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NAVAL AIR STATION MOFFETT FIELD
CALIFORNIA

TECHNICAL MEMORANDUM
PETROLEUM SITES
PETROLEUM CLEANUP LEVEL ANALYSIS

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CLEAN Contract Number N62474-88-D-5086
Contract Task Order 0235

Subject: **Draft Technical Memorandum Installation Restoration Program Petroleum Sites**
Petroleum Cleanup Level Options
Naval Air Station Moffett Field

Dear Camille and Stephen:

Enclosed are three copies of the above referenced report for your review. Additional copies are being forwarded to the regulatory agencies for review.

If you have any questions, please call us at (303) 295-1101.

Sincerely,

Michael S Allen

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ACRONYMS AND ABBREVIATIONS

ABAG	Association of Bay Area Governments
AICUZ	Air Installation Compatible Use Zone
BCRC	Base Closure and Realignment Commission
BTEX	Benzene, toluene, ethylbenzene, and xylene
CAP	Corrective action plan
CCR	California Code of Regulations
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
C_{gw}	Acceptable groundwater concentration
CLEAN	Comprehensive Long-term Environmental Action Navy
CNS	Central nervous system
COC	Chemical of concern
C_s	Acceptable soil concentration
CSF	Carcinogenic slope factor
DOD	Department of Defence
DTSC	California EPA Department of Toxic Substances Control
EPA	U.S. Environmental Protection Agency
ELCR	Excess lifetime cancer risk
FFA	Federal Facilities Agreement
ft/min	Feet per minute
foc	Organic carbon content
GAC	Granular activated carbon
g/L	Grams per liter
g/cm^3	Grams per cubic centimeter
HI	Hazard index
IRP	Installation Restoration Program
JP5	Jet fuel 5
JP4	Jet fuel 4
LTA	Lighter than air
µg/kg	Micrograms per kilogram
µg/L	Micrograms per liter
MCL	Maximum contaminant level
MGD	Million gallons per day
mg/kg	Milligrams per kilogram
mg/kg-day	Milligrams per kilogram per day
mg/L	Milligrams per liter
MOU	Memorandum of Understanding

ACRONYMS AND ABBREVIATIONS (Continued)

NAPL	Non-aqueous phase liquid
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration Ames Research Center
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NEX	Naval Exchange
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
OU	Operable unit
PAH	Polynuclear aromatic hydrocarbon
PCE	Tetrachloroethane
PRC	PRC Environmental Management, Inc.
RA	Resident Agency
RBC	Risk-based concentration
RCRA	Resource Conservation and Recovery Act
RD/RA	Remedial design and remedial action
RI/FS	Remedial investigation and feasibility study
RI	Remedial investigation
RWQCB	California Regional Water Quality Control Board, San Francisco Bay Region
SCVWD	Santa Clara Valley Water District
SFWD	San Francisco Water Department
SVE	Soil vapor extraction
SVOC	Semivolatile organic compound
SWRCB	State Water Resources Control Board
TDS	Total dissolved solids
TCE	Trichloroethene
TPH	Total petroleum hydrocarbons
UST	Underground storage tank
VOC	Volatile organic compound

1.0 INTRODUCTION

The U.S. Department of the Navy, as part of the Installation Restoration Program (IRP), has been identifying and evaluating past hazardous waste sites at Naval Air Station (NAS) Moffett Field and controlling the spread of contaminants from these sites. Environmental restoration activities are conducted under the Comprehensive Long-term Environmental Action Navy (CLEAN) contract. These activities are coordinated through a Federal Facilities Agreement (FFA) involving the Navy, the U.S. Environmental Protection Agency (EPA), the California Regional Water Quality Control Board, San Francisco Bay Region (RWQCB), and the California Environmental Protection Agency, Department of Toxic Substances Control (DTSC).

NAS Moffett Field is located approximately 1 mile from the southern end of the San Francisco Bay, adjacent to the cities of Mountain View and Sunnyvale, California (Figure 1). The base was commissioned in 1933 to support the west coast dirigibles of the lighter-than-air (LTA) program. A permit was granted to Ames Aeronautical Laboratory (later the National Aeronautics and Space Administration [NASA] Ames Research Center) to use part of the station in 1939. Since the 1950s, the primary mission of NAS Moffett Field has been to support antisubmarine warfare training and patrol squadrons. To complete these missions, the Navy and other government tenants commonly managed large quantities of fuel products in various sumps, aboveground tanks, and underground storage tanks (USTs). An inventory of tanks at NAS Moffett Field indicates that approximately 137 tanks were installed; the majority of these tanks were used to store petroleum products. As a result of previous operating practices, fuel products leaked or spilled near the tanks and spread to the surrounding subsurface, contaminating the subsurface soils and groundwater. The Navy recognizes the need to remediate the areas that pose a risk to human health and the environment and to reduce the potential for future releases. The Navy has been actively pursuing these objectives. Approximately 63 tanks have been removed and another 36 tanks are planned for removal in 1994. In addition, approximately 6,500 cubic yards of petroleum-contaminated soil have been remediated and two groundwater source control measures have been implemented at NAS Moffett Field.

To close out the tank sites and complete the necessary remediation, it is necessary to define cleanup goals for the contaminated media. The cleanup goals must be protective of human health and the environment, with particular attention to sensitive ecological receptors and groundwater quality. State of California guidance indicates that some water quality degradation (concentrations above background levels) may be allowed if it is in the best interest of the people of the state (SWRCB 1990;

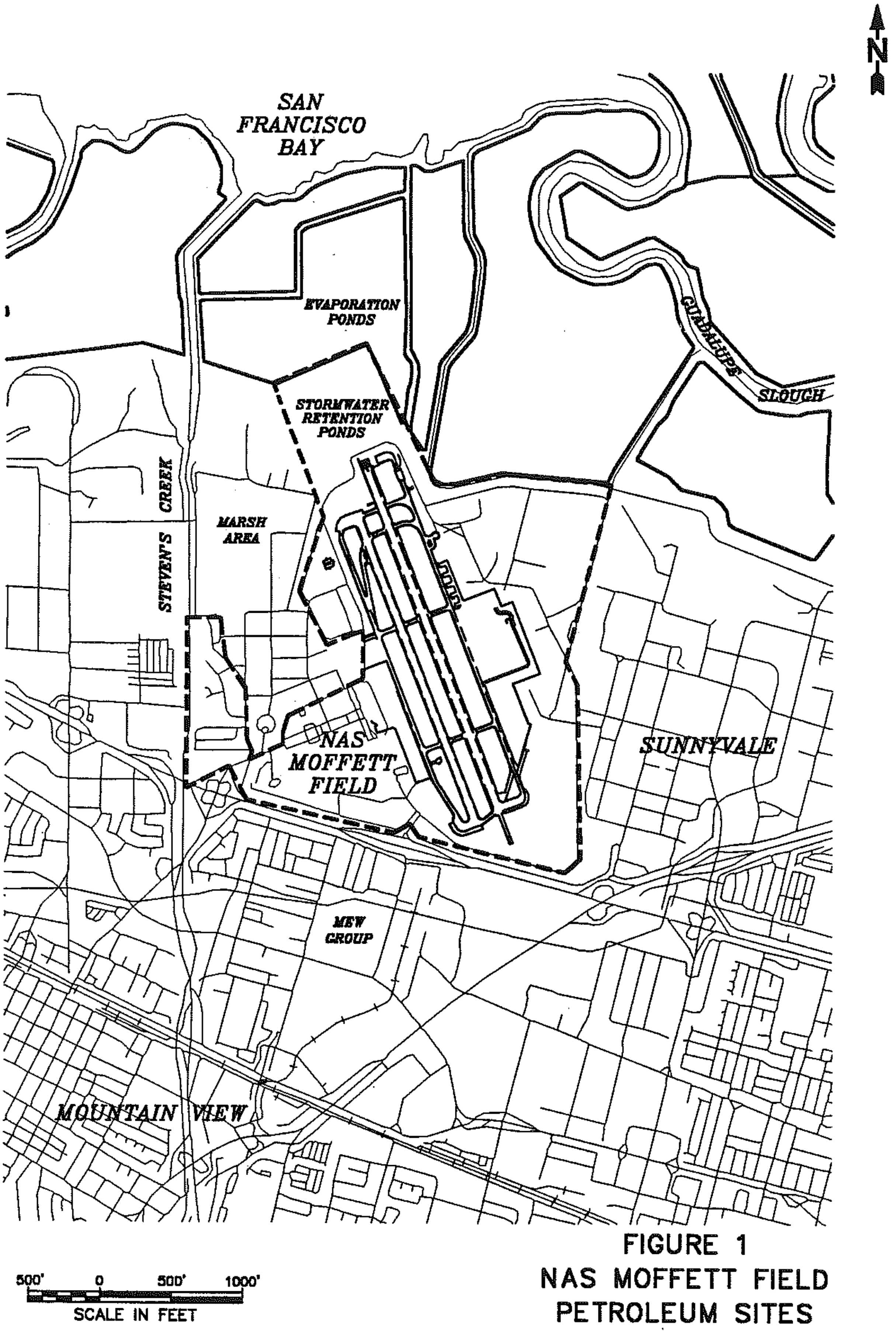

FIGURE 1
NAS MOFFETT FIELD
PETROLEUM SITES
BASE LOCATION MAP

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CVRWQCB 1992). However, this degradation should not cause adverse impacts to existing or probable future beneficial uses of waters of the state. Therefore, protective cleanup goals must maintain existing or probable future beneficial uses. In addition, federal and state guidances indicate that cleanup goals should be technically achievable and cost effective.

This technical memorandum presents a cost-benefit analysis of remediating petroleum-related contamination to several different protective cleanup goal levels. This analysis was undertaken to (1) present a comprehensive picture of the nature of petroleum contamination at NAS Moffett Field, (2) identify the possible effects this contamination may have on the environment and beneficial uses of the land and groundwater, (3) evaluate the benefits to the local community that may be acquired by implementing different remedial strategies, and (4) estimate the costs associated with attaining these benefits. These are all parameters that state and federal remedial programs require for consideration. This information forms the basis for a risk-based selection of the appropriate cleanup goals for petroleum contamination at NAS Moffett Field.

This technical memorandum is divided into eight sections. Section 1.0 contains the introduction and Section 2.0 summarizes the nature and extent of petroleum contamination. Section 3.0 describes petroleum characteristics, including chemical composition and toxicity, and geochemical fate and transport. Section 4.0 summarizes cleanup level options, discussing potential guidance, human health risk, and environmental risk-based levels. Section 5.0 presents remedial technology options and Section 6.0 describes the cost-benefit analysis of the cleanup level options. Section 7.0 presents conclusions and recommendations and Section 8.0 contains references. Appendix A provides details on the methodology used to derive human health risk-based levels. Appendix B provides details on the fate and transport development of environmental risk-based numbers for soils. Appendix C explains the development of groundwater environmental risk-based levels.

2.0 NATURE AND EXTENT OF PETROLEUM CONTAMINATION

The nature and extent of petroleum contamination at NAS Moffett Field has been summarized to identify the magnitude of contamination to which cleanup levels will be applied. The large quantity of materials (soils and groundwater) affected by petroleum contamination is one of the primary justifications for analyzing various cleanup levels and associated benefits.

Much of the information summarized below was described in the IRP petroleum sites characterization report (PRC 1994a), in addition to other reports (PRC 1990c; 1991; 1992). Data presented in these reports indicate that the primary areas of petroleum contamination at NAS Moffett Field are Sites 5, 9, 12, 14, 15, and 19. Sites 5, 9, and 14 contain the largest quantities of soils and groundwater affected by petroleum contamination; Sites 12, 15, and 19 contain smaller quantities. Data gaps were identified at most of these sites and an additional investigation was conducted during early February 1994 to fill these gaps (PRC 1994d). Results from this investigation, however, were not available for inclusion in this report. Subsequent versions of this report or future petroleum sites documents will include the additional data.

Petroleum groundwater contamination is almost exclusively confined to the shallowest aquifer zone (A1). The chemical segregation of the A1 and deeper A2 zones is due to the existence of confining layers and an upward hydraulic gradient (PRC 1994f; 1993d). Evidence of petroleum contamination in the A2 aquifer zone is limited to isolated sporadic low-level detections, typically below quantitation limits.

The following paragraphs summarize the petroleum contamination identified at Sites 5, 9, 12, 14, 15, and 19. The summary is not intended to provide a comprehensive review of all existing data, but rather to provide a general overview. A brief description of soil contamination data followed by groundwater contamination data is presented for each site.

Site 5

Site 5, known as the Fuel Farm, operates as the main fuel facility for NAS Moffett Field. This site includes 18 tanks, 11 of which are active fuel tanks (Tanks 4, 6, 7, 10, 11, 12, 13, 72, 73, 74, and 75). The remaining tanks have been removed or are inactive. Most of the tanks manage or previously managed jet fuel (JP5), some managed diesel fuel (Tanks 4, 5, and 18), and one managed waste oil (Tank 26). Site 5 is separated into northern and southern sections. The northern area is located in the triangular area bordered by Macon Road, Patrol Road, and the golf course. The southern area is bounded by a road to the east (unnamed), aircraft aprons to the south and west, and Hangar 3 to the north.

Soil data indicate that five areas of fuel-related contamination exist at Site 5: (1) the area north, west, and south of Tanks 10, 11, 12 and 13; (2) the area surrounding the former Tank 26 excavation;

(3) the area around the fuel station; (4) the area north of Tank 9; and (5) the area near Tanks 4 and 5. The contamination is characterized by detections of total petroleum hydrocarbons (TPH) extractable as JP5. Maximum detections include 1,460 milligrams per kilogram (mg/kg), 1,190 mg/kg, 1,000 mg/kg, and 940 mg/kg of TPH as JP5 from borings SB05-07, SB05-06, W05-07, and SB05-10, respectively. The soil contamination could originate from previous operational practices (such as tank stripping or accidental overfilling) or some tanks or lines may have leaked. However, some soil data gaps existed at Site 5 and additional data were collected during the February 1994 field work.

Floating fuel was observed during installation of wells in the shallowest aquifer zone (A1) near the northern Site 5 tanks during the operable unit (OU) 2 remedial investigation (RI), and subsequent sampling has confirmed the presence of free product at well FP05-01. The origin of this contamination has not been confirmed, and could be caused from either leaking tanks or from routine tank stripping activities performed in the past. One A1 aquifer zone well (W05-21) located downgradient from the tanks was sampled in November 1992 and no TPH constituents were detected. Samples from two other A1 aquifer wells collected during the same period, however, had detections of 26 micrograms per liter (μg/L) of TPH purgeable as other light components (W05-23) and 11 μg/L of TPH extractable as other heavy components (W05-25). TPH extractable as diesel was also detected (0.57 milligrams per liter [mg/L]) in a sample from downgradient well W05-27. No TPH contamination is present in the deeper A2 aquifer zone due to confining clay layers between the zones and upward hydraulic gradients.

These groundwater data indicate that groundwater in the uppermost aquifer zone northwest of Tanks 12 and 13, near Tank 26, and near Tanks 4 and 5 has been affected by petroleum releases. Groundwater near the fuel station and north of Tank 9 does not appear significantly affected. As new data become available, these conclusions may be revised accordingly.

Site 9

Site 9 includes the old fuel farm near Building 29, the old Naval Exchange (NEX) service station at Building 31, and the former laundry and dry cleaning facility at Building 88. The area surrounding Site 9 also contains other buildings that had operational practices involving the use or storage of petroleum products. This expanded Site 9 area encompasses approximately 30 acres on the western side of NAS Moffett Field. The expanded Site 9 includes the area approximately bounded by McCord Avenue on the west, Hangar 1 on the east, Bushnell Road on the north, and Wescoat Road on the south. Several areas of petroleum storage have previously been located within the expanded Site 9 area and these areas are referred to by building number. All of the tanks in these areas have been removed.

Building 29 and the surrounding area were the site of the old fuel farm. Aviation gasoline and jet fuels were stored in 13 USTs and one aboveground tank at the old fuel farm between the 1940s and 1964. Building 31 was the site of the old NEX service station. Fuel and waste oil were stored in four USTs (Tanks 56A through 56D). Fuel was also stored in two USTs in the vicinity of Building 10 (Tanks 1 and 32). These tanks stored auxiliary fuel for a boiler and generator. One fuel dispensing tank was also located near Building 15 (Tank 87).

Soil data indicate that three areas of fuel-related contamination exist at expanded Site 9: (1) the area north of the former tanks at Building 29, (2) the area north of the former tanks at Building 31, and (3) the area north and south of former Tank 1. Maximum concentrations include 4,600 mg/kg of TPH extractable as JP5 (sample SB-65), 4,570 mg/kg of TPH purgeable as gasoline (sample TN56CD-WX), and 2,270 micrograms per kilogram (μg/kg) of benzene (also sample TN56CD-WX). Soil contamination may originate from previous operational practices (such as accidental overfilling) or some tanks may have leaked. Soil data from Site 9, however, indicate that data gaps existed at each of the areas above. An additional investigation was conducted to fill these data gaps.

Contaminated groundwater beneath Site 9 is being addressed on a regional basis by a Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) response action and Navy source control actions. Source control actions include a groundwater extraction system with treatment by air stripping and granular activated carbon (GAC). Groundwater extraction wells have been placed in the vicinity of Buildings 29 and 31 for source control of gasoline-contaminated groundwater. Fuel contamination at Site 9 is largely restricted to the shallowest aquifer zone (A1). Historically, sporadic detections of TPH (gasoline) have been noted from deeper A2 wells (W29-7, W29-8 and W29-9) downgradient from tanks near Building 29. For well W29-7, TPH (gasoline) was detected at 1,400 and 1,600 μg/L in the July and November 1991 quarterly sampling events. For well W29-8 a detection of 2,900 μg/L (TPH gasoline) was detected in the July 1991 sampling event. For well W29-9, low detections (less than 100 μg/L) were detected in the July and November sampling events.

These indications of historical contamination in the deeper aquifer zone are problematic. No TPH (gasoline or BTEX) has been detected in subsequent sampling of these wells even though the tanks at Building 29 were not removed until July, 1993. The data indicating the past existence of TPH as gasoline in the A2 zone were not validated, and therefore the positive identification of gasoline is suspect, since these wells contain contamination of VOCs from the regional plume. Chemical communication between the A1 and A2 zones in the Site 9 area is limited by intervening clay layers (IT 1992, PRC 1993) and upward hydraulic gradients (May and September 1993 Quarterly Sampling). Therefore, if gasoline contamination did exist at one time in the deeper zone, it is likely due to direct contamination of the deeper zone. This explanation is supported by the fact that the bottom of these tanks were at least 18 feet below land surface (PRC 1992a). Borelogs for these A2 wells show that only thin (1 to 2 feet) clay and silt layers separate sand lenses in the lower A1 zone and sand lenses in the upper A2 zone. Whereas it is unlikely the fuel contamination in the upper A1 zone could migrate to the A2 (being separated by several feet of clay and upward hydraulic gradient), it is not unlikely that a portion of a fuel release in the lower A1 zone could impact the upper A2 zone. However, fuel introduced in a deeper zone would migrate upward over time due to buoyancy and upward hydraulic gradient.

Site 12

Site 12 was a fire fighting training area located on the western portion of NAS Moffett Field. The site consisted of an unlined 65-foot-by-65-foot pit with a surrounding berm about 1 foot high. Within the pit was a mockup of a plane used as a target. The site also contained a 5,000-gallon aboveground fuel tank located 90 feet north of the pit, that stored waste fuels used in the training exercises.

Data collected at Site 12 are documented in the Site 12 fire fighting training area action memorandum (PRC 1990b). Petroleum-related compounds and semivolatile organic compounds (SVOCs) were detected in soil samples, and recommendations for remediation were made. Remediation of Site 12 soils subsequently occurred beginning in fall 1993. Remediation consisted of excavation and treatment by catalytic oxidation. This treatment technology uses a batch process with hydrogen peroxide and a catalyst to chemically oxidize petroleum constituents. Excavation activities are completed and treatment operations are ongoing. The results of the Site 12 soil remediation, however, are not available for inclusion in this document. A technical memorandum documenting remediation results will be prepared as part of Site 12 activities after treatment activities are complete. Once the technical memorandum has been completed, any additional investigations, evaluations, and remediation required at Site 12 will be included in future petroleum sites documents.

Only minor levels of petroleum-related constituents were detected in groundwater samples from A1 wells collected in August 1992 from the six groundwater monitoring wells at Site 12 (PRC 1993d). No TPH contamination above a quantitation limit is present in the A2 aquifer zone at Site 12. Toluene and ethylbenzene (less than or equal to 0.5 μg/L) were detected in a sample from well W12-4. Additional collection and evaluation of Site 12 groundwater data are required after remediation is complete. Therefore, data from Site 12 will be addressed when the Site 12 technical memorandum is complete and will be included in future petroleum sites documents.

Site 14

Site 14 is an operating vehicle refueling and maintenance facility located at the intersection of South Gate and Macon Roads. Two potentially leaking USTs (Tanks 19 and 20) were removed in 1986. Two new double-walled USTs were installed adjacent to the location of the former tanks.

Soil data indicate that petroleum-related contamination is confined to the 15- to 25-foot interval (PRC 1990c). These soils are below the water table level and are therefore considered in the groundwater remediation discussions.

The groundwater in the vicinity of former Tanks 19 and 20 is contaminated with gasoline-related constituents (the maximum concentration was 23 mg/L TPH purgeable from well W14-2). The petroleum contamination is restricted to the shallowest aquifer zone (A1). No TPH purgeable as gasoline or BTEX contamination is present in the deeper A2 aquifer above quantitation limits at Site 14. This is due to confining clay units between the two aquifer zones and an upward hydraulic gradient.

Site 15

Site 15 consists of eight sumps and oil/water separators and one UST. The tank and sumps were used or are in use to collect liquid wastes accumulated in containment areas from various operations. The Site 15 tank and sumps are distributed throughout NAS Moffett Field. Tank 54 and Sumps 59, 63, and 65 are located in the eastern portion of the facility. Sumps 25, 42, 58, 62, and 64 are located in the western portion.

Of the one tank and eight sumps at Site 15, only three are active (Sumps 59, 63, and 65). Sump 42 was removed in October 1990 and Tank 54 was removed in June 1993. Sumps 25 and 58 are inactive and scheduled for removal in spring 1994. Sump 62 is currently inactive but NASA plans to reactivate this sump after assuming control of the station in July 1994. Sump 64, a stormwater diversion box, is inactive and will either be used in the future or closed.

Analytical data do not exist for soils surrounding Sumps 25, 58, 59, 62, 63, 64, and 65. Analytical data do not exist because evidence of releases from these sumps has not been identified and soil samples have not been collected until recently. Inspections and soil sampling were recently conducted to assess whether releases have occurred (PRC 1994d). Analytical results, however, are not yet available; if soil samples indicate soil contamination exists, groundwater impacts will be evaluated. Excavation samples, as required for closure, will be collected from beneath the sumps as they are removed (Sumps 25 and 58). Data, however, are available from the removals of Sump 42 and Tank 54.

Sump 42 was removed in 1990 during the excavation of Tanks 33 through 36 at the current NEX service station. Analytical results for soil samples collected below Sump 42 indicated concentrations of 32 mg/kg TPH purgeable as gasoline and 200 μg/kg benzene. The soil used as backfill for the tank excavations near Sump 42 had concentrations of 1,000 mg/kg TPH purgeable as gasoline. Groundwater samples from the nearest downgradient A1 zone well (W9-30) in the A1 zone did not have any petroleum-related detections. Because of the elevated backfill concentrations, further investigation of this sump and the associated USTs is being conducted during the investigation of the current NEX service station in February 1994 (PRC 1994e).

Tank 54 has been removed. Fuel-related compounds were not detected in any samples collected from the Tank 54 excavation. Analytical results from a groundwater sample collected from the downgradient A1 zone well (W6-10) also did not indicate detections of petroleum-related constituents.

Site 19

Site 19 includes Tanks 2, 14, 43, and 53. All of these tanks have been removed. Tank 2 was a 2,000-gallon tank that stored waste products emanating from the power plant shop in Hangar 3. Tank 14 was a 1,100-gallon tank that was used as a standby diesel fuel storage tank for the backup generator in Building 158, the operations building. Tank 43 was a 2,000-gallon tank that collected rinse water from the engine cleaning rack, drains, and sinks in Hangar 3. Tank 53 was a 500-gallon tank used for unleaded gasoline storage at the golf course maintenance area.

Soil data indicate that three areas of fuel-related contamination exist at Site 19: (1) the area northeast of former Tank 2; (2) the area southwest of former Tank 43; and (3) the area south of former Tank 53. Maximum concentrations near Tank 2 include 1,700 mg/kg TPH extractable as diesel and 610 mg/kg TPH purgeable as gasoline (sample TN2-NY). Samples near Tank 43 had TPH extractable as diesel concentrations ranging from 1.7 to 2,000 mg/kg. Samples near Tank 53 had maximum TPH purgeable as gasoline concentrations of 1,600 mg/kg and maximum benzene concentrations of 4,160 μg/kg (sample TN53-SY). Soil data from Site 19 indicate that some data gaps exist at each of the above areas and an additional investigation has been conducted to fill these data gaps. The soil contamination may originate from previous operational practices (such as accidental overfilling) or some tanks may have leaked.

Groundwater data collected from A1 zone wells in the vicinity of the Site 19 tanks indicate that only samples from well W43-1 (near Tank 43) had elevated concentrations of petroleum-related constituents (maximum concentration of 120 μg/L of TPH purgeable as gasoline). No other petroleum-related constituents were detected at any wells near the other Site 19 tank sites. However, groundwater samples collected from the Tank 2 and Tank 53 excavations had maximum concentrations of 610 mg/L of TPH extractable as diesel and 240 μg/L of benzene. Volatile organic compounds (VOCs) were detected in samples from wells in the A1 zone near Tanks 2 and 43. Maximum concentrations include 10 μg/L of trichloroethene (TCE) near Tank 2 and 120 μg/L of tetrachloroethene (PCE) near Tank 43. The 1993 quarterly sampling data show no VOC detections above quantitation limits in the A2 zone wells near these tanks. The VOC detections in the A1 zone are being addressed through the OU5 (east side aquifers) remedial investigation and feasibility study (RI/FS) process.

3.0 PETROLEUM CHARACTERISTICS

This section summarizes the chemical composition, toxicological characteristics, and the general geochemistry and fate and transport of refined petroleum products. The descriptions provide a general understanding of the characteristics of fuels to highlight their importance in developing appropriate petroleum cleanup level options. Information presented in this section also introduces the parameters that have been considered in modeling fate and transport of fuels in soils and groundwater.

3.1 CHEMICAL COMPOSITION

Petroleum products are complex mixtures (solutions) of nearly 200 different hydrocarbons and additives, with each compound exhibiting different physical and chemical properties. The chemical groups that make up the majority of the toxic, mobile, and persistent chemicals in petroleum products include: (1) benzene, toluene, ethylbenzene, and xylene (BTEX); (2) polynuclear aromatic hydrocarbons (PAHs); and (3) straight and branched-chain alkanes (alkanes). Because constituents within each of these groups behave relatively similarly, these groups will serve as the focus for consideration of the general behavior of fuels. In this discussion, two general fuel types, gasoline and diesel/jet fuel, will be considered since these represent the bulk of fuel contamination at NAS Moffett Field.

Fresh (undegraded) gasoline consists dominantly of lower molecular weight alkanes with typically 5 to 10 carbon atoms in the chain (lighter constituents) and BTEX constituents. In gasoline, the most common of these compounds are pentanes and hexanes (about 18 to 31 percent) and BTEX (7 to 36 percent). Only small amounts of PAHs are present in gasoline. Naphthalene is the most abundant PAH at a concentration range of 0.2 to 0.5 percent. Other PAHs, such as anthracene, benzo(a)pyrene, and benzo(b)fluoranthene are known to occur in some gasolines at minute concentrations, less than 0.0005 percent (Cline and others 1991; SWRCB 1989). No evidence exists to indicate the presence of lead in gasoline contamination at NAS Moffett Field. The maximum concentration of lead in unleaded gasoline is 0.013 grams per liter (g/L). In general, aviation gasoline is similar to automotive gasoline.

Fresh diesel and jet fuels are predominantly composed of higher molecular weight alkanes with typically 9 to 19 carbon atoms in the chain (heavier constituents) and small amounts (less than 1.0 percent) of PAHs. Diesel fuel is a middle distillate of petroleum with a low sulfur content. Diesel fuels have various compositions and are used as fuel for trucks, ships, and other automotive engines. JP5 is a petroleum distillate that is similar to kerosene with a higher percentage of alkanes. JP4 is a blend of kerosene with lower-molecular weight alkanes. The most abundant alkanes in diesel and jet fuels are decane (10 carbon atoms) through octadecane (18 carbon atoms) (about 65 percent). Naphthalenes are the most abundant PAHs in diesel, typically at concentrations of 0.6 to 0.9 percent. Similar to gasoline, other PAHs such as benzo(a)pyrene occur at concentrations less than 0.0005 percent.

Fresh fuels which are exposed to the environment immediately begin to degrade through a number of processes. Thus, the composition of a fuel spill or release will continuously change over time. Generally, the lighter constituents are more volatile and more easily degraded than heavier hydrocarbons. Therefore, the greater the time since a release, the more TPH will be composed of the heavier and immobile constituents. The weathering process of fuels will be discussed in more detail later in this section.

3.2 TOXICITY

The constituents of fuels that pose appreciable health hazards include BTEX and PAHs. Within these groups, toxicity and carcinogenic characteristics vary between compounds. Of most concern in gasoline is the carcinogen benzene, which is present in fresh fuel at a concentration of 0.12 to 3.5 percent. The suspected carcinogenic PAHs which occur in gasoline are in such small concentrations (for example, benzo(a)pyrene at 0.00002 to 0.00028 percent) that they do not add appreciably to gasoline's overall toxicity. In diesel fuel, BTEX compounds are not important because of their small concentrations, but noncarcinogenic and suspected carcinogenic PAHs, including naphthalene and benzo(a)pyrene, are present in small quantities. These PAHs represent the majority of the overall toxicity associated with diesel mixtures.

With the exception of gasoline, all fuel mixtures have been classified by the International Agency for Research on Cancer as Class C carcinogens (possibly carcinogenic in humans) (IARC 1989a, 1989b, and 1989c). Gasoline is classified as a Class B2 carcinogen (probably carcinogenic in humans). EPA has developed reference doses (RfDs) for gasoline, JP5/kerosene, and JP4, and has developed a carcinogenic slope factor (CSF) for gasoline. These values are presented in Appendix A. The following subsections summarize the toxicity of these three mixtures and the derivation of their toxicity values.

