Risk-Based Assessment of Appropriate Fuel Hydrocarbon Cleanup Strategies for Tank 325 Site at Nebo Annex Marine Corps Logistics Base Barstow, California

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Submitted to the U.S. Navy, Southwest Division
Naval Facilities Engineering Command, San Diego, California

January 1998

*University of California, Berkeley
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Acknowledgments

Table of Contents

Appendices

1. Program Overview

1.1. Introduction

In June 1994, the State Water Resource Control Board (SWRCB) contracted with the Lawrence Livermore National Laboratory/University of California (LLNL/UC) Leaking Underground Fuel Tank (LUFT) Team to study the cleanup of LUFTs in California. The study consisted of data collection and analysis from LUFT cases and a review of other studies on LUFT cleanups. Two final reports were submitted to the SWRCB in October and November 1995. These reports were entitled: *Recommendations To Improve the Cleanup Process for California's Leaking Underground Fuel Tanks (LUFTs)* (Rice et al., 1995a); and *California Leaking Underground Fuel Tank (LUFT) Historical Case Analysis* (Rice et al., 1995b).

1.2. LUFT Demonstration Cleanup Program

1.2.1. Background

One of the important recommendations of this study was to identify a series of LUFT demonstration sites and to form a panel of experts made up of scientific professionals from universities, private industry, and Federal and State regulatory agencies. This panel would provide professional interpretations and recommendations regarding LUFT evaluations and closures at demonstration sites.

As a result of this recommendation, ten Department of Defense (DOD) sites were selected. Site selection was coordinated through the California Military Environmental Coordination Committee (CMECC) Water Process Action Team (PAT). Sites were selected to represent each branch of the military services with bases in California, as well as a number of Regional Water Quality Control Boards (RWQCB) and the diverse hydrogeologic settings in California where fuel hydrocarbon contaminant (FHC) cleanup problems occur. The Barstow MCLC, Building 325 Site, within the Lahontan RWQCB, is one of the sites selected to participate in the DOD Petroleum Hydrocarbon Cleanup Demonstration (PHCD) Program. This program will be referred to as the DOD LUFT Demonstration Cleanup Program.

The other sites selected and their corresponding RWQCB region are:

- Army Presidio at San Francisco, San Francisco RWQCB.
- Camp Pendleton Marine Corps Base, San Diego RWQCB.
- Castle Air Force Base, Central Valley RWQCB.
- China Lake Naval Weapons Center, Lahontan RWQCB
- El Toro Marine Corps Air Station, Santa Ana RWQCB.
- George Air Force Base, Lahontan RWQCB.
- Port Hueneme Naval Construction Battalion Center, Los Angeles RWQCB.

- Travis Air Force Base, San Francisco RWQCB.

- Vandenberg Air Force Base, Central Coast RWQCB.

The Expert Committee (EC) selected to evaluate the selected demonstration sites are:

- Mr. David W. Rice, LLNL, Environmental Scientist; Project Director SWRCB LUFT Re-Evaluation Project; LLNL/UC LUFT Team member; DOD FHC Demonstration Program Coordinator.

- Dr. Walt McNab, LLNL, Hydrogeochemist, with expertise in the evaluation of passive bioremediation processes.

- Dr. William E. Kastenberg, UC, Berkeley, Professor and Chairman, Department o f Nuclear Engineering; member of LLNL/UC LUFT Team, with expertise in environmental decision making and decision analysis processes.

- Dr. Lorne G. Everett, UC, Santa Barbara, Hydrogeologist; Director, Vadose Zone Research Laboratory, member of LLNL/UC LUFT Team, Chief Hydrologist with Geraghty & Miller, Inc., with expertise in vadose zone FHC transport mechanisms and passive bioremediation processes.

- Dr. Stephen Cullen, UC, Santa Barbara, Hydrogeologist; member of LLNL/UC LUFT Team with expertise in vadose zone FHC transport mechanisms and passive bioremediation processes.

- Dr. Paul Johnson, Arizona State University, Chemical Engineer; primary author of *American Society for Testing and Materials (ASTM) RBCA* guidance, with expertise in chemical fate and transport.

- Dr. Michael Kavanaugh, former Chairman, National Research Council Alternatives for Groundwater Cleanup Committee; Vice President, Malcolm Pirnie, Inc., with expertise in evaluation of groundwater remediation alternatives and environmental decision making processes.

- Mr. Matthew Small, U.S. EPA Region IX, Hydrogeologist; Co-Chairman of U.S. EPA Remediation by Natural Attenuation Committee, with expertise in risk-based corrective action and passive bioremediation.

1.2.2. Risk-Based Corrective Action

The LLNL/UC recommendations report concluded that risk-based corrective action (RBCA) provides a framework to link cleanup decisions to risk. The DOD LUFT Demonstration Cleanup Program provides a series of sites where the application of a risk-based cleanup approach can be demonstrated.

For a risk to exist, there must be a source of a hazard, a receptor, and a pathway that connects the two. All three factors must be addressed to determine whether a LUFT release poses a risk to human health, safety, or the environment. If the source, pathway, or receptor are at all times absent, there is, by definition, no risk. The distinction between sources, pathways, and receptors may be context-dependent in many cases and therefore must be carefully defined. For purposes of the present assessment, definitions of these terms are developed by working backward from the receptor to the source:

<u>Receptor</u>: Human or ecological risk receptors which may potentially be subject to damage by exposure to hydrocarbons via ingestion, inhalation, or absorption. This definition also specifically includes water supply wells because it must be assumed that humans will be ingesting the water from these wells.

<u>Pathways</u>: Physical migration routes of contaminants from sources to risk receptors. This definition specifically includes the groundwater environment downgradient of the source that provides a medium through which dissolved contaminants may migrate to water-supply wells, as well as to surface water bodies which may serve as ecological risk pathways. The definition also includes the vadose zone in the immediate vicinity of the source, where vapor migration routes to nearby human receptors may exist.

<u>Sources</u>: Points of entry of contaminants into possible exposure pathways. In the case of hydrocarbon releases associated with LUFT sites, separate-phase hydrocarbon product which can either dissolve into the aqueous phase or volatilize into the gaseous phase constitutes a source. Primary sources will include underground tanks and associated piping; secondary sources will include any separate-phase hydrocarbon <u>or</u> free-product material residing within sediment pores.

From a mathematical viewpoint, sources and receptors represent boundary conditions for the problem of interest (influx and outflux, respectively); pathways represent the problem domain. Thus, in some special situations, the dissolved plume in groundwater may represent a source, such as in the case of Henry's law partitioning of contaminants from the aqueous phase into the gaseous phase. On the other hand, hydrocarbons which have adsorbed onto sediment surfaces from the aqueous phase cannot be regarded as potential sources in most situations according to this definition, but rather exist as part of the pathway.

Risk characterization is defined as an information synthesis and summary about a potentially hazardous situation that addresses the needs and interests of decision makers and of interested and affected parties. Risk characterization is a prelude to cleanup decision making and depends on an iterative, analytic, and deliberative process. This process attempts to gather all relevant data so the decision makers may then choose the best risk-management approach.

1.2.3. The Appropriate Use of Passive Bioremediation

The Recommendations Report also concluded that with rare exceptions, petroleum fuel releases will naturally degrade (passively bioremediate) in California's subsurface environments. The DOD LUFT Demonstration Cleanup Program provides sites where the appropriate use of passive bioremediation can be evaluated.

Passive bioremediation can control groundwater contamination in two distinct ways:

- First, passive bioremediation substantially lowers the risk posed to downgradient risk receptors through plume stabilization[1].

- Second, passive bioremediation actively destroys fuel hydrocarbon mass in the subsurface, leading to remediation of contamination over time (e.g., eventual contaminant

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[1] Even in the presence of a continuous constant source of fuel hydrocarbons (e.g., dissolution of residual free-product components trapped in the soil matrix), a groundwater plume subject to passive bioremediation will reach a steady-state condition in which plume length becomes stable. This will occur when the rate of hydrocarbon influx from dissolution of the residual free product source is balanced by the rate of mass loss via passive bioremediation, integrated across the entire spatial extent of the plume.

concentration decline and depletion of the dissolved hydrocarbon plume). From a risk-management viewpoint, the stabilization of the dissolved plume and associated reduction in exposure potential is the most important contribution of passive bioremediation.

The role of passive bioremediation in controlling the behavior of dissolved hydrocarbon plumes may be evaluated through both primary and secondary field evidence.

- Primary evidence includes quantitative evaluation of plume stability or plume shrinkage based upon trends in historical groundwater contaminant concentration data.

- Secondary evidence includes indirect indicators of passive bioremediation, such as variations in key geochemical parameters (dissolved oxygen, nitrate, sulfate, iron, manganese, methane, alkalinity/carbon dioxide, Eh, pH) between measurements in fuel hydrocarbon-impacted areas and background.

Although primary evidence of plume stability or decline generally provides the strongest arguments to support natural attenuation at a given site, such evidence may not be available because adequate historical groundwater monitoring may not exist. In these cases, short-term monitoring data providing secondary lines of evidence, in conjunction with modeling where appropriate, may support a hypothesis for the occurrence of passive bioremediation. Consequently, means for assessing the role of passive bioremediation in controlling risk by secondary lines of evidence should be fully explored at such sites.

Appropriate use of passive bioremediation as a remedial alternative requires the same care and professional judgment as the use of any other remedial alternative. This includes site characterization, assessment of potential risks, comparison with other remedial alternatives, evaluation of cost effectiveness, and the potential for bioremediation to reach remedial goals. Monitoring process and contingency planning must be considered as well.

