50-~~02~~
09

FINAL RECORD OF DECISION
SOILS AND GROUNDWATER OPERABLE UNIT
ARMY MATERIALS TECHNOLOGY LABORATORY
WATERTOWN, MASSACHUSETTS

Contract No. DAAA15-90-D-0009

September 1996

Prepared by:

Roy F. Weston, Inc.
Weston Way
West Chester, Pennsylvania 19380-1499

Work Order No. 02281-011-001

TABLE OF CONTENTS

LIST OF FIGURES

ACRONYM LIST

AEC	Army Environmental Center
ARARs	Applicable or Relevant and Appropriate Requirements
bgs	below ground surface
BRAC	Base Realignment and Closure
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
EC_{50}	effective concentration for 50% of the test organisms
EPA	U.S. Environmental Protection Agency
FFA	Federal Facilities Agreement
FS	Feasibility Study
GSA	General Services Administration
IRP	Installation Restoration Program
LC_{50}	lethal concentration for 50% of the test organisms
MADEP	Massachusetts Department of Environmental Protection
MCP	Massachusetts Contingency Plan
mg/kg	milligram per kilogram
MTL	Materials Technology Laboratory
NCP	National Contingency Plan
NPL	National Priorities List
NRC	Nuclear Regulatory Commission
O&M	operation and maintenance
PAH	polynuclear aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCE	tetrachloroethylene
POL	petroleum, oil, and lubricants
ppb	parts per billion
ppm	parts per million
RA	risk assessment
RAB	Restoration Advisory Board
RCRA	Resource Conservation and Recovery Act
RfD	reference dose
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
SVOC	semivolatile organic compound
TBC	To Be Considered
TCA	1,1,1-trichloroethane
TCE	trichloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
UCL	upper confidence limit
UST	underground storage tank
VOC	volatile organic compound

DECLARATION FOR THE

RECORD OF DECISION

I. DECLARATION FOR THE RECORD OF DECISION

SITE NAME AND LOCATION

Soils and Groundwater
Army Materials Technology Laboratory
Watertown, Massachusetts

STATEMENT OF PURPOSE AND BASIS

This decision document presents the U.S. Army's selected remedial action for soils and groundwater at the Army Materials Technology Laboratory (MTL), Watertown, Massachusetts. It was developed in accordance with the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) as amended, 42 USC 9601 *et seq.* and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), 40 CFR Part 300, to the extent practicable. The MTL Base Realignment Closure Environmental Coordinator; the Chief of Staff at Army Materiel Command; and the Director of the Office of Site Remediation and Restoration, U.S. Environmental Protection Agency (EPA) Region I have been delegated the authority to approve this Record of Decision.

This decision is based on the Administrative Record that has been developed in accordance with Section 113(k) of CERCLA. The Administrative Record is available for public review at the MTL Base Realignment and Closure (BRAC) Office, Building 313, 395 Arsenal Street, Watertown, Massachusetts, and at the Main Branch of the Watertown Public Library, Watertown, Massachusetts. The Administrative Record Index identifies each of the items considered during the selection of the remedial action. This index is included in Appendix A.

ASSESSMENT OF THE SITE

Actual or potential releases of hazardous substances from soil areas, if not addressed by implementing the response action selected in this Record of Decision, may present an imminent and substantial endangerment to the public health, welfare, or the environment.

DESCRIPTION OF THE SELECTED REMEDY

This remedial action addresses long-term residential and commercial exposure to contaminated soil. It consists of excavating the contaminated soil and transporting the soil for off-site disposal and/or reuse. Excavations are to be backfilled with clean soil. Once contaminated soil is removed, the bottom and sidewalls of the excavation areas will be sampled and analyzed to ensure that site cleanup goals are met. The remedy eliminates the source of the contamination and reduces the potential risk to residents and workers at MTL. The remedy is consistent with the overall remedial strategy for MTL. This remedy was presented as the contingency remedy in the Proposed Plan.

STATE CONCURRENCE

The Commonwealth of Massachusetts has concurred with the selected remedy. Appendix B of this Record of Decision contains a copy of the Declaration of Concurrence.

The foregoing represents the selection of a remedial action by the U.S. Department of the Army and the U.S. Environmental Protection Agency, with the concurrence of the Commonwealth of Massachusetts Department of Environmental Protection.

Concur and recommend for immediate implementation:

ROBERT E. CHASE
BRAC Environmental Coordinator

9/18/96
Date

The foregoing represents the selection of a remedial action by the U.S. Department of the Army and the U.S. Environmental Protection Agency, with the concurrence of the Commonwealth of Massachusetts Department of Environmental Protection.

Concur and recommend for immediate implementation:

BILLY K. SOLOMON
Major General, USA
Chief of Staff
U.S. Army Materiel Command

25 Sep 96
Date

The foregoing represents the selection of a remedial action by the U.S. Department of the Army and the U.S. Environmental Protection Agency, with the concurrence of the Commonwealth of Massachusetts Department of Environmental Protection.

Concur and recommend for immediate implementation:

Linda M. Murphy

LINDA M. MURPHY
Director, Office of Site Remediation and Restoration
U.S. Environmental Protection Agency, Region I

Sept. 26, 1996
Date

II. SITE NAME, LOCATION, AND DESCRIPTION

Army Materials Technology Laboratory Site
Watertown, Massachusetts

The MTL property is located on 48 acres of land in Watertown, Massachusetts, on the north bank of the Charles River, approximately 5 miles west of downtown Boston (see Figure 1). The installation is bounded on the north by Arsenal Street, on the south by the Charles River, on the east by Talcott Avenue, and on the west by the Veterans of Foreign Wars, USA, Burnham Manning Post No. 105, and private property (see Figure 2). Figure 2 also shows the proposed reuse zones—Zones 1 through 3 represent developed areas of the site, and Zone 4 and River Park represent undeveloped areas. MTL formerly contained 15 buildings and 15 associated structures. Included in the U.S. Army-owned Superfund site are 11 acres of land south of the enclosed portion of the installation and abutting the Charles River. This land consists of a public park and a yacht club south of North Beacon Street. The Commonwealth of Massachusetts has been granted an easement to this property.

The overburden deposits of the MTL site generally consist of (in ascending order) basal glacial till directly overlying bedrock, silty clay with some fine sand and gravel, interlayered outwash deposits of sand and gravel with some fine materials, and fill near the surface. In general, depth to groundwater is within 5 to 10 ft of the ground surface along the southeastern boundary of the facility adjacent to the Charles River. Depth to groundwater reaches a maximum of approximately 30 ft below ground surface (bgs) along the eastern boundary of the site, where the ground surface reaches its maximum elevation and coarse-grained deposits allow rapid soil drainage. Depth to groundwater in the central portion of the facility is on the order of 15 to 20 ft bgs for shallow wells and 20 to 25 ft bgs for deep (A-series) wells. Groundwater flow in both the deep and shallow overburden is south-southeast toward the Charles River (see Figure 3). The site groundwater meets the Commonwealth of Massachusetts definition of a nondrinking water aquifer (GW-3); therefore, there is no risk of exposure to human receptors. With the exception of a small part of the River Park, the site is not located within the Charles River 100-year floodplain, and there are no wetlands on-site. A more complete description of the site is presented in Sections 1 and 3 of the Remedial Investigation (RI) report (WESTON, 1994).

Because of the complexity of this site, the site has been divided into three distinct operable units, which are being handled separately. The first operable unit is for the outdoor areas of the site, specifically soil and groundwater. This Record of Decision addresses this operable unit. A separate CERCLA Record of Decision was signed in June 1996 to expedite the cleanup of a small area of soil contamination adjacent to Building 131. This expedited cleanup was implemented to facilitate future reuse. Contamination as a result of releases of petroleum, oil, and lubricants (POL) is not considered part of the evaluation of this operable unit because remedial actions under CERCLA do not extend to POL. Actions required to address POL are being conducted under the jurisdiction of the Massachusetts Department of Environmental Protection (MADEP). The second operable unit is for the remediation of site buildings, which is being performed under state cleanup authority. A Massachusetts Contingency Plan (MCP) Phase III Remedial Action Plan for the site buildings was submitted to MADEP in January 1996. The third operable unit involves Charles River surface water and sediments. Investigation of the Charles River is being implemented by the Army under CERCLA with EPA as the lead agency. Any future activities for the Charles River operable unit will not impact site reuse.

III. SITE HISTORY AND ENFORCEMENT ACTIVITIES

A. Land Use and Response History

The Watertown Arsenal facility has been in operation since 1816. It was established for the purposes of storage, repair, cleaning, and issue of small arms and ordnance supplies. Throughout the 1800s and until World War II, the installation's mission was continually expanded to include weapons development and production, and materials research experimentation and development. At the height of its activity (just after World War II), the site encompassed 131 acres with 53 buildings and structures and employed 10,000 people. In 1960, the Army's first nuclear research reactor was constructed, and it was used in research activities until its deactivation in 1970. Depleted uranium machining, milling, forging, and casting also were conducted on-site. Decommissioning of the reactor in accordance with the Nuclear Regulatory Commission (NRC) standards has been completed.

An operational phaseout of the arsenal was begun in 1967. At that time, approximately 55 acres of land were sold to the Town of Watertown, and 28.5 acres were transferred to the General Services Administration (GSA). At that time, the 48-acre MTL site was created from the remaining arsenal land. The parcel sold to Watertown currently contains a shopping mall, condominiums, and a public park and playground. Land transferred to GSA has undergone various improvements, including paving in some portions.

Previous investigations that pertain to environmental conditions at MTL were completed between September 1968 and December 1987. In 1987, the Army Environmental Center (AEC) initiated additional environmental investigations under the Army's Installation Restoration Program (IRP). A Preliminary Assessment/Site Inspection completed in 1988 was performed as the first step of this program. In December 1988, MTL was included on a list of U.S. Department of Defense installations recommended for closure; this list was subsequently approved by Congress. In March 1989, AEC was assigned responsibility for centrally managing the BRAC Environmental Restoration Program.

Although unrelated to the Superfund process, several cleanup activities have occurred at the MTL site. In 1991, six on-site underground storage tanks (USTs) were removed. Also in 1991 during the RI, a fuel oil leak was discovered at Building 227. A leaking oil line was repaired and contaminated soil was excavated to a 14-ft depth next to the building. Excavation ceased when it was determined that building structural damage would occur under continued excavation. The excavation was backfilled after approval by MADEP. Residual contamination exists, and continued cleanup efforts are under the jurisdiction of MADEP under the MCP. Because Section 101(14) of CERCLA contains an exclusion for petroleum, the cleanup of petroleum-contaminated soils at MTL is being conducted under MADEP jurisdiction and is not addressed in this Record of Decision.

The Army also has completed decommissioning of the nuclear reactor, and low-level radioactive waste has been removed. In 1994, sitewide radiological decontamination was completed to meet cleanup standards set by NRC, MADEP, and the Massachusetts Department of Public Health. Asbestos removal also has occurred in some of the site buildings.

In addition to the work previously completed, the Army will be conducting remediation of chemical contamination of interior building surfaces. For more information on this issue, refer to the Phase III Remedial Action Plan. Concurrent with this remediation, the Army will be

IV. COMMUNITY PARTICIPATION

Throughout the site's history, community concern and involvement have been high. The MTL Public Affairs Office has been active in responding to requests for information, concerns, and questions from the community. In March 1989, the Watertown Town Manager, in conjunction with the Town Council, formed the Watertown Arsenal Reuse Committee to study the community impact of the MTL closure. In addition, the MTL Restoration Advisory Board (RAB) was established in January 1994 to facilitate the exchange of information between MTL and the community. RAB members include members of the Army, EPA and state regulatory officials, and members of the community. MTL, EPA, and MADEP officials have participated in meetings of the Watertown Arsenal Reuse Committee as well as Town Council meetings, conducted public site tours, and have met with a number of community leaders and environmental and community organizations. The Army also has kept the community and other interested parties apprised of the site activities through fact sheets and press releases.

On June 7, 1991, the Army held an informational meeting in Watertown to discuss the results of the Phase 1 RI.

In February 1992, the Army released a Public Involvement and Response Plan outlining a program to address community concerns and keep citizens informed about and involved in activities during remedial activities. The Army revised and updated this plan, and in May 1995 released an updated Community Relations Plan, which summarized information about the environmental studies, identified community concerns, and outlined additional community relations activities.

In November 1993, the MTL Reuse Plan was completed by Goody, Clancy, and Associates. This plan was prepared for the Town of Watertown and the Watertown Arsenal Reuse Committee. Within this plan, the site was divided into zones that could be reused for commercial or residential development. The land reuse scenarios developed in this plan were based on input from the Town Council. The Reuse Plan was approved and accepted by the Town Council in January 1994.

On June 24, 1996, the Army made the administrative record available for public review at the installation and the Watertown Public Library. A copy of the Administrative Record Index is on file at the EPA's office in Boston. The Army published a notice and brief analysis of the Proposed Plan in *The Watertown Sun* on May 1 and May 8, 1996, and *The Watertown Press* on May 2 and May 9, 1996, and made the plan available to the public in the Administrative Record.

On April 16, 1996, the Army held an informational meeting to discuss the results of the RI and the cleanup alternatives presented in the FS and to present the Proposed Plan. During this meeting, the Army answered questions from the public. From April 22 to May 22, 1996, the Army held a 30-day public comment period to accept public comments on the alternatives presented in the FS and the Proposed Plan, and on any other documents released previously to the public. On May 13, 1996, the Army held a public hearing to discuss the Proposed Plan and to accept any oral comments. A transcript of this meeting, the comments received, and the Army's response to comments are included in the attached responsiveness summary in Appendix C.

VI. SUMMARY OF SITE CHARACTERISTICS

Section 1 of the FS contains an overview of the RI. The significant findings of the RI specific to this operable unit are summarized in the following sections.

