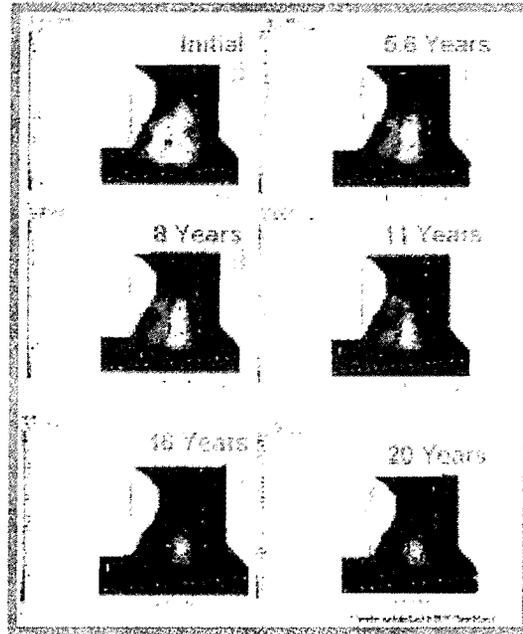


097282

**ESTCP**

# Cost and Performance Report

(CU-9518)



## Natural Attenuation of Explosives in Groundwater

June 1999



ENVIRONMENTAL SECURITY  
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

30754





## TABLE OF CONTENTS

	Page
1.0 EXECUTIVE SUMMARY .....	1
2.0 TECHNOLOGY DESCRIPTION .....	3
2.1 BACKGROUND .....	3
2.2 THEORY .....	3
2.3 SPECIFICATIONS .....	3
2.3.1 Performance .....	3
2.3.2 Personnel/Training Requirements .....	3
2.3.3 Health and Safety Requirements .....	4
2.3.4 Ease of Operation .....	4
2.4 MOBILIZATION, CONSTRUCTION, AND OPERATION REQUIREMENTS .....	4
2.5 KEY DESIGN CRITERIA .....	5
2.6 NATURE AND OPERATION OF MONITORED NATURAL ATTENUATION .....	5
2.7 ADVANTAGE AND STRENGTHS OF MONITORED NATURAL ATTENUATION .....	5
3.0 DEMONSTRATION DESIGN .....	7
3.1 PERFORMANCE OBJECTIVES .....	7
3.1.1 Objective in the Demonstration Plan .....	7
3.1.2 Performance Criteria Required for Acceptance of Monitored Natural Attenuation .....	7
3.1.3 Performance Metrics from the Demonstration Plan .....	8
3.2 PHYSICAL SETUP AND OPERATION .....	8
3.3 MONITORING PROCEDURES .....	9
3.4 ANALYTICAL PROCEDURES .....	10
3.4.1 Explosives and Their Degradation Products .....	10
3.4.2 Geochemical Parameters .....	10
3.4.3 Other Analyses .....	10
3.5 DEMONSTRATION SITE/FACILITY BACKGROUND .....	12
3.6 DEMONSTRATION SITE/FACILITY CHARACTERISTICS .....	13
4.0 PERFORMANCE ASSESSMENT .....	15
4.1 SIGNIFICANT DEVIATIONS FROM DEMONSTRATION PLAN .....	15
4.2 DATA ASSESSMENT .....	15
4.3 FIELD OBSERVATIONS AND COMPARISON TO TECHNOLOGY CLAIMS .....	15
4.4 OVERALL CONCLUSIONS .....	16
5.0 COST ASSESSMENT .....	17
5.1 TREATMENT COSTS FOR THE DEMONSTRATION .....	17

## TABLE OF CONTENTS

	Page
6.0	IMPLEMENTATION ISSUES ..... 19
6.1	COST OBSERVATIONS ..... 19
6.2	PERFORMANCE OBSERVATIONS ..... 19
6.3	REGULATORY AND OTHER ISSUES ..... 19
6.4	LESSONS LEARNED ..... 19
7.0	REFERENCES ..... 21
7.1	KEY REFERENCES ..... 21
7.2	GENERAL REFERENCES ..... 21
APPENDIX A:	Points of Contact ..... A-1
APPENDIX B:	Data Archiving and Demonstration Plan ..... B-1

## LIST OF FIGURES

		Page
Figure 1	Relationship between Dissolved Oxygen and Explosives Concentration . . . . .	9
Figure 2	Area P at LAAP Showing Former Lagoons, Capped Area, Monitoring Wells, and CPT Locations . . . . .	12
Figure 3	Conceptualization of the Lateral Distribution of RDX in the Upper Terrace Groundwater at LAAP Over Time . . . . .	14
Figure 4	Trends in Explosives Concentrations in Selected Monitoring Wells over the Two-Year Sampling Period at LAAP . . . . .	15

## LIST OF TABLES

	Page
Table 1 Explosives and Related Analytes Monitored in Groundwater at LAAP and JAAP . . . . .	11
Table 2 Geochemical Parameters Monitored in Groundwater at LAAP and JAAP . . . . .	11

## LIST OF ACRONYMS

---

AEC	Army Environmental Center
Ca	Calcium
Cl	Chloride
DO	Dissolved Oxygen
ECD	Electron Capture Detector
EL	(WES) Environmental Laboratory
ESTCP	Environmental Security Technology Certification Program
Fe	Iron
GMS	Groundwater Modeling System
HPLC	High Performance Liquid Chromatography
IDW	Investigation Derived Wastes
JAAP	Joliet Army Ammunition Plant
LAAP	Louisiana Army Ammunition Plant
Mg	Magnesium
Mn	Manganese
MNA	Monitored Natural Attenuation
NO <sub>2</sub> /NO <sub>3</sub>	Nitrate/Nitrite
PLFA	Polar Lipid Fatty Acids
PPE	Personal Protective Equipment
RDX	1,3,5-Trinitro-1,3,5-hexahydrotriazine
SERDP	Strategic Environmental Research and Development Program
SIC	Standard Industrial Classification
SO <sub>4</sub>	Sulfate
TNT	2,4,6-Trinitrotoluene
TOC	Total Organic Carbon
USEPA	U.S. Environmental Protection Agency
UV	Ultraviolet
WES	(U. S. Army Engineer) Waterways Experiment Station

## ACKNOWLEDGMENTS

This report was prepared by the Environmental Laboratory (EL) of the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. The demonstration was sponsored by the Environmental Security Technology Certification Program (ESTCP), Arlington, VA, Mr. Jeffrey Marqusee, Program Manager, Project Number 9518, and the Strategic Environmental Research and Development Program (SERDP), Arlington, VA, Dr. John Harrison and Mr. Bradley P. Smith, Executive Directors, Project Number 1043. The U.S. Army Industrial Operations Command, Rock Island, IL, Mr. Cyril Onewokae, Environmental Quality Directorate, funded monitoring at the validation site. The principal investigator was Dr. Judith C. Pennington, EL, WES.

The authors acknowledge the cooperation and site support received from Mr. Ira May, Mrs. Laurie Haines, and others, Army Environmental Center (AEC), Aberdeen Proving Ground, MD, Mr. Doyle Williams, Environmental Officer, Louisiana Army Ammunition Plant, Minden, LA, and Mr. Art Holz, Environmental Coordinator, Joliet Army Ammunition Plant, Wilmington, IL. The authors also acknowledge the advice of the following members of the Technical Review Committee for Natural Attenuation of Explosives: Mr. Michael Barden, Geosciences Resources LTD, Albuquerque, NM., formerly of Wisconsin Department of Natural Resources, Madison, WI; Mr. Patrick Haas, U. S. Air Force Center for Environmental Excellence, San Antonio, TX; Mrs. Laurie Haines; and Dr. David C. White, University of Tennessee, Knoxville, TN.

