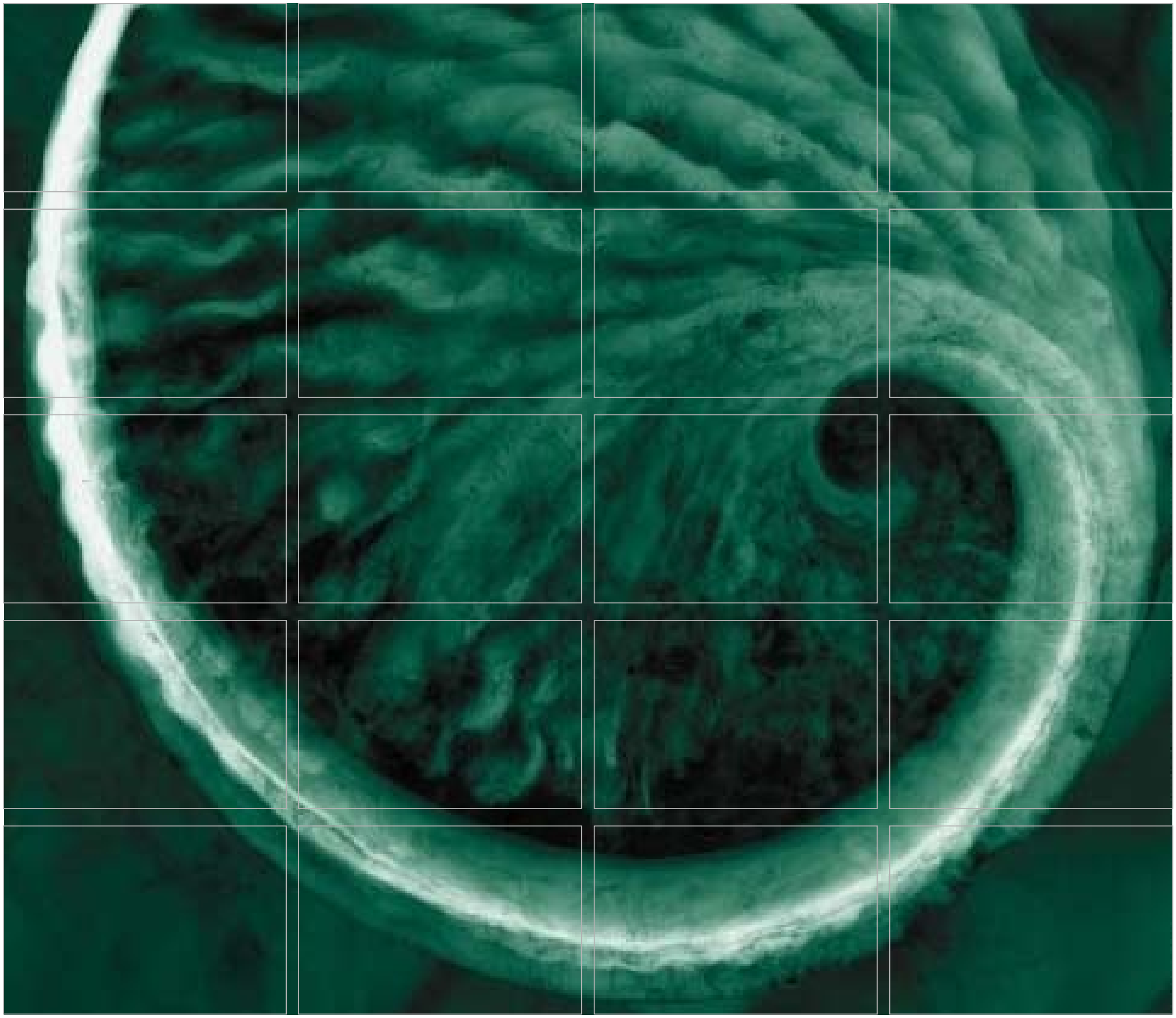

Raytheon Company

Phase III - Remedial Action Plan

Former Raytheon Facility
430 Boston Post Road
Wayland, MA

RTN 3-22408
Tier 1B Permit Number W045278
ERM Reference 0034354

16 December 2005

www.erm.com

REPORT

Raytheon Company

Phase III – Remedial Action Plan

Former Raytheon Facility

430 Boston Post Road

Wayland, Massachusetts

16 December 2005

RTN 3-22408

Tier 1B Permit Number W045278

ERM Reference 0034354

John C. Drobinski, P.G., LSP
Principal-in-Charge

Rachel B. Leary
Project Manager

Environmental Resources Management
399 Boylston Street, 6th Floor
Boston, Massachusetts 02116
T: (617) 646-7800
F: (617) 267-6447

EXECUTIVE SUMMARY *viii*

1.0 *INTRODUCTION* *1*

1.1 *BACKGROUND* *1*

1.2 *PURPOSE & SCOPE* *1*

1.3 *REPORT ORGANIZATION* *2*

2.0 *SUMMARY OF THE PHASE II – COMPREHENSIVE SITE ASSESSMENT* *3*

2.1 *PHASE II SUMMARY* *3*

3.0 *REMEDIAL ACTION OBJECTIVES* *6*

3.1 *OVERVIEW* *6*

3.2 *REMEDIAL ACTION OBJECTIVES* *6*
- 3.2.1 *Target Media and OHM* 6
- 3.2.2 *Target Cleanup Goals for Source Area Saturated Soils* 6
- 3.2.3 *Target Cleanup Goals for Groundwater* 6

4.0 *IDENTIFICATION AND INITIAL SCREENING OF REMEDIAL TECHNOLOGIES* *6*

4.1 *OVERVIEW* *6*

4.2 *SUMMARY OF TREATABILITY STUDIES* *6*
- 4.2.1 *Bioremediation* 6
- 4.2.2 *In Situ Chemical Oxidation* 6

4.3 *SCREENING CRITERIA* *6*

4.4 *TECHNOLOGY SCREENING - SOURCE AREA SATURATED SOILS* *6*
- 4.4.1 *No Action/Institutional Controls* 6
- 4.4.2 *Excavation and Treatment or Disposal* 6
- 4.4.3 *Pump and Treat* 6
- 4.4.4 *Air Sparging/Soil Vapor Extraction* 6
- 4.4.5 *Bioremediation* 6
- 4.4.6 *In Situ Chemical Oxidation* 6
- 4.4.7 *Thermal Treatment* 6
- 4.4.8 *Injectable Zero-Valent Iron* 6

4.5 TECHNOLOGY SCREENING - GROUNDWATER 6
4.5.1 Monitored Natural Attenuation (MNA) 6
4.5.2 Pump and Treat 6
4.5.3 Bioremediation 6
4.5.4 Permeable Reactive Barrier 6

4.6 REMEDIAL ALTERNATIVES 6

5.0 DETAILED EVALUATION OF ALTERNATIVES 6

5.1 OVERVIEW 6

5.2 SCREENING CRITERIA 6
5.2.1 Source Area Saturated Soils 6
5.2.2 Groundwater Plume 6

6.0 COMPARATIVE EVALUATION OF ALTERNATIVES 6

6.1 OVERVIEW 6

7.0 RECOMMENDED REMEDIAL ACTION PLAN 6

7.1 SELECTION OF REMEDIAL ACTION ALTERNATIVES 6

7.2 FEASIBILITY OF ACHIEVING BACKGROUND 6

7.3 IMPLEMENTATION SCHEDULE 6

8.0 PUBLIC NOTIFICATION DOCUMENTS 6

9.0 REFERENCES 6

LIST OF TABLES

TABLE 1 SUMMARY OF REMEDIAL TECHNOLOGY SCREENING

TABLE 2 DETAILED COST ESTIMATE FOR NO ACTION/INSTITUTIONAL CONTROLS ALTERNATIVE FOR SOURCE AREA SATURATED SOILS

TABLE 3 DETAILED COST ESTIMATE FOR EXCAVATION FOR SOURCE AREA SATURATED SOILS

TABLE 4 DETAILED COST ESTIMATE FOR BIOREMEDIATION IN SOURCE AREA SATURATED SOILS

TABLE 5 DETAILED COST ESTIMATE FOR BIOREMEDIATION IN SOURCE AREA SATURATED SOILS

TABLE 6 DETAILED COST ESTIMATE FOR THERMAL TREATMENT IN SOURCE AREA SATURATED SOILS

TABLE 7 DETAILED COST ESTIMATE FOR INJECTABLE ZVI IN SOURCE AREA SATURATED SOILS

TABLE 8 DETAILED COST ESTIMATE FOR MNA IN GROUNDWATER

TABLE 9 DETAILED COST ESTIMATE FOR PUMP AND TREAT IN GROUNDWATER

TABLE 10 DETAILED COST ESTIMATE FOR BIOREMEDIATION IN GROUNDWATER

LIST OF FIGURES

FIGURE 1 SITE LOCUS MAP

FIGURE 2 SITE MAP AND SURROUNDING FEATURES

FIGURE 3 SITE LAYOUT

LIST OF APPENDICES

APPENDIX A	*COPY OF BWSC FORM*
APPENDIX B	*MICROCOSM STUDY RESULTS SUMMARY*
APPENDIX C	*ISCO BENCH SCALE STUDY RESULTS*
APPENDIX D	*COPIES OF PUBLIC NOTIFICATION LETTERS*

LIST OF ACRONYMS AND ABBREVIATIONS

1,1-DCE	1,1-dichloroethene
AS	Air Sparging
AUL	Activity Use Limitation
BWSC	Bureau of Waste Site Cleanup
cDCE	cis-1,2-dichloroethene
CVOC	chlorinated volatile organic compounds
EPA	United States Environmental Protection Agency
ERM	Environmental Resources Management
ISCR	In Site Chemical Oxidation
ISCR	In Site Chemical Reduction
LSP	Licensed Site Professional
MA DEP	Massachusetts Department of Environmental Protection
MCP	Massachusetts Contingency Plan
MIP	Membrane Interface Probe
MMCL	Massachusetts Maximum Contaminant Levels
MNA	Monitored Natural Attenuation
MTBE	methyl-tert-butyl ether
MW	monitoring well
NOD	Natural Oxidant Demand
NPDES	National Pollution Discharge Eliminations System
OHM	oil and/or hazardous materials
ORP	oxidation-reduction potential
PCE	tetrachloroethene
RAO	Response Action Outcome
RAPS	Response Action Performance Standard
RC	reportable concentrations
RF	Radio Frequency
RIP	Remedy Implementation Plan

RTN	Release Tracking Number
SVE	Soil Vapor Extraction
TCE	trichloroethene
ug/g	micrograms per gram
ug/L	micrograms per liter
UV	Ultraviolet
VC	vinyl chloride
VOC	volatile organic compound
ZVI	Zero Valent Iron

EXECUTIVE SUMMARY

On behalf of Raytheon Company (Raytheon), Environmental Resources Management (ERM) has prepared this Phase III– Remedial Action Plan (Phase III) for Release Tracking Number (RTN) 3-22408, Tier IB Permit Number W045278, located at 430 Boston Post Road in Wayland, Massachusetts.