A. Soil Investigation

Soil investigation results are as follows:

- Soil samples collected from beneath concrete floors in Buildings 43, 311, and 312 showed elevated concentrations of semivolatile organic compounds (SVOCs). Contaminant concentrations were generally highest at the ground surface.
- Elevated concentrations of polynuclear aromatic hydrocarbons (PAHs) were detected in soil samples collected from borings completed in the grassy area between North Beacon Street and the Charles River. The highest levels of PAHs were detected adjacent to Buildings 39 and 227/60, and in the parking lot between Buildings 37 and 131 (see Figure 4). The maximum concentration of total PAHs detected was 99 parts per million (ppm).
- Polychlorinated biphenyls (PCBs) were detected at levels above the EPA action level of 1 ppm (maximum concentration of 4.9 ppm) at two site locations, near Structure 244/245 (propellant storage area), and at the eastern fenceline, approximately 100 ft east of the tennis courts (see Figure 4).
- The analytical results showed that the total uranium activity in all soils was below the federal maximum allowable standards.
- Metals concentrations (primarily lead) had their highest concentrations reported in shallow (less than 1 ft bgs) soil samples collected from immediately outside Buildings 39, 43, 311, 313, and 656, with a maximum lead concentration of 7,200 ppm (mg/kg).
- Pesticides were detected in surface soil samples, particularly in the grassy areas in the southeastern and central portions of the site and along the southern fenceline (maximum total pesticide concentration of 11 ppm).

In regard to the removal at Building 227 of soil contaminated by a fuel leak, analysis of excavated soils indicated the presence of fuel-related compounds. Excavation of soil was stopped when it was determined that structural damage to the building would occur if excavation continued. Residual fuel-contaminated soil remains and has yet to be fully characterized. Because Section 101(14) of CERCLA contains an exclusion for petroleum, the cleanup of petroleum-contaminated soils at MTL is being conducted under MADEP jurisdiction and is not addressed in this Record of Decision.

B. Groundwater Investigation

With the exception of one well, all upgradient wells showed detectable quantities of chlorinated solvents, which suggests that off-site sources have caused or aggravated on-site groundwater contamination. Chlorinated solvents identified in these wells include tetrachloroethylene (PCE), trichloroethylene (TCE), and 1,1,1-trichloroethane (TCA), with a maximum total volatile organic manholes upstream of Building 43 were lower, the contamination in the manhole connected to the drainlines from Building 43 appeared to have been augmented by former sources in Building 43. The storm sewer lines and sanitary sewer lines are separate systems; there are no sanitary sewer outfalls on-site from MTL to the Charles River.

In a separate remediation to remove radiological contamination, manholes along North Beacon Street, Arsenal Street, and exiting Buildings 312 and 43 were remediated. A subsequent radiological survey of the sewer line along Arsenal Street showed no remaining radiological contamination. The results are being reviewed by the NRC to determine whether any additional measures are required.

A complete discussion of site characteristics is presented in the RI Report, Section 4.

2. Exposure assessment, which identified actual or potential exposure pathways, characterized the potentially exposed populations, and determined the extent of possible exposure.

3. Toxicity assessment, which considered the types and magnitude of adverse health effects associated with exposure to hazardous substances.

4. Risk characterization, which integrated the three earlier steps to summarize the potential and actual risks posed by hazardous substances in the soil, including cancer and noncancer risks.

The results of the human health RA for this operable unit are discussed in the following subsections, followed by the conclusions of the ecological RA.

A. Human Health Risks from Site Soils

Fifteen contaminants of concern were selected for evaluation in the RA (see Table 1). These contaminants constitute a representative subset of the more than 40 contaminants identified at the site during the RI. Summaries of the health effects of each of the contaminants of concern are presented in Appendix R of the RI. The RA was originally conducted outside of the CERCLA program and some aspects of the RA do not strictly adhere to current guidance. However, these differences did not affect the overall outcome of the RA.

Potential human health effects associated with exposure to the contaminants of concern were estimated quantitatively or qualitatively through the development of several hypothetical exposure pathways. These pathways were developed to reflect the potential for exposure to hazardous substances based on the present uses, potential future uses, and location of the site. As stated previously, the site was divided into five different units—Zones 1 through 4 and River Park. An assessment was performed for each possible reuse; Zones 1 through 3 were assessed for commercial and residential reuse; Zone 4 was assessed for residential and public access reuse; and River Park was assessed for public access only. The following is a summary of the exposure pathways evaluated. A more thorough description is presented in Section 6 of the RI.

For future site residents, incidental soil ingestion and dermal contact were evaluated for the individual young child (age 1 to 2 years) for 1 year, child (age 1 to 8 years) for 7 years, and adult for 30 years. Resident exposure was based on 153 days per year for soil ingestion and 107 days per year for dermal contact. Adult and child visitors in Zone 4 were evaluated for soil exposure of 56 days for a 1-year duration. Adult and child visitors to River Park had the same soil exposure scenario as Zone 4 visitors, but also included incidental ingestion and dermal contact with Charles River surface water and sediments during swimming activities; exposure was based on 56 days for a 1-year exposure. Exposure for commercial workers was based on soil ingestion and dermal contact for 250 days per year for 25 years. Exposure for construction workers was based on soil ingestion and dermal contact for 18 days over a 1-year period.

Excess lifetime cancer risks were determined for each exposure pathway by multiplying the exposure level with the chemical-specific cancer factor. Cancer potency factors have been developed by EPA from epidemiological or animal studies to reflect a conservative upper bound of the risk posed by potentially carcinogenic compounds. That is, the true risk is unlikely to be greater than the risk predicted. The resulting risk estimates are expressed in scientific notation as a probability (e.g., 1E-06 for 1 in 1,000,000) and indicate (using this example) that an average individual is not likely to have greater than a 1-in-1-million chance of developing cancer over 70 years as a result of site-related exposure to the compound at the stated concentration.

Current regulatory practice considers cancer risks to be additive when assessing exposure to a mixture of hazardous substances.

A hazard index also was calculated for each pathway as the measure of the potential for noncancer health effects. The hazard index for a pathway is determined by using the sum of the hazard quotients for each contaminant in that specific pathway. A hazard quotient for each contaminant is calculated by dividing the exposure level by the reference dose (RfD) or other suitable benchmark for noncancer health effects for an individual compound. Reference doses have been developed by EPA to protect sensitive individuals over the course of a lifetime, and they reflect a daily exposure level that is likely to be without an appreciable risk of an adverse health effect. RfDs are derived from epidemiological or animal studies and incorporate uncertainty factors to help ensure that adverse health effects will not occur. The hazard quotient is often expressed as a single value (e.g., 0.3) indicating the ratio of the stated exposure as defined to the reference dose value (in this example, the exposure as characterized is approximately one-third of an acceptable exposure level for the given compound). The hazard quotient is considered additive only for compounds that have the same or similar toxic endpoint and the sum is referred to as the hazard index. For example, the hazard quotient for a compound known to produce liver damage should not be added to a second whose toxic endpoint is kidney damage.

Tables 2 through 10 summarize the cancer and noncancer risks for the 14 contaminants of concern in soil, listed in Table 1, for each of the possible site scenarios evaluated to reflect present and potential future commercial or residential reuse. Based on this summary, the majority of the cancer risk is due to soil ingestion. All 14 contaminants of concern contribute to this risk. There is no significant risk from the construction worker scenario for all zones. The hazard index for all zones and all exposure scenarios was less than the target number of 1.

As a separate document, a report entitled *Addendum to Human Health Evaluation* (WESTON, July 1996) was prepared. This evaluated the risks to children (age 1 to 8 years) and youths (age 7 to 17 years) as trespassers onto areas of the site remediated to commercial cleanup levels. The results of this evaluation showed that for exposure to soils (oral and dermal exposure), the total hazard index for both children and youths was less than the target number of 1. The total cancer risk for children and youths was within the EPA acceptable risk range.

B. Ecological Risks from Site Soils

As part of RI evaluations of the MTL facility, an assessment of risks to ecological receptors at the installation was conducted. The results of this assessment are presented in a report entitled *Baseline Risk Assessment—Environmental Evaluation* (Life Systems, Inc., December 1993). As part of the ecological RA, it was determined that terrestrial populations and communities in the area of the installation were not of ecological concern. For this reason, the only exposure endpoints evaluated were fish inhabiting the Charles River, and migratory birds visiting the river on a transient basis.

After the MTL site was added to the NPL, at the request of EPA, the issue of risks posed to terrestrial populations at the facility was revisited, and a *Terrestrial Ecological Risk Assessment* (WESTON, 1995) that complies with the substantive requirements of CERCLA was produced. This evaluation characterized risk to terrestrial wildlife, terrestrial vegetation, and soil invertebrates posed by MTL soil contaminants. Most of the MTL site has limited potential as ecological habitat. Suitable habitat for terrestrial vegetation and wildlife is restricted to the

Table 3

Summary of Chemical Cancer Risks—Zone 2 and 3 Resident

Potentially Exposed Population	Exposure Point	Exposure Medium	Exposure Route	Cancer Risk
Resident Adult	Zone 2	Soil (not excavated)	Ingestion Dermal	4E-05 6E-06
	River Park	Soil	Ingestion Dermal	1E-05 1E-06
	Charles River	Surface Water	Ingestion Dermal	1E-10 8E-09
		Sediment	Ingestion Dermal	2E-06 5E-09
		Fish	Ingestion	5E-08
	Zone 4—Open Area	Soil	Ingestion Dermal	4E-06 3E-06
			Total Site Risk:	7E-05
Resident Adult	Zone 3	Soil (not excavated)	Ingestion Dermal	5E-05 6E-06
	River Park	Soil	Ingestion Dermal	1E-05 1E-06
	Charles River	Surface Water	Ingestion Dermal	1E-10 8E-09
		Sediment	Ingestion Dermal	2E-06 5E-09
		Fish	Ingestion	5E-08
	Zone 4—Open Area	Soil	Ingestion Dermal	4E-06 3E-06
			Total Site Risk:	8E-05

Table 5

Summary of Chemical Cancer Risks—Worker Populations

Potentially Exposed Population	Exposure Point	Exposure Medium	Exposure Route	Cancer Risk
Commercial Worker	Zone 1	Soil	Ingestion	3E-06
	Zone 2	Soil	Ingestion	1E-05
	Zone 3	Soil	Ingestion	2E-05
Construction Worker	Zone 1	Soil	Ingestion	6E-08
		Dust	Inhalation	9E-07
			Total Risk:	1E-06
	Zone 4	Soil	Ingestion	2E-07
		Dust	Inhalation	9E-07
			Total Risk:	1E-06

Table 7

Summary of Hazard Indices—Zone 1 Resident

Potentially Exposed Population	Exposure Point	Exposure Medium	Exposure Route	Subchronic Hazard Index	Chronic Hazard Index
Resident Child	Zone 1	Soil (not excavated)	Ingestion Dermal	5E-02 1E-02	5E-02 1E-02
	River Park	Soil	Ingestion Dermal	3E-02 4E-03	2E-02 4E-03
	Charles River	Surface Water	Ingestion Dermal	4E-06 1E-04	3E-05 1E-03
		Sediment	Ingestion Dermal	1E-03 9E-04	2E-03 1E-02
		Fish	Ingestion	—	1E-02
	Zone 4—Open Area	Soil	Ingestion Dermal	7E-02 2E-02	4E-02 2E-02
	Total Site Hazard Index:			2E-01	2E-01
Resident Child	Zone 1	Soil (excavated)	Ingestion Dermal	5E-02 9E-03	4E-02 1E-02
	River Park	Soil	Ingestion Dermal	3E-02 4E-03	2E-02 4E-03
	Charles River	Surface Water	Ingestion Dermal	4E-06 1E-04	3E-05 1E-03
		Sediment	Ingestion Dermal	1E-03 9E-04	2E-03 1E-02
		Fish	Ingestion	—	1E-02
	Zone 4—Open Area	Soil	Ingestion Dermal	7E-02 2E-02	4E-02 2E-02
	Total Site Hazard Index:			2E-01	2E-01

Table 9

Summary of Hazard Indices—Zone 4 Resident

Potentially Exposed Population	Exposure Point	Exposure Medium	Exposure Route	Subchronic Hazard Index	Chronic Hazard Index
Resident Child	Zone 4	Soil (excavated)	Ingestion Dermal	2E-01 2E-02	1E-01 3E-02
	River Park	Soil	Ingestion Dermal	3E-02 4E-03	2E-02 4E-03
	Charles River	Surface Water	Ingestion Dermal	4E-06 1E-04	3E-05 1E-03
		Sediment	Ingestion Dermal	1E-03 9E-04	2E-03 1E-02
		Fish	Ingestion	—	1E-02
			Total Site Hazard Index:	2E-01	2E-01

southeastern corner of the site. This area of the site, which includes Zone 4 and River Park, was the focus of the terrestrial ecological RA. The terrestrial species evaluated and their relevant exposure pathways are as follows:

- Short-tailed shrew:
    - Ingestion of soil invertebrates (e.g., earthworms).
    - Incidental ingestion of soil.
- White-footed mouse:
    - Ingestion of vegetation (e.g., seeds).
    - Incidental ingestion of soil.
- American robin:
    - Ingestion of soil invertebrates (e.g., earthworms).
    - Incidental ingestion of soil.
- Song sparrow:
    - Ingestion of vegetation (e.g., seeds).
    - Incidental ingestion of soil.
- Terrestrial plants:
    - Direct contact with soil.
    - Absorption/concentration from soil.
- Soil invertebrates:
    - Direct contact with soil.
    - Absorption/concentration from soil.

The potential risk posed to ecological receptors (i.e., shrew, mouse, robin, and sparrow) was assessed by comparing estimated daily doses to reference toxicity values. This comparison, described as a hazard quotient, was calculated for each contaminant by dividing the estimated daily dose by the reference toxicity values. Hazard quotients were summed across all exposure pathways for each contaminant, by receptor, to develop chemical-specific hazard indices. Hazard quotients and hazard indices were not calculated for plants and soil invertebrates. Instead, available toxicity data were presented and compared directly to soil chemical data.

The hazard indices for all ecological receptors are presented in Section 5 of the *Terrestrial Ecological Risk Assessment* (WESTON, June 1995). The hazard quotients and hazard indices for ecological receptors were calculated using two exposure concentrations: the mean and the 95% upper confidence limit (UCL) of the mean.