The project represents the collective efforts of the following:

Groundwater Monitoring and Cone Penetrometry	Danny W. Harrelson, Judith C. Pennington, WES; Thomas F. Jenkins, U.S. Army Cold Regions Research and Engineering Laboratory; Charolett A. Hayes, ASCI
Site Capacity and Geochemistry	James M. Brannon, Tommy Myers, WES; Dan M. Townsend, North Carolina State University
Microbial Biomarkers	Douglas Gunnison, Herb Fredrickson, WES; Ed Perkins, ASCI; Dave Ringelberg, DynTel
Groundwater Modeling	Mansour Zakikhani, WES
Statistics	Joan U. Clarke, WES
Initial Draft Protocol	Rick Bowen, Janet Mahannah, Scot Gnewuch, Arthur D. Little, Inc.

This report was reviewed by Drs. James M. Brannon and William B. Davis, EL. The study was conducted under the direct supervision of Dr. Richard E. Price, Chief, Environmental Processes and Effects Division, and Dr. John Harrison, Director, EL. At the time of publication of this report, Commander and Acting Director of WES was COL Robin R. Cababa, EN. This report should be cited as follows:

Pennington, J. C., Zakikhani, M., Harrelson, D. W., and Allen, D.S. (1999). "Monitored Natural Attenuation of Explosives in Groundwater - Cost and Performance," Technical Report EL-99- , U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

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



## 1.0 EXECUTIVE SUMMARY

Monitored natural attenuation (MNA) is a remedial alternative for explosives contaminated groundwater at sites where a decline in contaminant mass can be demonstrated to occur at a rate sufficient to ensure the protection of potential receptors. MNA is not a "no action" alternative, but requires careful characterization of the site hydrogeology and contaminant distribution, long-term monitoring of groundwater, and groundwater modeling to conceptualize the contaminant plume and to predict future migration and attenuation. MNA in the context of the demonstration described here does not include intervention to promote natural processes.

Demonstrating that MNA is a viable remedial alternative requires gathering a "weight of evidence" that natural processes are sufficient to protect receptors of concern within a reasonable time-frame. Explosives are subject to several attenuation mechanisms that effectively reduce concentrations in natural systems. Some of these processes have been defined, while other are poorly understood. MNA relies upon quality site characterization data, carefully conducted long-term monitoring, and groundwater modeling for contaminant conceptualization and long-term predictions of contaminant fate. Determining attenuation rates for explosives requires demonstration of declining mass over time, and conservative extrapolation of attenuation capacity and microbial degradation potential from the laboratory to the field.

This demonstration was designed to define and optimize the data collection and processing procedures for evaluation, selection, and implementation of MNA for explosives. The demonstration was conducted at a former waste disposal lagoon site at the Louisiana Army Ammunition Plant, Minden, LA. Thirty wells were monitored quarterly over a two-year period. A cone penetrometry sampling event was also conducted to refine the conceptualization of the site hydrogeology and to collect aquifer material for development of microbial biomarker techniques for tracking attenuation processes. A conceptual model of the contaminant plume was developed and a numerical model was used to predict future plume migration and mass.

Overall costs of the demonstration were approximately four million dollars. Refinements in sampling protocols, biomarker techniques and modeling generated data that were sufficiently reliable for measuring and projecting trends in contaminant mass over time.

The overall cost (including pretreatment, treatment and after treatment costs) of MNA is projected to be about 25 % lower than the cost of in-situ bioremediation, and about 50 % lower than the cost of pump-and-treat using activated carbon adsorption over 20 years (*Monitored Natural Attenuation of Explosives in Groundwater - ESTCP Completion Report*, Pennington et al. in preparation c; Member Agencies of the Federal Remediation Technologies Roundtable 1995). However, if the treatment time is extended and only treatment costs (exclusive of pretreatment and after treatment costs) are used, cost savings from MNA over these other technologies increase over time. Treatment costs of MNA were 82% less than costs of in-situ bioremediation and 88 % less than costs of pump-and-treat remediation after 60 years. Therefore, the time required to achieve clean-up goals contributes significantly to the long-term savings of MNA.



## **2.0 TECHNOLOGY DESCRIPTION**

### **2.1 BACKGROUND**

Natural attenuation is defined as reduction of contaminant concentrations to environmentally benign levels through natural processes. Natural attenuation as a remedial alternative can be evaluated along with engineered remedies. Monitored natural attenuation (MNA) may be a viable candidate remedy at sites where contaminant concentration is so low that other remedial actions are not viable or cost effective, contaminant source has been remediated by engineered approaches leaving behind a low-level residue, contaminant attenuation has been demonstrated by existing site historical data, and/or the site is remote from receptors of immediate concern. Monitored natural attenuation is attractive for sites where disturbance of structures or sensitive habitat is undesirable, and/or immediate engineered remedial action is not required or not feasible. MNA may be useful at sites that meet well-defined selection criteria, acceptable risk levels, and that satisfy specific regulatory concerns.

### **2.2 THEORY**

Explosives are subject to several environmental fate processes that may result in attenuation, or reduction in the mass of contaminants in the groundwater. Some of these processes have been defined, while others are poorly understood. These processes occur through biotic or abiotic transformations of TNT to aminonitrotoluenes which are subject to immobilization by reaction with soil organic matter and exchange sites on clays, and microbial mineralization of RDX to simple, nonhazardous inorganic compounds. Immobilization and degradation can be demonstrated by proving that the contaminant plume is moving significantly more slowly than would be predicted by the flow rate of the groundwater, and by demonstrating that the total estimated mass of contamination is declining over time. Degradation/transformation can be demonstrated by identifying products of these processes during groundwater monitoring.

Potential disadvantages of MNA include the long time frames likely to be required to meet remediation goals, the necessity for institutional controls of the site, and the potential for unexpected changes in local groundwater hydrogeology over the extended monitoring period.

### **2.3 SPECIFICATIONS**

#### **2.3.1 Performance**

The primary technical performance criteria are described under Section III.A.3 Performance Metrics and are presented in the Demonstration Plan (Pennington unpublished).

#### **2.3.2 Personnel/Training Requirements**

All personnel are required to take the standard Hazardous Waste Site Worker (HWSW) course plus annual refresher courses if the site is classified under Super Fund. Training may be desirable for optimal well sampling using recommended standard operating procedures including purging well water before sampling, sample preservation and handling, and micro sampling if biomarkers are investigated (*Natural Attenuation of Explosives in Groundwater - Technology Demonstration Plan*,

Pennington et al. unpublished, and *Draft Protocol for Evaluating, Selecting, and Implementing Monitored Natural Attenuation at Explosives-Contaminated Sites*, Pennington et al. in preparation a).

### **2.3.3 Health and Safety Requirements**

The following three primary hazards are associated with implementation of MNA of explosives: (1) chemical and health hazards associated with exposure to explosives or their breakdown products, (2) normal field work hazards such as heat and cold exposure, heavy lifting, and working around drilling rigs and cone penetrometry trucks, and (3) normal laboratory hazards such as handling flammable solvents. Minimal hazard of explosion exists for explosives-contaminated groundwater; however, soils contaminated with greater than 10 percent total explosives by weight potentially pose an explosion hazard and should be handled with all the precautions recommended for handling explosives. Such soils usually exhibit visible chunks of explosives. Primary routes of potential exposure of workers to explosives include inhalation or ingestion of contaminated dust, skin absorption from direct contact, eye exposure from direct contact. EPA Level D protection is recommended as adequate for typical field activities.

### **2.3.4 Ease of Operation**

Procedures for site characterization and groundwater monitoring of contamination, hydrology, and geology are standard. Appropriate hardware and analytical laboratories are readily available from commercial suppliers. Analytical methods for the explosives in groundwater are standard USEPA Method 8330 (U. S. EPA 1994), or slight modifications thereof. Biomarker analyses are not standard procedures, however, and require the use of molecular microbiological tools and radioassays by a sophisticated laboratory. Radioassays require laboratories licensed by the Nuclear Regulatory Commission. Such capabilities are occasionally found commercially, and are usually available at larger universities. Refinements in sampling protocols and sample handling are readily available in *Monitored Natural Attenuation of Explosives in Soil and Water Systems at DoD Sites: Interim Report* (Pennington et al. in preparation b), and in the Draft Protocol (Pennington et al. in preparation a) (see Appendix A. Points of Contact).