The Phase III describes and documents the information, reasoning and results used to identify and evaluate remedial action alternatives in sufficient detail to support selection of the "preferred" remedial action alternative. The Phase III is used to identify remedial alternatives that are reasonably likely to achieve a level of "No Significant Risk," and where feasible, a Permanent Solution. The Phase III recommends the alternative(s) most likely to reduce the levels of oil and/or hazardous materials (OHM) in the environment to levels that will achieve a Permanent Solution, if feasible.

Residual OHM impacts that require active remediation are limited to the following volatile organic compounds (VOCs) in source area saturated soil and groundwater: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cDCE), vinyl chloride (VC), and toluene. Source area saturated soil will require abatement to achieve average VOC concentrations below Method 1 S-3/GW-1 standards to achieve a Permanent Solution. Groundwater will require abatement to below Massachusetts Maximum Contaminant Levels (MMCLs) to achieve a Permanent Solution.

Based on the technology screening, the following remedial alternatives were identified as candidates for the abatement of source area saturated soil and groundwater:

Source Area Saturated Soils

- Alternative #1 – No Action/Institutional Controls
- Alternative #2 – Excavation
- Alternative #3 – Bioremediation
- Alternative #4 – In Situ Chemical Oxidation (ISCO)
- Alternative #5 – Thermal Treatment
- Alternative #6 – Injectable Zero Valent Iron (ZVI)

Groundwater

- Alternative #1 – Monitored Natural Attenuation (MNA)
- Alternative #2 – Pump and Treat
- Alternative #3 – Bioremediation

Based on both detailed and comparative analyses of remedial alternatives using regulatory criteria stipulated in the Massachusetts Contingency Plan (MCP) 310 CMR 40.0000, Alternative #2, Excavation and Alternative #3, Bioremediation were selected as the preferred remedial action alternatives for abatement of source area saturated soil and groundwater, respectively.

1.0 INTRODUCTION

1.1 BACKGROUND

On behalf of Raytheon Company (Raytheon), Environmental Resources Management (ERM) has prepared this Phase III–Remedial Action Plan (Phase III) for Release Tracking Number (RTN) 3-22408, Tier IB Permit Number W045278, located at 430 Boston Post Road in Wayland, Massachusetts (defined as the "Site," Figure 1). The Site, surrounding properties and physical features are shown in Figure 2.

The Phase III was prepared to satisfy requirements of the Massachusetts Contingency Plan (MCP), specifically 310 CMR 40.0850, for the Site. The Phase III is the third part of a five-phase process required under the MCP for assessment and remediation of a release(s) of oil and/or hazardous materials (OHM) to the environment. The Phase III is based on the results of the Phase II-Comprehensive Site Assessment (Phase II) completed for the Site.

The Phase III is used to identify remedial alternatives which are reasonably likely to achieve a level of "No Significant Risk," and where feasible, a permanent solution. The Phase III recommends the alternative(s) most likely to reduce the levels of OHM in the environment to levels that will achieve a permanent solution, if feasible.

The original Bureau Waste Site Cleanup (BWSC) Form-108 is attached and a copy is included in Appendix A.

1.2 PURPOSE & SCOPE

The purpose of the Phase III is to support the selection of the proposed remedial action alternative and to document the information, reasoning and results used to identify and evaluate remedial action alternatives in sufficient detail to support selection of the "preferred" remedial action alternative. In accordance with 310 CMR 40.0850, the Phase III includes three primary activities:

- Identification and initial screening of remedial technologies that are reasonably likely to be feasible and achieve a level of "No Significant Risk."

- Identification and detailed evaluation of remedial action alternatives to ascertain which alternatives will meet the performance standards and requirements set forth in 310 CMR 40.0850, 40.0900 and 40.1000, and whether these alternatives constitute Permanent or Temporary Solutions.
- Selection of the preferred remedial action alternative(s) most likely to achieve a permanent solution.

1.3 REPORT ORGANIZATION

The report is organized to satisfy the requirements of the MCP (310 CMR 40.0850). The report contains the following sections:

Section 2.0 *Summary of the Phase II–Comprehensive Site Assessment*- includes a summary of the Phase II conclusions.

Section 3.0 *Remedial Action Objectives* - includes the identification of regulatory requirements, justification for selection of target cleanup levels and areas of OHM impacted media requiring abatement to achieve remedial goals.

Section 4.0 *Identification and Initial Screening of Remedial Technologies* - includes the identification of remedial technologies reasonably likely to achieve remedial goals and the basis for selection of alternatives for detailed evaluation.

Section 5.0 *Detailed Evaluation of Remedial Alternatives* - includes an evaluation of the degree to which each alternative meets detailed evaluation criteria including effectiveness, short-term and long-term reliability, technical difficulty, cost, risk, benefit, timeliness and aesthetic value.

Section 6.0 *Comparative Analysis of Alternatives* - includes a comparative analysis of criteria among alternatives including effectiveness, short-term and long-term reliability, technical difficulty, cost, risk, benefit, timeliness and aesthetic value.

Section 7.0 *Recommended Remedial Action Plan* - includes the rationale for, and selection of, the preferred remedial action alternative(s) and a projected schedule for implementation under Phase IV - Remedy Implementation Plan (RIP).

Section 8.0 *Public Notification Documentation*

Section 9.0 *References*

2.0 SUMMARY OF THE PHASE II – COMPREHENSIVE SITE ASSESSMENT

2.1 PHASE II SUMMARY

The Phase II included a series of field investigations to assess the source(s), nature and extent of OHM impacts to the environment associated with historic release(s). A Method 1 Risk Characterization was conducted to determine if a condition of "significant risk" exists under current and potential future scenarios. The Phase II presented the following conclusions:

1) ***The source, nature and extent of CVOC impacts in the Northern Area have been defined and delineated.***

Historical equipment testing activities were conducted in the Northern Area (Figure 3) of the Site prior to 1995, when Raytheon ceased operations at the facility. An apparent release of trichloroethene (TCE) occurred, resulting in impacts to groundwater at concentrations exceeding applicable MCP Reportable Concentrations (RCs). An extensive source area investigation identified the location of the release area and defined the horizontal and vertical extents of the source zone. The nature of chlorinated volatile organic compounds (CVOC) impacts in groundwater is defined as primarily TCE and its degradation products, cis 1,2-dichloroethene (cDCE) and vinyl chloride (VC), with some tetrachloroethene (PCE), and locally, toluene. The horizontal and vertical extents of CVOC impacts to groundwater have been delineated.

2) ***Northern Area Source Area Investigations have identified the residual source area.***

CVOCs were identified in the Northern Area source area within saturated zone soils to a maximum depth of approximately 25 feet. A dissolved phase CVOC plume continues to emanate from this source area following the initial release, suggesting that CVOCs remain in the source area as residual mass, sorbed to soil, and/or diffused into fine-grained soil horizons.

3) ***Northern Area CVOC impacts to groundwater pose minimal current and future potential for risk to the Baldwin Pond Wellfield.***

Groundwater in the Northern Area flows to the west toward the Sudbury River and associated wetlands, which represent the regional hydrologic discharge boundary. The Northern Area CVOC plume migrates from east to west toward the Sudbury River and associated wetlands. The western boundary of the CVOC plume was delineated to levels below applicable RCs within the wetlands east of the Sudbury River. The northern boundary of the CVOC plume was delineated to levels below applicable RCs approximately 0.4 miles south of the Baldwin Pond Wellfield. The plume is currently in steady state. Thus, future potential risk to the Baldwin Pond Wellfield is considered to be minimal.

4) ***Release of Methyl-tert-butyl-ether (MTBE) from an upgradient property has impacted groundwater quality in the Southern Area.***

MTBE was detected at concentrations exceeding RCs in groundwater in the Southern Area. The source of MTBE in the Southern Area (Figure 3) was likely a gasoline release at an upgradient gasoline service station located at 365 Boston Post Road (RTN 3-17974). Pursuant to 310 CMR 40.0180, Raytheon may file a Downgradient Property Status Submittal for the Southern Area. This release condition is not carried forward in the Phase III evaluation.

5) ***Naturally occurring arsenic has impacted groundwater quality in the Western Area.***

Arsenic was detected at concentrations exceeding RCs in groundwater in the Western Area (Figure 3). Naturally occurring arsenic present in soil has been mobilized as a result of the natural reducing conditions in the wetlands bordering the Sudbury River. The presence of arsenic in groundwater in the Western Area represents a background condition. This release condition is not carried forward in the Phase III evaluation.

6) ***Site groundwater poses a condition of "significant risk" under potential future conditions.***

OHM in Site groundwater (i.e., PCE, TCE, cDCE, 1,1-dichloroethene (1,1-DCE), VC, MTBE and toluene) poses a condition of "significant risk" to human health, as the Site is located within a Zone II aquifer protection area. This condition is also based on the potential for future exposure by hypothetical receptors (receptors that maintain a potential for future exposure in the absence of institutional controls or remediation). However, risks to human health posed by the Site under current conditions are considered negligible, because there is currently no complete exposure pathway (i.e., groundwater is not a current source of drinking water).

7) A Phase III is necessary.

Pursuant to 310 CMR 40.0852, a Phase III evaluation shall be conducted for any disposal Site for which a Phase II has been completed and a RAO in accordance with 310 CMR 40.1000 has not yet been achieved. The Phase III will include the identification of remedial alternatives to abate VOC impacts to groundwater and saturated soils that pose a condition of "significant risk." The Phase III will recommend preferred remedial alternative(s) for the Site. Design and implementation of the remedy will be conducted under a Phase IV RIP.