A hazard index of <1 indicates that adverse effects are not likely to occur, and no action is required. A hazard index of >10 indicates that risks are at a level of potential concern, and may warrant action, depending on the nature of the risk, the nature of the site and surrounding

> Chlordane exceeded concentrations at which sperm count depressions have been observed in earthworms, and DDE exceeded concentrations at which epidermal changes have been observed in earthworms.

The presence of hazardous substances in soil at this operable unit, if not addressed by implementing the remedial action selected in this Record of Decision, may present an unacceptable risk to human health and the environment. Remedial actions were developed to address the risks associated with site soils.

- Alternative(s) that involve little or no treatment but provide protection through engineering or institutional controls.

- A no-action alternative.

As discussed in Section 3 of the FS, the RI/FS identified, assessed, and screened technologies based on implementability, effectiveness, and cost. These technologies were combined into alternatives for soil remediation. Section 4 of the FS presented the remedial alternatives developed by combining the technologies identified in the previous screening process in the categories identified in Section 300.430(e)(3) of the NCP. The purpose of the initial screening was to narrow the number of potential remedial actions for further detailed analysis while preserving a range of options. Each alternative was then evaluated and screened in Section 4 of the FS.

In summary, of the six soil remedial alternatives screened in Section 4 of the FS, all six were retained for detailed analysis. Table 11 identifies the six alternatives that were retained through the screening process.

IX. DESCRIPTION OF ALTERNATIVES

This section provides a narrative summary of each alternative evaluated. A detailed tabular assessment of each alternative is presented in Table 6-1 of the FS.

In the FS, all alternatives were analyzed and costs determined for the three possible site reuse scenarios (as developed previously by the Watertown Arsenal Reuse Committee's approved MTL Reuse Plan). These scenarios are defined fully in Section 3 of the FS. The scenario defined as Reuse Scenario 3 is consistent with the Town of Watertown's intended future use of MTL as outlined in the Reuse Plan. The Reuse Plan was developed by the Arsenal Reuse Committee and approved by the Watertown Town Council. This reuse scenario is defined as a mixture of commercial and residential reuse for developed areas (commercial reuse for Zones 1 and 2 and residential reuse for Zone 3) and public access for undeveloped areas (Zone 4 and the River Park). This reuse scenario was used in establishing specific soil cleanup goals in each zone and determining the soil areas to be remediated. The approximate locations of areas requiring soil remediation are shown in Figure 4. An estimated total soil volume of 23,600 yd^3 will require remediation. This represents an increase in soil volume of approximately 800 yd^3 from the Proposed Plan. Cost estimates for the alternatives below have been adjusted accordingly to reflect the change in soil volume. See Section XIII for further description of soil volume and cost changes.

The following alternatives were evaluated (the designation "S" indicates that these alternatives refer to soil):

Alternative S1—No Action: This alternative was evaluated in detail in the FS to serve as a baseline for comparison with the other remedial alternatives under consideration. Under this alternative, no active or passive treatment or containment of contaminated areas would occur. The only activity would be an EPA-required site review every 5 years.

Estimated Time for Design and Construction: None.
Estimated Time of Operation: Indefinitely.
Estimated Capital Cost: None.
Estimated Operation and Maintenance Cost (30-year net present worth): $27,400.
Estimated Total Cost (30-year net present worth): $27,400.

Alternative S2—Institutional Controls: Under this alternative, no treatment or containment of contaminated areas would occur. The only effort that would be made to restrict potential exposure to site contaminants would be through the use of institutional controls, such as installing warning signs and fences around contaminated areas and imposing deed restrictions on site real estate transfer.

Estimated Time for Design and Construction: 6 months.
Estimated Time of Operation: Indefinitely.
Estimated Capital Cost: $12,000.
Estimated Operations and Maintenance Cost (30-year net present worth): $166,600.
Estimated Total Cost (30-year net present worth): $178,600.

Alternative S3—Capping of Soils: Alternative S3 would not involve removal of the contaminated soil. Instead, the contaminated areas would be covered with a permanent asphalt cap. The cap, which would prevent contact with the contaminated soil, would require long-term maintenance.

Estimated Time for Design and Construction: 32 months.
Estimated Time of Operation: Indefinitely.
Estimated Capital Cost: $2,868,000.
Estimated Operation and Maintenance Cost (30-year net present worth): $2,388,000.

Estimated Time for Design and Construction: 24 months.
Estimated Time of Operation: 6 to 8 months.
Estimated Capital Cost: $5,556,000.
Estimated Operations and Maintenance Cost (30-year net present worth): $27,000.
Estimated Total Cost (30-year net present worth): $5,583,000.

Alternative S5—Option B: Soil Excavation and Treatment Using On-Site Solvent Extraction: This alternative involves an on-site physical separation treatment called solvent extraction. In this alternative, all soil exceeding cleanup criteria would be excavated. Excavated material would be stockpiled on-site until treatment. During treatment, the contaminants in the soil would be removed by mixing the soil with a nontoxic solvent. Contaminants would be dissolved from the soil into the solvent. The solvent would be collected and the contaminants recovered from the solvent. The solvent would be recycled, and recovered contaminants would be disposed of off-site or treated on-site. The treated soil would be used to backfill the excavations. Any metals-contaminated soil requiring remediation would be excavated and disposed of off-site.

Estimated Time for Design and Construction: 30 months.
Estimated Time of Operation: 9 to 12 months.
Estimated Capital Cost: $11,828,000.
Estimated Operation and Maintenance Cost (30-year net present worth): $27,000.
Estimated Total Cost (30-year net present worth): $11,855,000.

Alternative S6—Soil Excavation and Off-Site Disposal/Reuse: In this alternative, all soil exceeding cleanup criteria would be excavated. Excavated material would be divided into hazardous and nonhazardous waste. All excavated soil would be disposed of off-site. Hazardous soil would be disposed of at a hazardous waste landfill. Nonhazardous waste would be disposed of at a nonhazardous landfill and/or an asphalt batching facility. The excavations would be backfilled with clean soil.

Estimated Time for Design and Construction: 6 months.
Estimated Time of Operation: 6 to 9 months.
Estimated Capital Cost: $5,741,000.
Estimated Operation and Maintenance Cost (30-year net present worth): $27,000.
Estimated Total Cost (30-year net present worth): $5,768,000.

Modifying Criteria—The modifying criteria are used in the final evaluation of remedial alternatives generally after the lead agency has received public comment on the RI/FS and Proposed Plan:

8. **State acceptance** addresses the state's position and key concerns related to the selected remedy and other alternatives, and the state's comments on ARARs or the proposed use of waivers.

9. **Community acceptance** addresses the public's general response to the alternatives described in the Proposed Plan and RI/FS.

A detailed assessment of each alternative according to the nine criteria is presented in Table 12.

Following the detailed analysis of each individual alternative, a comparative analysis, focusing on the relative performance of each alternative against the nine criteria, was conducted. This comparative analysis is included in Section 6 of the FS.

B. Discussion of Alternatives

The following subsections present the nine criteria and brief narrative summaries of the alternatives and the strengths and weaknesses according to the detailed comparative analysis.

Overall Protection of Human Health and the Environment—Successful application of Alternatives S4 (Options A, B, and C); S5 (Options A and B); and S6 would provide the highest level of overall protection by preventing direct contact with and ingestion of contaminants in site soil. Under these alternatives, the soil contaminants would be removed and treated on-site, treated off-site, or disposed of off-site. Alternative S4—Options A and C and Alternative S5—Options A and B would require treatability testing and/or pilot testing to determine whether cleanup goals would be achieved.

Alternative S3 also provides protection, but at a lesser level than Alternatives S4 through S6. Under Alternative S3, protection is provided by a cap, which would prevent direct contact with contaminated soil; however, contaminants would remain in-place, and protection would depend on continued cap maintenance. Under Alternative S2, protection of human health would be achieved through certain measures already taken to prevent people from coming into direct contact with and possible ingestion of contaminated materials at the site, provided such measures are maintained and/or improved. However, risks to the environment would not be controlled through such security measures, therefore, Alternative S2 would provide a minimal level of overall protection. Alternative S1 provides no level of overall protection.

Compliance with ARARs—There are no chemical-specific ARARs for this site because there are no promulgated soil cleanup standards. All of the alternatives meet the location- and action-specific ARARs (if applicable).

Long-Term Effectiveness and Permanence—Successful application of Alternatives S4 (Options A, B, and C); S5 (Options A and B); and S6 provides a similar degree of long-term effectiveness and permanence because all material that results in unacceptable risk based on intended use is removed and either treated on-site or taken off-site for treatment or disposal. Alternative S3, which isolates contaminants beneath a cap, provides a lesser degree of effectiveness and permanence, because effective containment of contaminants depends on continued cap

Table 12

Comparison of Soil Alternatives
(Continued)

Criteria	Alternative S1 No Action	Alternative S2 Institutional Controls	Alternative S3 Capping of Soils	Alternative S4 Option A Treatment Using On-Site Incineration	Alternative S4 Option B Treatment Using Off-Site Incineration	Alternative S4 Option C Treatment Using Thermal Desorption	Alternative S5 Option A Treatment Using Chemical Oxidation	Alternative S5 Option B Treatment Using Solvent Extraction	Alternative S6 Off-Site Disposal or Reuse
Long-Term Effectiveness									
• Adequacy and Reliability of Controls	Not applicable.	Not adequate to meet remedial action objectives for contaminated soils.	Asphalt cap would require a long-term maintenance commitment and institutional controls.	Soil contaminants would be destroyed by incineration, thereby eliminating the need for long-term controls.	Soil contaminants would be destroyed by incineration, thereby eliminating the need for long-term controls.	Soil contaminants would be removed and treated separately, thereby eliminating the need for long-term controls.	Soil contaminants would be destroyed by chemical oxidation, thereby eliminating the need for long-term controls.	Soil contaminants would be extracted, thereby eliminating the need for long-term controls.	Contaminated soils would be removed from the site; however, disposed of soils would have to be managed in a landfill indefinitely.
• Magnitude of Residual Risk	Risk not reduced.	No reduction in risk to ecological receptors.	Residual risk would be minimized as long as cap is properly maintained.	Risk would be reduced to background levels of contaminants (within NCP acceptable levels).	Risk would be reduced to background levels of contaminants (within NCP acceptable levels).	Risk would be reduced to background levels of contaminants (within NCP acceptable levels).	Risk would be reduced to background levels of contaminants (within NCP acceptable levels).	Risk would be reduced to background levels of contaminants (within NCP acceptable levels).	Risk would be reduced to background levels of contaminants (within NCP acceptable levels).
Reduction of Toxicity, Mobility, and Volume of Contaminants Through Treatment									
• Treatment Process Used and Materials Treated	Not applicable.	Not applicable.	An asphalt cap would provide a physical barrier preventing direct human receptor contact with risk-based contaminated soils.	Incineration would permanently remove contaminants of concern by thermal destruction.	Incineration would permanently remove contaminants of concern by thermal destruction.	Thermal desorption would permanently remove contaminants from site soil to be treated or destroyed separately.	Chemical oxidation would permanently destroy soil contaminants.	Solvent extraction would permanently remove soil contaminants and subsequently treat them.	Excavation and off-site disposal would not treat or destroy contaminants but would limit their mobility.

Table 12

Comparison of Soil Alternatives (Continued)

Criteria	Alternative S1 No Action	Alternative S2 Institutional Controls	Alternative S3 Capping of Soils	Alternative S4 Option A Treatment Using On-Site Incineration	Alternative S4 Option B Treatment Using Off-Site Incineration	Alternative S4 Option C Treatment Using Thermal Desorption	Alternative S5 Option A Treatment Using Chemical Oxidation	Alternative S5 Option B Treatment Using Solvent Extraction	Alternative S6 Off-Site Disposal or Reuse
Short-Term Effectiveness									
• Protection of Community During Implementation	Not applicable.	Institutional controls would restrict direct contact with soils.	Erosion and sedimentation as well as dust controls would be implemented during paving operations.	Erosion and sedimentation as well as dust controls would be implemented during excavation. Heavy truck traffic would result.	Erosion and sedimentation as well as dust controls would be implemented during excavation. Heavy truck traffic would result.	Erosion and sedimentation as well as dust controls would be implemented during excavation.	Erosion and sedimentation as well as dust controls would be implemented during excavation.	Erosion and sedimentation as well as dust controls would be implemented during excavation.	Erosion and sedimentation as well as dust controls would be implemented during excavation. Heavy truck traffic would result.
• Protection of Workers	Not applicable.	Not applicable.	Workers would be adequately protected during construction.	Workers would be adequately protected during soil remediation.	Workers would be adequately protected during soil remediation.	Workers would be adequately protected during soil remediation.	Workers would be adequately protected during soil remediation.	Workers would be adequately protected during soil remediation.	Workers would be adequately protected during soil remediation.
Implementability									
• Ability to Construct and Operate the Technology	Not applicable.	Not applicable.	Asphalt capping uses ordinary paving techniques.	Mobile incinerators are widely used and easily constructed and operated. Test burns would be required.	Off-site incinerators exist and are easily accessed.	Thermal desorption units are commercially available and easily operated. Pilot tests would be required.	Mobile chemical oxidation units can be easily installed and operated.	Solvent extraction units are commercially available and easily installed and operated.	Excavation and off-site disposal can be easily implemented through regular excavation activities.
• Ease of Site Preparation	Not applicable.	Not applicable.	Easily performed.	No site preparation needed.	No site preparation needed.	No site preparation needed.	No site preparation needed.	No site preparation needed.	No site preparation needed.