3.2.1 Gasoline

Acute inhalation exposures to gasoline may cause eye, mucous membrane, throat, and respiratory tract irritation. Overexposure to vapors may lead to bronchopneumonia. Inhalation of high concentrations can cause fatal pulmonary edema. Dermal contact with gasoline can cause dermatitis and blistering of the skin due to its defatting properties. Ingestion or inhalation exposures can cause inebriation, drowsiness, blurred vision, and other central nervous system (CNS) effects. Ingestion may also result in burning of the mouth or throat, gastrointestinal irritation, nausea, vomiting, and diarrhea.

Studies in animals have indicated that the kidney is a target organ for ingested gasoline, while inhalation is damaging to the lungs (EPA 1992c). One study of chronic gasoline exposure found an increased incidence of renal tumors that appeared to have a dose-response relationship. Epidemiological studies in humans have not positively demonstrated an association between gasoline exposure and cancer, although some studies suggest this association. EPA classifies gasoline as a probable human carcinogen (Class B2) and has developed a slope factor of 1.7×10^{-3} per milligram per kilogram per day ($[\text{mg/kg-day}]^{-1}$).

EPA has also derived a reference dose of 0.2 mg/kg-day for gasoline based on route-to-route extrapolation from inhalation data.

3.2.2 Jet Fuel

Many types of jet fuel exist, but their compositions are sufficiently similar that they cause similar toxic effects. Acute inhalation of jet fuel vapors may produce dizziness, headache, nausea, and fatigue. Dermal contact with jet fuels may produce skin irritation. Eye and respiratory irritation may occur through vapor exposure. Ingestion or inhalation of jet fuels may result in increasing levels of CNS depression that may progress to unconsciousness, coma, and death from respiratory failure. JP5 and JP4 are damaging to the lungs and cause inflammation of the lung tissue, which may lead to pulmonary edema and chemical pneumonitis as well as bleeding of the lung tissue.

Chronic inhalation of jet fuels may produce neurasthenic symptoms such as fatigue, anxiety, and memory difficulties. Chronic lung dysfunction may result from aspiration into the lungs. Animal studies have yielded conflicting results of the chronic toxicity of jet fuels (EPA 1992c). Reproductive and developmental toxicity of jet fuels have not been well studied but there was no indication of adverse effects in laboratory animals exposed via inhalation. EPA has not classified jet fuels as to their carcinogenicity. EPA-derived reference doses are 0.02 mg/kg-day for JP5 and 0.08 mg/kg-day for JP4.

3.2.3 Diesel Fuel

In general, diesel fuel is a skin irritant and CNS depressant when inhaled. Inhalation, depending on the extent of exposure, can also cause respiratory tract irritation, headache, dizziness, nausea, and vomiting. Secondary effects include hypoxia, pneumatocele formation, and chronic lung dysfunction. In some cases, inhalation may cause respiratory arrest and CNS toxicity. Ingestion of diesel fuel causes gastrointestinal irritation, vomiting, diarrhea, and in severe cases, death from CNS depression.

Chronic effects of exposure to diesel fuel are similar to those produced by JP4 and JP5. Diesel fuel is a Class C carcinogen (not classifiable as to human carcinogenicity). Reference doses have not been developed for diesel fuel.

3.3 GENERAL GEOCHEMISTRY OF FUELS

The behavior of fuels in the subsurface is governed by the physical and chemical properties of the fuels and characteristics of the materials through which the chemicals move. This section summarizes the general geochemistry of fuels and fuel constituents relevant to fate and transport mechanisms of fuels in soil and groundwater.

The general fate and transport behavior of fuels in the subsurface is described in various reference materials and will be summarized later in Section 3.4. However, since fuels are complex solutions and of variable composition, little information on their behavior is available that can be used to rigorously predict their migration in the subsurface. Although specific chemical information is available on many of the constituents of fuels, consideration of each fuel constituent is cumbersome. Additionally, the geochemical behavior of a complex solution may be quite different than the behavior of an individual constituent of that solution. The characteristics of fuels may be approximated by consideration of the primary groups of constituents comprising a general fuel type. For some of the discussion of the geochemistry and fate and transport of fuels, three groupings of fuel constituents will be made. Within each of these groups, some variation in geochemical behavior is displayed, but only one or two compounds which typify the behavior of the group are considered for the fate and transport modeling calculations presented later. The groups that will be discussed are: (1) the straight and branched chain compounds (alkanes), which comprise the bulk of fuels; (2) the aromatic compounds (that is, BTEX); and (3) the PAHs.

The behavior of fuels in soil and groundwater systems can be described in terms of migration of pure fuel or nonaqueous phase liquids (NAPLs) and migration of dissolved constituents. Certain chemical and physical properties of fuels are relevant to the discussion of pure-phase migration and others apply to dissolved-phase migration. Overall, the important properties of fuels which influence their fate and transport include volatility, density, surface tension, viscosity, solubility, sorption, reactivity, and degradation potential. Some important characteristics of the soil and aquifer systems which control fate and transport of fuels include porosity (void space), permeability (ease of flow), organic carbon and clay content, heterogeneity, soil or aquifer zone thickness, and water infiltration and flow rates. The size of a fuel spill or release has a direct bearing on the fate and transport of fuel contamination.

The physical properties of the pure fuels will be discussed first. These properties are presented to understand facilitating the process of fuel migration in the subsurface and potential limitations to remediation. For example, a small spill of relatively volatile gasoline may largely evaporate before significantly impacting soil or groundwater. The same volatility may allow for success of soil vapor vacuum extraction to remediate a larger gasoline spill in soils. However, the lower volatility of some heavier fuels would render this remedial alternative ineffective. After discussion of the properties of pure fuels, this section discusses the properties controlling fuels dissolved in water.

3.3.1 Properties of Pure Fuels - Volatility, Density, Surface Tension, and Viscosity

Gasoline, diesel, and jet fuels have many similar properties. Fuels are variably volatile, being available for evaporation under favorable conditions (high temperature, low humidity, high permeability). Due to the abundance of low molecular weight constituents, gasoline is more volatile than diesel fuel. Both are less dense than water (gasoline density is about 0.72 grams per cubic centimeter [g/cm^3]), and, therefore, float (are buoyant) when in contact with water. Jet fuel, which has a greater proportion of higher molecular weight hydrocarbons, is slightly denser than gasoline. Fuels have a lower surface tension than water and do not readily wet soil or aquifer sediments. Fuels will, therefore, not occupy all of the available pore space of a soil or aquifer material, especially if the material has been previously wetted by water. Both gasoline and diesel fuel are less viscous than water, which means that they flow more easily through soils than water. Gasoline is less viscous than diesel and jet fuels.

3.3.2 Properties of Dissolved Fuels - Solubility, Sorption, and Degradation

Fuels are generally insoluble in water, do not mix with water, and thus occur as NAPLs. Most fuel constituents have low solubilities in water (less than 100 mg/L), but some of the lower molecular weight hydrocarbons have moderate solubilities (more than 100 mg/L) (see Appendix C, Table C-1). The higher molecular weight alkanes and most of the PAHs may be considered essentially insoluble in water. Some fuel constituents, such as benzene, are relatively soluble which allows for preferential leaching or dissolution of the constituent from fuel contamination in a soil or aquifer. Over time, the selective mobility of benzene or other more soluble components may result in residual fuel contamination that is devoid of the mobile components. Thus, the process of fuel dissolution in water is constituent-selective and serves as a separator of the mobile and immobile components. Once in solution (whether in pore water, in soil, or in groundwater), the behavior of fuel contamination may only be represented by a summation of constituent behaviors controlled by the geochemical characteristics of the individual fuel constituents.

Sorption is the complex but important process that binds a chemical dissolved in water to the solid materials in a soil or aquifer. Sorption is dependent upon the chemical properties of the constituent (represented by partitioning or distribution coefficients) and the medium to which the chemical may be sorbed. Generally, the tendency of a chemical to be sorbed is a function of its solubility in water. Benzene and lower molecular weight alkanes will be less sorbed to soil or aquifer material, whereas higher molecular weight alkanes and PAHs will be strongly sorbed. Once sorbed, a chemical may be desorbed (returned to the water), mineralized and fixed, or degraded. The sorption of a chemical in a soil or aquifer depends on many factors, but for organic compounds the primary factor is the content of naturally occurring organic carbon in the soil or aquifer. Sorption, therefore, is a process of removal of contamination from groundwater and fixation for strongly sorbed chemicals such as PAHs. However, a chemical of low to moderate solubility that is sorbed in large quantities to an aquifer material with a high sorption capacity (high organic carbon content) will be available for desorption and allow for the long-term, low-level contamination of groundwater.

Degradation is the process by which a chemical is transformed into by-products with different chemical structures, thus affecting mobility and toxicity. Three types of degradation are considered important: (1) abiotic oxidation/reduction (mineralization), (2) anaerobic biodegradation, and (3) aerobic biodegradation (Dragun 1988; Chen and others 1992). Degradation of fuels is a primary mechanism of fuel contamination reduction. Several factors influence the rate at which a fuel constituent will degrade or be fixed due to mineralization. Some of these factors are compound related and others relate to soil or aquifer characteristics. In general, lower molecular weight compounds with simpler structures degrade more rapidly since they are more readily metabolized by microorganisms. Degradation of fuels largely occurs on individual constituents which are dissolved in water or are sorbed. Pure fuels (NAPLs) are not directly degradable since they are generally toxic to microorganisms and unreactive. Degradation of fuels largely occurs on individual constituents as they are dissolved in water or are sorbed.

Inorganic mineralization is probably the least important degradation process and is controlled largely by the availability of inorganic oxidizers such as iron^{3+}, manganese^{4+}, nitrate, and oxygen. Availability of these oxidizing components is poor in poor permeability soils and confined aquifers (both of which are common at NAS Moffett Field), which generally have reduced conditions. Moreover, once these oxidizers are consumed by reaction with fuel constituents, further mineralization can only occur where replenishment of the oxidizers is significant. It follows that mineralization will only be important in shallow soils and aquifer zones with high permeabilities and flow rates with at least some concentration of available oxidizers.

Anaerobic microbial degradation is the next important degradation process. This process occurs as a result of microbial (methanogenic bacteria) metabolism of complex compounds into simpler compounds, such as methane, under anoxic (oxygen-deficient) conditions. Anaerobic degradation half lives for some fuel constituents are presented in Appendix C, Table C-1. (A half life is the length of time required to reduce a compound to half of its initial concentration.) In general, anaerobic degradation is a slow process, and in the case of complex molecules such as PAHs, is largely unimportant. Values presented in Appendix C, Table C-1 are from studies at other sites and depend on several aquifer parameters including presence of microbes and nutrients, temperature, and constituent concentration.

Aerobic microbial degradation is perhaps the most important process of fuel degradation in soil and groundwater at most sites. In this process, microbes use available oxygen to metabolize fuel constituents, generating simpler-structure oxidized hydrocarbons and ultimately carbon dioxide and water. Aerobic degradation also depends on many of the same factors applicable to anaerobic degradation (microbe concentration, nutrient availability, and temperature), but primarily depends on oxygen availability. Aerobic degradation of fuels in low permeability soils and largely anoxic aquifers, such as at NAS Moffett Field, is limited by the low rate of oxygen replenishment. Since the flux of oxygen through different aquifer materials depends on the permeability of those materials, it is expected that aerobic degradation of fuel constituents in silt and clay materials will be several orders of magnitude slower than in sandy materials.

3.4 FATE AND TRANSPORT OF FUELS

Fuels can exist in the subsurface in four general states: (1) free NAPLs in soil or aquifer material, either mobile or fixed (residual); (2) sorbed to soil or aquifer material; (3) as vapor in soil; and (4) dissolved in water. The subsurface can generally be characterized by three distinct zones through which these states exist: (1) the unsaturated zone, (2) the capillary zone, and (3) the saturated zone. The following sections summarize the petroleum transport mechanisms in the unsaturated zone, the capillary zone, and the saturated zone, and summarize petroleum fate mechanisms.

3.4.1 Transport in the Unsaturated Zone

Fuel that has been released at the surface or near the surface in the unsaturated zone will begin to flow both vertically (due to gravity) and horizontally (due to capillary forces). The rate of migration depends on the density, viscosity, and surface tension of the fuel and the permeability of the soil. In less permeable formations, capillary forces will have a greater influence and migration may have a more significant horizontal component.

The vertical and horizontal extent that fuels penetrate the subsurface depends on the volatility of the fuel, the soil's retention capacity (residual saturation), and the volume of fuel released. A portion of the release will be transferred to the atmosphere through evaporation, depending on the fuel's volatility (most important for gasoline spills).

For the portion of fuel that does not evaporate, vertical and horizontal migration continue with a portion of fuel being trapped in available pore space in the soil. If the spill does not exceed the threshold of residual saturation (typically 10 to 30 percent of a soil's pore space), the release may be contained in the unsaturated zone. Fuel that remains in the unsaturated zone partitions among four phases: (1) pure phase retained in pore spaces by capillary forces, (2) vapor in the soil air, (3) dissolved fuel constituents in the soil pore water, and (4) solutes of fuel which are sorbed onto soil particles.

Estimating the amount of partitioning among the four phases is a complex task with many uncertainties. Several analytical models and computer codes are available to assist with these estimates. However, some of these tools are equally complex to use and interpret. Therefore, simplifying assumptions have been made and moderately conservative estimates used to model these processes at NAS Moffett Field. To simplify the estimates, only the processes contributing to the majority of the contaminant mobility and reduction have been estimated. A modified version of the Summer's Leaching Model (EPA 1989) was used to evaluate the fate and transport of fuels in the subsurface at NAS Moffett Field. This model includes:

- Sorption of chemicals to soil particles
- Groundwater and infiltration flow rates
- Surface area of contamination
- Aquifer thickness
- Degradation of chemicals over time

A more detailed description of the model, including results, appears in Appendix B.

Results of this model for fuel-contaminated sites at NAS Moffett Field indicate that, although there is potential for leached fuel constituents to migrate to groundwater, the bulk of the fuels will remain fixed or will degrade in the unsaturated soil zone. At Site 19 (Tank 53), the model indicates that observed concentrations of fuels are insufficient to significantly impact groundwater. In fact, no fuel-related groundwater contamination has been detected in groundwater samples from downgradient monitoring wells at this site. This lack of migration potential is due to the low permeability, low infiltration rates, and high sorption capacities of the site soils.

For larger releases, fuel which has not been trapped in soil pores will migrate until the capillary fringe zone of the aquifer is reached. In this zone, buoyancy of the fuel relative to water opposes further downward migration.

3.4.2 Transport in the Capillary Zone

The capillary fringe is the zone of water that is in direct contact with the water table and is held immediately above the water table by capillary forces acting against the force of gravity. When free product reaches the capillary zone, vertical migration is stopped. As more fuel descends, a layer of increasing thickness forms and a hydrostatic pressure is exerted, depressing the water table. Buoyant forces act to restore the original water level and lateral movement begins, causing the lens of free-phase fuel to spread out. The predominant direction of movement is with the slope of the water table. As the fuel spreads, portions are held by capillary forces and by sorption to soil particles. When no more free fuel is available, migration stops. Fuel at residual saturation in the capillary and unsaturated zones may be submerged following a rise in the water table. Capillary forces resist buoyant forces and, as a result, the fuel may remain trapped in the saturated zone and be subject to dissolution, sorption, and degradation.

3.4.3 Transport in Groundwater

The properties of solubility, density, surface tension, and viscosity determine the tendency of a fuel to occur as a NAPL, which may serve as a long-term source of groundwater contamination. However, the formation and persistence of fuel NAPLs is also controlled by the quantity of fuel released, how the fuel is introduced to the aquifer, the age of the release, and certain aquifer characteristics. Where there has been direct release to groundwater of a large quantity of fuel through leaking tanks, free NAPL will occur at or below the water table or along an upper confining surface where lateral migration will be controlled by aquifer permeability, groundwater flow, and buoyancy. In contrast, migration of fuel from a surface spill through soils may lead to introduction of only a small quantity of fuel to the capillary fringe zone where it will be fixed as residual saturation. Each of these scenarios will likely require remediation of the aquifer, but the former situation demands more immediate attention to minimize further migration and more widespread residual NAPL contamination. Residual NAPLs in low flow, anoxic aquifers tend to persist and become sources of long-term dissolved-phase TPH contamination. Remediation of residual NAPLs is difficult and may not allow attainment of stringent cleanup goals (Nyer and Skladany 1989; Borden and Kao 1992; EPA 1992b; Rao and others 1992; Cohen and Mercer 1993; Olsen and Kavanaugh 1993).

The ability of a fuel constituent to dissolve and be transported in groundwater is dependent on the compound's solubility, soil/water partitioning, and aquifer characteristics, such as flow rate, hydraulic conductivity, and composition. For example, Table C-1 in Appendix C shows that benzene has a relatively high solubility, low soil/water distribution coefficient and tends to be easily transported in solution. In contrast, straight chain alkanes such as n-hexane have lower solubilities, higher distribution coefficients, and are much less mobile in groundwater.

An analytical model was used to evaluate the migration of dissolved fuel constituents in groundwater at NAS Moffett Field. A more detailed discussion of the transport equation, the assumptions used for each model iteration, and results are presented in Appendix C. The model relies on a one-dimensional analytical advection/dispersion equation, but also includes retardation due to sorption, and degradation due solely to anaerobic decay. Only higher hydraulic conductivity cases (fine sand and silty sand with hydraulic conductivities of 0.01 and 0.001 feet per minute [ft/min]) were evaluated. Less permeable materials, such as silt and clay (with hydraulic conductivies of 0.0001 to 0.000001 ft/min) were not modeled since transport of most fuel constituents is negligible in these materials.

Figures C-1 to C-7 (Appendix C) illustrate the transport of some fuel constituents in groundwater under conditions similar to those in the shallow aquifer zone at NAS Moffett Field. The modeling shows that in permeable units (sand and silty sand), benzene is quite mobile relative to other fuel constituents but is readily diluted and degraded, thus limiting the distance it can travel in an aquifer (Figure C-1). In contrast, the alkanes and more complex PAH molecules are insoluble and immobile (Figures C-2, C-3, and C-4). Transport of these components is limited by sorption and degradation. The migration of all fuel constituents will be further limited in aquifer zones that have lower hydraulic conductivities and higher sorption capacities (Figure C-5). Contaminant mobility may be reduced by orders of magnitude as aquifer hydraulic conductivity is lowered by orders of magnitude.

Due to the distinct differences in the chemical properties of fuel constituents, the nature and extent of a groundwater plume will change with time. For example, a groundwater plume formed initially from a release of gasoline to groundwater through soil leaching may be quite extensive and characterized by high concentrations of the more mobile constituents, such as benzene and pentane. At some later time, as leaching, dilution, and degradation proceed, the groundwater plume from the same spill may be localized near the initial spill site and be comprised of heavier immobile constituents, such as n-octane and naphthalene. PAHs will likely be fixed in the soil profile above the water table and not be detected in groundwater samples.

4.0 CLEANUP LEVEL OPTIONS

A variety of cleanup goal options are potentially available for addressing petroleum contamination at NAS Moffett Field. These different cleanup goals will yield different remedial strategies. State and federal regulations and policies indicate that remediation or cleanup goals should be tailored to maintain beneficial uses. The Navy seeks cleanup goals that protect beneficial uses (thus, are protective of human health and the environment), are technically achievable, and are cost-effective.

This section discusses an array of cleanup level options for soils and groundwater, including guidance-based levels, human health risk-based levels, and environmental risk-based levels. This section also assembles protective cleanup level scenarios used for the cost-benefit analysis provided in Section 6.0. These scenarios are derived from the cleanup level options.

The UST regulations (California Code of Regulations, Chapter 16) and guidance (SWRCB 1989; RWQCB 1990) use the TPH analytical category as an indicator of required corrective action for releases from petroleum storage tanks. Therefore, the cleanup levels and scenarios developed in this report focus on groups of petroleum-related compounds that are quantified as purgeable and extractable TPH.

The cleanup goals will also serve as action levels for remediation. That is, if the in situ concentrations exceed the cleanup goal levels, remediation will be instituted; otherwise, no action will be the selected option. The cleanup level options discussed in this section are targeted at sorbed or dissolved-phase petroleum contamination. The Navy intends to remediate free or residual NAPLs in soil or groundwater, where practicable.

4.1 GUIDANCE-BASED CLEANUP LEVELS

Federal and state agencies have developed policies and guidance for protecting groundwater, including corrective measures for leaks or spills from petroleum UST sites. The primary authorities for petroleum remediation at NAS Moffett Field are the State Water Resources Control Board (SWRCB) and the RWQCB. This section summarizes the petroleum cleanup goals for soils and groundwater that have been derived from the groundwater protection policies and guidance.

4.1.1 Soils

Currently, there are no promulgated cleanup standards for petroleum-contaminated soils. However, RWQCB has established recommended petroleum cleanup goals for soils. These goals include:

- 10 mg/kg TPH purgeable as gasoline
- 50 mg/kg TPH extractable as diesel

The RWQCB has stated that these are the cleanup levels for soils unless it can be proven that alternative cleanup levels are protective of groundwater (RWQCB 1993). Although it is unclear where these levels originated, these values apparently either represent historical detection limits or are based on the toxicity of benzene and the leaching potential of fresh (undegraded) gasoline. In either case, these standards may not be representative of the degraded petroleum products at NAS Moffett Field because the degraded products differ in toxicity and mobility from fresh products. In general, degraded petroleum products are less toxic and less mobile than fresh products. However, to provide a complete evaluation, these guidance-based levels have been considered in the cost-benefit analysis.

4.1.2 Groundwater

Regulatory guidance, policies, and regulations include groundwater cleanup levels in the form of background levels, maximum contaminant levels (MCLs), and secondary MCLs. State groundwater protection policies indicate that a discharge to groundwater should be remediated to background conditions, when practicable, or to levels that maintain beneficial uses (SWRCB 1992). Background conditions would presumably be met if analytical practical quantitation reporting limits are reached. The quantitation reporting limits for the TPH analytical methods (SWRCB 1990) are:

- 50 μg/L for TPH purgeable as gasoline
- 50 μg/L for TPH extractable as diesel

MCLs are used for drinking water sources. There are no MCLs for TPH purgeable as gasoline or TPH extractable as diesel; however, there are secondary MCLs (5 μg/L and 100 μg/L, respectively). The secondary MCL for TPH purgeable as gasoline is below quantitation reporting limits; therefore, this level is a poor indicator of cleanup goals.

The quantitation reporting levels will be evaluated in the cost-benefit analysis. However, as this report will show, the Navy believes that attaining background conditions at NAS Moffett Field is not practicable and that current and probable future beneficial uses could be maintained using alternate concentration levels.

4.2 HUMAN HEALTH RISK-BASED CLEANUP LEVELS

A separate but parallel risk-based approach has been employed for fuel mixtures at NAS Moffett Field to make cleanup of petroleum mixtures consistent with other site-related chemicals and to promote protection of human health and the environment. The methodology used to derive human health risk-based concentrations (RBCs) for fuel mixtures is identical in all respects to that applied to other NAS Moffett Field chemicals of concern (COCs). (Section 4.3 discusses the environmental risk-based concentrations.) The consistent derivation and application of RBCs for all COCs will provide an overall remediation framework that will be comprehensive and make remedy selection comparable for all contaminants. This section summarizes the derivation of the RBCs. A detailed description appears in Appendix A.

Detailed guidance used to derive RBCs has been developed by EPA and is presented in Human Health Evaluation Manual, Part B: Development of Risk-based Preliminary Remediation Goals (RAGS-B; EPA 1991). This is a companion guidance document to Risk Assessment Guidance for Superfund, Human Health Manual, Volume I, Part A (RAGS-A; EPA 1989), which is also used in the RI/FS process to evaluate site-related human health risks. These documents present a comprehensive framework for developing RBCs based on current or potential risks for COCs that have EPA-derived or California EPA-derived toxicity values.

To calculate an RBC, an acceptable risk level that will promote protection of human health and the environment has been established. The National Oil and Hazardous Substances Pollution Contingency Plan (NCP) defines an acceptable carcinogenic risk in terms of a risk range of 1 x 10^{-6} to 1 x 10^{-4} excess lifetime cancer risk (ELCR) and a noncarcinogenic hazard index (HI) of 1.0. The 1 x 10^{-4} ELCR level has become EPA's de facto acceptable risk level, which can be used to derive chemical-specific RBCs for original petroleum mixtures or for indicator constituents in weathered fuel mixtures. In the analysis presented in this report, however, RBCs have been derived for the entire risk range of 1 x 10^{-6} to 1 x 10^{-4} and an HI of 1.0.

RBCs for undegraded petroleum mixtures have been developed by EPA and are applicable for recent spills or leaks (EPA 1992a). It is presumed that recent contamination contains the same fractional concentrations of all constituents that were present in the original fuel mixture. The RBCs for undegraded petroleum mixtures are conservative when applied to NAS Moffett Field degraded fuel contamination, since degraded fuel mixtures are generally less toxic than undegraded mixtures. Appendix A summarizes the RBCs for original mixtures for occupational and residential exposures. Although the residential scenario is unlikely to represent a future condition of NAS Moffett Field, it has been presented for comparison. These RBCs are calculated using inhalation CSFs and reference doses. These RBCs are applicable to soil and groundwater ingestion. A range of RBCs for acceptable risk levels of 1 x 10^{-6} to 1 x 10^{-4} ELCR has been calculated for gasoline, since it is the only fuel mixture that is considered by EPA to be carcinogenic. RBCs for noncarcinogens are based on an HI of 1.0.

4.2.1 Soils

The range of RBCs represent gasoline concentrations that are protective at 1 x 10^{-6} to 1 x 10^{-4} ELCR levels. The RBC ranges for carcinogenic effects of gasoline in soils are:

- 400 to 40,000 mg/kg for residential exposures
- 3,367 to 336,700 mg/kg for occupational exposures

The RBCs for noncarcinogenic effects for gasoline in soils are:

- 50,000 mg/kg for residential exposures
- 408,800 mg/kg for occupational exposures

The RBCs for noncarcinogenic effects of JP5/diesel fuel in soils are:

- 700 mg/kg for residential exposures
- 40,880 mg/kg for occupational exposures

4.2.2 Groundwater

The range of RBCs represent gasoline concentrations that are protective at 1 x 10^{-6} to 1 x 10^{-4} ELCR levels. The RBC ranges for carcinogenic effects of gasoline in groundwater are:

- 50 to 5,000 μg/L for residential exposures
- 3.4 x 10^{6} to 3.4 x 10^{8} μg/L for occupational exposures

The RBCs for noncarcinogenic effects of gasoline in groundwater are:

- 7,000 μg/L for residential exposures
- 4.1 x 10^{8} μg/L for occupational exposures

The RBCs for noncarcinogenic effects of JP5/diesel fuel in groundwater are:

- 700 μg/L for residential exposures
- 4.1 x 10^{7} μg/L for occupational exposures

4.3 ENVIRONMENTAL RISK-BASED CLEANUP LEVELS

The environmental risk-based cleanup levels correspond to levels that are protective of the environment. The site-wide ecological assessment indicates that petroleum-related compounds in soils or groundwater are not currently affecting ecological receptors (PRC 1994c). However, the regulatory agencies are concerned that fuel-related contamination left in place could migrate to sensitive wetland habitats in the future. Therefore, the Navy has evaluated the fate and transport of fuel constituents to derive environmental risk-based levels.

The following sections summarize fate and transport modeling and resulting environmental risk-based cleanup levels for soil and groundwater. Appendices B and C contain specific information regarding this methodology.

4.3.1 Soils

Concentrations of petroleum-related constituents in groundwater as a result of leaching and degradation in soil are estimated using the Summer's Leaching Model (EPA 1989) modified to include degradation. The model assumes that precipitation at the site will infiltrate through the subsurface and desorb contaminants from the soil based on equilibrium soil/water partitioning. The model also assumes that this contaminated infiltration will mix completely with the groundwater below the site, resulting in an equilibrium groundwater concentration.

The Summer's model was developed to estimate the point at which contaminant concentrations in the soil will produce groundwater contaminant concentrations at or below target levels. The resultant soil concentrations can then be used as guidelines for estimating the extent of soil contamination above an action level and for specifying soil cleanup goals. Two groundwater target levels are used to establish potential acceptable soil concentrations: (1) concentrations of fuel contamination that could remain in the groundwater and not migrate to the sensitive environments (see Section 4.3.2); and (2) the MCLs for specific constituents that compose fuel (see Appendix B).

Appendix B contains results of applying the modified Summer's model at Sites 5, 9, and 19. These results indicate that petroleum concentrations in soils of 1,000 mg/kg TPH purgeable as gasoline and 5,000 mg/kg TPH extractable as diesel or JP5 will be protective of the groundwater environmental risk-based levels (35 mg/L TPH purgeable as gasoline and 500 mg/L TPH extractable as diesel or JP5 [see Section 4.3.2]). That is, soils at these levels would not generate a leachate that would impact the sensitive environments. Model results indicate petroleum concentrations in soils of 150 mg/kg TPH purgeable as gasoline and 400 mg/kg TPH extractable as diesel or JP5 will not leach from soils above constituent-specific MCLs.

The modified Summer's model was also recalculated to use existing soil concentrations to estimate the concentrations in downgradient monitoring wells for each site (Appendix B). This was conducted by solving the modified Summer's equation for C_{gw} (acceptable groundwater concentration) rather than for C_s (acceptable soil concentration). Existing soil concentrations were used or estimated from measured TPH values and the resulting groundwater concentrations were evaluated. Comparing the model to actual downgradient concentrations measured at NAS Moffett Field (PRC 1993) indicates the model predicts much higher TPH concentrations than are actually present. This result indicates that the modified Summer's model is overly conservative in estimating groundwater impacts. Appendix B contains results of applying the modified Summer's model at Sites 5, 9, and 19.

