

RF/ER-96-0040.UN



WHITE PAPER

**ANALYSIS OF
VERTICAL CONTAMINANT
MIGRATION POTENTIAL**

FINAL
August 16, 1996



Prepared by
Rocky Mountain Remediation Services
Environmental Restoration

for

U S Department of Energy
Rocky Flats Environmental Technology Site
Golden, Colorado

ADMIN RECORD

A-0003 000514

RF/ER-96-0040.UN

WHITE PAPER

**ANALYSIS OF
VERTICAL CONTAMINANT
MIGRATION POTENTIAL**

**FINAL
August 16, 1996**

**Prepared by
Rocky Mountain Remediation Services
Environmental Restoration**

for

**U S Department of Energy
Rocky Flats Environmental Technology Site
Golden, Colorado**

Table of Contents

LIST OF TABLES	ii
LIST OF FIGURES	ii
LIST OF ATTACHMENTS	iii
EXECUTIVE SUMMARY	1
1 0 INTRODUCTION	4
1 1 Statement of Purpose	4
1 2 Site Description and Operational History	5
1 3 Overview of Vertical Migration Issues	7
2 0 SITE CONCEPTUAL MODEL	10
2 1 Contaminant Migration Pathway Scenarios	10
2 2 Physical Setting	12
2 3 Hydrostratigraphy	15
2 3 1 <i>Lithologic Properties of the Upper Hydrostratigraphic Unit</i>	16
2 3 2 <i>Lithologic Properties of the Lower Hydrostratigraphic Unit</i>	18
2 3 3 <i>Hydrologic Properties of the Upper Hydrostratigraphic Unit</i>	20
2 3 4 <i>Hydrologic Properties of the Lower Hydrostratigraphic Unit</i>	20
2 3 5 <i>Hydrologic Significance of Fractures Occurring in the Upper Laramie Confining Layer</i>	23
2 3 5 1 Fracture Occurrence	24
2 3 5 2 Origin of Fractures	25
2 3 5 3 Fracture Characteristics of Bedrock Hydrostratigraphic Units	26
2 4 Regional Groundwater Movement	28
2 5 Groundwater Movement at RFETS	30
2 5 1 <i>Upper Hydrostratigraphic Unit</i>	30
2 5 2 <i>Lower Hydrostratigraphic Unit</i>	30
2 6 Groundwater Contaminant Geochemistry	33
2 6 1 <i>LHSU Monitoring Well Network</i>	34
2 6 2 <i>Geochemical Data for LHSU Groundwater</i>	37
2 6 2 1 Volatile Organic Contamination	37
2 6 2 2 Radionuclide Contamination	39
2 6 3 <i>Hydrologic Significance of Contaminant Detections in Upper Laramie Confining Layer Groundwater</i>	41
2 7 Groundwater Development and Use	44
3 0 EVALUATION OF VERTICAL MIGRATION POTENTIAL	46
3 1 Conceptual Model Basis and Assumptions	46
3 2 Groundwater Flux, Flow Velocity and Travel Time	47
3 2 1 <i>LHSU Confining Layer</i>	47
3 2 2 <i>Laramie-Fox Hills Aquifer</i>	48
3 3 Contaminant Transport and Pathway Analysis	49
3 3 1 <i>Site Descriptions and History</i>	49
3 3 2 <i>DNAPL Behavior in the Subsurface</i>	51
3 3 2 1 DNAPL Occurrence and Properties	51

3 3 2 2 DNAPL Transport and Fate	52
3 3 3 <i>Solute Transport and Fate</i>	61
3 3 3 1 Hydrodynamic Dispersion	61
3 3 3 2 Contaminant Retardation	62
3 3 4 <i>Contaminant Velocity and Travel Time</i>	65
3 3 5 <i>Contaminant Mass Flux</i>	67
4 0 CONCLUSIONS	70
5 0 REFERENCES	73

List of Tables

Table 2-1 Listing of LHSU Wells	35
Table 3-1 Vertical Flux and Travel Time Calculation Results for the Upper Laramie LHSU Confining Layer	48
Table 3-2 Chemical and Physical Properties of Selected DNAPL Compounds	52
Table 3-3 DNAPL Fracture Disappearance Time and Retardation Factor Calculations	59
Table 3-4 Vertical Contaminant Velocities and Travel Time Calculations Results for the Upper Laramie LHSU Confining Layer	66
Table 3-5 Contaminant Mass Flux and Predicted Laramie-Fox Hills Aquifer Concentrations for IHSS 110 and 118 1 Based on Maximum Concentrations	68

List of Figures

Figure 1-1 Site Location Map	6
Figure 1-2 Schematic Illustration of a Fractured Porous Medium showing geologic and pore scales (from Pankow and Cherry, 1996)	9
Figure 2-1 RFETS and Surrounding Features	13
Figure 2-2 Location and Extent of Bedrock Aquifers in the Denver Groundwater Basin	14
Figure 2-3 Generalized Hydrostratigraphic Columnar Section	17
Figure 2-4 Vertical Profile of Hydraulic Conductivity Data	22
Figure 2-5 Location of Inferred Faults, IHSSs 110 and 118 1, and VOC Plume Boundaries	32
Figure 2-6 Location of LHSU Wells Near Industrial Area	36
Figure 3-1 Illustration of DNAPL Occurrence in the Alluvium and Definition of Capillary Pressure	55
Figure 3-2 Conceptualization of DNAPL persistence and distribution with DNAPL mass loss due to diffusion in water-saturated fractures in a porous medium (such as a fractured clay till or sedimentary rock) as a function of a) time, and b) fracture size (aperture) (from Pankow and Cherry, 1996)	58

List of Attachments

Attachment A	Fracture Data for Borehole 01193
Attachment B	Detected VOCs and Radionuclides in LHSU Wells
Attachment C	Shewhart Control Charts and Time-Series Plots for Selected LHSU Groundwater Monitoring Wells With Detectable VOC and Radionuclide Contaminants
Attachment D	2-D Contaminant Transport Calculations

EXECUTIVE SUMMARY

This white paper was prepared as part of a comprehensive environmental initiative, known as the Accelerated Site Action Project, that seeks to establish long term goals and approaches for the remediation of the Rocky Flats Environmental Technology Site. The purpose of this white paper is to describe and analyze the potential for shallow groundwater contaminants, particularly volatile organic compounds, to migrate vertically downward through a thick, laterally extensive confining layer and enter a deep regional artesian aquifer system known as the Laramie-Fox Hills Sandstone aquifer. The Laramie-Fox Hills Sandstone aquifer provides an important source of water for local and regional use and is the sole water supply for some residents in the Rocky Flats area.

Concerns related to contaminant migration and the long-term hydrologic integrity of this confining layer have recently been raised regarding the presence of dense non-aqueous phase liquids (DNAPLs) in the groundwater at some waste disposal sites and the occurrence of secondary permeability (i.e., fractures and faults) in bedrock materials. The combination of these factors at other hazardous waste sites have led to persistent groundwater contamination problems that have proven to be difficult to remediate and, thus, represent a long term contaminant migration threat. In order to evaluate the potential significance of vertical groundwater contaminant transport at Rocky Flats Environmental Technology Site, two individual hazardous substance sites (IHSSs 110 and 118.1) with evidence of chlorinated solvent releases were selected for analysis and discussion. The primary DNAPL and dissolved contaminants-of-concern identified at these sites are trichloroethene, tetrachloroethene, and carbon tetrachloride. Information from numerous site reports, unpublished site data, and recently published articles provide the basis for the analyses presented in this white paper.

The Rocky Flats Environmental Technology Site is underlain by a mantle of permeable Quaternary surficial geologic deposits deposited on a 600+ foot thick sequence of low permeability Cretaceous claystone and siltstone bedrock known as the upper Laramie Formation. The upper Laramie Formation functions as a confining layer for the underlying Laramie-Fox

Hills Sandstone aquifer which subcrops west of the Industrial Area and plunges eastward beneath the plant. Vertical hydraulic conductivities for the confining layer materials are estimated to range from about 2.8×10^{-10} to 2.5×10^{-7} centimeters/second, or roughly three to seven orders of magnitude lower than for the overlying surficial deposits. Due to this contrast in hydraulic conductivity, groundwater is expected to move predominantly laterally in the surficial deposits and vertically in the confining layer. Downward vertical hydraulic gradients observed in the confining layer indicate that shallow groundwater has the potential to recharge the Laramie-Fox Hills aquifer.

Faulting in the upper Laramie Formation has been documented regionally and recently has been documented at the Industrial Area. The influence of these fault zones on vertical groundwater flow is unknown, however, an observed trend of decreasing claystone permeabilities with depth is expected to result in a restrictive, rather than an enhanced, vertical groundwater flow regime. Fractures observed in bedrock core samples tend to be discontinuous, sub-horizontal to sub-vertical, and closed with depth. Trace concentrations of trichloroethene, tetrachloroethene, carbon tetrachloride, and chloroform found in some unweathered bedrock wells indicate that limited contaminant migration has occurred in the shallowest part of the confining layer beneath shallow groundwater plumes with high concentrations, although most detections are apparently related to laboratory or well cross contamination. Plutonium-239/240 was detected above background in three unweathered bedrock wells, but the available evidence indicates that these occurrences are attributable to cross contamination probably as a result of drilling through radionuclide contaminated soils.

Estimates of the vertical groundwater flow velocity through the confining layer indicate that groundwater movement is expected to be very slow. The calculated range of groundwater velocities, based on a potential range of vertical hydraulic conductivities, is 0.00054 to 0.468 feet/year which translates to travel times to the Laramie-Fox Hills aquifer of 1,300 to 1.1 million years. Consideration of the hydrologic setting and declining hydraulic conductivity trend with depth suggests that the actual groundwater flow velocity will be near the low end of the range.

Analysis of the behavior of dense nonaqueous phase liquids indicates that a potential exists for entry of DNAPL into fractured bedrock. However, the threat of DNAPL migration to the Laramie-Fox Hills aquifer is rapidly mitigated by diffusive disappearance of DNAPL from fractures into the claystone matrix, which has a large contaminant mass storage capacity. Dissolved and sorbed volatile organic contaminants derived from DNAPLs therefore represent the principal concern for vertical contaminant migration to the deep aquifer.

Organic contaminants are expected to move much slower than the groundwater flow velocity in the confining layer due to the effects of sorption by high organic carbon and clay contents, dispersion and molecular diffusion, and possibly *in situ* abiotic transformation reactions. The most rapidly transported contaminant, trichloroethene, is predicted to travel for 17,000 to 15 million years before reaching the Laramie-Fox Hills aquifer, with the most likely case being on the order of a hundred thousand years or more. Assuming that natural contaminant degradation is a viable process, some contaminants with short environmental half lives, such as carbon tetrachloride, may fully degrade before reaching the aquifer. The results of simple one- and two-dimensional analytical modeling of contaminant transport indicate that dispersion will reduce contaminant concentrations at the confining layer/aquifer interface by 6 to 99 percent, depending on magnitude of the vertical flux. Under worst case conditions, the resulting contaminant concentrations derived from mass flux calculations in the Laramie-Fox Hills aquifer exceed regulatory limits, however, these calculations are exceedingly conservative and ignore some important basic factors. Using a more realistic set of assumptions, it is expected that, if contaminants should ever reach the aquifer, the concentrations will be below regulatory limits.

It is concluded from this review and analysis that the upper Laramie Formation confining beds have a sufficient amount of hydrologic and geochemical integrity to provide long-term protection of the Laramie-Fox Hills aquifer. Monitoring of vertical contaminant migration at potential bedrock source areas, rather than remediation, appears to be the most prudent and cost effective option for protection of the Laramie-Fox Hills aquifer given the apparent robust geochemical nature of unweathered bedrock materials underlying the site.

1.0 INTRODUCTION

The U S Department of Energy (DOE) is currently developing a comprehensive environmental restoration initiative, known as the Accelerated Site Action Project (ASAP), for the purpose of establishing long term goals and approaches for the remediation of the Rocky Flats Environmental Technology Site (hereinafter referred to as the Site)

As part of the ASAP strategy, an evaluation of the long term potential for vertical contaminant migration to the deep Laramie-Fox Hills aquifer has been conducted using geologic and hydrologic data generated as a result of numerous site investigations performed over the last ten years This evaluation is intended to support decisions made regarding remedial actions at source areas where solvent releases have penetrated below the water table

The Laramie-Fox Hills aquifer is found at an estimated depth of 675 feet below the Industrial Area of the Site and is separated from surficial aquifers by an intervening fine-grained sequence of claystone, siltstone, and minor, discontinuous sandstone beds The Laramie-Fox Hills aquifer is of particular interest to this evaluation because it serves as an important water supply to the region The lateral migration of contaminants through shallow water-bearing units is addressed separately under the groundwater modeling and remediation components of ASAP

1.1 Statement of Purpose

The long term protection of deep drinking water aquifers underlying at the Site is a principal concern of ASAP that has received relatively little attention in past years This limited amount of attention is essentially rooted in the long held perception among earlier investigators (i e Hurr, 1976) that significant vertical contaminant migration through a thick sequence of intervening, low permeability claystones is minimal and probably negligible given the conceptual understanding of the Site hydrogeology and contaminant behavior that was prevailing at the time The consistent absence of groundwater contamination in deep monitoring wells, as revealed by routine groundwater sampling and analysis at the Site, and slow calculated

groundwater velocities are the most commonly cited types of evidence used to document the low potential for vertical contaminant migration to deep aquifers at the Site

Over the last ten years, an improved conceptual understanding of Site geologic and hydrogeologic conditions has evolved which implicates the role of secondary permeability, including fractures and faults, as a potential preferred pathway for bedrock groundwater flow. At the same time, there has been an increasing industry-wide realization among practicing groundwater scientists and researchers that a category of commonly used, heavier-than-water organic solvent compounds, known as dense, non-aqueous phase liquids (DNAPLs), represent a detrimental, long term, threat to groundwater supplies (Pankow et al, 1996). The recent identification of subsurface DNAPL releases to the environment at two areas of the Site, combined with renewed questions regarding the hydrologic integrity of the underlying claystone bedrock, has heightened concerns that the deep aquifer might be at risk from long term releases of DNAPL-derived dissolved organic contamination. These concerns have prompted a more detailed review and evaluation of potential bedrock migration pathways which is the focus of this white paper.

1.2 Site Description and Operational History

The Site is a DOE nuclear weapons component facility located on approximately 6,550 acres in northern Jefferson County, Colorado. As illustrated in Figure 1-1, the Site is situated approximately 16 miles northwest of downtown Denver and lies roughly midway between Golden and Boulder along State Highway 93. Primary facilities are located within a fenced central industrial complex which encompasses about 400 acres (the Industrial Area). The remaining plant area contains limited support facilities and serves as a buffer zone to the former production areas. The Site is a government-owned, contractor-operated facility that has been in operation since 1952. Kaiser-Hill, L L C is the current primary contractor which shares operating responsibility of the Site with four secondary subcontractor team members.