## **2.4 MOBILIZATION, CONSTRUCTION, AND OPERATION REQUIREMENTS**

Mobilization for MNA requires initial site reconnaissance, site conceptualization, development and initiation of a groundwater monitoring plan, and development and initiation of a cone penetrometry sampling event. Construction is limited to installation of any additional monitoring wells or sentinel wells between the contaminant plume and potential receptors of concern. No other physical construction is anticipated. Operations include groundwater and penetrometry sampling for contaminants, hydrogeological and microbiological characterization, and groundwater modeling. Data collection through quarterly sampling is recommended for the first year or two in order to refine sample collection and handling procedures and the site model. Once groundwater hydrology is understood, monitoring frequency can be revised to reflect the anticipated rate of change in contaminant mass or other pertinent site-specific issues related to risk assessment.

## **2.5 KEY DESIGN CRITERIA**

No engineering design criteria are associated with MNA. However, criteria for site characterization, monitoring and modeling are described in the Draft Protocol (Pennington et al. in preparation a). Time frame is an important consideration for MNA, since natural attenuation processes tend to be slow. USEPA (1998) recommends a comparison of estimates of remediation time frames for all appropriate remedy alternatives. This comparison should be included in the feasibility study when selecting a remedial option.

## **2.6 NATURE AND OPERATION OF MONITORED NATURAL ATTENUATION**

MNA does not require a treatment train, is not capital or operational and maintenance intensive, and produces no treatment residuals (U. S. Environmental Protection Agency and U.S. Air Force Environics Directorate 1993). MNA relies upon quality site characterization data, which is also required for implementation of other remedial options, carefully conducted long-term monitoring, and groundwater modeling for contaminant conceptualization and long-term predictions of contaminant fate. Determining attenuation rates for explosives requires demonstration of declining mass over time through collection of groundwater data, and conservative extrapolation of attenuation capacity and microbial degradation potential from the laboratory to the field.

## **2.7 ADVANTAGE AND STRENGTHS OF MONITORED NATURAL ATTENUATION**

The greatest advantage of MNA over engineered remedial alternatives is the potential cost savings. In a cost comparison of MNA with two other technologies, in-situ bioremediation and activated carbon adsorption, estimated cost savings by use of MNA were significant (Pennington et al. in preparation c). Monitored natural attenuation also generates less wastes, reduces the risk of human and environmental exposure to contaminants during remediation, and is less intrusive than other remedial alternatives. With the possible exception of biomarker technologies, procedures are commercially available, highly reliable and easily maintained (U. S. Environmental Protection Agency and U.S. Air Force Environics Directorate 1993).



## **3.0 DEMONSTRATION DESIGN**

### **3.1 PERFORMANCE OBJECTIVES**

#### **3.1.1 Objective in the Demonstration Plan**

Specific objectives of the demonstration were (1) to demonstrate that attenuation of explosives can be determined through appropriate site monitoring, (2) to develop guidance for selection of natural attenuation as a remediation alternative, (3) to develop guidance for establishing a site monitoring plan and point(s) of compliance, and (4) to gain regulatory acceptance of natural attenuation of explosive as a remedial alternative.

#### **3.1.2 Performance Criteria Required for Acceptance of Monitored Natural Attenuation**

The EPA draft policy directive (USEPA 1998) provides the following criteria for acceptance of MNA:

Once site characterization data have been collected and a conceptual model developed, the next step is to evaluate the potential efficacy of MNA as a remedial alternative. This involves collection of site-specific data sufficient to estimate with an acceptable level of confidence both the rate of attenuation processes and the anticipated time required to achieve remediation objectives. A three-tiered approach to such an evaluation is becoming more widely practiced and accepted. In this approach, successively more detailed information is collected as necessary to provide a specified level of confidence on the estimates of attenuation rates and remediation time frame. These three tiers of site-specific information, or "lines of evidence", are:

- (1) Historical groundwater and/or soil chemistry data that demonstrate a clear and meaningful trend<sup>1</sup> of decreasing contaminant mass and/or concentration over time at appropriate monitoring or sampling points. (In the case of a groundwater plume, decreasing concentrations should not be solely the result of plume migration. In the case of inorganic contaminants, the primary attenuating mechanism should also be understood.)
- (2) Hydrogeologic and geochemical data that can be used to demonstrate indirectly the type(s) of natural attenuation processes active at the site, and the rate at which such processes will reduce contaminant concentrations to required levels. For example, characterization data may be used to quantify the rates of contaminant sorption, dilution, or volatilization, or to demonstrate and quantify the rates of biological degradation processes occurring at the site.
- (3) Data from field or microcosm studies (conducted in or with actual contaminated site media) which directly demonstrate the occurrence of a particular natural attenuation process at the site and its ability to degrade the contaminants of concern (typically used to demonstrate biological degradation processes only).

---

<sup>1</sup> For guidance on statistical analysis of environmental data, please see USEPA, 1989, USEPA, 1993a, USEPA, 1993b, and Gilbert, 1987, listed in the •General References• section at the end of this Report.

Unless EPA or the implementing state agency determines that historical data (Number 1 above) are of sufficient quality and duration to support a decision to use MNA, data characterizing the nature and rates of natural attenuation processes at the site (Number 2 above) should be provided. Where the latter are also inadequate or inconclusive, data from microcosm studies (Number 3 above) may also be necessary. In general, more supporting information may be required to demonstrate the efficacy of MNA at those sites with contaminants which do not readily degrade through biological processes (*e.g.*, most non-petroleum compounds, inorganics), or that transform into more toxic and/or mobile forms than the parent contaminant, or where monitoring has been performed for a relatively short period of time. The amount and type of information needed for such a demonstration will depend upon a number of site-specific factors, such as the size and nature of the contamination problem, the proximity of receptors and the potential risk to those receptors, and other characteristics of the environmental setting (*e.g.*, hydrogeology, ground cover, climatic conditions).

### **3.1.3 Performance Metrics from the Demonstration Plan**

The technical performance criteria established in the demonstration plan included the following:

- (1) Decreases in concentrations of TNT and RDX below concentrations predicted from the site geology and hydrology. These results will suggest that the explosives are attenuated in the subsurface by degradation, transformation, and/or immobilization processes.
- (2) Increases in concentrations of transformation/degradation products of TNT and RDX. These results will demonstrate formation of known transformation and/or degradation products. Spatial distribution of these products relative to parent compounds and uncontaminated area can be used to assess the progression of degradation mechanisms. Some intermediates are considered environmentally undesirable; therefore, these intermediates must be tracked as carefully as the parent compounds. The amino substituted transformation products of TNT are much more subject to immobilization processes than the parent compound; therefore, their appearance and disappearance is also important to track.
- (3) Predictions by the model that potential receptors will be protected due to documented site geological and hydrological characteristics. The groundwater flow rate and subsurface permeability may be so low that receptors are protected for a significantly long period time. Site data together with application of a model will reveal the potential for acceptable risk.

## **3.2 PHYSICAL SETUP AND OPERATION**

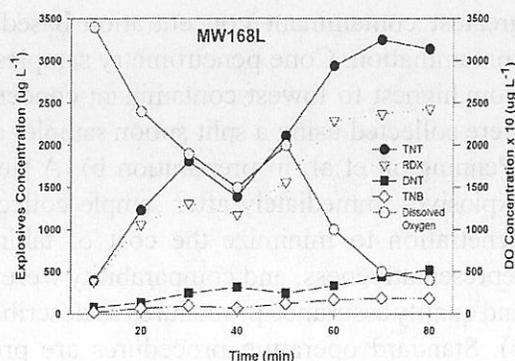
Preliminary to execution of the demonstration, tests were conducted to optimized the reliability of the monitoring data. Tests were conducted (1) to define the relationship between concentrations of explosives, dissolved oxygen and volume of water extracted, and (2) to optimized the preservation of analytes for chemical analyses. Results of the first tests revealed a general inverse relationship between explosives concentration and dissolved oxygen (Figure 1). No significant difference between removal of three well-volumes and the volume extracted when dissolved oxygen became stable were found. Therefore, for LAAP either bailing of three well-volumes or pumping until achieving stable DO was acceptable. Results of preservatives tests indicated that sodium bisulfate was better than mercuric chloride or no preservation.