Table 12

Comparison of Soil Alternatives
(Continued)

Criteria	Alternative S1 No Action	Alternative S2 Institutional Controls	Alternative S3 Capping of Soils	Alternative S4 Option A Treatment Using On-Site Incineration	Alternative S4 Option B Treatment Using Off-Site Incineration	Alternative S4 Option C Treatment Using Thermal Desorption	Alternative S5 Option A Treatment Using Chemical Oxidation	Alternative S5 Option B Treatment Using Solvent Extraction	Alternative S6 Off-Site Disposal or Reuse
State Acceptance	Not considered to be acceptable. Does not represent a permanent solution.	Not considered to be acceptable. Does not represent a permanent solution.	Not considered to be acceptable. Does not represent a permanent solution.	Is considered to be acceptable. Represents a permanent solution.	Is considered to be acceptable. Represents a permanent solution.	Is considered to be acceptable. Represents a permanent solution.	Is considered to be acceptable. Represents a permanent solution.	Is considered to be acceptable. Represents a permanent solution.	Is considered to be acceptable. Represents a permanent solution.
Community Acceptance	Not considered to be acceptable.	Not considered to be acceptable.	Not considered to be acceptable.	Not considered to be acceptable.	Considered to be acceptable.	Considered to be acceptable.	Considered to be acceptable.	Considered to be acceptable.	Considered to be acceptable

effective manner. Alternative S5—Option B could require multiple pilot studies to establish the best specific solvent to use; there are several proprietary solvent extraction systems that use different solvents. Alternative S6 is proven and can be implemented without requiring treatability testing. Implementation could be lengthy because of the volume of soil and waste that would have to be shipped to a hazardous waste and/or nonhazardous waste disposal facility. Delays in transportation for disposal could be possible. Alternatives S1 and S2 do not have significant implementation issues because no active remedial measures would be taken.

Cost—The capital, O&M, and total costs (present worth) for each alternative are included in Section IX. For alternatives involving removal and treatment/disposal of contaminated soil, Alternative S5—Option A and Alternative S6 are the most cost effective with total costs nearly equal for these two options. The next most cost effective is Alternative S5—Option B, the costs of which are more than twice that of Alternatives S5—Option A and S6. The least cost effective is Alternative S4—Option B, the costs of which are nearly 10 times those of Alternatives S5—Option A and S6.

State Acceptance—MADEP has been involved with this site since the beginning of closure activities and has reviewed the RI/FS and Proposed Plan. MADEP prefers that a permanent solution be selected if the aspects of the other eight criteria are relatively equal. The selected remedy represents a permanent solution, and MADEP concurs with the selection of Alternative S6.

Community Acceptance—In general, the community has supported the conclusions of the RI/FS and the alternatives presented in the Proposed Plan. The RAB co-chair, the technical advisor to the Watertown Citizens for Environmental Safety (recipient of the EPA Technical Assistance Grant), and other members of the community expressed their support, during the public comment period, of the Army's intended remedial action. In addition, some members of the community expressed a desire to remediate the entire site to residential standards, rather than the mixed commercial and residential site reuse, which is consistent with the intended reuse of the site as outlined in the Town-approved Arsenal Reuse Plan.

Table 13

MTL Site Soil Cleanup Goals*

Chemical	Zone 1 Commercial Reuse (mg/kg)	Zone 2 Commercial Reuse (mg/kg)	Zone 3 Residential Reuse (mg/kg)	Zone 4 Public Access (mg/kg)	River Park (mg/kg)
Benzo(a)anthracene	—	8.5	8.5	8.5	8.5
Benzo(a)pyrene	—	2.0	2.0	2.0	2.0
Benzo(b)fluoranthene	—	7.9	7.9	7.9	7.9
Benzo(k)fluoranthene	—	6.2	6.2	6.2	6.2
Chlordane	—	—	1.5	1.4	1.4
Chrysene	—	—	11.1	11.1	11.1
4,4'-DDD	—	—	—	13.7	13.7
4,4'-DDE	—	—	—	1.4E-01	1.4E-01
4,4'-DDT	—	—	—	1.7E-01	1.7E-01
Dibenz(a,h)anthracene	—	—	2.7E-01	—	2.7E-01
Dieldrin	—	—	—	3.5E-01	3.5E-01
Heptachlor epoxide	—	—	—	—	—
Indeno(1,2,3-cd)pyrene	—	3.0	3.0	3.0	3.0
Aroclor-1260	—	—	1.0	1.0	—

*The cleanup goals correspond to soil background concentrations, with the exception of Aroclor-1260, which is based on EPA guidance. Pesticide cleanup goals for Zone 4 Public Access and River Park are based on ecological risk.

XII. STATUTORY DETERMINATIONS

The remedial action selected for implementation at the MTL site is consistent with CERCLA and, to the extent practicable, the NCP. The selected remedy is protective of human health and the environment, attains ARARs, and is cost effective. The selected remedy does not satisfy the statutory preference for treatment that permanently and significantly reduces the mobility, toxicity, or volume of hazardous substances as a principal element. The selected remedy uses resource recovery technologies to the maximum extent practicable.

A. The Selected Remedy Is Protective of Human Health and the Environment

The selected remedy at this site will permanently reduce the risks posed to human health and the environment by eliminating, reducing, or controlling exposures to human and ecological receptors through soil excavation and off-site disposal/reuse. Institutional controls will be used for any soil areas not remediated to residential reuse cleanup levels. Deed restrictions, as discussed earlier, will be placed on the property at the time of transfer.

Moreover, the selected remedy will achieve a maximum level of protection of human health and environment for the intended future site reuse to the extent allowable by CERCLA and the NCP. The site soil cleanup goals to be achieved are background levels (with the exception of PCBs, which are based on EPA guidance).

B. The Selected Remedy Attains ARARs

This remedy will attain all applicable or relevant and appropriate federal and state requirements that apply to the site. The principal environmental laws from which ARARs are derived and the specific ARARs include:

- Resource Conservation and Recovery Act.
- Clean Air Act.
- Federal Protection of Floodplains Executive Order.
- National Historic Preservation Act.
- Archaeological and Historic Preservation Act.
- Massachusetts Hazardous Waste Management.
- Massachusetts Solid Waste Management.
- Massachusetts Air Pollution Control.
- Massachusetts Historical Commission Regulations.

The following policies, criteria, and guidances are to be considered (TBC) criteria for implementation of the remedial action:

- EPA Risk Reference Doses.
- EPA Carcinogen Assessment Group Potency Factors.
- Guidance on Remedial Actions for Superfund Sites with PCB Contamination.
- Test Methods for Evaluating Solid Waste and Physical/Chemical Methods.
- Massachusetts Policy on Allowable Sound Emissions.

A tabular summary of the ARARs and TBCs for the selected remedy is included in Appendix D.

For the remaining on-site treatment alternatives, Alternative S5—Option A is the most easily implemented because this remedy requires the least amount of treatability testing and because its on-site treatment system is the simplest to construct and operate. This results in shorter mobilization duration and a lower frequency of potential equipment failure causing temporary system shutdown. However, all alternatives that require treatability studies have the potential risk of not being able to achieve the desired cleanup goals. This is especially true for the more innovative soil treatment approaches of Alternative S5—Options A and B.

The selected remedy also is cost effective for the alternatives that can achieve overall protection of human health and the environment. The present-worth cost of the selected remedy ($5,768,000) is almost the same as the most cost-effective alternative, which is Alternative S5—Option A ($5,583,000). Present-worth costs of the remaining alternatives range from $11,855,000 for Alternative S5—Option B to $51,060,000 for Alternative S4—Option B.

In selecting the selected remedy, the factors that were the most determinative in the decision were implementability and cost-effectiveness. The selected remedy provided the lowest overall remediation cost, while also being the easiest and quickest to implement. Whereas similar remediation costs could be achieved for Alternative S5—Option A, this alternative could not be implemented as quickly as the selected remedy. Also, treatability tests for the alternative could have concluded that the remediation technology could not have achieved the desired goals, or could not have done so in a more cost-effective manner than the selected alternative. Both the state and the community concur with the selected remedy.

While the selected remedy does not achieve a reduction of toxicity, mobility, or volume of contaminants through treatment, this factor is outweighed by the level of the cost-effectiveness and implementability the selected remedy affords. In addition, the state and community support this remedy.

E. The Selected Remedy Does Not Satisfy the Preference for Treatment That Permanently and Significantly Reduces the Toxicity, Mobility, or Volume of the Hazardous Substances as a Principal Element

The statutory preference for treatment as a principal element is not satisfied by the selected remedy, because this remedy results in off-site disposal/reuse of contaminated soil. The fact that the selected remedy does not meet this statutory preference did not exclude this alternative from selection because there were no other equally cost-effective and easily implemented alternatives that could achieve the maximum extent of overall protection of human health and the environment. The selected remedy will result in reduction in mobility of contaminants through soil reuse in a landfill or through immobilization as reuse in asphalt batching.

A meeting was held on August 8, 1996 to explain this information to members of the public. As a result of the change in remediation cost for the selected remedy, members of the community have requested that the Army implement the selected remedy. In a letter dated August 14, 1996 from the Arsenal Reuse Committee, a request was made to implement the selected remedy because this would allow the soil remediation to be completed 1 year in advance of the original schedule for implementation of Alternative S5—Option A. This would allow for optimal economic redevelopment potential of the site for the town. The transcript of the August 8, 1996 meeting and public comment letters received are included in Appendix C.4.

2. The second change affects the amount of soil to be remediated. Based on several public comments to have the entire site remediated to residential levels instead of the mixed commercial and residential reuse identified in the Reuse Plan, the Army has decided to increase the level of remediation in two areas of concern in Zone 2 from commercial cleanup goals to residential cleanup goals. These two areas are shown in Figure 4 as Areas F and T.

Area F was previously identified as an area of concern for commercial cleanup; under this Record of Decision, this area will be remediated to residential cleanup goals. Although this does not change the estimated soil remediation volume for this area, the number of contaminants of concern in this area is increased from four to 11.

Area T is an area that was not included for remediation in the Proposed Plan because no contaminants in this area exceeded the commercial cleanup goals. However, for the residential reuse scenario, this was an area of concern. This area was previously delineated in the FS for site residential reuse as Area H (see Figure 3-2 of the FS). Adding this area to the total remediation volume will result in an estimated increase in soil volume of 800 yd^3. This also results in an increase in the cost estimate for remediation. The remediation alternative cost estimates and the selected remedy cost estimates in Sections IX and XII in this Record of Decision have been revised from the Proposed Plan to account for this increase in soil volume.

3. The third change refers to a change in the Accelerated Action for Area I/Building 131 vicinity and Area M (Yacht Club Tank Area) as discussed in the Proposed Plan. This Accelerated Action was to involve the separate remediation of Areas I and M as shown in Figure 4. The Area I accelerated action was deemed necessary to facilitate an anticipated transfer of Building 131 to the Massachusetts College of Professional Psychology in the spring of 1997. At the same time, the Yacht Club requested that the soil at Area M be remediated early to allow them to replace a UST used to store fuel for their boats. These two actions were included in the Proposed Plan as the Accelerated Action.

The Accelerated Action could result in a slight overall increase in site remediation cost to the Army. Because of the replacement of the UST, the Army Materiel Command Legal Office requested that Area M be deleted from the Accelerated Action and be included in the overall remedial action. Therefore, the Record of Decision signed on June 28, 1996 for the Accelerated Action included Area I only. The remediation of Area M is included under this Record of Decision.

DRAFT
7/31/94

TECHNICAL PROTOCOL FOR IMPLEMENTING THE INTRINSIC REMEDIATION WITH LONG-TERM MONITORING OPTION FOR NATURAL ATTENUATION OF DISSOLVED-PHASE FUEL CONTAMINATION IN GROUND WATER

by

Todd H. Wiedemeier and Douglas C. Downey
Engineering-Science, Inc.
Denver, Colorado

Dr. John T. Wilson and Dr. Donald H. Kampbell
United States Environmental Protection Agency*
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma

Lt. Col. Ross N. Miller and Jerry E. Hansen
Air Force Center for Environmental Excellence
Brooks Air Force Base, Texas

for

Air Force Center for Environmental Excellence
Brooks Air Force Base
San Antonio, Texas

---

*This United States Air Force guidance was developed in cooperation with United States Environmental Protection Agency (EPA) researchers but was not issued by the EPA and does not represent EPA guidance.

TABLE OF CONTENTS - Continued

FIGURES

TABLES

SECTION 1

INTRODUCTION

The intent of this document is to present a technical protocol for data collection, ground water modeling, and exposure assessment in support of intrinsic remediation (natural attenuation) with long-term monitoring for restoration of fuel-hydrocarbon-contaminated ground water. Specifically, this protocol is designed to evaluate the fate of dissolved-phase fuel hydrocarbons having regulatory maximum contaminant levels (MCLs). In many cases, the use of this protocol should allow the proponent of intrinsic remediation to show that natural degradation processes will reduce the concentrations of these contaminants to below regulatory standards before potential exposure pathways are completed. The intended audience for this document is United States Air Force personnel, scientists, consultants, regulatory personnel, and others charged with remediating fuel-hydrocarbon-contaminated ground water.

Intrinsic remediation is achieved when naturally occurring attenuation mechanisms, such as biodegradation (aerobic and anaerobic), bring about a reduction in the total mass of a contaminant dissolved in ground water. In some cases, intrinsic remediation will reduce dissolved-phase contaminant concentrations to below MCLs before the contaminant plume reaches potential receptors, even if little or no source removal/reduction takes place. In situations where intrinsic remediation will not reduce contaminant concentrations to below regulatory MCLs, less stringent cleanup goals may be implemented. This is especially likely if it can be demonstrated that intrinsic remediation will result in a continual reduction in contaminant concentrations over time such that calculated risk values are reduced. Advantages of intrinsic remediation include: 1) during intrinsic remediation, contaminants are ultimately transformed to innocuous byproducts (e.g., carbon dioxide and water), not just transferred to another phase or location within the environment; 2) intrinsic remediation is non-intrusive and allows continuing use of infrastructure during remediation; 3) current remedial technologies can pose greater risk to potential receptors than intrinsic remediation

The first line of evidence involves using measured dissolved-phase concentrations of biologically recalcitrant tracers found in fuels in conjunction with aquifer hydrogeologic parameters such as seepage velocity and dilution to show that a reduction in the total mass of contaminants is occurring at the site. The second line of evidence involves the use of chemical analytical data in mass balance calculations to show that a decrease in contaminant and electron acceptor concentrations can be directly correlated to increases in metabolic byproduct concentrations. This evidence can be used to show that electron acceptor concentrations are sufficient to degrade dissolved-phase contaminants. Numerical models can be used to aid mass-balance calculations and collate information on degradation. The third line of evidence, the microcosm study, involves studying site aquifer materials under controlled conditions in the laboratory to show that indigenous biota are capable of degrading site contaminants and to confirm rates of contaminant degradation measured at the field scale.