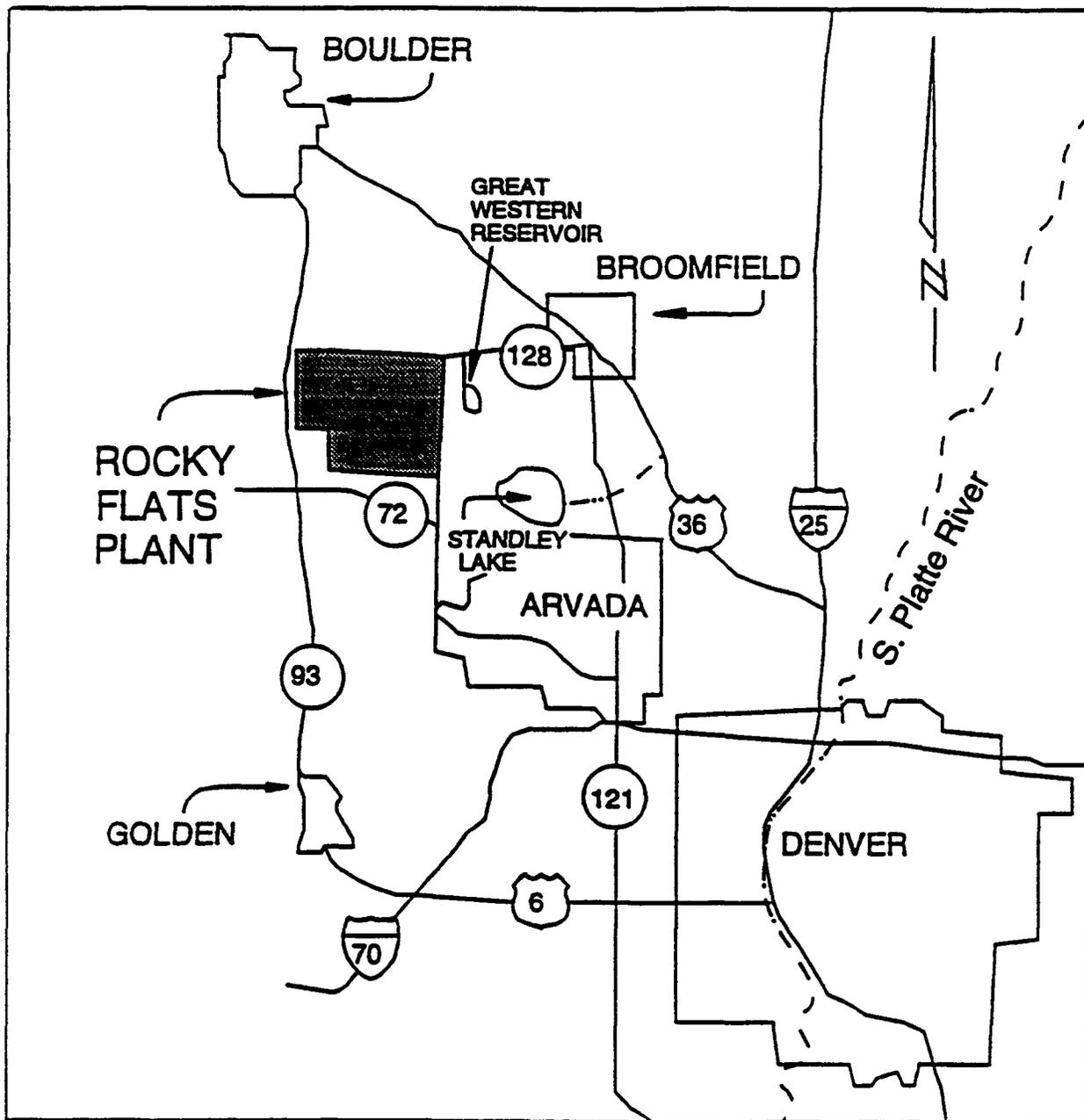


Figure 1-1 Site Location Map

Until January 1992, the Site was involved in the manufacture of plutonium, uranium, beryllium, and stainless steel components for nuclear weapons, reprocessing scrap metal and plutonium from dismantled weapons, and conducting laboratory research on the properties of nuclear materials. In January 1992, the primary mission of the Site changed from nuclear weapons component manufacturing and reprocessing to environmental restoration, waste management, decontamination and decommissioning, and economic development. In July 1994, the name of

the Site was changed from the Rocky Flats Plant to the Rocky Flats Environmental Technology Site to reflect this change in mission

Wastes produced during plant operations included hazardous wastes, low-level and transuranic radioactive wastes, and mixed wastes. Historically, these wastes have been either disposed onsite, stored in containers onsite, or disposed offsite. As a result of these past practices, the Site was proposed for inclusion on the Superfund National Priorities List (NPL) in 1984 and was included in the NPL in the October 4, 1989 Federal Register. Cleanup is being conducted under the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The U.S. Environmental Protection Agency (EPA) and the Colorado Department of Public Health and Environment (CDPHE) are the regulatory agencies responsible for overseeing the CERCLA and RCRA assessment and cleanup activities at the Site.

1.3 Overview of Vertical Migration Issues

As a result of extensive field investigations conducted over the past 10 years, areas of shallow groundwater contamination have been delineated within the Industrial Area and surrounding buffer zone which exceed regulatory requirements. The principal Contaminants of Concern detected in groundwater on a site-wide basis include halogenated aliphatic organic compounds (e.g. trichloroethene (TCE), perchloroethene (PCE), carbon tetrachloride (CT) and vinyl chloride (VC)), radionuclides (plutonium-239/240 and americium-241), and nitrate. The majority of these contaminants are believed to have been released from potential source areas known as Individual Hazardous Substance Sites (IHSS). One hundred and seventy-eight IHSSs, grouped into 16 Operable Units (OUs), have been identified onsite to date based on a comprehensive review of historical release records contained within the Historical Release Report (1992a).

Historically, only dissolved phase volatile organic contamination has been detected in groundwater at the Site. Recent field sampling efforts at IHSS 110 (a disposal trench (T-3) located in the east buffer zone area) and IHSS 118 I (the site of a former underground carbon

tetrachloride storage tank located in the Industrial Area near Building 701) have identified the presence of DNAPLs in soil and groundwater samples. The discovery of DNAPLs in groundwater at these sites raises special problems for groundwater remediation which have profound implications on the approach and long term success of groundwater remediation activities. These problems are related to the sinking behavior of DNAPLs which cause downward migration to occur until a stratum of sufficiently low permeability is encountered that allows the DNAPL to slowly accumulate into a pool. This behavior is illustrated schematically in Figure 1-2. Further downward migration of DNAPL into the low permeability strata can occur through openings, such as fractures and larger pores, as the pool reaches a critical thickness. From these openings, DNAPL will slowly become immobilized through dissolution and diffusion into the unfractured bedrock matrix. Dissolution of residual and pooled DNAPL below the water table, in combination with fracture invasion and matrix diffusion, can result in sources of dissolved contamination that can persist for decades, centuries or longer periods of time (Feenstra and Guiguer, 1996).

Experience with conventional pump and treat technologies applied to DNAPL source zones has generally proven to be futile given the persistence and pervasive nature of DNAPLs in the groundwater environment (Feenstra et al, 1996). Alternative remediation approaches to pump and treat are emerging for treating or containing source zones and plumes, however, these methods are generally applicable only to restoration of horizontal plumes. It is expected that the high dissolved concentrations associated with DNAPL source areas will continue to pose a potential downward vertical migration risk given the long term nature of DNAPL source areas and impracticality of remediating low permeability bedrock materials at the Site. However, research involving contaminant behavior has indicated that porous, fine-grained geologic formations, such as claystones, contain a significant natural attenuation capacity, which under certain circumstances, may be capable of effectively mitigating contaminant migration and reducing or eliminating risk. The degree of mitigation will be determined by factors such as sorptive capacity, contaminant biotic and abiotic degradation, contaminant residence time, and hydrodynamic dispersion.

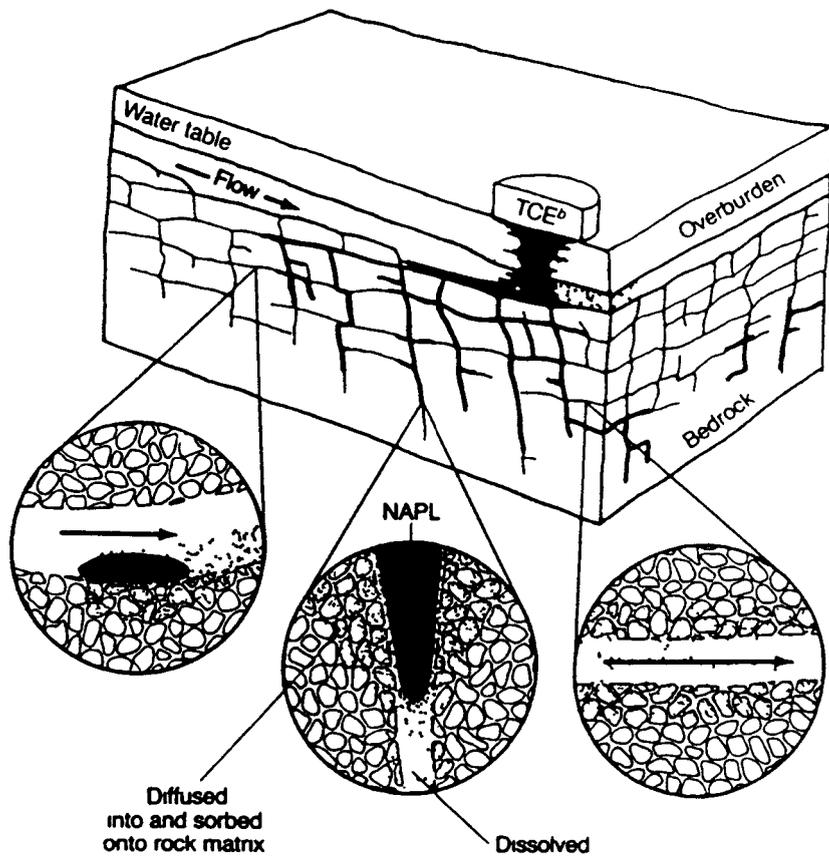


Figure 1-2 Schematic illustration of a DNAPL in a Fractured Porous Medium showing geologic and pore scales (from Pankow and Cherry, 1996)

2.0 SITE CONCEPTUAL MODEL

A conceptual understanding of the hydrogeology of the Site and immediate surrounding areas is presented in this section in order to provide a framework for the vertical groundwater transport and DNAPL migration analyses presented in Section 3.0. The section summarizes information gathered from published sources and studies performed at the Site. More detailed summaries of the site-specific and regional hydrogeologic setting are available in the Geologic, Hydrogeologic and Groundwater Geochemistry Reports of the Sitewide Geoscience Characterization Study (DOE, 1995a, 1995b, 1995c) and individual OU Remedial Investigation/RFI reports.

2.1 Contaminant Migration Pathway Scenarios

The potential for vertical contaminant migration into deep bedrock aquifers is a concern at many Denver area hazardous waste sites. Movement of groundwater and associated contamination between aquifers in the Denver groundwater basin can occur along at least four different vertical pathways as described by Romero (1976). These pathways include:

- (1) Intermingling of formation waters due to faulty or poorly designed wells,
- (2) Intermingling of bedrock and alluvial groundwater at alluvium-bedrock interfaces,
- (3) Vertical movement of groundwater through confining beds, and
- (4) Groundwater movement along fault traces.

A fifth potential pathway, known as a stratigraphic window, is not known to occur in the Denver groundwater basin since the upper Laramie confining layer is laterally continuous throughout the region.

Consideration of the pathways listed above indicate that only the last two are potential pathways for contaminant migration to the deep aquifer at the Site. Faulty or poorly designed wells are principally a concern for older groundwater and oil production wells that fully penetrate confining layers and allow intercommunication between aquifers. These types of wells are not known to exist in the Industrial Area of the Site. Monitoring wells installed at the Site since 1986 have followed industry standards for well drilling, design and construction. Site wells installed prior to 1986 have mostly been abandoned under the Well Abandonment and Replacement Program using the State of Colorado well abandonment procedures. Despite the large number of wells and boreholes drilled at the Site over four decades of operation, few penetrate more than 150 feet into the bedrock. Only one (borehole B304289) has fully penetrated the upper Laramie Formation confining layer. This borehole, abandoned in 1994, is located in a small isolated watershed that contains no IHSSs, and, therefore, does not represent a viable contaminant pathway to the Laramie-Fox Hills aquifer.

The second pathway, alluvial/bedrock aquifer contact, occurs within the west buffer zone along the north-south trending Laramie-Fox Hills aquifer subcrop. This subcrop zone is situated approximately 5,900 feet upgradient of the nearest Industrial Area IHSS area and, therefore, does not represent a threat from Site operations.

Vertical leakance (flux) of groundwater through confining layers occurs in virtually all hydrogeologic settings as a function of local hydrogeologic conditions. The presence of even small vertical fluxes through confining layers has been established as a significant source of recharge to regionally confined aquifers (e.g. Bredehoeft et al., 1983). Although groundwater movement through a confining layer is usually very slow, it is inevitable that, given enough time, this groundwater will contribute to the water supply of an aquifer. Vertical leakance of groundwater through the upper Laramie confining layer is consequently a plausible pathway for contaminant transport to the Laramie-Fox Hills aquifer. Conceptually, faulting which vertically displaces confining layers may, under favorable circumstances, create zones of enhanced vertical permeability that allow groundwater to circulate more freely between aquifers than otherwise possible through undisturbed geologic material. Faults of this type have recently been mapped at

the Site as described further in Subsection 2.5.2. Unlike the spatially uniform nature of vertical leakage from a confining layer to an aquifer, vertical groundwater flow associated with a fault zone is concentrated along the fault trace, and thus represents a concern that is distinct from the uniform vertical leakage case. These two pathways appear to represent the most likely routes for vertical contaminant transport to drinking water aquifers beneath the Site.

2.2 Physical Setting

The Site is situated at an elevation of approximately 6,000 feet above mean sea level along the western margin of the Colorado Piedmont region in an area of gently sloping upland topography known as Rocky Flats. This upland surface is formed by an ancient alluvial fan deposit of Coal Creek which has been deeply dissected by several small ephemeral streams. These streams drain eastward to the Great Western and Standley Lake reservoirs. Stream drainages that have been affected by plant operations include Woman Creek located south of the Industrial Area, and Walnut Creek located north of the Industrial Area. These streams are fed by surface runoff, contact springs found along the edge of the alluvial fan deposit, diversion ditches originating in Coal Creek and Rocky Flats Lake, and discharges resulting from routine plant operations. Figure 2-1 illustrates the relationship of the Site to surface water features in the Rocky Flats area.