Passive bioremediation may be implemented at a given petroleum release site either as a stand-alone remedial action or in combination with other remedial actions. The need for active source removal must also be addressed on a site-by-site basis. Source removal includes removing leaking tanks and associated pipelines, and any remaining free product and petroleum fuel saturated soil, as much as economically and technically feasible. When properly used, passive bioremediation can help manage risk and achieve remedial goals.

1.2.4. The DOD LUFT Demonstration Cleanup Program Steps

The demonstration program process can be summarized in the following nine steps:

Step 1: Site scoping meeting with site staff, regulators, and EC staff representatives. Develop and discuss site conceptual model. Identify and discuss pathways and receptors of concern.

Step 2: RBCA training for DOD Petroleum Hydrocarbon Cleanup Demonstration Program (PHCDP) participants.

Step 3: Site staff and contractors prepare the data package. EC staff reviews available data and identifies data gaps needed to apply a risk-based cleanup approach.

Step 4: EC visits site and receives briefing, on site characterization, conceptual model, and pathways and receptors of concern. Site tour is included in this briefing. Following EC's visit, a site characterization report is prepared by the EC containing recommendations for further data collection, if needed (See Appendix A).

Step 5:   EC staff applies a risk-based cleanup approach to the Site using best available data.

Step 6:   EC staff evaluates the natural attenuation potential for the Site using best available data. An estimate of the time to clean up and the uncertainty associated with this estimate will be made. Sampling and monitoring procedures to support intrinsic bioremediation for the site will be identified.

Step 7:   Based on the concept of applied source, pathways, and receptors as to potential hazards, site specific findings regarding natural attenuation potential, and discussion with regulators, the EC shall provide its recommendations for an appropriate risk-management strategy at the site and the set of actions needed to achieve site closure. The EC will present its recommendations at an appropriate forum.

Step 8:   The EC will provide a DOD LUFT Demonstration Cleanup Program overall evaluation comparing the effectiveness of risk-based cleanup at each site in the program. An estimation of the cost savings using risk-based cleanup protocols will be compared to baseline approaches. An estimation of the value of the remediated water will be made.

Step 9:   The EC Staff will produce a DOD *Risk Execution Strategy for Clean-Up* of the Environment (RESCUE) implementation guide and accompanying procedures manual (Phase I, Petroleum) that can be used in California and in other states by military bases.

2. Demonstration Site Overview

2.1. Background

Marine Corps Logistics Base (MCLB) Nebo Main Base is located near the town of Barstow in southeastern California. Building 325 is part of a small domestic wastewater treatment facility. The future use of this site is expected to be industrial wastewater treatment. Immediately adjacent to Building 325 are a golf course, open flood plain for the Mohave River, and railroad tracks. On the far side of the railroad tracks are warehouses and other industrial buildings associated with base activities. The area surrounding Nebo Main Base includes a rifle range, open space, residential areas for base personnel, and occasional private homes.

Tank 325 (T-325) was a 1,300 gallon, single walled, fiberglass, spherical underground storage tank installed in 1979. The tank supplied diesel fuel for Building 325's emergency generator, boiler, heater, and digester. The tank was taken out of service in 1994 and removed from the ground in March 1995. Soil from the excavation was combined with pea gravel and backfilled. Several investigations have been conducted for the T-325 Site and nearby areas (Jacobs, 1995 and 1996; Brown and Caldwell, 1996; PRC, 1996a and 1996b).

2.2. Site Conceptual Model

The T-325 site is located within the Mojave Desert Geomorphic Province, which is dominated by alluvial basins. A deep soil boring was conducted to develop cross sections for the Nebo Main Base with the closest boring to the Site being approximately 2,000 ft on the other side of the Harper Lake-Camp Rock Fault (Jacobs, 1996). There is some uncertainty regarding the continuation of alluvium layers across the fault; however, it is likely that the Site is underlain

by approximately 150–200 ft of younger alluvium on top of several hundred feet of older alluvium. The alluvial material encountered at the T-325 included fine to coarse-grained sands, gravely sands, silty sands, and clayey sands.

Groundwater at the T-325 Site is found at about 30 ft below the ground surface. The site is bounded to the north by the Mojave River, which acts as a recharge boundary for aquifers within the vicinity of the site. The water table elevation may increase several feet during a significant recharge event from the Mohave River and then gradually decrease or change only slightly for several years before another major storm flow. Figures in the Brown and Caldwell (1996) and PRC (1996a) reports indicate an approximate groundwater flow direction to the northeast with a horizontal gradient of approximately 0.003 ft/ft. Analysis of local water elevation data indicates the direction of the horizontal gradient may range from northeast to east. The two-year average vertical gradient was approximately 0.001 ft/ft downward, which is expected in a recharge zone. The vertical gradient also changes direction seasonally.

The horizontal extent of the resulting T-325 soil plume was delineated within approximately ± 50 ft in the downgradient and crossgradient directions using 11 boreholes in July 1995 (Brown and Caldwell, 1996).   Neither the upgradient nor the vertical extent of the soil contamination has been delineated. Three groundwater monitor wells have also been installed and were sampled four times between December 1995 and November 1996 (PRC, 1996a,b).   The soil contamination near the groundwater surface was approximately 150 ft by 350 ft in July 1995. As of November 1996, the BTEX plume in groundwater was 400- to 500-ft long as defined by the 1 ppb contour.

Because the groundwater plume is relatively young, long-term trends in well data which may indicate stability or bioattenuation of the plume are not available. In fact, the BTEX plume had possibly just reached MW-3 as of November 1996. As a secondary source of information, geochemical data from the monitoring wells was analyzed to determine if bioattenuation is likely occurring at Site 325. There is insufficient data to determine a degradation rate; however, reduced DO (dissolved oxygen) levels associated with high TPH-d indicate biological activity in these areas. Other geochemical indicators besides DO were either not measured or inconclusive.

A review of the adequacy of the conceptual model was presented to MCLB Nebo Main in a letter report dated May 8, 1997 (Appendix A).

3. Risk Analysis

A preliminary human health risk assessment was conducted for the T-325 Site as part of the site assessment (Brown and Caldwell, 1996); however, presentation of the data and methods was incomplete. Risks to human, as well as ecological, receptors will be re-considered in this report.

3.1. Sources

The source of fuel hydrocarbons beneath Facility 325 was a hole approximately one-third of the way down Tank 325. The estimate of release volume from T-325 is 18,000 to 23,000 gallons of diesel fuel based on fuel delivery records and the operations of a similar facility at MCLB Yermo Annex. Some portion of this volume migrated down to the water table and serves as the

primary source for groundwater contamination. In August 1996, there was approximately one ft of free product floating on the water table in MW-1 and 3 inches floating in MW-2. In October, there was still about one foot of product in MW-1, but the level in MW-2 decreased to less than an inch. By the end of November, there was less than one inch of product in both MW-1 and MW-2. As the water table fluctuates, the diesel will continue to be smeared onto the soil particles, becoming less mobile in the process.

Residual concentrations of diesel remain in the soil and provide a secondary source of groundwater contamination from leaching. The locations of contaminated soil include the back-filled area and soil below the former tank location, as well as the smear zone where the floating diesel migrated horizontally on the water table.

Conservative estimates of the initial masses of benzene, toluene, ethylbenzene and xylenes based on soil data were used because no data was available on the composition of the diesel fuel. Soil samples 1787-B2-30-S, 1787-B3-30-S, 1787-B8-30-S, and 1787-MW1-31-S were used as the basis for these estimates.

3.2. Exposure Pathways

For exposure and health risk to occur, there must be a pathway from the contaminant to the receptor. This section looks at the possible pathways for soil and groundwater contaminants under Facility 325 to reach receptors.

3.2.1. Ingestion Pathway

The ingestion pathway results from either contaminants migrating in the groundwater or direct ingestion of contaminated soil. There are many factors which affect transport and fate of chemicals in groundwater, including advection, dispersion, sorption onto the matrix, bioattenuation and vaporization. No transport and fate modeling was conducted for Building 325 in the previous reports and none is warranted given the minimal data available to calibrate a model. Using aquifer data obtained at other sites on Nebo Main, a range of water velocities was provided in the Letter Report (Appendix A). The range of average water velocity was estimated as 0.18 ft/day to 3.8 ft/day. These values can be used to estimate the minimum and maximum distances the plume could travel without attenuation.

It is known that diesel was present in the groundwater in B-8 on August 1, 1995, and on August 23, 1996, no fuel hydrocarbons were yet present above detection limits in MW-3. From the velocity range provided, the plume would be expected to travel between 70 and 1,500 ft due to advection only. The distance between B-8 and MW-3 is approximately 260 ft. Without hydraulic conductivity measurements at Facility 325, it is not possible to reduce the range of possible velocities and determine the extent of natural attenuation occurring at the site.

Direct ingestion of contaminated soil may occur because the soil removed during tank removal was back-filled without treatment. Although the amount of soil ingested by humans is typically small, consideration must be given to this pathway because the site may undergo construction associated with a new wastewater treatment plant.

3.2.2. Inhalation Pathway

Lighter constituents of the diesel in the soil may evaporate and migrate to the soil surface. The risk to personnel working at Facility 325 inhaling these vapors was estimated using CalTOX (DTSC, 1993a,b,c), a multimedia, multiple pathway model developed for the California Department of Toxic Substances Control. Although there are drinking water standards for several components of diesel, benzene is the primary concern for cancer risk, particularly through the inhalation of vapor pathway. Non-cancer health hazard was also calculated for toluene, ethylbenzene and xylenes. The CalTOX model consists of a box model representing the different soil layers, water bodies, air, and plants.