3.0 REMEDIAL ACTION OBJECTIVES

3.1 OVERVIEW

The purpose of this section is to establish objectives for remedial action of affected media that will enable achievement of a permanent solution, if feasible. Remedial action objectives will be expressed as media-specific target cleanup goals for OHM in groundwater and in source area saturated soils, that if achieved, would restore the Site to a condition of "no significant risk," meet MCP performance standards for the filing of a Response Action Outcome (RAO) Statement, and represent a permanent solution for the Site (DEP, 2005). Key MCP Response Action Performance Standards (RAPS) for achievement of a permanent solution include:

- Elimination or control of each source of OHM which is resulting, or is likely to result, in an increase in concentrations of OHM in an environmental medium, either as a consequence of a direct discharge, or through inter-media transfer (per 310 CMR 40.1003).
- Reduction in the concentration of OHM in affected media to levels that do not pose a condition of "significant risk" of harm to human health, safety, public welfare and the environment (per 310 CMR 40.1003).
- Reduction in the concentration of OHM in affected media to levels that would exist in the absence of the Site. Such measures shall, to the extent feasible, achieve or approach background levels of OHM in the environment as defined under 310 CMR 40.0006 (per 310 CMR 40.1020).
- Reduction in the overall mass and volume of OHM at the Site to the extent feasible, regardless of whether it is feasible to achieve one or more temporary or permanent solution(s), or whether it is feasible to achieve background for the entire Site (per 310 CMR 40.0191).
- Restoration of groundwater, where feasible, to the applicable standards of quality within a reasonable period of time to protect the existing and potential uses of such resources (per 310 CMR 40.0191).

Regulatory requirements applicable to the development of remedial action objectives and achievement of RAPS are discussed in this section by media.

3.2 REMEDIAL ACTION OBJECTIVES

3.2.1 Target Media and OHM

Based on performance standards defined above, in accordance with the MCP, achievement of a permanent solution would require abatement of two primary conditions:

- Volatile organic compounds (VOC) impacts to the source area resulting in average VOC concentrations in saturated soils below Method 1 S-3/GW-1 standards.
- Dissolved phase concentrations of VOCs in groundwater resulting in reduction of concentrations at or below Method 1 GW-1 standards.

3.2.2 Target Cleanup Goals for Source Area Saturated Soils

Data from assessment activities suggest the presence of residual, sorbed and/or dissolved phase VOCs located in saturated soils that represent the source of dissolved phase impacts in Site groundwater. Target cleanup goals are summarized in the table below.

Source Area Saturated Soils Target Cleanup Goals

Parameter	*S-3/GW-1 (µg/g)*
PCE	0.5
TCE	0.4
CDCE	2
VC	0.4
Toluene	90

Pre-remedial characterization activities will be conducted to identify CVOC concentrations in the source area saturated soil.

3.2.3 Target Cleanup Goals for Groundwater

The Site is located within a Current Drinking Water Source Area (i.e., the Zone II aquifer protection district for the Baldwin Pond Wellfield). The Site poses a risk to human health under future conditions (i.e. groundwater is not currently used as a source of drinking water within the defined or projected extent of the plume). A reduction of CVOCs in groundwater to concentrations below MMCLs is required in order to achieve a permanent solution.

A reduction in the concentrations of CVOCs to MMCLs would meet RAPs for achievement of "no significant risk." Therefore, MMCLs are adopted as initial target cleanup goals for CVOCs in groundwater and are summarized in the table below.

Groundwater Target Cleanup Goals

Parameter	*MMCLs (µg/L)*
PCE	5
TCE	5
cDCE	70
VC	2

To achieve a permanent solution, RAPS also requires consideration of abatement to background levels, if feasible. Available Massachusetts Department of Environmental Protection (MA DEP) guidance indicates that "achievement" of background is considered "generically infeasible" for chlorinated hydrocarbons in groundwater, but indicates that a reduction in contaminant concentrations should "approach" background, if feasible (MA DEP, 2004). Therefore, as a secondary target cleanup goal, abatement of PCE, TCE, cDCE and VC in groundwater will attempt to "approach" background, if feasible. The feasibility of abatement of CVOCs in groundwater to "approach" background will be evaluated based on the success of remedial measures at reducing CVOC concentrations in groundwater to MMCLs.

4.0 IDENTIFICATION AND INITIAL SCREENING OF REMEDIAL TECHNOLOGIES

4.1 OVERVIEW

This section presents a review of remedial technologies that were evaluated based on their ability to achieve abatement of OHM in source area saturated soils and groundwater. Selected technologies were screened using the specific criteria outlined in the following section. In accordance with 310 CMR 40.0856, a summary of the screening process for the remedial technologies is provided in Table 1. Technologies that passed the screening were incorporated into a series of media-specific remedial action alternatives. Proposed remedial management options consist of both engineered controls and risk management strategies (e.g., institutional controls and/or monitoring plans). Section 5.0 includes the identification and detailed evaluation of remedial alternatives.

4.2 SUMMARY OF TREATABILITY STUDIES

Bench-scale treatability studies were conducted using Site soils and groundwater to evaluate the potential efficacy of two in situ technologies: bioremediation and chemical oxidation. This section provides a brief overview of each technology and results of the treatability studies.

4.2.1 Bioremediation

A treatability study was conducted to evaluate the potential for enhancing intrinsic biodegradation of PCE, TCE and cDCE by amending groundwater with an additional carbon source, as well as introducing bacteria known to degrade these compounds completely to ethene. Terra Systems Inc., (Terra Systems) of Wilmington, Delaware performed the treatability study and was present during the collection of the groundwater and soil samples. The objectives of the treatability study were to:

- determine if and to what extent the native microbial population can degrade the chlorinated solvents with and without additional substrate; and
- evaluate potential substrates, such as lactate and soybean oil, to determine which substrate may work best at this Site.

Collection of Soil and Groundwater Samples

For the purposes of the treatability study, samples were collected in an anoxic environment to maintain the microbial populations in their native oxidation-reduction (redox) conditions. Sample bottles were placed inside a glove bag in the field. The contents of the bag were purged and filled with nitrogen twice and then sealed. Nitrogen was periodically pumped into the bag to maintain positive pressure in the bag and prevent air (oxygen) from entering. Six, one-liter amber jars were filled with groundwater from MW-268M. Water from two additional jars was reserved to add to the soil samples to maintain in situ redox conditions during transport.

Three split-spoon soil samples were collected from a depth of 75 to 85 feet, at a boring location adjacent to MW-268M. Once the split-spoons were removed from the borehole they were immediately placed in the nitrogen atmosphere within the glove bag. The split-spoons were then opened and the soil samples were placed in one-liter jars. Four jars were then topped off with groundwater from MW-268M to eliminate the headspace and shipped to Terra Systems to be used in the treatability study.

Microcosm Preparation

Soil and groundwater from the Site were mixed together, placed into sealed bottles, and amended with nutrients and a carbon source. Two different carbon sources were tested – lactic acid and emulsified soybean oil. Lactic acid is very soluble in water and easily spreads in groundwater after injection. Emulsified soybean oil also spreads readily, but is much less soluble and persists longer after injection.

The sealed microcosms were incubated for several months. Samples were taken from the bottles during weeks 2, 4, 6, 8 and 12 and analyzed for TCE, cDCE, VC, and ethene. At Week 12, additional lactic acid and emulsified soybean oil were added to the test bottles. Additional samples were taken at week 14 and 16 and analyzed for TCE, cDCE, VC, and ethene.

Study Results and Discussion

The addition of substrates such as lactic acid and emulsified soybean oil by themselves led to the dechlorination of TCE to cDCE, but did not lead to the complete dechlorination of TCE to ethane.

The treatability study results are not reflective of in situ conditions, based on geochemical data collected in the plume. The heterogeneity of the subsurface is likely the reason for the different assessment outcomes. In situ, the most reducing zones are located in the fine silty sand layers. A physical difference in the redox chemistry was noted during the review of the soil samples during drilling. The increased surface area of the fine particles also creates a more favorable environment for dehalogenating microbes. Intrinsic reductive dechlorination is likely occurring in these zones and discharging this "treated" water to the coarser sand layers below.

These coarser sand layers are where the downgradient groundwater monitoring wells are screened and where samples where taken for the microcosm studies and during routine groundwater monitoring activities. The difference in the redox states of the silty sand and the coarser sand units is likely the reason for the difference in microbial activity in situ and therefore the reason the microcosm results were improved by the addition of a dechlorinating enrichment culture.

A complete discussion of the microcosm treatability study is provided in Appendix B.

4.2.2 *In Situ Chemical Oxidation*

In situ chemical oxidation (ISCO) is the injection of an oxidizing agent to chemically degrade chlorinated solvents in the subsurface. PCE, TCE, cDCE and VC can be oxidized to produce inert by-products such as carbon dioxide, hydrochloric acid and water.

The chemical oxidant, potassium permanganate was evaluated in a bench scale study using media from the Site. Two soil samples were collected during the installation of MW-522 at a depth of 18 to 20 feet below ground surface (bgs). Natural oxidant demand (NOD) analysis was performed to estimate the quantity of potassium permanganate that would be consumed by naturally occurring materials in soil (e.g. organics, metals).

Seven jars containing aliquots of Site soils were exposed to varying concentrations (0 – 31,620 mg/L) of potassium permanganate for a 48-hour period. After 48 hours, the jar with the lowest residual potassium permanganate is then spectrophotometrically analyzed for concentration.

The results of the NOD analysis were low to moderate suggesting that application of potassium permanganate could effectively treat CVOCs in the subsurface. The results of the NOD analysis are in Appendix C.

4.3 SCREENING CRITERIA

The screening process is intended to identify those remedial technologies that maintain a potential to reduce OHM concentrations in source area saturated soils and groundwater to target cleanup goals. The screening includes an evaluation of the ability of promising remedial technologies to meet the following criteria:

- *Effectiveness* – the ability of the technology to achieve a permanent or temporary solution (i.e., meeting remedial action objectives).
- *Implementability* – the availability of personnel and equipment to implement the technology.

