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Risk-Based Assessment of Appropriate Fuel Hydrocarbon Cleanup Strategies for the Base Exchange Service Station at Vandenberg Air Force Base, California

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Submitted to the Air Force Center for Environmental Excellence
Environmental Restoration Directorate
Technology Transfer Division, Brooks Air Force Base, Texas

July 1998

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1. Program Overview

1.1. Introduction

In June 1994, the State Water Resources 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 the California LUFT Recommendations Report (Rice et al., 1995a) 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, the DoD Petroleum Hydrocarbon Cleanup Demonstration (PHCD) Program was initiated. This program will be referred to as the DoD LUFT Demonstration Cleanup Program. Ten Department of Defense (DoD) sites were selected within California. 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 Base Exchange Service Station (BXSS) Site at Vandenberg Air Force Base, within the Central Coast RWQCB, is one of the sites selected to participate in the DoD LUFT Demonstration Cleanup Program.

The other sites selected and their corresponding RWQCB region are:

- Army Presidio at San Francisco, San Francisco RWQCB.
- Barstow Marine Corps Logistic Center, Lahontan 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.
- Travis Air Force Base, San Francisco RWQCB.
- Port Hueneme Naval Construction Battalion Center, Los Angeles 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. 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. 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. 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. William E. Kastenberg, UC, Berkeley, Professor and Chairman, Department of Nuclear Engineering; member of LLNL/UC LUFT Team, with expertise in environmental decision making and decision analysis processes.
- 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.
- Dr. Walt McNab, LLNL, Environmental Scientist, with expertise in the evaluation of passive bioremediation 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 California LUFT 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.

Pathways: 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.

Sources: 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 or 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 California LUFT 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 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,

[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.

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: Risk Based Corrective Action (RBCA) training for DoD PHCD Program 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. Site Overview

2.1. Background

Vandenberg Air Force Base is located near the town of Lompoc, California, in the Santa Ynez River and San Antonio Creek basins. The Base Exchange Service Station (BXSS), which is currently in use, consists of gasoline dispensing islands, automotive service bays, and a car wash facility. Four 10,000-gallon underground gasoline storage tanks (USTs) were installed at the BXSS site in 1967, along with a 250-gallon waste oil tank and associated piping. The site is bounded by grassy open fields to the east and north and by eucalyptus trees to the south and west.

The four original gasoline tanks were replaced by two 10,000-gallon double-walled fiberglass USTs in 1985, with two additional USTs installed in 1991. The associated piping system was also replaced in 1991 and the 250-gallon waste oil tank removed. Contaminated soils were observed during tank removal, a small (unspecified) quantity of which was removed during excavation and replaced with clean fill material (IT Corporation, 1996). The U.S. Bureau of Reclamation conducted field investigations at the site to characterize soil and groundwater contamination. IT Corporation was retained in August 1996 to refine this characterization. Field investigations conducted at the site have included the installation of monitor wells (a total of 14) as well as continuous coring activities with a Geoprobe cone penetrometer (CPT) unit and onsite chemical analyses of soils and grab groundwater samples. In all, 59 borings have been sampled for soils and groundwater.

Groundwater contaminants which have been detected in association with the former LUFTs include benzene/toluene/ethylbenzene/xylenes (BTEX), 1,3,5-trimethylbenzene, and the fuel oxygenate methyl tertiary butyl ether (MTBE), which form plumes extending 200 to 300 ft downgradient of the source area. 1,2-dichloroethane (DCA), also a fuel additive, has historically been detected in some site monitor wells at low concentrations. However, DCA concentrations have declined with time, possibly a result of biodegradation. DCA was not detected in BXSS area groundwater samples during the September 1996 sampling round.

Passive bioremediation has been proposed as a remediation approach for BTEX components in groundwater cleanup at the BXSS site. Site groundwater investigation activities have included sampling and analyses designed to detect and characterize indicators of biodegradation reactions.

2.2. Site Conceptual Model

The sediments immediately underlying the BXSS site consist of shallow marine or lagoonal sands and clays lying above uplifted Pleistocene marine beach sands. The uppermost unit consists of fine-grained silty sands and ranges from ground surface to a depth of 12 to 15 ft. Beneath this sand lies a 2- to 4-ft-thick layer of mixed clay and sand, which does not appear to inhibit the vertical movement of water. A well-sorted fine-grained sand is present below the sandy clay from a depth of 19 to 28 ft below ground surface. Below the sand is a clay layer, 4- to 5-ft thick, dipping to the northwest. This clay apparently forms the base of a perched aquifer. Groundwater is encountered between 6 and 11 ft below ground surface; saturated conditions persist all the way to the basal clay unit, with a total saturated thickness ranging from 10 to 21 ft. Below the basal clay, an unsaturated gravel is present below a depth of 35 ft, underlain by more sands, silts, and clays, all unsaturated. No deep groundwater was encountered beneath the site to a depth of at least 60 ft; the maximum extent of any of the exploratory borings.

Groundwater elevation contours suggest that the shallow perched aquifer is recharged locally. Possible sources of recharge include lawn irrigation 400 to 600 ft to the southeast of the BXSS, as well as from the carwash and associated drains (which create an apparent local groundwater mound). To the north of the BXSS site, an elongated groundwater depression appears to exist, possibly due to evapotranspiration through large eucalyptus trees and bare soil in the area. Annual precipitation in the area is approximately 16 inches. Significant water level changes are associated with local recharge events, with groundwater water levels fluctuating by as much as one foot per week.

The groundwater flow direction in the perched aquifer is generally in a north-northeast direction, while the deep regional groundwater flow direction is generally in a southeast direction. The hydraulic gradient at the site is on the order of 0.01 to 0.02 ft/ft, although the direction and magnitude change in response to recharge. Hydraulic conductivity has been estimated as ranging between 0.2 and 2.6 ft/day, based on analyses of slug test data collected from site monitor wells. Assuming a porosity of 0.3, these data imply groundwater flow velocities on the order of 2 to 60 ft per year.

Contaminated soils containing hundreds of mg/kg of BTEX constituents and MTBE have been observed in soil borings drilled in the area of the old pump island, generally at depths between 4 and 12 ft below ground surface. Beyond this area, contaminant concentrations in shallow soil samples have generally not been detected. A groundwater BTEX plume exists in association with the BXSS site, with maximum concentrations reaching 6,800 parts-per-billion (ppb) for benzene, 8,200 ppb for toluene, 1,000 ppb for ethylbenzene, and 12,050 ppb for total xylenes (September 1996 sampling event data). The total length of the plume, as defined by the 10 ppb benzene contour, extends about 300 ft downgradient of the source area. MTBE has also been detected in monitor wells and groundwater samples collected from soil borings at the BXSS site; the maximum concentrations reported from the September 1996 sampling round was 5,500 ppb. The MTBE plume also extends approximately 200 ft downgradient of the source area and generally coincides with the BTEX plume.

Historical data are available for BTEX concentrations in seven site monitor wells from 1991 through 1996. No significant trends are apparent in the BTEX concentrations over this time period. Additional groundwater quality data, including MTBE concentrations, became available from seven new wells in 1996. The apparent lack of trends (i.e., plume stability) in the BTEX data probably do not alone constitute convincing evidence of passive bioremediation, particularly given the well locations and the relatively low groundwater flow velocities encountered at the site. However, geochemical indicators of bioattenuation do provide secondary evidence that is indicative of passive bioremediation at the BXSS site. These observations, together with the limited spatial extent of hydrocarbon plumes typically observed at LUFT sites (Rice et al., 1995; Mace et al., 1997), suggest that further significant migration of BTEX constituents is not likely.

A review of the adequacy of the site conceptual model was presented to VAFB in a letter dated October 29, 1997 (Appendix A).

3. Risk Analyses and Management

3.1. Sources

3.1.1. Primary Source(s)

Primary sources of FHC contamination include leaking USTs, sumps, and pipelines. At the BXSS site, the primary sources were four 10,000-gallon gasoline USTs and one 250-gallon waste oil UST, have been removed and replaced with leak-resistant structures (i.e., double-walled fiberglass USTs). The quantity of product released from these tanks between 1967 and 1985 is unknown. Inventory records do not indicate any catastrophic releases, so it is likely that the leaks persisted over much of the time period in question. The U.S. Bureau of Reclamation provided a value of 2,306 gallons as an estimated total volume as gasoline product released from the USTs.

Both leaded and unleaded gasolines were stored in the former USTs[2]. The presence of MTBE in soil and groundwater at the site also indicates that the fuel oxygenate was also present in gasoline held in the tanks, probably as an octane booster at a concentration on the order of 1%.

3.1.2. Secondary Source(s)

Secondary contamination sources include free product present in the soil, either as lenses floating on the water table or as material held by capillary tension in the vadose zone. Floating free product was not observed during tank excavation at the BXSS site nor has it been noted in any of the site monitor wells. However, partial saturation of shallow soils by hydrocarbon material was noted in samples collected from some of the soil borings, generally between 5 and 11 ft below ground surface. This locale is consistent with the highest observed FHC concentrations in groundwater. Shallow soil contamination appears to be limited to the area immediately surrounding the old pump island area. It is probable that residual-free product continues to remain in soils in the area, possibly including soils underneath the BXSS building.

3.2. Receptors

3.2.1. Present and Anticipated Future Human Health Receptors

Three local aquifers supply water to VAFB. These include a well in the Lompoc Plain aquifer (4.1 miles south of the BXSS site, in the upgradient direction), a well in the Lompoc Terrace aquifer (3 miles south of the site), and a well in the San Antonio Creek aquifer (3 miles to the north). Water production wells tap these formations at depths ranging from 200 to 400 ft.

It is considered highly unlikely that the perched zone in question will ever be tapped by water-supply wells in the future, given that it may exist largely as an artifact of local artificial sources of recharge. Further, the sustainable yield for the aquifer cannot support beneficial use. Nevertheless, as the BXSS site is located on U.S. Air Force property, it is anticipated that institutional controls will remain in place to restrict the installation of any water-supply wells in the effected perched zone.

Buildings at the BXSS site do constitute theoretical vapor receptors due to the proximity to the underlying FHC plume. Construction and excavation workers involved in future construction activities are also potential receptors.

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[2]Lead impact to soils at the site appears to be limited.

3.2.2. Ecological Risk Receptors

To our knowledge, no at-risk ecological risk receptors have been identified.

3.3. Exposure Pathways

To pose a human health or ecological risk, the source of contaminants (e.g., residual NAPL) must be linked to receptors (e.g., water-supply wells) via pathways. Groundwater provides such a pathway through advective, dispersive, and diffusive transport of dissolved contaminants. However, passive bioremediation processes tend to limit the migration of dissolved hydrocarbons; the input of dissolved FHCs from residual sources is balanced by FHC loss through passive bioremediation, integrated over the extent of the plume. This mass balance constraint is the likely explanation for the limited dissolved-phase plume lengths associated with the majority of LUFT sites (Rice et al., 1995) and the site BTEX plume. Such a limitation of dissolved plume length implies that the groundwater pathway is incomplete. Therefore, the problem of evaluating the groundwater exposure pathway is linked directly to an assessment of plume stability.