Monitoring frequency should be based upon known attenuation rates at the site. If the rate cannot be estimated from historical groundwater data, quarterly sampling for the first year or two should provide sufficient data to refine the monitoring plan. The following approach was employed at the LAAP site:

- (1) **Well Monitoring:** Wells were sampled quarterly for two years. Approximately five hours was originally needed to sample one well and move to the next. However, sampling time was greatly compressed (to about three hours) when two 2-man crews operated in "leap-frog" fashion, i.e., while one crew monitored and demobilized at one well, the other crew set up and initiated monitoring at the next well.
- (2) **Cone Penetrometry:** One sampling event was conducted at the LAAP. The time required depends upon the size of the area under examination and the extent of data required. A typical day without complications may accomplish 8 penetrations to a depth of 15 to 40 meters. At LAAP, 51 penetrations to a maximum depth of 40 meters were executed in 15 days with a 4 man crew operating the truck and performing decontamination of equipment between penetrations, and a 3 man crew processing samples for microbial and chemical analyses.
- (3) **Analytical Chemistry:** Samples must be processed within seven days. Six to seven days are required to analyze samples from one sampling event: one day to process, two days to extract, and three to four days for analysis, data reporting, etc.
- (4) **Radioassay:** Analysis requires approximately 48 days (approximately 10 days for acetate mineralization; 28 days for RDX and TNT mineralization; 14 days for liquid phase separation, solid phase burning, breakdown, and data preparation). Total time required is 2 to 2.5 months, depending on the number of samples collected at the site.
- (5) **Lipid Biomarker Analysis:** Sets of 8-12 samples can be processed in a three-day period.
- (6) **Nucleic Acid Analysis:** One person can process 8 samples in a three-day period.
- (7) **Statistical Analyses:** One statistician for .33 man years was employed over the two-year monitoring period.

### 3.3 MONITORING PROCEDURES

Monitoring well samples were collected using a micropurge sampling technique described in the Interim Report (Pennington et al. in preparation b). Wells were sampled in order from least to



**Figure 1. Relationship between Dissolved Oxygen and Explosives Concentration.**

greatest contaminant concentration based on existing data to minimize the potential for cross contamination. Cone penetrometry samples were collected along transects that bisected the plume from highest to lowest contaminant concentrations in four directions and vertically. Soil samples were collected using a split spoon sampler according to procedures described in the Interim Report (Pennington et al. in preparation b). A field test kit was used to determine the concentration of explosives immediately after sample collection. These analyses guided the placement of the next penetration to minimize the cost of taking data outside the plume. Data precision, accuracy, representativeness, and comparability were assured by adopting field and laboratory quality control and quality assurance procedures as described in the Interim Report (Pennington et al. in preparation b). Standard operating procedures are presented in the Demonstration Plan (Pennington et al. unpublished) and appended to the Draft Protocol (Pennington et al. in preparation a). (See Appendix A Points of Contact and Appendix B Data Archiving and Demonstration Plan.)

### **3.4 ANALYTICAL PROCEDURES**

#### **3.4.1 Explosives and Their Degradation Products**

Groundwater from quarterly monitoring and soils collected by CPT were analyzed by High Performance Liquid Chromatography (HPLC) using modifications of Method 8330 (U.S. EPA 1994). The modifications included expanding the analyte list and adoption of an extraction technique for soils (Pennington et al. in preparation b). Analytes for groundwater and soils are listed in Table 1.

#### **3.4.2 Geochemical Parameters**

The geochemical parameter determined on groundwater samples are given in Table 2. Methods are given in the Interim Report (Pennington et al. in preparation b).

Soil samples were analyzed for explosives (Table 1), particle size distribution, hydraulic conductivity, pH, nitrate/nitrite nitrogen, total Kjeldahl nitrogen, phosphorus, sulfate and total organic carbon as described in the Interim Report (Pennington et al. in preparation b).

#### **3.4.3 Other Analyses**

Groundwater, surface soils, and subsurface soils were tested for explosives mineralization potential, and the presence of lipid and nucleic acid biomarkers. Procedures are described in the Interim Report (Pennington et al. in preparation b).

Site capacity was determined by batch partitioning tests according to procedures in 40CFR796.2750 (sediment and soil adsorption isotherm) and presented in the Interim Report (Pennington et al. in preparation b) and in the Draft Protocol (Pennington et al. in preparation a).

Trend analysis was used to determine whether groundwater concentrations of any explosive, including transformation and degradation products, were significantly increasing or decreasing over time. The trend analysis consisted of normality testing, regression analyses, lack-of-fit analyses, and rank correlation analyses (See Interim Report, Pennington et al. in preparation b). Masses of

**Table 1.**  
**Explosives and Related Analytes Monitored in Groundwater at LAAP and JAAP.**

Chemical Name	Acronym
2,4,6-Trinitrotoluene	TNT
1,3,5-Trinitro-1,3,5-hexahydrotriazine	RDX
Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine	HMX
N,2,4,6-Tetranitro-N-methylaniline	Tetryl
1,3,5-Trinitrobenzene	TNB
2,6-Dinitrotoluene	2,6DNT
2,4-Dinitrotoluene	2,4DNT
1,3-Dinitrobenzene	1,3DNB
Nitrobenzene	NB
4-Amino-2,6-dinitrotoluene	4ADNT
2-Amino-4,6-dinitrotoluene	2ADNT
3,5-Dinitroaniline	35DNA
2,4-Diamino-6-nitrotoluene	24DANT
2,6-Diamino-4-nitrotoluene	26DANT
2,2',4,4'-Tetranitro-6,6'-azoxytoluene	66'AZOXY
4,4',6,6'-Tetranitro-2,2'-azoxytoluene	22'AZOXY
2,2',6,6'-Tetranitro-4,4'-azoxytoluene	44'AZOXY
Hexahydro-1-nitroso-3,5-dinitro-1,3,5-triazine	MNX
Hexahydro-1,3-dinitroso-5-dinitro-1,3,5-triazine	DNX
Hexahydro-1,3,5-trinitroso-1,3,5-triazine	TNX
Mononitroso-octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine	MN-HMX
Picric acid	

**Table 2.**  
**Geochemical Parameters Monitored in Groundwater at LAAP and JAAP.**

Assayed in the Laboratory		
Monitored in the Field	Aerobic Collection	Anaerobic Collection
pH	Total organic carbon	Reduced iron
Conductivity	Total iron	Methane
Dissolved oxygen	Calcium	
Temperature	Magnesium	
Redox potential	Manganese	
Turbidity	Nitrate/nitrite nitrogen	
Salinity	Sulfate	
	Chloride	

contaminants (TNT and RDX) were calculated using both measured and predicted concentrations along with iso-surface volume calculations from the groundwater modeling system (Department of Defense Groundwater Modeling System 1996) (See Interim Report, Pennington et al. in preparation b).

### 3.5 DEMONSTRATION SITE/FACILITY BACKGROUND

The LAAP was selected because the source of contamination had already been remediated, a large body of contaminant data was available (SAIC 1994), and the site was well-characterized with approximately 50 functional groundwater monitoring wells in place. The demonstration was conducted at Area P (Figure 2), the site where wastes from loading, assembling, and packing of munitions (SIC Code: 2892, chemical and allied products, explosives, Member Agencies of the Federal Remediation Technologies Roundtable 1995) had been disposed into 16 unlined lagoons. The lagoons had been pump out and the sediment excavated and incinerate in the late 1980s. The area was capped with clay compacted to 90 percent of the standard proctor density for the clay used. The cap was covered with 4 inches of topsoil with a slope of at least one percent to facilitate drainage. No formal approvals, licenses, or permits were required prior to conducting the demonstration.

