Pb mobility through precipitation reactions and are also difficult to vegetate. Thus, SAFR berms constructed entirely of unamended silicate sand may be more likely to release soluble Pb into the environment than berms that are constructed using other soil types. This shortcoming can be addressed by amending construction sand with materials that will buffer soil pH, enhance Pb adsorption, and (or) promote the precipitation of stable Pb salts.

2.1.2 Phosphate Amendments

The bioavailability and environmental risk of a contaminant are directly related to its accessibility to the biota in the soil medium, which is generally controlled by its solubility and mobility (Traina and Laperche, 1999; Brown et al., 2004). Linking Pb bioavailability to its solubility rather than to its total concentration makes possible the consideration of remediation strategies based on in situ reduction of contaminant solubility, rather than its complete removal or physical isolation (solidification). Due to the high costs of soil excavation and off-site remediation, in situ chemical stabilization with phosphorus (P)-based amendments has been investigated as a more efficient and cost-effective method of site remediation (Wilson et al., 2010; Hettiarachchi and Pierzynski, 2004; Traina and Laperche, 1999; Berti and Cunningham, 1997; Ma and Rao, 1997; Kumpiene et al., 2008; Mench et al., 2007; Vassilev et al., 2004, Nriagu, 1984; Ma et al., 1994). P-based amendments reduce the Pb bioavailability to allowable levels through the conversion of relatively soluble / bioavailable forms of Pb to relatively insoluble / less bioavailable pyromorphites ($Pb_5(PO_4)3X$ (s), where X = Cl^-, F^-, OH^-), the most stable forms of Pb in oxic surface soils under a wide range of environmental conditions (Traina and Laperche, 1999). Although P amendments have mainly been applied to remediate Pb-contaminated soil, they may also be applicable to other metals in firing-range soils such as cadmium (Cd) and zinc (Zn) (Hamon et al., 2002). The U.S. Environmental Protection Agency (USEPA) has recognized that bioavailability of Pb in contaminated soils varies greatly depending upon its form in the soil and has suggested that phosphate treatment has potential for in situ remediation of contaminated soils and sediments (USEPA, 2001).

Pb compounds show the greatest aqueous solubility at the acidic (pH<4) and alkaline (pH>11) ranges. Under acidic conditions, elemental Pb will dissolve, releasing a hydrated cation Pb^{2+}. Under alkaline conditions, elemental Pb will dissolve, theoretically forming the dissolved hydroxide complex $Pb(OH)_3^-$ and ion-pair $Pb(OH)_2$(aqueous) (ITRC, 2003).

Several factors affect the amount of Pb that is dissolved in water. In a typical water body, dissolved Pb forms precipitates of Pb hydroxide [$Pb(OH)_2$], Pb carbonate [$PbCO_3$, cerrusite], or basic Pb carbonate [$Pb_3(OH)_2$ $(CO_3)_2$, hydrocerrusite]. Overall, Pb solubility in a natural system is fundamentally determined by the concentrations of the anions in solution (e.g., the hydroxide and carbonate ions) and by the ionic strength of the solution, which affects the activity coefficients of the ions. These factors can be related to more directly measured parameters such as pH, alkalinity, and total dissolved solids (TDS) (Vaccari, 1992).

The metalloid Sb has also been detected in shooting range soil at high concentrations (Ackermann et al., 2009; Dermatas et al., 2006; Johnson et al.,2005; Kilgour et al., 2008; Klitzke and Lang, 2009). The Sb is added to Pb alloy as a hardening agent and is released, along with Pb, during the bullet corrrosion process. However, unlike the cation, Pb, Sb is an oxyanion and the geochemistry is different from that of Pb. The geochemistry has been reviewed by Wilson et al. (2010). Sb is reported to be associated with ferrihydrates, carbonates and oxides in soil. High pH (alklaine conditions) and anoxic conditions increase the dissolution of these complexes and lead to the release of Sb into the soil pore water and surface water (Chen et al., 2003; Johnson et al., 2005). Therefore, in conditions of well-drained soil with high concentrations of free carbonate and iron, a low percentage of clays and fines, and a low pH, Sb transport should not be a concern. However, when soil is amended with P for immobilization of Pb, the Sb may inadvertently be mobilized through competitive reactions with the P (Kilgour et al., 2008).

Fish bone is a form of biogenic apatite produced mechanically or enzymatically from fish industry by-products. This results in a composition of clean and dried fish bone and fish hard parts. The major elements of bones are calcium (Ca), P, sulfur (S), and magnesium (Mg) as well as several minor elements (Shinomiya et al., 1998). A study conducted by Shinomiya et al. (1998) investigated the eventual demineralization of mammal bones buried underground for 2 years and determined that phosphorous concentrations initially decreased within the bone and then increased, potentially due to nucleation sites (Wright et al., 2004) provided by the bone material. As a soil amendment, fish bone Apatite II has several advantages over other forms of natural apatite and terrestrial bone sources (e.g., cow bone). Apatite II has low trace metals concentrations and exhibits poor crystallinity compared to other naturally occurring forms of apatite (Conca et al., 2000). Unlike cow bones, Apatite II is highly microporous (Wright et al., 2004; Lu et al., 2001) and thus provides a readily available and reactive source of soluble phosphates along with a potential seed crystal for heterogeneous nucleation of Pb-pyromorphites (Wright et al., 2004). Depending on the presence of certain metals in solution, a Pb removal efficiency of 37 to 100% can be achieved through the process of hydroxyapatite dissolution and hydroxypyromorphite [$Pb_{10}(PO_4)_6(OH)_2$] precipitation (Ma et al., 1994; Wright et al., 2004). Fish bones used in the study at CAFB were thermally treated in a muffle furnace at 450° C to remove organic matter (Martin et al., 2008).

TRAPPS™ is a commercial off-the-shelf (COTS) product, a formulation of apatite and other insoluble phosphate mineral, in which Pb is precipitated as stable pyromorphite. According to the manufacturer, TRAPPS™ also does not cause increased mobilization of copper, arsenic, and Sb or release excessive amounts of phosphate (http://www.slateruklimited.co.uk/us/trapps_firing_range.html).

2.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this technology demonstration are to assess the environmental benefits, feasibility, and cost of using sand as a deceleration medium in SAFR berms in conjunction with amendments designed to retard the migration of Pb into the surrounding environment. The amendments provide for reduction of Pb solubility through pH buffering of pore fluids within the SAFR berm, as well as the sequestration of Pb through surface adsorption and the precipitation of insoluble Pb salts. This technology application is known as a PRBerm™. The purpose of the technology demonstration is to provide range operators with an economical means of controlling the off-site migration of Pb while maintaining the benefits of sand as a deceleration medium. The PRBerm™ technology is applicable to new and existing ranges. In particular, this technology is designed to address sites where the native soils available for SAFR berm construction either lack the characteristics necessary to retard the migration of soluble Pb (e.g., acidic soils) or are susceptible to erosion and off-site transport of Pb as a result of their high clay content.

2.3 REGULATORY DRIVERS

The regulatory drivers at the CAFB M-60 range were derived from the regulatory permitting requirements of the initial demonstration site, Barksdale Air Force Base (AFB), LA. The Louisiana Pollutant Discharge Elimination System (LPDES) permit LA0007293 issued to Barksdale AFB on April 1, 1997 and reissued November 1, 2002, established the SAFR complex daily maximum:

- Total Pb discharge limit to 0.15 mg/L (150 µg/L)
- Total copper limit of 0.5 mg/L
- Discharge pH between 6.0 and 9.0.

TSS is not a required measurement under the Barksdale AFB discharge permit, but since it is an important indicator of the potential metals leaving the range, TSS analysis was requested by the CAFB range personnel and was an additional parameter tested. Research performed by the Engineer Research and Development Center - Environmental Laboratory (ERDC-EL) has shown that the majority of the Pb in the runoff water occurs as insoluble Pb associated with suspended (colloidal) soil particles (Larson et al., 2007b).

3.0 TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

Pb enters the impact area at SAFRs primarily as intact bullets that break into pieces ranging in size from microscopic dust to large chunks of metal upon impact or smears onto soil particles. Due to weathering events, Pb will eventually corrode, resulting in soluble Pb in rain water that percolates through the soil as leachate or becomes a surface water runoff problem. As the water that contains soluble Pb passes over soils that have a high affinity for the charged Pb metal, the soil can provide a location for the Pb to attach to. If the soil particles are small, such as clay, then there is a tendency for these particles to be washed off of the range and thus provide an increase in total concentration of Pb leaving the range.

The PRBerm™ is designed to use sand as a nonreactive impact material thus limiting the reaction with soluble Pb. The amendment binds with the soluble Pb, potentially creating an insoluble Pb species such as plumbogumite or scotlandite that is less likely to leave the range. In addition there is potentially the transport problem of sand particles that have Pb smeared onto them. In this scenario, the sand used in the PRBerm™ matrix will consist of a ballistic sand that has an even particle size distribution, with limited fines and limited large sand particles. The limited fines will reduce the potential of suspended particles from leaving the range while the limited large particles will reduce the potential incident of bullet fragmentation upon impact.

Figure 3 shows a typical PRBerm™ cross section with the PRBerm™ technology application. A nonwoven geomembrane fabric is a barrier between native soils and the ballistic impact media. Amended sand is placed on top of the newly contoured earthen berm. A shock-absorbing concrete SACON® or timber toe support was placed at the base of the PRBerm™ to prevent excessive sand erosion from the berm.

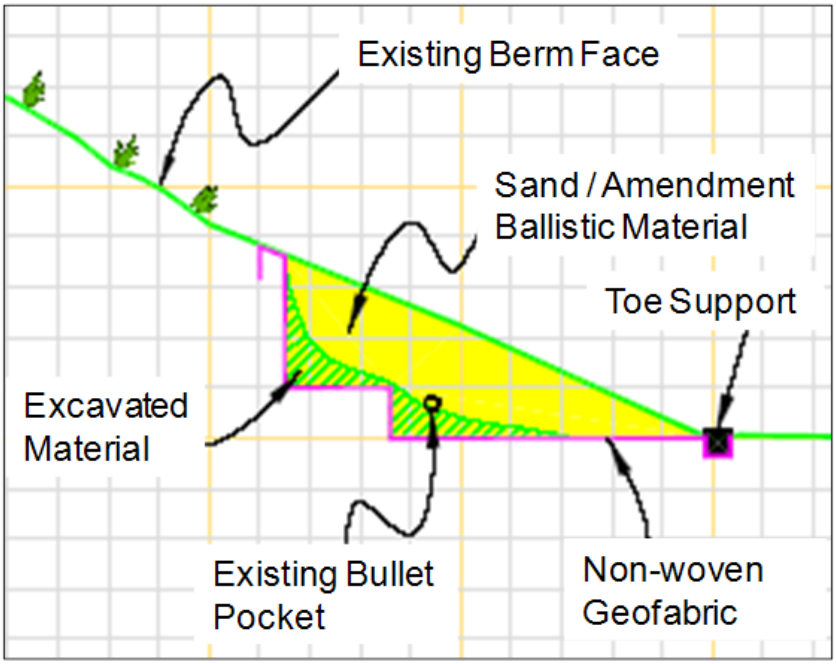

Figure 3. Schematic cross section of typical range berm with the PRBerm™ technology application.