The Site is located on the west flank of the Denver Basin, an asymmetric, north-south trending topographic and structural depression which contains an important regional aquifer system known as the Denver groundwater basin. The limits of the water-bearing bedrock portion of the basin are defined by the outcrop pattern of its deepest exploitable aquifer (the Laramie-Fox Hills aquifer). As shown in Figure 2-2, the Denver groundwater basin underlies approximately 6,700 square miles extending from the Front Range of the Rocky Mountains east to Limon and from Greeley south to near Colorado Springs. It yields water to wells as deep as 3,200 feet, and contains an appreciable reserve of bedrock groundwater that is used extensively by local communities, individual residences, and various industrial and agricultural concerns (Robson, 1989). In most places, bedrock groundwater flow moves in the general direction of surface water flow in the streams (Robson, 1989). Discharge of groundwater occurs naturally along the

northern basin margin and from pumping of an estimated 12,000 active wells scattered throughout the region (Robson, 1989)

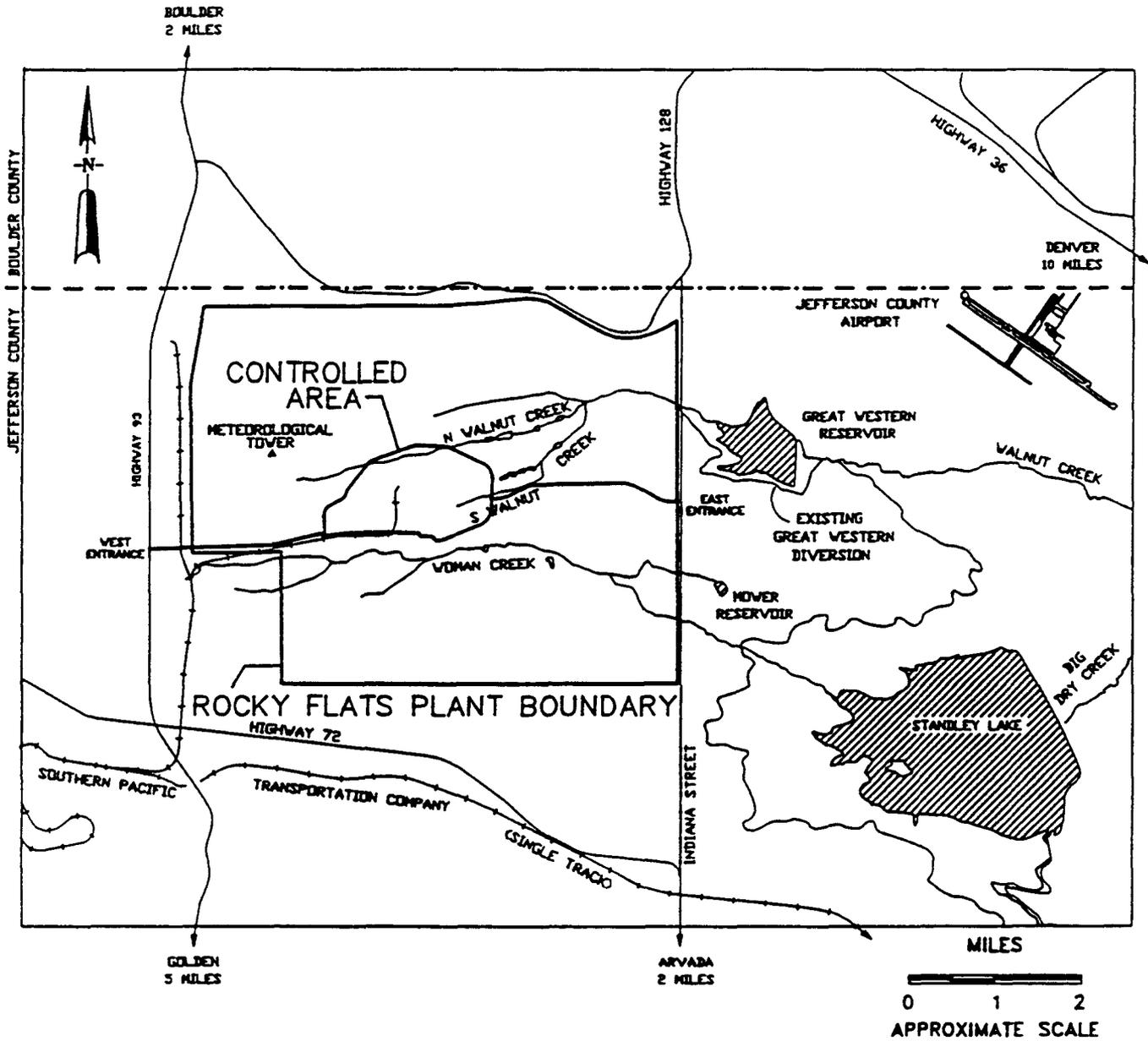
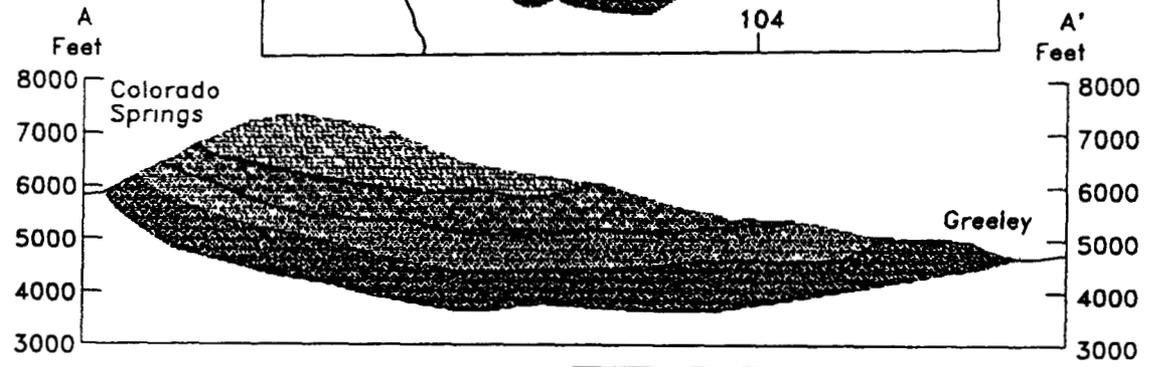
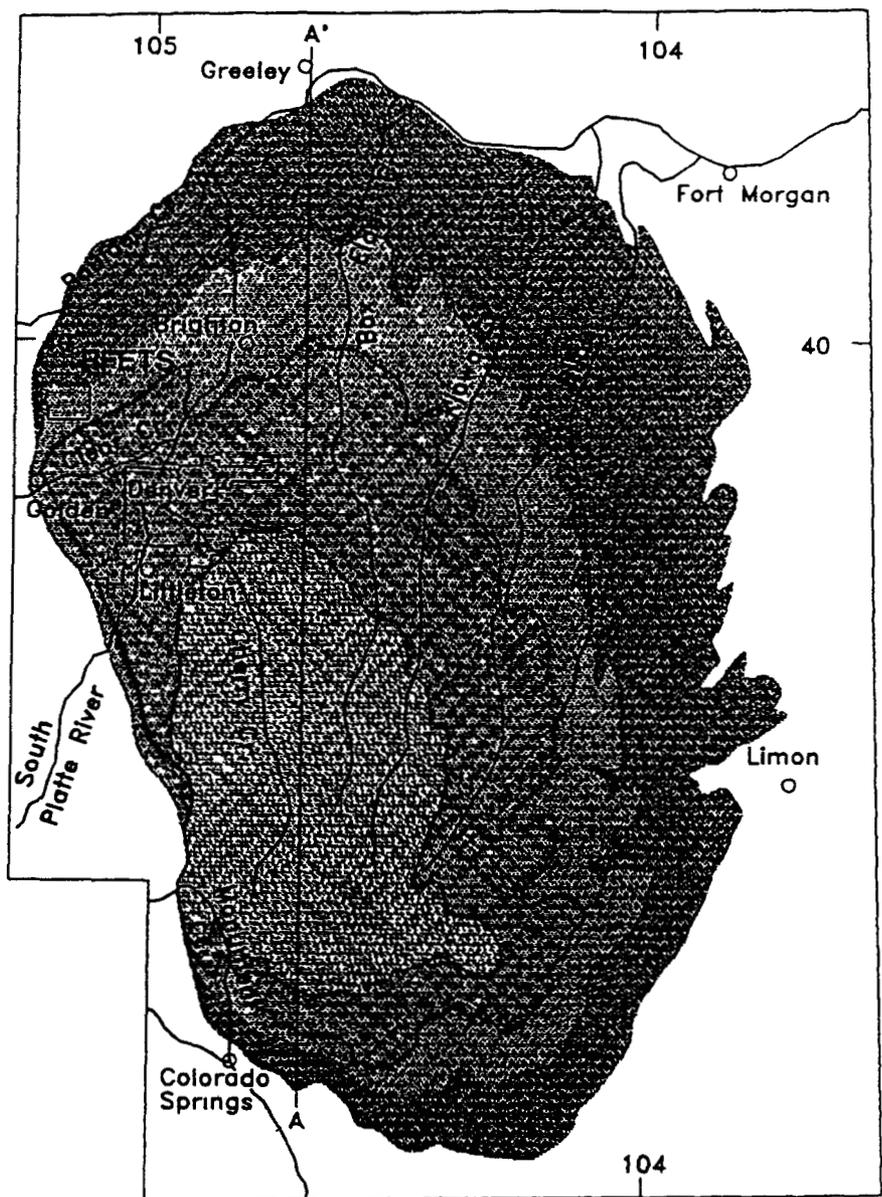
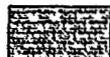


Figure 2-1 RFETS and Surrounding Features



-  DAWSON AQUIFER
-  DENVER AQUIFER
-  ARAPAHOE AQUIFER
-  LARAMIE-FOX HILLS AQUIFER

Modified from Robson (1987)

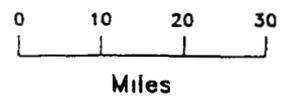
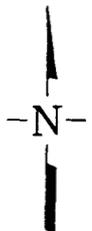


Figure 2-2

LOCATION AND EXTENT OF BEDROCK AQUIFERS IN THE DENVER GROUNDWATER BASIN

Date April 1995

The climate of the region is characterized as temperate and semiarid. Annual precipitation at the Site averages about 15.5 inches with almost 42 percent of the total falling during the period April through June (DOE, 1995b).

2.3 Hydrostratigraphy

Groundwater occurrence and distribution at the Site reflects local hydrogeologic conditions unique to the facility as well as hydrogeologic conditions that occur at the regional scale of the Denver Basin. Locally, three primary hydrostratigraphic units have been defined on the basis of observed similarities in the hydrologic characteristics of each unit as discussed in the Site-Wide Hydrogeologic Characterization Report (DOE, 1995b). Listed in descending order these units are:

- Upper Hydrostratigraphic Unit (UHSU) - consists of all surficial geologic deposits (Rocky Flats Alluvium, colluvium, and valley-fill alluvium), Arapahoe Formation sandstones in hydrologic connection with overlying surficial deposits, and weathered Laramie Formation claystone bedrock. The UHSU is considered to be equivalent to the "uppermost aquifer" as defined under RCRA.
- Lower Hydrostratigraphic Unit (LHSU) - consists of all unweathered Arapahoe and Laramie Formation bedrock strata, including the upper Laramie Formation claystone confining beds.
- Laramie-Fox Hills Aquifer Hydrostratigraphic Unit - consists of all unweathered lower Laramie Formation sandstone and Fox Hills Sandstone strata which comprise the regional Laramie-Fox Hills aquifer system.

The LHSU is immediately underlain by the Pierre Shale, a 7000+ foot thick sequence of clay-rich shale which acts as the basal confining layer for the Denver groundwater basin. Deeper

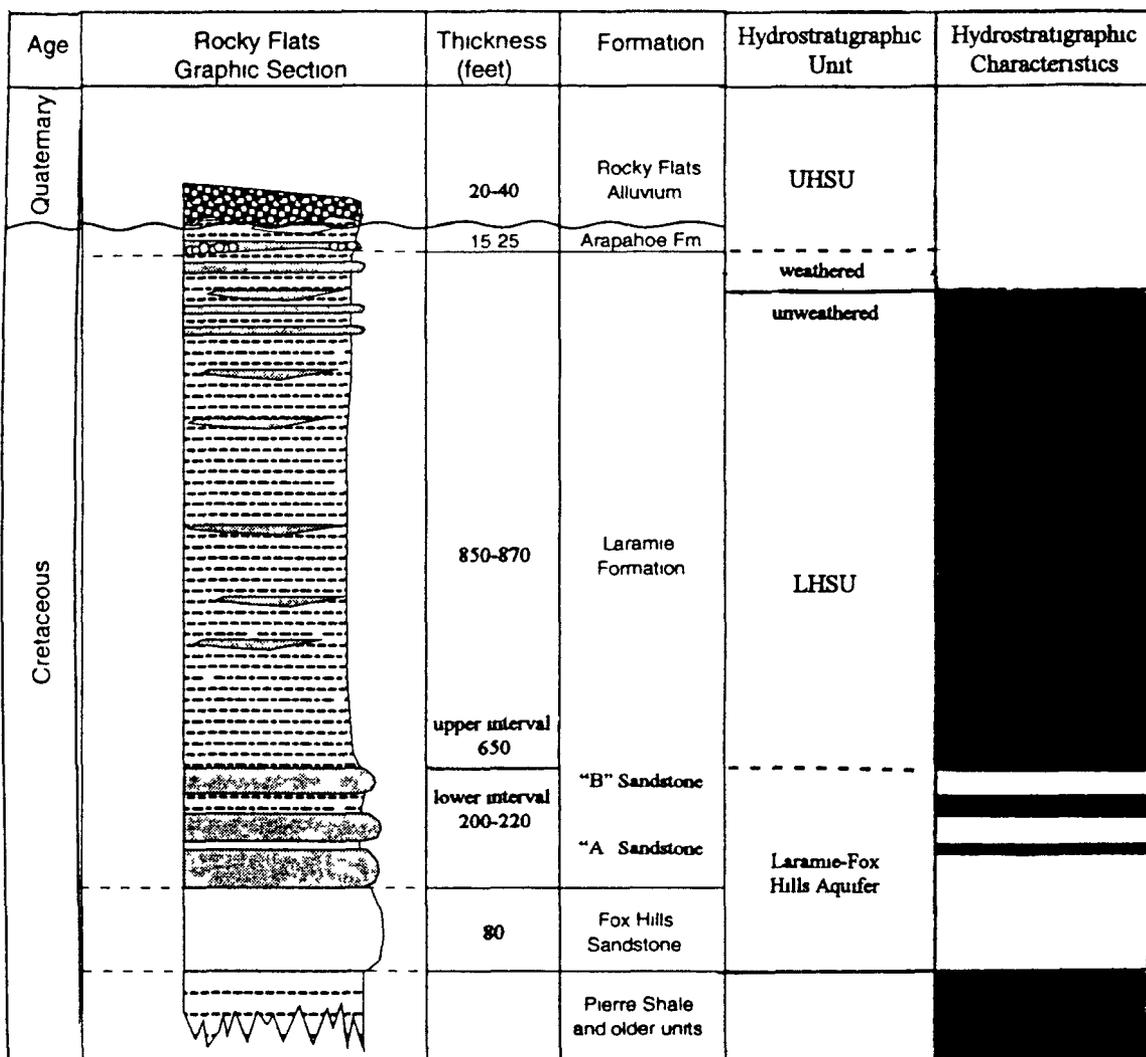
sedimentary and metamorphic formations are known to exist beneath the Pierre Shale in this part of the Denver basin, however these formations are not considered relevant for vertical transport analysis because the strong horizontal component of flow prevailing within the intervening Laramie/Fox Hills aquifer will serve to effectively intercept vertical flow from the overlying confining beds