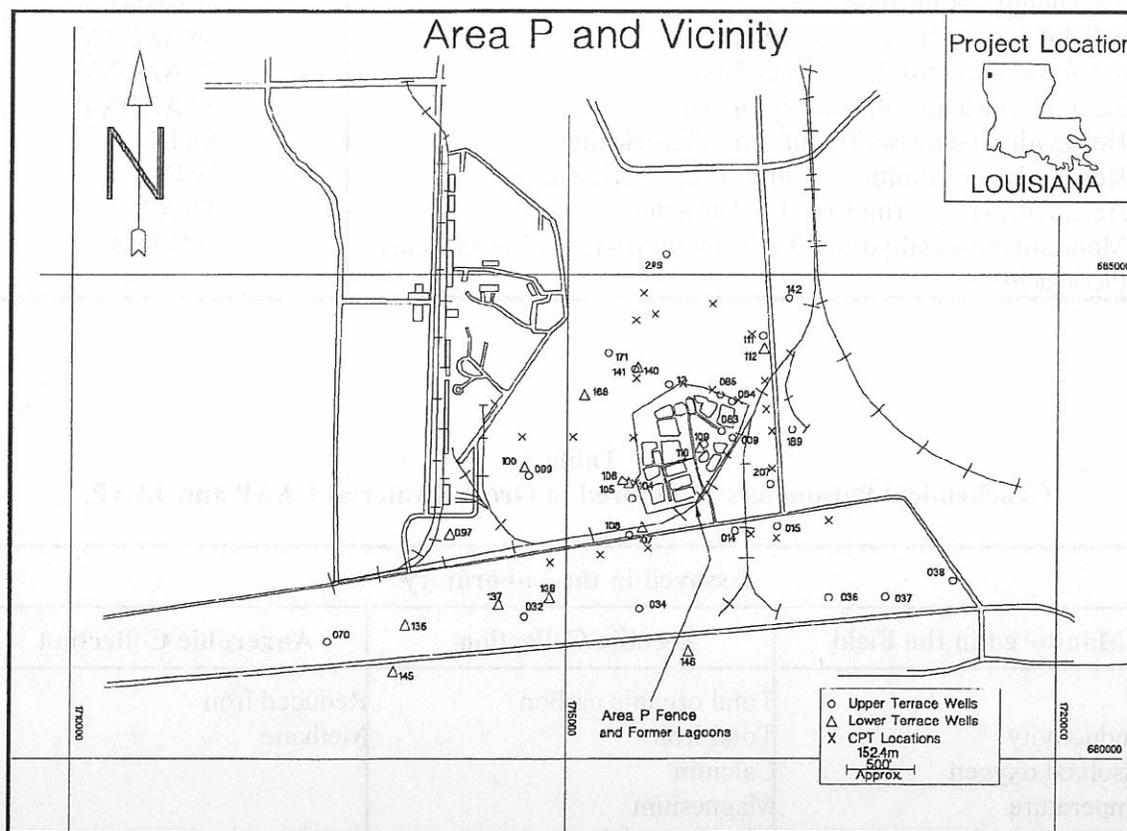
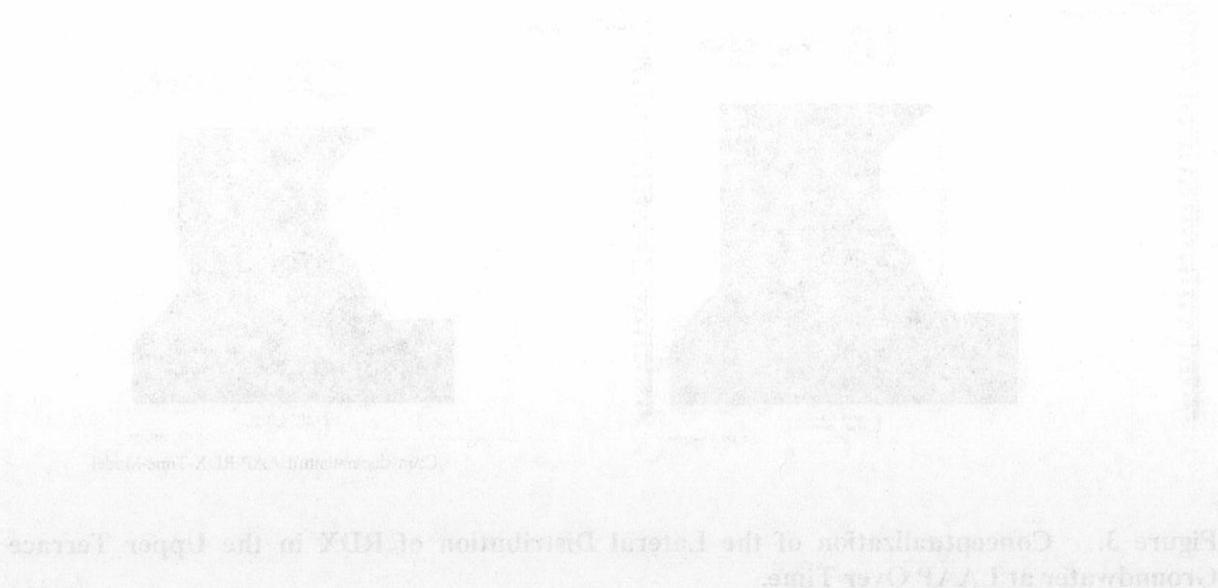


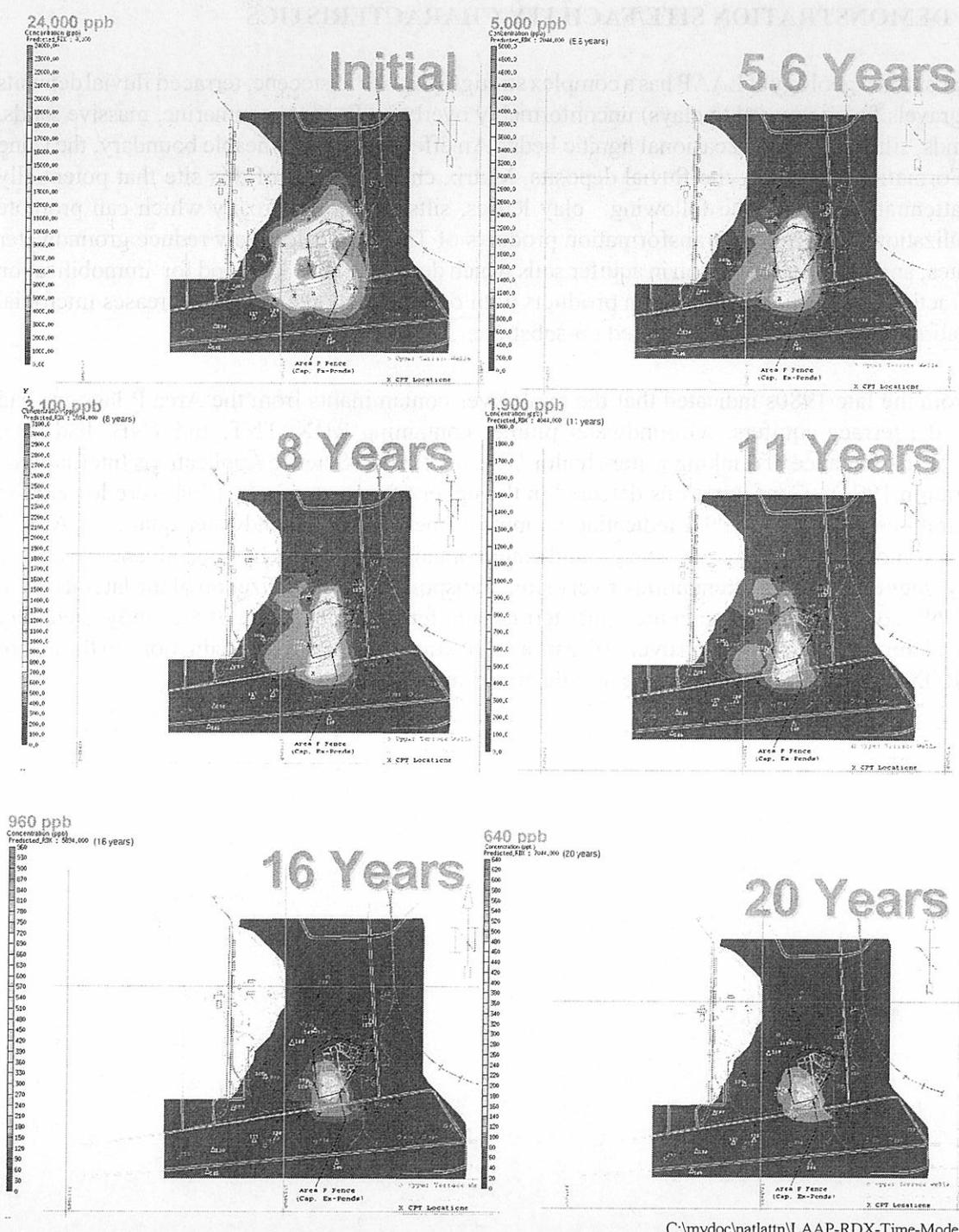
Figure 2. Area P at LAAP Showing Former Lagoons, Capped Area, Monitoring Wells, and CPT Locations.