Preconstruction views of the CAFB M-60 range are provided in Figures 4 and 5. A construction diagram detailing changes in the berm at the CAFB M-60 range for the installation of the PRBerm™ is shown in Figure 6.

Figure 4. Preconstruction view of the firing points and impact berm area at the CAFB M-60 range.
View is through the individual firing positions towards the impact berm.

Figure 5. Preconstruction close up view through the pipe that forms the firing line looking toward the berm.

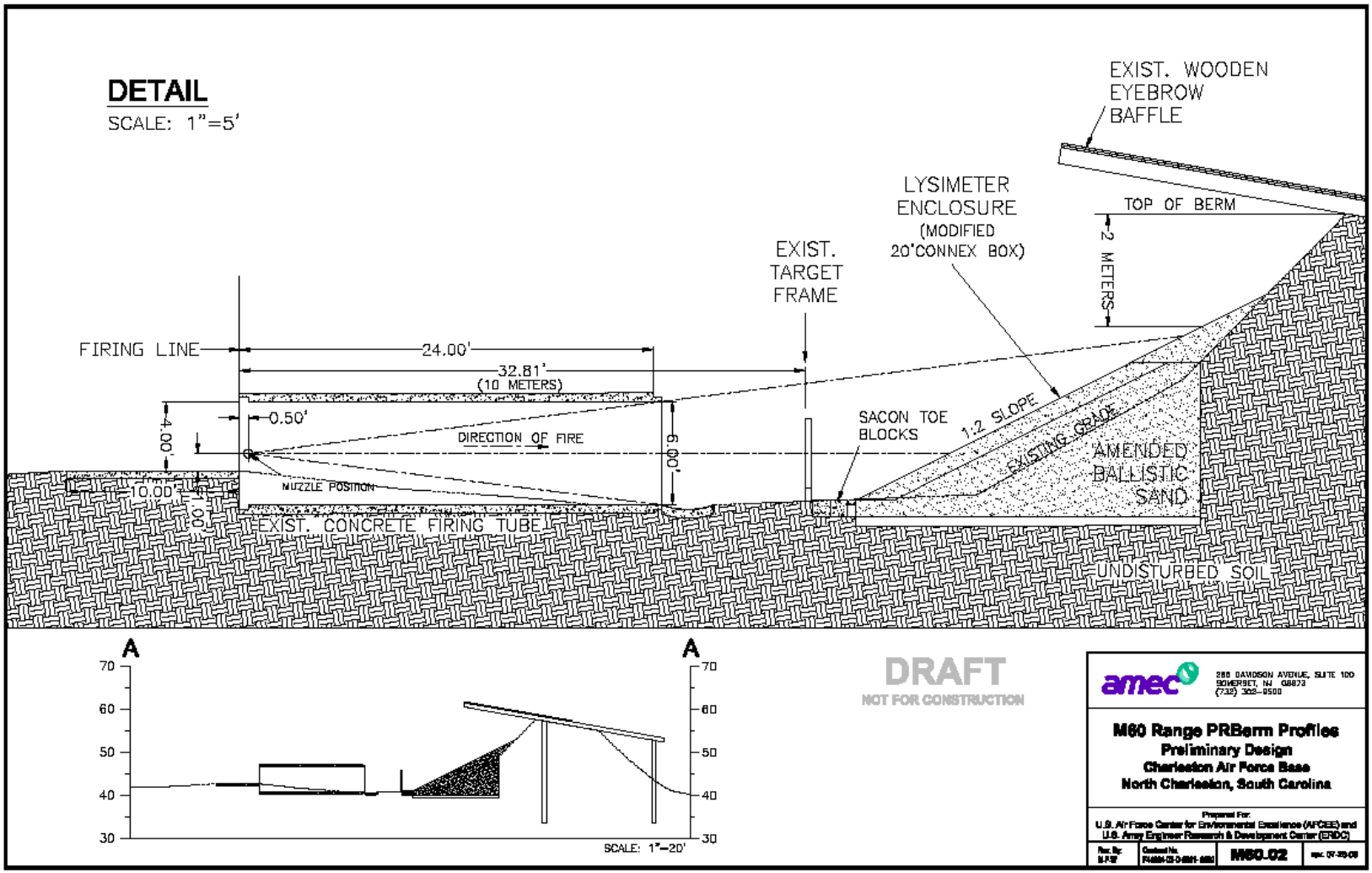

Figure 6. Designs for the implementation of the PRBerm™ technology at the CAFB, M-60 range.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The most commonly used technologies for metals containment at SAFRs range from using native earthen berms to installing steel bullet traps. The cost of the PRBerm™ technology will be compared against using a native earthen berm to installing a steel bullet trap. The cost basis for comparison will be dollars per running foot of PRBerm™ as compared to dollars per running foot of earthen berm and purchase and installation of a single steel bullet trap.

The sand or dirt berm is the oldest and most basic type of bullet trap. It uses the mass of the berm itself to stop and store bullets. Earthen backstops require immediate care to revegetate, to prevent potential ongoing erosion problems. Use of fiber mulch, filter fabric, or other material is almost certainly needed for a facility constructing a new earthen backstop. Proper seed mix recommendations, matching soil conditions, moisture, and sunlight conditions must be met for successful revegetation. Concentrations of Pb called hot spots can form behind the targets. Bullet deflection and splatter causing subsequent shots to ricochet and bounce back towards the shooter may begin to take place on an older, existing backstop if periodic removal is not included as a part of the maintenance plan of the range. In order to recover spent bullets, the berm must be mined and the Pb separated out. A certain amount of the sand will be contaminated and must be replenished each time the berm is rebuilt. Sand and dirt berms are coming under increasingly harsh environmental scrutiny due to high Pb levels in the ground around the impact areas and the tendency of the Pb to seep into surrounding groundwater and surface receiving waters.

The benefits of a sand berm include low installation cost and the speed with which they can be constructed using a bulldozer or some other piece of earth-moving equipment. Earthen berms also require relatively low maintenance and the ability to use any kind of ammunition. Weaknesses include potential environmental hazard, constant expensive maintenance, and the possibility of hot spot ricochet, mentioned above.

The benefits of a bullet trap include lower initial cost and simple installation. Some variations don't involve sand or granules. Most variations make it easier to collect the spent Pb bullets for recycling and disposal. Other benefits are the durability of steel and the smaller training space requirement. Weaknesses include bullet fragmentation on impact, Pb build-up and bullet ricochet, no close-range shooting, and high maintenance. The act of firing into a steel bullet trap is also a significantly different training experience from firing into a berm.

Advantages of the PRBerm™ technology include:

- Ease of procuring the amendments. The PRBerm™ is designed to minimize procurement problems by incorporating commonly available (i.e., off-the-shelf) construction materials such as masonry sand and landscaping fabric. Both of the buffer/Pb immobilization systems (Buffer Block and SulfiTech A/T) are available through authorized commercial suppliers. These are both proprietary technologies for use in remediation and management systems but with significant differences from the PRBerm™ approach. The associated transportation costs for these materials may vary by location.
- The technology can be installed using conventional construction machinery (e.g., frontloader with track excavator).

- Selection of amendments to address immobilization of both cationic and anionic metal species
- Impact media plus amendments passed the TCLP for waste disposal in a non-hazardous waste landfill, a considerable cost savings when considering removal of the training range berms.

Potential limitations of the PRBerm™ technology include:

- Possible solubilization of phosphate and transport of phosphate off the range in storm water runoff, depending on the type of amendment selected. High phosphate concentrations have been observed to result in algal blooms.
- Variation in the amount and type of rounds fired into berms has an effect on the Pb concentrations contained in leachate and runoff. Heavy use of the PRBerm™ with Pb ammunition will eventually fill all adsorption sites and increase the concentration of Pb released into the leachate and runoff water. Sampling should be continued in order to monitor the life cycle of the PRBerm™.

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4.0 PERFORMANCE OBJECTIVES

The performance objectives and results of the Performance Assessment for the CAFB PRBerm™ field demonstration are presented in Table 2.

Table 2. Performance objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance (Objective Met?)
Quantitative	Objective goals based on the treatability study and Barksdale AFB permit limits (carried through field demonstration for continuity purposes)	Bimonthly soluble Pb runoff ≤150 ppb	**Success**
		Bimonthly maintain pH 6 to 9	**Success**
		Bimonthly TOC*≤50 ppm[a]	**Success**
		Bimonthly soluble Cu** runoff ≤500 ppb	**Success**
Qualitative	Capture metals prior to off-range migration	Reduced Pb and other metals concentration results as compared to the control with no amendment	**Successful for the TTF amendment.**
	Reduce range operational costs	Provide comparable long-term cost savings as compared to steel bullet traps	**Success**
	Increase use of training availability	Provide a functional range for airmen to conduct regular small arms training	**Success**
	Provide Best Available Technology (BAT) for range operations	Low cost, ease of use, and minimal maintenance required by range personnel	**Success**
	Reduce the potential for leaching to groundwater	Compare metals leaching results (TCLP) to state/federal requirements	**Successful for the TTF amendment.**

[a]At the request of CAFB, TOC analysis was changed to TSS as the suspended solids were a greater concern to them.

*TOC = total organic carbon
**Cu = copper

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5.0 SITE DESCRIPTION

The CAFB range used during this demonstration was the M-60 range. There is an underground drain that allows the range runoff water to flow under a nearby road and into stormwater drainage nearby. This is a suitable means to collect and store rainwater for use in artificial raining of the PRBerm™, if needed. The drainage system located at the range will assist with collection of storm water samples leaving the range complex and prevents potential cross contamination of leachate water collection systems (i.e. on-site pooling of water).

5.1 SITE LOCATION AND HISTORY

CAFB, also known as Joint Base Charleston, is a U.S. AFB located in North Charleston, SC. CAFB is assigned to Air Mobility Command (AMC). A joint civil-military airport, CAFB shares runways with Charleston International Airport for commercial airline aircraft operations on the south side of the airfield and general aviation aircraft operations on the east side (Figure 7). CAFB is home to Joint Base Charleston 628th Air Base Wing (628 ABW), the "host wing for installation support." The 437th Airlift Wing (437 AW) focuses on operating the C-17 Globemaster III strategic airlift aircraft. The base has four operational groups consisting of 21 squadrons and two wing staff directorates. It is augmented by a parallel, collocated Air Force Reserve Command (AFRC) "associate" wing, the 315th Airlift Wing (315 AW), which shares the same C-17 aircraft with the 437 AW.

The 628th Air Base Wing's primary duties are to provide installation support to 53 DoD and federal agencies, servicing a total force of over 79,000 Airmen, Sailors, Soldiers, Marines, Coast Guardsmen, civilians, dependents and retirees on CAFB and Naval Weapons Station Charleston. Additionally, they also provide mission-ready expeditionary Airmen to combatant commanders in support of joint and combined operations.

The 437th Airlift Wing's mission is to fly C-17s and provide airlift of troops and passengers, military equipment, cargo, and aeromedical equipment and supplies worldwide in support of tasking by AMC and unified combatant commanders.