Several lines of evidence are available from BXSS site data which may be used to argue that passive bioremediation is actively limiting the downgradient migration of the FHCs (not including MTBE). These include:

- Changes in concentrations of BTEX constituents over time and distance (primary line of evidence).
- Changes in concentration ratios of BTEX components to those of presumed recalcitrant hydrocarbon tracers such as trimethylbenzene isomers (secondary line of evidence).
- Analyses of geochemical indicators of passive bioremediation (e.g., dissolved oxygen, nitrate/nitrite, sulfate, manganese, iron, alkalinity, methane, hydrogen sulfide, Eh) in groundwater (secondary line of evidence).

Concentrations of BTEX constituents have been monitored in at least seven site wells since 1991. While there are no clear trends in the data, which may at first glance be interpreted as evidence of plume stability, none of these wells exist on the periphery of the plume where evidence of plume movement would be most readily observed. Additional wells were installed in 1996 to address this problem but do not yet have a sufficient sampling history. Given the relatively low groundwater flow velocities associated with the BXSS site, a more extensive historical monitoring database would be needed to convincingly demonstrate passive bioremediation based on primary evidence alone. Experience has also shown that recalcitrant tracer analyses are often an unsatisfactory means for assessing passive bioremediation because of poor correlation of concentration ratios (BTEX vs. trimethylbenzene) with distance. The utility in conducting concentration ratio analyses involving 1,3,5-trimethylbenzene at the BXSS site is not clear, given the data presented to date (IT Corporation, 1996).

Analyses of geochemical indicators of passive biodegradation at the BXSS do provide substantive evidence of passive biodegradation (i.e., evidence supporting the oxidation of FHCs). Observations include:

- Elevated concentrations of iron and manganese in association with FHCs, indicating reduction and mobilization of these metals.
- Depleted sulfate concentrations and elevated hydrogen sulfide levels in association with the FHCs, suggesting sulfate reduction.
- Elevated methane concentrations near the source area, suggesting local methanogenesis.

- A general pattern of negative redox potentials in contaminated wells, consistent with the other geochemical parameters in indicating reducing conditions associated with hydrocarbon oxidation.

Analyses of dissolved oxygen and nitrate/nitrite are less convincing. Dissolved oxygen measurements are not consistent with the other redox indicators and probably reflect sample contamination by atmospheric oxygen. Nitrate/nitrite levels appear to reflect highly variable background concentrations. Nevertheless, given the observed behavior of the other geochemical indicators, experience at other LUFT sites, and microbiological and thermodynamic arguments, it is highly probable that oxygen and nitrate are also readily utilized as oxidizing agents in the passive bioremediation of FHCs at the BXSS site.

Microbial counts (heterotrophs, hydrocarbon degradors) were conducted on groundwater samples collected from selected BXSS area wells to identify further evidence supporting passive bioremediation. However, given the observed spatial distributions (IT Corporation, 1996), these data taken by themselves do not appear to provide convincing evidence of passive bioremediation.

3.3.1. Groundwater Hydrocarbon Plume Migration

Groundwater flow and contaminant transport modeling were conducted by IT Corporation (IT, 1996) to glean quantitative insights into the possible behavior of the FHC and MTBE plumes over time in the BXSS area. The stated objective of this modeling was to predict natural attenuation times for the contaminants in the absence of engineered remediation alternatives.

Steady-state groundwater flow modeling was performed using the finite-difference MODFLOW program, while contaminant transport was simulated using MT3D. Model assumptions included a two-dimensional representation of the perched zone, constant head and no-flow conditions along the boundaries of the simulation domain, evapotranspirative and recharge source/sink terms, and a uniform first-order decay approximation for passive bioremediation of the dissolved BTEX plume[3]. Groundwater gradients were based upon average historical groundwater levels in BXSS area wells.

Apparent stability observed with BTEX plumes at a large proportion of LUFT sites (Rice et al., 1995; Mace et al., 1997) can be viewed as reflecting a balance between mass loss due to passive bioremediation and influx of fresh contaminants from residual free-product source material. As such, the mathematical description of source term behavior in the model is a critical factor in influencing predictions of plume behavior and yet is still greatly misunderstood. For the BXSS model, an exponentially-decaying source term was selected as an idealized source scenario, presumably taking into account source depletion over time due to weathering effects (e.g., volatilization, dissolution). Modeling results suggest that the total BTEX plume would attenuate below 1 ppb after approximately 100 years using the specified set of parameters. The simulated BTEX plume shows little or no appreciable downgradient migration during this time period. However, the sensitivity of these predictions to the exponential decay model describing the source term (source concentration and decay rate) was not evaluated, so the uncertainty in the projected 100-year cleanup time is not quantified. Sensitivity analyses were conducted only on the decay rate and the longitudinal dispersivity. These analyses suggest that varying the value of the decay rate has a significant impact on the predicted attenuation time, while varying the dispersivity coefficient has little effect.

The limited spatial extent of FHC plumes in shallow groundwater systems has become well recognized (Rice et al., 1995; Mace et al., 1997). Probabilistic modeling approaches applied at other DoD Demonstration Program sites (e.g., George Air Force Base and Travis Air Force Base; McNab et al., 1997a,b, respectively) as well as more general studies (McNab et al., 1997c), also

[3] A degradation rate of 0.2 year^{-1} was assumed for total BTEX, which is probably a conservative estimate for typical groundwater environments.

suggest that plume FHC stability constitutes typical behavior. Thus, experience suggests that the FHC plume at the BXSS site has probably reached its maximum spatial extent. Therefore, little risk of adverse impact exists with regard to potential downgradient receptors despite the inherent uncertainty in the attenuation time estimate. Furthermore, the apparent isolation of the FHC in the perched zone underlying the BXSS area provides additional assurance against plume migration.

Modeling of the MTBE plume was conducted using the same assumptions as for the BTEX plume, except that degradation was not included (IT Corporation, 1996). Unlike BTEX, projected MTBE concentrations do not undergo significant decline during the 100-year simulation period. In addition, the simulations indicated that the leading edge of the MTBE plume, as defined by the 1 ppb contour, would migrate approximately 200 ft beyond its present location during this period. This is because the lack of biodegradation does not allow the development of a steady-state plume. As a result, additional analyses should be undertaken to examine the time that may be required for the MTBE plume to dissipate by dispersion effects. One possible approach is discussed in the following section and in Appendix B.

3.3.2. Groundwater MTBE Plume Migration

MTBE has been used as an additive in gasoline in southern California since the late 1970s, although its use has become more common, at higher volume fractions, in more recent years. The observed MTBE plume at the BXSS site does not appear to extend as far downgradient as the BTEX plume, most likely representing its relatively recent introduction into gasoline mixtures used in the former LUFTs at the site.

Unlike BTEX components and other FHCs, convincing evidence supporting the passive bioremediation of MTBE in the field has yet to be identified. Thus, simulation of the behavior of MTBE groundwater plumes typically assume a degradation rate of zero as a conservative model. Under such circumstances, the only mechanism available for natural attenuation of the MTBE plume is dispersion due to mechanical mixing and molecular diffusion (although some mass loss due to volatilization could also occur over time, particularly in the case of an unconfined aquifer). A very conservative approach at quantifying the time required for dispersion of the plume below some threshold concentration would be to assume an idealized aquifer of infinite extent and apply a simple advective-dispersive plume model to simulate plume behavior until dissipation occurs. In comparison to the BXSS site, such a model would be extremely conservative because:

- The localized perched zone underlying the site would be idealized as an aquifer of infinite extent.
- The apparent groundwater sink caused by the eucalyptus trees would not be considered.
- No MTBE degradation or mass loss of any kind would be considered over the entire simulation period.

For this purpose, a simple slug source model is advantageous since it allows a specified contaminant mass as a source term rather than a constant boundary concentration. For the MTBE plume at the BXSS site, a slug source model is appropriate because of the relatively short period of MTBE use, the removal of the primary source (i.e., the former LUFTs), and the relatively long period of time required for plume dissipation. Using the familiar Wilson and Miller (1978) slug source model and contaminant transport parameters representative of the BXSS site, projections of the MTBE plume length as defined by the 35 ppb contour suggest that the plume will reach a maximum length of approximately 500 m (1,640 ft) after approximately 125 years. The leading edge of the plume is forecast to reach approximately 900 m (2,950 ft) downgradient of the source area (implying a detached plume) after 225 years before undergoing rapid collapse due to dispersion. Uncertainty analyses using Monte Carlo techniques to address uncertainties in the forecasts suggest that the 80% confidence level for time to plume collapse due to dispersion is approximately 400 years. The development of the plume length model and its application to the BXSS site are discussed in detail in Appendix B.

Even under moderate assumptions of the conservative model, no existing risk receptors would be impacted by the MTBE plume before it dissipates due to dispersion. Because the property is likely to remain under the management of the U.S. Air Force, such potential future risk receptors such as nearby drinking-water wells can be controlled through institutional means. However, given the true nature of the perched zone under the BXSS site, any threat due to the MTBE plume is virtually non-existent. There is very little reason to anticipate development of the perched zone for water supply as it may exist only in response to anthropogenic recharge. The probable limited lateral extent of this water-bearing zone, and the hydraulic control offered by the eucalyptus trees, suggest that longer range plume migration, presented by the idealized model, is unlikely.

3.3.3. Hydrocarbon Vapor Migration

The threat posed by migration of hydrocarbon vapors to occupants of buildings at the BXSS site is very small in comparison to everyday workplace exposure levels encountered at gas stations and similar facilities. While there is some risk to human health associated with FHC vapors, such risks fall under the jurisdiction of occupational health and safety laws; the added risk from subsurface FHCs released to soils and groundwater is in all probability insignificant. The accumulation of methane gas to hazardous levels in the subsurface is unlikely because the area is not extensively covered by asphalt or concrete.

3.4. Remedial Goals

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 set by states 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.
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 allow 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, 1995):

- 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.
- Cleanup to a site-specific standard: The protectiveness of this approach is usually based on specified land uses and may need to be re-evaluated if changes occur. The cleanup levels are often more feasible and generally less expensive to achieve. However, this approach requires potentially expensive site-specific exposure and risk assessment, to determine threats and impacts.
- Risk management, or containment: When contaminant concentrations exceed safe levels, but cannot feasibly be cleaned up, or there are no current or future exposure pathways, 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.
- No Action: In some instances, monitoring may not be needed or may eventually be discontinued. As with monitored natural attenuation, this approach may require site-specific exposure and risk assessment, to determine threats and impacts to public health and the environment.

At BXSS site, the hydrologic setting associated with the shallow perched aquifer must be taken into consideration, as the aquifer may be only locally present and exist only in response to artificial recharge.

3.4.1. 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 as to how the cleanup technology or process actually accomplishes concentration reductions and where the removed contaminants or by-products are actually going. There are four basic alternatives:

1. Reuse/recycling,
2. Waste destruction (or conversion),
3. Media transfer, or
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 would thus be 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, 1995).

3.4.2. Remedial Goals and Technology/Process Selection for 43 Area MWR Gas Station

Remedial goals have not currently been clearly established for the site. However, we can match some possible remedial technologies with some possible remedial goals in the following hypothetical examples:

Example (1)

Remedial Goal: Reduce concentrations at all points in the plume to a low value in a short period of time.

Potential Remedial Alternative (1): Excavation of soil below the groundwater in the core of the plume and groundwater extraction with above ground treatment for soil and ground water. Monitored natural attenuation at the margins of the plume. This approach would be extremely expensive.

Example (2)

Remedial Goal: Reduce concentrations at all points in the plume to a low value in a longer period of time.