This document presents a technical course of action that allows converging lines of evidence to be used to scientifically document the occurrence of, and quantify rates of, intrinsic remediation. At a minimum, the first two lines of evidence should be used in the intrinsic remediation demonstration. To further document intrinsic remediation, a microcosm study can be performed. Such a "weight of evidence" approach will greatly increase the likelihood of successfully implementing intrinsic remediation at sites where natural processes are restoring the environmental quality of fuel-hydrocarbon-contaminated ground water.

Collection of an adequate database during the iterative site characterization process is an important step in the documentation of intrinsic remediation. At a minimum, the site characterization phase should provide data on the location and extent of contaminant sources [nonaqueous phase-liquid (NAPL) hydrocarbons present as mobile NAPL (NAPL occurring at sufficiently high saturations to drain under the influence of gravity to a well) and residual NAPL (NAPL occurring at immobile residual saturations which are unable to drain to a well by gravity]; the location, extent, and concentration of dissolved-phase contamination; ground water geochemical data; geologic information on the type and distribution of subsurface materials; and hydrogeologic parameters such as hydraulic conductivity, hydraulic gradients, and potential contaminant migration pathways to human or ecological receptors. Methodologies for determining these parameters are discussed in Appendix A.

Intrinsic remediation results from the integration of several subsurface attenuation mechanisms that are classified as either destructive or nondestructive. Destructive processes

Appendix B provides an in-depth discussion of the destructive and nondestructive mechanisms of intrinsic remediation. Appendix C describes numerical ground water modeling in support of intrinsic remediation. Appendix C also describes the post-modeling monitoring and verification process. Appendix D describes the exposure assessment portion of the intrinsic remediation investigation and the use of numerical modeling results to aid in the risk evaluation process. Appendices E, F, G, and H present case studies of site investigations and modeling efforts that were conducted in support of intrinsic remediation using the methods described in this document.

SECTION 2

PROTOCOL FOR IMPLEMENTING INTRINSIC REMEDIATION

The primary objective of the intrinsic remediation investigation is to show that natural processes of contaminant degradation will reduce contaminant concentrations in ground water to below regulatory standards before potential exposure pathways are completed. This requires that a projection of the potential extent and concentration of the contaminant plume in time and space be made. This projection should be based on historic variations in, and the current extent and concentration of, the contaminant plume as well as the measured rates of contaminant attenuation. Because of the inherent uncertainty associated with such predictions, it is the responsibility of the proponent to provide sufficient evidence to demonstrate that the mechanisms of intrinsic remediation will reduce contaminant concentrations to acceptable levels before potential receptors are reached. This requires the use of conservative input parameters and numerous sensitivity analyses so that consideration is given to all plausible contaminant migration scenarios. When possible, both historical data and modeling should be used to provide information that collectively and consistently supports the natural reduction and removal of the dissolved-phase contaminant plume. This section describes the steps that should be taken to gather the site-specific data necessary to predict the future extent of a contaminant plume and to successfully support the intrinsic remediation option.

Predicting the future extent of a contaminant plume requires the quantification of ground water flow and solute transport and transformation processes, including rates of natural attenuation. Quantification of contaminant migration and attenuation rates, and successful implementation of the intrinsic remediation option, require completion of the following steps, each of which is discussed in the following sections and outlined in Figure 2.1:

1) Review existing site data;
2) Develop preliminary conceptual model for the site and assess potential significance of intrinsic remediation;

3) Perform site characterization in support of intrinsic remediation;
4) Refine conceptual model based on site characterization data, complete pre-modeling calculations, and document indicators of intrinsic remediation;
5) Model intrinsic remediation using numerical fate and transport models that allow incorporation of a biodegradation term (e.g., Bioplume II or Bioplume III);
6) Conduct an exposure assessment;
7) Prepare long-term monitoring plan; and
8) Present findings to regulatory agencies and obtain approval for the intrinsic remediation with long-term monitoring option.

2.1 REVIEW EXISTING SITE DATA

The first step in the intrinsic remediation investigation is to review existing site-specific data to determine if intrinsic remediation is a viable remedial option. A thorough review of existing data also allows development of a preliminary conceptual model. The preliminary conceptual model will help identify any shortcomings in the data and will allow placement of additional data collection points in the most scientifically advantageous and cost-effective manner possible.

When available, information to be obtained during data review includes:

- Soil and ground water quality data:
    - Three-dimensional distribution of mobile and residual NAPL and dissolved-phase contaminants. The distribution of mobile and residual NAPL will be used to define the dissolved-phase plume source area.
    - Ground water and soil geochemical data.
    - Historic water quality data showing variations in contaminant concentrations through time.
    - Chemical and physical characteristics of the contaminants.
    - Potential for biodegradation of the contaminants.
- Geologic and hydrogeologic data:
    - Lithology and stratigraphic relationships.
    - Grain-size distribution (sand vs. silt vs. clay).
    - Aquifer hydraulic conductivity.

- Integration and presentation of available data, including:
    - Local geologic and topographic maps,
    - Hydraulic data,
    - Site stratigraphy, and
    - Contaminant concentration and distribution data.
- Conceptual model development.
- Selection of a numerical ground water model.
- Determination of additional data requirements, including:
    - Borehole locations and monitoring well spacing,
    - An approved sampling and analysis plan, and
    - Any data requirements listed in Section 2.1 that have not been adequately addressed.

After conceptual model development, an assessment of the potential for intrinsic remediation must be made. As stated previously, existing data can be useful in determining if intrinsic remediation will be sufficient to prevent a dissolved-phase contaminant plume from completing exposure pathways, or from reaching a predetermined point of compliance, in concentrations above applicable regulatory guidelines. Determining the likelihood of pathway completion is the ultimate objective of the intrinsic remediation investigation. This is achieved by estimating the migration and future extent of the plume based on contaminant properties, including biodegradability, aquifer properties, ground water velocity, and the location of the plume and contaminant source relative to the potential receptor (i.e., the distance between the leading edge of the plume and the potential receptor). Appendix B discusses the biodegradability of benzene, toluene, ethylbenzene, and the xylenes (BTEX) in both the laboratory and the field.

If intrinsic remediation is determined to be a significant factor in contaminant reduction, then site characterization activities in support of this remedial option should be performed. If exposure pathways have already been completed and contaminants pose an unacceptable risk, or if such completion is likely, then other remedial measures should be considered. Even so, the collection of data in support of the intrinsic remediation option can be integrated into a comprehensive remedial plan and may help reduce the cost and duration of other remedial measures such as intensive source removal operations or pump-and-treat technologies.

  - Site stratigraphy, including identification of transmissive and non-transmissive units.
  - Grain-size distribution (sand vs. silt vs. clay).
  - Aquifer hydraulic conductivity.
  - Ground water hydraulic information.
  - Preferential flow paths.
  - Location and type of surface water bodies.
  - Areas of local ground water recharge and discharge.
- Definition of potential exposure pathways and receptors.

The following sections describe the methodologies that should be implemented to allow successful site characterization in support of intrinsic remediation.

2.3.1 Soil Characterization

In order to adequately define the subsurface hydrogeologic system and to determine the amount and three-dimensional distribution of mobile and residual NAPL that can act as a continuing source of ground water contamination, extensive soil characterization must be completed. Depending on the status of the site, this work may have already been completed during previous remedial investigation work. The results of soils characterization will be used as input into a numerical model to help define a contaminant source term and to support the intrinsic remediation investigation.

2.3.1.1 Soil Sampling

The purpose of soil sampling is to determine the subsurface distribution of hydrostratigraphic units and the distribution of mobile and residual NAPL. These objectives can be achieved through the use of conventional soil borings or cone penetrometer testing. All soil samples should be collected, described, and analyzed in accordance with the procedures outlined in Appendix A.

2.3.1.2 Soil Analytical Protocol

The analytical protocol to be used for soil sample analysis is presented in Table 2.1. This analytical protocol includes all of the parameters necessary to document intrinsic remediation

Table 2.1. (Continued)

Matrix	Analysis	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Soil	Total hydrocarbons, volatile and extractable	GC method SW8015 [modified]	Handbook method; reference is the California LUFT manual	Data are used to determine the extent of soil contamination, the contaminant mass present, and the need for source removal	Each sampling round	Collect 100 g of soil in a glass container with Teflon-lined cap; cool to 4°C	Fixed-base
Soil	Moisture	ASTM D-2216	Handbook method	Data are used to correct soil sample analytical results for moisture content (e.g., report results on a dry weight basis)	Each soil sampling round	Use a portion of soil sample collected for another analysis	Fixed-base
Soil	Grain size distribution	ASTM D422	Procedure provides a distribution of grain size by sieving	Data are used to infer hydraulic conductivity of aquifer, and are used in calculating sorption of contaminants	One time during life of project	Collect 250 g of soil in a glass or plastic container; preservation is unnecessary	Fixed-base
Soil gas	Oxygen content of soil gas	Electrochemical oxygen meter operating over the range of 0–25 percent of oxygen in the soil gas sample	The concentration of soil gas oxygen is often related to the amount of biological activity, such as the degradation of petroleum hydrocarbons; soil gas oxygen concentrations may decrease to the point where anaerobic pathways dominate	Data are used to understand the oxygen concentration gradient with depth and to determine the presence or absence of aerobic degradation processes	Each sampling round	N/A	Field

Table 2.1. (Continued)

Matrix	Analysis	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Water	Chloride	Mercuric nitrate titration A4500-Cl^- C	Ion chromatography (IC) method E300 or method SW9050 may also be used	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Each sampling round	Collect 250 mL of water in a glass container	Field
Water	Oxygen	Dissolved oxygen meter	Refer to method A4500 for a comparable laboratory procedure	The oxygen concentration is a data input to the Bioplume model; concentrations less than 1 mg/L generally indicate an anaerobic pathway	Each sampling round	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen *in situ*	Field
Water	pH	E150.1/SW9040, direct reading meter	Protocols/Handbook methods	Aerobic and anaerobic processes are pH-sensitive	Each sampling round	Collect 100–250 mL of water in a glass or plastic container; analyze immediately	Field
Water	Conductivity	E120.1/SW9050, direct reading meter	Protocols/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Each sampling round	Collect 100–250 mL of water in a glass or plastic container	Field
Water	Alkalinity	A2320, titrimetric; E310.2, colorimetric	Handbook method	General water quality parameter used (1) as a marker to verify that all site samples are obtained from the same groundwater system and (2) to measure the buffering capacity of groundwater	Each sampling round	Collect 250 mL of water in a glass or plastic container; analyze within 6 hours	Field

Table 2.1. (Continued)

Matrix	Analysis	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Water	Methane; carbon dioxide	RSKSOP-114 modified to analyze water samples for methane and carbon dioxide by headspace sampling with dual thermal conductivity and flame ionization detection (also, see reference in note 10)	Method published and used by the U.S. Environmental Protection Agency (EPA) Robert S. Kerr Laboratory	The presence of methane suggests BTEX degradation via an anaerobic pathway utilizing carbon dioxide (carbonate) as the electron acceptor (methanogenesis); a redox potential measurement of less than -200 mV could be indicative of methanogenesis and should be followed by the analysis referenced here; the presence of free carbon dioxide dissolved in groundwater is unlikely because of the carbonate buffering system of water, but if detected, the carbon dioxide concentrations should be compared with background to determine whether they are elevated; elevated concentrations of carbon dioxide could indicate an aerobic mechanism for bacterial degradation of petroleum	Each sampling round	Collect water samples in 40 mL volatile organic analysis (VOA) vials with butyl gray/Teflon-lined caps; cool to 4°C	Fixed-base

Table 2.1. (Continued)

Matrix	Analysis	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Water	Aromatic hydrocarbons (BTEX, trimethylbenzene isomers)	Purge and trap GC method SW8020	Handbook method; analysis may be extended to higher molecular weight alkyl benzenes	Method of analysis for BTEX, which is the primary target analyte for monitoring natural attenuation; BTEX concentrations must also be measured for regulatory compliance; method can be extended to higher molecular weight alkyl benzenes; trimethylbenzenes are used to monitor plume dilution if degradation is primarily anaerobic	Each sampling round	Collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH 2	Fixed-base
Water	Total hydrocarbons, volatile and extractable	GC method SW8015 [modified]	Handbook method; reference is the California LUFT manual	Data used to monitor the reduction in concentrations of total fuel hydrocarbons (in addition to BTEX) due to natural attenuation; data also used to infer presence of an emulsion or surface layer of petroleum in water sample, as a result of sampling	One time per year or as required by regulations	Volatile hydrocarbons–collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH 2 Extractable hydrocarbons–collect 1 L of water in a glass container; cool to 4°C; add hydrochloric acid to pH 2	Fixed-base
Water	Polycyclic aromatic hydrocarbons (PAHs) (optional)	GC/mass spectroscopy method SW8270; high-performance liquid chromatography method SW8310	Analysis needed only for several samples per site	PAHs are components of fuel and are typically analyzed for regulatory compliance; data on their concentrations are not used currently in the evaluation of natural attenuation	At initial sampling and at site closure or as required by regulations	Collect 1 L of water in a glass container; cool to 4°C	Fixed-base

Table 2.1. (Concluded)

NOTES:

1. "HACH" refers to the HACH Company catalog, 1990.
2. "A" refers to *Standard Methods for the Examination of Water and Wastewater*, 18th edition, 1992.
3. "E" refers to *Methods for Chemical Analysis of Water and Wastes*, U.S. Environmental Protection Agency, March 1979.
4. "Protocols" refers to the AFCEE *Environmental Chemistry Function Installation Restoration Program Analytical Protocols*, 11 June 1992.
5. "Handbook" refers to the AFCEE *Handbook to Support the Installation Restoration Program (IRP) Remedial Investigations and Feasibility Studies (RI/FS)*, September 1993.
6. "SW" refers to the *Test Methods for Evaluating Solid Waste, Physical, and Chemical Methods*, SW-846, U.S. Environmental Protection Agency, 3rd edition, 1986.
7. "ASTM" refers to the *American Society for Testing and Materials*, current edition.
8. "RSKSOP" refers to *Robert S. Kerr (Environmental Protection Agency Laboratory) Standard Operating Procedure*.
9. "LUFT" refers to the state of California *Leaking Underground Fuel Tank Field Manual*, 1988 edition.
10. *International Journal of Environmental Analytical Chemistry*, Volume 36, pp. 249-257, "Dissolved Oxygen and Methane in Water by a Gas Chromatography Headspace Equilibration Technique," by D. H. Kampbell, J. T. Wilson, and S. A. Vandegrift.