The UHSU and LHSU at the Site are estimated to have a combined thickness of about 675 feet at the central Industrial Area. The thickness and extent of the UHSU and its minor subdivisions vary widely on a site-wide basis as a result of topographic setting and depositional controls. The aggregate thickness of the UHSU ranges from about 30 feet to over 100 feet in the west central area of the Site. Variation in the lateral extent and thickness of the LHSU is also evident at the Site, although these variations are thought to be limited to the upper Laramie confining beds

Figure 2-3 is a generalized hydrostratigraphic column that illustrates the lithologic, thickness and hydrologic characteristics of relevant surficial and bedrock formations present at the Industrial Area of the Site. These characteristics are described in more detail in the following sections of the report

2.3.1 *Lithologic Properties of the Upper Hydrostratigraphic Unit*

Surficial deposits at the Site consist of Quaternary-age units that unconformably overlie the Arapahoe and Laramie Formations. The Industrial Area is located on a pediment capped by the Rocky Flats Alluvium, which is the oldest and topographically highest of the surficial deposits in the area. The Rocky Flats Alluvium is composed of unconsolidated, well-graded clayey sands and gravels with a significant cobble fraction. Discontinuous lenses of clay, silt and sand are also common within the unit indicating the discontinuous nature of the Rocky Flats Alluvium. In the industrial and east buffer zone areas of the Site, the thickness of the Rocky Flats Alluvium typically ranges from 20 to 40 feet. The younger surficial deposits (colluvium and valley-fill alluvium) are restricted in occurrence to valley slopes and stream bottoms away from the main plant area and thus are not considered further in the vertical flow pathway analysis



LEGEND

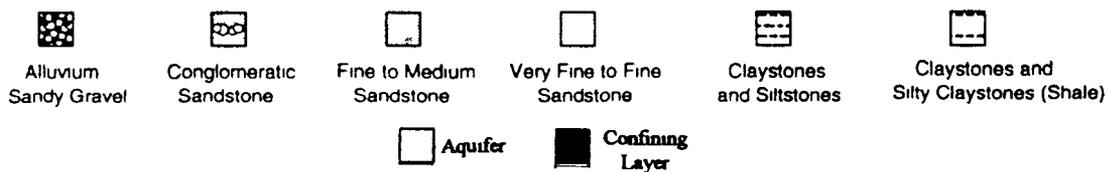


Figure 2-3 Generalized Hydrostratigraphic Columnar Section

Weathered bedrock is composed of yellowish gray and dark yellowish orange claystones, siltstones and fine to medium-grained sandstones which exhibit an abundance of iron-oxide

staining, healed and unhealed fractures, and increased friability in the coarser units. Sandstones and siltstones within weathered bedrock are commonly lenticular and discontinuous, and are usually isolated both vertically and horizontally by thick sequences of claystone or silty claystone. The Arapahoe Formation sandstone (also known as the Arapahoe Formation No. 1 sandstone) is a notably important component of weathered bedrock that is usually mapped separately because of its significance as a potential groundwater pathway. A conglomerate marker bed found regionally at the base of the Arapahoe Formation sandstone in the Denver Basin is absent at the Site. Weathered bedrock underlies the entire Site and ranges from less than 10 feet to more than 60 feet in thickness. These estimated thicknesses are based on borehole log interpretations presented in an isopach map of the weathered bedrock (Plate 5-12 in DOE, 1995a).

Laboratory analysis of organic carbon fraction (f_{oc}), bulk density (ρ_b), and total porosity (ϕ) have been performed on up to 25 weathered bedrock core samples as part of geologic characterization activities (DOE, 1995a). Average values of 0.165 percent organic carbon (25 samples), 2.03 g/cm³ bulk density (10 samples), and 24.8 percent porosity (10 samples) were determined from the analytical results of this study.

2.3.2 *Lithologic Properties of the Lower Hydrostratigraphic Unit*

The LHSU consists mainly of massive to faintly laminated, mixed-layer illite/smectite, olive gray to dark gray claystone and silty claystone with lesser amounts of quartz-rich siltstone, fine-grained sandstone, and thin coal beds. This unit forms a confining layer sequence that is laterally extensive throughout the Denver Basin. Like the weathered bedrock subunit of the UHSU, the sandstones and siltstones of the LHSU are commonly lenticular and discontinuous. All lithologies of the LHSU contain significant amounts of carbonaceous matter and may contain accessory minerals, such as siderite and pyrite, indicating of a reducing depositional environment. The upper Laramie Formation is approximately 650 feet thick at the Industrial Area based on projections derived from borehole geophysical log interpretation of the upper

Laramie/lower Laramie Formation contact in borehole B304289 This estimate results in an adjusted thickness of about 600 feet for the LHSU portion of the upper Laramie Formation

In the Denver groundwater basin, the lower Laramie and Fox Hills Sandstone Formations are normally undifferentiated and comprise a single aquifer system known as the Laramie-Fox Hills aquifer Locally, this hydrostratigraphic unit consists mainly of a 280 to 300 foot thick sequence of light gray, fine to coarse grained, massive quartzitic sandstones, kaolinitic claystones and subbituminous coal beds The three main sandstones within this hydrostratigraphic unit are more laterally extensive than those of the LHSU and, in ascending order, are referred to as the Fox Hills Sandstone, Laramie Formation "A" sandstone, and Laramie Formation "B" sandstone The "B" sandstone, as penetrated by borehole B304289 at the Site, is approximately 55 to 60 feet thick Geologic and geophysical logs from deep boreholes at the Marshall Landfill located 2 miles north of the Site indicate that the "A" and Fox Hills Sandstones are approximately 28 and 80 feet thick, respectively, in this area of the Denver Basin Coal seams, ranging in thickness from one to seven feet, are identified in lower Laramie Formation strata beneath the Site (borehole B304289) and were mined locally until the early 1950's Based on local mine map records, no coal mining is known to have occurred directly beneath the Site

The Pierre Shale confining layer conformably underlies the Laramie-Fox Hills aquifer and forms the base of the Laramie-Fox Hills Hydrostratigraphic unit It is composed of dark gray, smectite-rich shale with minor siltstone and very fine-grained sandstone laminae The Pierre Shale attains a thickness of greater than 7,000 feet at the Site (Wells, 1967)

Laboratory analysis of organic carbon fraction (f_{oc}), bulk density (ρ_b), and total porosity (ϕ) have been performed on up to 22 unweathered bedrock core samples as part of geologic characterization activities (DOE, 1995a) Average values of 1.03 percent organic carbon (25 samples), 2.07 g/cm³ bulk density (10 samples), and 22.2 percent porosity (10 samples) were determined from the analytical results of this study

2 3 3 *Hydrologic Properties of the Upper Hydrostratigraphic Unit*

Groundwater within surficial deposits generally occurs under unconfined conditions. Aquifer tests conducted at the Site indicate a wide range in hydraulic conductivity values spanning five orders of magnitude. The geometric mean of hydraulic conductivity values for the Rocky Flats Alluvium, colluvium, and valley-fill alluvium are 2.06×10^{-4} , 1.15×10^{-4} , and 2.16×10^{-3} cm/sec, respectively (DOE, 1995b). Well yields are typically low and range from below 0.05 gallons per minute (gpm) to several gpm in isolated areas.

Weathered bedrock groundwater occurs under both unconfined and confined conditions. The transmissive properties of the weathered bedrock UHSU subunit are controlled primarily by the presence of permeable sandstones and by the presence of permeable fractures in claystones and siltstones. The geometric means of hydraulic conductivity values for the weathered claystones, siltstone, Arapahoe Formation sandstone, and other UHSU sandstones are 8.82×10^{-7} , 2.88×10^{-5} , 7.88×10^{-4} , and 3.89×10^{-5} cm/sec, respectively (DOE, 1995b). Overall, well yields tend to be lower than the overlying surficial deposits UHSU subunit, but higher than the underlying LHSU confining layer beds. A downward vertical hydraulic gradient condition exists between the surficial and weathered bedrock subunits of the UHSU in virtually all areas of the Site (DOE, 1995b).

2 3 4 *Hydrologic Properties of the Lower Hydrostratigraphic Unit*

The claystones of the upper Laramie Formation serve as a confining layer for the more permeable sandstones of the Laramie-Fox Hills aquifer. Evidence for this condition exists in the form of steep local and regional vertical hydraulic gradients, slow water level recovery times in monitoring wells following sampling events (weeks to months), low hydraulic conductivity, contrasting groundwater geochemical and isotopic compositions with overlying subunits, and regional groundwater modeling results. At the Site Industrial Area, the vertical hydraulic gradient between the Rocky Flats Alluvium and Laramie-Fox Hills aquifer is estimated to range from 0.3 to 0.4 ft/ft based on the potentiometric surface configuration of the Laramie-Fox Hills aquifer presented by Robson and Banta (1987), the potentiometric surface configuration of the

Rocky Flats Alluvium and other surficial deposits provided in DOE (1995b), and an assumed claystone thickness of 650 feet. Vertical gradients calculated for well pairs in the uppermost 150 feet of the confining layer at the Site (DOE, 1995b) are, in some cases, greater than the regional estimate, however, these values are considered to be suspect because of complications related to incomplete water level recovery in bedrock wells. Water level recovery times projected for most bedrock wells are characteristically slow and often exceed the quarterly sampling schedule (DOE, 1995d). Because of the long recovery times associated with claystone bedrock wells, the volume of water available for sampling has historically been very limited.

Because the upper Laramie Formation functions hydraulically as a confining unit, the primary characteristic of importance is the vertical hydraulic conductivity. Estimates of this characteristic are not available from well tests, however, laboratory tests of core samples collected from the Site indicate a geometric mean value of 5.83×10^{-8} cm/sec. In a model developed to simulate regional groundwater flow in the Denver Basin, Robson (1987) found that model calibration of the hydraulic head distribution between the Arapahoe and Laramie-Fox Hills aquifers could only be attained if the bulk vertical hydraulic conductivity of the upper Laramie Formation confining layer was assumed to be 2.8×10^{-10} cm/sec or less. The geometric mean horizontal hydraulic conductivity of unweathered claystone and siltstone at the Site is 2.5×10^{-7} cm/sec as reported in DOE (1995b). Superimposed about this value is a pronounced trend of decreasing hydraulic conductivity with depth as illustrated in Figure 2-4. This trend is possibly caused by a decrease in the frequency and permeability of bedrock fractures as discussed further in Subsection 2.3.5. It is apparent from the available data that the low permeability and great thickness of the claystone, combined with steep vertical hydraulic gradients, reflect a condition of poor hydraulic communication between aquifers across the LHSU.

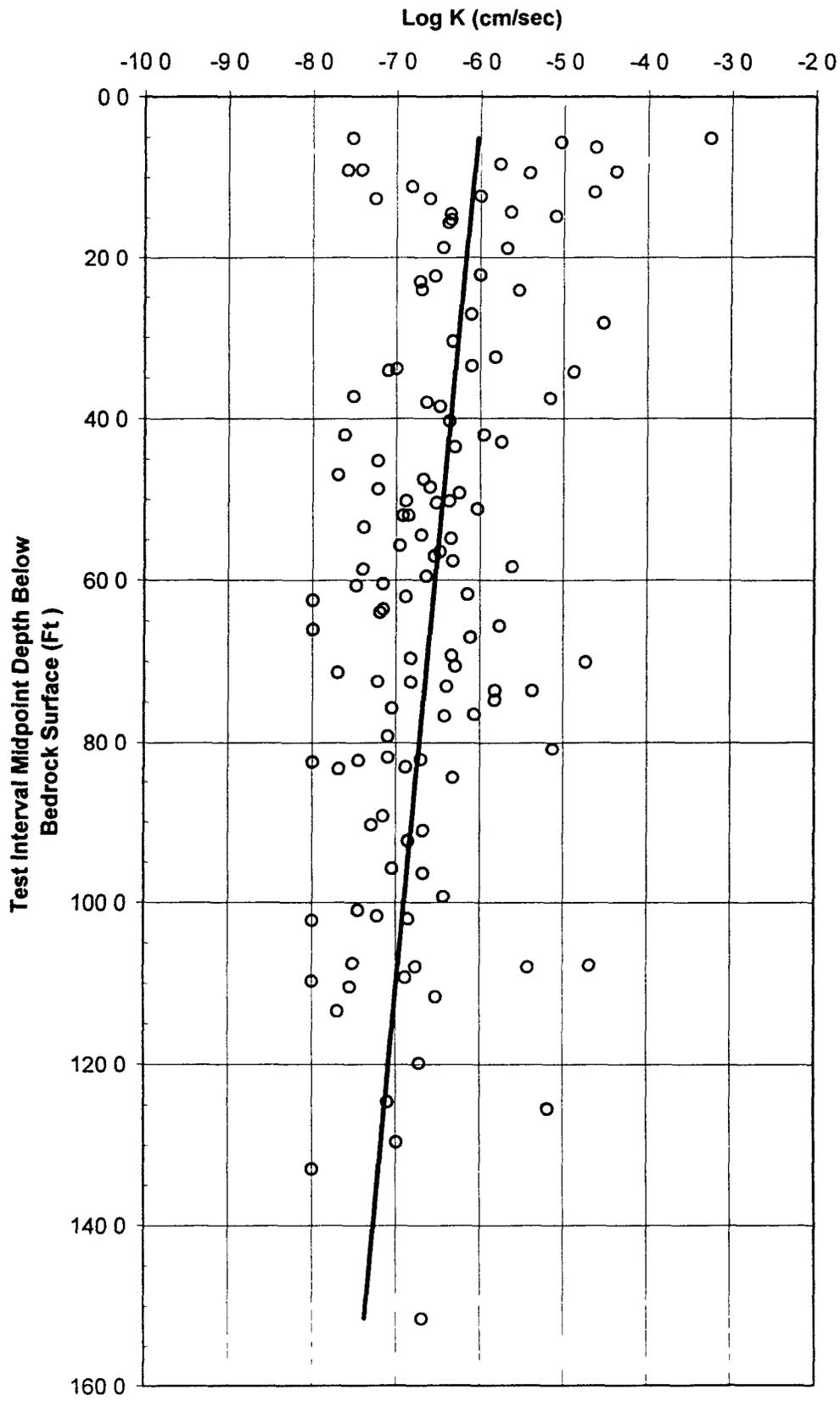


Figure 2-4 Vertical Profile of Hydraulic Conductivity Data

Various hydrologic properties of the LHSU have been measured from a number of field and laboratory testing programs conducted at the Site over the past few years. These programs have provided a relatively large amount of data that support the literature characterization of this subunit as an important confining layer sequence in the Denver Basin. Significant efforts to characterize the hydrologic integrity of the upper Laramie Formation at the Site have involved well drilling, hydraulic parameter testing, and groundwater monitoring activities.