3.2.3. Direct Dermal Contact Pathway

Direct contact between skin and contaminants may occur if workers dig into the soil where the former tank was located. This pathway must be considered because the future use of this site is wastewater treatment and the facility may be modified or replaced in the cleanup time frame.

3.3. Receptors

3.3.1. Human Health Receptors

There is currently no groundwater pumped on Nebo Main Base, and no active or inactive wells located on base, down gradient of Facility 325. The closest existing well is a private residence located approximately one mile (5,280 ft) downgradient of the initial source. From data collected for the LUFT study (Rice et al., 1995), it is highly unlikely that any of the fuel hydrocarbon contaminants from Facility 325 would extend off base to reach a current receptor.

The only receptors who may inhale vapors released from the soil are workers at Facility 325. As the site is expected to remain a wastewater treatment facility, exposure patterns common for industrial workers were used in this analysis. In addition to inhalation, construction workers at the site may be receptors for direct ingestion and dermal sorption through direct contact with contaminated soil.

3.3.2. Future Receptors

The future beneficial use of the groundwater under Nebo Main has been stated as a remedial goal and thus, land use planning must also be considered. Because the site is expected to remain a water treatment facility for the foreseeable future, it is unlikely that any new wells would be developed on base, downgradient of the facility within the next 20 to 40 years.

3.3.3. Ecological Receptors

The Jacobs (1995) report identified sensitive ecological receptors on both Yermo Annex and Nebo Main. None of these are expected to be impacted at T-325 because they do not come into contact with the groundwater and are not in the vicinity of the soil contamination.

3.4. Risk and Hazard Calculation

The risk to personnel working at Facility 325 from vapor inhalation, dermal sorption and ingestion of soil particles was estimated using a spreadsheet model. The value calculated for benzene is the incremental lifetime cancer risk due to the diesel remaining in the soil below the ground surface and does not include other types of worker risk. Although there are drinking water standards for several components of diesel fuel, benzene is the primary concern for cancer risk from diesel. While the State of California does not currently identify toluene, ethylbenzene or xylenes as cancerous, there are toxic effects associated with these compounds. These are calculated as a hazard level relative to the allowable daily intake (ADI).

CalTOX (DTSC, 1993a,b,c), a multimedia, multiple pathway model developed for the California Department of Toxic Substances Control was used to determine media concentrations and potential doses (or exposure) in this analysis. The CalTOX model combines a box model (representing the different soil layers, water bodies, air, and plants) with a risk model based on the US EPA *Risk Assessment Guidance for Superfund* (U.S. EPA, 1989). Additional information and parameters used in the risk and hazard calculations can be found in Appendix B.

The risk and hazard results are summarized in Tables 3.1 and 3.2. The incremental lifetime cancer risk for all pathways from benzene was calculated as 7.6×10^{-9}, while the hazard ratio for each pathway was $<10^{-10}$ for toluene, ethylbenzene and total xylenes.

Table 3.1. Incremental lifetime human cancer risk summary.

	Inhalation	Ingestion	Dermal	Total
Benzene	6.7×10^{-9}	3.2×10^{-10}	5.8×10^{-10}	7.6×10^{-9}

Table 3.2. Hazard ratio summary.

	Inhalation	Ingestion	Dermal	Maximum
Toluene	3.8×10^{-12}	4.9×10^{-14}	3.5×10^{-16}	3.8×10^{-12}
Ethylbenzene	3.2×10^{-39}	1.1×10^{-39}	8.8×10^{-42}	3.2×10^{-39}
Xylenes (total)	2.8×10^{-20}	3.6×10^{-21}	3.5×10^{-23}	2.8×10^{-20}

3.5. Remedial Goals

The management options available depend on the remedial goals or objectives, as well as technical considerations. Some of the remedial goals for Tank Site 325 have been implied in a draft letter by Curt Shifrer of the CRWQCB, but should be explicitly discussed among the concerned parties.

Cleanup requirements or standards are set by states to ensure that sufficient contamination is removed to protect human health and the environment. Under this broad umbrella of concerns, state-specific considerations such as groundwater use, aquifer beneficial use designation, cleanup

costs versus risks, technical feasibility of cleanup, available expertise, available funding, permitting, land use, and property transfers may also play a role in setting these standards.

The cleanup standards usually fall into one of three broad categories: (1) technology based standards, which are based on the detection limits of analytical laboratory equipment; (2) subjective standards, which are often adopted based on technology limits or in the absence of another mechanism; these standards may require cleanup to non-detectable or background levels; and (3) risk-based standards, which can be either an overall standard based on conservative yet realistic exposure and toxicity analysis, or site specific standards based on site specific conditions, land use, and exposure scenarios.

To establish remedial goals, these standards are then applied either at all locations throughout the plume or at some boundary beyond which the plume cannot be allowed to migrate. Remedial goals may also include some time frame within which the goals must be met. If conditions at the site do not exceed remedial goals, the site will usually receive a status of "no further action required at this time." However, if site conditions do exceed remedial goals, then several choices exist (Small, 1993):

Cleanup to background or non-detect: This approach is very protective of human health and the environment, but can often prove to be prohibitively expensive or technically infeasible.

Cleanup to an overall or generic standard: This approach is also protective, feasible in many cases, and generally less expensive than cleanup to background or non-detect levels. However, these levels may still prove to be prohibitively expensive, or even technically infeasible for some sites.

Risk management, or containment: When contaminant concentrations exceed the remedial goals, but such goals cannot feasibly be achieved, then risk management through containment of contamination to prevent further migration may be an option. Active containment systems are often expensive to install and maintain, and require long term institutional control. Passive containment systems are less expensive but have uncertain durability for long-term containment. The continued presence of contamination in the subsurface may also decrease the value of the property.

No Action: In some instances no remedial actions, including monitoring may be needed because of no or *de minimus* future risks to human health and the environment. As with monitored natural attenuation, this approach may require site-specific exposure and risk assessment, to determine whether the site poses unacceptable threats to public health and the environment.

3.6. Remedial Technology or Process Selection

If contaminant concentrations exceed remedial goals and cleanup is required, then a cleanup technology must be selected based on the information obtained from site assessment and characterization. This technology should be selected based on the ability to meet remedial goals, site conditions, and physio-chemical properties of the contaminants. The technology should not create additional hazards (e.g., air sparging without soil vapor extraction that may potentially transport vapors into buildings).

The technology should ideally perform this task as quickly, efficiently, and cost effectively as possible. It is also important to give some consideration to how the cleanup technology or process actually accomplishes concentration reductions and where the removed contaminants or byproducts are actually going. There are four basic alternatives:

1. Reuse/recycling.

2. Waste destruction (or conversion).

3. Media transfer.

4. Waste disposal.

Media transfer and disposal options may simply move the contamination to another location where it will have to be cleaned up again. Whereas reuse, recycling, and destruction technologies or processes offer more long-term or permanent solutions.

Monitored natural attenuation or passive bioremediation may provide cost effective containment at some sites. In some instances where contamination exceeds remedial goals, but no immediate threats or impacts are identified, it may be acceptable to allow contamination to remain in place without active remediation. Monitored natural dilution, attenuation, and degradation processes are allowed to slowly reduce concentration levels. However, this approach may require site-specific exposure and risk assessment, to determine threats and impacts to public health and the environment (Small, 1993).

If active cleanup is required, then a technology must be selected based on the information obtained from site assessment and characterization. This technology should be selected based on the ability to meet remedial goals, site conditions, and physio-chemical properties of the contaminants. The technology should not create additional hazards (e.g., air sparging without soil vapor extraction that may potentially transport vapors into buildings).

4. Summary and Recommendations

Sources. The underground storage tank which was the source of the spill has been removed. Contaminated soil remains, both in the immediate vicinity of the former tank location and in the smear zone near the water table.

Pathways. There is limited data indicating microbial activity in portions of the plume; however, the data is insufficient to determine stability or decline of the dissolved phase BTEX plumes. The current extent of the plume does not threaten any existing drinking water well, and given the nature of the existing facility, it is unlikely that new wells would be developed within a thousand feet of the water treatment plant as long as it remains a similar type facility. The vapor and direct contact pathways were estimated and found to yield very low exposures, and hence very low risk.

Receptors. Neither the onsite workers, nor the off-site water well, nor any near future on-base wells appear to be currently at risk. If the plume continues to expand, then the risk could change.

In summary, the T-325 diesel spill site is currently a low human health risk site. To meet the beneficial use cleanup objective and protect the future use of the aquifer, the concentrations of

contaminants will eventually need to be reduced. The question is, what is a reasonable time frame to restore the aquifer to acceptable levels of contaminants.   Although we cannot say for certain how long it will take for the diesel components to degrade, the future expected use of the site makes it reasonable to consider a longer cleanup time. Because of the low recharge rate and slow but significant changes in water table elevation, diesel components may remain in the soil above the water table for many years without impact to human health. As the diesel ages, though, the lighter fractions evaporate and the potential for remaining components to leach into the groundwater decreases with time.

Based on the low risk posed by the contaminants at T-325, we recommend continued sampling of MW-1, MW-2, MW-3, and NSI-3 on an annual basis for 5 years to monitor for benzene, toluene, ethylbenzene and xylene (BTEX), naphthalene, and total petroleum hydrocarbons as diesel (TPH-d) to ensure plume stability or decline. Because the plume is young, there may be an initial rise in contaminant concentrations in MW-3. MW-3 is located approximately 500 ft and NSI-3 approximately 725 ft from the former location of T-325. Based on the data obtained in the LUFT study, hydrocarbon plume stabilization would be expected well within these distances. If concentrations in MW-3 increase significantly, consideration should be given to installing an additional monitoring well. Because the water table gradients tend to shift direction seasonally, a good location for the additional well may be along the south fence line, opposite of NSI-3. This is approximately 700 to 750 ft due east of the initial source. In the unlikely event that the plume does not stabilize within five years, the Navy should reconsider active control of the plume.