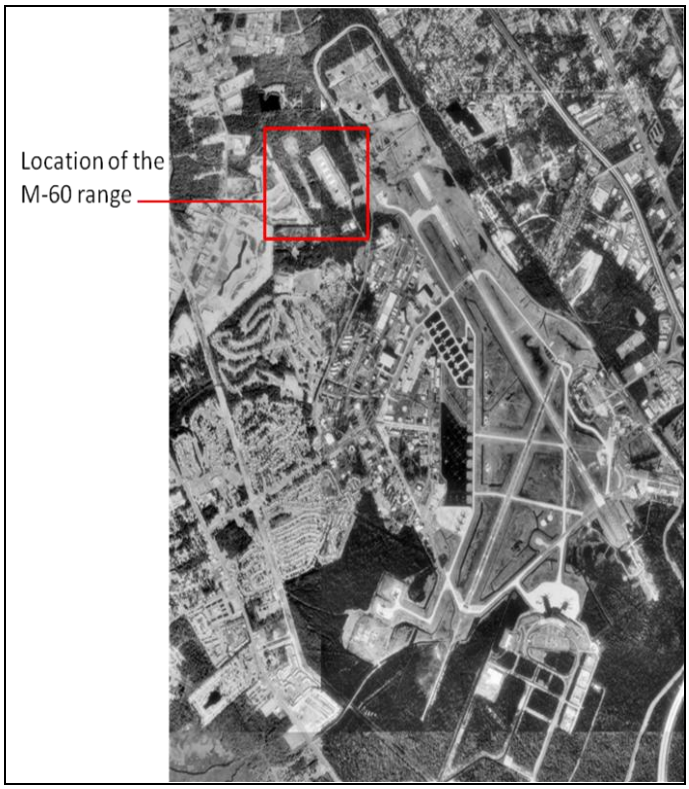

Figure 7. Aerial view of the CAFB with the location of the M-60 range indicated within the red box.

The CAFB M-60 range contains three firing positions that are used for the qualification and familiarization of the 5.56 mm (M249) and 7.62 mm (M240) weapons systems. The range has an adequate drainage system. Typically the Charleston AFB personnel fire more than 100,000 rounds of 5.56 mm or 7.62 mm ammunition per year for qualification and familiarization purposes (Figure 8).

Prior to installation of the PRBerm™ technology, installation range safety management determined the need for a new eyebrow over the firing line to limit the ricochet potential and possible harm to human dwellings and aircraft maintenance areas. The ricochet safety design is illustrated in Figure 9.

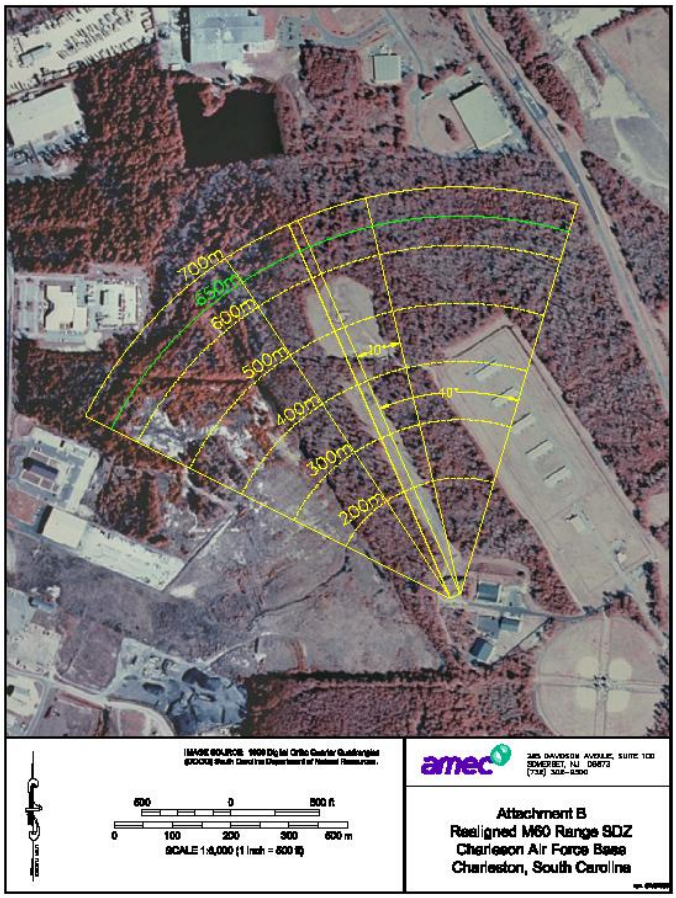

Figure 8. Aerial view of the M-60 range at CAFB indicating possible bullet firing distances.

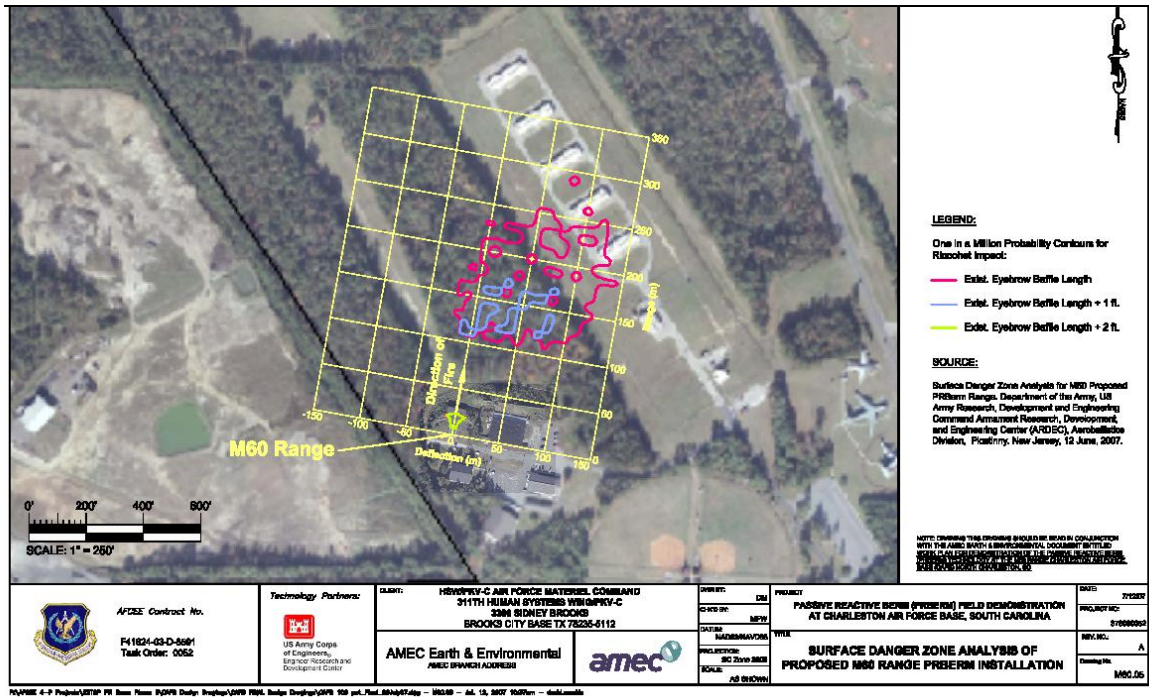

Figure 9. Surface danger zone (SDZ) analysis of proposed M-60 range PRBerm™ installation.

5.2 SITE GEOLOGY/HYDROGEOLOGY

The native soil at CAFB is characterized as 15 different soil types, primarily consisting of fine sands and fine sandy loams that provide the potential for suspended solids transport of Pb associated particulates from the SAFR berm if constructed from native soil.

5.3 CONTAMINANT DISTRIBUTION

CAFB has two SAFRs that are configured for M-9 and M-60 training. The SAFRs are located on the base that uses the same runway as the local Charleston airport. The CAFB range that will be used during this demonstration is the M-60 range. The current M-60 range has been in operation for over 20 years.

There is an underground drain that allows the range runoff water to flow under a nearby road and into stormwater drainage nearby. This is a suitable means to collect and store rainwater for use in artificial raining of the PRBerm™, if needed. The drainage system located at the range will assist with collection of storm water samples leaving the range complex and prevents potential cross-contamination of leachate water collection systems (i.e., on-site pooling of water).

As this was new construction and the construction designs themselves were part of the experimental design, there was no baseline sampling prior to the field demonstration.

6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

This technology demonstration assessed the environmental benefits, feasibility, and cost of using sand as a deceleration medium in SAFR berms in conjunction with amendments designed to retard the migration of Pb into the surrounding environment. The amendments provided for reduction of Pb solubility through pH buffering of pore fluids within the SAFR berm, as well as the sequestration of Pb through surface adsorption and the precipitation of insoluble Pb salts. This technology application is known as a PRBerm™.

The PRBerm™ can provide range operators with an economical means of controlling the off-site migration of Pb while maintaining the benefits of sand as a deceleration medium. In particular, this technology is designed to address sites where the native soils available for SAFR berm construction either lack the characteristics necessary to retard the migration of soluble Pb (e.g., acidic soils) or are susceptible to erosion and off-site transport of Pb as a result of their high clay content.

The amendments incorporated into the ballistic sand were TRAPPS™ and TTF, both phosphate-based amendments.

6.2 BASELINE CHARACTERIZATION

Baseline characterization was performed on soils from the initial demonstration site at Barksdale AFB, LA. Due to range construction at the Barksdale site, the field demonstration was moved to CAFB where an unused range was selected for the lysimeter construction. No baseline characterization studies were performed on the CAFB M-60 range site. The study design required that the previous impact berm, composed of native soil, be completely dismantled and replaced with the three test lysimeters of the PRBerm™.

6.3 TREATABILITY STUDY RESULTS

A treatability study (Larson et al., 2007a) evaluated the use of ballistic sand with amendments in the construction of impact berms. Laboratory and mesoscale studies using both static and live-fire lysimeters determined optimum sand/amendment combinations to immobilize soluble metals, such as Pb, in situ. Bench-scale studies determined that the incorporation of nonreactive ballistic sand with amendment(s) will contain metals within an impact berm. A sand to amendment ratio of 5% (w/w) was sufficient to contain greater than 90% of soluble Pb within the berm material.

Lysimeter studies then used regulated artificial rain events to evaluate the metals concentrations, TSS, dissolved organic carbon (DOC), and runoff and leachate pH over time for both the amended and sand-only (control) berms. Several phosphate-based amendments were evaluated including whole bone and crushed bone Apatite II. The results of static lysimeter studies I and III are presented in Table 3. These studies amended ballistic sand with 3%, 5%, or 8% Apatite II (w:w) or 5% Buffer Block #4 (w:w) or 5% TRAPPS™ or 5% TRAPPS™ and 7% Baked Apatite II (TTF). Two points were immediately apparent. First, the bench-scale studies

Table 3. Lysimeter leachate parameters from different ballistic sand and amendments*.