The Laramie-Fox Hills aquifer is an important local and regional aquifer that supplies water primarily for domestic, stock, and municipal use. In the vicinity of the Site, the water-bearing portion of the aquifer is estimated to be approximately 200 feet thick, including the major sandstone units described above and associated thinner, clayey sandstones and siltstones. Robson (1983) reports that the hydraulic conductivity of the Laramie-Fox Hills aquifer in the area of the Site is less than about 0.05 feet/day (1.8×10^{-5} cm/sec). Laboratory estimates of porosity for bedrock aquifers in the Denver Basin range from 12 to 46 percent with an average of 31 percent. The horizontal hydraulic gradient present in the Laramie-Fox Hills aquifer at the Site is estimated at 0.04 ft/ft toward the east-northeast based on the potentiometric surface map prepared by Robson and Banta (1987).

2.3.5 *Hydrologic Significance of Fractures Occurring in the Upper Laramie Confining Layer*

The discussion of LHSU confining layer properties has thus far considered only the unfractured aspects of the media. Fracturing in an otherwise impermeable rock mass can have a dominant effect on groundwater flow and contaminant transport (Freeze and Cherry, 1979). The significance of fracture control on vertical groundwater flow and transport in a particular rock depends mainly on fracture permeability, orientation (primarily the dip angle), and interconnectivity. Additional rock properties, such as matrix porosity, can have important mitigating effects on contaminant transport in fractures by mass transfer of dissolved contaminants from the fracture into the porous matrix via matrix diffusion. Geologic media such

as the LHSU confining layer which exhibit dual permeability and porosity characteristics are often referred to in the contaminant hydrogeology literature as a fractured porous media

This subsection serves to summarize the available site information on fracturing in UHSU and LHSU bedrock materials, and present an interpretation of the probable relative importance of fractures on vertical groundwater flow and transport to the Laramie-Fox Hills aquifer. Descriptions of fractures used in previous reports and borehole logs commonly refer to fractures as being either open or closed. This terminology has been adopted for this document to provide continuity with the existing database. Open fractures refer only to those fractures with a visible aperture or other evidence of groundwater flow that indicate a potential enhancement of bulk hydraulic conductivity. Closed fractures refer to fractures with no visible aperture or evidence of groundwater flow that appear to have been healed and thus indicate a minimal enhancement of bulk hydraulic conductivity.

2.3.5.1 Fracture Occurrence

Fractures are commonly observed in shallow drill cores and test pits at the Site and have recently been observed in association with faulting at the Systematic Evaluation Program (SEP) trench (Geomatrix Consultants, 1995). Mudge and Brown (1952) first reported the occurrence of fractures in weathered bedrock core samples during a siting study for the original Solar Ponds. More recently, fractures in weathered bedrock claystones at the Solar Ponds have been identified and described as part of an OU4 shallow drilling program (DOE, 1995e). These fractures were described as being inclined 10 to 40 degrees from horizontal. Zeff, Cogorno, and Sealy (1974) noted the presence of fractures in severely weathered claystones in borings and test pits to a depth of 5 feet in the No Name Gulch drainage below the Present Landfill. Fractures may also be associated with slump blocks along steep valley slopes, such as encountered in boreholes and excavations for the OU1 french drain (DOE, 1993).

The fractures observed in the SEP trench were associated with slumping, weathering, soft-sediment deformation, and faulting. Fractures that are apparently directly associated with

faulting are extensive and complex. Large blocks of claystone caved into the SEP trench revealing fresh fracture surfaces which were usually wet and commonly displayed slickensided surfaces. Seeps were commonly observed along fracture zones at the contact with the overlying Rocky Flats Alluvium.

2.3.5.2 Origin of Fractures

Small-scale bedding offsets have been observed in fractures and slickensides are common. Thin sections of fractured UHSU sandstones reveal the presence of microbreccias and healed cataclastic textures with fracture zones 1 to 2 millimeters thick (EG&G, 1992b). These textures, in combination with slickensided surfaces, suggest a tectonic origin for the fractures. The timing of fracturing has not been determined although it is reasonable to assume that most, if not all, fractures were created during faulting and Front Range uplift associated with the Laramide orogeny of late Cretaceous to early Tertiary age.

As a working hypothesis, it is postulated that a combination of physical and chemical weathering processes act to intensify and gradually open this structurally-induced fracture network over long periods of time. From this conceptual model, it can be expected that fracture densities will decrease downward through the weathered zone until the density equals the structurally-induced density of unweathered bedrock. Fracture apertures should likewise decrease downward through the weathered zone, but may also decrease with depth in the unweathered zone due to increasing lithostatic pressures and claystone ductility. The net effect of decreasing fracture densities and apertures would be a corresponding decrease in bulk hydraulic conductivity. Such an effect is consistent with the observed hydraulic conductivity profile displayed in Figure 2-4. The slow rate of the weathering process is evidenced by the fact that the weathering front has advanced only an average of about 40 feet in 700,000 years (the approximate minimum age of the Rocky Flats Alluvium) conservatively assuming that the Rocky Flats Alluvium was deposited on an unweathered bedrock surface. Changes in the depth of the weathering profile are therefore assumed to be negligible relative to vertical groundwater flow velocities.

Upper Hydrostratigraphic Unit

Weathering-enhanced and mechanically-induced fractures in UHSU (weathered) bedrock core samples, test pits, and outcrops are typically described in Site borehole logs and reports as being open, stained or lined with iron and manganese oxides, and exhibiting slickensided surfaces. Shallow bedrock fractures in areas of unsaturated overlying alluvium may also contain fillings of calcium carbonate (caliche). An increased frequency of fractures in borehole logs has been associated with the weathered zone. Permeable (open) fractures, in combination with permeable shallow bedrock sandstones, are thought to control the relatively high degree of groundwater flow activity in the UHSU bedrock. Open fractures have been reported to extend below the base of the weathered zone (i.e. open fractures observed to 100 feet in an acoustic televiewer log of borehole 25193 or 24 feet below the UHSU), although these instances appear to be uncommon based on numerous borehole log examinations. This condition is supported by the vertical distribution of environmental tritium data which indicates that few samples from LHSU wells show any evidence of mixing with young (post-1953) groundwater (DOE, 1995c).

Lower Hydrostratigraphic Unit

In contrast to the UHSU, LHSU fractures are characteristically closed and exhibit no staining or visible mineralization. Fracture occurrence is usually diagnosed solely on the basis of slickensided surfaces which are highly polished and sometimes smeared with a carbonaceous film. The depth of LHSU fracturing extends to at least 499 feet as recorded in SEP borehole 01193, the deepest cored borehole at 508 feet total depth. Based on the fracture distribution evident in this log, it can be assumed that fracturing probably extends throughout the entire upper Laramie Formation confining layer interval.

Saturated fracture zones and isolated zones of damp, pliable mud or clay in relatively dry or moist intact core have been observed in LHSU materials when the core is logged immediately

after drilling (F Grigsby, personal communication, 1996) These saturated fracture zones are typically two or more feet thick and have been documented to depths of up to 212 feet (borehole 42392) The maximum depth of saturated fracture zones in the LHSU claystone is unknown It has been speculated that these zones are probably associated with larger-scale faulting (DOE, 1995a) In many cases the zones coincide with carbonaceous claystone strata that appear to have a more brittle or fissile character than the surrounding lower carbon content claystone At present, these zones are interpreted as containing potentially open, permeable fractures and sheared material which may have been at least partially opened and invaded by drilling fluids during coring operations The hydrologic significance of these zones is subject to interpretation, but based on their association with a certain rock type, it seems probable that any permeability enhancement would be a horizontal rather than vertical phenomenon

Despite an abundance of evidence that describes the ubiquitous nature of fracturing in weathered and, to a lesser degree, unweathered Laramie Formation claystone bedrock, little quantitative data exists that can be directly applied to analyzing contaminant and DNAPL transport problems in a fractured porous media At best, estimates of fracture characteristics can be generated using representative data from selected borehole logs with detailed fracture descriptions Basic data on fracture occurrence and dip angle are available for many deep boreholes, but orientation and aperture width information are unavailable and unrecoverable In borehole 01193, approximately 209 individual fractures were logged with spacings ranging from 0 to 21.5 feet (2.32 foot average) and dip angles ranging from 0 to 90 degrees (38.4 degree average) as presented in Attachment A Information on fracture length and connectivity is unavailable, although some intersecting fracture sets (0 ft fracture spacing reported in Attachment A) are recorded in the log The low average dip angle may be an important characteristic that supports the case for a low unweathered bedrock fracture permeability because it is expected that overburden pressures would have a greater tendency to close horizontally rather than vertically oriented openings

The available data from borehole 01193 and other deep boreholes indicate that bedrock fracture patterns are complex and, at best, are only poorly understood Initial estimates of fracture

aperature can be derived from bulk hydraulic conductivity and fracture spacing data if some simplifying assumptions are made regarding the fracture network. Assuming a parallel system of regularly spaced, smooth-walled, planar fractures, the fracture aperature can be calculated from (Domenico and Schwartz 1990)

$$K_b = \frac{\rho_w g N (2b)^3}{12\mu} \quad (1)$$

where

K_b is the bulk hydraulic conductivity (cm/sec)

ρ_w is the density of water (g/cm³)

g is gravitational acceleration (980 cm/sec²)

N is the number of fractures per unit distance (m)

$2b$ is the fracture aperature (cm)

μ is the water viscosity (centipoise)

For an average bedrock groundwater temperature of 12°C (M. Siders, personal communication, 1996), the viscosity of pure water is 1.235 cp (Weast, 1984). Converting from a fracture spacing of 2.32 feet observed in borehole 01193 to an N value yields 1.414 fractures per meter. Using a bulk hydraulic conductivity value of 2.5×10^{-7} cm/sec (geometric mean for unweathered LHSU claystone), the estimated aperature of LHSU claystone fractures is about 0.0014 cm (14 μm), or roughly the thickness of a human hair. Because the method assumes that the bulk hydraulic conductivity is derived entirely from smooth-walled fractures, the calculated aperature will tend to be overestimated given that non-ideal fracture roughness and matrix groundwater flow are conditions that can reasonably be expected to occur in the LHSU claystones.

2.4 Regional Groundwater Movement

Large differences in the hydrologic characteristics of alluvial and bedrock aquifers of the Denver groundwater basin have resulted in substantially different patterns of groundwater movement.

Due to the large contrasts in hydraulic conductivity between aquifers, such as the UHSU and Laramie-Fox Hills aquifer, and confining layers, such as the upper Laramie Formation claystone, flow in aquifers will be predominantly horizontal while flow in the confining layers will be predominantly vertical

The structural setting of the Laramie-Fox Hills aquifer also has an important role in influencing groundwater movement within the vicinity of the Site as reflected by a general conformity in bedrock attitude and the regional potentiometric surface. The Laramie-Fox Hills aquifer outcrops (or subcrops) along the basin margin and dips gently toward the basin center. These exposures function as the principal recharge zones for the bedrock aquifers. As water infiltrates into the permeable sandstones, it will move parallel to bedding toward the basin center and eventually flow northward and northeastward out of the basin. Artesian heads begin to develop within the aquifer as the sandstone plunges beneath the overlying confining layers. Flow conditions within the confining layer will be determined by the head relationships existing between the overlying and underlying aquifers. At the Site and over much of the Denver Basin, water levels are currently lower in the Laramie-Fox Hills aquifer than the immediate overlying aquifers. This condition results in a downward gradient which causes a potential for groundwater to flow from the overlying aquifer through the confining layer in a downward direction toward the Laramie-Fox Hills aquifer.

Faulting represents a special kind of large-scale structural control that can significantly affect lateral groundwater movement in aquifers and vertical groundwater movement in confining layers. The presence of northeast-southwest trending faults that offset the Laramie-Fox Hills aquifer in the area north and northeast of the Site is well documented in the literature (Spencer, 1961 and Spencer, 1986). These faults are known to complicate and possibly disrupt Laramie-Fox Hills aquifer groundwater flow patterns in the affected areas (Robson, 1987 and Schneider, 1980). Previous investigators (Romero, 1976, Robson, 1987, and Schneider, 1980) have speculated on the potential role of these faults as vertical conduits for groundwater flow, although it is generally admitted that this possibility cannot be adequately addressed without further data.

2.5 Groundwater Movement at RFETS

2.5.1 *Upper Hydrostratigraphic Unit*

Shallow groundwater at the Site originates from infiltration of precipitation, exfiltration of surface water in diversion ditches and ponds, and subsurface water losses associated with plant utility lines. Groundwater in the UHSU generally flows from west to east across the Site following the regional topography of the bedrock surface and ground surface. Flow in the surficial deposits subunit is influenced by bedrock topography in the thicker saturated areas, and becomes increasingly controlled by bedrock surface features in areas of discontinuous saturation. The majority of UHSU groundwater flow eventually moves into the major stream drainages which serve to concentrate and channel flow eastward toward the east boundary along Indiana Street. Discharge of UHSU groundwater occurs as surface flow and transpiration by vegetation at seeps, infiltration into building footing drains, groundwater interception systems and other man-made structures, and infiltration into the underlying LHSU bedrock.

2.5.2 *Lower Hydrostratigraphic Unit*

Movement of groundwater in the upper Laramie Formation confining layer is expected to be primarily vertical because of steep vertical gradients and the lack of continuous, permeable sandy layers that would facilitate lateral groundwater movement. Recharge occurs via slow infiltration of groundwater from the overlying UHSU beds. Upper Laramie Formation LHSU groundwater discharges locally to the underlying Laramie-Fox Hills aquifer and to UHSU weathered bedrock subunit materials near stream bottoms in the Woman and Walnut Creek drainages.

The potential for preferred groundwater movement through fractures was discussed previously in Subsection 2.3.5. The possible effect of larger scale structural features (i.e. fault zones) on groundwater flow through the LHSU confining layer is now discussed in light of the lithologic and hydrologic properties of the LHSU claystones presented above.

Near-vertical bedrock faults have recently been mapped at the Site (DOE, 1995a), including some which traverse the Industrial Area and underlie UHSU groundwater plumes. Figure 2-5 shows the position of these faults relative to plant features, IHSSs 110 and 118 1, and the composite VOC plume. Although UHSU groundwater plumes overlie bedrock faults in several instances, it is evident that DNAPL source areas do not intersect any of the fault traces, which minimizes the potential for vertical DNAPL migration along the faults.