2.3.1.2.5 Grain Size Distribution

The grain size distribution of the aquifer matrix is an important indicator of hydraulic conductivity. In addition, clay minerals can be important sites for contaminant adsorption, especially when organic carbon comprises less than about 0.1 percent of the aquifer matrix. Because of this, knowledge of the relative abundance of clay minerals is important in sorption and solute retardation calculations.

2.3.1.2.6 Soil Gas Analysis

The concentrations of soil gas oxygen, carbon dioxide, and total combustible hydrocarbons are important in defining the extent of NAPL contamination. This information can be used to define the edge of the free-phase plume and to estimate the potential for natural biodegradation of vadose zone fuel residuals. Depleted oxygen levels and elevated carbon dioxide levels in soil gas are indicative of aerobic biodegradation of fuel hydrocarbons in the unsaturated zone, which may be enhanced if additional oxygen is provided through bioventing.

2.3.2 Ground Water Characterization

To adequately determine the amount and three-dimensional distribution of dissolved-phase contamination and to document the occurrence of intrinsic remediation, ground water samples must be collected. Biodegradation of fuel hydrocarbons brings about measurable changes in the chemistry of ground water in the affected area. By measuring these changes, the proponent of intrinsic remediation can document and quantitatively evaluate the importance of intrinsic remediation at a site.

2.3.2.1 Ground Water Sampling

Ground water sampling is conducted to determine the concentration and three-dimensional distribution of contaminants and ground water geochemical parameters. Ground water samples may be obtained from monitoring wells or point-source sampling devices such as the Geoprobe®, Hydropunch®, or the cone penetrometer. All ground water samples should be collected in accordance with the procedures outlined in Appendix A.

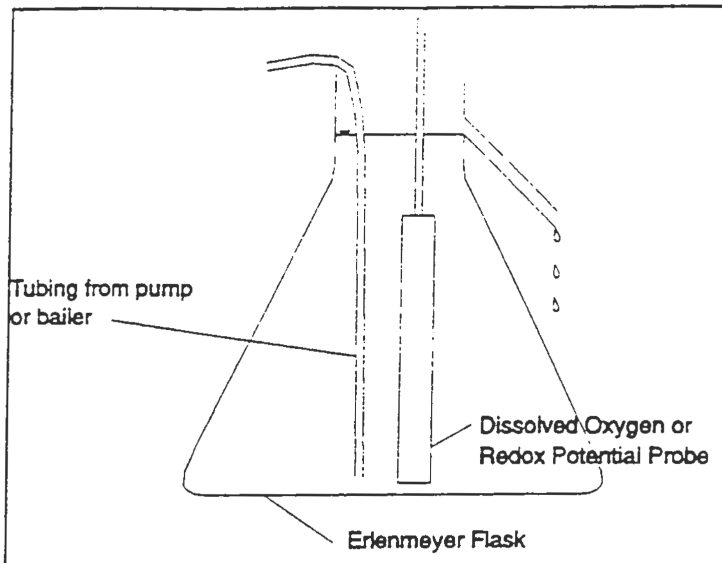


Figure 2.2

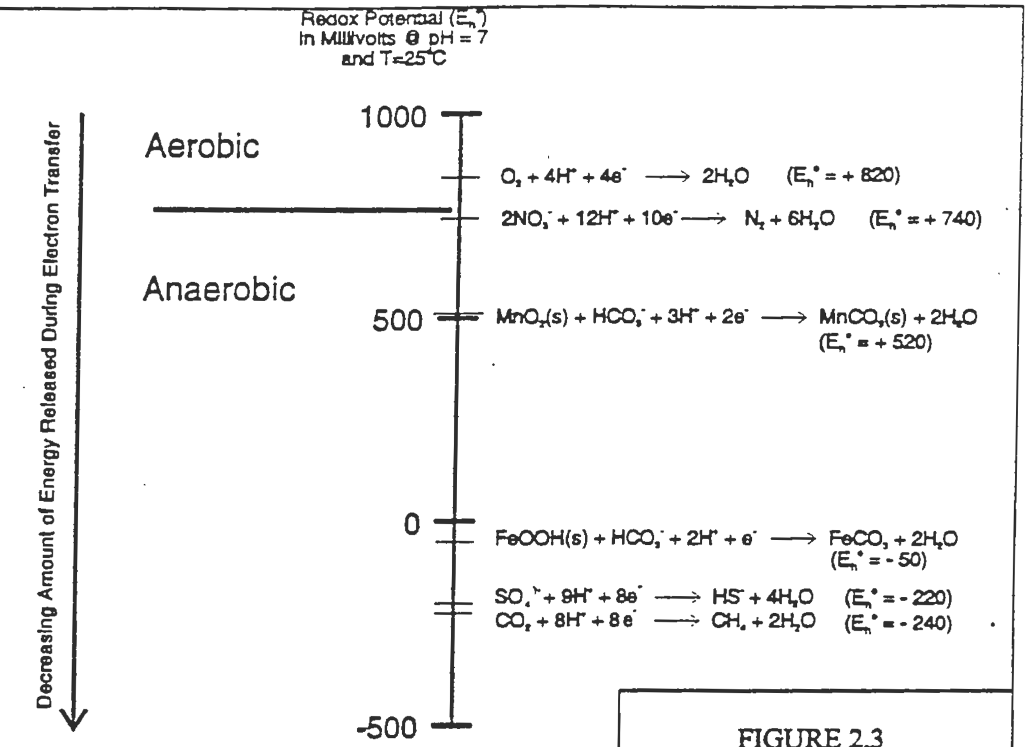
Diagram Showing the Suggested Procedure for Dissolved Oxygen and Oxidation-Reduction Potential Sampling

2) When using a bailer, the bailer should be slowly immersed in the standing column of water to minimize aeration. After sample collection, the water should be siphoned from the bailer into the sampling container and the tubing used for siphoning should be immersed alongside the dissolved oxygen probe beneath the water level in the sampling container (Figure 2.2). This will minimize aeration and keep water flowing past the dissolved oxygen probe's sampling membrane.

3) Down-hole dissolved oxygen probes can be used for dissolved oxygen analyses but such probes must be thoroughly decontaminated between wells. In some cases decontamination procedures can be harmful to the dissolved oxygen probe.

2.3.2.2.2 Oxidation/Reduction Potential (E_H)

The oxidation/reduction (redox) potential of ground water (E_H) is a measure of electron activity and is an indicator of the relative tendency of a solution to accept or transfer electrons. Redox reactions in ground water are usually biologically mediated and therefore, the redox potential of a ground water system depends upon and influences rates of



Modified From Norris et al., (1994)

FIGURE 2.3

Redox Potentials for Various Electron Acceptors

Aqueous conductivity is a measure of the ability of a solution to conduct electricity. The conductivity of ground water is directly related to the concentration of ions in solution; conductivity increases as ion concentration increases. Like chloride, conductivity is used to ensure that ground water samples collected at a site are representative of the water comprising the saturated zone in which the dissolved-phase contamination is present. If the conductivities of samples taken from different sampling points are radically different, then the waters may be from different hydrogeologic zones.

Ground water temperature directly affects the solubility of oxygen and other geochemical species. The solubility of dissolved oxygen is temperature dependent, being more soluble in cold water than in warm water. Ground water temperature also affects the metabolic activity of bacteria. Rates of hydrocarbon biodegradation roughly double for every 10°C increase in temperature ("Q"$_{10}$ rule) over the temperature range between 5 and 25°C. Ground water temperatures less than about 5°C tend to inhibit biodegradation, and slow rates of biodegradation are generally observed in such waters.

2.3.2.2.7 Ferrous Iron

In some cases ferric iron is used as an electron acceptor during anaerobic biodegradation of petroleum hydrocarbons. During this process, ferric iron is reduced to the ferrous form which may be soluble in water. Ferrous iron concentrations are used as an indicator of anaerobic degradation of fuel compounds. By knowing the volume of contaminated ground water, the background ferrous iron concentration, and the concentration of ferrous iron measured in the contaminated area, it is possible to estimate the mass of BTEX lost to biodegradation through ferric iron reduction. The degradation of 1 mg/L of BTEX results in the production of approximately 21.8 mg/L of ferrous iron during ferric iron reduction. Example calculations are presented in Appendix C. Iron concentrations will be used as a direct input parameter to Bioplume III.

2.3.2.2.8 Carbon Dioxide

Metabolic processes operating during biodegradation of fuel hydrocarbons leads to the production of carbon dioxide (CO_2). Accurate measurement of CO_2 produced during biodegradation is difficult because carbonate in ground water (measured as alkalinity) serves as both a source and sink for free CO_2. If the CO_2 produced during metabolism is not removed by the natural carbonate buffering system of the aquifer, CO_2 levels higher than background may be observed. Comparison of empirical data to stoichiometric calculations can provide estimates of the degree of microbiological activity and the occurrence of *in situ* mineralization of contaminants.

2.3.2.2.9 Methane

During methanogenesis (an anaerobic biodegradation process), carbon dioxide (or acetate) is used as an electron acceptor, and methane is produced. Methanogenesis generally occurs after oxygen, nitrate, and sulfate have been depleted in the treatment zone. The presence of methane in ground water is indicative of strongly reducing conditions. Because methane is not present in fuel, the presence of methane in ground water above background concentrations in contact with fuels is indicative of microbial degradation of fuel hydrocarbons. Methane concentrations can be used to estimate the amount of BTEX destroyed in an aquifer. By knowing the volume of contaminated ground water, the background methane concentration, and the concentration of methane measured in the contaminated area, it is possible to estimate the mass of BTEX lost to biodegradation through methanogenesis reduction. The contaminant migration. Estimates of hydraulic conductivity are used to determine residence times for contaminants and tracers and to determine the seepage velocity of ground water.

The most common methods used to quantify hydraulic conductivity in the subsurface are aquifer pumping tests and slug tests (Appendix A). One drawback to these methods is that they average hydraulic properties over the screened interval. To help alleviate this potential problem, the screened interval of the well should be selected after consideration is given to subsurface stratigraphy. Information about subsurface stratigraphy should come from geologic boring logs completed on continuous cores. An alternate method to delineate zones with high hydraulic conductivity is to use pressure dissipation data from CPT logs.

2.3.3.1.1 Pumping Tests

Pumping tests generally give the most reliable information on hydraulic conductivity but are difficult to conduct in contaminated areas because the water produced during the test generally must be contained and treated. In addition, a minimum 4-inch-diameter well is generally required to complete pumping tests in highly transmissive aquifers because the 2-inch submersible pumps available today are not capable of producing a flow rate large enough for meaningful pumping tests. In areas with fairly uniform aquifer materials, pumping tests can be completed in uncontaminated areas and the results used to estimate hydraulic conductivity in the contaminated area. Pumping tests should be conducted in narrowly screened wells that are screened in the most transmissive zones in the aquifer.

2.3.3.1.2 Slug Tests

Slug tests are a commonly used alternative to pumping tests. They are relatively easy to conduct and, in general, produce reliable information. One commonly cited drawback to slug testing is that this method generally gives hydraulic conductivity information only for the area immediately surrounding the monitoring well. Slug tests do, however, have two distinct advantages over pumping tests; they can be conducted in 2-inch monitoring wells, and they produce no water. If slug tests are going to be relied upon to provide information on the three-dimensional distribution of hydraulic conductivity in an aquifer, multiple slug tests must be performed. It is not advisable to rely on data from one slug test in one monitoring well. Because of this, slug tests should be conducted at several monitoring wells at the site. Like as sorptive as the BTEX compounds, but which is biologically recalcitrant. Two potential chemicals found in fuel hydrocarbon plumes are trimethylbenzene and tetramethylbenzene (Cozzarelli *et al.*, 1994, and Cozzarelli *et al.*, 1990). Appendix C (Section C.2.3.5) contains an example calculation of how to correct for the effects of dilution.

2.3.3.3.1 Dilution

Dilution results in a reduction in contaminant concentrations and an apparent reduction in the total mass of contaminant in a system. The two most common causes of dilution are infiltration and monitoring wells screened over large vertical intervals. Infiltration can cause an apparent reduction in contaminant mass by mixing with the contaminant plume, thereby causing dilution. Monitoring wells screened over large vertical distances may dilute ground water samples by mixing water from clean aquifer zones with contaminated water during sampling. This problem is especially relevant for dissolved-phase BTEX contamination which may remain near the ground water table for some distance downgradient of the source. To avoid potential dilution, monitoring wells should be screened over relatively short vertical distances (less than 5 feet). Nested wells should be used to define the vertical extent of contamination in the saturated zone.

2.3.3.3.2 Sorption (Retardation)

The retardation of organic solutes caused by sorption is an important consideration when modeling intrinsic remediation. Sorption of a contaminant to the aquifer matrix results in an apparent decrease in contaminant mass that must be accounted for. Dissolved oxygen and other electron acceptors present in the ground water travel at the advective transport velocity of the ground water. Any slowing of the solute relative to the advective transport velocity of the ground water allows replenishment of electron acceptors into upgradient areas of the plume. The processes of contaminant sorption and retardation are discussed in Appendix B.