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Appendix A

Site Assessment Review Application of Risk-Based Corrective Action (RBCA) Tank 325 Site Marine Corps Logistics Base, NEBO Annex Barstow, California

Letter Report

Lawrence Livermore National Laboratory

SITE ASSESSMENT REVIEW
APPLICATION OF RISK-BASED CORRECTIVE ACTION (RBCA)
TANK 325 SITE
MARINE CORPS LOGISTICS BASE, NEBO ANNEX
BARSTOW, CALIFORNIA

The Department of Defense (DoD) Petroleum Hydrocarbon Cleanup Demonstration Program (PHCDP) Expert Committee has reviewed the methods and findings of the site investigations conducted at Marine Corps Logistics Base (MCLB), Barstow, California to address petroleum hydrocarbon contamination of soil and groundwater at Facility 325 (T-325 Site). This letter report is our assessment of the adequacy of the site characterization and site conceptual model as a basis for applying risk-based corrective action (RBCA) methodologies and selecting an appropriate risk management strategy at the Site.

Recommendations regarding additional data needed to complete our assessment and refine the Site conceptual model are provided. This letter represents the first of two deliverable documents as part of our overall assessment of the Site. It is intended solely as a review of the existing Site data and risk characterization results.

A second deliverable will provide site-specific risk management recommendations. Included in the risk management recommendations will be a detailed analysis of key RBCA assumptions and an assessment of site-specific remedial options including the potential biodegradation of petroleum hydrocarbons.

SITE CONCEPTUAL MODEL

A well defined conceptual model of a site contains sufficient information to: a) identify sources of the contamination, b) determine the nature and extent of the contamination, c) identify the dominant fate and transport characteristics of the site, d) specify potential exposure pathways, and e) identify potential receptors that may be impacted by the contamination. Several investigations have been conducted for the T-325 Site and nearby areas (Jacobs, 1995 & 1996; Brown and Caldwell, 1996; PRC, 1996a &1996b).

The T-325 site is located within the Mojave Desert Geomorphic Province, which is dominated by alluvial basins. The site is bounded to the north by the Mojave River, which acts as a recharge boundary for aquifers within the vicinity of the site. The depth to groundwater at the T-325 Site is about 30 feet. A deep soil boring was conducted to develop cross sections for the Nebo Main Base with the closest boring to the Site being approximately 2000 ft on the other side of the Harper Lake-Camp Rock Fault (Jacobs, 1996). There is some uncertainty regarding the continuation of alluvium layers across the Fault; however, it is likely that the Site is underlain by approximately 150-200 ft of younger alluvium on top of several hundred feet of older alluvium. The alluvial material encountered at the T-325 included fine to coarse-grained sands, gravely sands, silty sands, and clayey sands. Soils are generally reddish brown in color and loose to very dense.

Sources

The primary source of soil and groundwater contamination at the Site has been clearly established. The area including building 325 and underground storage tank 325 (T-325) was a domestic waste water treatment facility. Tank 325 was a 1,300 gallon single walled fiberglass spherical tank installed in 1979. The tank supplied diesel fuel for Facility 325's emergency generator, boiler, heater and digester. The tank was taken out of service in 1994 and removed from the ground in March of 1995. Upon removal, a 3 inch by 6 inch hole was discovered approximately one third of the way down from the top of the tank. After samples were obtained from the pit walls and soil stockpile, the soil from the excavation was combined with pea gravel and backfilled without treatment.

Through comparison of fuel delivery records with those of a similar facility on the Yermo Base, base personnel estimated that 18,000 gallons of diesel fuel were lost between September 1992 and April 1994. Although the cause of the hole could not be confirmed, it is possible that it occurred or was aggravated during the June 1992 Landers Earthquake. In addition, it is postulated that there was possibly a smaller hole in the tank before the earthquake, which could have released an additional 2,000 - 5,000 gallons over a period of several years. Thus, the best estimate of release volume from T-325 is 18,000 - 23,000 gallons of diesel fuel.

During the excavation of T-325, a small area of soil contamination above the elevation of the tank was discovered. This was apparently minor spillage associated with the emergency generator. There are no other apparent sources of petroleum hydrocarbons contributing to the soil and groundwater contamination at the T-325 Site.

Nature and Extent of Contamination

The contaminants identified in the soil and groundwater include total petroleum hydrocarbons as diesel (TPH-d) and volatile organic compounds (VOCs). The volatile aromatic hydrocarbons, benzene, toluene, ethylbenzene and total xylenes (BTEX) and naphthalene are constituents of diesel which are of concern because of their mobility and potential adverse health affects.

During the Phase I site investigation for UST removal in July of 1995, 11 boreholes were sampled for soil and groundwater contamination (Brown and Caldwell, 1996). In the Phase II site investigation in December 1995, three monitor wells were installed. Again, soil and groundwater samples were collected and analyzed (Brown and Caldwell, 1996). These three monitoring wells and two nearby wells (NNP-3 and NSI-3) were also sampled in August, October and November of 1996 (PRC, 1996a&b).

The detection limits minimum reportable concentrations for BTEX varied depending on the sampling event and whether TPH-d was present. Concentrations of TPH-d and BTEX in groundwater were less than the detection limit of analysis at MW-3 during construction of the well, and also during the August and October 1996 sampling events. The edge of the benzene, ethylbenzene and total xylenes plumes reached MW-3 by November 1996; however, due to changes in analysis methods it is not certain exactly when this occurred in the August to November 1996 time period. The concentration of TPH-d in MW-3 was still below the detection analysis limit of 50 µg/L as of November 1996.

Samples from the August, October and November 1996 events were analyzed for VOCs. The VOCs, e.g., 1,3,5-Trimethylbenzene, 1,2,4-Trimethylbenzene, or 4-Isopropyltoluene, detected in MW-1 and MW-2 are common components of fuels. There are also sporadic

detections of low concentrations detections (< 10 µg/L) of tetrachloroethene in MW-3, which may not be associated with the diesel release from T-325.

The primary purpose for delineating the soil and groundwater plumes is to determine the extent of contamination in soil and groundwater. The horizontal extent of the T-325 soil plume is delineated within approximately plus or minus 50 feet in the down-gradient and cross-gradient directions. Neither the up-gradient nor the vertical extent of the soil contamination has been delineated. In spite of the limited information provided by sampling soil borings every 5 ft in depth, and at inconsistent depths in relation to the water table elevation, a reasonably clear picture of the history and progression of the diesel migration can be inferred when the data from the Phase I and II investigations, along with the more recent groundwater sampling events, are evaluated.

We believe that the soil contamination and the groundwater plumes at the T-325 Site are still relatively young. At the time of the Phase I investigation (July-Aug. 1995), diesel had reached the water table in the vicinity of B-3, which is the closest borehole to the former location of T-325. While other boreholes showed soil contamination, it is unlikely that the product had pooled extensively on the water table because no other groundwater samples from boreholes or during well construction showed saturation concentrations except for B-3. Approximately one year after the Phase I and II assessments, the monitor wells were again sampled. During the August 1996 sampling event, there was 0.975 ft of free product in MW-1 and 0.225 ft in MW-2. The October 1996 sampling event indicated 1.03 ft and 0.08 ft of product in MW-1 and MW-2, respectively. By the November 1996 sampling event, the product levels had decreased to 0.08 ft in MW-1 and 0.01 ft in MW-2. During this time, the water table steadily decreased in MW-2, but fluctuated down and up in MW-1. There is some uncertainty regarding the amount of free product trapped in the soil during the water table fluctuation and the extent of the lateral spread. It is likely that at this time there is a smear zone of diesel contamination in the soil a foot or two above and/or below the water table, extending somewhat larger than during the Phase I and II Assessments, but not reaching MW-3.

From the data reviewed above, it appears that the bulk of the T-325 release was continuing to migrate down through the soil to the water table during the Phase I and II Assessments (July-Aug. 1995). It formed a pool on the water table by August 1996, and may have dispersed somewhat since then. The groundwater plumes appeared to be co-located with the soil contamination plume during the initial assessments; however, the more soluble diesel BTEX constituents have since migrated and formed larger plumes.

Before concluding that the locations of the soil contamination and the groundwater plumes are now adequately known, consideration must be given to the possibility of diesel being trapped, and serving as a secondary source of contamination below the water table. This must be considered because of the possibility that the tank had a small leak for a long period of time before the large losses were reported in 1992 and there have been changes in the depth to groundwater at the Site.

A brief review of the water table elevation history is appropriate before considering this scenario. There are two wells (NSI-3 and NNP-3) reasonably close to the T-325 site, which were installed as part of a remedial investigation for Yermo and Nebo Main Base (Jacobs, 1995). These wells have been sampled for groundwater elevation at least since January 1993. In January 1993, the water table elevation in NSI-3 was 1980.6 ft above mean sea level (amsl), while in NNP-3 it was 1985.45 ft. In the spring of 1993 there was a hundred year flood event in the Mojave River, and groundwater recharge resulted in water table elevations of 2001.0 and 2004.8 ft amsl in NSI-3 and NNP-3, respectively. Since this

approximately 20 ft rise, the water table elevation has been declining, and in November 1996 was 1993.1 and 1997.1 ft amsl in NSI-3 and NNP-3, respectively.