Lysimeter study and amendments		Lead[b] (µg/L)		DOC (mg/L)	pH
		Filtered	Total		
Study Goals		**≤150**		**≤50**	**6 to 9**
Lysimeter Study I[a]	Ballistic sand (Control - no amendments)	<50	387	2	6.91
	3% Apatite II	646	2031	347	6.88
	5% Apatite II	1008	3143	934	6.74
	8% Apatite II	488	2050	1739	6.55
	5% Buffer Block #4	825	3231	8	10.67
Lysimeter Study III	5% TRAPPS	<50	529	ND[c]	ND
	5% TRAPPS and 7% Baked Apatite II (TTF)	<58	119	ND	ND

*Shaded values are those that met the goals
[a]Collected data from only four rain events on all samples due to high Pb concentrations
[b]ICP reporting limit = 50 µg/L
[c]ND = not determined

did not adequately predict the results of the lysimeter studies. The effect of aging on the sand and amendments was more pronounced than expected. Second, the leachate from the combination of TRAPPS and TTF were the only amendment that met the experimental parameters in all areas. However, static lysimeter study II observed high concentrations of DOC and TSS in the leachate from the Apatite II-amended lysimeters.

As reported in Larson et al. (2007a) the lysimeter cells containing the Mechanical Apatitie II amendment were terminated after four rain events due to elevated Pb concentrations and odor production. The four-rain event average Pb concentration exceeded the permit limit for the leachates and the runoff water, excluding the filtered leachate control and the filtered runoff from the control and the Buffer Block #4 amendment. The high pH of the Buffer Block #4 contributed to the high concentration of Pb released from this lysimeter. The DOC produced in the higher concentrations of the Mechanical Apatite II amendment appeared to be the result of biological activity due to the organic matter present on the biogenic apatite, which also may have increased the solubility of metals. Phosphate dissolution from the source was also limited due to the presence of the organic matter, which may decrease the nucleation site potential associated with the Apatite II.

The live-fire lysimeter study tested the sand and amendments under dynamic, realistic conditions while controlling the weathering events. The results are presented in Table 4. The results of the post-LFL TCLP of the berm sand amendments is presented in Table 5. By comparing the metals concentrations remaining in solution after 18 hours of tumbling in the TCLP extraction solution against control soils with no amendments, the amended soils decreased the leaching of Pb from 45 to 99%. The ballistic sand combined with TRAPPS and the baked apatite was most effective at reducing the Pb TCLP concentration at the lowest amendment loading rate.

Apatite II™ was further investigated for its ability to sequester Pb from solution (Martin et al., 2008). The treatability study reported that organic compounds were formed in the apatite-amended lysimeters during aging and this hindered Pb immobilization. Because Apatite II™ is known to contain up to 40% residual organics (Conca and Wright, 2006), the fish bones were treated using several different methods to remove the residual organics. Laboratory and column studies established that thermally treated Apatite II™ consistently removed >90% of soluble Pb from solution and reduced the biological oxygen demand (BOD) of the solutions to non-detect levels. For this reason it was chosen as one of the soil amendments in the PRBerm™ field demonstration.

6.4 FIELD TESTING

6.4.1 Amendments

Two amendments were selected for field testing at the CAFB M-60 range: TRAPPS™ (Slater, UK) and TTF. The TRAPPS™ would be tested alone and with the addition of the TTF. TRAPPS™ is a COTS product, a formulation of apatite and other insoluble phosphate mineral in which Pb is precipitated as stable pyromorphite. According to the manufacturer, TRAPPS™ also does not cause increased mobilization of copper, arsenic and Sb or release excessive amounts of phosphate (http://www.slateruklimited.co.uk/us/ trapps_firing_range.html).

Table 4. Live-fire lysimeter (LFL) leachate parameters from different ballistic sand and amendments*.

Lysimeter Study and Amendments		Pb[b] (µg/L, avg. n=10)		DOC (mg/L, avg., n=10)	pH (n=10)
		Filtered	Total		
Study Goals		**≤150**		**≤50**	**6 to 9**
LFL Study I[a]	Ballistic sand (Control - no amendments)	<62	1944	8	7.08
	Sand and 5% Buffer Block #5	<90	1667	9	7.55
LFL Study II	Sand and 5% TRAPPS 2	<50	<66	57	6.38
	Sand and 5% TRAPPS 1	<50	<52	47	6.44

*Shaded values are those that met the goals
[a]Collected data from 10 rain events
[b]ICP reporting limit = 50 µg/L

Table 5. Results of TCLP analysis of post-live-fire lysimeter berm sand and amendments (n=3).

Sample	TCLP Pb Concentration (mg/L)
Unamended ballistic sand	64.59
Ballistic sand with 5% TRAPPS 2	210.07
Ballistic sand with 5% TRAPPS 1	395.87
Ballistic sand with 5% TRAPPS 1 and 7% Baked Apatite II (TTF)	0.48

The second amendment is TFF. Fish bone is a source of biogenic apatite known to sequester Pb from solution (Martin et al., 2008). Although the fish bone amendment did not perform as well as the other amendments initially in the treatability study, the problem was identified and solved (Martin et al., 2008). Thermal treatment removes organic carbon that interferes with Pb sorption sites. This increases the treatment effectiveness over the long term versus increased product cost in the short term. The TTF was also found, in bench-scale studies, to achieve the regulatory TCLP discharge limit for Pb. This affected the decision to use a limited amount of the TTF in a concentrated area of the lysimeter and observe the benefit to heavy metal immobilization.

6.4.2 Lysimeter Construction and Installation

The three lysimeters placed inside the impact berm of the M60 range were constructed from the Industry Standard Object (ISO) Standard 20 ft by 8 ft insulated containers by Sea Box, Inc., located in East Riverton, NJ (Figure 10). The lysimeters were designed for the collection of surface runoff water and soil leachate. For the lysimeter that contained both TRAPPS™ and thermally treated fish bones, a high-density polyethylene lysimeter measuring 0.787 m (31 inch) by 0.787 m by 0.609 m (24 inch) (inside length x width x height) was placed inside the stainless steel lysimeter. The polyethylene lysimeter contained 5% TTF. Separate leachate collection piping was attached to the stainless steel lysimeter and the polyethylene lysimeter insert.

Figure 10. Completed field lysimeter prior to transport to the CAFB M-60 range.

The amendments used in the three lysimeters placed inside the impact berm of the M-60 range are illustrated in Table 6. A series of photographs (Figures 11, 12, 13, and 14) shows the sequence of construction steps to install the three lysimeters in the impact berm in front of the firing positions of the M-60 range.

Table 6. Amendment composition in the three field demonstration lysimeters.

Lysimeter Location and Amendment Composition		
Left Lysimeter	**Center Lysimeter**	**Right Lysimeter**
Clean ballistic sand mixed with 5% TRAPPS	Clean ballistic sand mixed with 5% TRAPPS	Clean ballistic sand
5% TTF in a separate container inset within the sand/TRAPPS		

Figure 11. Removal of the old impact berm composed of local soil from under the newly constructed protective eyebrow.

Figure 12. Placement of the three lysimeters in the impact berm in line with the three fixed firing positions.

Figure 13. Placement of the amended ballistic sand in the lysimeters.

Figure 14. The completed impact berm enclosing the three experimental treatment lysimeters on the M-60 range, CAFB.

6.4.3 Metal Contamination per PRBerm™

Metal contamination in each of the experimental berms was calculated based on the total number and type of rounds fired during training exercises. The Pb loading on the three lysimeters is detailed in Table 7. The 7.62 mm round, used in the M-60 machine gun, and the 5.56 mm round, used in the M-16 rifle, were both fired on the CAFB range.

Table 7. Type and number of rounds fired into each lysimeter on the CAFB M-60 range during the 2009 field demonstration.

	7.62-mm Rounds			5.56-mm Rounds		
Date	**Control**	**5% TRAPPS**	**5% TRAPPS + 5% TTF**	**Control**	**5% TRAPPS**	**5% TRAPPS + 5% TTF**
March 27	200	200	200	0	0	0
June 28	100	100	100	0	0	0
July 31	100	3400	0	2400	0	2400
August 18	0	0	0	0	0	1200
September 10	0	600	600	0	0	600
October 22	0	4200	4,200	0	0	0
December 4	4800	0	0	0	0	0
Total	**5100**	**8500**	**5,100**	**2400**	**0**	**4200**

The mass of the soil was the same in each of the lysimeters. The number of rounds varied per lysimeter. Based on the number of rounds fired and the metal available in each type of round, the potential metal contamination was calculated (Larson et al., 2011). The metal concentration in the lysimeters is shown in Table 8.

Table 8. Metal concentration in soil for both rounds.

Metals	Control (mg/kg)	5% TRAPPS™ (mg/kg)	5% TRAPPS™ + 5% TTF (mg/kg)
Pb	1553.29	2169.38	1742.03
Cu	873.43	1219.86	979.56
Zn	96.06	134.17	107.74
Fe*	480.85	671.57	539.28
Mg	1.10	0.82	1.55
Sb	15.66	21.88	17.56
Other metals	9.63	14.15	10.48

*Fe = iron

6.4.4 Sampling Methods

6.4.4.1 Berm Soil Samples

Initial and final soil samples were taken to determine metal concentrations, TCLP, and Synthetic Precipitation Leaching Procedure (SPLP) leaching concentrations, distilled deionized water (DDI) suspend and settle (DDI S&S) leaching concentrations, partition coefficient (K_d), and pH of the amended ballistic sand. For the final soil sampling, bulk and dimensional samples were taken from each of the lysimeters. The lysimeter dimensional samples were based on the following measurements:

1. 0-4 ft x 0-5 ft (length x height)
2. 0-4 ft x 5-10 ft (length x height)
3. 4-8 ft x 0-5 ft (length x height)
4. 0-4 ft x 5-10 ft (length x height)

These samples were taken with plastic cores 1 inch in diameter and 8 inch in length. Nine subsamples were taken from each of the different dimensions. Triplicate analysis was performed on each of the nine subsamples.

6.4.4.2 Surface Water Runoff and Leachate Samples

Stormwater runoff samples were collected biweekly using natural rain events. Leachate samples were collected at the same time from the built-in collection system of the lysimeter. Samples were collected by the CAFB Bioenvironmental Engineering personnel under the general supervision of the ERDC-EL principal investigator (PI) or a Co-PI.

While flow or time-averaged sampling may provide a better profile of runoff water quality over the storm event duration, there were logistical problems associated with collecting these samples. The proposed collection locations on the range could not use automated samplers because the equipment could not be located in areas that are out of the line of fire. The equipment could not be protected from being shot unless limits were placed on range use, which was not an option. As a result, manual grab samples were collected from sumps installed in the runoff flow path from each test cell on the berms.

Water samples were collected in 1-L plastic bottles. The sampling collection point was then drained. As part of the quality assurance/quality control (QA/QC) plan (ERDC, 2005, Appendix E), replicate samples were taken periodically in order to ensure that sampling was not biased. Samples were preserved in accordance with USEPA and the American Society for Testing and Materials (ASTM) preservation guidelines. Samples were properly labeled and tightly sealed to avoid cross-contamination during storage and shipment. Samples were packaged for shipment in rigid, insulated plastic ice chests. These samples were sent to ERDC-EL for analysis via overnight delivery.