Fracture zones associated with faults have the potential to be either permeable or impermeable with respect to the host rock depending on factors such as the type and geotechnical properties of the rock and presence of clayey gouge in fractures. Because the host rock at the Site consists entirely of relatively ductile fine-grained material, it is reasonable to assume that any sheared or broken rock will be contained within a low permeability clayey matrix. Fractures associated with faults can be expected to behave similarly to fractures found in unfaulted areas because they are subjected to the same stresses which control fracture permeability at depth in the confining layer. These general conclusions infer that fault zone permeabilities at the Site are likely to be very low. If it is assumed that shearing of beds parallel to the fault trace is the primary permeability control in the fault zone, then it seems reasonable to assume that, as a first approximation, the bulk permeability of fault zones at the Site will fall within the 10^{-8} to 10^{-7} cm/sec range reported for horizontal hydraulic conductivities of unweathered claystones and siltstones.

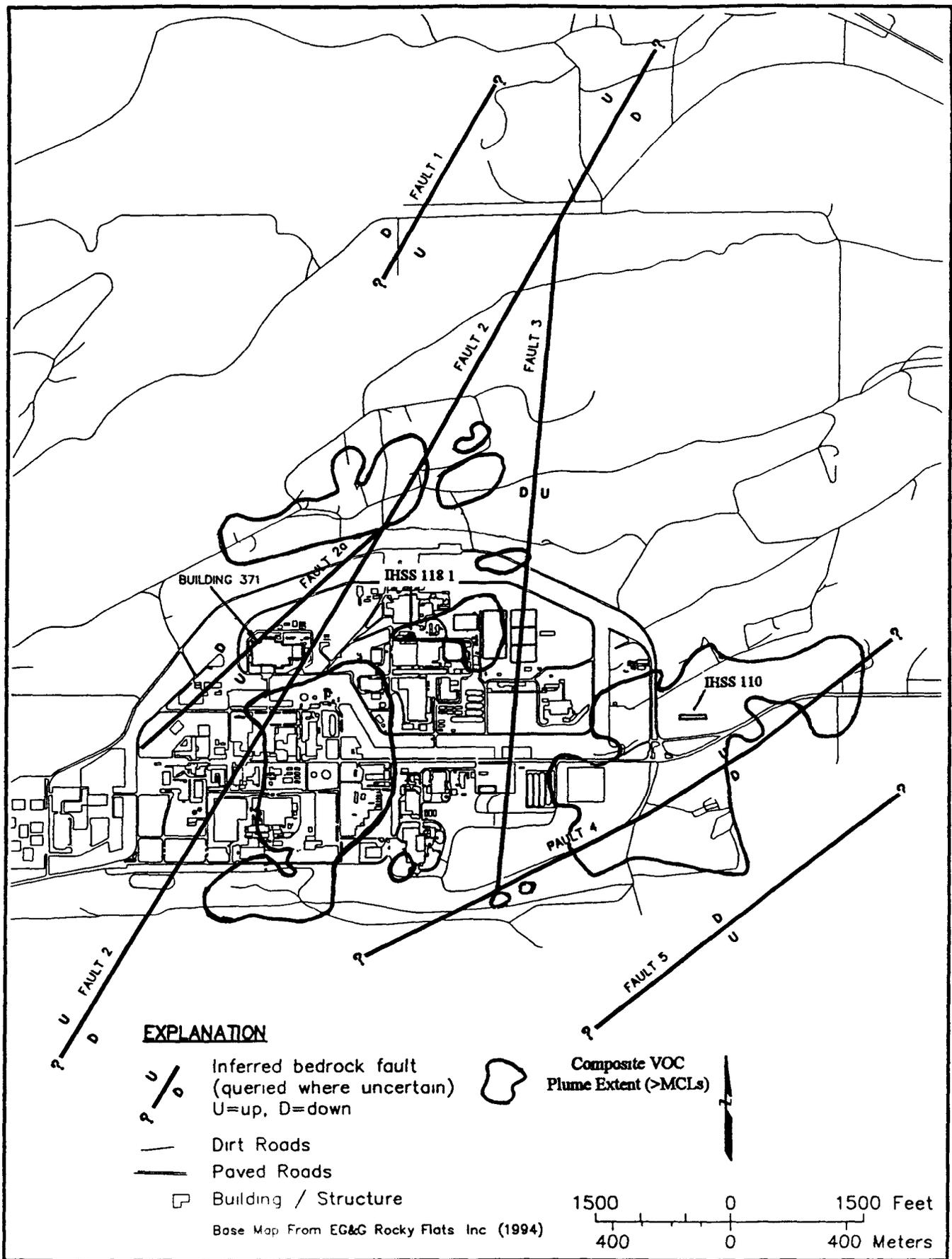


Figure 2-5 Location of Inferred Faults, IHSSs 110 and 118 1, and VOC Plume Boundaries

Limited information is available regarding the hydrologic properties of the fault zones present at the Site. Although none of the existing monitoring wells are thought to directly monitor fault zones, there is a limited amount of evidence that indicates the presence of an enhanced permeability zone associated with faults in the weathered bedrock. For example, the occurrence of saturated, brecciated claystone and clay gouge intervals have been observed in some weathered zone core samples during logging. In addition, a water-yielding, highly fractured weathered bedrock zone was mapped in association with a bedrock fault during the SEP trenching program (Geomatrix Consultants, 1995). These features have not been observed in deeper boreholes which penetrate into the unweathered zone, so it is unclear from borehole evidence whether or not the apparent increased permeability of these shallow intervals persists with depth. Given the probable ductile behavior and moderate swelling properties of the claystone combined with the squeezing effect of overburden pressures on fractures with depth, it appears likely that any fracture-controlled fault zone permeability found in the weathered zone will attenuate with depth.

2.6 Groundwater Contaminant Geochemistry

Hazardous and radioactive substances released to the shallow groundwater system since the inception of plant activities in 1952 provide yet another means for evaluating vertical groundwater movement in the LHSU and toward the Laramie/Fox Hills aquifer. Many of these substances, including chlorinated volatile organic compounds (VOCs) and radionuclides (plutonium-239/240 and americium-241), are not naturally occurring and, thus, their presence or absence in LHSU groundwater can potentially be used to evaluate contaminant behavior in the confining layer. These contaminants are known to be moderately to highly retarded in the groundwater environment and are expected to move very slowly, as discussed later in Section 3.3. It is, therefore, important to consider the actual vertical distribution of selected contaminants of concern in LHSU groundwater as a check against their expected behavior derived from empirical and theoretical considerations.

The RFETS groundwater monitoring program is conducted in accordance with the Environmental Restoration Program Quality Assurance/Quality Control Plan (Rockwell International, 1989) as amended by the Quality Assurance Project Plan (QAPjP) for CERCLA RI/FS and RCRA RFI/CMS activities (EG&G, 1991a). Analytical data for the groundwater monitoring program were generated using EPA and other well-established analytical methods identified in the General Radiochemistry and Routine Analytical Services Procedures (GRRASP) (EG&G, 1991b).

2.6.1 LHSU Monitoring Well Network

LHSU groundwater quality has been monitored by a network of 66 wells listed in Table 2-1 and shown in Figure 2-6. Many of these LHSU wells are located near IHSSs or within the known boundaries of UHSU groundwater plumes associated with the OU2 and Industrial areas of the Site. The screen midpoints of LHSU wells range anywhere from 4.3 feet (well 23193) to 142.9 feet (well 2887) below the base of UHSU weathered bedrock and average 50 feet below the base. This average depth corresponds to a monitoring zone that comprises the uppermost 8 to 9 percent of the upper Laramie LHSU confining layer.

Many early LHSU wells were installed using drilling and construction techniques that involved standard precautions for isolating UHSU contaminated zones from deeper zones during drilling and well installation. The potential for cross-contamination was undoubtedly recognized at the time, however, the level of diligence required to avoid cross-contamination, based on a present-day understanding of Site conditions, was apparently underestimated and may have been inadequate to prevent, in some cases, the introduction of trace concentrations of contaminants to wells. As a consequence, a potential exists for non-representative sample collection, which can complicate interpretations of the analytical results and may lead to erroneous conclusions. In 1993, the issue of vertical contaminant migration of VOCs from the UHSU into the LHSU was specifically addressed at five localities comprising the most highly contaminated areas of the VOC plumes in OU2 (DOE, 1995g). This was accomplished by the installation of a series of seven carefully constructed LHSU monitoring wells that were designed to exclude contact with

contaminated UHSU groundwater and formation materials during the drilling and well installation process. The related issue of potential cross-contamination of UHSU or LHSU groundwater from drilling and well installation in areas of radionuclide-contaminated surficial soils has not been investigated in the field and represents a source of uncertainty for analyses involving actinide migration in groundwater.

**Table 2-1
Listing of LHSU Wells**

RFP Well Name	Screen Midpoint Depth Below Bedrock Surface (ft)	Screen Midpoint Depth Below Weathered Bedrock Surface (ft)	RFP Well Name	Screen Midpoint Depth Below Bedrock Surface (ft)	Screen Midpoint Depth Below Weathered Bedrock Surface (ft)
0886	60.4	47.4	B304989	70.8	35.7
0986	98.7	71.5	B405289	34.9	7.5
1686	35.1	13.6	B206289	22.1	8.6
2186	36.1	13.1	B207089	36.2	14.7
2386	106.9	60.6	B207189	67.7	44.2
2586	62.9	19.0	P208889	86.9	55.9
2786	119.8	89.8	B315289	75.0	28.0
3286	119.2	62.2	P416989	123.4	83.4
3486	34.3	12.3	B317189	59.4	33.9
4086	60.7	47.4	B217289	116.9	79.0
4686	60.6	29.1	B217489	119.0	83.6
4886	129.5	93.5	B217589	70.7	n/d
5486	44.3	11.3	B217689	78.7	41.7
0387	84.5	56.8	B217789	54.3	35.9
0887	77.8	23.5	46692	55.3	16.1
1687	90.3	68.5	46792	80.1	55.6
1887	105.0	76.2	46892	130.4	70.3
2087	99.9	51.9	22093	46.7	4.5
2287	72.1	41.9	22193	44.5	6.0
2887	148.9	142.9	22293	53.5	4.4
3087	74.1	48.1	22393	102.1	61.4
3187	75.0	68.5	22593	82.0	23.7
3487	80.8	53.8	23193	62.3	4.3
3987	110.1	74.1	23293	60.6	n/d
4187	84.0	61.9	70293	n/d	n/d
4587	91.3	55.8	70593	107.2	72.5
B203789	107.7	94.9	70893	n/d	n/d
B203889	80.7	59.2	53094	46.0	n/d
B203989	105.5	92.9	57194	n/d	n/d
B204089	108.5	71.7	57594	76.8	n/d
B204189	84.7	37.5	59394	n/d	n/d
B304289	75.8	56.3	59894	93.0	n/d
B204689	106.5	79.5	71194	n/d	n/d

Note: n/d = not determined

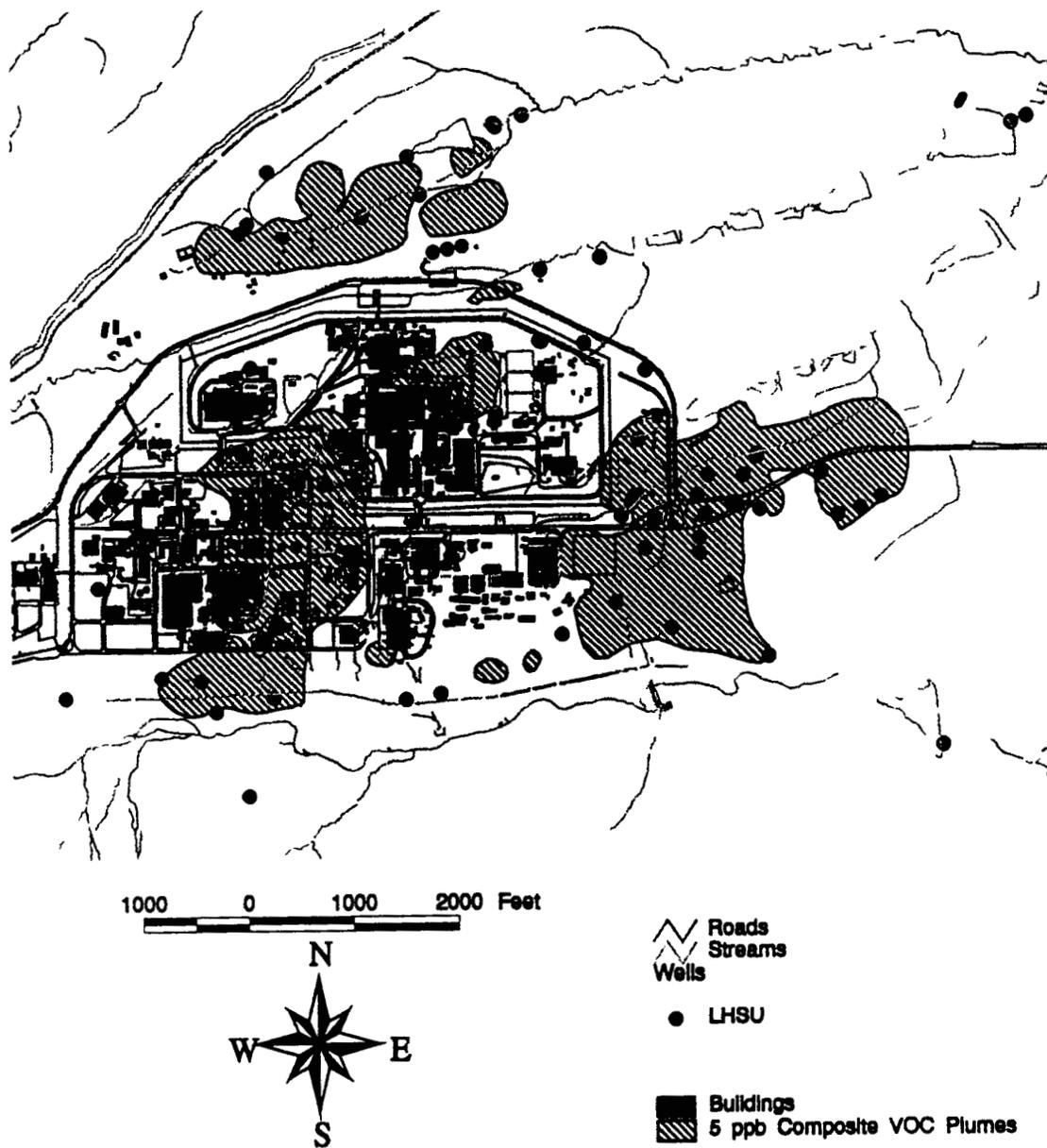


Figure 2-6 Location of LHSU Wells Near Industrial Area

Groundwater geochemical data for monitoring wells at the Site are stored in the Rocky Flats Environmental Database System (RFEDS). Data for detected concentrations of VOCs and activities of total and dissolved radionuclides greater than the background mean plus two standard deviations were retrieved from the database for LHSU wells for the period 1990 to present as presented in Attachment B. In general, the quality of the analytical data improves after 1991 because of increased laboratory performance requirements and internal checks applied to raw data transferred into the database. Pre-1990 analytical data reside in the database but were omitted from this analysis for reasons of concern over data quality. This omission will not adversely impact the analysis of vertical migration because, given the hydrogeologic setting, chemical concentrations and radionuclide activities in LHSU wells would be expected to increase, rather than decrease, with time.