4.3.2 Groundwater

A one-dimensional analytical advection/dispersion model was used to evaluate transport of fuel constituents in the shallow aquifer zones at NAS Moffett Field. This evaluation determined what concentrations of fuel contamination could remain in groundwater at Sites 5 and 9 to be protective of sensitive ecological habitats in the wetland areas along the northern portion of the station. The resultant concentrations can then be used as guidelines for estimating the extent of groundwater contamination above action levels and for specifying groundwater cleanup goals. The flow model assumes that the aquifer is homogeneous and isotropic (constant porosity and hydraulic conductivity) and has a constant hydraulic gradient. Hydraulic conductivity was varied between 0.01 and 0.001 feet per minute (ft/min) in different iterations to reflect fine sand and silty sand conditions. This is considered a conservative assumption since most of the shallow aquifer at NAS Moffett Field consists of silt and clay. Retardation (due to sorption) of the modeled fuel constituents was based on their soil/water partitioning coefficients and the organic carbon content (f_{oc}) of the aquifer materials at NAS Moffett Field (f_{oc} = 0.022 [fine sand] and 0.044 [silty sand]). The initial concentration used in the model represents the dissolved concentration of the constituent at the leading edge of the plume. The final (endpoint) concentration used in the model is the dissolved concentration of a constituent at the analytical detection limit at a distance equal to or less than the distance from the leading edge of the plume to the wetland areas. (The wetland areas were defined in the ecological assessment [PRC 1994c].) Degradation of the dissolved plume was modeled to follow a first-order decay rate. The degradation rate used in the model is highly conservative, since only anaerobic degradation was considered and the maximum half life available in the literature was used. A more detailed explanation of the model equation and the parameters used appears in Appendix C.

The results of the analytical groundwater model for Sites 5 and 9 indicate that significant quantities of fuel-related compounds in groundwater at these sites will not persist and be transported to ecologically sensitive areas (Figures C-1 to C-4). For gasoline at Site 9, the most mobile constituent, benzene, was modeled. Initial concentrations of 35 mg/L TPH purgeable as gasoline (modeled as all benzene) at the leading edge of the plume will attenuate through dilution and degradation to levels below 1

μg/L before reaching the wetlands 2,900 feet downgradient (Figure C-1). A maximum concentration of 0.5 μg/L at the wetlands will occur at 18 years in the future and decline thereafter. Modeling of the less mobile constituent, n-hexane, at an initial concentration of 500 mg/L TPH purgeable as gasoline, indicated that attenuation would occur to levels below 5 μg/L within less than 500 feet of the leading edge of the plume at approximately 21 years in the future. For the jet fuel contamination at Site 5, the constituents n-hexane and naphthalene were modeled (Figures C-2 and C-4). Although the low molecular weight alkane, n-hexane, is not present in jet fuel, its chemical mobility properties were considered in the modeling to be conservative. The results indicate that attenuation of initial concentrations of 500 mg/L TPH extractable as diesel or JP5 (modeled as all n-hexane or naphthalene) will occur to levels below 5 μg/L within a distance of 250 feet ($T_{maximum}$ = 8 years) for naphthalene and a distance of 500 feet ($T_{maximum}$ = 21 years) for n-hexane.

4.4 CLEANUP LEVEL SCENARIOS

The cleanup options described above have been evaluated to develop potential cleanup level scenarios for NAS Moffett Field. These scenarios were selected based on reaching the minimum standard of being protective of human health and the environment. The following sections describe the cleanup level scenarios for soil and groundwater, respectively. The cleanup level scenarios are composed of cleanup levels for TPH purgeable and TPH extractable. The scenarios presented herein are not exhaustive; that is, other possibilities exist. However, the scenarios presented below represent a low-, mid-, and high-level scenario. These scenarios will be compared further in the cost-benefit analysis in Section 6.0.

4.4.1 Soils

The low-range soil cleanup level scenario is remediating to state-recommended levels of TPH purgeable as gasoline equal to 10 mg/kg and TPH extractable as diesel or JP5 equal to 50 mg/kg (hereafter soil scenario A). The state has indicated that these levels can be altered if alternative cleanup levels can be shown to be protective of groundwater.

The mid-range cleanup level scenario for the soils at NAS Moffett Field is remediating soils to meet TPH purgeable as gasoline equal to 150 mg/kg and TPH extractable as diesel or JP5 to 400 mg/kg (hereafter soil scenario B). These levels in soil would result in a leachate with concentrations below MCLs (see Section 4.3). In addition, these soil levels are more stringent than the human health protective levels for both an occupational and residential exposure scenario (see Section 4.2).

The high-range cleanup level scenario evaluated in the cost-benefit analysis is remediating TPH purgeable as gasoline to 1,000 mg/kg and TPH extractable as diesel or JP5 to 5,000 mg/kg (hereafter soil scenario C). These soil concentrations do not exceed the human health limits for direct occupational and residential exposure to soils (see Section 4.2). In addition, soils at these concentrations will not leach into the groundwater waters at levels that will impact sensitive environments or exceed groundwater occupational human health limits (see Sections 4.2 and 4.3). The leachate generated from these soils does meet the groundwater human health risk levels based on residential exposure for TPH extractable as diesel; however, it does not meet the residential risk limit for TPH purgeable as gasoline.

4.4.2 Groundwater

The low-range cleanup level scenario for the A aquifer at NAS Moffett Field is remediating the groundwater to quantitation reporting limits of 50 μg/L TPH purgeable as gasoline and 50 μg/L TPH extractable as diesel or JP5 (hereafter groundwater scenario A).

The mid-range cleanup level scenario is remediating to levels of 50 μg/L TPH purgeable as gasoline and 700 μg/L TPH extractable as diesel or JP5 (hereafter groundwater scenario B). These levels were derived by selecting levels that are protective of residential exposure to groundwater and sensitive environments. These levels are below the residential human health risk limit and also will not affect the sensitive environments (see Sections 4.2 and 4.3).

The high-range cleanup level scenario is remediating to concentrations of 35 mg/L TPH purgeable as gasoline and 500 mg/L TPH extractable as diesel or JP5 (hereafter groundwater scenario C). These are the levels in groundwater at the leading edge of current plumes that would be below detection limits when the groundwater reached the wetlands (see Section 4.3). Therefore, these levels are protective of sensitive environments and they protect current and probable future beneficial uses. In addition, these levels are more stringent than the human health protective levels for occupational exposure (see Section 4.2).

5.0 REMEDIAL TECHNOLOGY OPTIONS

This cost-benefit analysis evaluates the costs associated with implementing a remedial technology that will reduce the petroleum contamination to the various cleanup level scenarios. These costs depend on the specific technology selected for each site, which in turn depends on the chemical characteristics, site conditions, and volumes of contaminated media. The draft corrective action plan (CAP) (PRC 1993c) provides a preliminary list of potential remedial technologies.

For the purposes of this cost-benefit analysis, however, the remedial technologies that can be readily employed have been summarized, and one technology each for soil and groundwater has been selected that appears most likely or reasonable to use. The selection minimizes the number of technologies and thereby keeps the subsequent cost-benefit analysis manageable. The technologies presented herein were identified based on their flexibility relative to site conditions and applications at other petroleum-contaminated sites. The discussion that follows is not meant to provide a feasibility study level of analysis (this type of analysis will be conducted in the final CAP). Rather, it summarizes the technologies, including potential limitations. Even though a single technology is selected each for soil and groundwater, the final remedy implemented at NAS Moffett Field will likely result in the same order-of-magnitude costs with respect to various cleanup levels.

5.1 POTENTIAL SOIL REMEDIAL TECHNOLOGIES

This section describes potential remedial technologies for remediating petroleum mixtures in soils. Included are excavation and ex situ bioremediation, bioventing, and soil venting.

5.1.1 Excavation and Ex-situ Bioremediation

Excavation involves the physical removal of contaminated soils, a common technology that is employed as part of corrective actions. Excavation of contaminated soils is a feasible and effective means of removing the source of contamination when the contaminants are limited to shallow depths in undeveloped areas. Conventional excavation methods are adequate for these conditions. The implementability of excavation depends on site-specific characteristics. Complications may arise at locations where underground utilities or storage facilities exist. Excavation around or near buildings may also add complications, such as the need for underpinning or sheet piling to stabilize the structure and rerouting of utility lines.

Following excavation, soils will be treated to reduce the TPH levels in the soil. Petroleum contamination is often remediated using bioremediation technologies. Stimulation of microbial growth and activity for TPH removal is accomplished primarily through the addition of oxygen and nutrients.

Ex situ bioremediation involves handling excavated soil on a bioremediation cell (one has been constructed at NAS Moffett Field as part of the Site 12 source control measure activities) and adding nutrients and oxygen to the contaminated soils to promote optimal microbial growth conditions. Ex situ treatment processes can often effectively treat excavated soils to protective cleanup levels. Lower cleanup levels typically require longer soil handling times in the bioremediation cell.

The major limitations of this technology are associated with the ability to excavate the soils, the need to excavate clean overlying soils, and the ability of the microorganisms to biodegrade the contaminants. The costs for this technology are moderate to high.

5.1.2 Bioventing

Bioventing is the process of supplying air or oxygen to the subsurface, where indigenous organisms are stimulated to aerobically metabolize fuel constituents. Air can be injected through boreholes screened in the unsaturated zone, or air can be extracted from boreholes, pulling air from the surface into a contaminated area. The major considerations for bioventing systems are whether the contaminants are amenable to biodegradation, bio-inhibitors are present at the site, and oxygen can be effectively transported within the soil to encourage microbial activity. The contamination at NAS Moffett Field is appropriate for this technology. Generally, migration of contaminants through the soil occurs in the more permeable channels underlying the sites. These channels would also transport oxygen to the microorganisms and, thus, this technology can be effective. In addition, recent studies have indicated that oxygen will transfer to a limited extent from the permeable zones into adjacent less permeable zones.

No excavation will be required and, therefore, no building or underground utility disturbances will be necessary for implementation of this option. This is particularly important for sites with buildings and underground utility lines. The costs are low to moderate for this option.

5.1.3 Soil Vapor Extraction

Soil vapor extraction (SVE) is an in situ soil venting process that promotes the mass transfer of volatile compounds from the soil or liquid media to the more mobile vapor phase. It uses vapor extraction wells and a vacuum pump to exert a pressure difference and induce volatilization of contaminants. Clean air may be injected into the contaminated soil through injection wells to enhance the vacuum extraction system. SVE systems are designed to yield a maximum recovery rate of volatile compounds from contaminated soil. SVE is effective for in situ treatment of low molecular weight fuels and solvents in contaminated soils. SVE has not generally been applied to heavier fuels because the larger fraction of high boiling point, high molecular weight constituents are not volatile. However, vendors indicate that SVE is appropriate for this type of contamination also.

Conventional SVE systems are operated at much higher flow rates and with configurations different than those of bioventing systems. In general, SVE systems can remediate low molecular weight distillates at a faster rate than bioventing systems.

As with bioventing systems, no excavation will be required and, therefore, no building or underground utility disturbances would be necessary for implementation of this option. This is particularly important for sites with buildings and underground utility lines. The costs associated with this technology are moderate.

5.2 POTENTIAL GROUNDWATER REMEDIAL TECHNOLOGIES

This section describes potential remedial technologies for remediating petroleum mixtures in groundwater. Included are pump and treat options, in situ bioremediation, and natural attenuation.

5.2.1 Pump and Treat

Groundwater extraction and treatment (pump and treat) systems address localized groundwater contamination. This alternative is the most common technology historically employed for site remediations. Pump and treat systems have been implemented for Sites 9 and 14 at NAS Moffett Field. A variety of treatment alternatives are possible for groundwater remediation, such as air stripping and carbon adsorption. This technology is typically effective for containing further migration of plumes. The major limitation of this technology is that the capillary zone and aquifer material will provide a continual source of contamination so that low cleanup levels are difficult to reach and, indeed, may not be technically achievable. The costs for this technology are moderate to high.

5.2.2 In Situ Bioremediation

Petroleum contamination is often remediated using bioremediation technologies. In situ bioremediation involves stimulating microorganisms to enhance microbial growth. Microorganisms use organic constituents in water and soil as a food source and ultimately oxidize the organic compounds to carbon dioxide and water. Nutrients and oxygen are critical to maintaining microbial activity. In situ bioremediation typically involves some type of oxygen and nutrient transport mechanism to maintain optimal microbial levels in the aquifer. This transport can be accomplished by circulating water-based solutions or air streams through the aquifer. A common in situ technology where air is bubbled into the aquifer is referred to as air sparging.

The major limitations of this technology are that the degradation will only occur in the zones of oxygen transfer and only on contaminants that are amenable to aerobic biodegradation. In addition, as with any technology that involves injection into a contaminated aquifer, the potential for dispersion of the contaminated plume must be addressed. In situ bioremediation technologies typically take longer than pump and treat systems to achieve similar levels. These technologies typically cannot achieve low cleanup goals because oxygen transfer will be limited in low permeability zones. If these zones are contaminated, they will act as continual contaminant sources. The costs for this technology are low to moderate.

5.2.3 Natural Attenuation

Natural attenuation processes and transport mechanisms are another option for achieving cleanup goals within a certain time frame. The preamble to the revised NCP (EPA 1990) states that:

> "Selection of natural attenuation does not mean that the groundwater has been written off and not cleaned up, but rather that biodegradation, dispersion, dilution, and adsorption will reduce contaminants."

The preamble also indicates that natural attenuation can be a viable remedial option for groundwater that is unlikely to be used in the foreseeable future and, therefore, can be remediated over an extended period of time (EPA 1990).

The groundwater on the western side of NAS Moffett Field has been contaminated by a regional plume. The design for remediation of the regional plume indicates that cleanup goals will be achieved in no less than 47 years. Therefore, it is possible that a relying on natural attenuation will achieve moderate cleanup goals. This alternative may include continued monitoring and some institutional controls (for example, restricting installation of water supply wells at NAS Moffett Field). This technology would have the lowest associated costs.

5.3 PROPOSED SUITABLE TECHNOLOGY

This section discusses the remedial technologies for soil and groundwater that are suitable and which are presented in the cost-benefit analysis. The costs to implement the proposed suitable technology is given for each cleanup level scenario (see Section 4.4).

5.3.1 Soils

SVE was selected as the soil remedial technology for integration in the cost-benefit analysis. This technology was selected since it represents middle range costs (between excavation and bioventing) and would be most representative of overall performance and cost. It is also the EPA presumptive remedy for soil contaminated with VOCs. In addition, the majority of the petroleum contamination at NAS Moffett Field is located in developed areas and below several feet of clean soil; therefore, an in situ treatment process is most reasonable.

The cost of remediation is based on the extent of contamination and the amount of soil to be treated. Data from the petroleum characterization report (PRC 1994a) were used to approximate the volume requiring remediation. The volume estimates are approximate since the areal extent of contamination was not well defined by the data in the characterization report. The Navy has recently completed additional sampling at several petroleum sites. These data should be available by April 1994 and will be used to adjust these volume estimates.

The approximate volume of contaminated soil and remediation costs for each of the cleanup level scenarios are listed in the following table:

Scenario	Cleanup Level (mg/kg)		Volume of Soil (cubic yards)	Cost to Remediate
	TPH Gas	TPH Diesel		
A	10	50	84,000	$17,900,000
B	150	400	47,000	$8,300,000
C	1,000	5,000	6,000	$1,040,000

5.3.2 Groundwater

The groundwater remedial technology selected for integration in the cost-benefit analysis is pump and treat for cleanup scenarios A and B. This technology was selected because it would provide the largest reduction in contaminant mass in the shortest time frame. Additionally, the regulatory agencies have indicated a preference for a technology that can minimize contaminant migration.

Cleanup levels described in scenario C are currently not exceeded at the site. Therefore, natural attenuation with groundwater monitoring is the technology that is used for this scenario in the cost-benefit analysis.

The costs to remediate the contaminated groundwater using a pump and treat system is primarily a function of the time period for which the treatment technology must be implemented to achieve cleanup goals. Due to the nature of the petroleum contamination and the presence of silty clay and clay material throughout the areas of contamination, it is questionable if the technologies can remediate groundwater to the more stringent cleanup level scenarios (see Sections 3.3 and 3.4, and Appendix C for details). However, remediation periods for a pump and treat system were predicted for cleanup scenarios A and B, assuming that all TPH gasoline constituents behave the same as benzene and all TPH extractable as diesel or JP5 constituents behave the same as n-hexane. The associated time frames derived from these assumptions are optimistic (that is, shorter than actual time frames) since most gasoline and diesel constituents will not desorb from soil and migrate as rapidly as n-hexane or benzene.

For scenario C, it was assumed that the groundwater will have to be monitored until the lowest cleanup standards were achieved through natural attenuation (see Section 3.3.2 and Appendix C for details). The costs for scenario C can be significantly reduced if the groundwater does not have to be monitored until the low-range cleanup goals are reached.

The approximate time to reach each cleanup scenario goals and associated costs for remediation are listed in the following table:

Scenario	Cleanup Levels (μg/L)		Implementation Time (years)	Cost to Remediate
	TPH Gas	TPH Diesel		
A	50	50	18	$9,200,000
B	50	700	9	$1,600,000
C	35,000	500,000	20	$1,200,000

6.0 COST-BENEFIT ANALYSIS

This section details cost-benefit analyses for different remedial strategies that address petroleum contamination at NAS Moffett Field. Each of the cleanup level scenarios meets minimum human health and environmental protection standards. The minimum standard is based on occupational human health exposure scenarios and protection of sensitive environments. Site-specific information has been compiled to identify community-specific benefits associated with remediating contaminated media to different cleanup levels. Corresponding remediation cost estimates, developed in Section 5.0, were also used. A comprehensive comparison of the benefits and costs associated with different cleanup scenarios is presented to provide a basis for subsequent risk management decisions. The information is integrated into the risk management decision process to yield appropriate cleanup goals for petroleum-contaminated media at NAS Moffett Field.

This section presents the methodology of the analysis in Section 6.1. Section 6.2 discusses cleanup costs and Section 6.3 discusses background information on future land use. Section 6.4 discusses those land and water uses that may potentially be impacted by the cleanup and Section 6.5 compares the costs and benefits for each cleanup level scenario.

6.1 METHODOLOGY

This section outlines the methodology used to analyze costs relative to benefits for each proposed cleanup scenario. First, Section 6.1.1 presents a step-by-step outline of the approach to the analysis. Second, Section 6.1.2 presents the assumptions made for purposes of the initial analysis.

6.1.1 Approach

The cost-benefit analysis includes the following steps:

(1) A baseline profile of the site is developed that considers those areas potentially affected by a change in groundwater quality or soil concentrations. These are termed "impacted areas." Areas not influenced by groundwater quality or soil concentrations are excluded from the analysis, and all other events, aside from the cleanup scenarios, are held constant, since they occur independently of the proposed remediation activity. Plant and animal habitat is one example of an impact area.

(2) The cost-benefit model examines the six cleanup level scenarios discussed in Section 4.4 of this report, three each for groundwater and soil. For those impact areas that are influenced by groundwater quality or soil concentrations, the cost-benefit model estimates the variance or change (increase or decrease) in that impact area from the baseline under each of the different cleanup level scenarios. For example, an evaluation is made of how the potential for residential water use would vary from the baseline if groundwater cleanup scenario A was implemented.

(3) A monetary value is assigned to each variance from the baseline that was projected to occur under each scenario. This is estimated as either a positive value (representing improved conditions) or a negative value (representing deteriorating conditions). For example, the economic value (if any) of restoring the potential for recreational use to a particular area of land is assessed. Some impact areas did not vary from the baseline.

(4) Probability coefficients are assigned to potential groundwater and land uses to reflect their likelihood of occurring in the future.

(5) Monetary values for projected variances are multiplied by the appropriate probability coefficient to arrive at an adjusted dollar amount that realistically reflects the economic value of improving or deteriorating site conditions from the baseline. In this way, if a potential future use is very unlikely, the monetary value in restoring this potentiality is diminished.

Five categories of potential groundwater and land use were examined: agricultural, municipal, industrial and commercial, recreational, and residential. These categories are mutually exclusive and the sum of their probabilities to occur in the future totals 1.00. In addition, groundwater recharge and plant and animal habitat were examined because they are areas potentially impacted by remediation implementation.

(6) The costs for each cleanup level scenario is compared with the monetary value (after probability adjustment) of expected variances from the baseline that would accompany the scenario to arrive at a net value for each scenario. A positive value represents a net gain to the community and a negative value represents a net loss to the community.

(7) If desired, sensitivity analyses can be conducted to analyze the impact of varying the assumptions and estimates that were used for the initial analysis.

6.1.2 Assumptions

The following assumptions are used for the initial cost-benefit analysis:

- The groundwater cleanup scenarios address only to the TPH-contaminated A aquifer at NAS Moffett Field. The following three groundwater remediation scenarios are considered:

  Scenario A: TPH purgeable as gasoline = 50 µg/L
  TPH extractable as extractable diesel or JP5 = 50 µg/L

  Scenario B: TPH purgeable as gasoline = 50 µg/L
  TPH extractable as diesel or JP5 = 700 µg/L

  Scenario C: TPH purgeable as gasoline = 35 mg/L
  TPH extractable as diesel or JP5 = 500 mg/L

- The soil cleanup level scenarios address only to the petroleum sites at NAS Moffett Field (approximately 8 acres). The following three soil remediation scenarios are examined:

  Scenario A: TPH purgeable as gasoline = 10 mg/kg
  TPH extractable as diesel or JP5 = 50 mg/kg

  Scenario B: TPH purgeable as gasoline = 150 mg/kg
  TPH extractable as diesel or JP5 = 400 mg/kg

  Scenario C: TPH purgeable as gasoline = 1,000 mg/kg
  TPH extractable as diesel or JP5 = 5,000 mg/kg

- Remediation technologies used for attainment of the proposed cleanup scenarios, and the costs associated with these technologies, are for pump and treat groundwater systems and SVE for soil remediation (see Section 5.0 for a more detailed discussion).
- Use of the land by federal agencies, such as the Navy and NASA, is classified as industrial and commercial for purposes of this analysis.
- Cleanup of these areas is considered independent of other cleanup initiatives in the NAS Moffett Field area. In this way, the singular impact of relevant cleanups can be examined.
- Monetary value of costs and benefits that occur in future years are discounted to calculate an appropriate present value. This is because the value of a dollar in the future is worth less than a dollar today. The annual discount rate used to deflate the future amounts is 4 percent to account for expected investment earnings above the inflation rate.
- A 20-year time horizon is used. This is the time that it would take to complete the longest term cleanup scenario under consideration. Any costs or benefits that extend beyond the 20-year time horizon are given a terminal value in year 20 to reflect all future years.

6.2 DETERMINATION OF COSTS

Because cleanup activities will be funded by the Navy, it is the federal government, or federal taxpayer, that will incur the costs. Expenditures are concentrated in the first year of the remediation program when major construction activities are completed. Expenditures in subsequent years are for operation and maintenance of the cleanup technology. The following comparison summarizes the present value cost figures for each groundwater and soil cleanup scenario examined in this analysis.

Scenario	Total
Groundwater:	
Scenario A:	$ 9,200,000
Scenario B:	$ 1,600,000
Scenario C:	$ 1,200,000
Soil:	
Scenario A:	$17,900,000
Scenario B:	$ 8,300,000
Scenario C:	$ 1,000,000

6.3 LAND AND AQUIFER USE BACKGROUND INFORMATION

This section provides background information on land and aquifer uses at NAS Moffett Field. This information defines current baseline conditions and supports future use estimates for the impact areas, which are individually addressed in Section 6.4.

6.3.1 Land Use

In April 1991, the U.S. Department of Defense (DOD) Base Closure and Realignment Commission (BCRC) voted to decommission NAS Moffett Field, to transfer its naval operations to other Navy facilities, and to transfer the majority of NAS Moffett Field property to NASA. In December 1992, a memorandum of understanding (MOU) between the Navy and NASA was signed (Navy and NASA 1992). The MOU documented the major points of agreement regarding transfer of the majority of NAS Moffett Field property to NASA jurisdiction. Additional, smaller land management responsibilities, including housing areas, were transferred to the DOD, with the Department of the Air Force acting as the DOD housing agency. The MOU documented the joint goals of the Navy and NASA: (1) to achieve a no-cost transfer of all land, buildings, facilities, infrastructure, and other property associated with NAS Moffett Field (excluding base family housing and related community support facilities); and (2) to identify NASA as the new federal host agency to all other users.

The stated future mission of NASA Ames Research Center is to conduct research and develop new aerospace technology to support space exploration efforts and improve the safety and performance of aircraft (NASA 1993b). NASA Ames Research Center provides a valuable resource to the Silicon Valley/Santa Clara County region. It supports vital research and development programs that are carried out by both federal staff and numerous civilian contractors and consulting companies. In doing so, NASA Ames Research Center acts as a major economic catalyst to the area. As of April 1990, the facility had a total value in excess of $873 million and an estimated replacement value of over $2 billion (NASA 1993a).

Historically, NAS Moffett Field has been the location of several tenant organizations known as Resident Agencies (RAs). RAs, such as state and federal military reserve units, have used facilities at the airfield. Each RA has assumed financial responsibility for their exclusively occupied facilities as well as assuming equitable financial agreements for shared airfield assets. To defray the costs of airfield operation, and to maintain the valuable mission of these RAs, NASA will continue the RA program following the Navy's departure. RAs that are current tenants and will continue to be so under NASA jurisdiction are the Naval Reserve, the California Air National Guard, and Onizuka Air

Force Base. Additional RAs that have recently expanded their presence at the airfield are the Marine Reserve and the Army Reserve. NAS Moffett Field also provides secure runways for the transportation of missiles, satellites, and other weapons systems for businesses in Silicon Valley (Commission on State Finance 1992).

NASA has indicated its desire to maintain a strong presence at NAS Moffett Field and is presently developing a comprehensive use plan for the base. This NASA use plan represents an effort to establish baseline (existing) conditions and near-term (1995) and long-range (20-year forecast) plans for additional land uses at NAS Moffett Field (NASA 1993b). The document will include a discussion of current land uses. The document will also evaluate comprehensive land-use alternatives designed to accommodate a host of growth opportunities. These alternatives will be designed to encourage the most facility-, community-, and economy-supportive land uses at NAS Moffett Field.

To project future land use, trends in the areas of construction activity, employment, and population were evaluated. Data indicate that both Mountain View and Sunnyvale have experienced a slowdown in new construction starts for residential units (U.S. Bureau of the Census 1980, 1990). This slowdown is probably a result of the recent economic recession and indicates that pressure for residential growth in the area is limited.

Strengths and weaknesses in a municipality's employment base are important factors in a comprehensive land-use analysis. The region's unemployment rates generally rank favorably with the state averages. Recent data show that defense cutbacks have caused a loss of approximately 10,000 jobs in the aerospace industry in Santa Clara County (U.S. Bureau of the Census 1980, 1990). Coupled with the expected loss of approximately 3,300 military and 630 civilian jobs due to the closure of NAS Moffett Field, the defense cutbacks will result in further decreased employment opportunities in the NAS Moffett Field vicinity. If NAS Moffett Field is transferred from federal government control, thousands of private industry jobs that depend on the availability of a secure runway could be jeopardized (Commission on State Finance 1992).

The Commission on State Finance anticipates that the state will lose as many as 90,000 more aerospace jobs and 35,000 civilian defense jobs by 1997. It is not clear how many of these jobs will be from the Mountain View and Sunnyvale areas. However, the loss of jobs throughout the state and additional base closures in the San Francisco Bay area may result in a potential decline in population in the Mountain View and Sunnyvale areas because equivalent jobs may not be found within the region.

Population trends are another essential component of any demographic and economic study. Using growth in 1980 as a baseline, projections show that both Mountain View and Sunnyvale will sustain slower growth over the next 20 years as compared to Santa Clara County and the San Francisco Bay area (U.S. Bureau of the Census 1992). This slow growth could indicate a lower economic growth in the immediate areas of both Mountain View and Sunnyvale. It is important to note that these projections do not include the impacts due to the closure of NAS Moffett Field and the additional job losses predicted by the Commission on State Finance. In short, slower growth in the area indicates less demand for residential development whether or not NAS Moffett Field reverts from government control.

For the near future, NAS Moffett Field will be used by NASA and governmental RAs. NASA's unique Ames Research Center research facilities, continued budget growth, and commitment to the community indicate that NASA plans to maintain control of NAS Moffett Field. Based on the attributes of NAS Moffett Field as a federally controlled airfield in the Silicon Valley, it is highly unlikely that the federal government will relinquish control of the base in the foreseeable future. In the unlikely event that NAS Moffett Field was returned to the jurisdictional control of the cities of Mountain View and Sunnyvale, the two cities would determine land usage. Zoning, demographic, employment, and economic forecasts for the Mountain View and Sunnyvale areas as predicted by the U.S. Bureau of the Census, the California Commission on State Finance, Association of Bay Area Governments (ABAG), and general plans of the cities indicate that commercial land use is the most likely option for the NAS Moffett Field area. Unemployment rates are likely to rise and population growth to slow based on predicted job losses in the area due to defense budget cutbacks. These factors indicate that if the federal government does relinquish control of NAS Moffett Field, the local communities would not use the area for residential buildup.

6.3.2 Aquifer Use

Potential beneficial uses applicable to main groundwater basins in the San Francisco Bay region are outlined in the San Francisco Bay Region Water Quality Control Plan (basin plan) and include municipal supply, industrial service, industrial process water supply, and agricultural supply (RWQCB 1991). However, potential uses for the A aquifer zones are limited due to various physical, environmental, health, and economic factors.

The City of Sunnyvale receives water from three distinct sources: municipal wells, the Santa Clara Valley Water District (SCVWD), and the City of San Francisco Water Department's (SFWD) Hetch-Hetchy aqueduct system. In 1991, the percentage of Sunnyvale's water supply coming from each of the three sources was as follows: (1) municipal wells screened in the C aquifer 8 percent, (2) SFWD 36 percent, and (3) SCVWD 56 percent (Sunnyvale 1993). The City of Mountain View owns and operates a drinking water utility; however, as in the case of Sunnyvale, much of the supply comes from outside sources. As of 1992, approximately 76 percent of the total 15.7 million gallons per day (MGD) Mountain View water supply was furnished by the SFWD Hetch-Hetchy system. Approximately 16 percent of the supply came from municipal wells screened in the C aquifer, with the remaining 8 percent provided by the SCVWD (Mountain View 1992).

In addition, both Mountain View and Sunnyvale report surplus water supplies. It is unlikely that groundwater use will be necessary in the future because of this surplus and the restrictions placed on wells drilled in the confined portions of aquifers underlying the NAS Moffett Field area.