6.4.5 Sample Analysis

6.4.5.1 Soil Leaching Tests

The TCLP was performed on both bulk soil and the dimensional core samples using a 1:20 soil:solution ratio. The SPLP was performed only on the bulk soil samples using Extraction Fluid #1 and a 1:20 soil:solution ratio. TCLP and SPLP samples were allowed to mix on the tumbler for 18±2 hours. After removal from the tumbler, samples were allowed to settle for about 30 minutes and filtrates were obtained using 0.45 micron filters attached to 10 mL syringes. The DDI S&S leaching procedure is a variation of the TCLP replacing the acid solution with DDI water. The DDI S&S test consisted of a 1-hour shake test and 18-hour settling time. After settling, samples were filtered using a 10 mL syringe with a 0.45 micron filter attached to 10 mL syringes. The pH was tested from the filtrates.

6.4.5.2 Determination of Partition Coefficient, K_d

A 24-hour partition coefficient was performed on the pre-fired soils following procedures established in Appendix 6 of USEPA (1999b). The metals of interest for these soils were Pb, Cu, and Fe. Stock solutions were prepared using Pb nitrate (CAS#10099-74-8, Fisher Scientific), copper II sulfate pentahydrate (CAS#7758-99-8, Sigma Aldrich) and ferrous sulfate (CAS#7782-63-0, Sigma Aldrich).

A 1:10 soil to solution ratio was used for the 24-hour test. Triplicate samples with 10 grams of soil per sample were weighed into each 125 mL nalgene bottle and 100 mL of each solution was added. Sample bottles were placed on the shaker for 24 hours, removed from shaker, and allowed to settle for 10 minutes. Liquid samples were filtered using a 0.45 micron syringe filter attached to a 10 mL syringe and stored in the dark at 4 °C until analysis was conducted.

6.4.5.3 Analysis methods

The methods and procedures detailed in Table 9 were used for chemical and physical analysis of the PRBerm™ samples. Both liquid and soil samples were analyzed for heavy metals using an inductively coupled plasma (ICP) atomic emission spectroscopy (AES), with a reporting limit of 0.025 mg L^{-1} for liquids and 5 mg/kg for soils (Perkin-Elmer Optima 4300 dual view, Perkin-Elmer, USA). Analyses for total metals in soils were performed using USEPA SW846 Method 3051 (1999a). Aqueous samples were analyzed in the laboratory for metals (total and dissolved) and TSS. Samples were field filtered using 0.45 micron filters prior to shipping for dissolved metals analysis in the laboratory.

Table 9. Analytical methods for sample analysis.

Contaminant/Parameter	Analytical Method	Analytical Frequency
Aqueous Samples		
Metals—total and dissolved	SW846-3015[a]	Biweekly
TSS	SM 2540D[b]	Biweekly
pH	Electrode	Biweekly
Soil Samples		
Metals—total and dissolved	SW846-3051[a]	Initial and final
pH	Electrode	Initial and final
TCLP	SW846-1311	Final
SPLP	SW846-1312	Final
DDI S&S	Modified SW846-1311	Final
K_d	24-hr partition coefficient test[c]	Final

[a]USEPA (1999a)
[b]American Public Health Association (1998)
[c]USEPA (1999b)

6.5 SAMPLING RESULTS

6.5.1 Aqueous Samples

Volumes of leachate and runoff water were measured biweekly. There was a total of three lysimeters—(1) Control [Right], (2) 5% TRAPPS™ + Sand [Center], (3) 5% TRAPPS™ + 5% TTF [Left]. Lysimeter 3, which was the left lysimeter, contained the inset box. Two leachate samples were collected from the left lysimeter, one from the large lysimeter labeled as Left 5% TRAPPS™ and one from the inset lysimeter labeled as Left 5% TTF.

Only one runoff sample was collected from each of the three lysimeters every 2 weeks.

The total volume of leachate and runoff water is shown in Table 10. The control lysimeter had the greatest total effluent. The volume of leachate from the experimental lysimeters ranged from 51% to 63% of the total for the 5% TRAPPS™ and the 5% TRAPPS™ +5% TTF, respectively. The volume of runoff water from the experimental lysimeters ranged from 37% to 49% of the

total volume for the 5% TRAPPS™ + 5% TTF and the 5% TRAPPS™, respectively. The most runoff was generated from the control lysimeter whereas the 5% TRAPPS™ + 5% TTF generated the most leachate.

Table 10. Volume of effluent (L) collected from the PRBerm™ lysimeters during the field demonstration.

Lysimeter	Total Leachate	Total Runoff	Total Effluent	Leachate (% of Total)	Runoff (% of Total)	Ratio of Leachate to Runoff
Control	23.02	36.11	59.12	39	61	0.64
5% TRAPPS™	21.94	20.68	42.62	51	49	1.04
5% TRAPPS™ + 5% TTF	27.87[a]	16.60	44.47	63	37	1.70

[a]Total leachate for 5% TRAPPS + 5% TTF includes leachate from both the main lysimeter and the inset lysimter (TRAPPS and the TTF)

The average pH of the leachate and runoff water collected from the three PRBerm™ lysimeters ranged from 6.44 to 7.01. The unamended lysimeter had the lowest pH in both leachate and runoff water samples. The TTF leachate sample had the highest pH and the 5% TRAPPS™ + 5% TTF sample had the lowest runoff pH. Both amended and unamended lysimeters had acidic pH readings, except for the TTF leachate sample. It has been reported that inducing acidic conditions will promote the solubility of Pb compounds leading to effective Pb immobilization via formation of Pb pyromorphite (Yang et al., 2001).

Suspended solids provide adsorption surfaces and a route of transmission for many organic contaminants, heavy metals, and some soil nutrients. The TSS concentrations from the lysimeters varied depending on the amendment. Table 11 shows the average TSS concentration for both leachate and runoff from each of the lysimeters. The lysimeter that was amended with 5% TRAPPS™ had the highest TSS concentration in both the leachate and runoff. High TSS has been correlated to higher concentrations of metals in the water (Larson et al., 2007). The 5% TRAPPS™ lysimeter had the highest concentration of TSS in both leachate and runoff water at 4000 mg/L and 545 mg/L, respectively. However, the TSS values in the leachate were highly variable with a % standard deviation (STDEV) of >300.

Table 11. Comparison of TSS concentrations (mg/L) in leachate and runoff water collected during the PRBerm™ demonstration at the CAFB M-60 range.

Lysimeter	TSS (mg/L)					
	Leachate			Runoff Water		
	AVG	STEDV	%STDEV	AVG	STEDV	%STDEV
Control	62.14	56.75	91	119.65	241.64	202
5% TRAPPS	4176.24	13,427.43	322	544.54	849.76	156
5% TRAPPS + 5% TTF	NA	1274.06	200	160.72	319.17	199
Inset (5% TTF)	411.84	712.81	173	NA	NA	NA
NA = not applicable						

Total (digested) metals occurred over a wide range of concentrations in runoff water and leachate from the lysimeters. The average concentration of total metals in the leachate and runoff water, are shown in Tables 12 and 13, respectively. The leachate concentration for all metals was high from the 5% TRAPPS™ lysimeter when compared to the other experimental lysimeters. The Pb leachate concentrations ranged from 0.08 (control lysimeter) to 50 mg/L (5% TRAPPS™ lysimeter). The concentrations of total (digested) metals in the runoff water were less in the 5% TRAPPS™ + 5% TTF compared to the 5% TRAPPS™ for all metals. The 5% TRAPPS™ lysimeter had the highest concentration of total metals in the runofff water of all the experimental lysimeters.

Table 12. Average concentration of total (digested) metals in lysimeter leachate (mg/L, n=3).

Metal	Lysimeter							
	Control		5% TRAPPS™		5% TRAPPS™ +TTF		5% TTF	
	AVG*	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
Pb	0.08	0.16	50.13	178.40	7.89	18.82	6.35	13.25
Cr	0.03	0.00	0.09	0.16	0.03	0.01	0.03	0.01
Cu	0.13	0.22	32.74	100.07	4.75	17.42	1.31	2.58
Ni	0.02	0.00	0.08	0.13	0.03	0.01	0.03	0.01
Zn	0.05	0.05	11.03	31.05	0.28	0.49	0.22	0.35
Fe	0.51	0.52	30.51	89.46	4.84	9.66	4.20	6.38
Mn	0.03	0.01	0.32	0.82	0.06	0.08	0.06	0.07
Sb	0.21	0.31	2.26	5.66	0.20	0.36	0.16	0.27
P**	5.00	0.00	70.90	40.01	40.52	26.96	38.55	17.45

*Averages and standard deviations are calculated based on a detection limit of 0.025 mg/L for all metals except for P.
**The detection limit for P is 5.00 mg/L.

Table 13. Average concentration of total (digested) metals in lysimeter runoff water (mg/L, n=3).

Metal	Lysimeter					
	Control		5% TRAPPS™		Left TRAPPS	
	AVG*	STDEV	AVG	STDEV	AVG	STDEV
Pb	0.62	1.07	9.78	19.48	2.34	5.20
Cr	0.04	0.01	0.05	0.02	0.03	0.00
Cu	0.42	0.55	2.09	3.67	0.54	0.92
Ni	0.04	0.02	0.05	0.01	0.03	0.00
Zn	0.04	0.02	0.05	0.01	0.03	0.00
Fe	0.83	0.99	7.82	14.77	2.46	4.08
Mn	0.04	0.01	0.10	0.12	0.10	0.23
Sb	0.44	1.03	0.50	0.96	0.30	0.41
P**	8.23	3.04	15.81	15.23	7.62	8.80

*Averages and standard deviations are calculated based on a detection limit of 0.025 mg/L for all metals except for P.
**The detection limit for P is 5.00 mg/L.

The average concentrations of soluble metals in the lysimeter leachate and runoff water are shown in Tables 14 and 15, respectively. The metal with the highest leachate concentration in all the lysimeters, except for P, was Sb. The 5% TRAPPS™ lysimeter had 74.09 mg/L of P compared to the unamended control lysimeter, which had 5.00 mg/L of P.

The soluble Pb, Cr, Cu, Zn, and Fe concentrations in the runoff water decreased in both amended lysimeters when compared to the control. The soluble Pb concentration in the control runoff water was 3.91 mg/L, 5% TRAPPS™ was 1.85 mg/L, and the 5% TRAPPS™ + 5% TTF was 0.95 mg/L. When compared to the 5% TRAPPS™ lysimeter, the Left TRAPPS™ lysimeter showed the greatest reduction for the soluble Pb, Cu, Ni, and Sb. The Fe concentration in the 5% TRAPPS™ lysimeter runoff water was decreased compared to the Left TRAPPS™.

Table 14. Average concentration of soluble metals in lysimeter leachate (mg/L, n=3).