If small amounts of diesel had been trapped below the current water table surface elevation, the entrapments would have occurred during the fast recharge event in Spring 1993. The trapped product or contaminated soil could remain relatively undetected by soil borings which only extend to the current water table and monitor wells which are screened continuously from approximately 10 -or 20 ft above the current water table down to the former water table elevation. The data gathered during the site assessments do not rule out the possibility that soil contamination below the current water table elevation may act as an on going secondary source; however, if this is a significant problem, higher TPH-d concentrations would be expected in MW-2 and MW-3.

Fate and Transport of Constituents

There are several factors affecting fate and transport of contaminants in groundwater. These include the groundwater gradient, hydrogeologic properties of the aquifer and degradation or transformation of the contaminants. The groundwater gradient will be considered first.

Figures in the Brown and Caldwell (1996), and PRC (1996a) reports indicate an approximate groundwater flow direction as to the northeast with a gradient of approximately 0.003 ft/ft. This is a very small gradient. Northeast is approximately in the direction from MW-1 to NSI-3, and nearly the direction from MW-1 to MW-3. The lack of contamination in B-9 and B-10 is consistent with the assumed groundwater flow direction; however, additional information may be obtained from analyzing the more recent water surface elevation measurements.

Data from the August, October and November sampling events were used to estimate the groundwater gradient in the vicinity of the T-325 site. Data for MW-1 was not used due to the presence of substantial free product in the well during the first sampling event. As the primary interest in conducting this analysis was to determine if the plume was likely to appear in MW-3 in the future, a local coordinate system was set up with MW-1 as the origin. The positive x direction is defined through MW-3 and z is the vertical direction. Three data points were used to define the groundwater surface plane and gradients in the x and y directions were taken. The negative of the vector sum of these gradients is the approximate flow direction.

The gradients are summarized in Table 1. In the x direction, from MW-1 towards MW-3, the calculated gradients are between -0.0017 and -0.0028 ft/ft. In the y direction, the calculated gradients are between 0.0008 and 0.0061ft/ft. Although the values for the y direction are less consistent, and therefore less reliable, they do indicate a gradient in the y direction of approximately the same magnitude as that in the x direction. Based on these results, the groundwater flow direction is approximately due east from August 1996 through November 1996. The magnitude of the gradient, however, is consistent with previous reports (Brown and Caldwell, 1996; PRC, 1996a).

Table 1. Horizontal Groundwater Gradients (ft/ft)

Gradient	Wells Used for Plane	8/23/96	10/22/96	11/25/96
$\partial h/\partial x$	MW-3,NSI-3,NNP-3	-0.0023	-0.0017	-0.0025
	MW-2,NSI-3,NNP-3	-0.0023	-0.0026	-0.0028
$\partial h/\partial y$	MW-3,NSI-3,NNP-3	0.0023	0.0061	0.0022
	MW-2,NSI-3,NNP-3	0.0021	0.0012	0.0008

The vertical groundwater gradient affects mixing within the aquifer and the potential for migration of dissolved phases deeper within the aquifer. This is an important consideration in determining if multiple screenings in monitor wells are necessary and how deep the wells need to be. The Jacobs study included estimations of vertical gradients at several locations including NSI-3. The two year average vertical gradient was approximately 0.001 ft/ft downward, which is expected in a recharge zone; however the gradient changed direction seasonally.

In addition to the gradient, advection of water and contaminants is also governed by the hydraulic conductivity and effective porosity. No measurements of porosity were located in any of the reports available to the Expert Committee; however, this parameter can be estimated reasonably well from soil boring logs. The hydraulic conductivity is less predictable, because it varies over many orders of magnitude for similar soils. The closest conductivity data to the T-325 Site are at the golf course and the NEP-4 area. Both of these sites are on the other side of the Harper Lake-Camp Rock Fault from T-325, but have similar soils. Multiple well pumping tests conducted at the golf course by OHM and interpreted by Jacobs (1996a) resulted in a horizontal conductivity estimate of 255 ft/d and a vertical to horizontal conductivity ratio of 0.01. Pump tests at the NEP-4 site yielded a horizontal conductivity estimate of 28 ft/d. There was no estimate of vertical conductivity at the NEP-4 site. From these conductivity estimates, an average horizontal gradient of 0.003 ft/ft, and an assumed porosity of 0.2 to 0.4, the average water velocity could range from 0.18 ft/day to 3.8 ft/day.

Other key parameters influencing fate and transport of fuel hydrocarbons include soil organic carbon fraction and the geochemical conditions in the aquifer. No data were reported on soil organic carbon, but it is expected to be low given the geologic information in the soil borings and well logs. The exception would be for the localized layers of sand mixed with clay and thin layers of clay.

A significant factor in determining if a plume may be stable and estimating the clean-up time to restore beneficial use of the groundwater is identifying what natural attenuation processes may be occurring and at what rates. There are three rounds of general minerals analyses and dissolved oxygen (DO) measurements (August, October and November 1996) for five wells (MW-1, MW-2, MW-3, NNP-3, and NSI-3) (PRC, 1996a&b), except for MW-1 which was not sampled in August 1996, nor did it have DO measured in October 1996. The DO levels in areas with high concentrations of TPH-d are consistently low, indicating the possibility of biotic activity in these areas. Areas with moderate or low levels of contaminants are less consistent in terms of their DO measurements. The general minerals data are useful for assessing the possible biotic transformations of aromatic hydrocarbons and will be evaluated as part of the Expert Committee's assessment of the T-325 plume behavior.

Exposure Pathways

A preliminary human health risk assessment was conducted for the T-325 Site as part of the site assessment (Brown and Caldwell, 1996). Their report listed the potential exposure pathways for industrial workers as "direct contact, vapor migration inside and outside, leaching to groundwater, and ingestion" of groundwater. More explicitly, these are direct contact with contaminated soil, migration of vapors from the soil and groundwater (either into buildings or outside), leaching of contaminants from the soil into the groundwater and ingestion of groundwater.

Although there are no residences located down gradient of T-325 on base, there are residences off-base. The exposure pathway for these receptors is migration of groundwater contaminant plumes to their private wells. The tap water exposure pathways include ingestion, dermal sorption, and inhalation of volatilized compounds.

Potential Receptors

The T-325 Site is expected to continue to be a waste water treatment facility of some kind. The Brown and Caldwell (1996) assessment considered the risk to workers at this site. There are currently no water supply wells operating on the Nebo Main Base. The aquifer may be used again in the future; however, it is unlikely that there will be any wells in the close vicinity of T-325 due to the nature of the facility and wellhead protection requirements. In addition to possible on-site receptors, the Expert Committee has been informed by base personnel that the nearest off-site well is a private residential water supply well located approximately one mile down gradient of T-325. The Jacobs (1995) report identified sensitive ecological receptors on both the Yermo and Nebo Main Base. None of these are expected to be impacted by the contaminants at T-325.

SITE RISK CHARACTERIZATION

Although a preliminary human health risk assessment was performed by Brown and Caldwell (1996) with the objective of supporting a risk based corrective action (RBCA), several details of the calculations were not available in the report. Limited additional information was obtained verbally from Brown and Caldwell (personal communication December 1996) regarding the methods used. Brown and Caldwell informed the Expert Committee that the US EPA slope factors had been used in place of the CAL EPA slope factors. Even considering the use of the US EPA factors, the allowable concentrations in soil and groundwater calculated for T-325 may be over estimated. This is particularly true considering that the ASTM Tier 1 risk calculations are intended to be highly conservative. The allowable or screening levels of contaminant concentrations for BTEX were compared to an estimate of the 95th percentile concentrations measured during the soil boring and monitor well installation. The 95th percentile concentrations may underestimated the true values due to insufficient data. These issues will be further researched and discussed as part of the Expert Committee assessment of the T-325 area plume behavior and site-specific risk management recommendations.

A screening/review of three remedial alternatives was provided in the Brown and Caldwell, 1996, Site Assessment. These included natural attenuation, groundwater air sparging with vapor extraction, and bioventing. Cost and clean-up duration were estimated for each option. Although the natural attenuation monitoring and verification design included most of the important features, there was insufficient data available to calculate a time to clean-up, and 20 years was assumed. These issues will also be discussed as part of the Expert

Committee assessment of the T-325 area plume behavior and site-specific risk management recommendations.

ADDITIONAL DATA NEEDS

• There are several possible reasons that the 1996 gradients do not match the previous estimates. It may be that the gradient is changing direction within 45 degrees, or that the earlier estimates did not have sufficient local data to accurately represent the flow in the vicinity of T-325. We recommend that this issue be resolved, as it determines whether an additional monitor well may be advised, and where it should be located. Additional groundwater surface elevation observations will resolve this issue. If the gradient appears to be changing direction, an additional monitor well may be is advised. If groundwater gradients shift significantly on a seasonal basis, then an additional well should be located approximately south of MW-3 and east of T-325.

• An analysis of the diesel product depths for MW-1 and MW-2 during the August, October and November 1996 sampling events is recommended to clarify whether or not there is still likely to be a pool of diesel on the water table.

• Additional sampling should be performed in any new wells, which have not been previously sampled. Samples should be analyzed for the same organic constituents previously measured (TPH-d, BTEX and VOCs) as well as general minerals, dissolved oxygen, other biodegradation indicators, and water elevation. An additional round of water sampling at MW-1, MW-2, MW-3, NSI-3, NNP-3, and any newly installed wells at the Site could provide better estimates biodegradation and plume stability. However, it is not clear how much value this additional sampling may have because of the rather flat groundwater gradient and relatively slow flow velocity. It is likely that little change would be observed, particularly in the geochemical indicators.
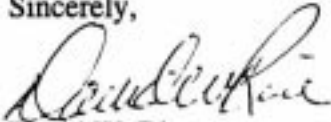
SUMMARY

Sufficient data have been collected to define the source of contamination, the nature of the contamination, the probable extent of the major constituents of concern, the rate of groundwater flow, and the potential pathways and receptors at the Site. The T-325 Site presents two major challenges, though. The first challenge is that the groundwater plumes appear to be relatively young, making it difficult to establish plume stability, estimate degradation rates, and to predict clean-up times. The second challenge is to interpret general mineral and DO data to estimate degradation rates for a plume, which is under a facility characterized by biological activity related to waste water treatment.