4.4 TECHNOLOGY SCREENING - SOURCE AREA SATURATED SOILS

4.4.1 No Action/Institutional Controls

The no action/institutional controls alternative involves leaving impacted source area saturated soils in place and addressing those impacts through a Site Activity and Use Limitation (AUL), and a Site soil management plan. Residual and sorbed phase VOCs will continue to act as a source of impacts to groundwater over time. This approach requires long-term monitoring and evaluation. This alternative could be a component of a permanent or temporary solution.

The no action/institutional controls alternative is implementable, but would not be an effective stand alone alternative to reach a permanent solution. This option is carried forward for consideration in conjunction with other treatment technologies.

4.4.2 Excavation and Treatment or Disposal

The excavation and treatment or disposal alternative involves excavating source area saturated soils with heavy equipment to eliminate the mass of residual and sorbed phase VOCs present in the subsurface. Dewatering and water treatment would also be required as part of this alternative. Following excavation, the soil would be transported off-Site for treatment or disposal by one of the options described below:

- Thermal treatment/Incineration is an ex-situ process that uses heat exchange to vaporize organic contaminants from soil. The vapors generated during treatment at an off-Site facility are then treated as necessary. Thermal treatment/incineration would be effective in achieving a permanent solution and is commonly implemented. Therefore thermal treatment/incineration is retained as an effective and implementable technology.

- Disposal involves excavating impacted saturated soil and disposing of the soil without any treatment at a secure, lined landfill. Off-Site disposal would be effective in achieving a permanent solution and is commonly implemented. Therefore off-Site disposal is retained as an effective and implementable technology.

Soil removal by excavation could enable achievement of a permanent solution and is therefore considered an effective technology. Excavation is implementable, since Site physical conditions are adequate to enable excavation and the equipment and personnel are available. Therefore excavation is carried forward for detailed analysis.

4.4.3 Pump and Treat

Pump and treat is a technology that includes a variety of process options. The three basic components of pump and treat are extraction, treatment, and discharge. A series of extraction wells screened in the overburden could be used to intercept the contaminant plume. The extracted groundwater could be treated by a number of processes, such as air stripping, activated carbon or chemical/ultraviolet oxidation. The treated groundwater would then be re-injected at the Site, or discharged to the stormwater conveyance system. Construction and operation of a pump and treat system is technically feasible.

Pump and treat technology can be used to treat VOC source areas. However, in heterogeneous aquifers, such as the one present at the Site, channelization of groundwater flow to the pumping well(s) commonly occurs, resulting in limited effectiveness. In addition, the fine-grained material of the source area soils allow for matrix diffusion, which would preclude effective treatment. The technology is readily implementable, but would not likely be effective, due to subsurface conditions. Therefore, this alternative is not carried forward for detailed evaluation.

4.4.4 Air Sparging/Soil Vapor Extraction

Air sparging (AS) involves the injection of air into groundwater to promote partitioning of VOCs into a vapor phase by volatilization. Soil vapor extraction (SVE) involves the removal of VOCs from the vadose zone using a vacuum extraction system. The combination of these technologies (AS/SVE) can be effective at reducing dissolved phase mass of VOCs in groundwater (US EPA, March 1998b). However, silt layers identified across the Site may cause channelization of air stream. Removal of VOCs in and below the silt layers will be limited by diffusion rates and depth of contaminants.

The technology is readily implementable, but would not likely be effective, due to subsurface conditions. Therefore, this alternative is not carried forward for detailed evaluation.

4.4.5 Bioremediation

Bioremediation involves stimulation of biodegradation processes by the injection of one or more of the following: electron donors (i.e. carbon substrate), nutrients, electron acceptors or exogenous microbes to promote degradation of the contaminants. Typically, an anaerobic environment is required for degradation of CVOCs (Weidemeier, 1999a). Bioremediation may include comprehensive groundwater sampling, microcosms studies and modeling to evaluate the effectiveness of the technology.

Bioremediation is an effective technology to reduce concentrations of CVOCs in groundwater. Bioremediation has previously been implemented at sites to abate CVOC impacted groundwater. Recent research indicates that injection of a substrate in source areas may stimulate microbiological degradation of CVOCs and/or dissolution of residual product. This technology is compatible with Site conditions. Bench scale studies discussed in Section 4.2 indicate it could be effective at achieving a permanent solution.

The technology is readily implementable and could be effective at achieving a permanent solution. Therefore, this alternative is carried forward for detailed evaluation.

4.4.6 In Situ Chemical Oxidation

In situ chemical oxidation involves the injection of a chemical oxidant, to chemically degrade the contaminants into non-toxic by-products. However, there are often competing reactions with naturally occurring reduced or oxidizable species such as metals or natural organic material (ITRC, 2001). The total non-contaminant related oxidant demand is referred to as the natural oxidant demand (NOD). The type and quantity of oxidant is dependent on the combined NOD of the aquifer and the demand of the contaminants present in groundwater.

A variety of chemical oxidants exist, including hydrogen peroxide, permanganate, persulfate and ozone (US EPA, 1998a). All of these oxidants have been proven effective at destroying TCE. Based on bench-scale NOD tests, permanganate will likely be the oxidant used.

Successful implementation of in situ chemical oxidation would be dependent on the effectiveness of delivering oxidants to the impacted groundwater. Transport of the oxidants within the aquifer may be conducted under either natural or forced hydraulic gradients.

ISCO is an implementable technology that has historically been effective in reducing the concentrations of chlorinated ethenes in groundwater and source areas. Bench scale studies suggest it could also be effective to treat groundwater impacts. The technology is readily implementable and could be effective at achieving a permanent solution. Therefore, this alternative is carried forward for detailed evaluation.

4.4.7 Thermal Treatment

In situ thermal treatment involves the heating of subsurface soil and groundwater to enhance volatilization of VOCs. These VOCs are captured by an SVE system and treated using an ex situ treatment system. Heating techniques include:

- Radio-frequency (RF) heating (US DOE, 1995)
- Three or Six-phase heating (US DOE, 1995)
- Conductive heating (Baker, 2004)
- Steam injection (US EPA, 1998c)

Thermal treatment is an innovative technology that has proven to be effective at other VOC sites. Thermal treatments are typically applied in source areas and would be difficult to implement over larger areas, such as the downgradient portion of the Site. Therefore, in situ thermal treatment is carried forward for consideration. This technology is readily implementable and could be effective at achieving a permanent solution. Therefore, this alternative is carried forward for detailed evaluation.

4.4.8 Injectable Zero-Valent Iron

In situ chemical reduction (ISCR) involves the injection of a reducing agent, such as zero-valent iron (ZVI), to promote the abiotic degradation of CVOCs into non-toxic by-products (Brown, 2005). ZVI can reduce CVOC via reductive dechlorination, abiotic natural attenuation and redox soil chemistry. ZVI is a strong chemical reductant that has been effectively used to reductively dechlorinate a variety of chlorinated solvents.

Nano-scale iron can be injected into the subsurface using wells and pressure grouting methods to create a reducing environment. Transport of the reductant within the aquifer may be conducted under either natural or forced hydraulic gradients and is limited by site heterogeneity. The installation of an injection well network at targeted zones in the source area would be an effective method of implementing this technology. This technology is implementable and could be effective at achieving a permanent solution. Therefore, this alternative is carried forward for detailed evaluation.

4.5 TECHNOLOGY SCREENING - GROUNDWATER

4.5.1 Monitored Natural Attenuation (MNA)

Natural attenuation is the combined effect of physical, chemical, and biological processes (e.g., dilution, dispersion, adsorption, and degradation) that act to reduce CVOC concentrations along the length of a groundwater plume (Weidemeier, 1999b). MNA as a remedy requires demonstration of a thorough understanding of CVOC transport, migration pathways, degradation rates and the ultimate fate of target compounds to establish and ensure ongoing protection of human health and the environment. This technology requires long-term monitoring and evaluation to demonstrate that conditions continue to progress toward the projected endpoint (US EPA, 1998d).

A detailed description of the source area, nature and extent of impact, contaminant fate and transport, and degradation processes operating at the Site, is presented in the Phase II report (ERM, 2005). MNA alone would not be effective in meeting the requirements of a Permanent Solution for the Site. However, in conjunction with source abatement alternatives, MNA could be implemented and is effective as a remedial solution for downgradient plume abatement. Therefore, MNA is carried forward as a downgradient alternative.

4.5.2 Pump and Treat

Pump and treat is a technology that includes a variety of process options. The three basic components of pump and treat are extraction, treatment, and discharge. A series of extraction wells screened in the overburden could be used to intercept the contaminant plume. The extracted groundwater could be treated by a number of processes, such as air stripping, activated carbon or chemical/ultraviolet oxidation. The treated groundwater would then be re-injected at the Site, or discharged to the stormwater conveyance system.

Pump and treat technology is commonly used to prevent contaminant migration. The alternative has the ability to achieve a temporary solution; therefore it is carried forward for detailed evaluation. The technology is readily implementable and could be effective at achieving a permanent solution. Therefore, this alternative is carried forward for detailed evaluation.

4.5.3 Bioremediation

Bioremediation, as described in Section 4.4.5, is commonly implemented to treat CVOC plumes at sites with reducing groundwater conditions, such as those present at the Site. Bench scale studies discussed in Section 4.2 indicate it could be effective at achieving a permanent solution.

The technology is readily implementable and could be effective. Therefore, this alternative is carried forward for detailed evaluation.

4.5.4 Permeable Reactive Barrier

Traditional applications of permeable reactive barrier (PRBs) involve the placement of chemical permeable media into the subsurface positioned to intercept and treat impacted groundwater along flow paths downgradient of a source(s) (NRC, 1997). PRBs involve the injection of a reducing agent, such as ZVI, to promote the abiotic degradation of VOCs into non-toxic by-products`.

PRBs can be installed by trenching or by pressure injection of ZVI into the aquifer. Biofouling can occur within the treatment wall, resulting in decreased hydraulic conductivity and reactivity of the wall. If this occurs, then the wall would require cleaning or replacement. Given the presence of VOCs to depths of 80 feet, a traditional PRB would not be technically feasible at the Site.

The technology could be effective but would be difficult to implement. Therefore, this alternative is not carried forward for detailed evaluation.