Potential Remedial Alternative (1): Enhanced or engineered solutions to accelerate removal of source material and attenuate the core of the plume, coupled with above ground treatment for ground water. Engineered approaches for cleanup in the source area could include bioventing, for example. Monitored natural attenuation could address remediation at the margins of the plume. The potential cost-effectiveness of applying these technologies to the BXSS has not yet been determined.

Potential Remedial Alternative (2): Discontinue irrigation of the lawn areas surrounding the site and discontinue use of the car wash at the BXSS to eliminate artificial recharge of the aquifer. In essence, this approach would achieve the goal of reducing aqueous-phase concentrations by eliminating the artificial perched aquifer. Because of the depth to the next underlying water bearing zone, and the presence of intervening low-permeability strata, further threat to groundwater resources would be extremely low. In considering this remedial alternative, the economic consequences of closing the car wash must be addressed, along with the aesthetic issues involved in discontinuing irrigation.

Example (3)

Remedial Goal: Non-migration or containment of the plume, no demonstrable surface water impacts.

Potential Remedial Alternative: Passive bioremediation and monitored natural attenuation for the entire plume. For the BTEX plume, data suggest that passive bioremediation is an important process at the site. For the MTBE plume, the evidence for passive bioremediation has not been demonstrated, thus dilution and dispersion effects will constitute the primary means of natural attenuation.

Phytoremediation also appears to hold promise for assisting in natural attenuation at the BXSS site. Potentiometric surface maps indicate that a grove of eucalyptus trees downgradient of the source area creates a zone of low potential as a result of transpiration. In essence, these trees may be viewed as behaving as a natural pump-and-treat system for removing contaminated groundwater.

4. Summary and Recommendations

The Base Exchange Service Station (BXSS) at Vandenberg provides an illustration of the trade-offs between the uncertainty in potential risks and value and cost of additional information or active remediation (McNab et al, 1998b). During tank removal soil saturated and partially saturated with hydrocarbons was discovered in the area of the BXSS USTs. Over excavation was performed on soils showing signs of discoloration or residual hydrocarbon saturation. The site hydrogeologic and contaminant distribution conceptual model is well developed through 59 borings with associated samples from soils and groundwater. The impacted groundwater is a shallow seasonal perched aquifer in fine-grained clay sediments above a 400 foot Monterey shale unsaturated zone. The fractures in the Monterey shale are filled with clay minerals. Presently, there is minimal or absent free-product thickness and the fine-grained clay sediments limit any residual hydrocarbon mobility and recovery efforts. An MTBE plume has been detected at the site. Both the BTEX and MTBE plumes appear to be presently stable. The groundwater capture zones of nearby Eucalyptus trees have been observed within both the BTEX and MTBE plumes and are having a significant impact on the groundwater flow in the area.

For a dissolved hydrocarbon plume to pose a risk to human health or to the local ecology, a source, pathway, and receptor must all simultaneously co-exist. The absence of any of these elements implies that there is no associated risk. At the BXSS site at Vandenberg AFB, each of these elements has been assessed independently.

Sources. Leaking USTs and associated piping have been replaced; contaminated soil was removed during excavation. Although some residual hydrocarbon product may remain in the soils in the vadose zone, no free product has been observed on the water table itself. Therefore, additional groundwater contamination would probably occur through leaching in the vadose zone by recharge water, not directly from any free-product dissolution.

Receptors. There are no receptors at risk of detrimental impact by the dissolved hydrocarbons in the subsurface; the nearest downgradient water-supply wells are three miles away and are screened in a much deeper water-bearing zone. The potential future use of the perched groundwater is very limited due to the uncertainties in continued anthropogenic recharge and the very low yields of the aquifer. The nearest drinking water sources are three miles up gradient in a deep regional aquifer that is below the extensive unsaturated zone. Thus it is reasonable to anticipate that the perched groundwater will likely never be used for beneficial use.

Furthermore, because the hydrocarbon plume remains on Air Force property, institutional controls can be implemented to assure against hydrocarbon exposure risks associated with unanticipated land use or groundwater use activities. Potential vapor receptors do exist in the vicinity (buildings at the BXSS site itself). No ecological risk receptors have been identified.

Pathways. Geochemical indicators provide strong secondary evidence of passive bioremediation of FHCs at the BXSS site. Additionally, the evapotransportation of the eucalyptus trees appears to have a significant impact on the groundwater flow budget. Given the limited spatial extent typically associated with hydrocarbon plumes as a result of passive bioremediation, further downgradient migration of the BTEX plume is not likely. Using generally conservative assumptions, modeling results presented by IT Corporation (1996) suggest that the BTEX plume will diminish below MCLs in a time span on the order of 100 years. Thus, the receptor exposure pathway for FHCs is incomplete.

The MTBE plume at the BXSS site is presumably not subject to passive bioremediation and, in theory, is capable of persisting longer than the BTEX plume. The groundwater capture by the eucalyptus trees may act to limit the MTBE plume. Assuming the perched aquifer is of infinite extent and ignoring the effects of evapotranspirative pumping associated with the nearby grove of eucalyptus trees, dispersion of the MTBE plume below the 35 ppb threshold would require some 200 years, during which time the plume would migrate approximately 3,000 ft downgradient and reach a length of 1,600 ft. However, even under this very conservative scenario, no risk receptors would be effected due to restrictions in the usability of the perched aquifer. Thus, the receptor exposure pathway for MTBE is also incomplete.

The key risk uncertainty is the possibility of downward migration of contaminated perched groundwater through the fractured Monterey shale to the regional aquifer. This uncertainty can be addressed two ways: (1) aggressively perform active remediation to eliminate the uncertainty of this threat or (2) construct monitor wells within the Monterey shale below the perched contaminated groundwater. There are technical limitations associated with active remediation. An extraction well field has been installed and the combined yield is about two gallons per day because of the restricted permeability of the clays at the site. Construction of deep monitor wells introduce new uncertain risks by potentially providing a transport pathway through the impermeable shale that may not have existed. The practical considerations and potential risks associated with these alternatives must be weighed in light of the degree of certainty in the site characterization and the assumption that contaminated perched groundwater will not migrate through the clay filled fractures in the shale. In this case, the EC agrees that it is very unlikely that mobile gasoline constituents, such as MTBE, will migrate through the 400 ft unsaturated zone during the time-frame that natural process will remediate the site. Methane gas accumulation below areas covered by concrete or asphalt is unlikely, but should be periodically checked.

Low-cost residual hydrocarbon remediation alternatives, such as passive soil vapor venting, phytoremediation, or curtailment of horticultural watering and other perched aquifer recharge mechanisms, may provide the means for removing residual hydrocarbon material without incurring substantial operating costs or posing significant risks to potential future receptors.

In summary, the risks associated with the BTEX and MTBE plumes at the BXSS site at Vandenberg AFB are minimal; pathways linking the contaminants to existing receptors far downgradient do not exist and likely-use constraints, as well as institutional controls will prevent future risk receptors (i.e., water-supply wells) from developing near the BXSS site. Furthermore, the perched aquifer zone appears to exist only as a result of artificial recharge and thus does not warrant active remedial measures. Given this, we believe that remediation by natural attenuation as advocated by Vandenberg AFB and IT Corporation will protect human health and the environment, and is thus an acceptable means of remediation at the site. In this case, natural attenuation specifically includes the potential phytoremediation of the eucalyptus trees, dispersion of the MTBE plume, and passive bioremediation of the BTEX plume. As a safeguard measure, we recommend that at least two wells, located near the downgradient edge of the dissolved plume, be chosen as sentry wells and be monitored for BTEX components annually for up to five years to validate predicted plume stability. Furthermore, MTBE concentrations in at least one well in the source area should be monitored annually to assure that concentrations eventually decline and are not associated with any continuing leaks. A phytoremediation study to determine the impact of the on-site eucalyptus trees on the fate of the BTEX and MTBE plumes is recommended.

5. References

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Appendix A
Vandenberg Air Force Base Site Assessment Evaluation Letter

SITE ASSESSMENT REVIEW
TO
APPLY RISK BASED CORRECTIVE ACTION
AT
VANDENBERG AFB, BASE EXCHANGE SERVICE STATION AREA

The Department of Defense (DoD) Petroleum Hydrocarbon Demonstration Project (PHCDP) Expert Committee (EC) has reviewed the methods and findings of site environmental investigations conducted to address Leaking Underground Fuel Tank (LUFT) release impacts to soil and groundwater at the Vandenberg Air Force Base (VAFB) Base Exchange Service Station (BXSS), located at the corner of Herado Avenue and California Boulevard, and hereafter referred to as the "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.

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. Recommendations regarding additional data needed to complete our assessment and refine the Site conceptual model are provided.

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.

SUMMARY OF FINDINGS

Based on review of the documentation provided regarding the BXSS, the PHCDP-EC feels that the Site characterization conducted at the BXSS is reasonably thorough and, with augmentation based on the following review, should provide a credible basis upon which to proceed in the development of risk-based corrective action plan.

In general, the PHCDP-EC recommends that only a limited amount of additional data is needed to facilitate development of a risk-based approach to closure at the Site.

The PHCDP-EC feels the report and Site characterization can be improved by incorporation of additional interpretive discussion of data and information that is readily available to VAFB staff regarding sources, source mass, regional hydrogeology and groundwater resources, soil and groundwater plume anomalies, abandoned wells in the vicinity, and land use control issues.

Comments are also provided concerning the predictive modeling effort presented in the Technical Report. The EC feels that several critical assumptions used in the modeling merit reconsideration. Furthermore, the modeling results which predict the time required to naturally attenuate the plume concentrations should be presented as a range of values which reflect the results of a sensitivity analysis.

PURPOSE OF THE EXPERT COMMITTEE REVIEW

The following comments and critique are provided by the EC with the purpose of providing constructive technical review of the Site characterization investigations conducted to date. The review, as provided, attempts to consider technical, regulatory, and public perception issues that the EC perceives will be significant in evaluating the potential for and gaining acceptance for a risk-based corrective action approach to closure at the Site.

ORGANIZATION OF THE REVIEW

The following review has been subdivided into sections which address:

- The Site conceptual model,
- The source(s) of the petroleum hydrocarbon release to the subsurface,
- Potential contaminant migration pathways at the Site,
- Receptors which are likely susceptible to Site contaminants,
- Comments on the predictive modeling effort,
- Land Use Options which are available for Site management.

Site Conceptual Model

A well defined conceptual model of a site contains sufficient information to: a) identify the sources of contamination, b) identify the contaminant fate and transport characteristics of the site, c) determine the nature and extent of the contamination, d) specify potential exposure pathways, and e) identify potential receptors that may be impacted by the contamination.

The BXSS petroleum release area is part of a building complex that includes three gasoline dispensing islands, six automobile service bays, and a four-bay car wash building. The BXSS area is bordered by grassy open fields to the north-east and south-east, with Herado Avenue and a paved parking lot to the south-west and California Blvd. to the north-west. The BXSS Area has been the subject of several environmental investigations starting with Battelle Corp., 1987. A Site Assessment Report providing information on Site Characterization and Remedial Alternative Screening has been prepared by the Bureau of Reclamation (BOR)[1]. A DoD Petroleum Hydrocarbon Cleanup Demonstration Program Expert Committee Briefing Package has also been prepared[2] and a BXSS, Operable Unit 6, IRP Site 1, Draft Technical Report is in preparation[3].