In addition to municipal water supplies, private residential and commercial wells are permitted in both cities. Private wells are subject to regulation by the SCVWD, the County Land Development Committee, and the County Health Department. Within the confined aquifers of the Santa Clara Valley Basin, which includes NAS Moffett Field and the two cities, "all municipal wells...take water from the lower aquifers [because] groundwater in the upper zone has been noted to be of variable quality" (SCVWD 1989). Water in the A1-, A2-, B2-, and B3-aquifer zones (upper zones) is not currently used for any domestic or industrial purposes at NAS Moffett Field (IT 1993). Wells installed in the upper aquifer zones are for groundwater monitoring only.

The upper aquifers are generally not considered suitable as sources of drinking water due to high natural total dissolved solids (TDS) and other inorganic content. For example, groundwater in 75 wells out of a total of 179 A1 wells (42 percent) at NAS Moffett Field have naturally occurring TDS concentrations which exceed the basin plan limit of 500 mg/L. Although the highest concentrations of TDS occur in groundwater samples from wells in the northern area of the station, groundwater samples from wells from all IRP sites exceeded the basin plan limit. Elevated TDS concentrations at these sites are largely comprised of sodium, calcium, magnesium, and the anionic species chloride, sulfate, and carbonate. Groundwater samples with elevated TDS contents often contain chloride and sulfate concentrations in excess of the basin plan drinking water limit (250 μg/L) for these constituents. Sulfate was detected in samples above the basin plan drinking water limit in 67 percent (36 out of 54) of the A1 wells sampled for sulfate.

High concentrations of naturally occurring heavy metals were detected in samples from most of the A1 wells at NAS Moffett Field. For example, manganese was detected in concentrations in excess of the basin plan limit for municipal drinking water of 50 μg/L in samples from 153 A1 wells (86 percent). Iron was detected in concentrations in excess of the basin plan limit for municipal drinking water of 300 μg/L in samples from 139 A1 wells (78 percent). Taken collectively, inorganic constituents in groundwater from only 15 out of 179 A1 wells (8 percent) meet basin plan objectives for municipal drinking water sources.

For the A2 zone, concentrations of inorganic constituents in groundwater are somewhat less than for the A1 zone. However, TDS and metal concentrations in groundwater from the A2 zone also commonly exceed basin plan municipal supply limits. Groundwater samples from 15 of 68 A2 wells (22 percent) at NAS Moffett Field have naturally occurring TDS concentrations which exceed the basin plan limit of 500 mg/L. Iron and manganese were detected at concentrations in excess of the basin plan limits for municipal drinking water in samples from 59 A2 wells (87 percent).

In addition, due to the availability of alternate sources and the limited productivity of the A aquifer zones, it is not probable that the A1 and A2 zones would constitute a future supply source. Future drinking water and commercial wells, if necessary, would likely be installed in the C aquifer. However, continued integrity of the C aquifer plays a key role in prevention of salt water intrusion into fresh water areas of the subsurface. Use of the C aquifer is currently restricted to prevent land subsidence and salt water intrusion. Similar concerns will likely dominate future use of water from the C aquifer.

The upper aquifers are also unattractive for use as agricultural supply due to elevated salinity and limited productivity. Irrigation with the high TDS content water could result in an increase in soluble salt accumulations in irrigated lands. In addition, approximately 71 percent of the samples from A1 wells and 43 percent of the samples from A2 wells exceeded basin plan agricultural limits for manganese or iron. Therefore, use of the A aquifer for agricultural supply is unlikely.

Other potential uses applicable to groundwater at NAS Moffett Field are industrial service supply and industrial process supply. Most industrial service supplies, such as water used for mining, gravel washing, and fire protection, have broad constraints on water quality. Water from the upper aquifers may be used in this capacity. Water quality requirements for different industrial processes vary but are generally more restrictive than those for industrial service supply. Water from the upper aquifer zones could potentially be used for some process applications.

The A aquifers also act as a source of surface water replenishment. Surface water replenishment provided by the aquifers presently assists in maintaining wildlife habitats associated with the nearby wetlands and contributes to maintenance of ecological diversity in the San Francisco Bay area. In addition, the upper aquifers at NAS Moffett Field currently reduce land subsidence and salt water intrusion. These are the most probable beneficial uses for the foreseeable future.

6.4 IMPACT AREAS: BASELINE PROFILE AND PROJECTED VARIANCES DUE TO CLEANUP LEVEL SCENARIOS

The following subsections provide groundwater and soil information for each impact area. The baseline situation is discussed first, which considers both the present use of the resource as well as the existing potential for future use of the resource. Then this section discusses potential variances from the baseline stemming from the cleanup level scenarios, along with an estimated monetary value for each variance. It presents rationale for assigned probability coefficients followed by a table that summarizes the groundwater and soil probability coefficients for each scenario.

The cost-benefit analysis considered both existing and potential uses of the groundwater and land that may be affected by groundwater quality or soil contaminant concentrations. Even if the water or land is not currently being used for a particular purpose, there is a value to its potential use in that capacity. To accurately reflect the potential for a particular use, a probability coefficient (expressed as a two-place decimal figure) was assigned to each future groundwater and land use. Each probability coefficient was developed using available technical information and research on future land and water use, which is summarized in Section 6.3.

When there was no change from the baseline situation, a probability coefficient was not relevant and therefore not determined. In these instances, the probability coefficient was recorded as NA, representing not applicable. A probability coefficient, however, was determined for all of the future land use categories, even when there was no change from the baseline. This illustrates that the sum of all probability coefficients equals 1.00.

The following sections discuss impact areas considered in the analysis. (The tables in Section 6.5 summarize the numeric data presented here.)

6.4.1 Current and Potential Agricultural Use

6.4.1.1 Groundwater

Agricultural use would include crop, orchard, and pasture irrigation; stock watering; support of vegetation for range grazing; and all other uses in support of farming and ranching operations. At present, there is no use of A aquifer zones for agricultural purposes and limitations to A aquifer use exist. Most significant is that the rate of groundwater extraction from the A aquifer zones could not meet agricultural needs. Also, the presence of elevated concentrations of inorganic constituents makes the groundwater unsuitable for future agricultural use. The groundwater would remain unusable for agricultural use under any of the cleanup level scenarios because the elevated inorganic constituents are not eliminated and productivity of the A1 aquifer is not increased. Therefore, no change from the baseline would be realized for potential agricultural groundwater use.

6.4.1.2 Land

There is no current agricultural land use, and the potential for agricultural land use will not improve under the cleanup scenarios. The land is suitable for agricultural purposes. In fact, Pal and Overcash (1991) report that hydrocarbon levels up to 1 percent may stimulate plant growth and crop yield.

Potential agricultural use was assigned a low probability based on land-use research conducted for NAS Moffett Field. Land apparently will be much more valuable to the community in other, nonagricultural uses.

Projection Item	Scenario		
	A	B	C
Probability of future agricultural groundwater use	NA	NA	NA
Probability of future agricultural land use	0.01	0.01	0.01

6.4.2 Current and Potential Municipal Use

6.4.2.1 Groundwater

Municipal water supply use includes pumping, treating, and storing the groundwater as a drinking water supply. As described, groundwater quality does not meet the municipal water quality guidelines defined in the basin plan (due to elevated inorganic compound concentrations) and there is no current municipal use (RWQCB 1991). Additionally, the aquifer yields are too low for municipal requirements. For these reasons, there is no potential for municipal groundwater use (RWQCB 1991; PRC 1994f). The potential for municipal groundwater use will not improve under any of the cleanup level scenarios because groundwater yield limitations will still exist and the cleanup specifications would not address the elevated inorganic concentrations present in the groundwater. Both conditions prohibit groundwater use as a municipal source. Therefore, there is no change from the baseline under any of the scenarios.

6.4.2.2 Land

Municipal land use includes office buildings or storage and maintenance facilities. Municipal land use is similar to industrial and commercial use (Section 6.4.3). There is no current municipal land use at NAS Moffett Field, but the land could be used for municipal purposes. Petroleum-contaminated land at current soil concentrations does not pose a risk in an occupational exposure scenario. Therefore, under the cleanup level scenarios there will be no improvement over the baseline situation for municipal land use. Because federal agency use is likely to continue under an industrial and commercial classification, the probability of future municipal land use is low.

Projection Item	Scenario		
	A	B	C
Probability of future municipal groundwater use	NA	NA	NA
Probability of future municipal land use	0.08	0.08	0.08

6.4.3 Current and Potential Industrial and Commercial Use

6.4.3.1 Groundwater

Industrial and commercial groundwater use includes use as a process water supply and all uses related to product manufacturing. Currently, there is no industrial and commercial use of the groundwater, although groundwater quality is thought to be suitable for industrial and commercial uses. Low yields, however, present a major limitation (RWQCB 1991), and many uses are not possible due to elevated salt concentrations. Nonetheless, groundwater may have potential industrial and commercial uses sooner under cleanup level scenarios A and B, which rely on pump and treat systems, than it would under either the baseline case or scenario C, which rely on natural attenuation. The value of realizing this earlier use potential case is calculated as the number of years of groundwater use gained times the estimated annual replacement cost of water ($130,000) for those years. (Replacement cost was derived using an estimate of the amount of water industry could extract from the A aquifer [a rate equal to surface infiltration rate] and the per gallon cost of water purchased from the City of Sunnyvale.) The following paragraphs summarize the approximate water value to industry realized under each scenario.

- Scenario A: The gain to industrial and commercial users by requiring this most stringent cleanup level would be approximately 2 years (years 19 and 20). This is because the scenario A cleanup level would be realized in year 18 with a pump and treat system, rather than in year 20 under the baseline if no active remediation is implemented.

  Present value = $130,000

- Scenario B: The gain to industrial and commercial users by requiring this level of cleanup would be approximately 3 years (years 10, 11, and 12). This is because the scenario B cleanup level would be realized in year 9 with a pump and treat system, rather than in year 12 under the baseline if no active remediation is implemented.

  Present value = $250,000

- Scenario C: There would be no gain to industrial and commercial users over the baseline, because both scenario C and the baseline achieve cleanup levels after 20 years.

Theoretically, the actual lost value to industry will equal the difference between the replacement cost and the cost to industry to extract the groundwater from the aquifer. The extraction cost will primarily include the cost of well installation and water storage, which is insignificant in comparison to the calculated replacement costs. Therefore, no adjustment was made for this difference in the analysis.

It is highly unlikely that the A aquifer will be used as water source because of the low water yield and because other water resources are available to industry. Therefore, a very low probability is assigned to potential future industrial and commercial groundwater use.

6.4.3.2 Land

Currently, there is industrial and commercial land use by federal agencies and the petroleum site areas do not exceed the industrial exposure risks for soil. Therefore, under the cleanup level scenarios there will be no improvement over the baseline for potential industrial and commercial land use.

A high probability was assigned to potential future industrial/commercial land use, given that the land was historically and is currently used in this manner. Also, NASA recently indicated its intention to remain at NAS Moffett Field by signing an MOU to use the property (Navy and NASA 1992).

Projection Item	Scenario		
	A	B	C
Probability of future industrial and commercial groundwater use	0.01	0.005	0.001
Probability of future industrial and commercial land use	0.88	0.88	0.88

6.4.4 Current and Potential Recreational Use

6.4.4.1 Groundwater

Groundwater is not used for recreational purposes; however, groundwater periodically recharges surface water under dry conditions, and surface water may be used recreationally. Currently, some types of recreational activities, such as duck hunting and fishing, occur along the coastline area north of NAS Moffett Field. However, the concentrations of petroleum-related constituents currently in the groundwater will not migrate to the areas of surface water recharge at levels above detection limits (see Section 4.3). Consequently, there would be no change from the baseline resulting from cleanup.

6.4.4.2 Land

There is no recreational use of the petroleum sites at present. The potential for recreational use is now slightly impaired because certain recreational uses, such as a park, in the immediate area of high petroleum contamination are limited by the presence of the contamination. For this analysis, it is assumed that the land cannot be used for recreational purposes if the soils exceed the 10^{-5} residential human health risk limit or the HI = 1 limit. (This is a conservative assumption since the 10^{-4} risk level is typically the level that EPA uses to require remediation [see Section 4.2].) Based on this assumption, about 1 acre is now unsuitable for recreational use. All three scenarios will leave the petroleum sites suitable for recreational use; this represents an improvement over the baseline. The benefit of cleanup would be the restored potential for use of the land in this capacity. This is valued using a land value of a comparable property in the area. The property value is 400,000.

The probability assigned to potential future recreational land use was arrived at by examining the likelihood that the property will be used for other purposes, such as industrial and commercial. Also, there are other, less-developed areas of NAS Moffett Field that would have more aesthetic appeal as a recreation area and it is not likely that the petroleum sites areas would be selected for this use. Therefore, a low probability was assigned to potential recreational land use.

Projection Item	Scenario		
	A	B	C
Probability of future recreational groundwater use	NA	NA	NA
Probability of future recreational land use	0.01	0.01	0.01

6.4.5 Current and Potential Residential Use

6.4.5.1 Groundwater

At present, the A aquifer does not meet guidelines for domestic water use as defined in the basin plan, primarily due to the presence of elevated concentrations of inorganic compounds, and there is no residential use. Elevated concentrations of inorganic constituents and low yield also inhibit the potential for future residential use of the groundwater. The potential for groundwater use will not improve under any of the cleanup level scenarios because they do not address the elevated concentrations of inorganic constituents or the low water yield.

6.4.5.2 Land

Currently, there is no residential use of the petroleum-contaminated areas. The potential for residential land use exists in all areas except for those areas of high contamination. For this analysis, it is assumed that the land cannot be used for residential purposes if the soils exceed the 10^{-5} residential human health risk limit or the HI = 1 limit (see Section 4.2). Based on this assumption, about 1 acre is now unusable for residential use. All three soil cleanup level scenarios will leave the petroleum sites suitable for residential use; this represents an improvement over the baseline. The value of this improvement was derived by using a land value of a comparable property in the area. The property value is $400,000.

There is a very low probability of future residential use for several reasons: (1) the planned occupancy by federal agencies, (2) the surrounding industrial and commercial land use, and (3) the petroleum sites area is presently within an Air Installation Compatible Use Zone (AICUZ) because of its proximity to the airfield. Residential development is considered incompatible with an AICUZ. Therefore, a very low probability was assigned to potential residential land use.

Projection Item	Scenario		
	A	B	C
Probability of future residential groundwater use	NA	NA	NA
Probability of future residential land use	0.02	0.02	0.02

6.4.6 Current and Potential Groundwater Recharge

Groundwater periodically (during dry periods) recharges surface water. This recharge is beneficial because it establishes a hydraulic gradient that inhibits the intrusion of salt water into the aquifer system. The aquifer also helps maintain downgradient wetland environments and reduces land subsidence. If not disturbed, the aquifer may continue serving these purposes indefinitely. Removing water from the aquifer will diminish its ability to recharge surface water, inhibit salt water intrusion, and reduce land subsidence. (In addition, if water is withdrawn from the aquifer [disturbed] it could induce increased migration of the regional VOC plume.) Therefore, extraction of groundwater will detract from the baseline situation.

It is assumed that reinjection will be required under two of the scenarios to maintain groundwater hydraulic gradients. No reinjection is required for scenario C. The cost of reinjection is used in this analysis as a financial measure of loss. This cost differs by scenario because different volumes of water will need to be reinjected over different periods of time. The present value costs for each scenario are as follows:

Scenario A:	$ 630,000
Scenario B:	$ 130,000
Scenario C:	No reinjection required

Projection Item	Scenario		
	A	B	C
Probability of required groundwater reinjection	1.00	1.00	0.00

6.4.7 Current and Potential Plant and Animal Habitat

Based on preliminary findings of the phase I ecological assessment, there is no noticeable impact, in either reduced numbers or health effects, of petroleum contamination to the plants and animals living in the area of NAS Moffett Field (PRC 1994c). Given the current site conditions, there is no information to indicate that this habitat would be affected in the future. Fate and transport modeling indicates acceptable groundwater levels at petroleum contamination source areas (see Sections 3.0 and 4.3). This verifies that sensitive ecosystems will not be affected by the petroleum plume migration. Therefore, the cleanup scenarios do not represent an improvement over the baseline in this impact area.

6.5 COMPARISON OF COSTS AND BENEFITS FOR EACH SCENARIO

Tables 1 and 2 summarize the costs and benefits of the proposed groundwater and soil remediation scenarios. The "net benefit to society" values that appear at the bottom of each column represent the difference between the cost of cleanup and the monetary value of benefits for a given scenario. A positive figure represents a net benefit and a negative figure represents a net cost.

TABLE 1

SOIL CLEANUP COST-BENEFIT SUMMARY

		SCENARIO A		SCENARIO B		SCENARIO C
Total Cleanup Cost (PV)		$17,900,000		$8,300,000		$1,040,000
Impact Area (Current and Potential Use)	p	Original Value p Adjusted Value	p	Original Value p Adjusted Value	p	Original Value p Adjusted Value
Agricultural	0.01	— $0	0.01	— $0	0.01	— $0
Municipal	0.08	— $0	0.08	— $0	0.08	— $0
Industrial and commercial	0.88	— $0	0.88	— $0	0.88	— $0
Recreational	0.01	$400,000 $4,000	0.01	$400,000 $4,000	0.01	$400,000 $4,000
Residential	0.02	$400,000 $8,000	0.02	$400,000 $8,000	0.02	$400,000 $8,000
Groundwater recharge	—	— $0	—	— $0	—	— $0
Plant and animal habitat	—	— $0	—	— $0	—	— $0
Total Benefits		$12,000		$12,000		$12,000
NET BENEFIT (COST)		($17,890,000)		($8,290,000)		($1,030,000)

Note: cost unmbers have been rounded

p = probability of event occurring in the future

TABLE 2

GROUNDWATER CLEANUP COST-BENEFIT SUMMARY

	SCENARIO A		SCENARIO B		SCENARIO C	
Total Cleanup Cost (PV)		$9,200,000		$1,600,000		$1,200,000
Impact Area (Current and Potential Use)	p	Original Value p Adjusted Value	p	Original Value p Adjusted Value	p	Original Value p Adjusted Value
Agricultural	–	– $0	–	– $0	–	– $0
Municipal	–	– $0	–	– $0	–	– $0
Industrial and commercial	0.01	$130,000 $1,300	0.005	$250,000 $1,300	0.001	– $0
Recreational	–	– $0	–	– $0	–	– $0
Residential	–	– $0	–	– $0	–	– $0
Groundwater recharge	1.00	($630,000) ($630,000)	1.00	($130,000) ($130,000)	0.00	– $0
Plant and animal habitat	–	– $0	–	– $0	–	– $0
Total Benefits		($630,000)		($130,000)		$0
NET BENEFIT (COST)		($9,830,000)		($1,730,000)		($1,200,000)

Note: cost numbers have been rounded

p = Probability of event occurring in the future

7.0 CONCLUSIONS AND RECOMMENDATIONS

The Navy believes cleanup levels for petroleum contamination at NAS Moffett Field should be protective, technically achievable, and cost effective. Selecting protective cleanup goals is a complex task since (1) petroleum products are mixtures of nearly 200 hydrocarbons and additives; (2) the fate and transport of the mixtures are dependent on the site-specific environmental characteristics and the components of the mixtures; (3) the threat to the environment from the mixtures depends on the type of mixtures, the receptors, and the way in which the receptors will be exposed to the mixtures; and (4) the mixtures undergo continual changes in the environment that affect the toxicity and fate and transport of the mixture.

The high-range cleanup level scenarios presented in this report (the C scenarios) are believed to be protective based on the current and probable future beneficial uses, fate and transport predictions, and toxicity evaluations presented herein. The cost-benefit analysis results for the scenarios indicate that spending to remediate to lower levels does not yield an improved net value to the community. In addition, the low-range cleanup level scenarios are probably not technically achievable.

The Navy has recently completed sampling (the data are not yet available but are expected by April 1994) that will provide a constituent-specific profile of the petroleum contamination at NAS Moffett Field and an indication of the leaching characteristics of these constituents. The Navy recommends that this information be used to support or modify the fate and transport and toxicity evaluations presented in this report and to finalize cleanup level scenarios that are protective of current and probable future beneficial uses, the environment, and human health.

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APPENDIX A

DETERMINATION OF HUMAN HEALTH RISK-BASED PETROLEUM CLEANUP LEVELS

CONTENTS

TABLES

1.0 INTRODUCTION

This appendix describes the approach, procedures, and results for determining risk-based petroleum cleanup levels. For most hazardous wastes sites, a remedial investigation and feasibility study (RI/FS) is conducted to evaluate current and potential future site-related risks. Site-specific cleanup levels are subsequently based on the estimated risk. According to the U.S. Environmental Protection Agency (EPA), the primary purpose of the RI/FS process is to ensure that remediation is protective of human health and the environment. This goal is presented in the National Oil and Hazardous Substances Contingency Plan (NCP) as one of the threshold criteria which must be satisfied during remedy selection at sites investigated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). To determine whether the selected remedy will ultimately be protective, EPA requires that cleanup levels be derived in the FS based on site-specific exposure conditions and acceptable risk levels for each chemical of concern (COC). Cleanup levels developed in such a manner are termed risk-based concentrations (RBCs). Only by using RBCs as target cleanup goals for all chemicals can the regulatory agencies and the public be confident that human health and the environment will be protected.

EPA methodology to calculate risk and develop RBCs can be applied to all chemicals. However, the NCP specifically excludes from baseline risk assessments petroleum products such as those found at Sites 5, 9, 12, 15, and 19 at Naval Air Station (NAS) Moffett Field. Therefore, human health and environmental risks from exposure to petroleum-related contaminants have not been assessed at these sites, precluding the derivation of RBCs in the conventional RI/FS process. Calculation of exposure risks and RBCs is further complicated by degradation of the original fuel mixture. "Weathered" petroleum mixtures have altered compositions due to several natural in situ processes including biotransformation, abiotic mineralization, and volatilization. Therefore, EPA-derived toxicity values for petroleum compounds may not accurately reflect risks from exposures to weathered petroleum spills because original and weathered mixtures differ significantly with regard to individual constituents, particularly the more toxic compounds. To fully characterize cleanup goals at the petroleum sites, mixture-specific RBCs will need to be calculated for both original and weathered petroleum mixtures.

A separate but parallel risk-based approach will be employed for all petroleum mixtures at NAS Moffett Field to make cleanup of fuel mixtures consistent with other site-related chemicals and to ensure protection of human health and the environment. The methodology used to derive RBCs for fuel mixtures is identical in all respects to that applied to other NAS Moffett Field COCs. The consistent derivation and application of RBCs for all COCs provides an overall remediation framework that is comprehensive and makes remedy selection comparable for all contaminants.

This appendix is divided into five sections. Section 1.0 contains the introduction and Section 2.0 describes the general approach for determining risk-based cleanup levels. Section 3.0 describes the procedures employed, including media of concern, COCs, toxicity evaluation, and exposure pathways. Section 4.0 presents the acceptable RBCs for soils and groundwater and Section 5.0 presents references.

2.0 APPROACH

Detailed guidance used to derive RBCs for COCs has been developed by EPA and is presented in Human Health Evaluation Manual, Part B: Development of Risk-based Preliminary Remediation Goals (RAGS-B; EPA 1991). This is a companion guidance document to Risk Assessment Guidance for Superfund, Human Health Manual, Volume I, Part A (RAGS-A; EPA 1989) which is also used in the RI/FS process to evaluate site-related human health risks. RAGS-B used in combination with RAGS-A presents a comprehensive framework for developing RBCs based on current or potential risks for all COCs that have EPA-derived or California EPA-derived toxicity values.

Basing remedial decisions on an RBC assessment for all COCs at a Superfund site has three advantages over the application of generic standards which may underestimate potential risks, be overly conservative, or not be applicable for a particular site. First, the final remedy will be selected in accordance with the NCP. That is, it can be directly determined from the results of the RBC analysis whether human health and the environment will be protected. This information is not available if cleanup is based on a variety of nonsite-specific standards. Second, it will provide consistency to all risk management decisions without regard to an arbitrary classification of select groups of contaminants. Third, it will "limit the number of alternatives analyzed and streamline the process" (EPA 1991).

If nonsite-specific standards are applied exclusively for petroleum mixtures, inconsistent criteria will be used in risk management decisions. Moreover, using a separate process to derive cleanup standards for petroleum mixtures undermines the intent of the NCP and makes communicating remedy selection with the public difficult. Therefore, although petroleum products are excluded from evaluation under the NCP, RBCs for fuel-related compounds will be calculated using the same procedures as other contaminants at NAS Moffett Field.

The purpose of this appendix is to identify and evaluate chemical-specific target remediation goals for the petroleum sites at NAS Moffett Field. The remedy must satisfy the two "threshold criteria" of the NCP; (1) protection of human health and the environment, and (2) compliance with applicable or relevant and appropriate requirements (ARARs). According to CERCLA, Section 121(d)(1): "Remedial actions selected... under this Act shall attain a degree of cleanup of hazardous substances, pollutants, and contaminants released into the environment and of control of further release at a minimum which assures protection of human health and the environment." The NCP defines protection of human health in terms of risk but does not define a discrete point of reference. Instead, EPA defines an acceptable risk range. The range is between one-in-a-million (1×10^{-6}) and one-in-ten-thousand (1×10^{-4}) excess lifetime cancer risk (ELCR) for carcinogens and hazard index (HI) of 1.0 for noncarcinogens. The upper bound risk, namely a carcinogenic risk of 1×10^{-6} and HI of 1.0, is defined as the point of departure for risk management decisions. That is, risks less than the point of departure are insignificant and need not be considered further in the RI/FS process.

In an attempt to address inconsistencies inherent in applying an acceptable risk range in developing remedial strategies rather than a well-defined acceptable single risk level, EPA's Office of Solid Waste and Emergency Response has recently refined the definition of an acceptable risk level:

> "Where the cumulative carcinogenic risk to an individual based on reasonable maximum exposure for both current and future land use is less than 1×10^{-4}, and the non-carcinogenic HI is less than 1.0, action generally is not warranted unless there are adverse environmental impacts."

Accordingly, a carcinogenic risk of 1×10^{-4} and an HI of 1.0 have become EPA's de facto acceptable risk levels that are used to trigger a remedial response.

It is important to emphasize that an acceptable risk level is based on a concept of reasonable maximum exposure (RME). Risk is highly dependent on the particular exposure scenario expected at the site. Depending on exposure conditions, the estimated risk for a particular chemical or groups of chemicals could be unacceptable, negligible, or insignificant. When no completed exposure pathway exists, there is no risk regardless of the toxicity and concentration of contaminants. Thus, it is necessary to base remedial decisions on exposure scenarios and pathways that are representative of RME exposures for each potential receptor. Specific exposure conditions are defined as those that best reflect site-specific conditions under both current and future land use activities (EPA 1989).

Risk estimates based on residential exposures do not represent RME conditions because it is unlikely that NAS Moffett Field will be developed for future residential use. This conclusion is further supported by results of the future land use analysis of the area. Therefore, RBCs for the petroleum sites will be based on occupational use of NAS Moffett Field, although residential estimates have been included for comparison.

3.0 PROCEDURES

The risk-based approach developed by EPA (EPA 1991) will be closely followed for the derivation RBCs for petroleum mixtures. This approach involves calculating an exposure concentration for each mixture under the appropriate site-specific exposure scenario that will be protective of human health. The calculation of an RBC is essentially a back-calculation of the analysis conducted in the risk assessment. In a risk assessment, risk is calculated from site-specific chemical concentrations, EPA-verified toxicity values, and site-specific exposure conditions. In an RBC assessment, the health protective chemical-specific concentration is calculated from the acceptable risk level, EPA-verified toxicity values, and site-specific exposure conditions. The same database and information is used in both assessments. RBCs represent acceptable chemical-specific concentrations to which specified receptors, including sensitive subgroups, may be exposed without adverse effects over a lifetime or part of a lifetime. An adequate margin of safety is incorporated into RBCs to protect receptors even under maximum exposure conditions.

The following subsections discuss the development of RBCs including discussions on the media of concern, chemicals of concern, toxicity evaluation, and exposure pathways.

3.1 MEDIA OF CONCERN

At Sites 5, 9, 12, 15, and 19, there are three environmental media of concern that may be affected by fuel spills or leaks: (1) surficial soil, (2) subsurface soil, and (3) groundwater. The media of concern for this evaluation are selected based on current and potential future activities at these sites.

The potential for current human exposure is considered low due to the limited amount of activity at Sites 5, 9, 12, 15, and 19. Current occupational exposures consist mainly of irrigation, maintenance operations, and routine service of the pump stations positioned along Patrol Road.

Aquifers at the site are roughly delineated into upper and lower aquifers. The upper aquifer is further divided into A1, A2, B2, and B3 zones. The lower aquifer is termed the C aquifer and is separated from the upper aquifer by a thick, relatively impermeable clay aquitard. Use of groundwater for domestic purposes is unlikely as the ground water at NAS Moffett Field is generally nonpotable.

Although the majority of the fuel-related contamination is present in soils, it is possible for contaminants in soils to leach to groundwater in the future. Therefore, the primary media of concern for this evaluation are surficial soils and groundwater. Even though groundwater is not likely to be used for drinking water purposes, it is possible that groundwater could be used for irrigation of native plants and grasses, although, this is unlikely due to the salinity in the A aquifer. There is also an irrigation well in the southeastern corner of NAS Moffett Field, but it is screened in the deep C aquifer. For the purpose of this assessment, however, it is assumed that groundwater in the A aquifer could be used for irrigation purposes.

3.2 CHEMICALS OF CONCERN

Petroleum mixtures detected at NAS Moffett Field that are considered site-specific COCs and include diesel and jet fuels (JP5) (Sites 5 and 12) and gasoline (Sites 9 and 19 [Tank 53]). There are only two groups of indicator chemicals in these fuel mixtures that pose appreciable health hazards: water-soluble chemicals that include benzene, toluene, ethylbenzene, and xylene (BTEX) and the nearly insoluble polynuclear aromatic hydrocarbons (PAHs). These chemicals, some of which are present only in minute quantities in fuels, represent the majority of the overall toxicity associated with original (undegraded) fuel mixtures. With the exception of gasoline, all fuel mixtures have been classified by the International Agency for Research on Cancer (IARC 1989a, 1989b, and 1989c) as Class C carcinogens (possibly carcinogenic in humans). Gasoline is classified as a Class B2 carcinogen (probably carcinogenic in humans).