Following receipt of the additional site data, and the recommended evaluations, we will prepare the final deliverable containing our recommendations on the application of the RBCA process to the Site, and procedures to achieve closure of the Site.

Sincerely,
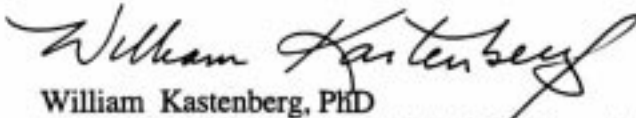
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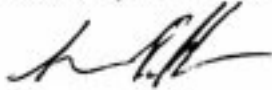
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PRC (1996a). "T-325 Groundwater Testing Results - October 1996"

PRC (1996b). "Data/results for Nov. 25 groundwater sampling event," Facsimile dated December 3, 1996.

Appendix B

Calculation of Health Risk to Workers at Facility 325

Appendix B

Calculation of Health Risk to
Workers at Facility 325

There are two pathways for contaminants from the release at Tank-325 to reach workers at Facility 325. Lighter constituents of the diesel in the soil may evaporate and migrate to the soil surface. Also, workers may come in direct contact with the contaminants during construction of a new treatment plant or any other work requiring digging into the soil in the vicinity of the former T-325. The risk to personnel working at Facility 325 from vapor inhalation, dermal sorption and ingestion of soil particles was estimated using a spreadsheet model. The value calculated for benzene is added cancer risk due to the diesel remaining in the soil below the ground surface and does not include other types of worker risk. Although there are drinking water standards for several components of diesel fuel, benzene is the primary concern for cancer risk from diesel. While the State of California does not currently identify toluene, ethylbenzene or xylenes as carcinogens, there are toxic effects associated with these compounds. These are calculated as a hazard level relative to the allowable daily intake (ADI).

CalTOX (DTSC, 1993a,b,c), a multimedia, multiple pathway model developed for the California Department of Toxic Substances Control was used to determine media concentrations and potential doses (or exposure). The CalTOX model combines a box model (representing the different soil layers, water bodies, air, and plants) with a risk model based on the US EPA *Risk Assessment Guidance for Superfund* (U.S. EPA, 1989). Mass conservation and transport equations are written as linear, first order differential equations in terms of fugacity. The exposure model includes toggles to control which pathways are calculated.

The CalTOX model requires initial contaminant concentrations in the various soil layers to describe the source. Estimates of the initial mass of benzene, toluene, ethylbenzene and total xylenes were based on soil data, and were used because no data was available on the fractions of various components in the diesel fuel. None of the samples from the T-325 excavation showed benzene above detection limits, so the initial fraction was assumed to be the detection limit of the sample divided by the TPH diesel concentration. Soil samples 1787-B2-30-S, 1787-B3-30-S, 1787-B8-30-S, and 1787-MW1-31-S were used as the basis for determining the percentage of diesel which could be benzene, toluene, ethylbenzene, and xylene. The concentration was assumed to be the detection limit where ever it was below non-detect. This can lead to overestimation of risk because the actual value may be much less than the detection limit. The diesel oil specific gravity was assumed to be approximately 0.9 and concentration values were based on a total spill volume of 23,000 gallons.

The area modeled was 60×60 m in the horizontal directions, the soil was 9-m thick above the water table, and the air compartment was 3-m tall. While contaminants were allowed to leach into the groundwater, no calculations were made regarding aquifer concentrations or transport. Data and calculation of the source terms are provided in Table B-1. The initial

concentration in soil was 0.135 mg/kg for benzene and toluene, 0.161 mg/kg for ethylbenzene, and 0.582 mg/kg for total xylenes.

Values for the chemical, landscape and exposure parameters are contained in Tables B-2, B-3, and B-4, respectively. Because of the low concentrations, the transport of each contaminant was calculated separately, with no adjustment for partial pressures of vapors. The landscape and exposure parameters were selected to represent the potential risk near the former tank site. The receptors for vapors are the plant workers at the current or future facility. The receptors for direct contact (ingestion of soil and dermal contact) are assumed to be workers who may be building a new facility, installing piping, or doing other trench work. A six-month exposure period of 10 hours per day at the work site was assumed to be an upper reasonable value for how long a worker might be in direct contact with the contaminated soil.

Potential doses for benzene from each pathway considered are presented in Table B-5. These are the amounts of contaminant which cross the human boundaries and are considered potential because they do not account for contaminant which leaves the body without entering the blood stream. Because benzene is a carcinogen, the benzene doses are based on contaminant concentrations at the mean exposure time. Table B-6 contains potential doses for toluene, ethylbenzene and xylenes according to uptake method. These are maximum doses within the exposure period because toluene, ethylbenzene and xylenes present non-cancer hazards. Table B-7 contains the California cancer potency, or slope, factors and non-cancer hazard factors.

The incremental lifetime cancer risks from benzene are presented in Table B-8, and the total risk was calculated as 7.6×10^{-9}. Hazard ratios are summarized in Table B-9. The maximum hazard ratios calculated are all less than 10^{-10} for toluene, ethylbenzene and total xylenes, respectively. The risk and hazard values are very low numbers, which is to be expected for this type of exposure scenario.

Table B-1. Calculation of BTEX source terms.

Sample number	TPH$_d$ (mg/kg)	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	Total xylenes (mg/kg)
1787-B2-30-S	1.2 E+04	1 E-01	1 E-01	5.7 E-01	2.1 E+00
1787-B3-30-S	2.1 E+04	5 E-01	5 E-01	2.0 E+00	5.1 E+00
1787-B8-30-S	2.6 E+03	5 E-01	5 E-01	5 E-01	4.2 E+00
1787-MW1-31-S	1.4 E+04	5.0 E+00	5.0 E+00	5.0 E+00	6.6 E+00
Compound fraction of TPH$_d$	–	1.5 E-04	1.5 E-04	1.7 E-04	6.3 E-04
Approximate initial mass of diesel (kg)	–	7.8 E+04	–	–	–
Soil in model (kg) (60 × 60 × 9 m)	–	8.4 E+07	–	–	–
Initial compound concentration (mg/kg)	–	1.35 E-01	e.35 E-01	1.61 E-01	5.82 E-01

Notes:

mg/kg= **Milligrams per kilogram.**

TPH$_d$ = **Total petroleum hydrocarbons, diesel.**

m = **Meter(s)**

Table B-2. Chemical Parameters.

	Benzene	Toluene	Ethylbenzene	Xylenes
Molecular weight (g/mol)	7.81 E+01	9.21 E+01	1.06 E+02	1.06 E+02
Octanol-water partition coeff.	1.51 E+02	4.82 E+02	1.33 E+03	1.30 E+03
Melting point (K)	2.79 E+02	1.78 E+02	1.78 E+02	2.48 E+02
Vapor pressure in (Pa)	1.27 E+04	3.77 E+03	1.28 E+03	1.07 E+03
Solubility in mol/m^3	2.25 E+01	6.22 E+00	1.64 E+00	1.78 E+00
Henry's law constant (Pa-m^3/mol)	5.74 E+02	6.63 E+02	8.26 E+02	6.91 E+02
Diffusion coeff. in pure air (m^2/d)	7.56 E-01	7.52 E-01	6.48 E-01	6.22 E-01
Diffusion coeff. in pure water (m^2/d)	9.63 E-05	8.51 E-05	7.66 E-05	7.66 E-05
Organic carbon partition coeff. Koc	5.51 E+01	1.39 E+02	2.28 E+02	2.71 E+02
Partition coeff. in ground/root soil layer	4.13 E-01	1.04 E+00	1.71 E+00	2.03 E+00
Partition coeff. in vadose zone soil layer	4.13 E-01	1.04 E+00	1.71 E+00	2.03 E+00
Partition coeff. in aquifer layer	n/a	n/a	n/a	n/a
Partition coeff. in surface water sediments	1.10 E+00	2.78 E+00	4.56 E+00	5.42 E+00
Partition coeff. plant (above ground)/soil (kg[s]/kg[pFM])	3.00 E+00	2.17 E-01	1.21 E-01	1.22 E-01
Biotransfer factor, plant/air (m^3[a]/kg[pFM])	8.73 E-03	1.94 E-02	4.02 E-02	4.70 E-02
Biotransfer factor; cattle-diet/milk (d/L)	1.61 E-06	3.83 E-06	1.06 E-05	1.03 E-05
Biotransfer factor; cattle-diet/meat (d/L)	1.62 E-05	1.21 E-05	3.34 E-05	3.27 E-05
Biotransfer factor; hen-diet/eggs (d/L)	1.20 E-03	7.64 E-05	2.11 E-04	2.06 E-04
Biotransfer factor; breast milk/mother intake (d/kg)	3.01 E-05	9.64 E-05	2.66 E-04	2.60 E-04
Bioconcentration factor; fish/water	6.79 E+00	2.31 E+01	6.38 E+01	6.24 E+01
Skin permeability coeff.; cm/h	1.86 E-01	1.11 E-01	2.30 E-01	2.27 E-01
Skin-water partition coeff.	1.52 E+01	3.57 E+01	7.95 E+01	7.82 E+01
Reaction half-life in air (d)	5.91 E+00	2.38 E+00	1.96 E+00	9.71 E-01
Reaction half-life in surface soil (d)	1.90 E+02	2.84 E+01	6.50 E+00	1.51 E+01
Reaction half-life in root zone soil (d)	1.90 E+02	2.84 E+01	6.50 E+00	1.51 E+01
Reaction half-life in vadose zone soil (d)	2.43 E+02	1.09 E+02	1.17 E+02	1.87 E+02
Reaction half-life in groundwater (d)	n/a	n/a	n/a	n/a
Reaction half-life in surface water (d)	1.12 E+01	1.30 E+01	6.50 E+00	1.75 E+01
Reaction half-life in sediments (d)	2.23 E+02	1.07 E+02	1.16 E+02	1.84 E+02

Notes: g/mol = Grams per mole.
      coeff. = Coefficient.
        K = Kelvin.
       Pa = Pascal.
    mole/m^3 Moles per cubic meter.
  Pa-m^3/mol = Pascal cubic meters per mole.
      m^2/d Cubic meters per day.
      koc = Octanol/water partitioning coefficient.
      n/a = Not applicable.
  kg[s]/kg[pFM] = Kilograms in soil per kilogram in plant fresh mass.
  m^3[a]/kg[pFM] = Cubic meters of air per kilogram of plant fresh mass.
      d/L = Days per liter.
     d/kg = Days per kilogram.
     cm/h = Centimeters/hour.