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[1] U.S. Dept. of Interior, Bureau of Reclamation. 1993. Site Assessment Report, Vols. I, II, II. Remediation of Contaminated Groundwater at the Base Exchange Service Station (BXSS), Vandenberg Air Force Base.

[2] International Technology Corp. 1996. DoD Petroleum Hydrocarbon Cleanup Demonstration Program Expert Committee Briefing Package.

[3] International Technology Corp. 1996. Base Exchange Service Station, Operable Unit 6, IRP Site 1, Technical Report, Vandenburg AFB, California.

The information in the BXSS Draft Technical Report indicates that the lateral extent of the plume is adequately characterized, but the discussion presented with respect to the vertical extent of contamination is confusing. The discussion of the shallow perched saturated zone on p. 3-7 states that the lack of a deeper perched saturated zone indicates that little water is migrating through the deep vadose zone (sic). The following sentence which states "The clay bed at a depth of 15 feet is not expected to be a barrier to groundwater movement because of the disturbed nature of the bed." seems contradictory to the Site observations previously discussed. An explicit discussion of the vertical extent of contamination is needed and should be dovetailed into the discussion of the regional hydrogeology as discussed below.

The local geologic constraints to plume migration are well characterized. However, the brevity of the characterization of the regional hydrogeology is noticeable. The statement on page 5-1 that "The regional aquifer was not encountered at the site" leaves the reader with many questions. An expanded characterization of the regional hydrogeology is needed such that the reader has a more complete understanding of the regional aquifers that are under and/or in the vicinity of the Site. It is clear from the report that the saturated zone just under the Site is perched on a low permeability layer. Are there other deeper groundwater resources on Site? What evidence exists that this resource has not and will not be impacted by the shallow groundwater plume at the Site?

Electron acceptor data are reported which provide the basis for an assessment of the Site potential for ongoing biodegradation.

Variability in shallow groundwater elevation and gradient has been well characterized by bracketing the high and low water table situation over a period greater than ten years which has included time intervals of drought and excessive rain.

The interpreted drawings of the constituent plumes indicate that the extent of the contaminated groundwater has been laterally characterized to the non-detect lines. An explanation is presented in the BXSS Technical Report (p. 3-8) for the observation of a separate area of higher gasoline constituent concentrations around SB22 to the north of the paved area. However, no explanation is given for the area of increased MTBE concentration around BXS-MW-5 as indicated by BXSS Technical Report Figure 4-9. The PHCDP-EC recommends that a component to the site conceptual model be developed that incorporates this finding.

Sources

Four 10,000 gallon and one 250 gallon, single walled, steel fuel underground storage tanks have been in use since 1967. The larger tanks held leaded and unleaded gasoline and the smaller tank held waste oil. Two of the gasoline tanks were replaced with double-walled, fiberglass tanks in 1985 and the remaining two replaced with double-walled, fiberglass tanks in 1991. The small waste oil tank was removed in 1991. During the replacement of the gasoline tanks, soil saturated and partially saturated with hydrocarbons was discovered in the vicinity of the USTs. Only a limited amount of soil was excavated during the removal of the USTs and the site was back-filled with clean material.

Limited information is available about the primary source of the release (i.e., with respect to the amount of product released from the tanks and associated piping. This is, however, common at LUFT release sites. The time frame of the release is bracketed to within a range of just over twenty years (from 1967 when the tanks were first installed, to 1990 when the last two of four tanks were upgraded and replaced). The 1993 BOR Site Assessment Report indicated that an estimated 2300 gallons of fuel was released. A statement is needed which indicates whether or not the mass released can be estimated and, if so, at what level of certainty. Modeling assumptions stated in the Draft BXSS Technical Report[3], (p. 6-1) suggest that the release of contaminants occurred in the unsaturated zone in a relatively short time span shortly after the installation of the tanks, or around 1970. This may be may not be the case in view of the presence of methyl *tertiary* butyl ether (MTBE) in the plume. MTBE manufacture in the US began in the late 1970's. It is possible, and perhaps likely, that the release has taken place over a longer period of time.

The available data does not indicate the presence of an extensive secondary source (free phase product in the vadose zone or saturated zone). This is important with respect to the source strength and the time that will be required to remediate the plume. An explicit statement to this effect is an important result of the investigation findings.

Information derived from the plume data seem to provide the best indication of the location and relative magnitude of the source. This is tangible evidence which should be included in discussion of the source.

Contaminants of concern are well characterized. The contaminants identified in the soil and groundwater at the Site consist of gasoline compounds, specifically benzene, toluene, ethyl benzene, and xylenes (BTEX), 1,2,5-trimethylbenzene, MTBE, and scavenger product halocarbons. Potential conduits have been adequately identified (specifically, utility trenches and zones of relatively high permeability) and the lateral extent of the soil contamination is well bounded. The highest BTEX and MTBE soil concentrations were around the old pump island.

Information about the disposition of the former USTs is provided. However no conclusion, based on direct information or evidence, is presented which indicates whether or not there is an ongoing source. An explicit statement addressing this issue should be made, based on Site historical use information and/or field data.

Migration Pathways

The shallow subsurface hydrogeologic setting has been well characterized through 59 borings to sample sediments and construct groundwater monitor wells and piezometers. In addition to 19 monitoring wells sampled since 1991, 40 Geoprobe holes have been used to collect soil and groundwater data. In 13 of the Geoprobe holes, cores were continuously collected and logged. As a result, geologic and depositional site conceptual models are well developed.

Based on BOR Site Assessment Report, the BXSS area sits on an uplifted marine terrace consisting of layers of sand and clay. The upper bed is fine sand to a depth of about 12 to 15 feet. Between 12 and 16 feet is a layer of clay and sand with deformed and irregular dip and thickness. A perched saturated zone about 15 feet thick sits on the clay bed. The soils below this bed appear to be unsaturated, suggesting no substantial leakage through the clay layer. Sampling to a depth of about 60 feet indicate no other saturated zones.

Between 19 to about 28 feet bgs is a layer of fine sand, and below this layer is a 4 to 5 foot thick bed of fat clay. Below this layer, sands and gravel beds are present to a depth of about 43 feet where the Tertiary Monterey bed rock formation is encountered.

Variability in shallow groundwater elevation and gradient has been well characterized by bracketing the high and low water table situation over a period greater than ten years which has included time intervals of drought and above average rain. Depth to groundwater varies over a range of about six feet seasonally, with fluctuations of one foot or more on a weekly or daily basis. The major recharge to the perched, unconfined, aquifer appears to be landscape watering near the BXSS. Groundwater flow gradients change with water level fluctuations, but over all general flow is to the north.

While the local geologic constraints to plume migration are well characterized, an expanded characterization of the regional hydrogeology is needed such that the reader has a more complete understanding of the regional aquifers that are under and/or in the vicinity of the Site. It appears from the BOR Site Assessment Report that the saturated zone just under the Site is perched on a low permeability layer. Are there other deeper groundwater resources beneath Site? What evidence exists that this resource has not and will not be impacted by the shallow groundwater plume at the Site? The PHCDP-EC recommends that the site prepare a more complete discussion of the potential for fuel hydrocarbons, including MTBE, to migrate through the Monterey Formation to deep regional aquifers.

Soil vapor survey data are not included in the report. This data is needed to evaluate the potential inhalation hazards to receptors. Information on shallow soil contamination (i.e. <10 ft.) may be adequate to characterize the potential exposure to receptors by soil ingestion and to construction workers. However, there are areas of high constituent concentrations where the shallow soil concentrations have not been reported. This information should be reported if available.

No information or statement was made with respect to the potential presence of abandoned water wells from activities prior to or associated with the Site and the nearest (especially downgradient) producing wells have not been identified. While lack of such a statement may be indicative that this does not represent a problem at the Site, the issue needs to be specifically addressed. Figure VII, Site Assessment Report, Vol. II, indicates the Santa Ynez River Well Field is about four miles south-east of the site.

Potential conduits have been adequately identified (specifically, utility trenches and zones of relatively high permeability).

Potential Receptors

There do not currently appear to be any current impacts to receptors at the site. Additional information and discussion is needed which characterizes the near- and long- term anticipated uses of the groundwater and land at the Site, institutional land use controls available for use at the Site, and land use demands that will reasonably drive future Site land use decision making.

The nearest (especially downgradient) producing wells have not been identified. Such information should be provided and could later be used to emphasize the value of a risk-based corrective action as being protective of groundwater.

Information on shallow soil contamination (i.e. <10 ft.) may be adequate to characterize the potential exposure to receptors by soil ingestion and to construction workers. However, there are areas of high constituent concentrations where the shallow soil concentrations have not been reported. This information should be reported if available.

Additional information is needed on the near- and long-term anticipated uses of the groundwater at the Site.

Additional information is needed on the presence or absence of sensitive ecosystems which might be impacted.

How is the aquifer characterized with respect to the Central Coast Regional Water Quality Control Board Groundwater Basin Plan? What is the total dissolved solids (TDS) of the groundwater? It may be useful to discuss the capacity of the aquifer to meet the Regional Board's anticipated beneficial use designation.

Since the groundwater in the BXSS area, including impacted groundwater, may be deemed "low probability of use", an extended time frame for cleanup, perhaps on the order of 40 to 50 years may be acceptable. Thus, cleanup by natural attenuation processes may be a viable remedial alternative at the Site. Indications of these processes will be evaluated as part of the Risk Management Report to be prepared by the PHCD Program. A performance standard or performance based remedial goal may also be viable alternatives at the Site.

The potential for inhalation hazards to humans from the BXSS plume is very unlikely since relatively low concentrations of volatile petroleum hydrocarbon compounds have been observed. Soil vapor sampling can likely be used to confirm that no potential exposure exists.

Predictive Modeling

The statement is made in the BXSS Technical Report (p 6-1, last paragraph) that, "The release of contaminants occurred in the unsaturated zone over a relatively short time span." The EC does not agree with this statement; as long as the tanks were present, leakage could have continued. It's only after the tanks were removed that a decaying source makes the most sense.

It is the EC's opinion that, in the presence of a continuous source, concentrations near the source without biodegradation will not necessarily increase over time because of solubility constraints and simple dispersion (discussion in BXSS Technical Report p.6-2, first paragraph). A more effective argument is that, without biodegradation, the overall length of the dissolved plume would be much longer. An evaluation of BXSS groundwater contaminant plume stability will be provided as part of the PHCD Program Risk Management Report.

The discussion in the BXSS Technical Report (p. 6-4, second-to-last paragraph) relies on assuming that an equilibrium exists between recharge of BTEX from the source and BTEX degradation which is also based on the assumption that the plume is stationary. This justification seems somewhat speculative. There is too much variability in the monitoring data to justify making these kinds of statements. For example, if you assume a degradation rate that is stable in time, one would reasonably expect to see a pulsating plume that grows and shrinks in response to seasonal changes in the hydraulic gradient. Is there enough resolution in the data to indicate something like this? Intuitively, the notion presented in this discussion seems plausible, but its speculative nature cannot be overlooked. The EC recommends that this discussion be reconsidered and a determination be made as to whether it is necessary at all.

In the discussion on p. 6-7, Section 6.3.1, BXSS Technical Report, an exponential decay model is used to describe the source term. An exponential decay model is also used to describe the behavior of the dissolved contaminant in the plume. The distinction between the two, needs to be stated more explicitly. Numerical values for both should be stated. Model sensitivity to both parameters should be evaluated.