2.3.3.3.3 Hydrodynamic Dispersion

The dispersion of organic solutes in an aquifer is an important consideration when modeling intrinsic remediation. The dispersion of a contaminant into relatively pristine portions of the aquifer allows the solute plume to admix with uncontaminated ground water containing higher concentrations of electron acceptors. Dispersion occurs both downgradient and, more importantly, crossgradient from the direction of ground water flow.

2.4 REFINE CONCEPTUAL MODEL, COMPLETE PRE-MODELING CALCULATIONS, AND DOCUMENT INDICATORS OF INTRINSIC REMEDIATION

Site investigation data should first be used to refine the conceptual model and calculate rates of ground water flow, sorption, dilution, and biodegradation. The results of these calculations are then used to scientifically document the occurrence and rates of intrinsic remediation and to help model intrinsic remediation. No single piece of data is sufficient to successfully support the intrinsic remediation option at a given site. Because the burden of proof is on the proponent, all available data must be integrated in such a way that the evidence in support of intrinsic remediation is sufficient and irrefutable.

2.4.1 Conceptual Model Refinement

Conceptual model refinement involves integrating newly gathered field data to refine the preliminary conceptual model that was developed based on previously existing site-specific data. During conceptual model refinement, all available site-specific data should be integrated to develop an accurate three-dimensional representation of the hydrogeologic and contaminant transport system. This conceptual model can be used for contaminant fate and transport modeling. Conceptual model refinement consists of several steps including boring log preparation, hydrogeologic section preparation, potentiometric surface map preparation, contaminant contour map preparation, and preparation of electron acceptor and metabolic byproduct contour maps.

2.4.1.1 Geologic Boring Logs

Geologic boring logs of all subsurface materials encountered during the soil boring or cone penetrometer testing (CPT) phase of the field work should be constructed. Descriptions of the aquifer matrix should include relative density, color, major textural constituents, minor constituents, porosity, relative moisture content, plasticity of fines, cohesiveness, grain size, structure or stratification, relative permeability, and any other significant observations such as visible fuel or fuel odor. It is also important to correlate the results of volatiles screening using headspace vapor analysis with depth intervals of geologic materials. The depth of lithologic contacts and/or significant textural changes should be recorded to the nearest 0.1 foot. This resolution is necessary because preferential flow and contaminant transport paths may be limited to a stratigraphic unit on the order of 6 inches thick.

2.4.1.5 Contaminant Contour Maps

Contaminant contour maps should be prepared for each of the BTEX compounds present and for total BTEX. Such maps allow interpretation of data on the distribution and the relative transport and degradation rates of contaminants in the subsurface. In addition, contaminant contour maps are necessary so that contaminant concentrations can be gridded and used for input into the Bioplume II model.

If mobile and residual NAPL are present at the site, a contour map showing the thickness and distribution of each phase should be prepared. These maps will allow interpretation of the distribution and the relative transport rate of NAPL in the subsurface. In addition, these maps will aid in partitioning calculations and numerical model development. It is important to note that because of the differences between the magnitude of capillary suction in the aquifer matrix and the different surface tension properties of fuel and water, NAPL thickness observations made at monitoring points may not provide an accurate estimate of the actual volume of mobile and residual NAPL in the aquifer. To accurately determine the distribution of NAPLs, it is necessary to take continuous soil cores. Appendix C discusses the relationship between actual and apparent NAPL thickness.

2.4.1.6 Electron Acceptor and Metabolic Byproduct Contour Maps

Contour maps should be prepared for electron acceptors consumed (dissolved oxygen, nitrate, and sulfate) and metabolic byproducts produced (iron II, sulfide, and methane) during biodegradation. The electron acceptor and metabolic byproduct contour maps provide evidence of the occurrence of intrinsic remediation at a site.

2.4.1.6.1 Electron Acceptor Contour Maps

Contour maps should be prepared for the electron acceptors including dissolved oxygen, nitrate, and sulfate. During aerobic biodegradation, dissolved oxygen concentrations will decrease to levels below background. Similarly, during anaerobic degradation, the concentrations of nitrate and sulfate will be seen to decrease to levels below background. The electron acceptor contour maps allow interpretation of data on the distribution of the electron acceptors and the relative transport and degradation rates of contaminants in the subsurface. Bioplume II will allow direct input of all these parameters. Thus, electron acceptor contour indicative of anaerobic hydrocarbon biodegradation. The contour maps described in Section 2.4.1 can be used to provide visible evidence of these relationships.

Microorganisms generally utilize dissolved oxygen and nitrate in areas with dissolved-phase fuel- hydrocarbon contamination at rates which are instantaneous relative to the average advective transport velocity of ground water. This results in the consumption of these compounds at a rate approximately equal to the rate at which they are replenished by advective flow processes. For this reason, the use of these compounds as electron acceptors in the biodegradation of dissolved-phase fuel-hydrocarbons is a mass-transport-limited process (Borden and Bedient, 1986; Wilson *et al.*, 1985). The use of dissolved oxygen and nitrate in the biodegradation of dissolved-phase fuel-hydrocarbons can be modeled using Bioplume II. The use of Bioplume II for modeling these processes is discussed in Appendix C.

Microorganisms generally utilize sulfate, iron III, and carbon dioxide in areas with dissolved-phase fuel-hydrocarbon contamination at rates that are slow relative to the advective transport velocity of ground water. This results in the consumption of these compounds at a rate that could be slower than the rate at which they are replenished by advective flow processes. Therefore, the use of these compounds as electron acceptors in the biodegradation of dissolved-phase fuel-hydrocarbons may be a reaction-limited process that is approximated by first-order kinetics. The Bioplume II model utilizes a first-order rate constant to model such biodegradation. Determination of first-order decay rate constants is discussed in Appendix C.

2.4.2.1.2 Metabolic Byproduct and BTEX Data

Elevated concentrations of the metabolic byproducts iron II and methane in areas with fuel hydrocarbon contamination are indicative of hydrocarbon biodegradation. The contour maps described in Section 2.4.1 can be used to provide visible evidence of these relationships.

2.4.2.2 Sorption and Retardation Calculations

Contaminant sorption and retardation calculations should be made based on the total organic carbon (TOC) content of the aquifer matrix and the organic carbon partitioning coefficient (K_{oc}) of each contaminant. The average TOC concentration from the most transmissive zone in the aquifer should be used for retardation calculations. At a minimum, of dilution and volatilization. This is accomplished by normalizing the concentration of each contaminant to the concentration of a tracer that is at least as sorptive, but which is biologically recalcitrant. Two chemicals that have good potential that are found in fuel hydrocarbon plumes are trimethylbenzene and tetramethylbenzene. Both of these compounds have been shown to be recalcitrant under anaerobic conditions. It is important to note however, that all refined fuel components will degrade in a ground water system undergoing intrinsic remediation. Trimethylbenzene and tetramethylbenzene, while being recalcitrant under anaerobic conditions, will degrade under aerobic conditions.

When sulfate is being used as an electron acceptor and sulfate concentrations are greater than 10 milligrams per liter (mg/L), the first-order rate constant is appropriate. To adequately describe biodegradation rates using a first-order rate constant during methanogenesis, the total alkalinity for the system should be greater than about 50 mg/L.

An example anaerobic biodegradation rate constant calculation is given in Appendix C. Bioplume III, now under development by AFCEE, will allow direct input of anaerobic electron acceptor data so that aerobic and anaerobic degradation can be simulated.

2.5 MODEL INTRINSIC REMEDIATION USING NUMERICAL MODELS

Modeling of intrinsic remediation allows prediction of the migration and attenuation of the contaminant plume over time. Intrinsic remediation modeling is a tool that allows site-specific data to be used to predict the fate and transport of solutes under governing physical, chemical, and biological processes. Hence, the results of the modeling effort are not in themselves sufficient proof that intrinsic remediation is occurring at a given site. The results of the modeling effort are only as good as the original data input into the model. In some cases, simple calculations of contaminant attenuation rates are all that is required to successfully support intrinsic remediation.

Several well documented and widely accepted numerical models are available for modeling the fate and transport of fuel hydrocarbons under the influence of advection, dispersion, sorption, and biodegradation. One such model that is readily available (non-proprietary) and that is well documented is Bioplume II. The use of numerical fate and transport modeling in the intrinsic remediation investigation is described in Appendix C.

Point-of-compliance (POC) monitoring wells are wells that are installed at locations downgradient of the contaminant plume and upgradient of potential receptors. POC monitoring wells are generally installed along a property boundary or at a location approximately 5 years downgradient of the current plume at the seepage velocity of the ground water or 1 to 2 years upgradient of the nearest downgradient receptor, whichever is more protective. The final number and location of POC monitoring wells will depend on regulatory considerations. Long-term monitoring wells are wells that are placed upgradient of, within, and immediately downgradient of the contaminant plume. These wells are used to monitor the effectiveness of intrinsic remediation in reducing the total mass of contaminant within the plume. Required are, one well upgradient of the contaminant plume, one well within the anaerobic treatment zone, one well in the aerobic treatment zone and one well immediately downgradient of the contaminant plume. The final number and location of long-term monitoring wells will depend on regulatory considerations.

Figure 2.4 shows a hypothetical long-term monitoring scenario. The results of a numerical model such as Bioplume II can be used to help site both the long-term and POC monitoring wells. In order to provide a valid monitoring instrument, all monitoring wells must be screened in the same hydrogeologic unit as the contaminant plume. This generally requires detailed stratigraphic correlation. To facilitate accurate stratigraphic correlation, detailed visual descriptions of all subsurface materials encountered during borehole drilling should be prepared prior to monitoring well installation. . The final placement of all monitoring wells should be determined in collaboration with the appropriate regulators.

The ground water sampling and analysis plan should be prepared in conjunction with POC and long-term monitoring well placement. Analyses should be limited to determining BTEX, dissolved oxygen, nitrate, and sulfate concentrations. Water level and NAPL thickness measurements must be made during each sampling event. Sampling frequency is dependent on the final placement of the POC monitoring wells. For example, if the POC monitoring wells are located 2 years upgradient of the nearest downgradient receptor, then an annual sampling frequency should be sufficient. If the POC monitoring wells are located 1 year upgradient of the potential receptor, then a semiannual sampling frequency should be sufficient. The final sampling frequency should be determined in collaboration with regulators.

SECTION 3

REFERENCES

Abdul, A.S., Kia, S.F., and Gibson, T.L., 1989, Limitations of monitoring wells for the detection and quantification of petroleum products in soils and aquifers: Ground Water Monitoring Review, Spring, 1989, p. 90-99.

Alvarez, P.J.J., and Vogel, T.M., 1991, Substrate interactions of benzene, toluene, and para-xylene during microbial degradation by pure cultures and mixed culture aquifer slurries: Applied Environmental Microbiology, v. 57, p. 2981-2985.

Anderson, M.P., and Woessner, W.W., 1992, Applied Ground water Modeling - Simulation of Flow and Advective Transport: Academic Press, New York, New York, 381p.

Anderson, M.P., 1979, Using models to simulate the movement of contaminants through ground water flow systems: CRC Critical Review in Environmental Control, no. 9, p. 97-156.

Atlas, R. M., 1981, Microbial degradation of petroleum hydrocarbons - an Environmental Perspective; Microbiological Reviews, 45(1):180-209.

Atlas, R. M, 1984, Petroleum Microbiology: Macmillan Publishing Co., New York.

Atlas, R.M., 1988, Microbiology - Fundamentals and Applications: Macmillan, New York.

Avon, L., and Bredehoeft, J.D., 1989, An analysis of trichloroethylene movement in ground water at Castle Air Force Base, California: Journal of Hydrology, v. 110, p. 23-50.

Baedecker, M.J., Siegel, D.I., Bennett, P.C., and Cozzarelli, I.M., 1988, The fate and effects of crude oil in a shallow aquifer: I. The distribution of chemical species and geochemical facies, In, G.E. Mallard, and S.E. Ragone, editors, U.S. Geological Survey Toxic Substances Hydrology Program, Proceedings of the Technical Meeting, Phoenix, Arizona, September 26-30, 1988: U.S. Geological Survey Water-Resources Investigations Report 88-42320, p. 13-20.

Bailey, G.W., and White, J.L., 1970, Factors influencing the adsorption, desorption, and movement of pesticides in soil, In Residue Reviews, F.A. Gunther and J.D. Gunther, editors: Springer Verlag, p. 29-92.

Barker, J.F., Patrick, G.C., and Major, D., 1987, Natural attenuation of aromatic hydrocarbons in a shallow sand aquifer: Ground Water Monitoring Review, Winter 1987, p. 64-71.

Cerniglia, C. E. 1984. Microbial transformation of aromatic hydrocarbons, In Petroleum Microbiology. R. M. Atlas editor: Macmillan Publishing Co., New York., p. 99-128.

Chapelle, F.H., 1993, Ground-Water Microbiology and Geochemistry: John Wiley & Sons, Inc., New York, 424 p.

Chiang, C.Y., Salanitro, J.P., Chai, E.Y., Colthart, J.D., and Klein, C.L., 1989, Aerobic biodegradation of benzene, toluene, and xylene in a sandy aquifer - data analysis and computer modeling, Ground Water, v. 27, no. 6, p. 823-834.

Chiou, C.T., Porter, P.E., and Schmedding, D.W., 1983, Partition equilibria of nonionic organic compounds between soil organic matter and water: Environmental Science and Technology: v. 17, no. 4, p. 227-231.

Cline, P.V., Delfino, J.J., and Rao, P.S.C., 1991, Partitioning of aromatic constituents into water from gasoline and other complex solvent mixtures: Environmental Science and Technology, v. 25, p. 914-920.

Concawe, 1979, Protection of groundwater from oil pollution; Den Haag, Report No. 3/79.

Cozzarelli, I. M., Eganhouse, R.P., and Baedecker, M.J., 1990, Transformation of monoaromatic hydrocarbons to organic acids in anoxic ground water environment: Environ. Geol. Water Science, 16.