Metal	Lysimeter							
	Control		5% TRAPPS™		5% TRAPPS + 5% TTF		5% TTF	
	AVG*	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
Pb	0.03	0.01	0.11	0.28	0.03	0.02	0.03	0.01
Cr	0.03	0.00	0.04	0.01	0.03	0.00	0.03	0.00
Cu	0.03	0.02	0.09	0.08	0.03	0.00	0.03	0.00
Ni	0.03	0.00	004	0.01	0.03	0.00	0.03	0.00
Zn	0.03	0.01	0.03	0.00	0.03	0.02	0.06	0.13
Fe	0.04	0.03	0.06	0.05	0.03	0.00	0.03	0.07
Mn	0.03	0.00	0.05	0.01	0.03	0.00	0.03	0.00
Sb	0.30	0.39	0.65	1.51	0.13	0.18	0.09	0.12
P**	5.00	0.00	74.09	48.32	40.13	31.06	38.85	20.00

*Averages and standard deviations are calculated based on a detection limit of 0.025 mg/L for all metals except for P.
**The detection limit for P is 5.00 mg/L.

Table 15. Average concentration of soluble metals in lysimeter runoff water (mg/L, n=3).

Metal	Lysimeter					
	Control		5% TRAPPS™		5% TRAPPS + 5% TTF	
	AVG*	STDEV	AVG	STDEV	AVG	STDEV
Pb	0.18	0.29	0.15	0.32	0.06	0.08
Cr	0.04	0.01	0.03	0.01	0.03	0.00
Cu	0.24	0.38	0.23	0.30	0.08	0.10
Ni	0.04	0.01	0.05	0.01	0.03	0.00
Zn	0.04	0.01	0.03	0.01	0.03	0.00
Fe	0.30	0.36	0.15	0.17	0.25	0.51
Mn	0.04	0.01	0.04	0.01	0.04	0.07
Sb	0.38	0.71	0.53	0.92	0.37	0.50
P**	8.33	2.71	9.83	3.92	5.32	1.05

*Averages and standard deviations are calculated based on a detection limit of 0.025 mg/L for all metals except for P.
**The detection limit for P is 5.00 mg/L.

Based on the total mass of Pb and other metals added to the amended impact media, the control lysimeter had the highest Pb concentration in the soluble runoff (Table 16). The 5% TRAPPS™ lysimeter had the highest soil Pb concentration. Surface runoff transports soil particles containing adsorbed Pb, which assists in the migration and subsequent desorption of Pb from contaminated soils. The high content of P in the 5% TRAPPS™ + 5% TTF lysimeter soil reduced the filtered Pb in the runoff samples through the formation of Pb phosphates. Santillian-Medrano and Juntiak (1975) suggested that Pb pyromorphite is the primary mineral controlling Pb solubility in soils amended with various forms of phosphates.

Table 16. Calculated Pb concentration in lysimeters.

Lysimeter	Pb in soil (mg/kg)	Soluble leachate (mg/L)		Soluble runoff (mg/L)		Total leachate(mg/L)		Total runoff (mg/L)	
		Avg.	St. Dev	Avg.	St. Dev	Avg.	St. Dev	Avg.	St. Dev
Control	1553.29	0.0265	0.01	0.1745	0.30	0.0809	0.16	2.3350	5.20
5% TRAPPS™	2169.38	0.1137	0.28	0.1398	0.32	50.1319	178.40	9.7802	19.48
5% TRAPPS™ + 5% TTF	1742.03	0.0365	0.15	0.0637	0.08	11.1417	28.56	0.6163	1.07
Left 5% TRAPPS™	NA	0.0334	0.02	NA	NA	7.8897	18.82	NA	NA
Left Inset 5% TTF	NA	0.0303	0.01	NA	NA	6.3549	13.25	NA	NA

NA = not applicable

6.5.2 Soil Samples

There was a slight increase in the pH readings of the post-demonstration soils when compared to the pre-demonstration soils for all the lysimeters. The maximum final pH of 8.06 was recorded from the control lysimeter soil. All of the pre-and post-demonstration soils yielded pH values that were in the neutral to alkaline range (6.95 to 8.06).

Table 17 shows the average total (digested) metal concentrations in the post-firing bulk soil samples taken at the conclusion of the field demonstration. The unamended control lysimeter had the highest concentrations of Pb, Cu, Zn, Sb, and As when compared to the amended lysimeters. The lysimeter amended with TRAPPS™ only had lower Pb, Cu, Zn, and Sb concentrations than the other amended lysimeters.

Table 17. Average concentration of total (digested) metals in bulk lysimeter soil post-firing (mg/Kg, n=3).

	Lysimeter							
	Control		5% TRAPPS™		Left 5% TRAPPS™		5% TTF	
Metal	AVG	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
Pb	10,215	1842	2477	894	6566	546	186	15
Cr	ND	*	13	0.5	ND	*	24	5
Cu	905	249	354	12	628	12	95	22
Ni	ND	*	8	0.5	ND	*	16	4
Zn	92	24	37	3	62	1	13	2
Fe	656	63	6742	386	2078	497	15,537	4754
Mn	ND	*	39	1	10	2	87	29
Sb	115	16	28	15	74	16	ND	*
Ca	372	26	3761	92	1098	7	4,273	213
As	7	2	ND	*	ND	*	ND	*
P**	ND	*	2942	143	2098	96	3729	218

ND = non-detect. The detection limit is 0.025 mg/Kg for all metals except P
*Not applicable
**The detection limit for P is 5.00 mg/Kg.

The Pb TCLP concentration (Table 18) was higher than the USEPA regulatory concentration level of 5-mg/L for all lysimeters except for the inset lysimeter, which contained 5% TTF + 5% TRAPPS™. The amended lysimeters had lower TCLP metal concentrations of Pb, Cu, Zn, Sb, and As compared to the control lysimeter. The control lysimeter, which has the higher total Pb concentration, also has the highest TCLP Pb concentration.

In order to compare the Pb leachability ratios, the TCLP Pb was divided by the Total Pb. The TCLP Pb was first multiplied by 20 (the ratio of liquid to solid in the TCLP procedure). The highest leachability ratio was in the 5% TRAPPS™ lysimeter (119.00%) > control lysimeter (92.68%) > Left 5% TRAPPS™ lysimeter (19.55%), > inset lysimeter (18.15%) (Table 19). The control lysimeter had a leachability ratio smaller than the amended lysimeters. TCLP concentrations in the post-firing soil increased for all metals except Ca and P, which decreased in the amended lysimeters. There was an increase in post-firing soil Ca concentration for the control lysimeter.

When soils were sampled at different dimensions in the lysimeters, the highest concentrations of Pb, Cu, and Zn were observed in soils closest to the surface; lowest concentrations were determined to be at the deepest points in the lysimeters.

Table 18. Average TCLP metal concentration of post-firing bulk lysimeter soils (mg/Kg, n=3).

	Lysimeter							
	Control		5% TRAPPS™		Left 5% TRAPPS™		5% TTF	
Metal	AVG	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
Pb	473	9	147	3	64	0.4	2	1
Cr	ND	*	0.1	0	0.1	0	ND	*
Cu	28	0	6	0.1	7	0	ND	*
Ni	<1	0	0.1	0	0.2	0	0.2	0
Zn	3	0	1	0	1	0	0.1	0
Fe	7	0.3	71	2	45	1	6	1
Mn	<1	0	2	0	1	0	1	0
Mo	ND	*	ND	*	ND	*	<1	0
V	ND	*	ND	*	ND	*	ND	*
Sb	5	0.1	<1	0	<1	0	<1	0

ND = non-detect. The detection limit is 0.025 mg/Kg for all metals.
*Not applicable

Table 19. TCLP Pb, Total Pb, and the Pb leachability ratios (TCLP to total Pb) in lysimeters.

Lysimeter	TCLP Pb (mg/L)	Total Pb (mg/Kg)	Leachability ratio (%)
Control	473	10,215	93
5% TRAPPS™	147	2,477	119
Left 5% TRAPPS™	64	6,566	20
5% TTF	2	186	18

The average concentration of metals in solution determined by the DDI S&S procedure is shown for the post-firing bulk soil samples in Table 20. The Pb concentrations ranged from 0.04-0.56 mg/L. The Left 5% TRAPPS™ lysimeter had the lowest Pb concentration and the 5% TRAPPS™ lysimeter had the highest Pb concentration. For all three lysimeters tested, the Pb, Cu, and Sb concentrations were higher in the post soils than in the pre-soils

When sampled through cross sections of the lysimeters, DDI S&S leaching of the post-firing soil showed no P was detected in either the unamended or the amended lysimeters. Leached metal concentrations were greatest in samples taken from the surface areas of the lysimeters.

Table 20. Average metal concentrations (mg/L) for post-firing bulk lysimeter soil samples analyzed using the DDI S&S leaching procedure (n=3).

Metal	Lysimeter							
	Control		5% TRAPPS™		Left 5% TRAPPS™		5% TFF	
	AVG	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
Pb	0.37	0.01	0.44	0.01	0.04	0.00	0.36	0.05
Cr	ND	*	ND	*	ND	*	ND	*
Cu	0.04	0.00	0.06	0.00	ND	*	0.56	0.02
Ni	ND	*	ND	*	ND	*	ND	*
Zn	ND	*	ND	*	ND	*	0.10	0.00
Fe	0.04	0.00	0.35	0.00	ND	*	ND	*
Mn	ND	*	ND	*	ND	*	ND	*
Mo	ND	*	ND	*	ND	*	ND	*
V	ND	*	ND	*	ND	*	ND	*
Sb	0.15	0.00	0.17	0.00	0.29	0.01	0.20	0.00

ND = non-detect. The detection limit is 0.025 mg/Kg for all metals.
*Not applicable

Table 21 shows the SPLP leaching concentrations for the post-firing soils. Most Pb was leached from the control lysimeter, followed by the 5% TRAPPS™ lysimeter, Left 5% TRAPPS™, and the 5% TTF. The control lysimeter had more Cu and Zn than the other three samples. More Sb was leached from the Left 5% TRAPPS™ and more Fe from the 5% TRAPPS™ lysimeter when compared to the other lysimeters.

Table 21. Average metal concentrations (mg/L) for bulk lysimeter soil samples post-SPLP (n=3).

Metal	Lysimeter							
	Control		5% TRAPPS™		Left 5% TRAPPS		5% TFF	
	AVG	STDEV	AVG	STDEV	AVG	STDEV	AVG	STDEV
Pb	2.46	2.65	0.53	0.41	0.13	0.01	0.12	0.04
Cr	0.03	0.00	0.03	0.00	0.03	0.00	0.03	0.00
Cu	0.62	0.59	0.13	0.08	0.09	0.00	0.03	0.01
Ni	0.03	0.00	0.03	0.00	0.03	0.00	0.03	0.00
Zn	0.15	0.11	0.03	0.00	0.05	0.00	0.03	0.00
Fe	0.06	0.06	0.40	0.29	0.07	0.01	0.18	0.02
Mn	0.03	0.00	0.03	0.00	0.05	0.00	0.03	0.00
Mo	0.03	0.00	0.03	0.00	0.03	0.00	0.03	0.00
V	0.03	0.00	0.03	0.00	0.03	0.00	0.03	0.00
Sb	0.21	0.06	0.12	0.01	0.38	0.01	0.03	0.00

ND = non-detect. The detection limit is 0.025 mg/Kg for all metals.
*Not applicable

The data generated from the Pb and Sb sorption K_d experiments yielded adsorption isotherms for each soil type in the three lysimeters. Metal soil concentrations were obtained by subtracting the concentration of the given metal from the total mass of metal added to the system. While filtering is a possible source of metal loss, standard procedure for K_d determination using the batch method involves analysis of a filtered solution. The material retained on the filter is

defined as insoluble material (USEPA, 1999a). Complete data on the triplicate metal analyses (including average and standard deviation) for each lysimeter soil is reported in Larson et al. (2011). A representative example is given here for linear isotherms obtained from the experimental soils.