The BXSS Technical Report discussion (p. 6-8, last paragraph) on the differences between the different MTBE plume simulations is not clear and needs to be clarified.

Concluding that the modeling suggests that MTBE might be undergoing some degradation (p. 6-9, last paragraph) is somewhat speculative given that the current research on this subject is limited. Given all of the uncertainties regarding the nature of the MTBE source, the EC advises that the wording of this conclusion be reconsidered.

The conclusion is made (p. 8-1, third paragraph, BXSS Technical Report) that "Based on fate and transport modeling, the BTEX attenuation time to achieve 1 ppb was estimated at approximately 100 years." The discussion on page 6-9, second-to-last paragraph, indicates this conclusion is drawn based on one presented scenario. Given the Site data variability and assumptions built into the modeling effort, the EC feels that a sensitivity analysis be conducted and discussed in the report. The "attenuation time" should be presented as a range which encompasses the range of plausible outcomes produced as a product of simulations conducted while varying the parameters identified as critically sensitive in the sensitivity analysis.

Land Use Options

Additional information and discussion is needed which characterizes the near- and long-term anticipated uses of the land at the Site, institutional land use controls available for use at the Site, and land use demands that will reasonably drive future Site land use decision making.

SUMMARY AND RECOMMENDATIONS

To assist the Air Force in refining the BXSS Site conceptual model and address areas of uncertainty the Expert Committee makes the following recommendations and requests for additional data:

Conceptual Model: While the local shallow geologic constraints to plume migration are well characterized, an expanded characterization of the regional hydrogeology is needed along with a complete discussion of the potential for fuel hydrocarbons, including MTBE, to migrate through the Monterey Formation to deep regional aquifers. The PHCDP-EC recommends that the Site prepare a more complete discussion of the potential for fuel hydrocarbons, including MTBE, to migrate through the Monterey Formation to deep regional aquifers.

The nature of the contamination is well defined and the contaminants of concern are BTEX compounds and MTBE. There is a question as to why separate areas of higher constituent concentrations are observed around gasoline area SB22 to the north of the paved area, or the MTBE area around BXS-MW-5. The PHCDP-EC recommends that a component to the Site conceptual model be developed that incorporates the elevated MTBE and gasoline constituent concentrations around BXS-MW-5 and SB22 respectively. An explicit discussion of the vertical extent of contamination is needed and should be dovetailed into the discussion of the regional hydrogeology.

Sources: Sufficient data have been collected to define the source of contamination resulting from the BXSS leak and the source area has been removed to the extent practicable. No additional data needed at this time.

Pathways: Soil vapor survey data should be incorporated in a discussion which evaluates the potential inhalation hazard to receptors. A statement with respect to the potential presence or absence of abandoned water wells or other drinking water wells is needed.

Potential receptors: There do not currently appear to be any current impacts to receptors at the Site. The low probability of groundwater ingestion or use indicates that the Site may have a low probability of impacting any future receptors. Additional information and discussion is needed which characterizes the near- and long- term anticipated uses of the groundwater and land at the Site, institutional land use controls available for use at the Site, and land use demands that will reasonably drive future Site land use decision making. Additional information is needed on the presence or absence of sensitive ecosystems which might be impacted.

Predictive modeling: Comments are provided concerning the predictive modeling effort presented in the Draft BXSS Technical Report. The EC feels that several critical assumptions used in the modeling merit reconsideration and that result of the modeling regarding the time required to naturally attenuate the plume concentrations be presented as a range of values which reflect the results of a sensitivity analysis.

Conclusions

Based on review of the documentation provided regarding the BXSS, the PHCDP-EC feels that the Site characterization conducted at the BXSS is thorough and, with augmentation based on this review, will provide a credible basis upon which to proceed in the development of risk-based corrective action. In general, the PHCDP-EC recommends that only a limited amount of additional data is needed to facilitate a risk-based closure at the Site.

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

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Appendix B
Forecasting Behavior of MTBE Groundwater Plume at BXSS, Vandenberg AFB

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Forecasting Behavior of MTBE Groundwater Plume at BXSS, Vandenberg AFB

In addition to dissolved fuel hydrocarbons, a plume of methyl tertiary butyl either (MTBE) also exists in groundwater at the BXSS site (Fig. B-1). Unlike FHCs, the potential for biologically-mediated or abiotic degradation of MTBE has not been established in the literature. Furthermore, because of the low organic carbon partitioning coefficient associated with MTBE, approximately 9 mL/g, the compound does not readily adsorb onto soils. As a consequence of these two factors, the potential for significant migration of MTBE downgradient of the source area is much more significant in comparison to most FHCs. Hence, an evaluation of risk posed by an MTBE plume involves an assessment of the time required for plume collapse by dispersion, the primary remaining natural attenuation mechanism in the absence of engineered remediation.

B-1. Modeling Approach

To forecast possible future behavior of the MTBE plume at the BXSS site, an analytical solution to the advective-dispersive transport equation was used to model current observed MTBE concentrations. The same model was then used to forecast plume lengths and plume leading-edge travel distances using a Monte Carlo approach to assign probabilities of plume collapse over time due to dispersion.

Wilson and Miller (1978) presented an analytical expression describing solute transport in a homogeneous, infinite aquifer of constant thickness with a uniform fluid flow field assuming an instantaneous point source (i.e., finite slug source). Modified to account for retardation, this solution may be expressed as,

$$c(x,y,t) = \frac{M}{4\pi\phi t H\sqrt{D_l D_t}} \exp\left[-\frac{(x - \frac{v}{R}t)^2}{4\frac{D_l}{R}t} - \frac{y^2}{4\frac{D_t}{R}t} - \lambda t \right] \qquad \text{(B-1)}$$

where M is the instantaneous contaminant mass, ϕ the porosity, H the aquifer thickness, D_l and D_t the longitudinal and transverse dispersion coefficients, respectively; v the groundwater velocity, R the retardation coefficient, and x, y, and t the distances between the source location and the monitor point and the elapsed time between source introduction and sampling time, respectively.

Equation B-1 describes an idealized, elliptical Gaussian plume characterized by concentric contours of constant concentration at a particular instant in time. Along the center longitudinal axis of the plume (i.e., the line defined by $y = 0$), the locations of the leading and trailing edges of a given contour interval relative to the source may be quantified by rearranging Equation B-1 so that *x* is the dependent variable and *c* is specified:

$$x = \sqrt{-\frac{4D_l t}{R}\left[\ln\left(\frac{4\pi c\phi tH\sqrt{D_l D_t}}{M}\right)+\lambda t\right]}+\frac{vt}{R} \tag{B-2}$$

Because of its quadratic nature, Equation B-2 will have two solutions which correspond to the locations of the leading and trailing edges of the contour interval defined by *c*. In instances were the solutions are complex, the plume length is undefined. This latter condition will occur when the plume is sufficiently dispersed so that at no location is *c* met or exceeded.

The assumptions of an infinite, homogenous aquifer of uniform thickness characteristic of the Wilson and Miller (1978) model are common to most analytical solutions of the solute transport equation. Thus, in the case of the BXSS site, transpiration pumping effects of nearby trees, pinching out of the shallow perched water-bearing zone, or changes in groundwater velocity due to changes in recharge from irrigation cannot be taken into account. Hence, modeling results presented in this analysis are to be considered highly idealized and generally conservative in nature.

B-2. Application to the BXSS Site

Probability distributions for the governing parameters appearing in Equations B-1 and B-2 are shown on Table B-1. Wherever possible, the values were obtained directly from site-specific data (e.g., the range of hydraulic conductivity values available from slug tests in monitoring wells) or else were based on best professional judgment. The first-order decay coefficient, λ, was assumed to equal zero. While several of the parameters can be estimated directly, (e.g., source release time, dispersivity ratios), others must be calculated based on other parameters. For example, groundwater velocity, *v*, is calculated from Darcy's law,

$$v = \frac{K\nabla h}{\phi} \tag{B-3}$$

where *K* refers to the hydraulic conductivity, ∇h the hydraulic gradient, and ϕ the porosity. Based on the probability distributions given for these parameters (Table B-1), the median pore velocity is 9.78×10^{-2} m/day. The retardation coefficient, *R*, is calculated from the relationship,

$$R = 1 + \frac{K_{oc} f_{oc} \rho_b}{\phi} \tag{B-4}$$

where K_{oc} is the organic carbon partitioning coefficient (9 mL/g for MTBE), f_{oc} the fractional soil organic carbon content, and ρ_b the bulk density. Based on the probability distributions given for these parameters (Table B- 1), the median retardation coefficient is 1.02.

Longitudinal and transverse dispersion coefficients, D_l and D_t, respectively, are macroscale pseudo-diffusion coefficients used to describe mechanical mixing processes. They are estimated from the dispersitivities, or characteristic lengths, of the flow domain and the groundwater velocity:

$$D_l = \alpha_l|v| \tag{B-5a}$$

$$D_t = \alpha_t|v| \tag{B-5b}$$

Usually, α_l is conveniently defined as a fraction (typically 10%) of the length scale of the contaminant plume. This length scale may be defined as the product of the flow velocity and time (i.e., the distance over which a volume of groundwater would advect over time *t*). α_t is usually modeled as some fraction (e.g., 10%) of α_l.

As stated, the Wilson and Miller (1978) plume model assumes an instantaneous slug source of contaminant mass *M*. Such an assumption could rarely be considered strictly valid for most LUFT contamination scenarios, as FHC releases are better described by a continuous source term representing the ongoing leakage from an underground tank or the presence of entrapped or floating free product. However, MTBE has only come into widespread use in gasoline since approximately 1985, the year that the former LUFTs at the BXSS site were replaced. Assuming that the new tank and piping system have not experienced any significant releases, a slug source model may be appropriate, particularly given that free product has not been observed in BXSS wells and that MTBE is highly soluble in water. In projections of unmitigated MTBE plume behavior many decades into the future (refer to Section B-3), a slug source model is perhaps even more appropriate, provided again that no further releases occur.

The instantaneous contaminant mass, *M*, could not be estimated *a priori*. Instead, *M* was estimated by a search procedure that minimized the differences between forecast and measured concentrations using median values of the other governing parameters[1]. The estimated value of *M*, approximately 12 kg, is equivalent to approximately 40 to 400 gallons of gasoline, assuming 1% to 11% MTBE by volume (the quantity of MTBE used in gasoline has changed within the last 10 years).

The forecast spatial distribution of MTBE in the BXSS area, using Equation B-1, the median values of the governing parameters (listed on Table B-2), and the optimized value of *M* is shown on Figure B-2. The contour plot was created using only predicted concentrations at actual monitoring well and soil boring locations, as opposed to a regularly-spaced grid, to mimic the contouring of the field data for a more straightforward comparison. In general, the modeled plume agrees fairly well with measured distributions of MTBE. Thus, even if the slug source model is not entirely appropriate over the time scale since releases occurred from LUFTs at the BXSS site, the mass estimate of approximately 12 kg MTBE is probably reasonable given that MTBE does not readily biodegrade nor sorb significantly onto soils.

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[1]Calculations were performed by programming the Wilson and Miller (1978) solution into a Microsoft Excel spreadsheet and using the built-in solver procedure to find an optimal value of M, which minimized the sum of the squares of the differences between measured and forecast concentrations. Median values were assumed for the other governing parameters, as given on Table B-1.