Table B-3.　Landscape parameters.

California sandy soil	Value used
Contaminated area in m²	3.60 E+03
Annual average precipitation (m/d)	1.10 E-03
Flux; surface water into landscape (m/d)	0.00 E+00
Land surface runoff (m/d)	2.75 E-04
Atmospheric dust load (kg/m³)	6.15 E-08
Deposition velocity of air particles (m/d)	5.00 E+02
Plant dry-mass inventory (kg[DM]/m²)	7.00 E-01
Plant dry-mass fraction	2.00 E-01
Plant fresh-mass density (kg/m³)	1.00 E+03
Ground water recharge (m/d)	1.20 E-04
Evaporation of water from surface water (m/d)	4.38 E-06
Thickness of the ground soil layer (m)	1.00 E-02
Soil particle density (kg/m³)	2.60 E+03
Water content in surface soil (vol fraction)	1.80 E-01
Air content in the surface soil (vol fraction}	2.20 E-01
Erosion of surface soil (kg/m²-d)	3.00 E-04
Thickness of the root zone soil (m)	4.00 E+00
Water content of root zone soil (vol. fraction)	1.80 E-01
Air content of root zone soil (vol. fraction)	2.20 E-01
Thickness of the vadose zone soil (m)	6.00 E+00
Water content; vadose zone soil (vol. fraction)	1.80 E-01
Air content of vadose zone soil (vol. fraction)	2.20 E-01
Thickness of the aquifer layer (m)	n/a
Solid material density in aquifer (kg/m³)	n/a
Porosity of the aquifer zone	n/a
Fraction of land area in surface water	1.00 E-04
Average depth of surface waters (m)	5.00 E+00
Suspended sediment in surface water (kg/m³)	8.00 E-01
Suspended sediment deposition (kg/m²/d)	1.05 E+01
Thickness of the sediment layer (m)	5.00 E-02
Solid material density in sediment (kg/m³)	2.60 E+03
Porosity of the sediment zone	2.00 E-01
Sediment burial rate (m/d)	1.00 E-06
Ambient environmental temperature (K)	2.88 E+02
Surface water current in m/d	0.00 E+00
Organic carbon fraction in upper soil zone	7.50 E-03
Organic carbon fraction in vadose zone	7.50 E-03

Table B-3. (Continued)

California sandy soil	Value used
Organic carbon fraction in sediments	2.00 E-02
Boundary layer thickness in air above soil (m)	5.00 E-03
Yearly average wind speed (m/d)	3.40 E+05

Notes:

m^2 = Cubic meters.

m/d = Meters per day.

kg/m^3= Kilograms per cumic meters.

DM = Dry mass.

vol. = Volume.

n/a = Not applicable.

K = Kelvin.

Table B-4. Human exposure factors, worker.

	Value used
Body weight (kg)	7.14 E+01
Surface area (m^2/kg)	2.60 E-02
Active breathing rate (m^3/kg-h)	1.29 E-02
Resting breathing rate (m^3/kg-h)	6.40 E-03
Soil ingestion (kg/kg-d)	9.33 E-06
Exposure time, outdoors (hours/day)	8.00 E+00
Exposure time, indoors resting (hours/day)	2.00 E+00
Exposure frequency to soil on skin (day/years)	6.71 E-01
Soil adherence to skin (mg/cm^2)	6.50 E-01
Exposure duration (years)	6.50 E+00
Average time (days)	2.56 E+04

mg/cm2 = Milligrams per cubic centimeters.

kg-h = Kilogram-hour

DM = Dry mass.

Table B-5. Benzene potential doses at the mean exposure time [mg/kg-d].

Pathways	Air (gases and particles)	Surface soil	Root-zone soil
Inhalation	6.7 E-08	–	–
Ingestion: soil	–	9.7 E-12	3.2 E-09
Dermal uptake	–	1.7 E-11	5.8 E-09

Table B-6. Maximum potential doses [mg/kg-d].

	Inhalation	Ingestion	Dermal uptake
Toluene	1.1 E-13	9.8 E-15	6.9 E-17
Ethylbenzene	9.7 E-40	1.1 E-40	8.8 E-43
Xylenes	5.6 E-20	7.2 E-21	7.0 E-23

Table B-7. California cancer potency and hazard coefficients.

	Benzene	Toluene	Ethylbenzene	Xylenes
Inhalation cancer potency	0.1	0.0	0.0	0.0
Ingestion cancer potency	0.1	0.0	0.0	0.0
Dermal cancer potency	0.1	0.0	0.0	0.0
Inhalation-dose ADI for noncarcinogenic effects	0.0	0.03	0.3	2.0
Ingestion-dose ADI for noncarcinogenic effects	0.0	0.2	0.1	2.0
Dermal-dose ADI for noncarcinogenic effects	0.0	0.2	0.1	2.0

Note:

ADI = Allowable daily intake.

Table B-8. Incremental lifetime human cancer risk summary.

	Inhalation	Ingestion	Dermal	Total
Benzene	6.7 E-09	3.2 E-10	5.8 E-10	7.6 E-09

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Appendix C

Forecasting Plume Stability

C-1. Modeling Approach

The LUFT Historical Cases Analysis (Rice et al., 1995) revealed statistical evidence suggesting that dissolved BTEX plumes typically stabilize after reaching a certain length. Benzene plume lengths, for example, ranged from approximately 100 ft (50th percentile) to 260 ft (90th percentile) among the sites examined. This plume length stabilization reflects a balance between dissolved contaminant mass introduced from residual sources and attenuation processes (particularly passive bioremediation) integrated across the plume.

Simple analytical solutions to the advective-dispersive solute transport equation may be used to assess plume stability and to forecast the probability of further plume expansion, given certain assumptions concerning boundary conditions and representative transport parameters. Domenico (1987) presented a solution of the form,

$$C(x,y,t) = \left(\frac{C_0}{4}\right)\exp\left\{\left(\frac{x}{2\alpha_x}\right)\left[1 - \left(1 + \frac{4\lambda\alpha_x}{v}\right)^{1/2}\right]\right\}\mathrm{erfc}\left[\frac{x - vt(1 + 4\lambda\alpha_x/v)^{1/2}}{2(\alpha_x vt)^{1/2}}\right]$$

$$\bullet\left\{\mathrm{erf}\left[\frac{(y + Y/2)}{2(\alpha_y x)^{1/2}}\right] - \mathrm{erf}\left[\frac{(y - Y/2)}{2(\alpha_y x)^{1/2}}\right]\right\} \tag{C-1}$$

for two-dimensional transport where C_0 refers to the source concentration, α_x the longitudinal dispersivity, α_y the transverse dispersivity, λ the first-order decay coefficient, v the groundwater pore velocity, Y the width of the line source, t the monitor time, and x and y the coordinates of the monitor point relative to the source. The solution assumes uniform, steady flow and a continuous line source which may be thought of as representing a residual lens of NAPL. The geometry corresponding to this plume model is shown on Figure C-1.

At some particular time t, the length of the plume in the downgradient direction (i.e., the distance between the origin and some specified contour interval), L, may be calculated by setting $y = 0$ and solving Equation C-1 for x in an iterative manner using the bisection method or Newton's method. Plume length estimates via Equation C-1 depend on the values of the longitudinal and transverse dispersivities, α_x and α_y, which are used to account for the macrodispersive effects of a flow field exhibiting local-scale variability. Longitudinal dispersivity is commonly assumed to be equivalent to some fraction of the length scale of the plume; typically a value on the order of 0.1 is used. Calculation of dispersivity values and plume lengths can be

viewed as an iterative process. As a first approximation, longitudinal dispersivity is assumed to equal a fraction of the length scale of the plume as defined by the groundwater velocity multiplied by elapsed time. This is used to obtain a preliminary estimate of plume length. The longitudinal dispersivity value is then refined according to the new plume length estimate.   Transverse dispersivity is assumed to equal a fraction of the longitudinal dispersivity.