4.6 *REMEDIAL ALTERNATIVES*

Based on the technology screening, the following remedial alternatives are identified as candidates for the abatement of groundwater and source area saturated soils are carried forward for detailed evaluation:

Source Area Saturated Soils

- Alternative #1 – No Action/Institutional Controls
- Alternative #2 - Excavation
- Alternative #3 - Bioremediation
- Alternative #4 – ISCO
- Alternative #5 – Thermal Treatment
- Alternative #6 – Injectable ZVI

Groundwater

- Alternative #1 – MNA
- Alternative #2 – Pump and Treat
- Alternative #3 - Bioremediation

5.0 DETAILED EVALUATION OF ALTERNATIVES

5.1 OVERVIEW

Pursuant to 310 CMR 40.0857, this section includes a detailed evaluation of remedial alternatives identified in the initial screening of remedial technologies presented in the previous section. Proposed remedial alternatives for source area saturated soils and the groundwater plume are listed below and consist of both engineered controls and risk management strategies (MA DEP, 2004).

Pursuant to 310 CMR 40.0858, the detailed evaluation must consider seven criteria for each alternative, which are defined in Section 5.2. Each source area saturated soils alternative is evaluated relative to these criteria in Section 5.3. Each groundwater plume alternative is evaluated relative to this criterion in Section 5.4. A comparative analysis of the alternatives relative to each screening criteria is presented in Section 6.0.

5.2 SCREENING CRITERIA

A detailed evaluation of the alternatives includes a brief description of the site-specific aspects of each alternative. This is followed by an evaluation of each alternative using the following criteria:

Effectiveness — This criterion identifies whether the alternative will achieve a Permanent or a Temporary Solution. It also addresses how contaminant concentrations will be reduced and the likelihood that residual concentrations will approach or achieve "background."

Reliability — This criterion addresses the likelihood that the alternative will be successful and the effectiveness of any measures required to manage waste streams generated by the alternative.

Implementability — This criterion addresses the technical complexity of the alternative and its compatibility with site constraints. It also addresses whether the remedial alternative has successfully been used at other sites in similar situations.

Cost	This criterion addresses the short-term and long-term costs associated with implementing the alternative. A 30-year operation and maintenance period was assumed using a seven percent discount rate for each alternative. The costs presented are intended for use in the comparative analysis in Section 6.0.
Risks	This criterion addresses the expected short-term and long-term risk associated with the alternative.
Benefits	This criterion addresses the expected benefits associated with the alternative.
Timeliness	This criterion compares the timeliness of each alternative in terms of achieving a level of "no significant risk". A 30-year evaluation period was selected for the purposes of the evaluation.

Note: The cost estimates presented in this section are not intended for budgeting or contracting purposes, but were prepared for comparison of the alternatives. Actual costs may vary. Supplemental investigation activities and detailed-design phases would provide the specific information needed to increase the accuracy of the cost estimates.

5.2.1 *Source Area Saturated Soils*

Alternative #1 – No Action/Institutional Controls

Source area saturated soils would be left in place and managed with a deed restriction and a Site soils management plan. Periodic sampling of existing groundwater monitoring wells would be performed to evaluate Site conditions.

Effectiveness

Over time, dilution, volatilization, biodegradation, advection, adsorption and subsurface chemical reactions would likely reduce the chemical concentrations in the source area. The toxicity, mobility, and volume of the contaminants may be reduced slightly over time due to these natural processes. The presence of residual and sorbed phase VOCs at the site constitutes an on-going source. Therefore, this alternative would not achieve a permanent solution.

Reliability

The implementation of an AUL on the property would be a reliable method of controlling and managing soil access and management at the Site.

Implementability

The no action/institutional controls alternative would be easy to implement because no construction, or operation and maintenance activities would be required.

Cost

The costs associated with the no action alternative are summarized in Table 2. There are no significant short-term costs. Long-terms cost include groundwater sampling. For cost estimating purposes, ERM assumed that 10 wells would be sampled semi-annually for VOCs (EPA Method 8260). The present worth of the monitoring costs is estimated to be $300,000.

Risks

The Site does not currently pose any short-term risks other than during potential excavation activities. The Phase II Method 1 Risk Characterization did identify future potential risks associated with off-Site migration and use as drinking water aquifer.

Benefits

The benefits of the no action/institutional controls alternative are that there is no disruption to the Site and that the AUL manages short-term risks.

Timeliness

This alternative would take the longest to achieve the remedial action objectives.

Alternative #2 – Excavation of Source Area Saturated Soils

Excavation of source area saturated soils would target a specific area delineated by the previous Membrane Interface Probe (MIP) investigation. The removal of these soils by excavation would abate the source of groundwater impacts. The primary components of this alternative include the following:

- *Site Preparation* – clear the Site, potential GeoProbe soil boring installation, establish staging areas and final perimeter of excavation by survey.
- *Potential Installation of Sheet Pile* – install sheet pile at source area perimeter to enable excavation to 30 or 35 feet deep and below the groundwater table.
- *Excavation and Dewatering* – excavate soils and dewater to facilitate excavation process. Excavated materials to be temporarily staged and segregated, setting aside clean material from above the water table. Soils will then be transported to an appropriate disposal facility for thermal treatment or landfilling (depending upon soil characterization and evaluation of disposal options). Dewatered groundwater would be pre-treated for sediment removal, pumped through activated carbon for further treatment and discharged in accordance with National Pollution Discharge Eliminations System (NPDES) regulations to surface water or storm water conveyance system. Samples would be collected from the floor of the excavation and analyzed for CVOCs.
- *Backfill* – backfill excavation, re-compacted, returned to its original condition.

Effectiveness

Excavation is an effective method and a proven traditional approach to remove impacted soils. The excavation and off-Site treatment/disposal alternative would be a successful method of remediating residual and sorbed-phase VOCs in saturated soils and could achieve a temporary or permanent solution in conjunction with downgradient plume treatment.

Reliability

Excavation would provide permanent removal of impacted saturated soils present in the delineated source area. Thermal treatment or landfilling of the soils would provide destruction or secure disposal, respectively. Nonexcavated materials and potential residual contaminants in soil would remain in-place at the Site, but are not expected to pose a significant risk.

Implementability

Excavation of targeted soils would be readily implementable at this Site. The excavation area is in an open field and easily accessible. No utility relocation would be required.

Cost

The costs associated with the excavation and soil disposal/treatment are summarized in Table 3. The costs associated with excavation of the source area saturated soils are $1,400,000.

Risks

The short-term risks associated with this alternative are primarily related to the excavation and handling of the impacted soils and groundwater. Precautions would be taken during excavation and treatment activities to mitigate the risk to workers during these activities.

Benefits

The impacted soils would be eliminated and treated/disposed off-Site and the potential for exposure to contaminants ex situ would be minimized.

Timeliness

It is estimated that the excavation component of this alternative would require approximately four to six months to be completed.

Alternative #3 - Bioremediation

Bioremediation is a method that relies on indigenous or cultured microbes to degrade contaminants in situ. PCE, TCE, and cDCE can be naturally degraded in a reducing (sulfidic or methanogenic) environment through the process of reductive dehalogenation. The more chlorinated the compound the more susceptible it is to reductive dehalogenation. For example, PCE is more rapidly dehalogenated than TCE. Reductive dehalogenation is inhibited in aerobic environments.

Bioremediation has been used with varying degrees of success to treat source areas (Lee, 2004). Injection of slow release carbon sources such as emulsified soybean oil have been shown to promote dissolution of residual and sorbed phase CVOCs to make them available for reductive dechlorination.

In addition to a reducing environment, the dehalogenation process requires four essential elements: microbes, nutrients, a carbon source (i.e. substrate), and electron donors. Bioremediation involves maintaining the right balance of these elements in the subsurface to maximize the long-term degradation rate. Each element is described below.

- Nutrients are required to optimize microbial activity. Nitrogen and phosphorous are the most common nutrient supplements that are used to enhance the natural degradation process. The amount of nutrients that are added is contingent upon site-specific characteristics. In some cases, naturally occurring nutrients in the subsurface are sufficient to promote bioremediation.
- Natural carbon sources are sometimes sufficient to maintain a healthy microbe population and optimize the rate of CVOC degradation, but a carbon source (i.e., substrate) can also be added.
- Electron donors are necessary for the dehalogenation process to proceed. Chlorinated solvents, such as TCE, serve as electron acceptors; therefore, an electron donor must be present in the aquifer. If there are not sufficient electron donors in the subsurface, then compounds such as hydrogen, lactate or soybean oil must be added. Some of these compounds may also serve as a carbon source.

The primary components of Alternative #3 include biogeochemical monitoring, system design and installation, and groundwater monitoring. Each of these components is described briefly below:

- *Biogeochemical monitoring* – collection of groundwater data to evaluate oxidation-reduction conditions, organic carbon concentrations, presence of electron acceptors, nutrient concentrations and the presence of biological activity.
- *System design and implementation* – design and construction of a full-scale system based on results of the microcosm.
- *Groundwater monitoring* – conduct long-term groundwater monitoring to evaluate the efficacy of the system and modify system parameters over time, if necessary.

Effectiveness

There is significant evidence at the Site of biologically-mediated PCE and TCE degradation (i.e. presence of daughter products such as cDCE, VC and ethene). Historic groundwater monitoring data indicate that the source area is aerobic, but the plume becomes anaerobic as it migrates west. The detection of TCE daughter products in the plume is direct evidence that indigenous microbes are present and reductive dechlorination is occurring. Bench-scale studies indicate that the addition of lactate or soybean oil, results in dechlorination of PCE and TCE to cDCE. Addition of dechlorinating enrichment culture resulted in complete degradation to ethene. Collectively, these Site-specific data indicate that bioremediation could be effective at the Site.

The effectiveness of this alternative would ultimately depend upon the ability to distribute a carbon source into the subsurface, and for natural or enchriched microbes to degrade PCE, TCE and cDCE to innocuous products. Using an injection well network or infiltration gallery, substrate can be added to the subsurface to create favorable conditions in the source area for reductive dechlorination and distribute the carbon source to the downgradient plume. Bioremediation could reduce CVOC concentrations to levels necessary to achieve a permanent solution and/or background conditions within the foreseeable future.