B-3. Projected Future Behavior

Both the future position and length of the BXSS MTBE plume can be forecast using the median values of the governing parameters shown on Table B-2 and Equation B-2 for a specified contour interval. For this evaluation, the 35 parts-per-billion (ppb) contour interval was chosen as this concentration represents a possible action level for MTBE which has been proposed by the California Environmental Protection Agency (Cal EPA).

Projected plume lengths, defined as the distance between the trailing and leading edges of the plume, and downgradient distances, the distance from the source location to the leading edge of the plume, are shown on Figure B-3. Modeling results suggest that the plume length will grow to a maximum extent of approximately 600 meters in about 125 years before declining as a result of dispersion. At the same time, the leading edge of the plume will reach a maximum distance of approximately 900 meters downgradient from the source after about 200 years. Separation of the plume length and downgradient distance after approximately 75 years is indicative of detachment of the plume from the source area, which is expected for a slug source model. The plume as defined by the 35 ppb contour is predicted to “wink out” after 225 years. Shorter dispersal times are observed for different contour levels, such as the 70-ppb proposed Federal action level or the 200-ppb potential health-impact level, as shown on Figures B-4 and B-5, respectively.

In the absence of any degradation reactions, dispersion is the only means by which MTBE concentrations decline over time. Thus, the method employed to model dispersion over long length scales must be evaluated for its effects on projected plume length. To address this issue, two dispersion models were used. The linear model assumes that α_l is directly proportional to the length scale of the plume, *L*, as defined by,

$$L = vt \tag{B-6}$$

The alternative model is a power law relationship suggested by Neuman (1990), which quantifies longitudinal dispersivity by,

$$\alpha_l = 0.32L^{0.83} \tag{B-7}$$

for plumes with length scales greater than 100 meters. Both relationships were used to generate the projections shown on Figures B-3 through B-5. Results indicate that the projected plume lengths and downgradient distances are not sensitive to the choice of dispersion model.

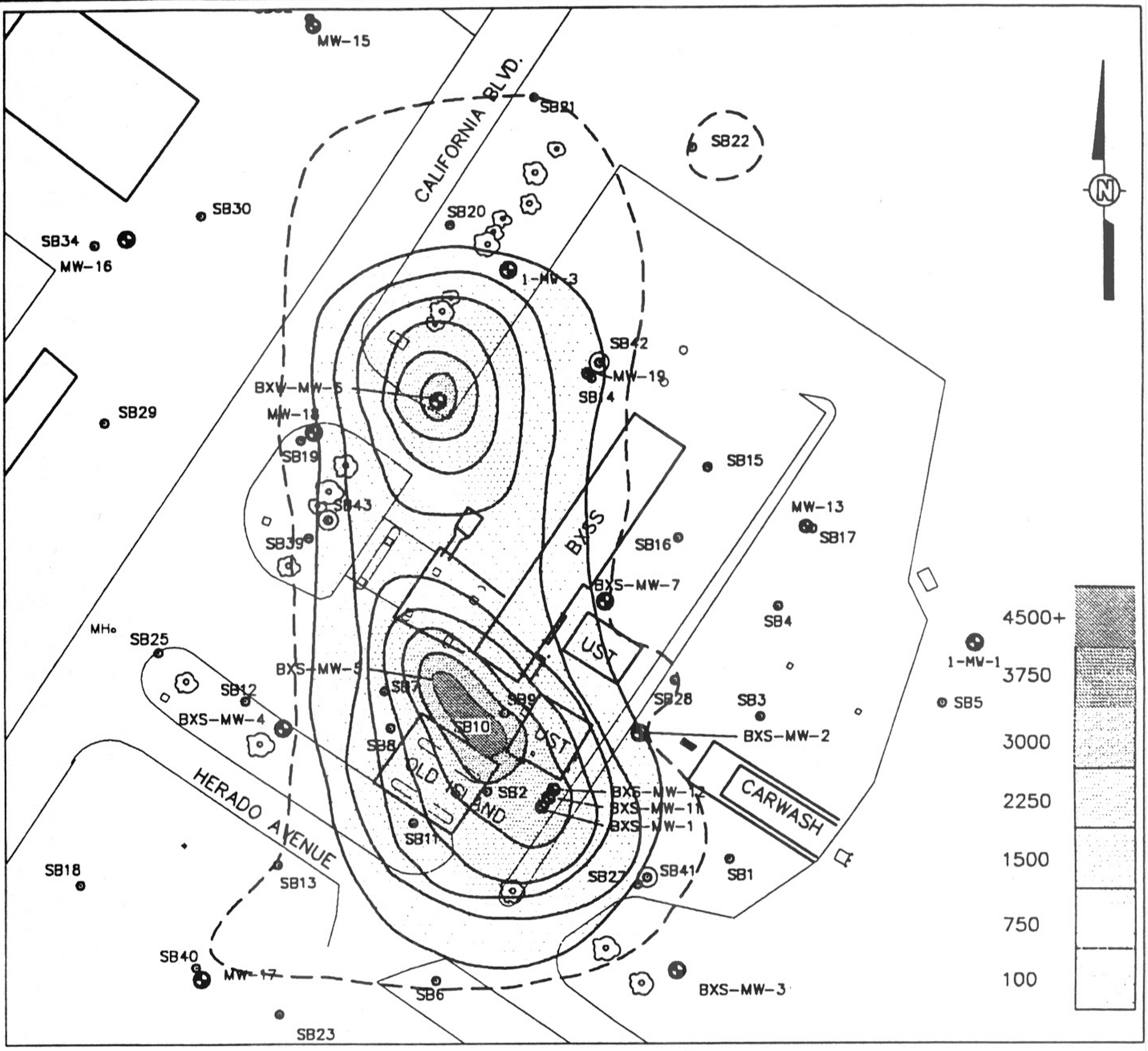
A Monte Carlo approach was used to quantify the probability of plume collapse due to dispersion as a function of time. This analysis involved generating multiple sets of governing parameters that appear in Equation B-2 based upon prescribed probability distribution functions (Table B-1). Individual simulations using each data set are referred to as realizations; results of multiple realizations can be interpreted as forecast probability distribution functions.

Plume behavior was quantified over a period of 500 years by assuming a uniform probability distribution function for *t* ranging between 5 and 500 years. The linear dispersion model was used to estimate dispersivities over the large length scales. A total of 5,000 Monte Carlo realizations were used. Forecast plume length distributions as a function of time are shown on Figure B-6, along with the projected median behavior. Clearly, a great deal of scatter is associated with Monte Carlo realizations, primarily due to variance in flow velocity resulting from prescribed uncertainties in hydraulic conductivity, gradient, and porosity (analysis not shown). To quantify the probability of plume collapse as a function of time, the realizations spanning the 500-year evaluation period were sorted into 10-year increments; the percentage of plumes which have collapsed to zero plume length during by each time increment were then calculated. The resulting forecast probability of plume collapse as a function of time is shown on Figure B-7. An exponential decay curve describes the output of the Monte Carlo analysis, with the median plume collapse time corresponding to approximately 200 years as expected, with the 80% confidence level extending to about 440 years.

B-4. References

Neumann, S. P., and Y. K. Zhang (1990), “A Quasi-Linear Theory of Non-Fickian and Fickian Subsurface Dispersion, 1, Theoretical Analysis with Application to Isotropic Media,” *Water Resources Research* **26**(5), pp. 887–902.

Wilson, J. L., and P. G. Miller (1978), “Two-Dimensional Plume in Uniform Ground-Water Flow,” *in Proceedings of the American Society of Civil Engineers, J. Hydraulics Division* **104**(HY4), 503–514.



SCALE:

0 40 80 160 FEET

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EXPLANATION

GROUNDWATER MONITORING WELL
MW-13

DIRECT-PUSH SOIL BORING
SB8

AUGER SOIL BORING
SB41

MTBE CONCENTRATIONS IN ug/L

ND NON-DETECT

DRAFT

FIGURE B-1

MTBE CONCENTRATION CONTOURS
BASE EXCHANGE SERVICE STATION

PREPARED FOR

U.S. AIR FORCE
VANDENBERG AIR FORCE BASE
CALIFORNIA

INTERNATIONAL TECHNOLOGY CORPORATION

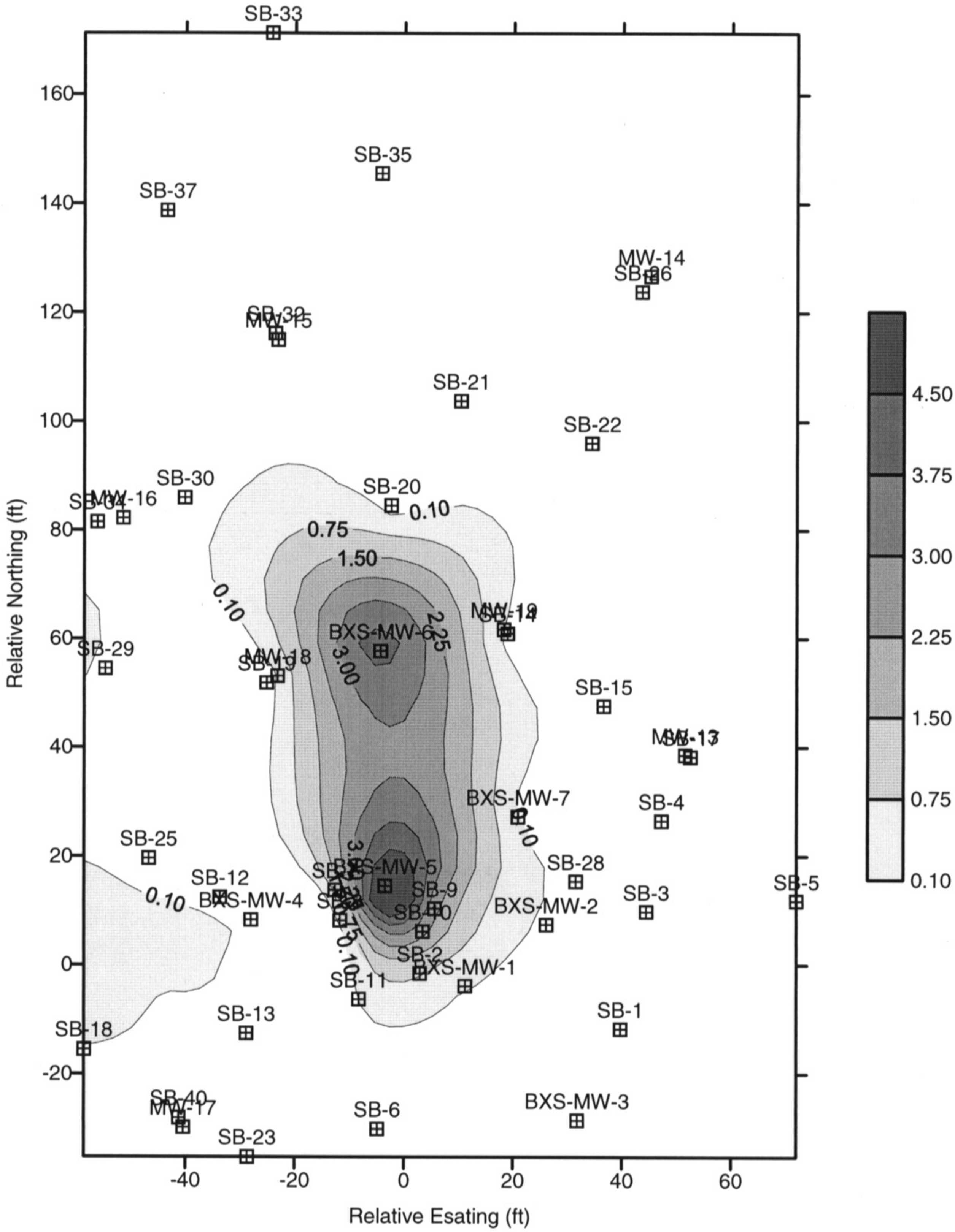

Fig. B-2. Forecast MTBE distribution in BXSS area, 10 years after source introduction, using median values of governing parameters.