3.3 TOXICITY

The EPA Office of Environmental Criteria and Assessment has recently derived provisional toxicity values for original fuel mixtures (EPA 1992b). Provisional reference doses for original gasoline, JP5/kerosene, and JP4 mixtures have been developed as well as a provisional carcinogenic slope factor (adapted from an interim EPA value) for gasoline. These toxicity values have been derived from information reported in numerous peer-reviewed toxicology publications where a route-to-route extrapolation was made from inhalation exposures to direct ingestion of various petroleum mixtures.

EPA recognizes that the provisional toxicity values for original petroleum mixtures are not applicable for weathered mixtures because "differential volatilization and biodegradation will further alter the composition of the fuel mixtures in the environment. The relative contribution of various compounds to both the water soluble fraction and the remaining insoluble fraction will change continuously with the passage of time due to differential occurrence of these fate processes" (EPA 1992b).

Original petroleum hydrocarbon fuels are complex mixtures composed of individual hydrocarbons that possess a wide range of toxic properties, from those that are virtually nontoxic to those that are possibly carcinogenic in humans. The effect of weathering significantly changes the composition of the original petroleum mixture, rendering the weathered mixture less toxic. Benzene, for example, is one of the more toxic constituents of gasoline but is rapidly detoxified through biotransformation under oxidizing conditions (Hadley and Armstrong 1991). Weathered gasoline contamination would, therefore, not pose the same potential risks to human health and environment as fresh gasoline contamination. For weathered petroleum mixtures, cleanup levels should be based on the concentration of the individual toxic constituents. The application of toxicity values for original petroleum mixtures to weathered mixtures which have been detoxified is overly conservative, overly protective, and may not be cost-effective. Thus, RBCs for weathered petroleum mixtures that are based on detected constituents better represent protective site-specific contaminant levels than a generic standard developed for the original mixture. However, to present a conservative approach, EPA-derived toxicity values for petroleum components were used to calculate the RBCs presented here. The following subsections discuss toxicity of fuel mixtures and the derivation of their toxicity values.

3.3.1 Gasoline

Lead-free automotive gasoline is a volatile blend of hydrocarbons. The exact composition of gasoline varies, but it may contain up to 5 percent benzene. The maximum concentration of lead in unleaded gasoline is 0.013 grams per liter (g/L). In general, aviation gasoline is similar to automotive gasoline.

Acute inhalation exposures to gasoline may cause eye, mucous membrane, throat, and respiratory tract irritation. Overexposures to vapors may lead to bronchopneumonia. Inhalation of high concentrations can cause fatal pulmonary edema. Dermal contact with gasoline can cause dermatitis and blistering of the skin due to its defatting properties. Ingestion or inhalation exposures can cause inebriation, drowsiness, blurred vision, and other central nervous system (CNS) effects. Ingestion may also result in burning of the mouth or throat, gastrointestinal irritation, nausea, vomiting, and diarrhea.

Studies in animals have indicated that the kidney is a target organ for ingested gasoline while inhalation is damaging to the lungs (EPA 1992b). One study of chronic gasoline exposure found an increased incidence of renal tumors that appeared to have a dose-response relationship. Epidemiological studies in humans have not positively demonstrated an association between gasoline exposure and cancer, although some studies suggest this association. EPA classifies gasoline as a probable human carcinogen (class B2) and has developed a slope factor of 1.7×10^{-3} per milligram per kilogram-day ($(\text{mg/kg-day})^{-1}$). EPA has also derived a reference dose of 0.2 mg/kg-day for gasoline, based on route-to-route extrapolation from inhalation data.

3.3.2 Jet Fuel

JP5 is a petroleum distillate that is similar to kerosene, with a lower percentage of aromatic hydrocarbons. JP4 is a blend of kerosene with lower-boiling, lower molecular weight hydrocarbons. JP4 and JP5 cause similar toxic effects.

Acute inhalation of jet fuel vapors may produce dizziness, headache, nausea, and fatigue. Dermal contact with jet fuels may produce skin irritation. Eye and respiratory irritation may occur through vapor exposure. Ingestion or inhalation of jet fuels may result in increasing levels of CNS depression which may progress to unconsciousness, coma, and death from respiratory failure. JP5 and JP4 are damaging to the lung and cause inflammation of the lung tissue which may lead to pulmonary edema and chemical pneumonitis as well as bleeding of the lung tissue.

Chronic inhalation of jet fuels may produce neurasthenic symptoms such as fatigue, anxiety, and memory difficulties. Chronic lung dysfunction may result from aspiration into the lung. Animal studies have yielded conflicting results of the chronic toxicity of jet fuels. Reproductive and developmental toxicity of jet fuels has not been well studied but there was no indication of adverse effects in lab animals exposed via inhalation. EPA has not classified jet fuels as to their carcinogenicity. EPA-derived reference doses are 0.02 mg/kg-day for JP5 and 0.08 mg/kg-day for JP4.

3.3.3 Diesel Fuel

Diesel fuel is a middle distillate of petroleum with a low sulfur content. Diesel fuels have various compositions and are used for fuel for trucks, ships, and other automotive engines.

In general, diesel fuel is a skin irritant and CNS depressant when inhaled. Inhalation can also cause respiratory tract irritation, headache, dizziness, nausea, and vomiting, depending on the extent of exposure. Secondary effects include hypoxia, pneumatocele formation, and chronic lung dysfunction. In some cases, inhalation may cause respiratory arrest and CNS toxicity. Ingestion of diesel fuel causes gastrointestinal irritation, vomiting, diarrhea, and in severe cases, death from CNS depression.

Diesel fuel is a class C carcinogen (not classifiable as to human carcinogenicity), however, reference doses have not been developed. Since chronic effects of exposure to diesel fuel are similar to those produced by JP5, diesel fuel will be grouped with JP5, which has the more conservative jet fuel reference dose.

3.4 EXPOSURE CONDITIONS

The second key component in conducting an RBC assessment is an analysis of site-specific factors that influence current and potential exposures. As part of this analysis, current and future land uses, which define receptor populations, have been evaluated. Environmental factors that differentially affect fate and transport of petroleum constituents in different environmental media have also been investigated.

According to EPA, an exposure pathway describes the course a chemical takes from the chemical source to the exposed individual (EPA 1989). A completed exposure pathway consists of: (1) a source and mechanism of release, (2) a transport medium, (3) a point of potential human contact known as an exposure point, and (4) an exposure route. Identification of reasonable exposure pathways is based on current and future land use. The concept of reasonable scenarios underlies the RME concept developed by EPA. The RME is defined as an exposure evaluation that is conservative but within a range that could reasonably be expected to occur at a site. The operative term is "reasonable," since RAGS-A states: "Estimates of the reasonable maximum exposure necessarily involve the use of professional judgement." EPA (1989) recommends the following activities to collect information to support future land use assumptions and define reasonable exposure conditions for chemical-specific RBCs:

- Characterize the exposure setting and identify potential current and future human receptors
- Identify complete exposure pathways and routes of exposure for each potential receptor
- Estimate exposure point concentrations based on actual or potential exposure units

Exposure assumptions used in the calculation of chemical-specific RBCs are conventionally calculated for current and hypothetical future receptors. Typically, information on current receptors can be easily gathered at most CERCLA sites but detailed information on hypothetical future receptors is generally lacking. For this reason, EPA guidance (EPA 1989 and 1991) suggests that one of two methods be used to estimate site-specific risks and derive RBCs under future exposure conditions. These are to (1) simply default to a worst-case exposure scenario when an analysis of potential future exposures will not be conducted, or (2) conduct a detailed future land-use analysis and base remediation target goals on the most likely exposure scenario.

The Navy has elected to spend considerable time and effort carrying out an independent future land use analysis for NAS Moffett Field. This is the only scientific approach that can be used to evaluate site-specific future exposure conditions. The analysis indicates that the current exposure scenario involving occupational workers will not change after the base is transferred to the National Aeronautics and Space Administration (NASA). Under these conditions, it is most appropriate to derive chemical-specific RBCs for each petroleum mixture based an occupational scenario. However, in the present analysis, a wide range of media-specific RBCs have been calculated for both residential and occupational exposure scenarios for comparison purposes.

State statutes or codes must also be taken into account in the exposure assessment, as well as local ordinances that may preclude certain exposures to specific receptors. For example, RBCs derived for chemicals in groundwater may not be applicable for all groundwater sources at NAS Moffett Field. California state code as applied by the Santa Clara Valley Water District (SCVWD) policy will effectively prevent direct ingestion of groundwater in the upper aquifers. Groundwater from 0 to 150 feet below ground surface must be protected by a 50-foot sanitary seal according to Standards for the Construction and Destruction of Wells and other Deep Excavation in Santa Clara County (SCVWD 1989), which was developed by SCVWD to meet the requirements of Sections 13800 through 13806 of the California Water Code. A 150-foot sanitary seal must also be placed on wells drilled deeper than 150 feet. These requirements would preclude direct ingestion of groundwater in the uppermost aquifer zones. It would still be necessary, however, to determine whether there are vertical connections between aquifers and evaluate the possibility that the more water soluble and mobile petroleum constituents could migrate into underlying aquifers.

In addition to the potentially exposed receptors and site-specific exposure conditions, the derivation of RBCs is dependent on the contaminated environmental media. At NAS Moffett Field, there are three environmental media of concern that may be affected by fuel spills or leaks: surficial soil, subsurface soil, and groundwater. Direct ingestion is considered for surficial soils, but subsurface contaminants are evaluated only with respect to potential migration into groundwater. For example, recent spills in surficial soils can pose significant human health hazards. In contrast, weathered petroleum mixtures in subsurface soils, where direct exposure is unlikely, pose little hazard. Whereas petroleum contamination in surficial soils would be evaluated as a direct exposure to original petroleum mixtures, direct exposure to subsurface petroleum contaminants would be considered an incomplete direct exposure pathway. Subsurface contaminants would, however, be evaluated with respect to the leaching potential into groundwater. If the evaluation indicated leaching was possible, direct exposure to groundwater contaminants would then be evaluated and RBCs for petroleum constituents in groundwater would be applied. The determination as to whether subsurface contaminant migration into groundwater will exceed the groundwater RBC has been ascertained by a separate fate and transport modeling analysis (see Appendix B).

Exposure conditions estimate intake of petroleum constituents from all environmental media. Exposure assumptions can be based on conservative EPA standard default exposure parameters developed for the general population or site-specific information. Both are single-point estimates that are used with EPA-derived algorithms to calculate upper-bound or high end chemical-specific RBCs for the maximum exposed individual. Alternatively, chemical-specific RBCs can be calculated based on the entire site-specific database using a Monte Carlo simulation. In the present RBC assessment, conservative EPA standard default exposure parameters are used to calculate RBCs for petroleum products. RBCs for petroleum mixtures in surficial soils are based on direct ingestion of soil contaminants. Groundwater RBCs for petroleum mixtures are based on leaching of soil contaminants. The assumptions underlying the RBCs for occupational and residential exposure assumptions appear in Tables A-1 through A-4.

TABLE A-1

RISK-BASED EXPOSURE ALGORITHM AND INTAKE PARAMETERS(1) COMMERCIAL/INDUSTRIAL SOIL INGESTION NONCARCINOGENIC EFFECTS

$$C\ (\text{mg/kg; risk-based}) = \frac{\text{THI} \times \text{BW} \times \text{AT}}{\text{ED} \times \text{EF} \times (1/\text{RfD}_o) \times 10^{-6}\ \text{kg/mg} \times \text{IR}_{soil}}$$

Parameter			Value
C	=	Chemical concentration in soil (mg/kg)	--
THI	=	Target hazard index (unitless)	1
RfD_o	=	Oral chronic reference dose (mg/kg-day)	Chemical-specific
BW	=	Adult body weight (kg)	70 kg
AT	=	Averaging time (days)	9,125 days
EF	=	Exposure frequency (days/yr)	250 days/yr
ED	=	Exposure duration (yr)	25 yr
IR_{soil}	=	Soil ingestion rate (mg/day)	50 mg/day

Notes:

(1) EPA 1991

TABLE A-2

RISK-BASED EXPOSURE ALGORITHM AND INTAKE PARAMETERS(1)
COMMERCIAL/INDUSTRIAL SOIL INGESTION
CARCINOGENIC EFFECTS

$$C\ (\text{mg/kg; risk-based}) = \frac{TR \times BW \times AT}{EF \times ED \times CSF_o \times 10^{-6}\ \text{kg/mg} \times IR_{soil}}$$

Parameter			Value
C	=	Chemical concentration in soil (mg/kg)	–
TR	=	Target excess individual lifetime cancer risk (unitless)	10^{-6}
CSF_o	=	Oral cancer slope factor ($(\text{mg/kg-day})^{-1}$)	Chemical-specific
BW	=	Adult body weight (kg)	70 kg
AT	=	Averaging time (days)	25,550 days
EF	=	Exposure frequency (days/yr)	250 days/yr
ED	=	Exposure duration (yr)	25 yr
IR_{soil}	=	Soil ingestion rate (mg/day)	50 mg/day

Notes:

(1) EPA 1991

TABLE A-3

RISK-BASED CONCENTRATION ALGORITHM AND EXPOSURE PARAMETERS
RESIDENTIAL EXPOSURE: SOIL INGESTION

$$C\ (\text{mg/kg; risk-based}) = \frac{TR \text{ x } BW \text{ x } AT}{EF \text{ x } ED \text{ x } TF \text{ x } IR \text{ x } IE^{-6}}$$

Parameter			Default Value
C	=	Chemical concentration (mg/L)	Site-specific
TR	=	Target risk	10^{-6} to 10^{-4}
		Carcinogenic	1
		Noncarcinogenic	
TF	=	Toxicity Factor-Oral	
		Oral slope factor (mg/kg-day^{-1} or inverse	Chemical-specific
		oral reference dose (mg/kg-day)	Chemical-specific
IR	=	Ingestion rate (mg/day)	
		Child	200
		Adult	100
EF	=	Exposure frequency (days/year)⁽²⁾	350
ED	=	Exposure frequency (years)⁽¹⁾	30
BW	=	Body weight (kg)⁽¹⁾	70
AT	=	Averaging time (days)⁽³⁾	
		Noncarcinogenic	10,950
		Carcinogenic	25,550

(1) EPA 1989b.

(2) EPA 1993.

(3) EPA 1989a.

TABLE A-4

RISK-BASED CONCENTRATION ALGORITHM AND EXPOSURE PARAMETERS
RESIDENTIAL EXPOSURE: GROUNDWATER INGESTION

$$C \text{ (mg/kg; risk-based)} = \frac{TR \times BW \times AT}{EF \times ED \times TF \times IR}$$

Parameter			Default Value
C	=	Chemical concentration (mg/L)	Site-specific
TR	=	Target risk	
		Carcinogenic	10^{-6} to 10^{-4}
		Noncarcinogenic	1
TF	=	Toxicity Factor-Oral	
		Oral slope factor $(\text{mg/kg-day})^{-1}$ or inverse	Chemical-specific
		oral reference dose (mg/kg-day)	Chemical-specific
IR	=	Ingestion rate (L/day)	2
EF	=	Exposure frequency (days/year)⁽²⁾	350
ED	=	Exposure duration (years)⁽¹⁾	30
BW	=	Body weight (kg)⁽¹⁾	70
AT	=	Averaging time (days)⁽³⁾	
		Noncarcinogenic	10,950
		Carcinogenic	25,550

(1) EPA 1989b.

(2) EPA 1993.

(3) EPA 1989a.

4.0 ACCEPTABLE RISK LEVELS

To calculate an RBC, an acceptable risk level which will ensure protection of human health and the environment has been established. The NCP defines an acceptable carcinogenic risk in terms of a risk range of 1 x 10^{-6} to 1 x 10^{-4} ELCR and a noncarcinogenic HI of 1.0. However, the 1 x 10^{-4} ELCR risk level has become EPA's de facto acceptable risk level which can be used to derive chemical-specific RBCs for original petroleum mixtures or indicator constituents in weathered petroleum mixtures. In the present analysis, however, RBCs have been derived for the entire risk range of 1 x 10^{-6} to 1 x 10^{-4} and an HI of 1.0.

4.1 ORIGINAL MIXTURES

RBCs for original petroleum mixtures at Sites 5, 9, 12, 15, and 19 were presented by EPA in the Health Effects Assessment Summary Tables (HEAST) (EPA 1992a) and are only applicable for recent spills or leaks. It is presumed that recent contamination contains the fractional concentration of all constituents that are present in the original petroleum mixture. The RBCs for original mixtures appear in Tables A-5 and A-6 for occupational and residential exposures, respectively. Although the residential scenario is unlikely, it has been presented for comparison. As previously discussed, these RBCs are calculated using the inhalation cancer slope factors and reference doses. EPA has stated that these RBCs are applicable to soil and groundwater ingestion (EPA 1992b). A range of RBCs has been calculated for gasoline, since it is the only petroleum mixture that is considered by EPA to be carcinogenic.

TABLE A-5

TOXICITY VALUES AND RISK-BASED CONCENTRATIONS FOR PETROLEUM MIXTURES BASED ON OCCUPATIONAL EXPOSURES

Petroleum Mixture	Reference Dose (mg/kg-day)	Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$	Risk-Based Concentrations in Soil (mg/kg)[1]				Risk Based Concentration in Groundwater (μg/L)			
			Risk = 1 x 10^{-6}	Risk = 1 x 10^{-5}	Risk = 1 x 10^{-4}	HI = 1.0	Risk = 1 x 10^{-6}	Risk = 1 x 10^{-5}	Risk = 1 x 10^{-4}	HI = 1.0
Gasoline	2.0 x 10^{-1}	1.7 x 10^{-3}	3,367	33,670	336,700	408,800	3 x 10^{6}	3.4 x 10^{7}	3.4 x 10^{8}	4.1 x 10^{8}
JP-5/Diesel	2.0 x 10^{-2}	NA	NA	NA	NA	40,880	NA	NA	NA	4.1 x 10^{7}
JP-4	8.0 x 10^{-2}	NA	NA	NA	NA	163,520	NA	NA	NA	1.6 x 10^{8}

Notes:

NA Not applicable

(1) The residential risk-based concentrations developed by EPA are also based only on ingestion pathways. (EPA 1992).

TABLE A-6

TOXICITY VALUES AND RISK-BASED CONCENTRATIONS FOR PETROLEUM MIXTURES BASED ON RESIDENTIAL EXPOSURES

Petroleum Mixture	Reference Dose (mg/kg-day)	Cancer Slope Factor $(mg/kg\text{-}day)^{-1}$	Risk Based Concentration in Soil (mg/kg)[1]				Risk-Based Concentrations in Groundwater (μg/L)[1]			
			Risk = 1.0×10^{-6}	Risk = 1.0×10^{-5}	Risk = 1.0×10^{-4}	HI = 1.0	Risk = 1.0×10^{-6}	Risk = 1.0×10^{-5}	Risk = 1.0×10^{-4}	HI = 1.0
Gasoline	2.0×10^{-1}	1.7×10^{-3}	400	4,000	40,000	50,000	50	500	5,000	7,000
JP-5/Diesel	2.0×10^{-2}	NA	NA	NA	NA	5,000	NA	NA	NA	700
JP-4	8.0×10^{-2}	NA	NA	NA	NA	20,000	NA	NA	NA	3,000

Notes:

NA Not applicable
[1] EPA 1992

The range of RBCs represent gasoline concentrations that are protective at 1 x 10^{-6} to 1 x 10^{-4} ELCR levels. For residential exposures, the RBC range for carcinogenic effects in groundwater is 50 micrograms per liter (μg/L) to 5,000 μg/L and for occupational exposures the range is 3.4 x 10^6 to 3.4 x 10^8 μg/L. For noncarcinogenic effects, the RBC is 7,000 μg/L for residential exposures and 4.1 x 10^8 μg/L for occupational exposures. The RBCs for JP5/diesel and JP4 are based on noncarcinogenic effects only. The RBCs for JP5/diesel are 700 and 4.1 x 10^7 μg/L for residential and occupational exposures, respectively. The RBCs for JP4 are 3,000 and 1.6 x 10^8 μg/L, respectively.

RBCs are also calculated for soils. For gasoline, the RBCs for carcinogenic effects are 400 to 40,000 mg/kg for residential exposures and 3,367 to 336,700 milligrams per kilogram (mg/kg) for occupational exposures. The RBCs for noncarcinogenic effects for JP5/diesel are 5,000 and 40,880 mg/kg for residential and occupational exposures, respectively. The RBCs for noncarcinogenic effects for JP4 are 20,000 and 163,520 mg/kg for residential and occupational exposures, respectively.

4.2 WEATHERED MIXTURES

For weathered petroleum mixtures, RBCs are calculated on the basis of detected indicator chemicals in each contaminated environmental medium. The two toxic groups typically used as indicator chemicals for weathered petroleum mixtures include the water-soluble BTEX compounds and PAHs. Because petroleum constituents occur together, remediation of the indicator chemicals effectively reduces the concentration of all petroleum constituents. For this reason, it is appropriate to target for remediation only those indicator chemicals for petroleum mixtures that pose the greatest risk to human health and the environment. RBCs for weathered petroleum mixtures in soil and groundwater, however, are not estimated at this point for this evaluation as the RBCs for the original petroleum mixtures are more conservative.

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APPENDIX B

DETERMINATION OF ENVIRONMENTAL RISK-BASED PETROLEUM CLEANUP LEVELS FOR SOILS

CONTENTS

TABLES

1.0 INTRODUCTION

This appendix summarizes the approach, procedures, and results for estimating fate and transport-based petroleum cleanup levels for soils. This determination presents a quantitative means of estimating cleanup levels for soils based on the potential impact of petroleum contamination on groundwater quality.

This appendix contains five sections. Section 1.0 contains the introduction and Section 2.0 describes the approach used to determine fate and transport-based petroleum cleanup levels for soils. Section 3.0 describes the model, including parameters, assumptions, and model sensitivity. Section 4.0 presents the results. All tables are presented at the end of Section 4.0 and Section 5.0 lists references.

2.0 APPROACH

Petroleum products are complex mixtures of constituents, some of which are highly toxic and mobile (water soluble and easily leached from the soil), and many of which are not toxic and not mobile. The toxic and mobile petroleum constituents are most likely to adversely affect human health and the environment and, therefore, are the basis for establishing cleanup levels after conducting a contaminant fate and transport evaluation. Petroleum cleanup levels have been based on individual constituents. Total petroleum hydrocarbon (TPH) concentrations have been estimated from these constituents based on the weight percentage of the constituent in the petroleum mixture.

Developing cleanup levels based on individual constituents focuses attention on petroleum degradation products. Degradation is important because at many sites the petroleum spilled or leaked from underground storage tanks (USTs) years earlier. As noted in the risk assessment model, CalTOX, the "absence of information about environmental degradation could make some estimates of health risks orders of magnitude too conservative" (DTSC 1993).

The original composition of petroleum products is not likely to be present years after being exposed to degradation mechanisms. For example, benzene, a common constituent of gasoline, was not detected in some soil samples which had high levels of TPH purgeable as gasoline (PRC 1993). This suggests that the benzene may have degraded or volatilized at the source. Recent publications on California groundwater quality confirm that benzene biodegrades near its source (Hadley and Armstrong 1991). Therefore, it is important to identify the constituents the petroleum has degraded to, so that cleanup levels and corrective action technologies are based on constituents present.

Petroleum fate and transport at NAS Moffett Field are evaluated using a simple mass balance analytical model. The model focuses on estimating potential impacts to groundwater caused by petroleum constituents leaching from soils. The concentration of a chemical in groundwater is a function of the amount of the chemical degrading and infiltrating through the soil column and the sorption potential of the chemical and the soil. The chemical concentration is also affected by the volume of water into which it is dissolved, the surface area of contaminated soil, and the orientation of this area relative to the direction of groundwater flow.

Concentrations of petroleum-related constituents in groundwater as a result of leaching and degradation in soil are estimated using the Summer's Leaching Model (EPA 1989a) modified to include degradation. The Summer's model was developed to estimate the point at which contaminant concentrations in the soil will produce groundwater contaminant concentrations at or below target levels. The resultant soil concentrations can then be used as guidelines for estimating the extent of soil contamination and for specifying soil cleanup goals. The model assumes that precipitation at the site infiltrates through the subsurface and desorbs contaminants from the soil based on equilibrium soil/water partitioning. The model also assumes that this contaminated infiltration mixes completely with the groundwater below the site, resulting in an equilibrium groundwater concentration.

3.0 FATE AND TRANSPORT MODEL

The model estimates the maximum allowable concentration of the contaminant in soil. The maximum allowable leachate concentration can be calculated by using the appropriate groundwater cleanup goal and aquifer parameters. This calculation takes into account the groundwater cleanup goal, the volumetric flow rate of infiltration through the soil, the volumetric flow rate of the groundwater, and the background concentration of the chemical in the aquifer (assumed to be zero to establish a baseline for evaluation of the remediation goals).

Once the maximum allowable contaminant concentration in the leachate has been determined, the maximum allowable contaminant concentration in the soil can be calculated. This contaminant concentration is the soil cleanup level that should be attained to be protective of groundwater. The soil concentration is estimated by multiplying the leachate concentration by the equilibrium partition coefficient. The calculations for the leachate concentration and soil concentrations are then combined and rearranged to solve for an acceptable concentration in soil:

$$C_s = \frac{C_{gw}\,(Q_p + Q_a)\,K_d}{Q_p} \qquad \text{(EPA 1989a)}$$

where:

C_s = Acceptable soil concentration in micrograms per kilogram (μg/kg)

C_{gw} = Contaminant concentration in groundwater (such as an MCL or PRG) in micrograms per liter (μg/L)

Q_p = Volumetric flow rate of infiltration in cubic feet per day (ft^3/day)
= $V_{dz}(A_p)$

Q_a = Volumetric flow rate of groundwater (ft^3/day) under contaminated area
= $V_d(h)(w)$

K_d = Soil/water equilibrium partitioning coefficient in liters per kilogram (L/kg)
= $K_{oc}(f_{oc})$

V_{dz} = Darcy infiltration velocity in downward direction in feet per day (ft/day)

A_p = Surface area of contamination (ft^2)

V_d = Darcy groundwater velocity in aquifer (ft/day)

h = Aquifer thickness (ft)

w = Width of contamination perpendicular to flow direction in aquifer (ft)

K_{oc} = Water/organic carbon partitioning coefficient (L/kg)

f_{oc} = Fraction organic carbon in soils (unitless)

Finally, degradation of organic compounds can be predicted using the power law. The power law assumes first order decay and states that the degradation rate of an organic chemical is proportional to the organic chemical's concentration (Dragun 1988):

$$C_t = C_o e^{-kt}$$

where:
C_t = Concentration at time (t) (μg/kg)
C_o = Initial concentration (μg/kg)
k = Biodegradation rate constant per unit time (1/time)
e = The base of the natural logarithms, the unique positive real number such that $\{\ln e = 1\}$

Assuming the concentration at time t (C_t) is equal to the acceptable soil concentration (C_a), the initial concentration is the soil concentration that would be protective of groundwater quality allowing for degradation. Setting C_a equal to C_t and solving for C_o yields the modified Summer's model that will be used for predicting acceptable petroleum constituent concentrations in soil:

$$C_o = \left[\frac{C_{gw} \, (Q_p + Q_a) \, K_d}{Q_p} \right] / e^{-kt}$$

The model is designed to be conservative and intended to be protective of groundwater quality. The model uses the following simplifying assumptions:

- No chemical volatilization is occurring (conservative).
- The soil/water system is at equilibrium.
- No chemical attenuation is occurring (conservative).
- The unsaturated soil zone is homogeneous down to the aquifer.
- Chemicals are mixed throughout the thickness of the impacted material.

The model does not account for any contaminant dilution or attenuation due to horizontal transport within the aquifer. Maximum allowable soil concentrations are, therefore, estimated based on the assumption that groundwater must meet acceptable levels within the aquifer directly beneath the source, which is a conservative assumption.

To the extent possible, site-specific parameters (such as infiltration and groundwater flow velocities) have been used in the model. If no site-specific data exist (such as chemical specific values for K_{oc}), parameters have been estimated from published values (such as Howard and others 1991) that most closely represent site conditions at NAS Moffett Field.

3.1 INPUT PARAMETERS

The input parameters used in the modified Summer's model are listed below. Descriptions and rationales for selection of the values for these parameters follow. The actual parameter values used appear in Tables B-1, B-3, and B-5 presented at the end of the appendix. The corresponding results appear in Tables B-2, B-4, and B-6 and are summarized in Section 4.0.

- Weight percentage (Wt%)
- Half life ($t_{1/2}$)
- Organic carbon partition coefficient (K_{oc})
- Fraction organic carbon in soil (f_{oc})
- Acceptable groundwater concentration (C_{gw})
- Thickness of the upper aquifer (h)
- Surface area of contamination (A_p)
- Width of contamination perpendicular to groundwater flow (W)
- Upper aquifer velocity (V_d)
- Infiltration rate (V_{dz})

3.1.1 Weight Percentage

Weight percentage has been included as a means of relating the concentration of individual constituents (such as benzene or naphthalene) to the overall concentration of the petroleum mixture. Weight percentage was incorporated because of the difficulties involved in attempting to model petroleum mixtures. Few data exist on estimating the transport of a petroleum mixture itself. However, more data and information are available regarding the transport of individual constituents. Therefore, the transport of petroleum itself has been estimated by modeling the primary individual constituents and, using the weight percentage of the individual constituent to calculate a value for purgeable or extractable TPH corresponding to the entire petroleum mixture.

The weight percentage values used in the model are from literature references, primarily the California leaking underground fuel tank field manual (SWRCB 1989). This reference contains information on the chemical compositions of gasoline and diesel fuels. Almost all weight percentage data reflect new or fresh fuel products. Using these values to characterize older petroleum contamination is a conservative assumption since biotransformation processes have reduced the concentrations of many of the individual constituents. The results of using weight percentage values, therefore, include the worst-case scenario that original concentrations of the individual constituents are still present.

3.1.2 Half Life

Half life values for individual petroleum constituents are from literature references such as Environmental Degradation Rates (Howard and others 1991). The values selected represent the longest rate published, regardless of degradation conditions. For example, the degradation rate used for benzene represents a value measured for groundwater anaerobic conditions. However, many of the shallow soils are under aerobic conditions, which would actually decrease the half life. Using higher degradation rates results in a conservative estimate of persistence; chemicals will remain in the soils longer than actually anticipated.