Cozzarelli, I.M., Baedecker, M.J., Eganhouse, R.P., and Goerlitz, D.F., 1994, The geochemical evolution of low-molecular-weight organic acids derived from the degradation of petroleum contaminants in groundwater: Geochimica et Cosmochimica Acta, v. 58, no. 2, p. 863-877.

Cripps, R. E., and Watkinson, R.J., 1978, Polycyclic aromatic hydrocarbon metabolism and environmental aspects, In J. R. Watkinson, editor, Developments in Biodegradation of Hydrocarbons - 1, Applied Science Publishers, Ltd., London, p. 133-134.

Dalton, H., and Stirling, D.E., Co-metabolism: Philos Trans R Soc Lond, 297:481-496.

Davies, J. S. and Westlake, D.W.S., 1979. Crude oil utilization by fungi: Canadian Journal of Microbiology, 25:146-156.

Davis, R.K., Pederson, D.T., Blum, D.A., and Carr, J.D., 1993, Atrazine in a stream-aquifer system - estimation of aquifer properties from atrazine concentration profiles: Ground Water Monitoring Review, Spring, 1993, p. 134-141

Davis, J.W., Klier, N.J., and Carpenter, 1994a, Natural biological attenuation of benzene in ground water beneath a manufacturing facility: Ground Water, v. 32, no. 2, p. 215-226.

Davis, A., Campbell, J., Gilbert, C., Ruby, M.V., Bennett, M., and Tobin, S., 1994b, Attenuation and biodegradation of chlorophenols in ground water at a former wood treating facility: Ground Water, v. 32, no. 2, p. 248-257.

Dawson K.J. and Istok, J.D., 1991, Aquifer Testing - Design and analysis of pumping and slug tests: Lewis Publishers, Chelsa, Michigan, 344 p.

Dean, J. A., 1972, *Lange's Handbook of Chemistry*, 13th ed.: McGraw-Hill, New York

Grbic´-Galic´, D., and Vogel, T.M., 1987, Transformation of toluene and benzene by mixed methanogenic cultures: Applied and Environmental Microbiology, v. 53, p. 254-260.

Grbic´-Galic´, D., 1990, Anaerobic microbial transformation of nonoxygenated aromatic and alicyclic compounds in soil, subsurface, and freshwater sediments: In, J.M. Bollag and G. Stotzky, editors, Soil Biochemistry: Marcel Dekker, Inc., New York, p. 117-189.

Hall, R.A., Blake, S.B., and Champlin, S.C. Jr., 1984, Determination of hydrocarbon thicknesses in sediments using borehole data: In, Proceedings of the Fourth National Symposium on Aquifer Restoration and Ground Water Monitoring: May 23-25, 1984, p. 300-304.

Hampton, D.R., and Miller, P.D.G., 1988, Laboratory investigation of the relationship between actual and apparent product thickness in sands: NEED REFERENCE, SEE PETE GUEST

Harlan R.L., Kolm, K.E., and Gutentag, E.D., 1989, Water-Well Design and Construction, Developments in Geotechnical Engineering, Number 60: Elsevier, 205 p.

Hassett, J.J., Means, J.C., Banwart, W.L., and Wood, S.G., 1980, Sorption Properties of Sediments and Energy-Related Pollutants: EPA/600/3-80-041, U.S. Environmental Protection Agency, Washington, D.C.

Hassett, J.J., Banwart, W.L., and Griffin, R.A., 1983, Correlation of compound properties with sorption characteristics of nonpolar compounds by soils and sediments; concepts and limitations, In, C.W. Francis and S.I. Auerbach, editors, Environment and Solid Wastes: Butterworths, Boston, p. 161-178.

Hem, J.D., 1989, Study and Interpretation of the Chemical Characteristics of Natural Water: United States Geological Survey Water Supply Paper 2254, 264 p.

Higgins, I.J., and Gilbert, P.D., 1978, The biodegradation of hydrocarbons, In, K.W.A. Chator and H.J. Somerville, editors, The Oil Industry and Microbial Ecosystems: Heyden and Sons, London, p. 80-114.

Hopper, D. J., 1978, Incorporation of [^{18}O] water in the formation of p-hydroxybenzyl alcohol by the p-cresol methylhydroxylase from *Pseudomonas putida*: Biochem. J., 175:345-347.

Hughes, J.P., Sullivan, C.R., and Zinner, R.E., 1988, Two techniques for determining the true hydrocarbon thickness in an unconfined sandy aquifer: In Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground water: Prevention, Detection, and Restoration Conference: NWWA/API, p. 291 -314.

Hunt, J.R., Sitar, N., and Udell, K.S., 1988, Nonaqueous phase liquid transport and cleanup, 1. Analysis of mechanisms: Water Resources Research, v. 24, no. 8, p. 1247-1258.

Hutchins, S.R., 1991a, Biodegradation of monoaromatic hydrocarbons by aquifer microorganisms using oxygen, nitrate, or nitrous oxide as the terminal electron accpetor: Appl. Environ. Microbiol., v. 57, p. 2403-2407.

Kruseman, G.P. and de Ridder N.A., 1991, Analysis and Evaluation of Pumping Test Data: International Institute for Land Reclamation and Improvement, The Nederlands, 377 p.

Kuhn, E.P., Colberg, P.J., Schnoor, J.L., Wanner, O., Zehnder, A.J.B., and Schwarzenbach, R.P., 1985, Microbial transformations of substituted benzenes during infiltration of river water to ground water: laboratory column studies: Environmental Science and Technology, v. 19, p. 961-968.

Kuhn, E.P., Zeyer, J., Eicher, P., and Schwarzenbach, R.P., 1988, Anaerobic degradation of alkylated benzenes in denitrifying laboratory aquifer columns: Applied and Environmental Microbiology, v. 54, p. 490-496.

Kukor, J.J., and Olsen, R.H., 1989, Diversity of toluene degradation following long-term exposure to BTEX in situ: *Biotechnology and Biodegradation*, Portfolio Publishing, The Woodlands, Texas, p. 405-421.

Langmuir, D. and Whittemore, D. O., 1971, Variations in the stability of precipitated ferric oxyhydroxides, In J. D. Hem (ed.), *Nonequilibrium Systems in Natural Water Chemistry*, Advances in Chemistry Series 106: Am. Chem. Soc., Washington, D.C..

Leahy, J. G., and Colewell, R.R., 1990, Microbial degradation of hydrocarbons in the environment: Microbiological Reviews, 53(3):305-315.

Lee, M.D. 1988. Biorestoration of Aquifers Contaminated with Organic Compounds. CRC Critical Reviews in Environmental Control. v. 18. p. 29-89.

Lenhard, R.J., and Parker, J.C., 1990, Estimation of free hydrocarbon volume from fluid levels in monitoring wells: Ground Water, v. 28, no. 1, p. 57-67.

Lovely, D.R., Baedecker, M.J., Lonergan, D.J., Cozzarelli, I.M., Phillips, E.J.P., and Siegel, D.I., 1989, Oxidation of aromatic contaminants coupled to microbial iron reduction: Nature, v. 339, p. 297-299.

Lovely, D.R., 1991, Dissimilatory Fe(III) and Mn(IV) reduction: Microbiological Reviews, June 1991, p. 259-287.

Lyman, W.J., 1982, Adsorption coefficient for soils and sediment, In, W.J. Lyman *et al.*, editors, Handbook of Chemical Property Estimation Methods: McGraw-Hill, New York, 4.1-4.33.

Lyman, W.J., Reidy, P.J., and Levy, B., 1992, Mobility and Degradation of Organic Contaminants in Subsurface Environments: C.K. Smoley, Inc., Chelsea, Michigan, 395 p.

MacIntyre, W.G., Boggs, M., Antworth, C.P., and Staufer, T.B., 1993, Degradation kinetics of aromatic organic solutes introduced into a heterogeneous aquifer: Water Resources Research, v. 29, no. 12, p. 4045-4051.

Major, D.W., Mayfield, C.I., and Barker, J.F., 1988, Biotransformation of benzene by denitrification in aquifer sand: Ground water, v. 26, p. 8-14.

Payne, W.J., 1981, The status of nitric oxide and nitrous oxide as intermediates in denitrification: In, C.C. Delwiche, editor, Denitrification, Nitrification, and Atmospheric Nitrous Oxide: Wiley-Interscience, New York, New York, p. 85-103.

Perry, J. J, 1984, Microbial metabolism of cyclic alkanes, In, Petroleum Microbiology. R. M. Atlas, editor, Macmillan Publishing Co., New York, p. 61-67.

Postgate, J. R. 1984. The sulfate-reducing bacteria. Cambridge University Press, New York.

Rao, P.S.C., and Davidson, J.M., 1980, Estimation of pesticide retention and transformation parameters required in nonpoint source pollution models, In, M.R. Overcash and J.M. Davidson, editors, Environmental Impact of Nonpoint Source Pollution: Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, p. 23-67.

Reinhard, M., Goodman, N.L., and Barker, J.F., 1984, Occurrence and distribution of organic chemicals in two landfill leachate plumes: Environmental Science and Technology, 18:953-961.

Rifai, H.S., Bedient, P.B., Wilson, J.T., Miller, K.M., and Armstrong, J.M., 1988, Biodegradation modeling at aviation fuel spill site: Journal of Environmental Engineering, v. 114, no. 5, p. 1007-1029.

Roy, W.R., Krapac, I.G., Chou, S.F.J., and Griffin, R.A., 1992, Batch-type procedures for estimating soil adsorption of chemicals: United States Environmental Protection Agency Technical Resource Document EPA/530-SW-87-006-F, 100 p.

Sellers, K.L., and Schreiber, R.P., 1992, Air sparging model for predicting ground water clean up rate: Proceedings of the 1992 NGWA Petroleum Hydrocarbons and Organic Chemicals in Ground Water, Prevention, Detection, and Restoration Conference, November, 1992.

Singer, M. E., and Finnerty, W.R., 1984, Microbial metabolism of straight-chain and branched alkanes, In, R.M. Atlas, editor, Petroleum Microbiology: Macmillan Publishing Co., New York, p. 1-59.

Smith, J.H., Harper, J.C., and Jaber, H., 1981, Analysis and environmental fate of Air Force distillate and high density fuels: Report No. ESL-TR-81-54, Tyndall Air Force Base, Florida, Engineering and Services Laboratory.

Smith, M. R, 1990, The biodegradation of aromatic hydrocarbons by bacteria: Biodegradation, 1:191-206.

Srinivasan, P., and Mercer, J.W., 1988, Simulation of biodegradation and sorption processes in ground water: Ground Water, v. 26, no. 4, p. 475-487.

Starr, R.C. and Gillham, R.W., 1993, Denitrification and organic carbon availability in two aquifers: Ground Water, v. 31, no. 6, p. 934-947

Stotzky, G., 1974, Activity, ecology, and population dynamics of microorganisms in soil, In A. Laskin and H. Lechevalier editors, Microbial ecology: CRC Press, Cleveland, p. 57-135.

Wiedemeier, T.H., Guest, P.R., Henry, R.L., and Keith, C.B., 1993, The use of Bioplume to support regulatory negotiations at a fuel spill site near Denver, Colorado, In Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground water: Prevention, Detection, and Restoration Conference: NWWA/API, p. 445 -459.

Wiedemeier, T.H., Miller, R.N., Wilson, J.T., and Kampbell, D.H., 1994a, Proposed Air Force guidelines for successfully supporting the intrinsic remediation (natural attenuation) option at fuel hydrocarbon contaminated sites: Accepted for presentation at the 1994 NWWA/API Outdoor Action Conference.

Wiedemeier, T.H., Blicker, B., and Guest, P.R., 1994b, Risk-based approach to bioremediation of fuel hydrocarbons at a major airport: Federal Environmental Restoration III & Waste Minimization Conference & Exhibition.

Wilson, J.T., McNabb, J.F., Cochran, J.W., Wang, T.H., Tomson, M.B., and Bedient, P.B., 1985, Influence of microbial adaptation on the fate of organic pollutants in ground water: Environmental Toxicology and Chemistry, v. 4, p. 721-726.

Wilson, J.T., Leach, L.E., Henson, M., and Jones, J.N., 1986, In Situ biorestoration as a ground water remediation technique: Ground Water Monitoring Review, Fall 1986, p. 56-64.

Wilson, B. H., Smith, G.B., and Rees, J.F., 1986, Biotransformations of selected alkylbenzenes and halogenated aliphatic hydrocarbons in methanogenic aquifer material - A microcosm study: Environmental Science and Technology, 20:997-1002.

Wilson, B.H., Bledsoe, B., and Kampbell, D., 1987, Biological processes occurring at an aviation gasoline spill site, In R. C. Averett and D. M. Mcknight editors, Chemical Quality of Water and the Hydrologic Cycle: Lewis Publishers, Chelsea, Michigan, p. 125-137.

Wilson, B.H., Wilson, J.T., Kampbell, D.H., Bledsoe, B.E., and Armstrong, J.M., 1990, Biotransformation of monoaromatic and chlorinated hydrocarbons at an aviation gasoline spill site: Geomicrobiology Journal, v. 8, p. 225-240.

Wilson, J.T., Kampbell, D.H., and Armstrong, J., 1993, Natural bioreclamation of alkylbenzenes (BTEX) from a gasoline spill in methanogenic ground water: Proceedings of the Environmental Restoration Technology Transfer Symposium, San Antonio, Texas

Young, L.Y., 1984, Anaerobic degradation of aromatic compounds, In, D.R. Gibson, editor, Microbial Degradation of Aromatic Compounds: Marcel-Dekker, New York.

Zehnder, A. J. B., 1978, Ecology of Methane Formation, In, R. Mitchell editor, Water Pollution Microbiology: Wiley, New York, p. 349-376.

Zeyer, J., Kuhn, E.P., and Schwarzenbach, R.P., 1986, Rapid microbial mineralization of toluene and 1,3 dimethylbenzene in the absence of molecular oxygen: Applied & Environmental Microbiology, v. 52, p. 944-947.