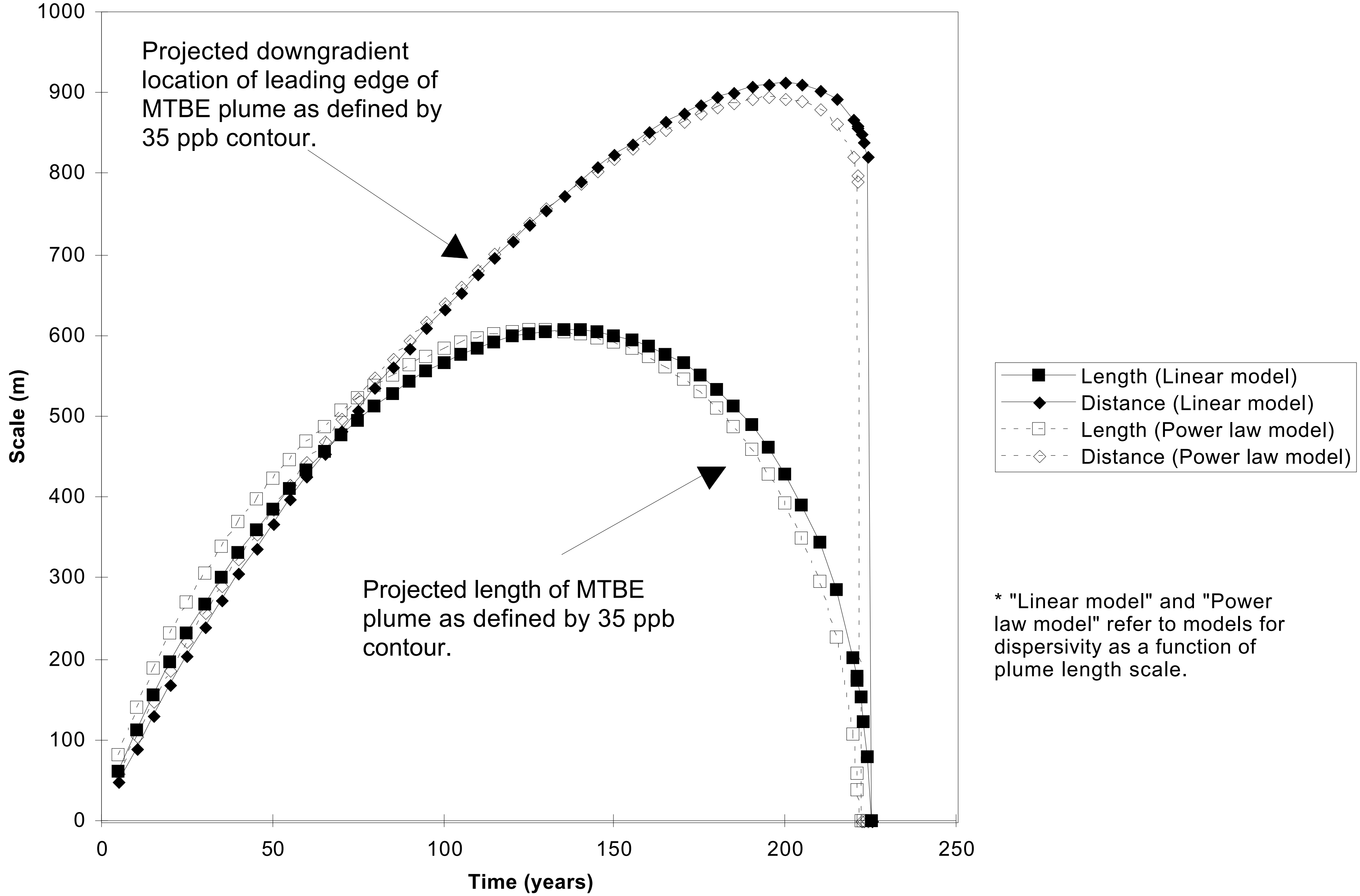

Fig. B-3. Projected MTBE plume lengths as defined by the 35 ppb contour interval.

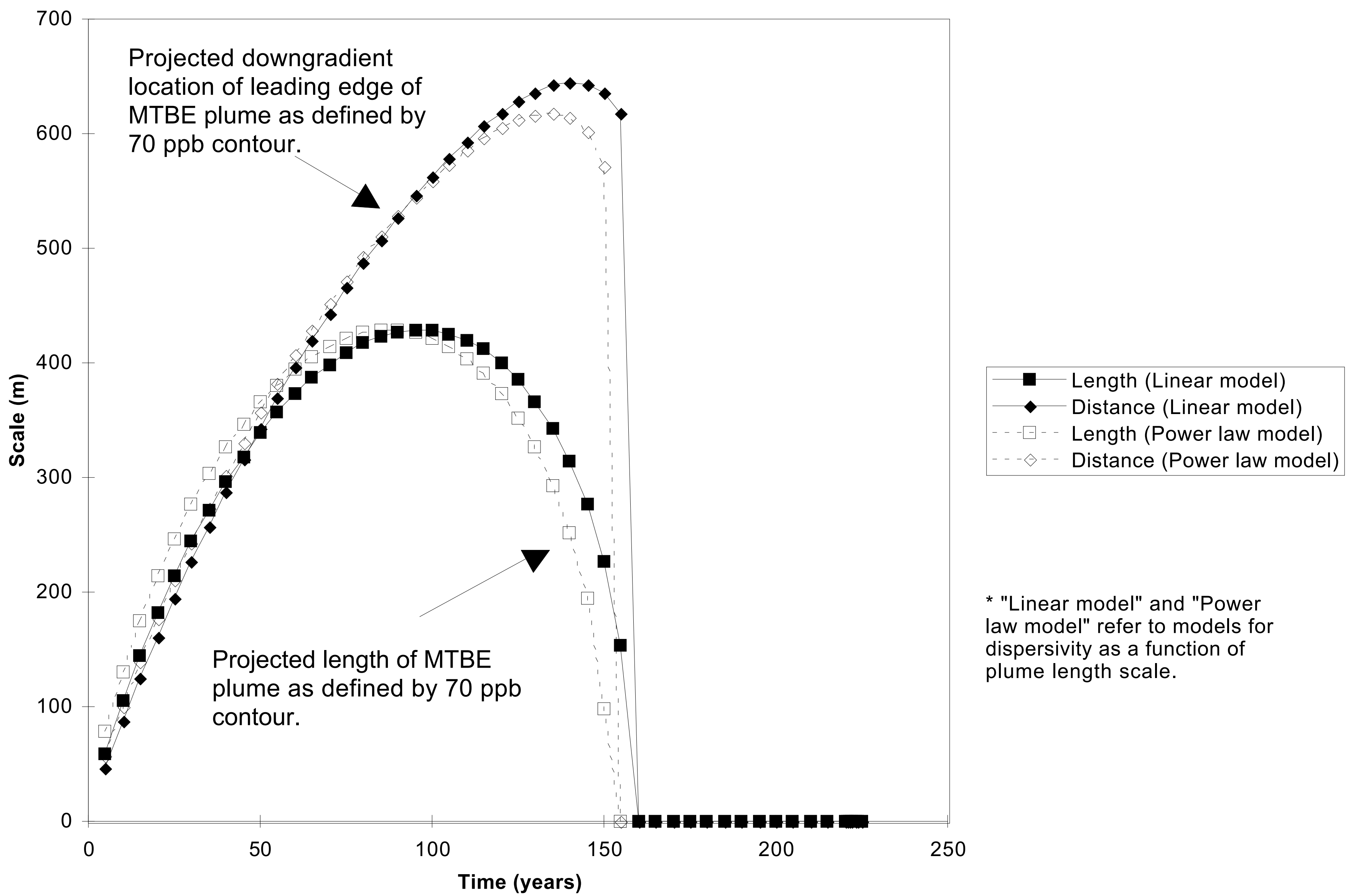

Fig. B-4. Projected MTBE plume lengths as defined by the 70 ppb contour interval.

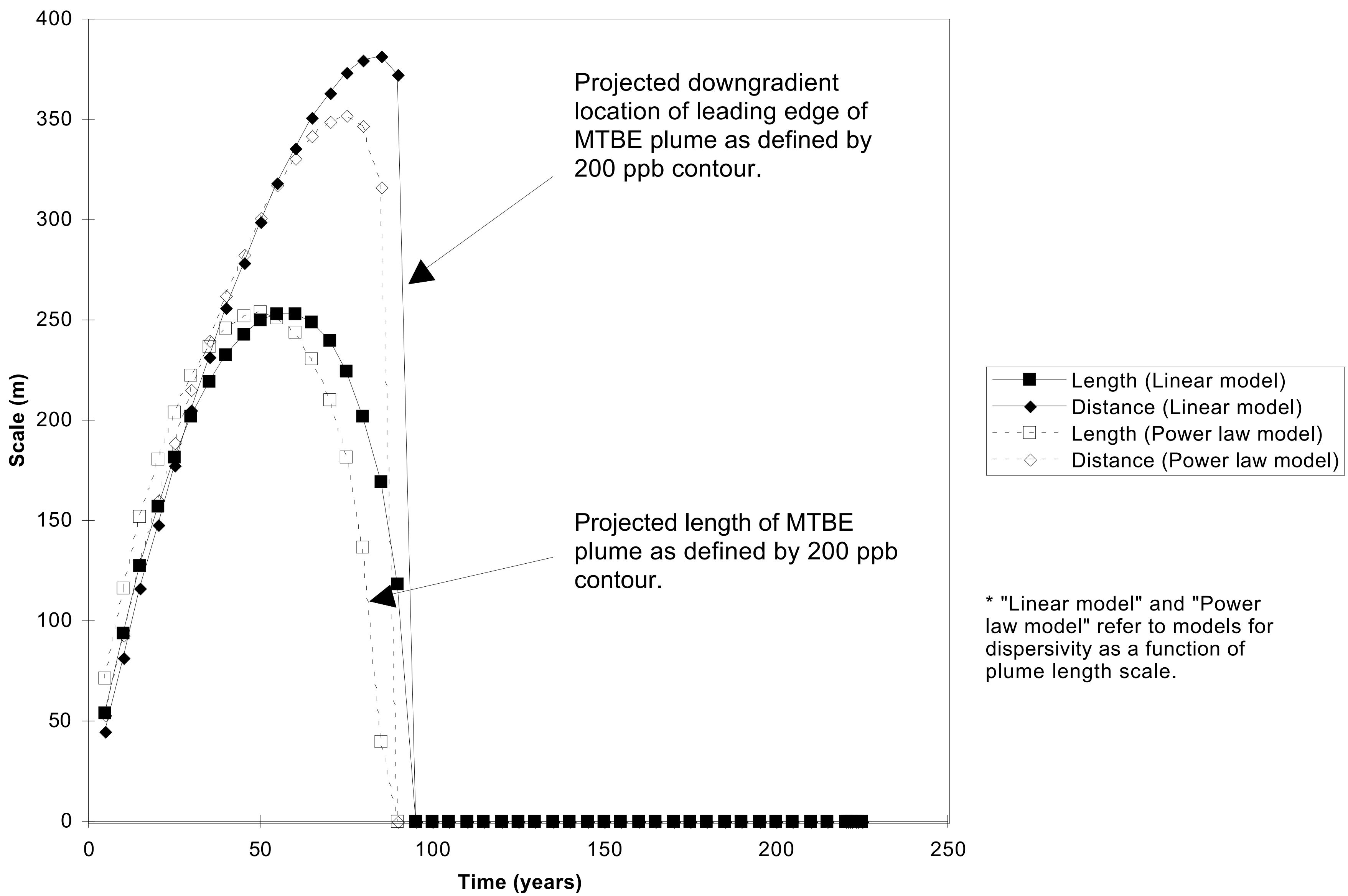

Fig. B-5. Projected MTBE plume lengths as defined by the 200 ppb contour interval.