### 3.6 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

The near surface geology at LAAP has a complex stratigraphy of Pleistocene, terraced fluvial deposits (basal gravels fining upward to clays) unconformably overlying Eocene, nonmarine, massive sands, silty sands, silty clays, and occasional lignitic beds. An effectively impermeable boundary, the Cane River Formation lies below the fluvial deposits. Matrix characteristics of this site that potentially affect attenuation include the following: clay lenses, silts, and low porosity which can promote immobilization processes for transformation products of TNT and effectively reduce groundwater flow rates; and low organic carbon in aquifer soils which decreases the likelihood for immobilization by interactions of TNT transformation products with organic carbon and also decreases microbial degradation potential because of limited co-substrate.

Data from the late 1980s indicated that the explosives contaminants from the Area P lagoons had entered the terrace aquifers. Groundwater plumes containing RDX, TNT, and TNB had been detected in exceedance of drinking water Health Advisory Levels (Science Applications International Corporation 1994). Concentrations detected in the upper terrace aquifer in 1994 were lower than concentrations detected in 1990, indicating an improvement in the groundwater quality at Area P since the removal of the lagoons. The groundwater contaminant plumes had not advanced very far laterally, suggesting either attenuation or very slow transport. Conceptualization of the lateral extent of the TNT contaminant plume in the upper terrace aquifer at the inception of the study (February 1996) and the predicted reduction over 20 years are illustrated on the cover. Reductions in the extent of the RDX plume predicted over time are illustrated in Figure 3 on page 14.





C:\nydoc\atlattn\LAAP-RDX-Time-Model

Figure 3. Conceptualization of the Lateral Distribution of RDX in the Upper Terrace Groundwater at LAAP Over Time.

## 4.0 PERFORMANCE ASSESSMENT

### 4.1 SIGNIFICANT DEVIATIONS FROM DEMONSTRATION PLAN

Modifications to the sampling plan set forth in the Demonstration Plan were (1) refinements in the procedure used to clear the well-head of oxidized water prior to sampling; and (2) a reduction in the number of wells routinely monitored. In the first case, if dissolved oxygen (DO) stabilized, the procedure outlined in the demonstration plan was used. If the DO did not stabilize, three well volumes were removed by pumping before the sample was collected. In the second case, the demonstration plan called for sampling thirty wells during each sampling event. However, contaminant concentration levels in many wells were below detection limits. Therefore, these wells were sampled only once per year to verify that concentrations remained below detection.

### 4.2 DATA ASSESSMENT

Trends in contaminant concentrations over the two-year study period were analyzed statistically for the 11 wells in which most analytes were consistently detected. Significant declines in contaminant concentrations occurred in 9 of the 11 wells over the two-year study period (Figure 4). Contaminant mass calculations also indicated declining mass from 52 and 78 to 50 and 68 metric tons for TNT and RDX, respectively.

### 4.3 FIELD OBSERVATIONS AND COMPARISON TO TECHNOLOGY CLAIMS

The monitoring well sampling procedures and modifications made during the course of the demonstration project performed well. The monitoring protocol required no further modifications when applied to a second site at Joliet Army Ammunition Plant (JAAP), Joliet, IL. The cone penetrometry sampling protocols also applied well to JAAP. Biomarker results for JAAP surface soils, which exhibited higher contaminant concentrations than soils examined at LAAP (the surface soil source at JAAP had not yet been remediated), indicated the effectiveness of the techniques for determining site potential for attenuation of TNT and RDX. The modeling procedures were effective at both sites.

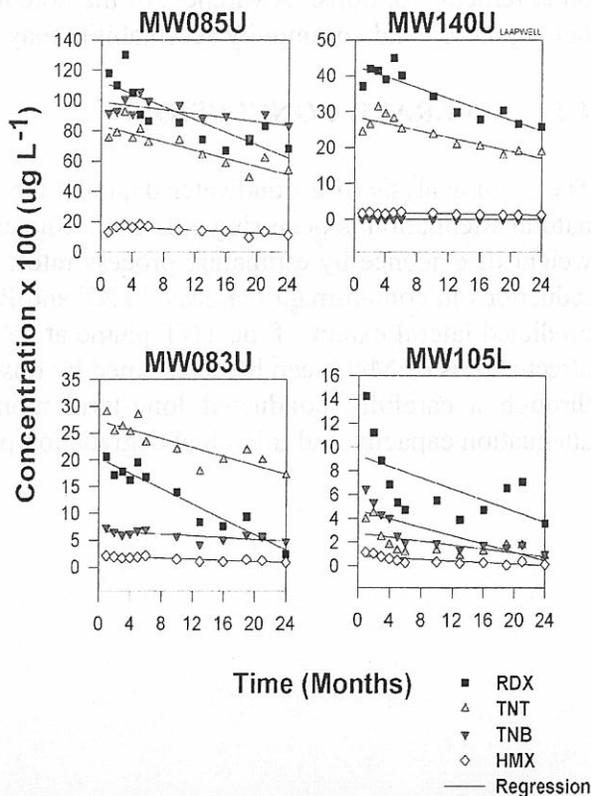


Figure 4. Trends in Explosives Concentrations in Selected Monitoring Wells over the Two-Year Sampling Period at LAAP.

Personnel and training were adequate. The demonstration plan called for the use of Modified Level C PPE. This was later reduced to Level D and consisted of steel-toed shoes and safety goggles. Latex gloves were also required due to irritants in the groundwater at several wells.

Groundwater monitoring procedures were easy to execute. Efficiency was improved by using two two-man field crews. Execution of biomarker analyses is not yet a standard, "off-the-shelf" technology; however, commercially available capabilities are anticipated to develop rapidly for various applications over the next several years. Most large universities already have the necessary capabilities. Existing groundwater models are readily adapted to use in MNA (See lists of models in the Draft Protocol, Pennington et al. in preparation a).

The current state-of-the-science allows for indirect determinations of subsurface attenuation processes via contaminant concentration monitoring, and measurements of site capacity and microbial degradation potential. Therefore, a weight-of-evidence is required to demonstrate that natural attenuation is sufficient to meet remediation goals. Time to complete cleanup may be longer than with other remedial options. Awareness of the potential for MNA as a remedial alternative is growing, but regulatory and community acceptability may be limited.

#### 4.4 OVERALL CONCLUSIONS

The trend analysis of groundwater data and the reduction in contaminant mass demonstrated that natural attenuation is occurring at LAAP. Site capacity and biomarker techniques contributed to a weight of evidence by estimating process rates. Numerical models predict significant continuing reductions in contaminant masses of TNT and RDX over 20 years (cover figures show initial and predicted lateral extent of the TNT plume at LAAP). The demonstration project showed that the effectiveness of MNA can be determined by observation of declining contaminant mass over time through a carefully conducted long-term monitoring plan and conservative extrapolation of attenuation capacity and microbial degradation potential from the laboratory to the field.