Reliability

Bioremediation has been demonstrated as a reliable alternative for reducing concentrations of PCE and TCE. A source of uncertainty is the ability to achieve the appropriate balance of microbes, nutrients, and electron donor in a heterogeneous aquifer to ensure complete degradation of the target compounds. The presence of cDCE, VC and ethene in groundwater indicates that biological degradation of TCE is occurring in areas of the Site.

Implementability

This alternative would be feasible to implement. The source area is accessible where additional wells or injection systems could be installed, if necessary. Existing monitoring wells could also be utilized as injection and/or monitoring points. Bioremediation has been successfully implemented at several sites to remediate PCE and TCE impacts to groundwater. The oxidative nature of the source area may require the injection of excess substrate and take the aquifer longer to be conditioned before reductive dechlorination may occur.

Cost

The cost associated with the bioremediation alternative is summarized in Table 4. Initial capital costs are estimated at $342,540. The annual operation and maintenance cost is estimated to be $234,926 in year 2 and $125,983 in years 3 through 10. The present worth of this alternative is estimated at $1,600,000.

Risks

The short-term risk associated with this alternative is the potential for worker exposure to Site contaminants. Precautions would need to be taken during the drilling to minimize this possibility. Potential worker exposure to Site contaminants would be minimized because personnel trained in hazardous waste operations would be installing the wells and appropriate precautions would be taken to prevent exposure.

There are no long-term risks associated with this technology. However, if bioremediation were only partially successful, it would continue to allow impacted groundwater to migrate from the source area. Long-term groundwater monitoring would need to be performed. The operation and maintenance of a bioremediation system is not expected to pose any long-term risks.

Benefits

The benefit of bioremediation is that an enhanced natural process could be used to achieve the remedial action objectives with minimal disturbance of Site operations and without the generation of remediation wastes requiring treatment or disposal. Bioremediation would likely be beneficial in restoring groundwater quality to achieve a permanent solution and/or background conditions.

Timeliness

Bioremediation would require time for microbial populations to acclimate to source area conditions. Due to the variability of natural rates and geologic heterogeneity, it is difficult to predict the time frame for this alternative. The timeliness of this technology can be better predicted following the first year of implementation. Based on experience at similar sites, we estimate that bioremediation would require between five and ten years to complete.

Alternative #4 –In Situ Chemical Oxidation

This alternative involves the injection of an oxidant (i.e., potassium permanganate) to chemically transform chlorinated ethenes to harmless by-products (e.g., carbon dioxide, water and chloride). Potassium permanganate is a non-selective oxidant. This means that in addition to chlorinated ethenes the oxidant will oxidize other reduced soil and groundwater constituents, such as natural organic carbons (i.e., humic and fulvic acids) and reduced minerals. The NOD was determined using bench-scale laboratory tests. Observed field parameter data in Site groundwater suggest that the oxidant demand will increase downgradient with decreasing oxidation-reduction values (ORP) values. The concentration and volume of oxidant to be injected were calculated using the NOD and the observed concentrations of chlorinated ethenes in the source area and downgradient plume.

The primary components of Alternative #4 include, pilot study, system design and implementation and groundwater monitoring. Each of these components is described briefly below:

- *System design and implementation* – design and construction of a full-scale system based on results of the pilot studies.
- *Groundwater monitoring* – conduct long-term groundwater monitoring to evaluate the efficacy of the system and modify system parameters over time, if necessary.

Effectiveness

ISCO using permanganate has been demonstrated to decrease PCE, TCE, cDCE and VC concentrations in groundwater. The ultimate effectiveness of potassium permanganate in treating PCE, TCE and cDCE is dependent upon the ability to inject and deliver the oxidant to areas containing CVOCs. Groundwater in the downgradient plume area becomes highly reducing and may require a significant quantity of permanganate to overcome the increased natural oxidant demand.

The presence of residual and sorbed phase product in the source area would likely require multiple oxidant injections.

Reliability

ISCO has been demonstrated as a reliable technology for reducing concentrations of TCE. The reliability of the technology is affected by the natural oxidant demand of a heterogeneous aquifer and the ability to distribute oxidant to the impacted media. The reliability will be also be affected by the increasing oxidant demand of the aquifer as the plume travels downgradient, and dissolution and de-sorbtion of residual and sorbed phase CVOCs in source area saturated soils.

Implementability

This alternative is feasible to implement. Chemical oxidation has been successfully implemented at sites with similar subsurface impacts and hydrogeologic conditions. The source area is accessible and natural or forced gradients may be used to transport oxidants. Existing monitoring wells could also be utilized during the injection.

Cost

The costs associated with chemical oxidation are summarized in Table 5. Initial capital costs are estimated at $456,030. Annual Operating costs for four additional years are estimated at $91,325. The present worth of this alternative is estimated at $1,200,000.

Risks

Short-term risks associated with this alternative include the potential to mobilize contamination and the potential for worker exposure to Site contaminants and oxidants. Precautions would need to be taken during the installation of delivery wells to minimize this exposure. Worker exposure to Site contaminants and oxidants would be minimized since personnel trained in hazardous waste operations would be installing the wells and appropriate precautions would be taken to prevent exposure.

Short-term risk associated with ISCO is the potential to displace CVOCs during the permanganate injections. This can be addressed for in the remedial design.

Benefits

A benefit of chemical oxidation is that it can be implemented with minimal disturbance to the Site and without waste generation. If successful, chemical oxidation will reduce the impact of CVOCs to the aquifer to achieve a permanent solution.

Timeliness

Chemical oxidation can reduce concentrations of chlorinated ethenes in source area saturated soils and groundwater significantly over a relatively short period of time. The presence of residual and sorbed phase CVOCs in the source makes the timeframe to reach a permanent solution uncertain. ERM estimates that ISCO would require approximately five years to have achieved a permanent solution.

Alternative #5 – Thermal Treatment

Implementation of thermal treatment for source area saturated soils abatement will desorb and volatilize VOCs, without applying hydraulic stresses to the source area that could result in enhanced VOC migration. The advantage of thermal conduction over other thermal technologies is groundwater is only heated to 100°C, generating in situ steam. Thermal wells and heated extraction wells would be installed in alternating transects in the source area. As a result, thermal conduction and convection occur in the bulk of the soil volume. The heated extraction system is used to recover the contaminants.

Thermal conduction can treat residual, sorbed and dissolved phase impacts in saturated soils. Implementation of thermal conduction for source area abatement, if effective, is estimated to result in achievement of treatment objectives within source area over a period of one year. The effects of source area abatement by thermal treatment are estimated to translate to down-gradient groundwater via advective groundwater flow within a period of three to five years. The primary components of thermal treatment are:

- *System design, installation and operation* – The design of the thermal conduction system will determine the number of heating wells and extraction wells required to treat the source area. The heat and extraction wells will be drilled and piped together above ground to a collection and treatment system. The system requires 24-hour oversight to ensure safe and efficient operation.
- *Groundwater monitoring* – Short-term groundwater monitoring will be conducted during the system operation to evaluate system efficiency and progress. Long-term groundwater monitoring would be conducted to evaluate mass removal and effects on the downgradient plume.

Effectiveness

Thermal conduction is an effective method for abatement of VOCs in overburden soils. Thermal conduction may eliminate residual and sorbed phase VOCs in the source area and reduce dissolved phase concentrations of VOCs by volatilization and extraction at elevated temperatures. Thermal conduction is a technology that has the potential to be effective in achieving a permanent solution within the foreseeable future.

Reliability

Thermal conduction has been implemented at numerous sites since the 1980s. Although it has proven to be a highly effective technology, it is still a relatively innovative technology.

Implementability

This alternative is feasible to implement. The target area is accessible and there are no structures or utilities in the source area.

Cost

The costs associated with this alternative are shown in Table 6. For costing purposes, it is assumed that the thermal conduction system would operate for a period of one year, followed by five years of monitoring downgradient. The present worth of the combined one-year thermal conduction and five-years of groundwater monitoring is $2,100,000.

Risks

ERM has evaluated the potential for mobilizing residual and sorbed phase VOCs in the short term as a result of increased groundwater temperatures and determined that there is a relatively low likelihood of this occurring. This is due to the fact that when the residual VOCs are heated it will have a tendency to dissolve, thermally degrade, or volatilize and become captured by the extraction system. Vapor phase VOCs would be captured in carbon, requiring management and transportation for off-Site disposal. There are no long-term risks associated with this technology.

Worker exposure to Site contaminants and electricity would be minimized because personnel trained in hazardous waste operations and electrical safety would be installing the wells and appropriate precautions would be taken to prevent exposure.

There are no risks associated with the generation of toxic by-products under this alternative that would pose short- or long-term risks to human health or the environment.

Benefits

The benefit of thermal treatment is that it can be implemented with minimal disturbance to the Site over a relatively short time period. Thermal treatment would likely be beneficial in restoring groundwater quality to achieve a permanent solution and minimize the potential for future degradation of property value.

Timeliness

Of the technologies considered, thermal treatment would, if successful, result in a relatively short remediation period. It is estimated that source area cleanup criteria could be achieved in a period of one year, if thermal conduction is successful.

Alternative # 6 - Injectable ZVI

Injectable ZVI relies on the abiotic degradation of CVOCs in groundwater. The technology consists of injecting a reduced form of iron, commonly ZVI, into source area. ZVI is an electron donor that supplies electrons from the metal surface of iron to the chlorinated compound, resulting in abiotic reductive dechlorination of the compound to produce innocuous by-products, such as ethane or ethene. ZVI is effective at degrading chlorinated ethenes (i.e., TCE). Some of the electrons generated by this process react with water to generate hydrogen gas, which is an electron donor that can enhance biodegradation of TCE. Thus, implementation of ZVI could treat source area saturated soils and maintain or enhance the reducing environment in the downgradient plume.

For this alternative, ZVI consisting of iron impregnated sand would be injected into the subsurface via injection wells. The primary components of this alternative are:

- *Remedial design and implementation* –The size of the source area is estimated at 40 feet wide by 60 feet long. Based on an assumed ZVI application rate of 0.6 pounds per cubic yard, a total of 28,100 pounds of ZVI is estimated for this alternative. Implementation of this alternative would consist of mixing iron impregnated ZVI in water to create an iron slurry for injection into wells. Since the injectate is a dense slurry, the radius of influence would be lower than the radius of influence when injecting oxidants or a carbon substrate. Radius of influence testing will be required prior to completion of the final design.