3.1.3 Organic Carbon Partition Coefficient

K_{oc} values used in the model are from literature references such as Research Triangle Institute (RTI) Soil Action Levels (EPA 1992). For chemicals with several published values (such as BTEX constituents), the values selected represent the average of published values. For chemicals with few or no published values (such as the alkanes), K_{oc} values were either calculated based on the chemical's solubility or estimated from other chemicals with similar characteristics and behavior.

3.1.4 Fraction Organic Carbon in Soil

Typically, f_{oc} is a site-specific value. However, due to the heterogeneity of the subsurface soils, an average value was used that represents the various soil types at NAS Moffett Field. Consequently, an average value will be more representative of varying soil types, than specific values for specific soil types. A value of 0.01 was selected for all sites. This value was derived in the NAS Moffett Field operable unit 2 remedial investigation report (IT 1993).

3.1.5 Acceptable Groundwater Concentration

Two acceptable groundwater concentration scenarios were used in the model. The first scenario was that drinking water standards had to be met for each of the individual constituents at each site. The second scenario was that the groundwater concentrations developed from the groundwater fate and transport analysis (35 mg/L TPH purgeable as gasoline and 500 mg/L TPH extractable as diesel) had to be met at each site. This scenario required back calculating an individual constituent groundwater concentration from the weight percentage of each constituent in the petroleum mixture. These scenarios provide a range of acceptable soil concentrations depending on the groundwater quality goals. Generally, the more stringent the groundwater quality goal, the more stringent the acceptable soil level.

3.1.6 Thickness Upper Aquifer

The thickness of the upper aquifer includes the thickness of the materials through which infiltration and contaminant migration occurs. The model assumes that contaminant leachate in the unsaturated zone is in equilibrium with the groundwater directly under the contamination. The model further assumes that mixing occurs within the thickness of upper aquifer. Because petroleum products are generally less dense than water, they tend to float or mix within the first few feet of groundwater. Therefore only the first few feet of groundwater should be considered in addition to the unsaturated soils through which migration occurs.

An average upper aquifer thickness was selected for use in the model at all sites. The rationale is because of the heterogeneity of the subsurface soils at NAS Moffett Field and the similar depth to groundwater at each site. The heterogeneity of the subsurface soils includes clay layers that create localized confined conditions and the depth to groundwater measured in wells in these areas are not necessarily representative of the actual mixing zone. The depth to groundwater at NAS Moffett Field is approximately 10 to 20 feet below ground surface. An average aquifer thickness of 20 feet was selected for all sites assuming an average depth to groundwater of 15 feet and a 5-foot thick mixing zone in the groundwater.

3.1.7 Surface Area of Contamination

This parameter was estimated from the extent of contamination maps in the petroleum sites characterization report (PRC 1994a). The areas of contamination were approximated using rectangular areas covering the detections of TPH and petroleum-related constituents (such as BTEX) because the exact extent of contamination at the sites is unclear.

3.1.8 Width of Contamination Perpendicular to Groundwater Flow

The groundwater flow direction on the eastern side of NAS Moffett Field is generally to the north, and the direction on the western side is to the northeast. These directions were compared to the areal extent of the contamination, and a width perpendicular to the flow direction was estimated.

3.1.9 Upper Aquifer Velocity

An average velocity of the upper aquifer was selected for all sites. This value is from the NAS Moffett Field OU4 feasibility study (FS) (PRC 1992). The FS represents a comprehensive evaluation of the west side aquifers, and for the purpose of this model, it was assumed that these values are approximately similar on the eastern side of the station. Groundwater gradients across NAS Moffett Field generally support this assumption.

3.1.10 Infiltration Rate

This value is based on the average annual rainfall at NAS Moffett Field (IT 1993). It has been assumed that 10 percent of the rainfall is available for infiltration. This assumption provides a conservative estimate because most of the petroleum contamination at NAS Moffett Field lies underneath pavement, where little, if any, infiltration occurs. Additionally, mechanisms associated with runoff, evaporation, and evapotranspiration also minimize the quantity of rainfall available for infiltration.

3.2 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to evaluate which parameters the modified Summer's model is sensitive to. The analysis consisted of selecting a site and varying the input parameters to evaluate the changes in results. For this evaluation, benzene contamination at Site 19, Tank 53, was selected. Benzene was selected because its chemical properties (toxicity and mobility) suggest it is the dominant chemical of concern. Site 19, Tank 53, was selected because of the high benzene concentrations observed at the site and knowledge of the extent of contamination.

The sensitivity analysis was conducted by first establishing a baseline condition for the site using the most appropriate input parameters. Then, each of the input parameters were varied above and below the baseline condition. Table B-7 presents the baseline condition for benzene, depicts the input variations, and presents the results of those variations.

The results of the sensitivity analysis reveal that the modified Summer's model is particularly sensitive to changes in K_{oc}, f_{oc}, infiltration velocity, acceptable groundwater concentrations, and over time, half life. These sensitivities are expected because the model evaluates sorption and degradation as the primary fate and transport mechanisms. The use of average or maximum values in the model will minimize the variations caused by these sensitivities, yet yield conservative results.

4.0 RESULTS

Results of applying the modified Summer's model at Sites 5, 9, and 19 are contained in Tables B-2 and B-4 (the corresponding input parameters appear in Tables B-1 and B-3, respectively). These results indicate that petroleum concentrations in soils of 1,000 mg/kg TPH purgeable as gasoline and 5,000 mg/kg TPH extractable as diesel will be protective of the groundwater fate and transport-based scenario (35 mg/kg TPH purgeable as gasoline and 500 mg/kg TPH extractable as diesel), allowing 10 years for degradation. Petroleum concentrations in soils of 150 mg/kg TPH purgeable as gasoline and 400 mg/kg TPH extractable as diesel will be protective of the drinking water-based scenario, allowing 10 years for degradation. A 10-year degradation period was chosen to correspond with future land use.

The modified Summer's model was also recalculated to use existing soil concentrations to estimate the concentrations that would be expected in samples from downgradient monitoring wells for each site (Tables B-5 and B-6). This was conducted by solving the modified Summer's equation for C_{gw} (acceptable groundwater concentration) rather than for C_s (acceptable soil concentration). Existing soil concentrations were used or estimated from TPH values and the resulting groundwater concentrations were evaluated. Comparing these results to actual downgradient concentrations observed at NAS Moffett Field (PRC 1994b) indicates that the model predicts much higher TPH concentrations than are actually present. This result indicates that the modified Summer's model is overly conservative in estimating groundwater impacts.

TABLE B-1

INPUT PARAMETERS
FATE AND TRANSPORT USING ESTIMATED GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \Big/ \exp[-0.693 * time/(t\,1/2)]$$

where; $Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL INPUTS												
	Wt% Weight Percent Chemical in TPH (1) (percent)	t 1/2 Half Life (2) (days)	Koc Organic Carbon Partition Coefficient (3) (l/kg)	foc Fraction Organic Carbon in Soil (4) (unitless)	Kd Equilibrium Partition Coefficient (l/kg)	Cgw Acceptable Groundwater Concentration (5) (ug/l)	h Thickness Uppermost Aquifer (ft)	Ap Surface Area of Contamination (6) (sq.ft)	W Width Perpendicular to Groundwater Flow (ft)	Vd Uppermost Aquifer Velocity (7) (ft/day)	Vdz Infiltration Velocity (8) (ft/day)	Qp Infiltration Flow Rate (cu.ft/day)	Qa Groundwater Flow Rate (cu.ft/day)
						SITE 5 (TPH as Diesel/JP5)							
Benzo[a]pyrene	0.13	2,117	398,000	0.01	3,980	650	20	135,000	300	0.2304	0.0003	40.5	1382.4
Naphthalene	0.91	258	871	0.01	8.71	4,550	20	135,000	300	0.2304	0.0003	40.5	1382.4
Phenanthrene	0.13	799	22,910	0.01	229.10	650	20	135,000	300	0.2304	0.0003	40.5	1382.4
n-Decane	2.00	1,460	4,735	0.01	47.4	10,000	20	135,000	300	0.2304	0.0003	40.5	1382.4
						SITE 9 - BLDG 29 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1,225	20	4,500	100	0.2304	0.0003	1.35	460.8
Toluene	21.8	210	163	0.01	1.63	7,630	20	4,500	100	0.2304	0.0003	1.35	460.8
Ethylbenzene	2.9	228	165	0.01	1.65	1,015	20	4,500	100	0.2304	0.0003	1.35	460.8
Xylene	3.9	365	187	0.01	1.87	1,365	20	4,500	100	0.2304	0.0003	1.35	460.8
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	175.0	20	100,000	200	0.2304	0.0003	30	921.6
Naphthalene	0.5	258	871	0.01	8.71	175	20	100,000	200	0.2304	0.0003	30	921.6
n-Hexane	3.5	1,460	1,097	0.01	11.0	1,225	20	100,000	200	0.2304	0.0003	30	921.6
Pentane	10.9	1,460	1,000	0.01	10.00	3,815	20	100,000	200	0.2304	0.0003	30	921.6
						SITE 9 - BLDG 31 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1,225	20	9,500	150	0.2304	0.0003	2.85	691.2
Toluene	21.8	210	163	0.01	1.63	7,630	20	9,500	150	0.2304	0.0003	2.85	691.2
Ethylbenzene	2.9	228	165	0.01	1.65	1,015	20	9,500	150	0.2304	0.0003	2.85	691.2
Xylene	3.9	365	187	0.01	1.87	1,365	20	9,500	150	0.2304	0.0003	2.85	691.2
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	175.0	20	67,500	150	0.2304	0.0003	20.25	691.2
Naphthalene	0.5	258	871	0.01	8.71	175	20	67,500	150	0.2304	0.0003	20.25	691.2
n-Hexane	3.5	1,460	1,097	0.01	11.0	1,225	20	67,500	150	0.2304	0.0003	20.25	691.2
Pentane	10.9	1,460	1,000	0.01	10.00	3,815	20	67,500	150	0.2304	0.0003	20.25	691.2

TABLE B-1 (continued)

INPUT PARAMETERS
FATE AND TRANSPORT USING ESTIMATED GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} / \exp[-0.693 * time/(t\ 1/2)]$$

where; $Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL INPUTS											
	Wt%	t 1/2	Koc	foc	Kd	Cgw	h	Ap	W	Vd	Vdz	Qp	Qa
	Weight Percent Chemical in TPH (1) (percent)	Half Life (2) (days)	Organic Carbon Partition Coefficient (3) (l/kg)	Fraction Organic Carbon in Soil (4) (unitless)	Equilibrium Partition Coefficient (l/kg)	Acceptable Groundwater Concentration (5) (ug/l)	Thickness Uppermost Aquifer (ft)	Surface Area of Contamination (6) (sq.ft)	Width Perpendicular to Groundwater Flow (ft)	Uppermost Aquifer Velocity (7) (ft/day)	Infiltration Velocity (8) (ft/day)	Infiltration Flow Rate (cu.ft/day)	Groundwater Flow Rate (cu.ft/day)
						SITE 19 - TANK 53 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1,225	20	3,600	60	0.2304	0.0003	1.08	276.48
Toluene	21.8	210	163	0.01	1.63	7,630	20	3,600	60	0.2304	0.0003	1.08	276.48
Ethylbenzene	2.9	228	165	0.01	1.65	1,015	20	3,600	60	0.2304	0.0003	1.08	276.48
Xylene	3.9	365	187	0.01	1.87	1,365	20	3,600	60	0.2304	0.0003	1.08	276.48
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	175.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Naphthalene	0.5	258	871	0.01	8.71	175	20	3,600	60	0.2304	0.0003	1.08	276.48
n-Hexane	3.5	1,460	1,097	0.01	11.0	1,225	20	3,600	60	0.2304	0.0003	1.08	276.48
Pentane	10.9	1,460	1,000	0.01	10.00	3,815	20	3,600	60	0.2304	0.0003	1.08	276.48

NOTES:

(1) Wt% is maximum value from California LUFT manual (SWQCB 1989). Wt% values for some polycyclic aromatic hydrocarbons (PAHs) were not available and were estimated to be less than or equivalent to the Wt% of naphthalene.

(2) t 1/2 values are the longest values from the Handbook of Environmental Degradation Rates (Howard and others 1991). t 1/2 values for alkanes were not available and were estimated to be equivalent to twice the half life of benzene since alkanes are readily degradable.

(3) Koc values for BTEX constituents are from RTI Soil Action Levels (EPA 1992) and represent an average of published values. Koc values for PAHs are from the Groundwater Chemicals Desk Reference (Montgomery and others 1990) and from the Database of Chemical Properties for SARA (EPA 1989b). Koc values for alkanes are from Cleanup of Releases From Petroleum USTs: Selected Technologies (EPA 1988).

(4) foc value is from the NAS Moffett Field OU2 Remedial Investigation Report (IT 1993).

(5) Cgw values are based on an overall acceptable groundwater concentrations of 500,000 ug/l TPH as diesel and 35,000 ug/l TPH as gasoline multiplied by Wt%. These TPH values are from the groundwater fate and transport evaluation.

(6) Surface area (Ap) was estimated from the Petroleum Sites Characterization Report (PRC 1994a). Ap for Site 9 BTEX was estimated from the Buildings 29 and 31 benzene plumes.

(7) Vd is from OU4 FS (PRC 1992).

(8) Vdz is estimated at 10% of the annual rainfall (IT 1993).

TABLE B-2

RESULTS

FATE AND TRANSPORT USING ESTIMATED GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} / \exp[-0.693 * time/(t\ 1/2)]$$

where; $Qp = Ap * Vdz$

$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL OUTPUT (1)									
	Cs (initial)		Cs (1 year)		Cs (2 years)		Cs (5 years)		Cs (10 years)	
	Acceptable Chemical Soil Concentration to Achieve Cgw Today (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 1 Year (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 2 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 5 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 10 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)
				SITE 5 (TPH as Diesel/JP5)						
Benzo[a]pyrene	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000
Naphthalene	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000
Phenanthrene	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000
n-Decane	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000
				SITE 9 - BLDG 29 (TPH as Gasoline)						
Benzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Toluene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Ethylbenzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Xylene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Benzo[a]pyrene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Naphthalene	48,349	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
n-Hexane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Pentane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
				SITE 9 - BLDG 31 (TPH as Gasoline)						
Benzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Toluene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Ethylbenzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Xylene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Benzo[a]pyrene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Naphthalene	53,552	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
n-Hexane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Pentane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000

TABLE B-2 (continued)

RESULTS
FATE AND TRANSPORT USING ESTIMATED GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \; / \; \exp [-0.693 * time/(t\ 1/2)]$$

where;
$Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL OUTPUT (1)									
	Cs (initial)		Cs (1 year)		Cs (2 years)		Cs (5 years)		Cs (10 years)	
	Acceptable Chemical Soil Concentration to Achieve Cgw Today (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 1 Year (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 2 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 5 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 10 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)
				SITE 19 - TANK 53 (TPH as Gasoline)						
Benzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Toluene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Ethylbenzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Xylene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Benzo[a]pyrene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Naphthalene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
n-Hexane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Pentane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000

NOTES:

(1) Upper limits have been established for chemical and total petroleum hydrocarbon (TPH) concentrations to limit the uncertainty of modeling the fate and transport of high chemical concentrations. Additionally, upper limits were established to correspond with acceptable human health risk levels, since results significantly above human health risk levels cannot be considered protective. Upper limits are 100,000 ug/kg for individual chemicals, 1,000 mg/kg for TPH purgeable as gasoline, and 5,000 mg/kg TPH extractable as diesel.

TABLE B-3

INPUT PARAMETERS
FATE AND TRANSPORT USING MCL GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \ / \ \exp[-0.693 * time/(t\ 1/2)]$$

where; Qp = Ap * Vdz
Qa = Vd * W * h

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL INPUTS												
	Wt% Weight Percent Chemical in TPH (1) (percent)	t 1/2 Half Life (2) (days)	Koc Organic Carbon Partition Coefficient (3) (l/kg)	foc Fraction Organic Carbon in Soil (4) (unitless)	Kd Equilibrium Partition Coefficient (l/kg)	Cgw Acceptable Groundwater Concentration (5) (ug/l)	h Thickness Uppermost Aquifer (ft)	Ap Surface Area of Contamination (6) (sq.ft)	W Width Perpendicular to Groundwater Flow (ft)	Vd Uppermost Aquifer Velocity (7) (ft/day)	Vdz Infiltration Velocity (8) (ft/day)	Qp Infiltration Flow Rate (cu.ft/day)	Qa Groundwater Flow Rate (cu.ft/day)
						SITE 5 (TPH as Diesel/JP5)							
Benzo[a]pyrene	0.13	2,117	398,000	0.01	3,980	0.2	20	135,000	300	0.2304	0.0003	40.5	1382.4
Naphthalene	0.91	258	871	0.01	8.71	20	20	135,000	300	0.2304	0.0003	40.5	1382.4
Phenanthrene	0.13	799	22,910	0.01	229.10	0.0028	20	135,000	300	0.2304	0.0003	40.5	1382.4
n-Decane	2.00	1,460	4,735	0.01	47.4	400	20	135,000	300	0.2304	0.0003	40.5	1382.4
						SITE 9 - BLDG 29 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1	20	4,500	100	0.2304	0.0003	1.35	460.8
Toluene	21.8	210	163	0.01	1.63	1,000	20	4,500	100	0.2304	0.0003	1.35	460.8
Ethylbenzene	2.9	228	165	0.01	1.65	680	20	4,500	100	0.2304	0.0003	1.35	460.8
Xylene	3.9	365	187	0.01	1.87	1,750	20	4,500	100	0.2304	0.0003	1.35	460.8
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	0.2	20	100,000	200	0.2304	0.0003	30	921.6
Naphthalene	0.5	258	871	0.01	8.71	20	20	100,000	200	0.2304	0.0003	30	921.6
n-Hexane	3.5	1,460	1,097	0.01	11.0	400	20	100,000	200	0.2304	0.0003	30	921.6
Pentane	10.9	1,460	1,000	0.01	10.00	400	20	100,000	200	0.2304	0.0003	30	921.6
						SITE 9 - BLDG 31 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1	20	9,500	150	0.2304	0.0003	2.85	691.2
Toluene	21.8	210	163	0.01	1.63	1,000	20	9,500	150	0.2304	0.0003	2.85	691.2
Ethylbenzene	2.9	228	165	0.01	1.65	680	20	9,500	150	0.2304	0.0003	2.85	691.2
Xylene	3.9	365	187	0.01	1.87	1,750	20	9,500	150	0.2304	0.0003	2.85	691.2
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	0.2	20	67,500	150	0.2304	0.0003	20.25	691.2
Naphthalene	0.5	258	871	0.01	8.71	20	20	67,500	150	0.2304	0.0003	20.25	691.2
n-Hexane	3.5	1,460	1,097	0.01	11.0	400	20	67,500	150	0.2304	0.0003	20.25	691.2
Pentane	10.9	1,460	1,000	0.01	10.00	400	20	67,500	150	0.2304	0.0003	20.25	691.2

TABLE B-3 (continued)

INPUT PARAMETERS
FATE AND TRANSPORT USING MCL GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} / \exp[-0.693 * time/(t\ 1/2)]$$

where;
$Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL INPUTS												
	Wt%	t 1/2	Koc	foc	Kd	Cgw	h	Ap	W	Vd	Vdz	Qp	Qa
	Weight Percent Chemical in TPH (1) (percent)	Half Life (2) (days)	Organic Carbon Partition Coefficient (3) (l/kg)	Fraction Organic Carbon in Soil (4) (unitless)	Equilibrium Partition Coefficient (l/kg)	Acceptable Groundwater Concentration (5) (ug/l)	Thickness Uppermost Aquifer (ft)	Surface Area of Contamination (6) (sq.ft)	Width Perpendicular to Groundwater Flow (ft)	Uppermost Aquifer Velocity (7) (ft/day)	Infiltration Velocity (8) (ft/day)	Infiltration Flow Rate (cu.ft/day)	Groundwater Flow Rate (cu.ft/day)
						SITE 19 - TANK 53 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1	20	3,600	60	0.2304	0.0003	1.08	276.48
Toluene	21.8	210	163	0.01	1.63	1,000	20	3,600	60	0.2304	0.0003	1.08	276.48
Ethylbenzene	2.9	228	165	0.01	1.65	680	20	3,600	60	0.2304	0.0003	1.08	276.48
Xylene	3.9	365	187	0.01	1.87	1,750	20	3,600	60	0.2304	0.0003	1.08	276.48
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	0.2	20	3,600	60	0.2304	0.0003	1.08	276.48
Naphthalene	0.5	258	871	0.01	8.71	20	20	3,600	60	0.2304	0.0003	1.08	276.48
n-Hexane	3.5	1,460	1,097	0.01	11.0	400	20	3,600	60	0.2304	0.0003	1.08	276.48
Pentane	10.9	1,460	1,000	0.01	10.00	400	20	3,600	60	0.2304	0.0003	1.08	276.48

NOTES:

(1) Wt% is maximum value from California LUFT Manual (SWQCB 1989). Wt% values for polycyclic aromatic hydrocarbons (PAHs) were not available and were estimated to be less than or equivalent to the Wt% of naphthalene.

(2) t 1/2 values are the longest values from the Handbook of Environmental Degradation Rates (Howard and others 1991). t 1/2 values for alkanes were not available and were estimated to be equivalent to twice the half life of benzene since alkanes are readily degradable.

(3) Koc values for BTEX constituents are from RTI Soil Action Levels (EPA 1992) and represent an average of published values. Koc values for PAHs are from the Groundwater Chemicals Desk Reference (Montgomery and others 1990) and from the Database of Chemical Properties for SARA (EPA 1989b). Koc values for alkanes are from Cleanup of Releases From Petroleum USTs: Selected Technologies (EPA 1988).

(4) foc value is from the NAS Moffett Field OU2 Remedial Investigation Report (IT 1993).

(5) Cgw values are from A Compilation of Water Quality Goals (RWQCB 1991) and Water Quality Goals for Components of Petroleum-Based Fuels in "Mun" Designated Water Memorandum (RWQCB 1993). Cgw values for most alkanes were not available and were estimated to be equivalent to n-Hexane.

(6) Surface area (Ap) was estimated from the Petroleum Sites Characterization Report (PRC 1994a). Ap for Site 9 BTEX was estimated from the Buildings 29 and 31 benzene plumes.

(7) Vd is from OU4 FS (PRC 1992).

(8) Vdz is estimated at 10% of the annual rainfall (IT 1993).

TABLE B-4

RESULTS
FATE AND TRANSPORT USING MCL GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \; / \; \exp[-0.693 * time/(t\ 1/2)]$$

where;
$Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL OUTPUT (1)									
	Cs (initial)		Cs (1 year)		Cs (2 years)		Cs (5 years)		Cs (10 years)	
	Acceptable Chemical Soil Concentration to Achieve Cgw Today (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 1 Year (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 2 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 5 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 10 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)
				SITE 5 (TPH as Diesel/JP5)						
Benzo[a]pyrene	27,966	5,000	31,515	5,000	35,515	5,000	50,826	5,000	92,372	5,000
Naphthalene	6,120	673	16,314	1,793	43,485	4,779	100,000	5,000	100,000	5,000
Phenanthrene	23	17	31	24	42	33	110	84	534	411
n-Decane	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000	100,000	5,000
				SITE 9 - BLDG 29 (TPH as Gasoline)						
Benzene	226	6	320	9	452	13	1,278	37	7,225	206
Toluene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Ethylbenzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Xylene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Benzo[a]pyrene	25,249	1,000	28,454	1,000	32,065	1,000	45,888	1,000	83,398	1,000
Naphthalene	5,526	1,000	14,729	1,000	39,260	1,000	100,000	1,000	100,000	1,000
n-Hexane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Pentane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
				SITE 9 - BLDG 31 (TPH as Gasoline)						
Benzene	161	5	227	6	321	9	909	26	5,139	147
Toluene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Ethylbenzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Xylene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Benzo[a]pyrene	27,966	1,000	31,515	1,000	35,515	1,000	50,826	1,000	92,372	1,000
Naphthalene	6,120	1,000	16,314	1,000	43,485	1,000	100,000	1,000	100,000	1,000
n-Hexane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Pentane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000

TABLE B-4 (continued)

RESULTS
FATE AND TRANSPORT USING MCL GROUNDWATER CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \; / \; \exp[-0.693 * time/(t\ 1/2)]$$

where; $Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL OUTPUT (1)									
	Cs (initial)		Cs (1 year)		Cs (2 years)		Cs (5 years)		Cs (10 years)	
	Acceptable Chemical Soil Concentration to Achieve Cgw Today (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 1 Year (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 2 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 5 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 10 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)
					SITE 19 - TANK 53 (TPH as Gasoline)					
Benzene	170	5	240	7	339	10	959	27	5,424	155
Toluene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Ethylbenzene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Xylene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Benzo[a]pyrene	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Naphthalene	44,769	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
n-Hexane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000
Pentane	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000	100,000	1,000

NOTES:

(1) Upper limits have been established for chemical and total petroleum hydrocarbon (TPH) concentrations to limit the uncertainty of modeling the fate and transport of high chemical concentrations. Additionally, upper limits were established to correspond with acceptable human health risk levels, since results significantly above human health risk levels cannot be considered protective. Upper limits are 100,000 ug/kg for individual chemicals, 1,000 mg/kg for TPH purgeable as gasoline, and 5,000 mg/kg for TPH extractable as diesel.

TABLE B-5

INPUT PARAMETERS
ESTIMATING POTENTIAL GROUNDWATER CONCENTRATIONS USING EXISTING SOIL CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \; / \; \exp[-0.693 * time/(t\,1/2)]$$

where; $Qp = Ap * Vdz$
$Qa = Vd * W * h$

$$Cgw = \frac{Cs * Qp * \exp[-0.693 * time/(t\,1/2)]}{(Qp + Qa) * Kd}$$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL INPUTS												
	Wt%	t 1/2	Koc	foc	Kd	Cs	h	Ap	W	Vd	Vdz	Qp	Qa
	Weight Percent Chemical in TPH (percent)	Half Life (days)	Organic Carbon Partition Coefficient (l/kg)	Fraction Organic Carbon in Soil (unitless)	Equilibrium Partition Coefficient (l/kg)	Existing Soil Concentration (1) (ug/kg)	Thickness Uppermost Aquifer (ft)	Surface Area of Contamination (sq.ft)	Width Perpendicular to Groundwater Flow (ft)	Uppermost Aquifer Velocity (ft/day)	Infiltration Velocity (ft/day)	Infiltration Flow Rate (cu.ft/day)	Groundwater Flow Rate (cu.ft/day)
						SITE 5 (TPH as Diesel)							
Benzo[a]pyrene	0.13	2,117	398,000	0.01	3,980	1,900	20	135,000	300	0.2304	0.0003	40.5	1382.4
Naphthalene	0.91	258	871	0.01	8.71	13,300	20	135,000	300	0.2304	0.0003	40.5	1382.4
Phenanthrene	0.13	799	22,910	0.01	229.1	1,900	20	135,000	300	0.2304	0.0003	40.5	1382.4
n-Decane	2.00	1,460	4,735	0.01	47.4	29,200	20	135,000	300	0.2304	0.0003	40.5	1382.4
						SITE 9 - BLDG 29 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	1,100	20	4,500	100	0.2304	0.0003	1.35	460.8
Toluene	21.8	210	163	0.01	1.63	460	20	4,500	100	0.2304	0.0003	1.35	460.8
Ethylbenzene	2.9	228	165	0.01	1.65	18,000	20	4,500	100	0.2304	0.0003	1.35	460.8
Xylene	3.9	365	187	0.01	1.87	8,800	20	4,500	100	0.2304	0.0003	1.35	460.8
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	23,000	20	100,000	200	0.2304	0.0003	30	921.6
Naphthalene	0.5	258	871	0.01	8.71	23,000	20	100,000	200	0.2304	0.0003	30	921.6
n-Hexane	3.5	1,460	1,097	0.01	11.0	100,000	20	100,000	200	0.2304	0.0003	30	921.6
Pentane	10.9	1,460	1,000	0.01	10	100,000	20	100,000	200	0.2304	0.0003	30	921.6
						SITE 9 - BLDG 31 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	4,450	20	9,500	150	0.2304	0.0003	2.85	691.2
Toluene	21.8	210	163	0.01	1.63	10,100	20	9,500	150	0.2304	0.0003	2.85	691.2
Ethylbenzene	2.9	228	165	0.01	1.65	12,200	20	9,500	150	0.2304	0.0003	2.85	691.2
Xylene	3.9	365	187	0.01	1.87	85,700	20	9,500	150	0.2304	0.0003	2.85	691.2
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	22,850	20	67,500	150	0.2304	0.0003	20.25	691.2
Naphthalene	0.5	258	871	0.01	8.71	22,850	20	67,500	150	0.2304	0.0003	20.25	691.2
n-Hexane	3.5	1,460	1,097	0.01	11.0	100,000	20	67,500	150	0.2304	0.0003	20.25	691.2
Pentane	10.9	1,460	1,000	0.01	10	100,000	20	67,500	150	0.2304	0.0003	20.25	691.2

TABLE B-5 (continued)

INPUT PARAMETERS
ESTIMATING POTENTIAL GROUNDWATER CONCENTRATIONS USING EXISTING SOIL CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \Big/ \exp[-0.693 * time/(t\ 1/2)] \qquad \text{where;} \quad Qp = Ap * Vdz$$

$$Qa = Vd * W * h$$

$$Cgw = \frac{Cs * Qp * \exp[-0.693 * time/(t\ 1/2)]}{(Qp + Qa) * Kd}$$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL INPUTS												
	Wt% Weight Percent Chemical in TPH (percent)	t 1/2 Half Life (days)	Koc Organic Carbon Partition Coefficient (l/kg)	foc Fraction Organic Carbon in Soil (unitless)	Kd Equilibrium Partition Coefficient (l/kg)	Cs Existing Soil Concentration (1) (ug/kg)	h Thickness Uppermost Aquifer (ft)	Ap Surface Area of Contamination (sq.ft)	W Width Perpendicular to Groundwater Flow (ft)	Vd Uppermost Aquifer Velocity (ft/day)	Vdz Infiltration Velocity (ft/day)	Qp Infiltration Flow Rate (cu.ft/day)	Qa Groundwater Flow Rate (cu.ft/day)
						SITE 9 - BLDG 31 (TPH as Gasoline)							
Benzene	3.5	730	66	0.01	0.66	4,160	20	3,600	60	0.2304	0.0003	1.08	276.48
Toluene	21.6	210	163	0.01	1.63	6,810	20	3,600	60	0.2304	0.0003	1.08	276.48
Ethylbenzene	2.9	228	165	0.01	1.65	14,950	20	3,600	60	0.2304	0.0003	1.08	276.48
Xylene	3.9	365	187	0.01	1.87	77,710	20	3,600	60	0.2304	0.0003	1.08	276.48
Benzo[a]pyrene	0.5	2,117	398,000	0.01	3,980	8,000	20	3,600	60	0.2304	0.0003	1.08	276.48
Naphthalene	0.5	258	871	0.01	8.71	8,000	20	3,600	60	0.2304	0.0003	1.08	276.48
n-Hexane	3.5	730	1,097	0.01	11.0	56,000	20	3,600	60	0.2304	0.0003	1.08	276.48
Pentane	10.9	730	568	0.01	5.68	100,000	20	3,600	60	0.2304	0.0003	1.08	276.48

NOTES: PAHs and alkanes were not analyzed. PAH and alkane concentrations were estimated from the maximum TPH concentrations detected at each site multiplied by Wt%. Maximum detections include 1,460 mg/kg (TPH as diesel, Site 5), 4,600 mg/kg (TPH as gasoline, Site 9 - Building 29), 4,750 mg/kg (TPH as Gasoline, Site 9 - Building 31), and 1,600 mg/kg (TPH as gasoline, Site 19 - Tank 53). An upper limit of 100,000 ug/kg was established for unknown concentrations since site data do not indicate concentrations above these levels. BTEX data are from the Petroleum Sites Characterization Report (PRC 1994a) and represent the maximum values detected.