## 5.0 COST ASSESSMENT

### 5.1 TREATMENT COSTS FOR THE DEMONSTRATION

Treatment costs associated with the LAAP natural attenuation demonstration project amounted to approximately four million dollars. These costs consisted of refinements in site characterization, site monitoring, modeling and development of biomarker techniques. Although extensive site characterization had been performed previously at LAAP, additional hydrogeologic and microbiological data were acquired. Site characterization costs, including the cone penetrometry for characterization, site capacity determinations, and biomarker analyses were approximately 2.5 million dollars. The principal costs were for labor (approximately 2 million dollars) and chemical analyses (approximately 0.5 million).

The LAAP demonstration project was a full, field-scale demonstration encompassing the whole contaminant plume and its potential receptors. However, implementation costs will be lower than demonstration project costs for three reasons. First, procedures for microbiological analyses were developed and refined during the demonstration. Costs for future implementation of these procedures will be significantly less. Second, costs of monitoring will be lower because experiments for refining monitoring techniques were part of demonstration costs, but will not be part of implementation costs. Third, improved sampling procedures significantly lowered the length of time required for a single sampling event. Cost estimates for full implementation of MNA prepared according to the guidelines for work breakdown structure (WBS) (U.S. Army Corps of Engineers 1996) and using cost estimates prepared by Environmental Cost Handling Options and Solution (ECHOS, 1998a, b) are presented in the ESTCP Completion Report (Pennington et al. in preparation c). That document also contains cost and performance comparisons with two other remediation technologies.



## **6.0 IMPLEMENTATION ISSUES**

### **6.1 COST OBSERVATIONS**

Since many aspects of the demonstration included significant experimentation, costs associated with implementation at another site are expected to be lower. The cost differences between demonstration and implementation are due to improved familiarity with the technology. Lessons learned during the demonstration project resulted in greater labor and cost efficiencies in the areas of groundwater sampling and microbiological analysis. In the case of groundwater sampling, modifications which improved sampling procedures and the incorporation of fall-back procedures led to greater labor efficiencies. These efficiencies led to savings when LAAP groundwater sampling procedures were applied to JAAP. For microbiological analyses, improved analytical procedures, e.g., adaptation to microtiter plate scale of operations, significantly lowered analytical costs, with costs falling over the course of the project from \$1,250.00 to \$600.00 and from \$530.00 to \$344.00 for radioassays and lipid biomarker analyses, respectively.

Factors that will influence costs in the future implementation of MNA are the suitability of existing site characterization data, the size and concentrations of the contaminant plume, site hydrogeology, and the method used for IDW disposal. These are discussed in the ESTCP Completion Report (Pennington et al. in preparation c)

### **6.2 PERFORMANCE OBSERVATIONS**

Periodic re-assessment, e.g., every five years depending upon site specific conditions, will be necessary to assure that MNA is protective of human health and the environment. At that time the monitoring plan should be reviewed and any revisions made, groundwater models should be up-dated, and contingency plans reviewed in light of changing site conditions and developing technologies that may be suitable replacements for the contingencies selected earlier.

### **6.3 REGULATORY AND OTHER ISSUES**

Regulatory issues will be site-specific. However, the U.S.EPA (1998)draft directive is a useful guide. Early involvement of the regulatory community and other interested parties will contribute to acceptance.

### **6.4 LESSONS LEARNED**

An important lesson learned from the demonstration project is that the sampling protocol must be specific and followed consistently to generate data that are adequate for measuring trends in contaminant mass over time. The influence of oxygenated water at the well head on explosives concentration data has been demonstrated at LAAP. Pumping with a low-flow pump to match removal rates to recharge rates minimizing the influence of removal on the contaminant plume, and removing at least three-well volumes before collection of the groundwater sample contribute to reliability of data.

Cone penetrometry was a useful activity for refining the conceptualization of the site hydrogeology and contaminant distribution and provided subsurface sample material for biomarker analyses. Another important lesson learned was the importance of discourse between personnel generating data and personnel generating the model. For example, data must be translated into units of measure suitable for incorporation into the model. The scale of measurement actually taken and those need for modeling often differ significantly.

## 7.0 REFERENCES

### 7.1 KEY REFERENCES

1. Department of Defense Groundwater Modeling System. (1996). *GMS v2.0, Reference Manual*. Brigham Young University, Engineering Computer Graphic Laboratory, Provo, UT.
2. Environmental Cost Handling Options and Solutions (ECHOS). (1998a). "*Environmental remediation cost data - Assemblies*." Delta Technologies Group, Inc., ed., 4<sup>th</sup> ed., R. S. Means Company, Inc. and Delta Technologies Group, Inc., Englewood, CO.
3. Environmental Cost Handling Options and Solutions (ECHOS). (1998b). "*Environmental remediation cost data - Unit price*." Delta Technologies Group, Inc., ed., 4<sup>th</sup> ed., R. S. Means Company, Inc. and Delta Technologies Group, Inc., Englewood, CO.
4. Member Agencies of the Federal Remediation Technologies Roundtable. (1995). "Guide to documenting cost and performance for remediation projects," EPA-542-B-95-002, U.S. environmental Protection Agency, Washington, DC.
5. U.S. Army Corps of Engineers. (1996). *Technical Requirements for Specifications to Report HTRW Environmental Restoration Cost and Performance*. Engineering Pamphlet: EP 01-110-1-19, 15, Washington, DC.
6. U. S. Environmental Protection Agency. (1998). "Use of monitored natural attenuation at Superfund, RCRA corrective action, and underground storage tank sites," Draft Monitored Natural Attenuation Policy Memorandum Office of Solid Waste and Emergency Response (OSWER) Directive 9200.1-17, U. S. Environmental Protection Agency, Washington, DC.
7. U. S. Environmental Protection Agency and U.S. Air Force Environics Directorate. (1993). "Remediation technologies screening matrix and reference guide," Version 1, joint U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, DC and the U.S. Air Force Environics Directorate, Armstrong Laboratory, Tyndall Air Force Base, FL.

### 7.2 GENERAL REFERENCES

1. Gilbert, R. O. (1987). *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold Co., New York, NY, 320p.
2. Pennington, J. C., Harrelson, D. W., Zakikhani, M., Gunnison, D., Hayes, C. A., Clarke, J. U., Perkins, E., Ringelberg, D., McGrath, C. J., Fredrickson, H., and May, J. H. (1998). "Feasibility of using monitored natural attenuation as a remedial alternative for explosives-contaminated groundwater at Site L1, Joliet Army Ammunition Plant, Joliet, Illinois," Technical Report EL-98-8, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

3. Pennington, J. C., Bowen, R., Brannon, J. M., Gunnison, D., Harrelson, D. W., Zakikhani, M., Clarke, J., Mahannah, J., and Gnewuch, S. (in preparation a). "Draft protocol for evaluating, selecting and implementing monitored natural attenuation at explosives-contaminated sites," Technical Report in preparation, EL-98-, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
4. Pennington, J. C., Gunnison, D., Harrelson, D. W., Brannon, J. M., Zakikhani, M., Jenkins, T. F., Clarke, J. U., Hayes, C. A., Myers, T., Perkins, E., Ringleberg, D., Townsend, D., Fredrickson, H., May, J. H. (in preparation b). "Monitored natural attenuation of explosives in soil and water systems at DoD sites: Interim Report," Technical Report in preparation, EL-98- , U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
5. Pennington, J. C. Zakikhani, M., and Harrelson, D. W. (in preparation c). "Monitored Natural Attenuation of Explosives in Groundwater - ESTCP Completion Report," Technical Report EL-99- , U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
6. Pennington, J. C., McCartney, S., May, I., Haines, L., Harrelson, D. W., and May, T. H. (unpublished). "Natural Attenuation of Explosives in Groundwater - Technology Demonstration Plan," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Washington, DC.
7. Science Applications International Corporation (SAIC). (1994). "Five-year review report of interim remedial action at former Area P lagoons, Louisiana Army Ammunition Plant, Shreveport, LA," Prepared for U. S. Army Toxic and Hazardous Materials Agency Contract No. DAAA15-91-D0017, by Science Applications International Corporation, McLean, VA.
8. U. S. Environmental Protection Agency. (1989). *Methods for evaluation attainment of cleanup standards, Vol. 1: Soils and solid media*, EPA/230/02-89-042, Office of Solid Waste. Washington, DC.
9. U. S. Environmental Protection Agency. (1993a). *Guidance document on the statistical analysis of ground-water monitoring data at RCRA facilities*, Office of Solid Waste. Washington, DC.
10. U. S. Environmental Protection Agency. (1993b). *Methods for evaluation attainment of cleanup standards, Vol. 2: Ground Water*, EPA/230/R-92/014, Office of Policy, Planning, and Evaluation, Washington, DC.
11. U. S. Environmental Protection Agency. (1994b). *Nitroaromatic and Nitramines by HPLC*. 2<sup>nd</sup> update, SW846, Method 8330, Sept. 1994. Office of Solid Waste and Emergency Response, Washington, DC.
12. White, D. C., Davis, W. M., Nickels, J. S., King, J. D., and Bobbie, R. J. (1979). "Determination of the sedimentary microbial biomass by extractable lipid phosphate," *Oecologia*, Vol. 40, pp. 51-62.