2.6.2.1 Volatile Organic Contamination

As previously mentioned, the contaminants of concern in shallow groundwater at the Site include various chlorinated VOCs that have been widely used over the years in plant operations. Chemical contaminants such as VOCs will tend to migrate mainly as solutes in distinct individual or intermingled plumes that are associated with UHSU deposits. Under Phase 1 of ASAP, UHSU plume mapping identified areas of VOC contamination that are delineated in the composite plume map illustrated in Figure 2-6. These plumes are the primary source areas of VOC contamination for subsequent transport to LHSU groundwater. The principal VOC plume components include TCE and PCE, with CT and vinyl chloride occurring to a lesser extent. It should be noted that the spatial distribution of individual VOC contaminants is not shown on this map. In some areas, specific VOCs may comprise the entire plume (i.e., CT at IHSS 118.1) or be entirely absent from other multicomponent plumes.

Of the 66 LHSU wells on Site, 58 wells contained at least one reported detection of VOCs in groundwater samples (see Attachment B). The results from these wells are reviewed in more detail below, in order to assess their potential hydrologic significance.

To understand the significance of these data, it is first necessary to eliminate any unreliable values, which are caused by extraneous factors such as analytical data quality, laboratory contamination, and database entry errors. Analytical data for the Site are validated by an independent, third-party contractor following EPA functional guidelines for data validation (EPA, 1988a, 1988b). Validated data are classified in one of three ways: V = valid and useable without qualification, A = acceptable for use with qualification (also JA), and R = rejected or unacceptable for use. Judging from the type of validation codes reported in Attachment B, the analytical data for detected VOCs are of acceptable quality for use. Consequently, poor quality data do not appear to be a detracting factor for interpreting this set of data.

Laboratory contamination of samples from solvents used in the laboratory can occur during VOC analysis and are normally reported in the sample analytical results. One method of detecting laboratory contamination involves the analysis of laboratory blank samples, which are prepared in the laboratory and are subsequently analyzed with the field samples. Any analytical result qualified as 'B' or 'BJ' indicates that this analyte was detected in blank samples and probably signifies laboratory contamination, especially if the result is close to the analytical detection limit. The analytes most commonly associated with laboratory contamination include methylene chloride, acetone, toluene, 2-butanone, and phthalates, but trace levels of other contaminants may occur.

In addition to laboratory contaminants, compounds with single or spurious detections, particularly if present in the pre-1992 data, were also eliminated from the list of real contaminants. It was also assumed that the most likely type of contaminants found in LHSU wells would reflect conditions existing in the overlying UHSU groundwater. Based on consideration of these factors, the list of potential real contaminants in LHSU wells was reduced to PCE, TCE, CT, and chloroform. Applying these criteria, the list of 58 wells with VOC

detections reduces to a list of 17 wells. The significance of VOCs in samples from these wells are further examined using the time-series plots presented in Attachment C.

Time-series plots provide a graphical means for evaluating the analytical history of sample results for a given well. Using these plots, wells with consistent detections are easily distinguished from wells showing spurious or inconsistent detections. In terms of identifying LHSU wells that are potentially contaminated by VOCs, the most likely candidates appear to be the following nine wells: 1687 (PCE), 1887 (CT, chloroform and PCE), 2087 (PCE and TCE), 2887 (PCE and TCE), 46692 (TCE), 22093 (TCE), 22593 (TCE), 23193 (TCE), and 23293 (TCE). Most of these wells show low, but generally persistent, levels of contaminants over time, the concentrations of VOCs are generally below the 5 µg/L drinking water standard set for PCE, TCE and CT. The potential hydrologic significance of VOC detections in these wells will be addressed later in Section 2.6.3.

2.6.2.2 Radionuclide Contamination

Radionuclide contaminants in Site groundwater are detected sporadically in LHSU wells and, depending on the radioisotope, may move either in a dissolved (i.e. uranium and tritium) or colloid-facilitated transport phase (Pu-239/240 and Am-241). The principal radionuclide contaminants of concern for long-term transport at the Site are Pu-239/240 and its daughter radioisotope, Am-241. Unlike VOCs, the distribution of Pu-239/240 and Am-241 in groundwater cannot be reliably represented by a plume map due to uncertainty involving the type of transport mechanisms controlling Pu-239/240 and Am-241 migration into and through groundwater. It is generally observed that Pu-239/240 and Am-241 in UHSU groundwater is more commonly associated with source areas, such as the 903 Pad, than in other areas, however, the nature of this association is only poorly understood at the present time. Because the subject of Pu/Am transport in UHSU groundwater is currently being evaluated by a separate ASAP working group, it will not be addressed at length in this white paper.

The remaining radionuclide constituents detected in LHSU groundwater, although more mobile than Pu/Am, either occur naturally (such as uranium and radium) or are reported only rarely in the database. Their utility as groundwater tracers is, therefore, somewhat compromised by the uncertainty associated with their original background activities in LHSU groundwater at potential source areas. For example, the occurrence of natural uranium isotopes in groundwater, in conjunction with a complex plant process history involving both enriched and depleted uranium, greatly complicates the vertical migration analysis for U-235 and U-238 at the Solar Ponds. The issue of uranium contamination will be considered separately by the ASAP Actinide working group. Consequently, a detailed discussion and analysis of these analytes are not presented as part of this white paper.

Analyses of LHSU groundwater samples have been performed for both total and dissolved Pu-239/240 and Am-241. Analytical data for groundwater samples collected from the 66 LHSU wells indicate that, for total and dissolved Pu-239/240 and Am-241, 14 wells yielded at least one sample with total Pu-239/240 activities in excess of the background mean value plus two standard deviations (background plus 2SD). Twelve wells contained at least one sample with total Am-241 activities in excess of background plus 2SD. Dissolved Pu-239/240 or Am-241 were not detected above background plus 2SD in any of the wells. The results from these wells are presented in Attachment B.

For the most part, recurring Pu-239/240 contamination appears to be restricted to only a few LHSU wells. These wells, designated 1687, 46692, 46792 and 46892, are located east and northeast of the 903 Pad in areas of sporadic UHSU groundwater contamination and known low-level surface-soil contamination. Time-series plots prepared for these wells (Attachment C) illustrate the trend of total Pu-239/240 in each well. The most consistent record of LHSU contamination is found in well 1687, which is located 280 feet east of the 903 Pad. Multiple instances of Pu-239/240 detection are also associated with wells 46692, 46792, and 46892, a nested set with vertically staggered midpoint completion depths ranging from 16.1 to 70.3 feet below the base of weathered bedrock. The remaining wells with positive detections do not indicate a persistent Pu-239/240 presence that might otherwise implicate the LHSU as potentially

contaminated in these areas. Am-241 is generally found at lower activities in wells with Pu-239/240 detections and, itself, does not appear to constitute a pattern significantly different from its parent radioisotope. As with VOC contamination, the potential significance of the Pu/Am data will be discussed in the next section.

2.6.3 Hydrologic Significance of Contaminant Detections in Upper Laramie Confining Layer Groundwater

The analytical data described above indicate the presence, but not the mechanism of transport, of low-level VOC and radionuclide contaminant detections in certain LHSU wells. The two most plausible explanations for contaminant detection in these wells are 1) the natural migration of VOC and radionuclide contaminants into the upper Laramie Formation confining layer via fractures or porous matrix transport, and 2) the presence of cross-contamination from overlying contaminated materials introduced to the well completion zone during drilling and well installation or by leakage along faulty well seals. Due to the nature of the problem, it is often not possible to conclusively resolve which of the two is the dominant mechanism, although the circumstances surrounding each well sometimes provide clues that favor a particular explanation.

As a general rule, it is very difficult to avoid cross-contamination during drilling and well installation at source areas (Feenstra and Cherry, 1996), particularly where source concentrations are high and minimal measures have been taken to isolate source zones from the well completion zone. In these situations, the presence of deep, persistent contamination, especially at trace levels, must be critically assessed to determine whether the usual assumptions of well integrity and sample representativeness are reasonable for the wells in question.

The list of LHSU wells with VOC and radionuclide detections includes wells drilled using standard single casing-isolation techniques (1687, 1887, 2087, 2887, 46692, 46792, and 46892) and custom multiple-casing isolation techniques (22093, 22593, 23193, and 23293). LHSU wells drilled in 1987 (designated with the '87' suffix) have surface isolation casings that were set in bedrock above the base of the UHSU. This type of completion increases the potential for cross-contamination in these wells because contamination may extend to the base of the UHSU.

below the casing point. These wells have relatively deep completion zones (see Table 2-1) that are isolated by neat cement-grout annular seals. Wells 1687 and 2087 both exhibit low, relatively steady VOC contaminant levels. Well 1687 also contains an elevated level of Pu-239/240. Although difficult to prove, the circumstances surrounding these wells (i.e., standard care for well construction, deep completion zones, presence of Pu-239/240, etc.) suggest that cross-contamination is the likely cause for contaminant detections in these wells. Support for this conclusion is provided by the analytical results for well 22393, which was drilled to verify the VOC contaminant levels detected in well 2087 and revealed no detectable contamination. The potential for cross-contamination via leakage along neat cement-grout annular seals is implicit in the research results of Kurt and Johnson (1982), who measured longitudinal (vertical) permeabilities in the range of 2×10^{-4} to 1×10^{-3} cm/sec for various PVC casing and neat cement-grout combinations. These permeabilities are three to four orders of magnitude higher than measured for LHSU claystones.

Well 46692, a shallower LHSU well than the rest in this group, was constructed using a single isolation casing and neat bentonite-slurry annular grout. With the exception of a single spurious sampling event (12/9/93), the time-series plots of this well indicate levels of VOCs, particularly TCE, that are at or below the detection limit. Because the most recent samples show TCE at below the 0.2 µg/L detection level, it is assumed that the earlier detections are related to residual levels of cross-contamination.

The time-series plots for wells 1887 and 2887 indicate sharp increases in contaminant concentrations for samples collected in 3rd quarter of 1994, concentrations subsequently decrease in later samples. Especially notable is the trend in well 2887 for TCE, which rises rapidly from a record of below-detection results at 0.2 µg/L, to an estimated peak value of 63 µg/L in only a four-month period. The cause for the sudden increase and decline in VOC concentration for these deeply completed wells cannot be ascertained with the available data, although partial annular-seal failure is a distinct possibility. Further monitoring will be required to establish the persistence and trend of contaminant concentrations.

Compared to the above wells, the presence of detectable VOC concentrations in multiple cased LHSU wells 22093, 22593, 23193, and 23293 provides a more convincing argument that contaminants have penetrated into the shallowest strata of the upper Laramie confining layer. The depth of penetration appears to be limited to the upper 24 feet (well 22593), which corresponds to the maximum depth of open fractures in the LHSU observed in borehole 25193 (see Section 2.3.5.3). Even so, the potential for cross-contamination in some wells may still exist, as suggested by the declining trend for TCE in well 23193.

For LHSU wells with total Pu-239/240 detections above background, the most probable cause is contamination of the well completion zone by drilling fluids that contact radiologically contaminated surface soils. Plutonium and americium are strongly sorbed to soils and are expected to migrate very slowly through the soil profile (Litaor et al., 1994, Fig. 2). Transport of plutonium in groundwater is usually attributed to colloid and particulate movement, which can mobilize sorbed Pu-239/240 in a porous or fractured media.

Unless special precautions are taken to isolate deeper strata during drilling, soil-borne radionuclide contaminants can be introduced into the borehole, and can provide a potentially long-term source of trace contamination in groundwater samples. In LHSU wells, this problem is exacerbated by low well yields, which limit the effectiveness of well sampling and development. Groundwater samples collected from wells at the Site characteristically contain moderate to high levels of total suspended solids, which result from agitation of fine-grained materials in the well intake interval during sample collection. The amount of suspended solids in a sample from a specific well will vary mainly as a function of sampling technique. The natural total suspended solids content of in situ groundwater is assumed to be very low, as indicated by the turbid-free quality of groundwater issuing from springs at the Site. If it is assumed that Pu-239/240 migrates through a geologic media strictly as a sorbed or colloidal phase with no wellbore cross-contamination, then the Pu-239/240 activity level should remain constant regardless of the level of total suspended solids in the sample. If, on the other hand, Pu-239/240 is associated with borehole cross-contamination introduced during drilling, the activity of Pu-

239/240 in samples should proportionally increase with an increasing total suspended solids concentration. Analysis of the Pu-239/240 activity and total suspended solids concentration relationship for individual wells indicates that a strong proportional relationship is observed in the data which lends support to the cross-contamination hypothesis (e.g., DOE, 1995c, Fig. 5-2).

2.7 Groundwater Development and Use

Groundwater resources in the immediate Rocky Flats area have experienced a moderate amount of development in terms of well density and use. Approximately 239 wells tapping a variety of bedrock and alluvial aquifers are permitted within a 5 mile radius of the Site according to records obtained from the Office of the Colorado State Engineer. The majority of these wells are located more than 3 miles from the Site with the greatest density of wells situated to the southeast near Standley Reservoir. In general, more wells are located east and south of the Site than other directions. A significant number of wells are also located to the northeast near the town of Superior. The closest downgradient Laramie-Fox Hills aquifer well is about 2.5 miles northeast from IHSS 118.1 in the Industrial Area, and 1.9 miles from IHSS 110, the easternmost IHSS source considered under this analysis.

The main factors that have determined groundwater development in the area include land use, aquifer extent, depth to water, aquifer hydraulic properties, water quality, and water rights issues. Development of the Laramie-Fox Hills aquifer as a primary water source near the Site is most likely in areas where surface water supplies are unavailable and surficial aquifers are absent or are incapable of supplying reliable quantities of water. The most common off-site well use classifications listed in the permitted well records are domestic and monitoring uses. Sixteen of the wells are permitted for municipal use, 18 are permitted for industrial or commercial use, and two are permitted for irrigation use (DOE, 1995b). Wells located closest to the Site generally have domestic use classifications.