TABLE B-6

RESULTS
ESTIMATING POTENTIAL GROUNDWATER CONCENTRATIONS USING EXISTING SOIL CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} / \exp[-0.693 * time/(t\ 1/2)]$$

where;

$Qp = Ap * Vdz$

$Qa = Vd * W * h$

$$Cgw = \frac{Cs * Qp * \exp[-0.693 * time/(t\ 1/2)]}{(Qp + Qa) * Kd}$$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL OUTPUT									
	Cgw (initial)		Cgw (1 year)		Cgw (2 years)		Cgw (5 years)		Cgw (10 years)	
	Estimated Chemical Concentration in Groundwater Today (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 1 Year (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 2 Years (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 5 Years (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 10 Years (ug/l)	Corresponding TPH Concentration (ug/l)
				SITE 5 (TPH as Diesel)						
Benzo[a]pyrene	0	10	0	9	0	8	0	6	0	3
Naphthalene	43	4,776	16	1,792	6	672	0	35	0	0
Phenanthrene	0	182	0	132	0	96	0	37	0	8
n-Decane	18	878	15	738	12	621	7	369	3	155
				SITE 9 - BLDG 29 (TPH as Gasoline)						
Benzene	5	139	3	98	2	70	1	25	0	4
Toluene	1	4	0	1	0	0	0	0	0	0
Ethylbenzene	32	1,114	11	367	3	121	0	4	0	0
Xylene	14	355	7	178	3	89	0	11	0	0
Benzo[a]pyrene	0	37	0	33	0	29	0	20	0	11
Naphthalene	83	16,989	31	6,374	12	2,391	1	126	0	1
n-Hexane	287	8,211	242	6,905	203	5,806	121	3,453	51	1,452
Pentane	315	2,887	265	2,428	223	2,042	133	1,214	56	511
				SITE 9 - BLDG 31 (TPH as Gasoline)						
Benzene	28	791	20	559	14	396	5	140	1	25
Toluene	25	117	8	35	2	10	0	0	0	0
Ethylbenzene	30	1,062	10	350	3	115	0	4	0	0
Xylene	188	4,863	94	2,432	47	1,216	6	152	0	5
Benzo[a]pyrene	0	33	0	30	0	26	0	18	0	10
Naphthalene	75	15,239	28	5,717	11	2,145	1	113	0	1
n-Hexane	259	7,413	218	6,234	183	5,242	109	3,117	46	1,311
Pentane	285	2,607	239	2,192	201	1,843	120	1,096	50	461

TABLE B-6 (continued)

RESULTS

ESTIMATING POTENTIAL GROUNDWATER CONCENTRATIONS USING EXISTING SOIL CONCENTRATIONS

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} / \exp[-0.693 * time/(t\ 1/2)]$$

where;

$Qp = Ap * Vdz$

$Qa = Vd * W * h$

$$Cgw = \frac{Cs * Qp * \exp[-0.693 * time/(t\ 1/2)]}{(Qp + Qa) * Kd}$$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Chemical	MODEL OUTPUT									
	Cgw (initial)		Cgw (1 year)		Cgw (2 years)		Cgw (5 years)		Cgw (10 years)	
	Estimated Chemical Concentration in Groundwater Today (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 1 Year (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 2 Years (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 5 Years (ug/l)	Corresponding TPH Concentration (ug/l)	Estimated Chemical Concentration in Groundwater in 10 Years (ug/l)	Corresponding TPH Concentration (ug/l)
				SITE 9 - BLDG 31 (TPH as Gasoline)						
Benzene	25	701	17	496	12	350	4	124	1	22
Toluene	16	75	5	22	1	7	0	0	0	0
Ethylbenzene	35	1,233	12	406	4	134	0	5	0	0
Xylene	162	4,178	81	2,069	40	1,045	5	131	0	4
Benzo[a]pyrene	0	2	0	1	0	1	0	1	0	0
Naphthalene	4	729	1	274	1	103	0	5	0	0
n-Hexane	20	568	14	401	10	284	4	100	1	18
Pentane	69	627	48	444	34	314	12	111	2	20

TABLE B-7

SENSITIVITY ANALYSIS USING BENZENE

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} \, / \, \exp[-0.693 * time/(t\ 1/2)]$$

where;
$Qp = Ap * Vdz$
$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Parameter Changes (Site 19 - Tank 53)	MODEL INPUTS (1)											
	Wt% Weight Percent Chemical in TPH (2) (percent)	t 1/2 Half Life (3) (days)	Koc Organic Carbon Partition Coefficient (4) (l/kg)	foc Fraction Organic Carbon in Soil (5) (unitless)	Kd Equilibrium Partition Coefficient (l/kg)	Cgw Acceptable Groundwater Concentration (6) (ug/l)	h Thickness Uppermost Aquifer (ft)	Ap Surface Area of Contamination (7) (sq.ft)	W Width Perpendicular to Groundwater Flow (ft)	Vd Uppermost Aquifer Velocity (8) (ft/day)	Vdz Infiltration Velocity (9) (ft/day)	Qp Infiltration Flow Rate (cu.ft/day)	Qa Groundwater Flow Rate (cu.ft/day)
Baseline	3.5	730	66	0.01	0.66	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Increase Koc	3.5	730	83	0.01	0.83	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Decrease Koc	3.5	730	49	0.01	0.49	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Decrease foc	3.5	730	66	0.002	0.132	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Increase Vdz	3.5	730	66	0.01	0.66	1.0	20	3,600	60	0.2304	0.003	10.8	276.48
Decrease Wt%	2.0	730	66	0.01	0.66	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Increase Wt%	5.0	730	66	0.01	0.66	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Decrease t 1/2	3.5	365	66	0.01	0.66	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Increase t 1/2	3.5	1460	66	0.01	0.66	1.0	20	3,600	60	0.2304	0.0003	1.08	276.48
Decrease h	3.5	730	66	0.01	0.66	1.0	10	3,600	60	0.2304	0.0003	1.08	138.24
Increase h	3.5	730	66	0.01	0.66	1.0	30	3,600	60	0.2304	0.0003	1.08	414.72
Decrease Ap	3.5	730	66	0.01	0.66	1.0	20	1,000	60	0.2304	0.0003	0.3	276.48
Increase Ap	3.5	730	66	0.01	0.66	1.0	20	5,000	60	0.2304	0.0003	1.5	276.48
Decrease W	3.5	730	66	0.01	0.66	1.0	20	3,600	40	0.2304	0.0003	1.08	184.32
Increase W	3.5	730	66	0.01	0.66	1.0	20	3,600	80	0.2304	0.0003	1.08	368.64
Increase Vd	3.5	730	66	0.01	0.66	1.0	20	3,600	60	0.3	0.0003	1.08	360.00
Decrease Vd	3.5	730	66	0.01	0.66	1.0	20	3,600	60	0.15	0.0003	1.08	180.00
Decrease Cgw	3.5	730	66	0.01	0.66	0.49	20	3,600	60	0.15	0.0003	1.08	180.00
Increase Cgw	3.5	730	66	0.01	0.66	4.9	20	3,600	60	0.15	0.0003	1.08	180.00

NOTES:

(1) Highlighted parameters indicate model changes.
(2) Wt% is maximum value from California LUFT manual (SWQCB 1989).
(3) t 1/2 value is the longest value from the Handbook of Environmental Degradation Rates (Howard and others 1991).
(4) Koc value for benzene is from RTI Soil Action Levels (EPA 1992) and represents an average of published values.
(5) foc value is from the NAS Moffett Field OU2 Remedial Investigation Report (IT 1993).
(6) Cgw value is from A Compilation of Water Quality Goals (RWQCB 1991). Cgw values were changed to represent a 1 x 10-6 residential risk (0.49 ug/l) and a 1 x 10-5 residential risk (4.9 ug/l).
(7) Surface area (Ap) was estimated from the Petroleum Sites Characterization Report (PRC 1994a).
(8) Vd is from OU4 FS (PRC 1992).
(9) Vdz is estimated at 10% of the annual rainfall (IT 1993).

TABLE B-7 (continued)

SENSITIVITY ANALYSIS USING BENZENE

$$Cs = \frac{Cgw * (Qp + Qa) * Kd}{Qp} / \exp[-0.693 * time/(t\ 1/2)]$$

where;

$Qp = Ap * Vdz$

$Qa = Vd * W * h$

MODIFIED SUMMER'S MODEL FOR ESTIMATING ACCEPTABLE PETROLEUM LEVELS IN SOILS

Parameter Changes (Site 19 - Tank 53)	MODEL OUTPUT									
	Cs (initial)		Cs (1 year)		Cs (2 years)		Cs (5 years)		Cs (10 years)	
	Acceptable Chemical Soil Concentration to Achieve Cgw Today (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 1 Year (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 2 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 5 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)	Acceptable Chemical Soil Concentration to Achieve Cgw in 10 Years (ug/kg)	Corresponding TPH Concentration (mg/kg)
Baseline	170	5	240	7	339	10	959	27	5,424	155
Increase Koc	213	6	302	9	427	12	1,206	34	6,821	195
Decrease Koc	126	4	178	5	252	7	712	20	4,027	115
Decrease foc	34	1	48	1	68	2	192	5	1,085	31
Increase Vdz	18	1	25	1	35	1	99	3	561	16
Decrease Wt%	170	8	240	12	339	17	959	48	5,424	271
Increase Wt%	170	3	240	5	339	7	959	19	5,424	108
Decrease t 1/2	170	5	339	10	678	19	5,424	155	173,435	4,955
Increase t 1/2	170	5	202	6	240	7	403	12	959	27
Decrease h	85	2	120	3	170	5	481	14	2,722	78
Increase h	254	7	359	10	508	15	1,437	41	8,125	232
Decrease Ap	609	17	861	25	1,218	35	3,443	98	19,471	556
Increase Ap	122	3	173	5	245	7	692	20	3,911	112
Decrease W	113	3	160	5	227	6	641	18	3,623	104
Increase W	226	6	320	9	452	13	1,278	37	7,225	206
Increase Vd	221	6	312	9	441	13	1,248	36	7,056	202
Decrease Vd	111	3	156	4	221	6	626	18	3,539	101
Decrease Cgw	54	2	77	2	108	3	307	9	1,734	50
Increase Cgw	542	15	767	22	1,084	31	3,066	88	17,339	495
									Average	422

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APPENDIX C

SUMMARY OF ANALYTICAL MODELING OF TRANSPORT OF PETROLEUM CONTAMINATION IN GROUNDWATER

CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

This appendix summarizes the approach, procedures, and results from analytical modeling of fuel-related constituents in groundwater under conditions believed to represent the shallow aquifer at Naval Air Station (NAS) Moffett Field. The results of this modeling are used in predicting the general behavior of fuel constituents in groundwater, to evaluate levels of contamination in an aquifer which will be protective of ecologically sensitive wetland areas at the station, and to evaluate constraints (time frames and cleanup limitations) on remedial technologies.

This appendix contains five sections. Section 2.0 describes the rationale and approach used for evaluating fuel constituent transport in groundwater. Section 3.0 presents the analytical transport equation and the assumptions used in model calculations. Section 4.0 summarizes the results of the modeling calculations and Section 5.0 lists references.

2.0 APPROACH

The following discussion of the fate and transport of fuel constituents in groundwater is based on extensive review of prior research on the topic. For more detailed descriptions of the behavior of organic constituents in groundwater may be found in the following publications: Smith and others (1981), Nyer and Skladany (1989), Davis and Olsen (1990), Olsen and Davis (1990), Testa and Winegardner (1990), MacKay and others (1991), McFarland and Sims (1991), Borden and Kao (1992), Chen and others (1992) and Olsen and Kavanaugh (1993).

The behavior of fuels in groundwater/aquifer systems can be described in terms of migration of pure fuel nonaqueous phase liquid (NAPL) and migration of dissolved constituents. The factors which determine whether pure or dissolved fuel phases will impact groundwater have been discussed in Sections 3.3, 3.4, and Appendix B of this report. In summary, these factors include: (1) the volume, type, and age of the petroleum release, (2) the physical and chemical properties of the fuel, and (3) the characteristics of the soil between the release and the water table (including soil thickness, retention capacity, permeability, oxidation conditions, and sorption capacity).

Since fuels are generally insoluble in water and do not mix with water, they tend to form NAPLs. The direct introduction of fuel NAPL into an aquifer poses a complex and long-term problem for removal of contamination if deemed necessary. NAPLs which are free (mobile) or residual in an aquifer will be long-term sources of dissolved groundwater contamination because most fuel constituents have a very small, but measurable, solubility and will continuously dissolve into groundwater. It is assumed that NAPLs pose a threat to human health and the environment and immediate action is warranted to limit their impact on uncontaminated portions of an aquifer. It should be noted, however, that remediation of an aquifer with residual NAPLs is difficult and may not allow for attainment of stringent cleanup goals (Nyer and Skladany 1989, Borden and Kao 1992, EPA 1992, Rao and others 1992, Cohen and Mercer 1993, Olsen and Kavanaugh 1993). The migration and impact of NAPLs in an aquifer is beyond the scope of this report and will not be addressed. Only migration of dissolved fuels will be considered.

Modeling the transport of fuels in groundwater cannot be done directly since: (1) fuels are complex mixtures (solutions) of a wide variety of constituents, (2) fuels vary in composition, and (3) little specific information useful in modeling is available for bulk fuels, and (4) the process of dissolution is chemical-specific and segregates fuel constituents. Specific chemical information is available on many of the constituents of fuels which can be used to describe the behavior of dissolved fuels. However, consideration of all fuel constituents would be cumbersome. The characteristics of fuels may be approximated by considering the primary groups of constituents comprising a general fuel type. This report makes three groupings of fuel constituents: (1) the straight and branched chain compounds (alkanes), which comprise the bulk of fuels; (2) the aromatic compounds benzene, toluene, ethylbenzene, and xylene (BTEX); and (3) the polynuclear aromatic hydrocarbons (PAHs). Within each of these groups, some variation in geochemical behavior is displayed, but only one or two compounds which typify the behavior of the group are considered for fate and transport modeling. However, this is a simplifying assumption necessary to conduct the modeling and the geochemical behavior of a complex solution may be different than the behavior of an individual constituent of that solution. Selection of modeling parameters in this report was always conservative in favor of protecting human health and the environment. For example, when modeling the transport of gasoline using geochemical parameters for benzene, the initial concentration of the contamination was assumed to be comprised solely of benzene. Benzene does not typically occur above 3.5 percent in fresh gasoline, and may not even be present in older releases.

Transport Properties

Fuel constituent properties that influence the fate and transport of these constituents in groundwater include solubility, sorption, reactivity, and degradation potential. (Diffusion of fuel constituents is accounted for in the transport equation, but is negligible in the permeable aquifer materials modeled.) Other parameters related to the aquifer that control fate and transport of fuel constituents include porosity (void space), permeability (ease of flow), sorption capacity (which depends on organic carbon and clay content), heterogeneity, aquifer thickness, flow rate, and degradation potential. All of these parameters are accounted for in the modeling, except the heterogeneity of the aquifer. Modeling of heterogeneity would require a sophisticated numerical computer model requiring an expenditure of effort beyond the scope of this task. In this case, assumption of a homogeneous aquifer of moderate to higher permeability results in an overestimation of transport and adds to the conservatism of the model. A short discussion of each transport process is presented below.

The ability of a fuel constituent to dissolve and be transported in groundwater depends on the compound's solubility, soil/water partitioning, and aquifer characteristics, such as flow rate, permeability, and composition. Table C-1 presents solubility, soil/water distribution coefficients, and retardation factors (the rate relative to water that a contaminant will travel in an aquifer) for representative fuel constituents. Benzene has a moderate solubility, low soil/water distribution coefficient, and tends to be easily transported in solution. In contrast, straight-chain alkanes, such as n-hexane, have lower solubilities, higher distribution coefficients, and are much less mobile in groundwater. Complex molecules such as PAHs are essentially insoluble and are immobile in an aquifer.

Sorption is the complex process that binds a chemical once dissolved in water to the solid materials in an aquifer. Sorption depends on the chemical properties of the constituent (represented by partitioning or distribution coefficients) and the medium to which the chemical may be sorbed. Generally, the tendency of a chemical to be sorbed is a function of its solubility in water. Therefore, benzene and lighter alkanes will be less sorbed to aquifer material, whereas heavier alkanes and PAHs will be strongly sorbed. Once sorbed, a chemical may be desorbed (returned to the water), mineralized and fixed, or degraded. The sorption of a chemical in an aquifer depends on many factors, but for organic compounds the primary factor is the content of naturally occurring organic carbon in the aquifer. (Adsorption onto clay minerals is ignored, adding further conservatism to the model.) Sorption, therefore, is a process of removal of contamination from groundwater and fixation of strongly sorbed chemicals such as PAHs. However, a chemical of low to moderate solubility which is sorbed in large quantities to an aquifer material with a high sorption capacity (high organic carbon content) will be available for desorption. This allows for long-term, low-level contamination of groundwater.

TABLE C-1.

SOLUBILITY, DISTRIBUTION COEFFICIENTS, RETARDATION FACTORS, AND ANAEROBIC DEGRADATION HALF LIVES FOR SELECTED FUEL CONSTITUENTS

Compound	Material	Solubility (mg/L)	f_{oc}	K_{oc}	K_d	R_f	Half Life
n-Pentane (Alkane)		360		568			<730
	Fine Sand		0.0022	568	1.2	7.4	
	Silty Clay		0.0044	568	2.5	10.6	
n-Hexane (Alkane)		13		1,097			<730
	Fine Sand		0.0022	1,097	2.4	13.3	
	Silty Clay		0.0044	1,097	4.8	19.5	
n-Decane (Alkane)		0.009		4,735			<730
	Fine Sand		0.0022	4,735	10.4	54.1	
	Silty Clay		0.0044	4,735	20.8	80.7	
Benzene (BTEX)		1,780		59			730
	Fine Sand		0.0022	59	0.1	1.7	
	Silty Clay		0.0044	59	0.3	2.0	
Xylene (BTEX)		175		255			>730
	Fine Sand		0.0022	255	0.6	3.9	
	Silty Clay		0.0044	255	1.1	5.3	
Naphthalene (PAH)		31		664			258
	Fine Sand		0.0022	664	1.5	8.5	
	Silty Clay		0.0044	664	2.9	12.2	
Benz(a)anthracene (PAH)		0.014		1,380,000			2,719
	Fine Sand		0.0022	1,380,000	3,036	15,485	
	Silty Clay		0.0044	1,380,000	6,072	23,226	

Notes:

See text for sources of values used in this table.
The chemical group represented by each compound is shown in parenthesis following each compound name.

f_{oc} = fraction of organic carbon in aquifer (values from NAS Moffett Field data)
K_{oc} = organic carbon/water partition coefficient
K_d = soil/water distribution coefficient (f_{oc}*K_{oc})
R_f = retardation factor {[1 + (ρ/n)*K_d] where ρ = bulk density (1.53 g/cm3) and n = porosity}
Half life = anaerobic (only) degradation half life

Degradation is the process by which a chemical is transformed into by-products with different chemical structures, thus affecting mobility and toxicity. Three types of degradation are considered important: (1) abiotic oxidation/reduction (mineralization), (2) anaerobic biodegradation, and (3) aerobic biodegradation (Dragun 1988, Chen and others 1992). Degradation of fuels is a primary mechanism of fuel contamination reduction. Several factors influence the rate at which a fuel constituent will degrade or be fixed due to mineralization. Some of these factors are compound-related and others relate to soil or aquifer characteristics. In general, lower molecular weight compounds with simpler structures degrade more rapidly since they are more readily metabolized by microorganisms. Degradation of fuels largely occurs on individual constituents which are dissolved in water or are sorbed. Pure fuels (NAPLs) are not directly degradable since they are generally toxic to microorganisms and unreactive.

Inorganic mineralization is probably the least important degradation process and is controlled largely by the availability of inorganic oxidizers such as iron^{3+}, manganese^{4+}, nitrate, and oxygen. Aerobic microbial degradation is an important process of fuel degradation in soils and groundwater in shallow unconfined aquifers with oxidizing conditions. This process relies on microbes to use available oxygen to metabolize fuel constituents. Aerobic degradation, therefore, also depends on the availability and replenishment of oxidizers in groundwater. However, in the confined, reduced-condition, shallow aquifer at NAS Moffett Field, replenishment of oxidizers to an aquifer zone contaminated by fuels is limited. Therefore, these degradation mechanisms are not considered in the transport modeling. This omission adds to the conservatism of the model.

Anaerobic microbial degradation may be the most important hydrocarbon degradation process operating in the aquifers at NAS Moffett Field. This process occurs as a result of microbial metabolism of complex compounds into simpler compounds, such as methane, under anoxic (oxygen-deficient) conditions. Anaerobic degradation half lives for some fuel constituents are presented in Table C-1. (A half life is the length of time required to reduce a compound to half of its initial concentration.) In general, anaerobic degradation is a slow process, and in the case of complex molecules such as PAHs, is largely unimportant. The values presented in Table C-1 are the longest half lives reported in the literature, providing for the slowest degradation rate of fuel constituents. The rate of anaerobic degradation at a given site depends on several factors including the presence of microbes and nutrients, temperature, and the concentration of fuels constituents in the aquifer or groundwater.

The model used in this report relies on a one-dimensional analytical advection-dispersion equation, but also includes retardation due to sorption, and degradation due solely to anaerobic decay. Only higher hydraulic conductivity cases (fine sand and silty sand with hydraulic conductivities of 0.01 and 0.001 feet per minute [ft/min]) were evaluated. Less permeable materials, such as silt and clay (with hydraulic conductivities of 0.0001 to 0.000001 ft/min) were not modeled since transport of most fuel constituents is negligible in these materials. In these materials, degradation is most the important process affecting attenuation of fuel constituents.

3.0 TRANSPORT MODEL EQUATION AND ASSUMPTIONS

The horizontal migration of contaminants is described by a simplified analytical model. Lateral and vertical advection and dispersion which would cause more rapid attenuation of a contaminant plume is not considered. This analytical model is not expected to reflect exact contaminant concentrations over time at specific locations, but instead provides a conservative estimate of concentrations of selected constituents at preselected points downgradient.

Contaminant migration consists of transport by the mass movement of groundwater (advection) and by diffusion and by dispersion. (Diffusion and dispersion are the components of hydrodynamic dispersion. Diffusion, though accounted for in the equation, is negligible for the cases considered.) The one-dimensional form of the advection-dispersion equation was used to describe contaminant transport (Ogata 1970):

$$C = \frac{Co}{2}\left[\operatorname{erfc}\left[\frac{x - V^{*}t}{2\sqrt{D^{*}t}}\right] + \exp\left[\frac{V^{*}x}{D^{*}}\right]\operatorname{erfc}\left[\frac{x + V^{*}t}{2\sqrt{D^{*}t}}\right]\right]$$

Where:

C = contaminant concentration at time t

Co = initial contaminant concentration (t = 0)

erfc = complementary error function

exp = e, the base of the natural logarithms

t = time

x = distance along flow path

V* = average contaminant velocity

D* = dispersion coefficient including retardation due to adsorption

Additionally:

$$V^* = V/R_f$$

and:

$$R_f = 1 + (\rho/n)K_d$$

where:

R_f = retardation factor

V = average linear velocity

ρ = bulk density

n = porosity

K_d = soil/water distribution coefficient

and:

$$V = V_d/n = (K \cdot i)/n$$

where:

V_d = Darcy velocity

K = hydraulic conductivity

i = hydraulic gradient

and further:

$$D^* = D_{xx}/R_f$$

and:

$$D_{xx} = D_{diff} + \alpha_L \cdot V$$

where:

D_{xx} = coefficient of hydrodynamic dispersion

D_{diff} = coefficient of molecular diffusion

α_L = longitudinal dispersivity

As a simplifying assumption, the subsurface geology is considered a homogeneous and isotropic fine sand (or silty sand for benzene) with infinite areal extent. As mentioned previously, the subsurface geology at NAS Moffett Field differs from this assumption. The aquifer parameters, conductivity (K), porosity (n), hydraulic gradient (i), and sorption (f_{oc}, K_d), used in this modeling are taken from several sources (IT 1992, 1993; PRC 1992a, 1992b, 1993). The hydraulic conductivity (K) used for fine sand was 0.01 ft/min and for silty sand was 0.001 ft/min. The value of 0.3 for porosity is conservative (that is, low) allowing for a higher flow velocity. An average hydraulic gradient of

0.005 feet per foot (ft/ft) was used and is believed to be representative of low and high flow rate conditions in the shallow aquifer a NAS Moffett Field. For the pumping scenarios considered, the hydraulic gradient in fine sand was allowed to increase two-fold above the natural gradient and in silty sand was allowed to increase 20-fold. This reflects the relatively large but less pronounced drawdown cone produced in higher conductivity aquifer materials and the smaller but more pronounced drawdown cone for less conductive aquifer materials. The resultant average linear velocity (V) for fine sand is 87 feet per year (ft/year) and for silty sand is 8.7 ft/yr for silty sand.

The retardation factor (R_f) is used to account for the lag in contaminant transport relative to water in an aquifer due to sorption of a contaminant to aquifer materials. Values for the retardation factor were calculated using the equation presented above. The soil/water distribution coefficient (K_d), in the retardation equation, is equal to the fraction of organic carbon (f_{oc}) in an aquifer multiplied by the chemical-specific organic carbon/water partition coefficient (K_{oc}). Chemical specific solubility and K_{oc} values are from several sources, including McCarty and others (1981), Chiou and Schmedding (1982), Montgomery and Welkom (1989), Nyer and Skladany (1989), and SWRCB (1989). For fine sand, an f_{oc} value of 0.0022 was used and for silty sand an f_{oc} value of 0.0044 was used to reflect the generally higher organic carbon contents of finer-grained aquifer materials at NAS Moffett Field. The other parameters used in calculating R_f are bulk density (ρ) and porosity (n). An average value for ρ is 1.53 g/cm^3, and a conservative value for n for fine or silty sand is 0.3. The values for f_{oc}, K_{oc}, K_d, and R_f used in this modeling are presented in Table C-1.

The product of longitudinal dispersivity (α_L) and average linear velocity is added to diffusion (D_{diff}) to equal hydrodynamic dispersion (D_{xx}). Diffusion constants are used for the coefficient of molecular diffusion. The value of 0.0002 ft^2/day was used for diffusion in this modeling is a conservatively high value that is more representative of solutes in coarse-grained aquifers (Freeze and Cherry 1979, Chen and others 1992). As stated previously, the effect of diffusion is negligible in moderate to high permeability aquifers where flow (advection) is the dominant transport process. As a measure of longitudinal dispersivity (α_L), Fetter (1988) suggests using α_L equal to one-tenth of the length of the flow path. For example, α_L is 1 foot when the flow path is 10 feet.

To account for degradation of fuel constituents, only anaerobic degradation of the source plume was allowed. This conservative approach does not account for inorganic or microbial oxidation, and also does not apply to the fraction of the constituent that has been transported from the initial plume. Degradation of the source follows the first order rate decay law given below:

$C = C_0 \exp^{(-kt)}$ where,

C = concentration of source at time t
C_0 = initial concentration of source at t = 0
exp = e, the base of the natural logarithms
k = the first order rate decay constant (k = 0.693/[half life]) and
t = time

The half life used in modeling the degradation of each constituent is the longest anaerobic half life given in the Handbook of Environmental Degradation Rates (Howard and others 1991). Half lives for representative fuel constituents are presented in Table C-1. Half lives for the alkanes are not available, and are represented by the half life for benzene. This is believed to be conservative since the straight and branched chain hydrocarbons (4 to 20 carbon atoms) are more easily broken down (easier to metabolize) than the double-bond ring structure of benzene which is more toxic to microorganisms. For modeling the transport of n-decane, which is relatively immobile, the effect of varying half lives is presented. The half lives in these cases were increased and decreased two-fold.

4.0 RESULTS

The modeling results are used to predict the general behavior of fuel constituents in groundwater, to evaluate levels of contamination in an aquifer which will be protective of ecologically sensitive wetland areas at the station, and to evaluate constraints (time frames and cleanup limitations) on remedial technologies.