Results of a linear fit determination of sorption K_d for Sb using a section of the curve in the linear region (USEPA, 1999b) is provided in Table 22. A least squares fit was performed using selected points in the linear portion of the isotherm to produce a K_d value that is valid for entire concentration range.

The Sb(III) K_d values ranged from a high of 15.77 (Left 5% TRAPPS™) to a low of 0.75 (Control) (Table 22). The Sb(V) K_d values ranged from a high of 1.51 (Left 5% TRAPPS™) to a low of 0.49 (Control). All three lysimeter soils had low K_{d100} values (<10).

Table 22. Summary of Sb(III) and Sb(V) linear K_d data.

Lysimeter	Sb(III)		Sb(V)	
	K	R^2	K	R^2
Control	0.75	1.00	0.49	0.91
5% TRAPPS™	8.81	0.91	0.64	0.98
Left 5% TRAPPS™ + 5% TTF	15.77	0.96	1.51	0.96

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7.0 PERFORMANCE ASSESSMENT

The objectives of this technology demonstration were to:

- Assess the environmental benefits, feasibility, and cost of using sand as a deceleration medium in SAFR berms
- Assess sand amendments to retard the migration of Pb and Sb into the surrounding environment through reduction of Pb solubility through pH buffering of pore fluids within the SAFR berm, as well as the sequestration of Pb through surface adsorption and the precipitation of insoluble Pb salts
- Provide range operators with an economical means of controlling the off-site migration of munitions metals, while maintaining the benefits of sand as a deceleration medium.

The PRBerm™ technology is applicable to new and existing ranges. In particular, this technology is designed to address sites where the native soils available for SAFR berm construction either lack the characteristics necessary to retard the migration of soluble Pb (e.g., acidic soils) or are susceptible to erosion and off-site transport of Pb as a result of their high clay content.

7.1 QUANTITATIVE PERFORMANCE OBJECTIVES

The results of the Quantitative Performance Objectives are outlined in Section 4, Table 2, and discussed below.

7.1.1 Meet State Release Permit Requirements for Release of Munitions Metals in Runoff Water

The success criteria for this objective were to observe monthly soluble Pb concentrations in runoff water that were $\leq$150 ppb and monthly soluble Cu concentrations $\leq$500 ppb. This criterion is addressed by results presented in Section 6.5.1. Soluble concentrations of cationic metals, such as Pb and Cu, were increased in the amended lysimeters over the control lysimeter with the unamended ballistic sand. TTF produced the best performance of the amendments.

7.1.2 Meet State Release Permit Requirements for pH of Discharge Water

As discussed in Section 6.5.1, the pH of the discharge water (runoff water) was maintained between 6 to 9 and required no further treatment.

7.2 QUALITATIVE PERFORMANCE ASSESSMENT

The Qualitative Performance Objectives are outlined in Section 3, Table 2, and discussed below.

7.2.1 Reduce Transport of Munitions Metals from the Range

As discussed in Section 6.5.1 for total and soluble metals in the leachate and runoff water and in Section 6.5.2 for metals in soils, concentrations of munitions metals in the discharge water met

state regulatory permits. The concentrations of metals in amended soils were lowest with the 5% TRAPPS™. The soil leaching potential of the munitions metals was established by TCLP analysis. The Pb concentration from TCLP was higher than the USEPA regulatory concentration level of 5-mg/L for all lysimeters except for the inset lysimeter, which contained 5% TTF + 5% TRAPPS™. The amended lysimeters had lower TCLP metal concentrations of Pb, Cu, Zn, Sb, and As when compared to the unamended control lysimeter but did not meet the TCLP criterion. The low K_d values for Sb from the amendment containing the TTF confirmed the efficacy of the biogenic apatite in reducing transport of metals from the range.

7.2.2 Reduce Range Operational Costs

Elimination of fines for non-compliance with discharge regulations reduced operational costs. Installation and maintenance costs, compared to a steel bullet trap are also reduced.

7.2.3 Provide BAT for Range Operations

Anecdotal evidence from range personnel indicates the ease of use and maintenance.

8.0 COST ASSESSMENT

The cost of using sand and amendments as a ballistic media to prevent transport of munitions metals off-range is dependent on the number of impact berms being replaced and the amendment used. In the treatability study (Larson et al., 2007), five sands and five amendments were evaluated to determine the proper amendment ratio for immobilization of metals. The field demonstration looked at the best performing of these sands and amendments that were available at the time as well as an alternative amendment selected to perform well in the new field demonstration location.

8.1 COST MODEL

The cost elements that influence the installation of a PRBerm™ to immobilize metals in a SAFR impact berm include initial treatability testing required to determine the appropriate sand and amendment for the metals of concern, and cost of construction and installation. Labor for sampling and analysis costs will be incurred for long-term monitoring (LTM) of the runoff water and leachate to determine when amendment replenishment will be required. No permitting or environmental reporting costs were incurred other than the initial filing of the appropriate National Environmental Policy Act (NEPA) documentation prior to the berm installation.

In the field demonstration, three PRBerm™s were installed, one to be used as an untreated control, one filled completely with a sand and amendment mixture, and the third with the same sand and amendment mixture and a small added test area of a second amendment. This is not a situation that would be encountered on a range. In the assessment, the costs will be calculated as (1) sand with 5% TRAPPS amendment and (2) sand with 5% TTF amendment, compared to an untreated control. These PRBerm™s will be compared to the cost of installation of a fully contained bullet trap system. The relevant costs, documented in Table 23, reflect a "per berm" cost to construct and install a PRBerm™. Generally, these costs will not scale linearly with increasing numbers unless cost breaks are given by the manufacturer for a large number of berms since the cost of sand and amendments is relatively small.

The majority of the costs associated with the PRBerm™ are material cost and labor. Baseline characterization should not be needed because these areas generally have already been characterized to support ongoing monitoring of range activities. Minor treatability costs are incurred prior to the construction and installation to determine metal leaching to establish the appropriate sand and amendment concentrations. No waste disposal costs were incurred. Some monitoring of the runoff water will be required to confirm the installation continues to meet state permits for discharge.

Table 23. Cost Model for a PRBerm™.

Cost Element	Data Tracked During the Demonstration	Costs	
Treatability study	• Personnel required and associated labor • Materials • Analytical laboratory costs	Program manager Student	$20,000 $10,000
		Materials[1]	$4000
		Analytical laboratory[1]	$5000
Material cost	Unit: $ per pound for reactive material Data requirements: • Initial amount of sand and amendment material required based on size of the PRBerm™ • Reapplication necessary – accessed via laboratory testing	Amendments Excavation	$20,000 $15,000
Installation	Unit: $ per berm Data requirements: • Recommended installation method • Mobilization cost • Time required	Installation	$22,145
Waste disposal	Standard soil disposal, no cost tracking	NA	
Operation and maintenance (O&M) costs	• No unique requirements recorded	NA	
LTM	• Standard discharge or runoff water monitoring, no cost tracking	NA	
[1] Detailed list of materials and analytical costs provided in Final Report			

8.2 COST DRIVERS

Cost drivers that should be considered when implementing the technology include the cost of metal fabrication, materials, and labor. Additional cost drivers are installation labor and down-time of the range. Management goals and regulatory permit monitoring requirements may require more frequent monitoring to verify that source zone contaminant levels are controlled in source or transport media.

8.3 COST ANALYSIS

8.3.1 Technology cost comparison

It is intended that the PRBerm™ technology be installed on SAFRs with fixed firing positions. In general, the cost of a PRBerm™ is slightly more than a traditional earthen berm due to the addition of the amendment but significantly less than the cost of a steel bullet trap system.

The cost and maintenance of a PRBerm™ is compared to a traditional earthen berm and a steel bullet trap in Table 24. The cost of the PRBerm™ (construction and installation) is more expensive than the earthen berm but less expensive than the bullet trap. Maintenance of the PRBerm™ is minimal, little more than what is required for an earthen berm. Life-cycle cost analysis should note that the PRBerm™ reduces metal migration, therefore the potential of

permit problems and regulatory fines, range shutdown issues, and a reduced training capability. In addition, Pb recycling from the PRBerm™ could offset yearly maintenance costs.

Table 24. Comparative cost and maintenance of the PRBerm™.

Technology	Construction Cost	Yearly O&M[a]	Overhaul at 10 Years	Cleanup Cost at 40-Year Lifespan	40-Year Total Cost ($K)
Earthen berm	100	0	50	350**	350
PRBerm™	1000	30*	100	0	2600
Steel bullet trap	3000	350	2500	0***	7000

[a]O&M = operation and maintenance
*Estimated cost for amendment replacement and sand addition
**Assumes 7-yd^3 per running foot of berm
***Cleanup costs currently unknown

8.3.2 Life-Cycle Costs of the PRBerm™

Life-cycle cost specifically associated with the PRBerm™ technology is related to construction of the PRBerm™ and selection of the amendment. In this study, Pb was selected as the heavy metal to track as it is the predominant metal of concern on SAFRs. Depending on soil type, initial pH, climate, and regulatory concerns, another metal may be of greater interest and a different amendment configuration may be selected.

The initial assumptions made when considering this technology are listed below. These assumptions are based on previous work as well as the results from the current application (Larson et al., 2004; Larson et al., 2005; Larson et al., 2007a; Larson et al., 2007b; Martin et al., 2008). The assumptions that indicate a technology such as the PRBerm™ might be required are:

- Soils that are characterized by high acidity (low pH),
- Soils that are characterized by high alkalinity (high pH),
- Soils with high permeability,
- Soils with low soil/water K_d values for Pb

As indicated in Section 1.0, these soils may be ineffective in retarding the migration of soluble Pb into nearby groundwater or surface water bodies.

On the other hand, if a situation exists in which soils:

- Have neutral to slightly basic pH conditions,
- Have relatively low permeability
- Exhibit a high K_d value for Pb.

These soils may be effective in limiting the mobility of soluble Pb to the surrounding environment and the PRBerm™ technology would not be required. However, mechanical erosion and transport of such soils (especially clay-rich soils) can lead to offsite transport of Pb in surface water runoff.

The cost factors involved in successfully applying this technology on a site are listed in Table 25 along with site details that will affect those costs. Costs of this technology are highly dependent on site soil conditions as described in Section 8.3.2.

Table 25. Life cycle cost factors for applying the PRBerm™ technology.

Cost Factor	Affected by:
Construction cost of PRBerm™	Range size/number of berms required
Amendment	Metal of concern
Sampling/monitoring	Area of potential concern (i.e., groundwater vs. surface water)
O&M	Frequency of use and type of ammunition
	Bimonthly sampling and analysis of leachate and runoff water for concentration of metals
Disposal	Proper choice of amendment will allow disposal of the sand as a nonhazardous waste
	Removal and recycling of bullets and bullet fragments will offset disposal costs

8.3.3 Life-Cycle Costs of a Steel Bullet Trap

The objective of the life-cycle analysis was to determine recurring and nonrecurring costs associated with the steel deceleration trap. This analysis is based on purchase cost estimates provided by the manufacturer, engineering estimates for installation of the trap based on manufacturer's installation specifications, and maintenance and disposal cost estimates based on information extrapolated from field test activities and data. All costs in this analysis are based on 1998 material and labor costs as provided in Furnati and Fabian (2003).