- *Groundwater monitoring* – Post injection groundwater monitoring could be completed immediately downgradient of the ZVI injection wells to evaluate the change in aquifer geochemistry in response to ZVI. Quarterly monitoring would be conducted for a five year period following the injections to evaluate the effects of ZVI on CVOC concentrations in source area saturated soils.

Effectiveness

ZVI has been successfully implemented at other sites to treat chlorinated solvents. The majority of these sites consist of engineered permeable reactive barriers to ensure contact between the ZVI and CVOCs migrating in groundwater. The effectiveness of this alternative at the Site would be dependent upon the ability to inject ZVI at a sufficient radius of influence within the source area. This technology could reduce CVOC concentrations to levels necessary to achieve a permanent solution (i.e., MMCLs).

Reliability

ZVI has been demonstrated as a reliable alternative for chlorinated solvents. The reliability of ZVI would be dependent on the ability to emplace the ZVI slurry within the source area.

The alternative is an effective means of managing waste streams, as none are generated during the remedial process, provided the reaction is carried through to completion.

Implementability

This alternative is feasible to implement. ZVI has been successfully implemented at sites with similar subsurface impacts and hydrogeologic conditions. The source area is accessible and natural or forced gradients may be used to transport ZVI.

Cost

The cost associated with the injectable ZVI alternative is estimated at $1,400,000. Table 7 outlines detailed costs associated with this alternative.

Risks

Short-term risks associated with this alternative include the potential to mobilize contamination and the potential for worker exposure to Site contaminants. Precautions would need to be taken during the installation of delivery wells to minimize this possibility. Worker exposure to Site contaminants and injectants would be minimized because personnel trained in hazardous waste operations would be installing the wells and appropriate precautions would be taken to prevent exposure.

There are no risks associated with the generation of toxic by-products under this alternative that would pose short- or long-term risks to human health or the environment.

Benefits

A benefit of this alternative is that it requires minimal operations and maintenance after completing the ZVI injections.

Timeliness

It is assumed that the injection will be completed within one year with a total of five years of groundwater monitoring.

5.2.2 Groundwater Plume

Alternative #1 – Monitored Natural Attenuation

MNA includes periodic groundwater monitoring, as well as modeling and evaluation of contaminant degradation rates and pathways. Although it has been assumed modeling would be used to evaluate natural attenuation, other approaches, such as evaluation of historic Site data and lab studies, could be used in addition to, or in place of modeling, to document the effectiveness of natural attenuation.

Modeling would be performed to evaluate how contaminant concentrations in groundwater are expected to change over time. The model would be periodically recalibrated with new data as necessary to incorporate changes in the groundwater conditions due to source control or other Site factors (i.e. redevelopment). The approach used for the modeling of natural attenuation would be based on the nature and availability of Site data.

Based on the results of the groundwater sampling data and the modeling efforts, the progress towards achieving the remedial action objectives would be periodically reviewed. As necessary, the sampling program would be revised or additional monitoring wells would be installed to evaluate contaminant fate and transport.

Effectiveness

Dilution, volatilization, adsorption, biodegradation, and other naturally occurring chemical reactions would likely reduce contaminant concentrations in groundwater. The downward trend in contaminant concentrations at the Site would be modeled to project the time frame necessary to achieve the remedial action objectives for the Site. When combined with source control or abatement measures, natural attenuation could achieve a temporary or permanent solution or background conditions in the foreseeable future.

Reliability

MNA has been demonstrated to be reliable at many sites. There are no waste streams or by-products generated as part of this alternative.

Implementability

Monitoring and modeling would be feasible to implement, and would not require any construction, or operation and management activities. The United States Environmental Protection Agency (EPA) and other regulatory agencies have accepted natural attenuation as an acceptable form of remediation. MA DEP considers MNA a permanent solution. Therefore, natural attenuation is technically and administratively feasible.

Cost

No capital is required for the natural attenuation component of this alternative. The present worth of the monitoring and modeling costs are estimated to be $600,000 (Table 8).

Risks

There is no short-risk associated with MNA. Modeling would be used to monitor the progress of natural attenuation.

Benefits

The benefit of the natural attenuation alternative is that the remedial objectives could be achieved without the generation of remediation wastes, and the potential for exposure to contaminants ex-situ would be minimized.

Timeliness

At this time, it is difficult to evaluate the timeliness of the natural attenuation alternative. However, once the modeling has been performed, an estimate will be available and the timeliness can be evaluated more definitively.

Alternative #2 - Pump and Treat

Pump and Treat involves extracting groundwater from the subsurface, treating it using an ex situ treatment system, and discharging to surface water, the stormwater system, or groundwater. Groundwater monitoring would also be performed.

The primary components of Pump and Treat include system design, system installation, operations and maintenance, and groundwater monitoring. Each of these components is described briefly below:

- *System design* – design of a full-scale system based the results of a groundwater flow model and a 72-hour pumping test.
- *System installation* – install a full-scale system, including extraction well installation, trenching, piping and construction of the ex situ treatment system.
- *Operations and maintenance* – long-term operation and maintenance of the full-scale system.
- *Groundwater monitoring* – conduct long-term groundwater monitoring to evaluate the efficacy of the system and modify system parameters over time, if necessary.

The exact configuration of the treatment system would be determined during the design phase. Alternatives to air stripping, such as chemical/UV oxidation, could be considered along with alternatives to vapor-phase carbon, such as thermal oxidation. The exact configuration of the treatment system would be determined based on design factors, derived from the results of a 72-hour pumping test, and performance factors, such as effectiveness, reliability, and operation and maintenance costs.

Effectiveness

The effectiveness of the pump and treat alternative is primarily related to the ability of the extraction well(s) to create a zone of capture. Due to the nature of contaminant migration in heterogeneous overburden, effective capture of the plume could be difficult. Extractions in heterogeneous aquifers typically result in channelization of groundwater flow; therefore removal of CVOCs would be limited by diffusion rates. Data regarding the site geology, groundwater flow patterns, and contaminant trends would be used to identify the optimum well locations and configurations.

The presence of residual and sorbed phase CVOCs in the source area saturated soils would likely impede the actual decrease of CVOC concentrations in groundwater, as continuous dissolution and de-sorption would be expected over the life of the system. The removal/treatment of the source area saturated soils would likely improve the effectiveness of pump and treat in groundwater.

Air stripping is considered to be effective at treating organic compounds that have Henry's Law constants greater than 0.01 (LaGrega, 1994). The primary constituents of concern at the Site are amenable to treatment using air stripping.

Liquid-phase carbon would be effective as a polishing step to further reduce the concentration of residual CVOCs and inorganics.

Reliability

Pump and treat is generally a reliable treatment alternative. However, the mechanical pumping and treatment equipment is subject to malfunctions. Fouling of inorganics (e.g., iron) or biological growth, as well as fluctuations in contaminant concentrations, especially in a source area, can affect system performance. In addition, the groundwater extraction wells may not be able to fully capture the impacted groundwater due to the nature of the heterogeneous overburden.

The processes for managing the waste streams generated by the treatment system are expected to be very reliable. The groundwater would be treated on-Site and discharged. With proper operation and maintenance, the treatment system would be expected to consistently meet the treatment objectives.

Implementability

Construction and operation of a pump and treat system is technically feasible. Once the groundwater has been extracted, treatment would be relatively easy to implement. The treatment system would need to be inspected at least weekly to ensure proper operation. Ongoing maintenance activities would need to be performed to ensure proper operation. The treated water discharge and off-gas emissions would need to satisfy applicable standards and permitting requirements.

Pump and treat is a commonly used technology for preventing the migration of contamination and is used to control dissolved phase contamination.

Cost

The costs associated with the Pump and Treat are summarized in Table 9. Initial capital costs are estimated at $902,500. Additional annual operation and maintenance expenses are estimated to be $162,840. The present worth of the total projected cost for this alternative is estimated at $3,100,000.

Risks

The short-term risk associated with this alternative is worker exposure to Site contaminants. Precautions would need to be taken during the drilling to minimize this possibility. Worker exposure to Site contaminants would be minimized because personnel trained in hazardous waste operations would be installing the wells and appropriate precautions would be taken to prevent exposure. Long-term groundwater monitoring would need to be performed to monitor this situation. The risk of generation of toxic by-products is low.

Benefits

The pump and treat alternative would permanently reduce the mass of contaminants in the aquifer. The extraction wells could capture a large portion of contamination migrating from the source area through the aquifer. Source area impacts may not be addressed by this technology.

Timeliness

A pump and treat system would require long-term operation. Historically, pump and treat is not a highly efficient technology especially in the presence of residual and sorbed phase product. Mass removal is limited to system capture zone and diffusion rates. The unpredictability of the rate of mass removal makes it difficult to determine the timeframe of treatment. Typically, 30 years is considered a reasonable timeframe for implementation of pump and treat.

Alternative #3 – Bioremediation

Refer to Alternative #3 in Section 5.2.1 for a description of the technology.

Effectiveness

Bioremediation is highly effective at treating dissolved phase plumes. This is particularly true if remediation of the source area has been conducted significantly reducing mass flux from the upgradient source.

Reliability

Bioremediation is a technology that has been successful at many sites in the last 15 years. The presence of cDCE, VC and ethene in groundwater indicates that intrinsic biodegradation of TCE is occurring in areas of the Site.

Implementability

This alternative would be feasible to implement. The plume is accessible beneath an open field.

Cost

The costs associated with bioremediation of the plume are summarized in Table 10. The Year 1 costs associated with bioremediation in groundwater is $206,829. The present worth of ten years of injection and monitoring are estimated to be $900,000.

Risks

There are no long-term risks associated with bioremediation in groundwater. Long-term groundwater monitoring would need to be performed. The operation and maintenance of a bioremediation system is not expected to pose any long-term risks.

Benefits

The benefit of bioremediation is that an enhanced natural process could be used to achieve the remedial action objectives with minimal disturbance and waste generation. Bioremediation would likely be beneficial in restoring groundwater quality to achieve a permanent solution.