## APPENDIX A

### Points of Contact

Dr. Judith C. Pennington  
Principal Investigator  
U.S. Army Engineer Waterways Experiment  
Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: (601) 634-2802  
Fax: (601) 634-3410  
E-mail: penningj@ex1.wes.army.mil

Dr. Douglas Gunnison  
Principal Project Microbiologist  
U.S. Army Engineer Waterways Experiment  
Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: (601) 634-3873  
Fax: (601) 634-4017  
E-mail: gunnisd@ex1.wes.army.mil

Mr. Danny W. Harrelson  
Principal Project Geologist  
U.S. Army Engineer Waterways Experiment  
Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: (601) 634-2685  
Fax: (601) 634-3153  
E-mail: harreld@ex1.wes.army.mil

Dr. James M. Brannon  
Principal Project Geochemist  
U.S. Army Engineer Waterways Experiment  
Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: (601) 634-3873  
Fax: (601) 634-4017  
E-mail: brannoj@ex1.wes.army.mil

Dr. Mansour Zakikhani  
Principal Project Groundwater Modeler  
U.S. Army Engineer Waterways Experiment  
Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: (601) 634-3806  
Fax: (601) 634-3129  
E-mail: zakikhm@ex1.wes.army.mil

Dr. Thomas F. Jenkins  
Principal Project Analytical Chemist  
U.S. Army Cold Regions Research and  
Engineering Laboratory  
72 Lyme Road  
Hanover, NH 03755-1290  
Telephone: (603) 646-4385  
Fax: (603) 646-4785  
Email: jenkins@crrel41.crrel.usace.

Dr. Joan U. Clarke  
Project Statistician  
U.S. Army Engineer Waterways Experiment  
Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: (601) 634-2954  
Fax: (601) 634-3120  
E-mail: clarkej@ex1.wes.army.mil

Drs. Mike Reynolds and Paul Miyares  
Stable Isotopes  
U.S. Army Cold Regions Research and  
Engineering Laboratory  
72 Lyme Road  
Hanover, NH 03755-1290  
Telephone: (603) 646-4394; (603) 646-4394  
Fax: (603) 646-4785  
Email: jenkins@crrel41.crrel.usace.army.mil

Ms. Laurie Haines  
LAAP Site Geologist  
U. S. Army Environmental Center  
ATTN: SFIM-AEC-IR-G  
BLDG E4435  
Aberdeen Proving Ground, MD  
Telephone: (410) 671-1512  
Fax: (410) 671-1548  
E-mail: lbhaines@aec.apgea.army.mil

Mr. Doyle Williams  
Environmental Officer  
Louisiana Army Ammunition Plant  
Hwy 80  
Minden, LA 71055  
Telephone: (318) 459-5108  
Fax: (318) 459-5114

Mr. Cyril Onewokae  
Validation Site Sponsor  
Environmental Quality Directorate  
HDQ, Industrial Operations Command  
BLDG 390  
Rock Island, IL 61299-6000  
Telephone: (309) 782-1350  
Fax: (309) 782-1457  
E-mail: conewoka@riaemh2.army.mil

Mr. Art Holz  
Environmental Coordinator  
Joliet Army Ammunition Plant  
29401 South, Route 53  
Wilmington, IL 60481-8879  
Telephone: (815) 423-2877  
E-mail: aholz@ria-emh2.army.mil

Dr. Rick Bowen  
Arthur D. Little, Inc.  
Acorn Park  
Cambridge, MA 02140-2390  
Telephone: (617) 498-5406  
Fax: (617) 498-7221  
E-mail: bowen.r@adlittle.com

Ms. Diana Mally  
U.S. Environmental Protection Agency,  
Region V  
ATTN: SRF-5J  
77 West Jackson Blvd.  
Chicago, IL 60604-7275  
Telephone: (312) 886-7275

Ms. Caroline Ziegler  
1445 Ross Ave., Suite 1200  
U.S. Environmental Protection Agency,  
Region VI  
Dallas, TX 75202  
Telephone: (214) 665-2178

## APPENDIX B

### Data Archiving and Demonstration Plan

Requests concerning data from the Louisiana Army Ammunition Plant should be addressed to:

Dr. Judith C. Pennington, CEWES-ES-P  
U.S. Army Engineer Waterways Experiment Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: 601-634-2802  
penninj@ex1.wes.army.mil

Requests concerning the project demonstration plan and standard operational procedures for the field efforts should be addressed to:

Mr. Danny Harrelson, CEWES-GG-YG  
U.S. ARMY Engineer Waterways Experiment Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: 601-634-2685  
harrelsa@ex1.wes.army.mil

Request concerning groundwater modeling should be addressed to:

Dr. Mansour Zakikhani, CEWES-ES-Q  
U.S. ARMY Engineer Waterways Experiment Station  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199  
Telephone: 601-634-3806  
zakikhm@ex1.wes.army.mil

The following technical reports concerning the project are available by e-mail request from any of the above contacts or from Ms. Betty Walker at walker@ex1.wes.army.mil.

Pennington, J. C., Harrelson, D. W., Zakikhani, M., Gunnison, D., Hayes, C. A., Clarke, J. U., Perkins, E., Ringelberg, D., McGrath, C. J., Fredrickson, H., and May, J. H. (1998). "Feasibility of using monitored natural attenuation as a remedial alternative for explosives-contaminated groundwater at Site L1, Joliet Army Ammunition Plant, Joliet, Illinois," Technical Report EL-98-8, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

- Pennington, J. C., Bowen, R., Brannon, J. M., Gunnison, D., Harrelson, D. W., Zakikhani, M., Clarke, J., Mahannah, J., and Gnewuch, S. (In preparation). "Draft protocol for evaluating, selecting and implementing monitored natural attenuation at explosives-contaminated sites," Technical Report in preparation, EL-98-, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Pennington, J. C., Gunnison, D., Harrelson, D. W., Brannon, J. M., Zakikhani, M., Jenkins, T. F., Clarke, J. U., Hayes, C. A., Myers, T., Perkins, E., Ringleberg, D., Townsend, D., Fredrickson, H., May, J. H. (In preparation). "Monitored natural attenuation of explosives in soil and water systems at DoD sites: Interim Report," Technical Report in preparation, EL-98- , U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Pennington, J. C. Zakikhani, M., and Harrelson, D. W. (in preparation c). "Monitored Natural Attenuation of Explosives in Groundwater - ESTCP Completion Report," Technical Report EL-99- , U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Pennington, J. C., McCartney, S., May, I., Haines, L., Harrelson, D. W., and May, T. H. (unpublished, August 1996). "Natural Attenuation of Explosives in Groundwater - Technology Demonstration Plan," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Washington, DC.



**ESTCP Program Office**

901 North Stuart Street  
Suite 303  
Arlington, Virginia 22203  
(703) 696-2117 (Phone)  
(703) 696-2114 (Fax)  
e-mail: [estcp@estcp.org](mailto:estcp@estcp.org)  
[www.estcp.org](http://www.estcp.org)