1. Nonrecurring Costs. Nonrecurring costs include the initial purchase of the bullet trap, site preparation, installation of the trap on the range, and any documentation required to permit installation of the trap. The initial equipment purchase and installation estimates (Table 26) were based on the bullet trap manufacturer's quote for equipping a 200-ft wide, 20-lane outdoor 25-meter range.

Table 26. Cost estimate for bullet trap purchase and installation.

Item	Cost ($)[c]
Trap	186,011
Roof	42,279
DCU[a]	30,099
Materials	1500
Installation[b]	14,500
TOTAL	**274,390**

[a]dust collection unit
[b]Installation includes travel, lodging, equipment, and labor
[c]Cost estimate based on 1998 material and labor costs

Site preparation estimates were based on preparing a range at Aberdeen Test Center (ATC) to accept the commercial trap. Preparation would entail the construction of a 200 ft by 21 ft by 6-

inch thick concrete pad. The cost estimate for this pad is shown in Table 27. This estimate includes site grading, a 6-inch layer of compacted sand, wood forms, expansion joints, welded wire fabric, concrete, placing concrete, breakers, switches, wire and electric utility installation. The estimate was derived using R. S. Means 1997 Building Construction Cost Data.

Table 27. Estimate for concrete pad.

Cost Element	Quantity		Labor		Material		Total Cost[a], ($)
	No. of Units	Unit of Measure	Per Unit	Total Labor	Per Unit	Total Material	
Site grading	466.67	Square yards	1.84	859	NA	NA	858.67
Sand	286.22	Cubic yards	3.92	1,122	8.35	2,389.94	3511.92
Compaction	286.22	Cubic yards	0.65	186	NA	NA	186.04
Concrete form	842	Linear feet	0.90	758	1.16	976.72	1734.52
Expansion joint	84	Linear feet	1.09	92	1.35	113.40	204.96
Welded wire fabric	42	100 linear feet	16.90	710	19.85	833.70	1544
Concrete	77.78	Cubic yards	NA	NA	56.00	4,355.68	4355.68
Placing concrete	77.78	Cubic yards	17.05	1,326	NA	NA	1326.14
Panel board	1	Each	370	370	560.00	560	930
Circuit breakers	20	Each	24	480	10.00	200	680
Safety switch	20	Each	75	1,500	49.50	990	2490
Conduit (rigid)	2200	Linear feet	3	6,600	1.58	3,476	10,076
Wire	2200	Linear feet	24	52,800	9.75	21,450	74,250
Subtotal							102,147.93
1998 inflation adjustment						5%	5107.39
						TOTAL	**107,255.32**

NA = not applicable
[a]Cost estimate based on 1998 material and labor costs

Other nonrecurring costs include site evaluation and equipment integration costs. These costs include conducting an NEPA evaluation, surveying, conducting a utility avoidance sweep, and modifying operational procedures. Assumptions were made that a Record of Environmental Consideration (REC) would be sufficient to satisfy NEPA requirements and that surveying, utility avoidance, and modifying operational procedures would be similar for the implementation of each of the technologies. These costs plus the site preparation and bullet trap purchase and installation total costs are presented in Table 28. The total nonrecurring cost to acquire and install the steel deceleration trap is approximately $385,000.00.

Table 28. Nonrecurring costs for a steel deceleration trap.

Cost Category	Labor Rate $/hour	Number of Hours	Cost[a] $
Site preparation (Table 27)	NA	NA	107,255.32
Bullet trap purchase and installation (Table 26)	NA	NA	274,379.95
NEPA evaluation	45	4	180.00
Surveying	40	40	1600.00
Utilities sweep	Flat rate	NA	300.00
Operational procedures	45	16	720.00
Modification of range drawings	40	16	640.00
		TOTAL	**385,075.27**

[a]Cost estimate based on 1998 material and labor costs.
NA – not applicable

2. Recurring Costs. Recurring costs include annual O&M costs and environmental costs associated with handling recyclable or waste material. These costs are discussed below and summarized in Table 29

Table 29. Recurring costs for steel deceleration trap.

Cost Category	Labor Rate, $/hour	No. of Hours	Cost[b], $
O&M	30	Unknown[a]	Unknown[a]
Consumable supplies	Unknown[a]	Unknown[a]	Unknown[a]
Waste disposal	Unknown[a]	Unknown[a]	Unknown[a]
Environmental management	Unknown[a]	Unknown[a]	Unknown[a]
Environmental testing	Unknown[a]	Unknown[a]	Unknown[a]
Training	30	48	1680.00
Overhead	NA	NA	1000.00
		TOTAL	**Unknown[a]**

[a]Could not be estimated with available information.
[b]Cost estimate based on 1998 material and labor costs.

Annual O&M activity cost estimates were based on utilizing existing ATC labor and disposal mechanisms, except as noted otherwise. Daily Project Configuration Management System (PCMS) requirements would entail a visual inspection to ensure adequate filter differential pressure and general fitness of the trap. Daily PCMS was assumed to take about 30 minutes to complete at an annual cost of $3750. The cost was based on an estimated 250 training days per year. Since testing at ATC was terminated prior to determining the durability of the trap when exposed to military ammunition, the life of the plates, deceleration chamber, and DCU could not be determined by government testing. Annual O&M costs could not be included in Table 25 due to the unknown durability and required maintenance frequency of the trap.

Environmental management costs for the steel deceleration trap would involve administrative work and analytical testing to characterize the waste. It appears that only a minimal amount of hazardous waste would be generated. This hazardous waste would consist primarily of spent filters and materials used to clean accumulated particulate. Bullet debris and metal panels following a render-safe would likely be reclaimed as a scrap metal. The annual environmental management costs are dependent upon the annual maintenance requirements for the trap. This could not be established based on the testing conducted or available manufacturer's information that pertained to the trap's use with military ammunition. As a result, annual environmental costs were not included in Table 28.

Annual operator training was assumed to include equipment O&M training, environmental (or hazardous waste handling) training, and Occupational Safety and Health Administration (OSHA) training. Annual training was estimated at 14 hours per person for four range workers. Training costs were estimated to be $1680 annually. Overhead for ordering materials, preparing for maintenance, and the like was estimated at $1000 annually.

3. Other Costs. In addition to the nonrecurring and recurring costs identified above, another cost associated with use of the steel bullet trap is the disposal cost of the bullet trap when it has reached the end of its useful life. The cost of disposing of the steel deceleration trap includes disassembly of the trap, rendering safe the trap material, and treatment of soil in front of the trap to remove Pb contamination. The cost for the actual disposal of the trap metal material is considered negligible and is offset by the trap's potential scrap value.

Final disposal cost is estimated by adding the disassembly and render-safe cost, which are assumed to be equal to the installation costs ($14,500) and soil treatment costs ($326,000). Soil treatment costs are likely to be incurred as result of the steel deceleration trap's failure to contain particulate emissions. The soil requiring remediation was estimated to have a volume of 61 meters long by 20 meters wide by 1 meter deep. ATC assumed that interim remediation efforts would not be required to maintain compliance with environmental regulations. Pb contaminated soil removal cost was estimated based on ex situ treatment (solidification and stabilization followed by land filling) of the Pb contaminated soil. A cost of $164 per ton was used to estimate the cost of soil remediation. The mass of the soil was assumed to be 1.63 tons per cubic meter of soil.

4. Conclusions. The steel deceleration trap life-cycle cost estimates are summarized in Table 30. The annual cost to operate and maintain the trap could not be determined from the information available. The annual costs should vary slightly with usage, decreasing for ranges with a lower throughput and increasing for ranges with a higher throughput.

Table 30. Summary costs for steel deceleration trap.

Cost Category	Total Cost
Nonrecurring costs (initial purchase and setup)	$385,159.81
Recurring costs (annual O&M)	Unknown[a]
Disposal costs	$340,500.00
[a]Could not be estimated with available information.	

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9.0 IMPLEMENTATION ISSUES

9.1 ENVIRONMENTAL CHECKLIST

The PRBerm™ technology does not involve the use of any toxic or hazardous chemicals. The TRAPPS™ amendment is not regulated and is approved for addition to soils. The thermally treated fish bones are also nonregulated.

9.2 REGULATORY ISSUES

The potential for off-range migration of munitons metals 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 or Safe Drinking Water Act regulations may be of concern to ongoing range operations.

9.3 END-USER ISSUES

The primary end user for this innovative in situ technology will be managers of active small arms ranges. The technology is expected to stabilize munitions metals within the impact berm before they can migrate to surface water or storm water discharge areas.

9.4 MANAGEMENT COSTS

Several factors determine the constituent management costs:

- *Analytical cost.* Periodic sampling to monitor metals concentrations in runoff water.
- *Capital cost.* Capital costs will include PRBerm™ construction and installation, preparation of the impact media with amendments, and filling the berm and, if planned into regular berm maintenance, should run similar to scheduled maintenance procedures.
- *Operation and monitoring cost.* O&M costs will mainly encompass the costs associated with labor, water sampling, and analysis.
- *Management goal.* More stringent management goals may require additional monitoring to verify that regulatory levels of discharge are maintained.

9.5 LESSONS LEARNED

The PRBerm™ is not suitable for all range backstops. Range operations and range soil conditions dictate what type of application, if any, is needed in order to reduce metals migration off the SAFRs. An alternative to the PRBerm™, for example, is the fully contained bullet trap system. Although the bullet trap will reduce the potential migration of metals into the environment, significant cost, O&M, and loss of training value is associated with such a system.

Depending on the PRBerm™ soil amendment type, one potential limitation is the solubilization of phosphate and transport of phosphate off the range in storm water runoff. High phosphate

concentrations have been observed to result in algal blooms. Phosphate concentrations in leachate water and surface water from simulated berms were measured during both the treatability study and field demonstration phases of the project.

Another potential limitation is the occurrence of ricochets or rounds skipping over the berm, impacting the SDZ. Richochet modeling was conducted in order to mitigate the risk of ricochets leaving the range through improper design of the PRBerm™.

Lessons learned from this demonstration include:

- *Flexibility in site selection.* At the conclusion of the Treatability Phase of the Demonstration, the Barksdale AFB, LA range was transitioned into a steel bullet trap so it would not be available for use as the field demonstration site as originally planned.
- *Flexibility in personnel.* With personnel shifts the core team must remember to "cross-train" in order to provide project continuity.
- *Rainwater.* Find a suitable means to collect and store rainwater for use in artificial raining on the PRBerm™, if needed.
- *Drainage.* The need for a drainage system located at the range that will assist with collection of storm water samples leaving the range complex and prevent potential cross contamination of leachate water collection systems.
- *Environmental Drivers*. Determination that there are no known environmental drivers that limit the technology use at the selected site.

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