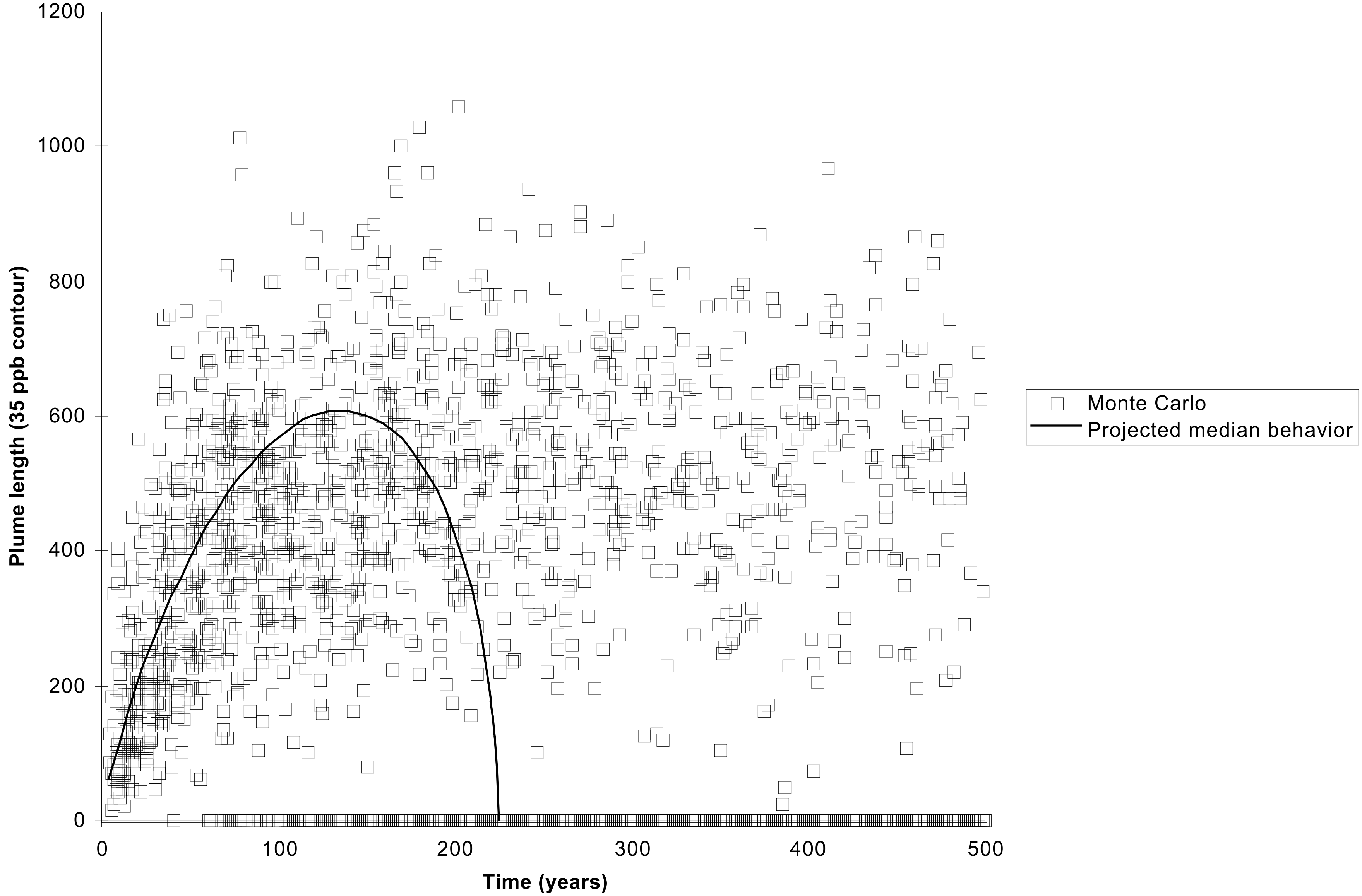

Fig. B-6. Forecast plume lengths as a function of time (5,000 Monte Carlo realizations).

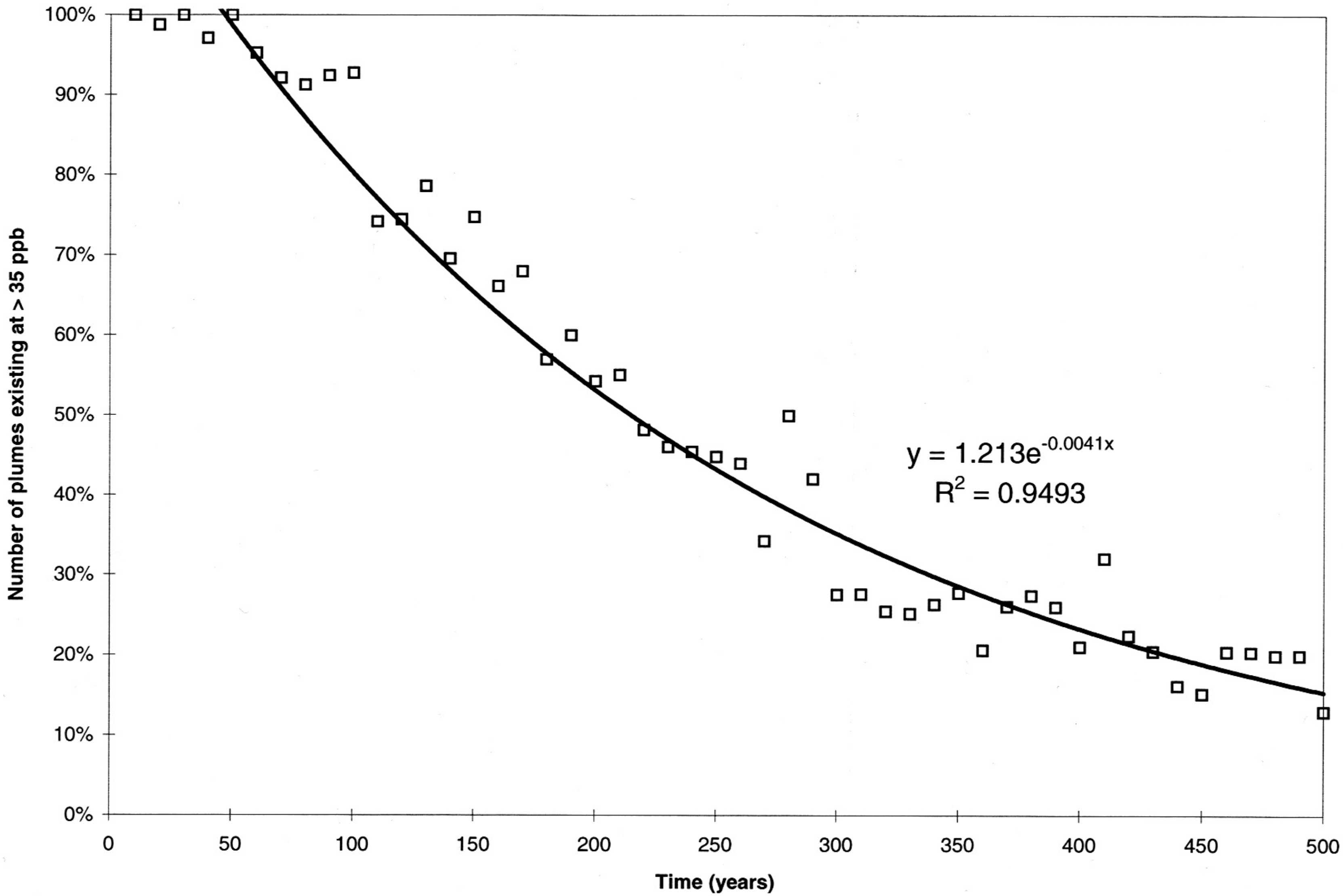

Fig. B-7. Forecast probability of plume collapse as a function of time.

Table B-1. Model parameter values.

Parameter	Description	Remarks	Prescribed distribution
t	**Elapsed time since source mass release**	**Idealized slug release assumed to have occurred in 1985.**	**Lognormal distribution.** **10 ± 1 years**
M	**Source mass**	**Estimated from optimal fit of model to measured data. Refer to discussion in text.**	**Normal distribution.** **12 ± 1.2 kgs**
K	**Hydraulic conductivity**	**Distribution of values from a fit of a lognormal distribution function to results of slug testing in site wells (IT Corp., 1996).**	**Lognormal distribution.** **0.24 ± 0.28 m/day**
∇**h**	**Hydraulic gradient**	**Estimated from potentiometric surface contours (IT Corp., 1996).**	**Lognormal distribution.** **0.021 ± 0.01**
ϕ	**Porosity**	**Estimated range based on best professional judgment.**	**Normal distribution.** **0.30 ± 0.03**
α_l**:L ratio**	**Ratio of longitudinal dispersivity to plume length**	**Based on best professional judgment (median = 0.1, a typical value).**	**Lognormal distribution.** **0.13 ± 0.11**
$\alpha_t:\alpha_l$ **ratio**	**Ratio of transverse to longitudinal dispersivity**	**Based on best professional judgment (median = 0.1, a typical value).**	**Lognormal distribution.** **0.13 ± 0.11**
f_{oc}	**Fractional organic carbon content**	**Based on best professional judgment. Because the K_{oc} value associated with MTBE is only 9 mL/g, retardation is not an important parameter.**	**Lognormal distribution.** **0.30 ± 2.6%;** **(5th percentile = 0.001%** **95th percentile = 1.0%)**
ρ_b	**Bulk density**	**Based on best professional judgment. Because the K_{oc} value associated with MTBE is only 9 mL/g, retardation is not an important parameter.**	**Normal distribution.** **1.65 ± 0.03 g/cm^3**

Table B-2. Median model parameter values.

Parameter	Median value
t	**3590 days**
	(9.8 years)
M	**12 kg**
v	**9.78×10^{-2} m/day**
ϕ	**0.3**
α_l**:L ratio**	**0.1**
α_t**:**α_l **ratio**	**0.11**
R	**1.02**