Figures C-1 to C-4 show model results for the extent of migration of benzene, n-hexane, n-decane, and naphthalene as a function of concentration, time, and distance downgradient from the initial dissolved source (the leading edge of the initial fuel plume). Figure C-1 is a graph of the migration of the most mobile constituent, benzene, and illustrates downgradient concentrations at selected distances and times. The source is considered continuous but degrading due to anaerobic decay. With time, benzene migrates farther from the source but declines in concentration due to dilution (advection and dispersion), sorption, and degradation. At a point 1,000 feet downgradient of a dissolved source of 2,500 μg/L, the maximum benzene concentration would be below 2 μg/L and would occur at about 12 years in the future. Similarly, modeling the transport of gasoline contamination (as benzene) from Site 9 to a sensitive wetland in the northern part of the base

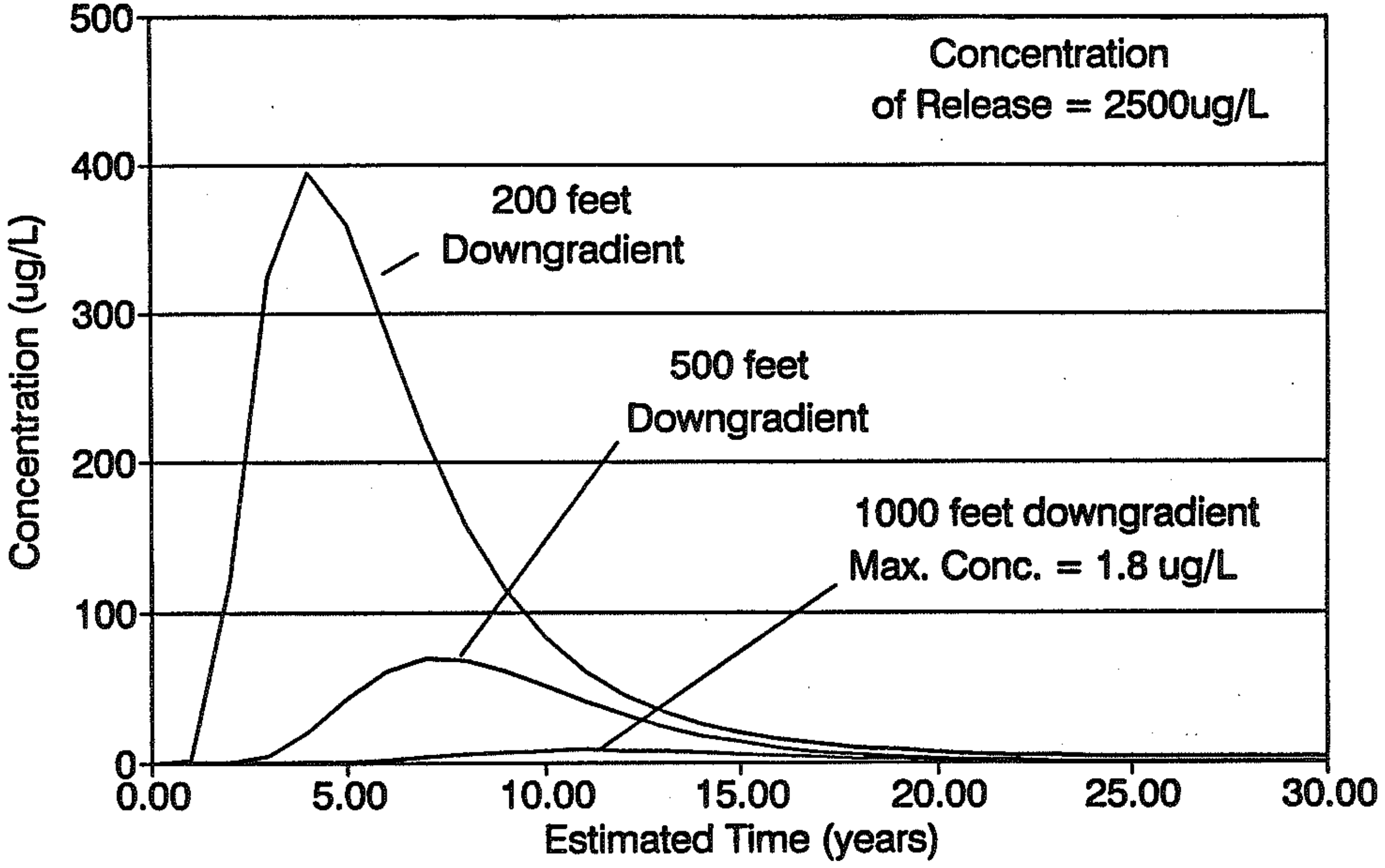

FIGURE C-1
NAS MOFFETT FIELD
BENZENE MIGRATION
FINE SAND AQUIFER

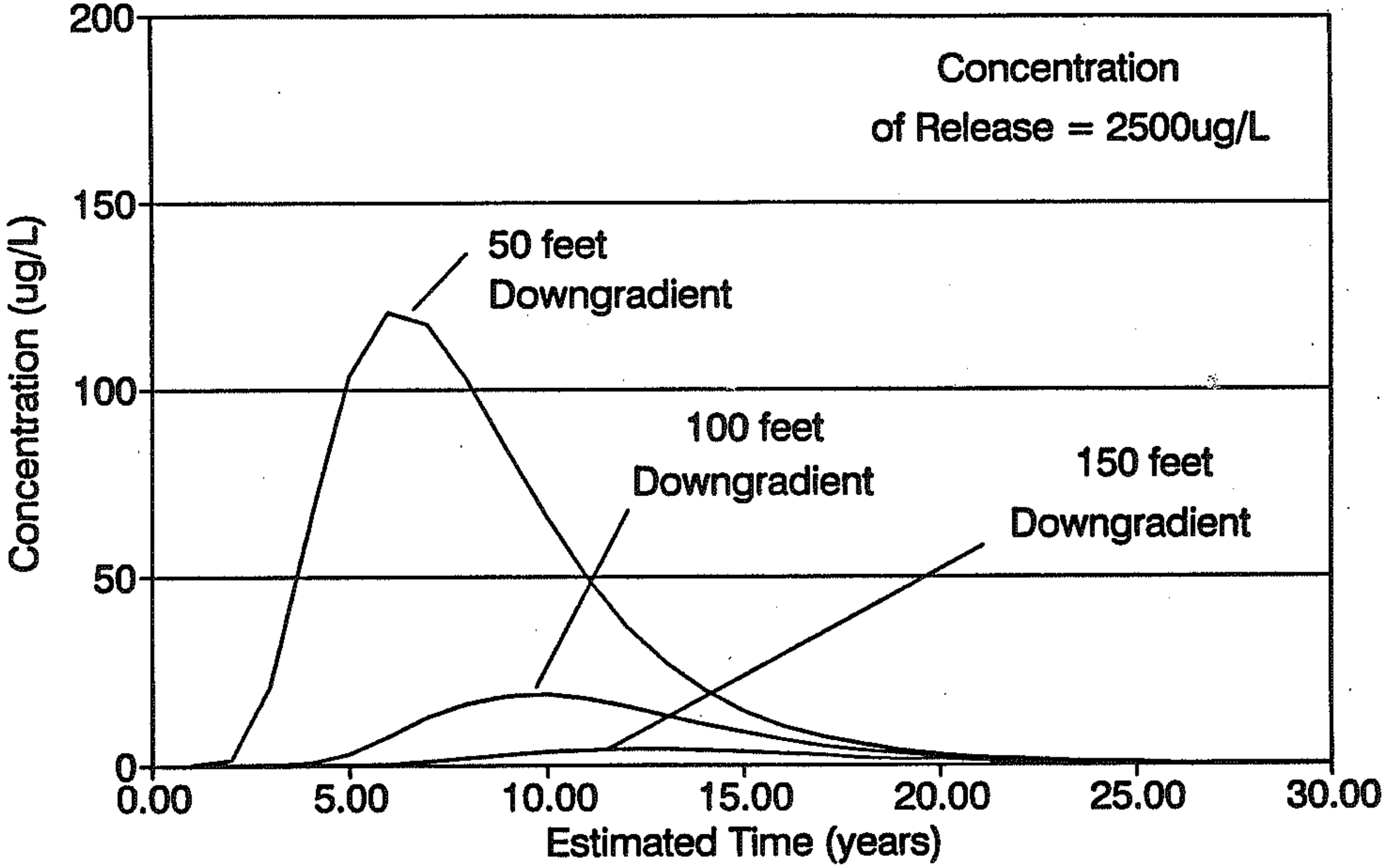

FIGURE C-2
NAS MOFFETT FIELD
n-HEXANE MIGRATION
FINE SAND AQUIFER

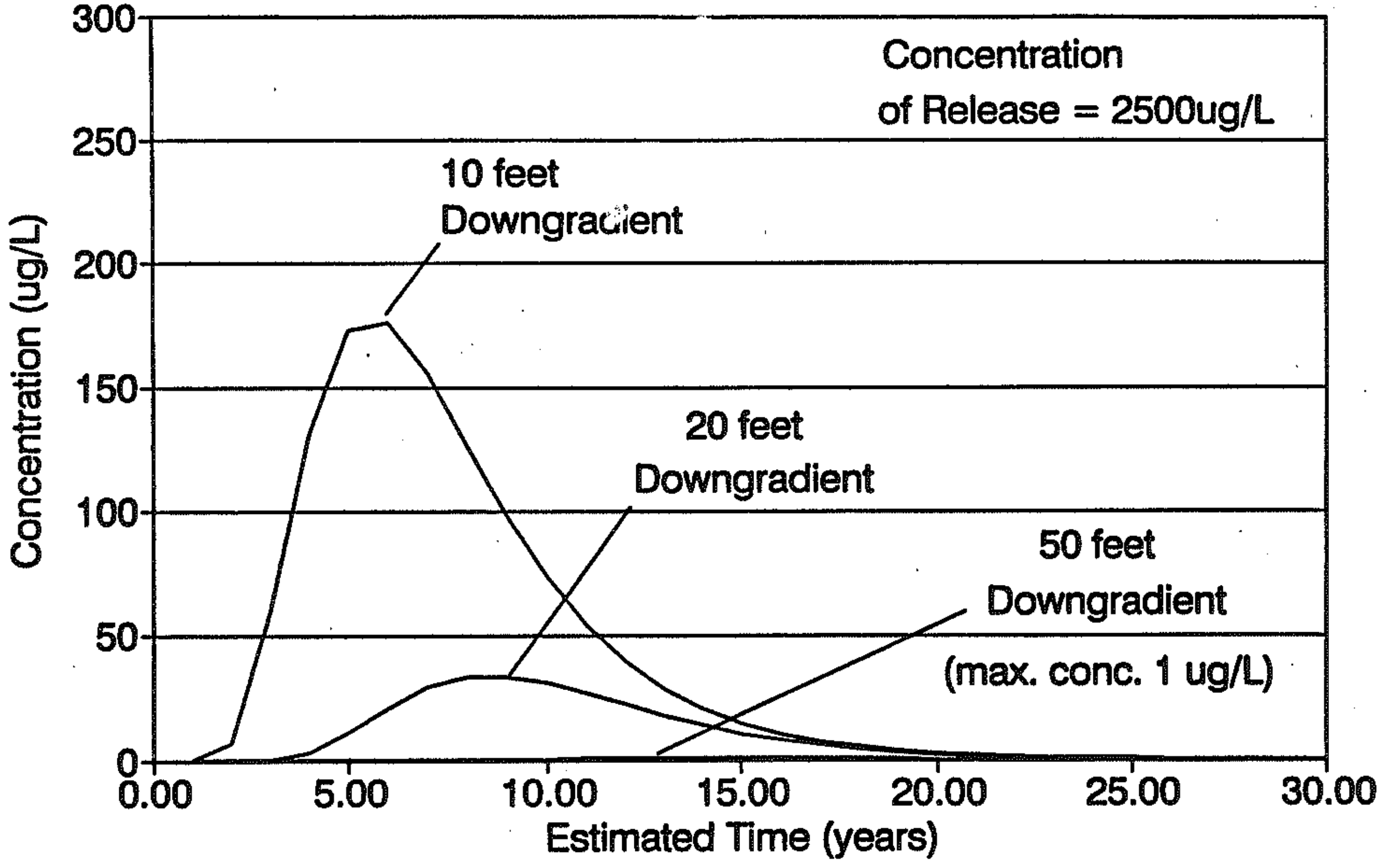

FIGURE C-3
NAS MOFFETT FIELD
n-DECANE MIGRATION
FINE SAND AQUIFER

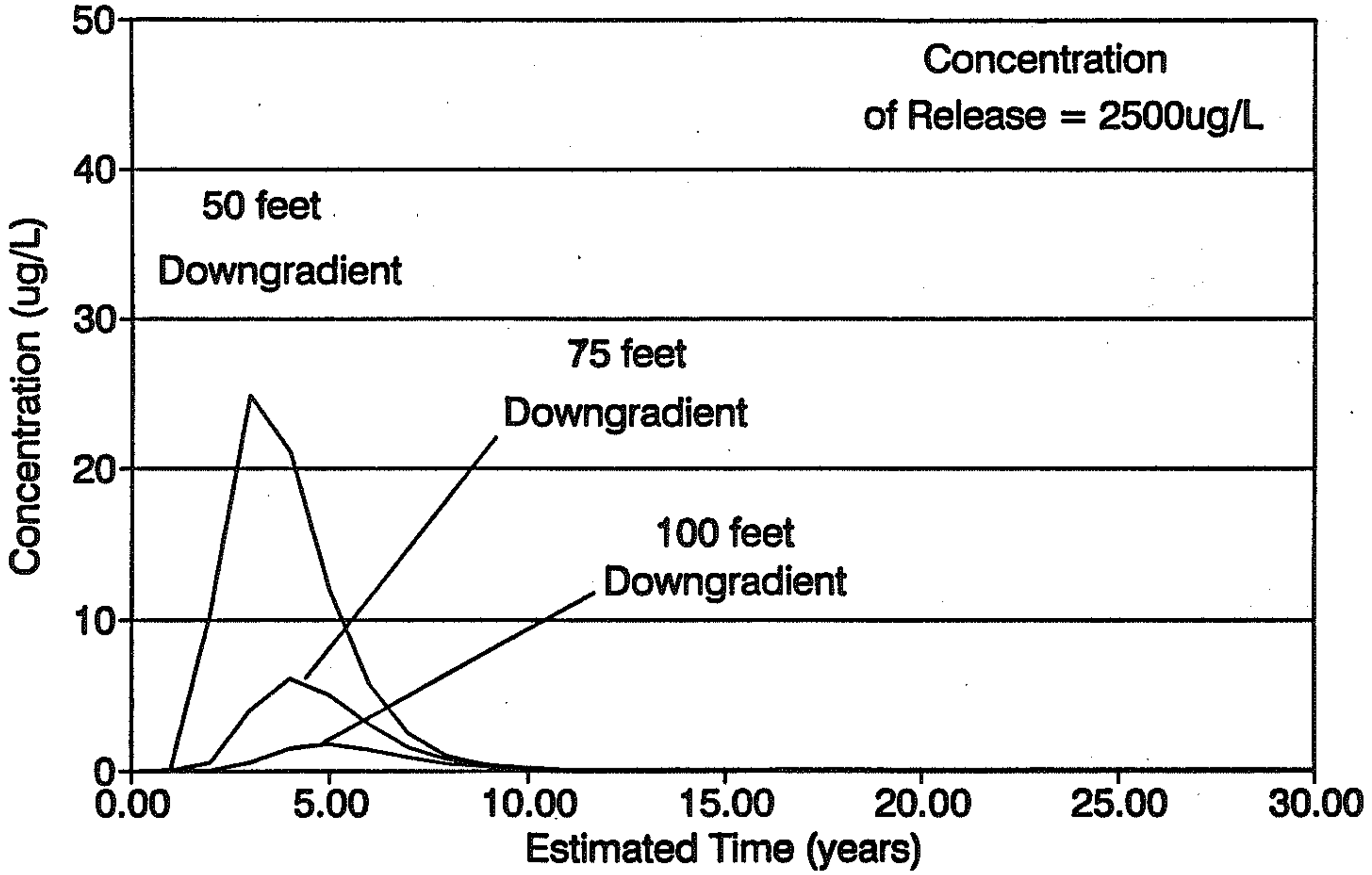

FIGURE C-4
NAS MOFFETT FIELD
NAPHTHALENE MIGRATION
FINE SAND AQUIFER

approximately 2,900 feet downgradient indicates that a hypothetical initial concentration of 35,000 μg/L at Site 9 would migrate and attenuate to a concentration of 0.5 μg/L in groundwater at the wetland at about 18 years in the future. A further reduction in concentration (10 to 100) times would occur as groundwater is introduced to surface water.

It can be seen in Figure C-2 that for the less mobile n-hexane, migration is limited to a much greater degree. An initial concentration of 2,500 μg/L would attenuate to less than 50 μg/L in only 100 feet downgradient from the initial dissolved plume at about 12 years in the future. Modeling the transport of jet fuel (as n-hexane) contamination from Site 5 to a sensitive wetland 2,000 feet downgradient indicates that a hypothetical initial concentration of 500,000 μg/L at Site 5 would attenuate to nondetectable (less than 50 μg/L) values in groundwater long before reaching the wetland (200 feet downgradient from initial source plume). This is a conservative estimate since jet fuel is composed of higher molecular weight, less mobile alkanes than n-hexane. Figures C-3 and C-4 show that n-decane and the relatively mobile PAH naphthalene will be transported much less than n-hexane in groundwater.

Figures C-5 through C-7 show the attenuation/remediation reduction predicted by the model equation for contaminant plumes of benzene, n-hexane, and naphthalene, respectively. All aquifer parameters used in the construction of these figures are the same as for modeling the migration of the constituents presented above (unless noted otherwise). The attenuation shown in these figures is based on a contaminant plume that is 300 feet long and at an initial concentration of 2,500 μg/L. From these graphs, cleanup times may be estimated and the relative importance of dilution and degradation may be evaluated.

Figure C-5 indicates that natural attenuation (dilution and degradation) of benzene occurs relatively quickly (5 to 20 years). Attenuation of benzene in sand is faster than in silty sand aquifers due to greater dilution (advection) and less retardation in the more permeable material that has less organic carbon. The effect of pumping (increasing the hydraulic gradient) can be seen on the attenuation of benzene in this graph. Pumping may significantly reduce remediation time in these permeable materials. However, in finer-grained materials such as clays, pumping will have little to no effect and attenuation of benzene will be controlled by degradation.

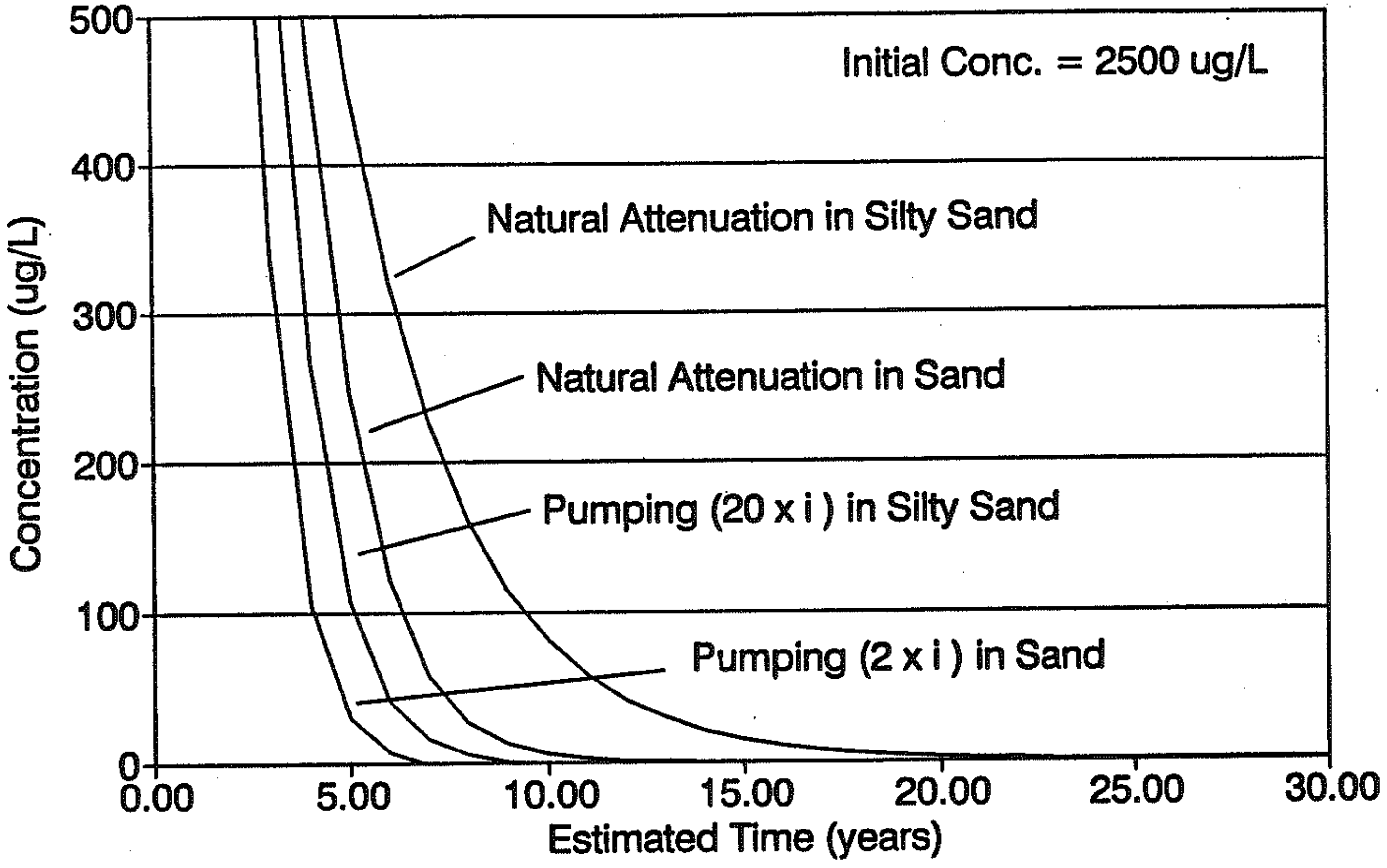

FIGURE C-5
NAS MOFFETT FIELD
BENZENE ATTENUATION/REMEDIATION

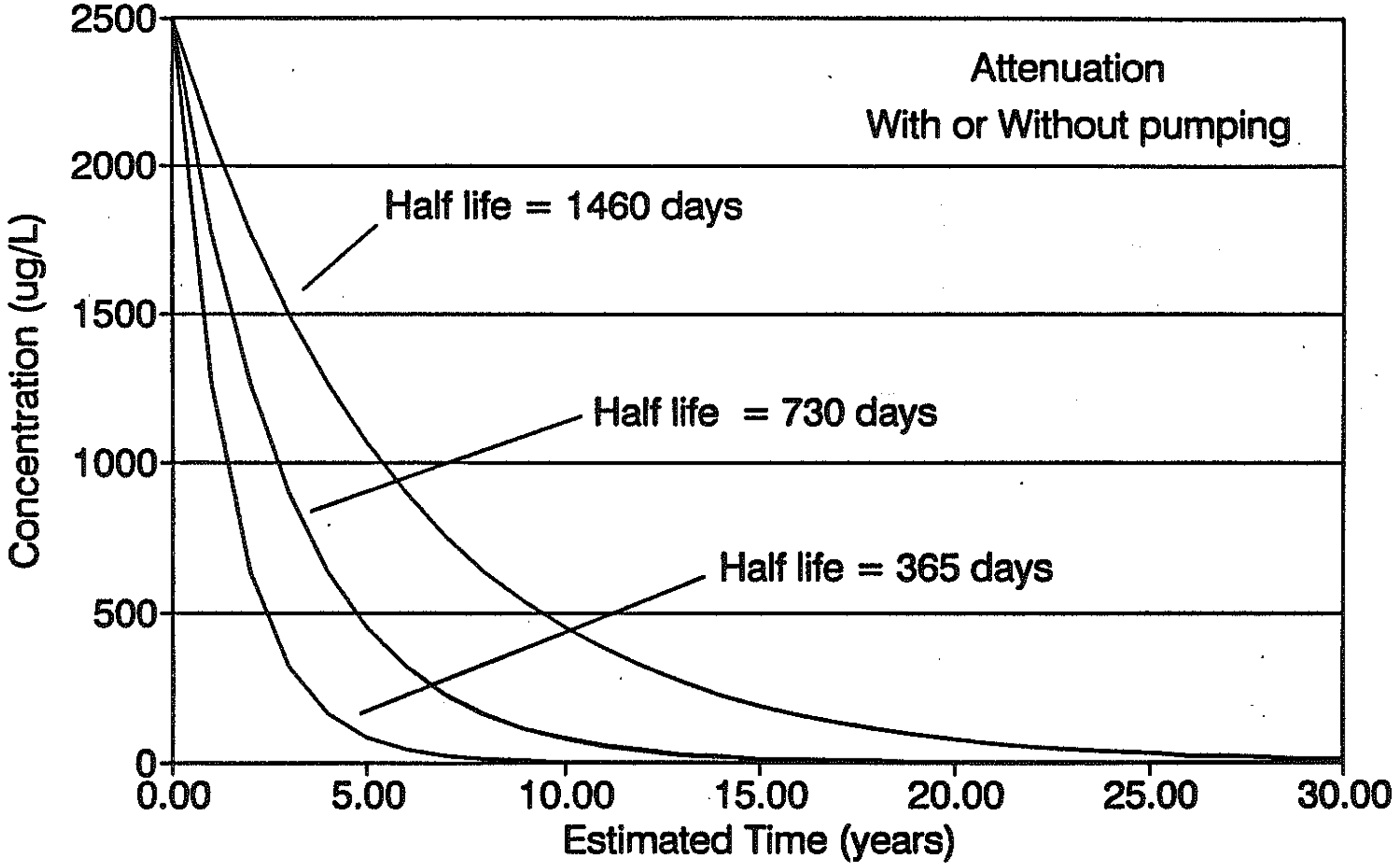

FIGURE C-6
NAS MOFFETT FIELD
n-HEXANE ATTENUATION/REMEDIATION

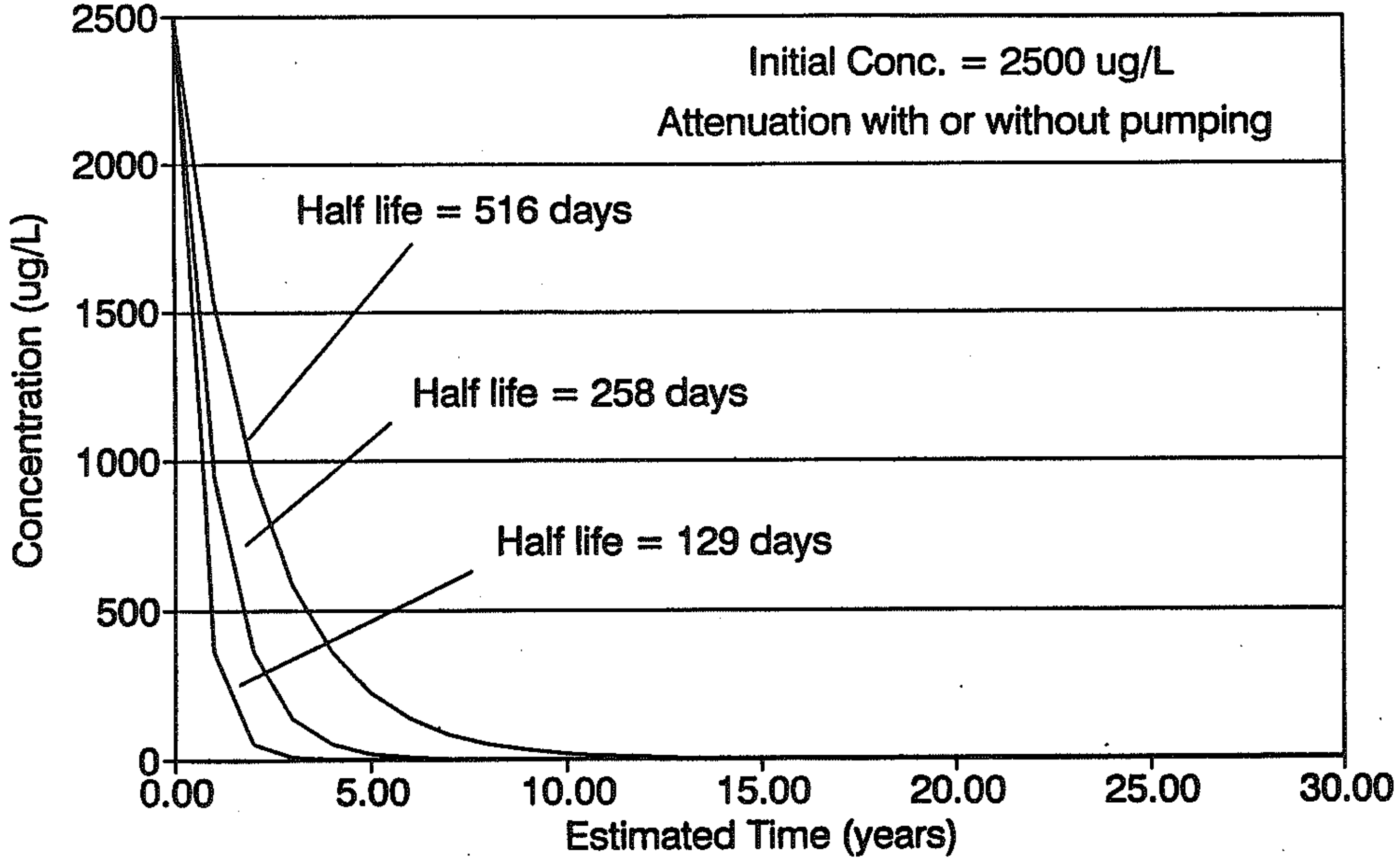

FIGURE C-7
NAS MOFFETT FIELD
NAPHTHALENE ATTENUATION/REMEDIATION

Figures C-6 and C-7 show that natural attenuation of n-hexane and naphthalene occurs in about the same amount of time as benzene. However, the attenuation curves presented in these graphs indicate that concentration reductions depend primarily on degradation. (That is, the no pumping and pumping curves are the same.) An increase in flow due to pumping will not have a significant effect on the attenuation of these chemicals due to their high sorption (retardation) on aquifer materials.

The accurate estimation of cleanup times for the alkanes and the PAHs depends on the accurate determination of degradation. Cleanup technologies for fuels in groundwater based on pump and treat are of limited value for the bulk of fuel constituents because of their limited mobility. Enhanced bioremediation using pump and treat with reinjection, air sparging, or other oxygen enhancement method may be of some value in aquifers of moderate to high permeability.

Due to the distinct differences in chemical properties of fuel constituents, the nature and extent of a groundwater plume will change with time. For example, a groundwater plume formed initially from a release of gasoline to groundwater through soil leaching may be quite extensive and characterized by high concentrations of the more mobile constituents, such as benzene and pentane. At some later time as leaching, dilution, and degradation proceed, the groundwater plume from the same spill may be localized near the initial spill and be comprised of heavier immobile constituents, such as n-octane and small quantities of naphthalene. Other PAHs will likely be fixed at the location of the release.

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