Timeliness

Bioremediation would require time for microbial populations to acclimate to site conditions and could take up to ten years to achieve a permanent solution and/or background conditions.

6.0 *COMPARATIVE EVALUATION OF ALTERNATIVES*

6.1 *OVERVIEW*

This section presents a comparative analysis of the remedial alternatives. This evaluation compares remedial alternatives for each screening criterion and determines which alternative is most likely to satisfy the requirements of that criterion. The purpose of the comparative analysis is to assist in selecting the remedial alternative that appears most likely to achieve the remedial goals for the Site (i.e., the alternative that best satisfies the majority of screening criteria).

To assist in this analysis, a numerical score of one to six, one being most desirable and six being least desirable as compared to the other alternatives was assigned to each of the detailed options. The scores were summed for each alternative to identify the most desirable alternative based on lowest numerical score. The basis for numerical scores for each of the comparative evaluation criteria is summarized in the following table:

Basis for Numerical Scoring of Evaluation Criteria

Effectiveness	1-2: Likely to achieve a permanent solution. 3-4: Ability to achieve a permanent solution uncertain. 5-6: Unlikely to achieve a permanent solution.
Timeliness	1-2: May achieve a permanent solution and/or background conditions in 1 to 5 years. 3-4: May achieve a permanent solution and/or background conditions in 5 to 10 years. 5-6: Unlikely to achieve a permanent solution and/or background conditions in 10 to 30 years.
Reliability	1-2: Alternative proven successful under similar conditions; eliminates and/or minimizes waste generation requiring management. 3-4: Alternative not proven under similar conditions; minimizes waste generation requiring management. 5-6: Alternative not proven under similar conditions; generates waste requiring management.
Implementability	1-2: Relatively easy to implement at the Site. 3-4: Can likely be implemented at the Site. 5-6: Difficult to implement at the Site.
Risk	1-2: Low risk of enhancing CVOC migration or generation of toxic by-products. 3-4: Some risk of enhancing CVOC migration or generation of toxic by-products. 5-6: High risk of enhanced CVOC migration or generation of toxic by-products.
Benefit	1-2: The level of restoration is adequate to achieve a permanent solution. 3-4: The level of restoration may to achieve a permanent solution. 5-6: The level of restoration in is inadequate for achievement of a permanent solution.
Cost	1-2: Comparative cost low with respect to other alternatives. 3-4: Comparative cost similar to other alternatives. 5-6: Comparative cost high with respect to other alternatives.

The comparative evaluation scores for each alternative are summarized below in the following table. If two or more alternatives were equal in the evaluation, the scoring was divided equally between the alternatives.

Comparative Analysis of Source Area Saturated Soils Alternatives

Alternative	Effectiveness	Timeliness	Reliability	Implementability	Risk	Benefit	Cost	**Score (Low = Best)**
#1 – No Action/Institutional	6	6	6	1	6	5	1	**31**
#2 - Excavation	1	1	1	1	1	1	4	**10**
#3 - Bioremediation	3	5	3	3	3	3	3	**25**
#4 – ISCO	3	3	3	3	3	3	3	**21**
#5 – Thermal Treatment	2	2	2	2	2	2	6	**17**
#6 – Injectable ZVI	3	4	3	4	3	3	4	**22**

Based on the comparative evaluation scores above, Alternative #2 - Excavation of Source Area Saturated Soils received the lowest score.

Comparative Analysis of Groundwater Alternatives

Alternative	Effectiveness	Timeliness	Reliability	Implementability	Risk	Benefit	Cost	**Score (Low = Best)**
#1 – MNA	6	6	4	1	3	4	1	**25**
#2 - Pump and Treat	5	5	4	3	3	3	6	**29**
#3 - Bioremediation	3	3	2	3	2	2	3	**18**

Based on the comparative evaluation scores above, Alternative #3 - Bioremediation in groundwater received the lowest score.

7.0 RECOMMENDED REMEDIAL ACTION PLAN

7.1 SELECTION OF REMEDIAL ACTION ALTERNATIVES

Based on the results of the comparative analysis, Alternative #2 - Excavation of Source Area Saturated Soils and Alternative #3 - Bioremediation in Groundwater are the preferred remedies for abatement of Site impacts. These remedies are effective, reliable, feasible to implement, cost-effective, poses minimal risk, and could achieve the remedial objectives in a timely manner.

ERM anticipates that the sequence of remedial activities will be as follows:

- excavation and off-Site disposal or treatment of saturated source area soils;
- backfill the excavation with clean fill;
- monitor the effects of source area abatement on near-source groundwater quality;
- initiate carbon substrate amendments to abate CVOC impacts to groundwater, as appropriate; and
- continue monitoring groundwater quality over time.

7.2 FEASIBILITY OF ACHIEVING BACKGROUND

The MCP (310 CMR 40.0860(6)(a)) states that achieving background should be considered feasible unless "the incremental cost of conducting the remedial alternative is substantial and disproportionate to the incremental benefit of risk reduction, environmental restoration, and monetary and non-pecuniary values." Using a benchmark comparison approach, ERM evaluated the cost of additional remediation to approach or achieve background to the cost of achieving a condition of “no significant risk” at the Site.

In the case of impacts to groundwater, the remedial technology chosen may be able to approach background. As stated in Section 3.2.2, MA DEP guidance indicates that the “achievement” of background concentrations is considered infeasible for chlorinated ethenes in groundwater. The implementation of Excavation of Source Area Saturated Soils and

Bioremediation in Groundwater will attempt to "approach" background concentrations, as a secondary remedial objective. The feasibility of approaching background will be evaluated based on the success of the remedies in meeting target cleanup goals.

7.3 IMPLEMENTATION SCHEDULE

Raytheon is scheduled to submit the Phase IV RIP, as described in 310 CMR 40.0874, to MA DEP by December 2006. A tentative schedule for Phase IV activities is provided below:

- Submit Draft Phase IV Remedy Implementation Plan (RIP) – Spring 2006

- Implement Phase IV Activities – Summer/Fall 2005

8.0 PUBLIC NOTIFICATION DOCUMENTS

Public involvement activities will be conducted in accordance with the MCP. Specifically, notification letters of availability for the Phase III Remedial Action Plan will be sent to the Chief Municipal Officer and Board of Health for the Town of Wayland. Copies of the Phase III Remedial Action Plan will be available in the public repositories established for this Site. Copies of these notices may be found in Appendix D.

9.0 REFERENCES

Baker, Ralph S., Heron, Gorm, TerraTherm, "In-Situ Delivery of Heat by Thermal Conduction and Steam Injection for Improved DNAPL Remediation". 2004.

Brown, Richard A., Lewis, Richard L., Environmental Resources Management, *In Situ Chemical Reduction, An Evolving Technology, ConSoil Conference*, Bordeaux, France, October 2005.

ERM Draft Phase II - Comprehensive Site Assessment, Former Raytheon Facility, 430 Boston Post Road, Wayland, Massachusetts, ERM, 19 October 2005.

Interstate Technology and Regulatory Cooperation Work Group (ITRC), *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater*, prepared by the In Situ Chemical Oxidation Work Group, June 2001.

LeGrega, Michael D., Phillip L. Buckingham, Jeffrey C. Evans, and The Environmental Resources Management Group, *Hazardous Waste Management.* McGraw-Hill, Inc. 1994.

Lee, M. D., R. L. Raymond, Jr., and C. A. Nehrig. 2004. Source area bioremediation of chlorinated solvents with -edible oil emulsion. In V. S. Magar and M. E. Kelly (eds.), *In Situ and On-Site Bioremediation – 2003. Proceedings of the Seventh International In-Situ and On-Site Bioremediation Symposium. Orlando, FL, June 2003.* Battelle Press, Columbus, OH. Paper A26.

Massachusetts Department of Environmental Protection, Phase III Initial Screening Evaluation of Remedial Alternatives, 18 January 2005.

Massachusetts Department of Environmental Protection, Conducting Feasibility Evaluations under the MCP. Policy #WSC-04-160, 16 July 2004.

McCarty, P., "An overview of anaerobic transformation of chlorinated solvents," in Symposium on Natural Attenuation of Groundwater, EPA/600/R-94/162, pp. 104-108, September 1994.

National Research Council (NRC), *Barrier Technologies for Environmental Management: Summary of a Workshop*, National Academy Press, 1997.

U. S. Environmental Protection Agency, "Field Applications of *In Situ* Remediation Technologies: Chemical Oxidation", EPA/542/R-98/008, September, 1998a.

U.S. Environmental Protection Agency, "Ground Water Currents: Air Sparging/High Vacuum Extraction to Remove Chlorinated Solvents in Ground Water." EPA 542-N-98-004, March 1998b.

U.S. Department of Energy, "Six Phase Soil Heating Demonstrated at U.S. Department of Energy M Area Savannah River Site and 300-Area Hanford Site, Aiken SC and Richland, WA: Innovative Technology Summary Report," Office of Environmental Management, Office of Technology Development, April 1995.

U.S. Environmental Protection Agency, "Ground Water Issue: Steam Injection for Soil and Aquifer Remediation." EPA 540-S-97-505, January 1998c.

U. S. Environmental Protection Agency, *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*, EPA/600/R-98/128, September, 1998d.

Weidemeier, Todd H., Rifai, Hanadi S., Newell, Charles J., Wilson, John T. "Anaerobic Biostimulation of Fuels and Chlorinated Solvents in the Subsurface". 1999a.

Wiedemeier, T.H., Rifai, H.S., Newell, C.J., and Wilson, J.T., *Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface*. John Wiley & Sons, Inc. New York. 1999b.

ERM has over 100 offices
Across the following countries worldwide

Argentina
Australia
Azerbaijan
Belgium
Brazil
Canada
Chile
China
France
Germany
Hong Kong
Hungary
India
Indonesia
Ireland
Italy
Japan
Kazakhstan
Korea
Malaysia
Mexico
The Netherlands
Peru
Poland
Portugal
Puerto Rico
Russia
Singapore
South Africa
Spain
Sweden
Taiwan
Thailand
UK
US
Vietnam
Venezuela

ERM's Boston Office

399 Boylston Street, 6th Floor
Boston, MA 02116
(617) 646-7800
(617) 267-6447 (fax)

ERM