The absolute plume growth rate may be calculated by,

$$\frac{dL}{dt} \approx \frac{L_{Q2} - L_{Q1}}{\Delta t} \tag{C-2}$$

where L_{Q1} and L_{Q2} refer to plume lengths over consecutive quarters, and Δt the monitoring period (e.g., one quarter, or approximately 91 days). A normalized plume growth rate, which expressed plume growth rate as a simple percentage in units of time^{-1}, can be calculated by dividing dL/dt by the mean plume length,

$$L_{mean} = \frac{L_{Q2} + L_{Q1}}{2} \tag{C-3}$$

C-2. Plume Stabilization and Probabilistic Modeling

Application of this modeling procedure to a site such as the B-637 area clearly implies a high degree of idealization because a simple analytical solution is not capable of simulating the effects of heterogeneities in the flow field or complex boundary and initial conditions. However, such a modeling approach is useful for illustrating general trends which would be expected in the data, based on simple assumptions concerning the subsurface environment. Inspection of Equation C-1 indicates that values of C_0, Y, λ, v, R, α_x, α_y, and t must be provided to the model in order to generate an estimated plume length.   Some of these parameters may be estimated using conservative assumptions (e.g., C_0, λ) or else estimated from site data, as in the case of v, which may be calculated by Darcy's law,

$$v = \frac{K \nabla h}{\phi} \tag{C-4}$$

where K refers to hydraulic conductivity, ∇h the hydraulic gradient, and ϕ the sediment porosity.

Probability distributions for the pertinent parameters, and the rationale for the proposed distributions, are listed on Table C-1.   A simple example of plume stabilization can be demonstrated by calculating plume length as a function of time, using the procedure outlined above, for representative values of model parameters selected from these distributions. Results of this type of calculation using the representative values given on Table C-1 are shown on Figure C-2. Using these values and the assumptions and procedures presented above, the model predicts that the gasoline range hydrocarbon plume, as defined by the 10 ppb contour, should stabilize at approximately 620 feet after 10 years elapsed time. This is roughly consistent with present observation. Nevertheless, the considerable uncertainty associated with each of the model parameters implies that a broader range of plume evolution histories must be considered and parameter sensitivies evaluated.

Table C-1. Assumptions used in probability forecast model.

Parameter	Units	Distribution	Typical representative value (for demonstration only)	Basis
C_0, source concentration	mg/L	Normal. 100 ± 10.	50	Based on typical observed maximum aqueous concentrations of gasoline (assuming contact with NAPL).
Y, source width	ft	Lognormal. 10% = 10; 90% = 100.	30	Postulated.
λ, decay coefficient	day^{-1}	Lognormal. 10% = 0.05%; 90% = 0.50%.	0.20%	Postulated, based on reported values for mean first-order degradation constants at other LUFT sites (e.g., MacIntyre et al., 1993; Wilson et al., 1995; Buscheck et al., 1996; Chapelle et al., 1996); adjusted downward to address non-BTEX constituents under strictly anaerobic conditions (see Appendix B).
K, hydraulic conductivity	ft/day	Lognormal. 10% = 27; 90% = 45.	36	Based on site data.,
∇h, hydraulic gradient	–	Lognormal. 10%=0.002; 90%=0.006.	0.004	Based on site data.
ϕ, porosity	–	Lognormal. 0.25 ± 0.03.	0.25	Postulated.
R, retardation coefficient		Lognormal. 10% = 2; 90% = 20.	5	Postulated.

Table C-1. (Continued)

Parameter	Units	Distribution	Typical representative value (for demonstration only)	Basis
α_x ratio (ratio of longitudinal dispersivity to plume length scale, vt).	–	Lognormal. 10% = 0.03; 90% = 0.33 (median = 0.10).	0.1	Postulated (based on the standard assumption that $\alpha_x \sim 10\%$ plume length).
α_y ratio (ratio of transverse dispersivity to longitudinal dispersivity).	–	Lognormal. 10% = 0.03; 90% = 0.33 (median = 0.10).	0.1	Postulated (based on the standard assumption that $\alpha_y \sim 10\% \times \alpha_x$).
t, time elapsed between introduction of source and groundwater quality sample	years	Lognormal. 10% = 5; 90% = 50.	–	Postulated; based on history of ASTs.

Monte Carlo analyses offer a means by which probabilistic forecasts of plume length may be developed. This approach involves generating random sets of model parameters from the prescribed probability distribution functions and conducting multiple simulations, or realizations, each with an individual plume length (and growth rate). The resulting assemblage of lengths and growth rates may be used to construct probability distribution functions. Sensitivity analyses may then be performed which quantify the correlation between variance in forecast values and uncertainties in model parameters.

The forecast probability distribution of plume lengths for 2,000 Monte Carlo realizations is shown on Figure C-3. The median forecast length, approximately 560 ft, is reasonably consistent with the observed extent spatial extent of the present plume. The corresponding forecast probability distribution of plume growth rates is shown on Figure C-4. The median forecast rate of growth is approximately 3×10^{-6} day^{-1} (essentially stable).

Sensitivity analyses were performed using a rank correlation method (Kendall's τ) to develop correlation coefficients between forecast lengths and growth rates and model parameter values. The resulting correlation coefficients are given on Table C-2.

Table C-2. Correlation coefficients relating model forecasts to parameter values, as determined by Kendall's τ.

Parameter	Plume length	Plume growth rate
C_0, source concentration	0.015	-0.003
Y, source width	0.063	0.037
λ, decay coefficient	-0.350	-0.433
K, hydraulic conductivity	0.077	-0.021
∇h, hydraulic gradient	0.220	-0.017
ϕ, porosity	-0.037	-0.004
R, retardation coefficient	-0.449	-0.016
α_x ratio (ratio of longitudinal dispersivity to plume length scale, vt).	0.222	-0.050
α_y ratio (ratio of transverse dispersivity to longitudinal dispersivity).	-0.019	0.005
t, time elapsed between introduction of source and groundwater quality sample	0.150	-0.458

The sensitivity analyses suggest that variance in forecast plume lengths most strongly reflects uncertainty in the first-order decay coefficient as well as the retardation coefficient, whereas variance in plume growth rate primarily reflects the age of the plume and the decay coefficient. The relationships between plume length, growth rate, elapsed time, and decay rate are further illustrated on Figure C-5 and Table C-3.

Table C-3. Median forecast plume lengths and growth rates over intervals of elapsed time since source initiation.

Elapsed time (years)	Plume length (ft)	Plume growth rate (day^{-1})
<5	332	5.0×10^{-4}
5-25	552	1.9×10^{-5}
>25	614	6.0×10^{-9}

In summary, probabilistic modeling results suggest that the likelihood of significant further expansion of the hydrocarbon plume at the B-637 site is probably very low, even given all of the uncertainties in model parameters. The only scenario by which significant further plume growth could be expected would involve a very young plume subject to little retardation or passive bioremediation. The site history, the high organic carbon content of subsurface sediments, and independent evidence supporting passive bioremediation imply that this scenario is not likely. Furthermore, the model results are conservative in that a constant source concentration is assumed.

In reality, this would be expected to diminish substantially over time following remedial action, such as contaminated soil excavation, as well as secondary residual pestroleum hydrocarbon depletion resulting from dissolution and volatilization.

C-3. Constraints On Plume Dissipation

The Domenico (1987) solution to the solute transport equation assumes a constant concentration boundary condition, which is a highly conservative assumption, given that contaminant sources will decline through time as the NAPL becomes depleted due to dissolution, volatilization, and other mechanisms (including engineered source removal and excavation). An alternative solution to the Domenico (1987) model is that of Cleary and Ungs (1978), which uses the same assumptions but also includes a source attenuation term, β, which is a first-order decay coefficient:

$$C(x,y,t) = \frac{C_0 x}{4\sqrt{\pi D_1}} \exp\left(\frac{vx}{2D_1} - \beta t \right) \bullet \int_0^{t/R} \exp\left[-\left(\lambda R - \beta R + \frac{v^2}{4D_1} \right)\tau - \frac{x^2}{4D_1 \tau} \right]\tau^{\frac{-3}{2}} \tag{C-5}$$

$$\bullet \left[\operatorname{erf}\left(\frac{a-y}{2\sqrt{D_t \tau}} \right) + \operatorname{erf}\left(\frac{a+y}{2\sqrt{D_t \tau}} \right) \right] d\tau$$

Plume lengths as a function of time using the Cleary and Ungs (1978) model are shown on Figure C-6. Domenico (1987) forecast plume lengths are shown for comparison; the difference between the Domenico model and the conservative version of the Cleary and Ungs (1978) model (no source attenuation; $\beta = 0$) is due to different assumptions in the mathematical formulations of the two models. The results how that source attenuation limits the downgradient extent of the plume to some degree but also results in retreat of the plume; rapid collapse is observed when the source attenuation half-life is on the order of three years.

Clearly, the source attenuation rate is critical in evaluating the time required for complete plume dissipation. However, this rate cannot be quantified easily from field data, particularly when the exponential source decay model is an idealization of the cumulative effect of a number of processes. However, constraints may be placed on the plume dissipation rate by evaluating the assumed residual hydrocarbon volume. The volume of hydrocarbon material in the dissolved state, as implied by the model, can be calculated by assuming the water flowing through a cross-section of the aquifer defined by the residual hydrocarbon width and assumed aquifer thickness equilibrates with the prescribed residual hydrocarbon concentration, corrected for source decay as a function of time. The implied cumulative residual hydrocarbon volumes derived from this calculation are shown on Figure C-7.

Given the release scenario at Building 637 and the residual hydrocarbon removal activities at the Site, a residual hydrocarbon volume of about 250–1,000 gallons may be realistic. Larger residual hydrocarbon volumes of several thousand gallons may not be realistic. If it is assumed that there is a decrease of half the residual TPH volumn every three to fifteen years ($t_{1/2}$ = 3–15years), then the plume may be expected to dissipate in several decades.

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