Water-quality data obtained in 1973 from deep wells completed in the Laramie-Fox Hills aquifer near Rocky Flats and at the U.S. Department of Energy Wind Research Site show dissolved

solids concentrations ranging from 200 to 714 mg/L (DOE, 1995b) With one exception, sulfate concentrations were less than 10 mg/L These data were obtained in 1976 and showed an increase in concentration from west to east The results are consistent with the results of Robson (1989) In addition, these wells, with the exception of the Wind Site well, were sampled and analyzed for Site-related radionuclides, including plutonium, uranium, and tritium The results of testing indicated that there was no difference between up and downgradient water quality and that the wells were free of radionuclide contaminants (Illsley, 1976) The available water quality data indicate that the Laramie-Fox Hills aquifer in the Rocky Flats area is generally potable and suitable for most uses

3.0 EVALUATION OF VERTICAL MIGRATION POTENTIAL

3.1 Conceptual Model Basis and Assumptions

The analytical methods chosen for evaluating contaminant migration through aquifers and confining layers at the Site are based on simple, one-dimensional concepts which are capable of approximating, within reasonable limits, the transport and fate of DNAPLs and dissolved organic contaminants in saturated geologic media. In certain respects, the utilization of one-dimensional techniques imparts a somewhat conservative bias to the results. This bias serves to help offset some of the non-conservative assumptions that must necessarily be made due to a lack of adequate data or imprecise understanding of site conditions. One critical assumption made in the analysis is that fractures occurring in the LHSU claystones impart only a minimal enhancement to the bulk rock hydraulic conductivity. This assumption is supported by core and other observations presented in the preceding sections. Because the permeability enhancement is minimal, it is further assumed that the rock mass, on average, can effectively be treated as a porous media. This assumption is described in further detail in Section 3.3.2. Other key assumptions made including their impacts are

- (1) the LHSU confining layer acts as a homogeneous, isotropic and fully saturated geologic media based on minimal fracture/fault enhancement of hydraulic conductivity,
- (2) contaminant behavior is conservative (non-reactive) and is not subject to degradation or transformation reactions, and
- (3) groundwater flow occurs under steady state conditions

Additional assumptions are made, where necessary, as cited in the text

3.2 Groundwater Flux, Flow Velocity and Travel Time

3.2.1 LHSU Confining Layer

The magnitude of downward vertical groundwater flow from the UHSU into the LHSU (and from the LHSU into the Laramie-Fox Hills aquifer) can be estimated using Darcy's Law and site-specific data. Assuming homogeneous, isotropic, steady-state, one-dimensional flow and full saturation, the vertical flux rate is calculated from

$$q = K_v \frac{dh}{dz} \quad (2)$$

where

q equals the vertical flux rate (cm/sec)

K_v is the vertical hydraulic conductivity (cm/sec)

dh/dz is the vertical hydraulic gradient (dimensionless)

Applying this equation, vertical flux rates for a range of possible K_v values were determined using a hydraulic gradient of 0.4 (see Section 2.3.4). The geometric mean horizontal hydraulic conductivity value of 2.5×10^{-7} cm/sec is included with these values as a possible upper bound given that fracturing, with an average dip angle of 40 degrees from horizontal, will potentially contribute almost equally to the vertical hydraulic conductivity. These results are summarized below in Table 3-1.

Using the previously stated assumptions and a mean porosity value (ϕ) of 0.22, the vertical seepage velocity, v_w , can be obtained from the Darcy flux with the following relationship

$$v_w = \frac{q}{\phi} \quad (3)$$

where the total porosity is considered equal to the effective porosity based on similar practice for clayey confining layers used by Desaulniers, et al (1981) and McKay, et al (1993).

Table 3-1
Vertical Flux and Travel Time Calculation Results
for the Upper Laramie Formation LHSU Confining Layer

K_v (cm/sec)	Vertical Flux		Vertical Seepage Velocity		Travel Time To Laramie-Fox Hills Aquifer (yrs)
	(cm/sec)	(ft/yr)	(cm/sec)	(ft/yr)	
2.5 x 10 ⁻⁷ (1)	1.0 x 10 ⁻⁷	0.104	4.5 x 10 ⁻⁷	0.468	1,300
1.0 x 10 ⁻⁷ (2)	4.0 x 10 ⁻⁸	0.041	1.8 x 10 ⁻⁷	0.185	3,200 ³
5.8 x 10 ⁻⁸ (3)	2.3 x 10 ⁻⁸	0.024	1.0 x 10 ⁻⁷	0.108	5,500
1.0 x 10 ⁻⁸ (2)	4.0 x 10 ⁻⁹	0.0041	1.8 x 10 ⁻⁸	0.018	33,000
2.8 x 10 ⁻¹⁰ (4)	1.1 x 10 ⁻¹⁰	0.00012	5.0 x 10 ⁻¹⁰	0.00054	1,100,000

(1) geometric mean unweathered claystone/siltstone K_v (DOE, 1995b)
(2) Assumed from Figure 2-4
(3) geometric mean laboratory K_v (DOE 1995b)
(4) Robson (1987)

The seepage velocity represents the advective transport rate for nonreactive contaminants. The range of calculated values presented in Table 3-1 demonstrates the relatively slow vertical movement of groundwater in the LHSU. A more meaningful presentation of the seepage velocity results involves the concept of contaminant travel time to a receptor. For an assumed LHSU confining layer thickness of 600 feet (182.9 meters) and seepage velocity results of Table 3-1, the travel times for a conservative contaminant to migrate from the UHSU to the Laramie-Fox Hills aquifer ranges from 1,300 to 1.1 million years. As shown in later sections, the hydrologic and geochemical properties of the LHSU have a substantially greater ability to attenuate DNAPL and dissolved contaminant migration and affect contaminant fluxes into the Laramie-Fox Hills aquifer than presented here.

3.2.2 Laramie-Fox Hills Aquifer

Estimated horizontal groundwater flux rates for the Laramie-Fox Hills aquifer at the Industrial Area were also determined using the Darcy equation and assuming a K_h value of 1.8 x 10⁻⁵ cm/sec and dh/dx value of 0.04, as presented previously in Subsection 2.3.4. The calculated Darcy flux of 7.2 x 10⁻⁷ cm/sec is about 7 to 6550 times larger per unit area than the vertical flux occurring across the confining layer, depending on the assumed vertical hydraulic conductivity.

As discussed later in Subsection 3.3.4, the relative difference between aquifer and confining layer groundwater fluxes is of interest because the ultimate impact of a dissolved contaminant plume entering the Laramie-Fox Hills aquifer will depend on the mass flux at the aquifer/confining layer boundary.

3.3 Contaminant Transport and Pathway Analysis

DNAPLs or high levels of DNAPL-derived groundwater contamination indicative of DNAPL presence have been detected in various areas of the Site. These areas include the 903 Pad, Mound, Industrial Area (multiple sources), 881 Hillside (IHSS 119.1), Ryan's Pit (IHSS 109), east trenches (IHSSs 110, 111.1, etc.) and IHSS 118.1. In this section, the potential for vertical contaminant transport from two IHSS areas, 110 and 118.1, is evaluated based on the Site hydrologic conditions and concepts presented above. These areas were chosen because they are located in areas that are representative of industrial area conditions, contain documented evidence of DNAPL presence, differ in the chemical characteristics of the DNAPL source, and are the focus of current accelerated clean-up activities.

3.3.1 Site Descriptions and History

IHSS 118.1

IHSS 118.1 is related to a 5,000 gallon underground steel storage tank that contained carbon tetrachloride (CT) located adjacent to the west side of Building 730, just north of Building 776. The IHSS was originally defined as a 50- by 180-foot area between Buildings 776 and 701 (EG&G, 1990). More recent information provided by Doty and Associates (1992) has indicated that IHSS 118.1 should be redefined as a 30- by 13-foot area located adjacent to the east side of Building 701.

Engineering drawings indicate that the tank was approximately 14 feet in length (north-south) and approximately 8 feet in diameter. The south end of the tank was enclosed in a concrete

structure which provided access and encased the tank piping. The structure was approximately 6 feet wide, 12 feet long, and 12 feet deep. The structure encased only about three feet of the south end of the tank. An 18-inch square concrete sump pit, located in the southwestern corner at the bottom of the structure, provided drainage.

The tank has a history of numerous spills and leaks, as described in DOE (1994), which date back to the pre-1970's. On June 18, 1981, the tank failed, releasing carbon tetrachloride into the sump. The tank was subsequently removed following this failure (DOE, 1992a).

IHSS 110

IHSS 110 (Trench T-3) is located north of Central Avenue, east of the inner fence, and south of South Walnut Creek. An evaluation of recently collected geological and geophysical data indicate that Trench T-3 is approximately 5 to 10 feet in depth, 19 to 23 feet wide, and 135 to 140 feet long (DOE, 1995f). It is one of several trenches located in the east buffer zone that was used for waste disposal. The trench was operated sometime during the July 1965 through August 1968 time period.

According to the Historical Release Report (DOE, 1992a), the trench was primarily used for the disposal of uranium and plutonium-contaminated sanitary sewage sludge and flattened drums potentially containing uranium and waste oils. It is unknown, however, how much residual material may have remained in the drums at the time of burial. The trench has been extensively investigated in recent years as part of RCRA Facility Investigation/Remedial Investigation and Soil Vapor Extraction pilot testing activities (DOE, 1995f), and is currently being excavated for remediation of PCE and other VOCs.

3 3.2 *DNAPL Behavior in the Subsurface*

3 3 2 1 DNAPL Occurrence and Properties

Field investigations conducted in the IHSS 110 and 118 1 areas of the Site have detected the presence of chlorinated DNAPLs or dissolved chlorinated hydrocarbons in soils and groundwater. These areas have been scheduled for remediation activities that will remove or stabilize the source material and associated soils to clean-up levels established by the proposed 1996 Rocky Flats Compliance Agreement (currently released for public comment). Recovery of DNAPL below the water table is currently not planned at IHSS 110, but may be feasible at IHSS 118 1 pending further evaluation of site conditions.

At IHSS 110, field sampling programs have collected mixed phase liquid samples from inside the trench boundary. At least one sample was observed to consist of three layers: a black floating oily top layer, a yellowish brown aqueous middle layer, and a black liquid (possibly DNAPL) bottom layer. During shipment to the laboratory, the bottom layer apparently dissolved, leaving only the floating and aqueous layers separated in the sample. Chemical analysis of the bulk sample using distillation procedures revealed a composition of about 48.4% water, 8.4% DNAPL, 2.7% LNAPL, 0.8% undifferentiated phase, and 39.7% residue. The DNAPL fraction consisted primarily of PCE and TCE which comprised about 60% and 10% of the total fraction, respectively. The remaining fraction of DNAPL in these samples was composed of a mixture of semivolatile and petroleum hydrocarbon compounds (DOE, 1995f). DNAPL has not been detected in soil or groundwater samples outside of the trench, however, the presence of 221 mg/L TCE in a groundwater sample from well 3687 strongly suggests that DNAPL has mobilized from one of the trenches into the underlying Arapahoe Formation sandstone. The volume, extent, and thickness of DNAPL residing in Trench T-3 and other nearby trenches and associated underlying unsaturated and saturated zones is unknown.

The CT composition of the IHSS 118 1 DNAPL is assumed from process history associated with the IHSS 118 1 underground CT storage tank, and from CT detection in field screening samples by Draeger tube analysis of sample headspace from an adjacent tank investigation. Pooled

DNAPL was detected in the bottom of two boreholes (02695 and 02995) located at the northwest and northeast corners of tank T-9, with an estimated thickness of one foot. These boreholes are located approximately 20 feet east of IHSS 118 1. Estimates of DNAPL volume and extent are unavailable. However, depth to bedrock evidence from adjoining boreholes suggests that the lateral extent of DNAPL may be influenced by local depressions in the bedrock that were potentially made during tank installation. It is clear from the presence of CT in boreholes 02695 and 02995 that DNAPL has migrated laterally at least 20 feet from the source tank.

Selected physical and chemical properties of the principal DNAPL compounds found at IHSSs 110 and 118 1 are summarized in Table 3-2. These properties, in addition to the lithologic and hydrologic characteristics of the LHSU confining layer provided in subsections 2.3.2 and 2.3.4, will be used to evaluate the potential for vertical contaminant migration to the Laramie-Fox Hills aquifer in the next section.

**Table 3-2
Chemical and Physical Properties of Selected DNAPL Compounds**

(1) Compound	(2) Aqueous Solubility (mg/L)	(3) K _{oc} (mL/g)	(4) DNAPL Density ρ _{DNW} (g/cm ³)	(5) ρ _{DNW} - ρ _w (g/cm ³)	(6) Interfacial Tension, σ (dynes/cm)	(7) Aqueous Diffusion Coefficient, D (cm ² /sec)	(8) Effective Diffusion Coefficient, D _e (cm ² /sec)
Carbon Tetrachloride (CT)	798	439	1.59	0.59	45.0	7.1 × 10 ⁻⁶	1.42 × 10 ⁻⁶
Trichloroethylene (TCE)	1,566	126	1.46	0.46	34.5	7.4 × 10 ⁻⁶	1.48 × 10 ⁻⁶
Tetrachloroethylene (PCE)	240	364	1.63	0.63	44.4	6.8 × 10 ⁻⁶	1.36 × 10 ⁻⁶
(1)	Pankow and Cherry (1996) for 10°C			(5)	Mercer and Cohen (1990)		
(2)	Pankow and Cherry (1996)			(6)	Pankow and Cherry (1996) for 10°C		
(3)	Pankow and Cherry (1996)			(7)	Assumes tortuosity = 0.2		
(4)	Assumes ρ _w = 1 g/cm ³						

3.3.2.2 DNAPL Transport and Fate

DNAPL transport and fate is a complex topic that, despite over 10 years of intensive research and field experience, is still only imperfectly understood. It is known that DNAPL movement and behavior is strongly affected by subsurface conditions which are site-specific and can be highly variable and unpredictable. For DNAPL releases that are sufficiently large to sink below the water table and pool above an impermeable bedrock surface, vertical migration of DNAPL into

the bedrock will be determined by capillary forces and pool thickness. Recent publications, including Pankow and Cherry (1996) and Cohen and Mercer (1993), have summarized the available information and approaches for evaluation of DNAPLs in groundwater. The reader is referred to these references for a more comprehensive discussion of DNAPL behavior in the subsurface environment.

The following analysis approach draws heavily from the work of Keuper and McWhorter (1991) on capillary pressures, as presented in a technical paper presented by Sale et al (1992) for the Laramie Tie Plant site in Laramie, Wyoming, and the work of Parker et al (1996) for diffusive loss of DNAPL from fractures in a fractured porous media.

Capillary Pressure Control of DNAPL Migration

From the available evidence at each IHSS site, it is assumed that DNAPL has penetrated through the alluvium to the underlying bedrock surface and formed a pool as displayed in Figure 3-1. The role of capillary pressure in controlling DNAPL migration into the bedrock is described in an excerpt from Sale et al (1992) as follows:

Water and DNAPL simultaneously occupy the pore space in the alluvium. Water has a stronger tendency to coat the solid grains and, therefore, is the wetting fluid. DNAPL is the non-wetting fluid, it occupies the portion of the pore space most remote from the solid surfaces.

Under these conditions, the pressures of the water and DNAPL increase with depth caused by the weight of the overlying fluids. Since the density of the DNAPL exceeds the density of water, the DNAPL pressure increases more rapidly with depth than does the water pressure. As a result, a pressure differential occurs between the DNAPL and water. This differential increases with depth in the DNAPL pool.

The difference between the DNAPL pressure and the water pressure, called capillary pressure, is defined as

$$P_c = P_{nw} - P_w \quad (4)$$

where

- P_c = capillary pressure
- P_{nw} = pressure of DNAPL (nonwetting)
- P_w = pressure of water (wetting)

For static conditions, the pressure variation in the two fluids is linear, as shown in Figure 3-1. At the bottom of the pool, the capillary pressure is at its maximum and is given by

$$P_c = (\rho_{nw} - \rho_w) g T \quad (5)$$

where

- P_c = capillary pressure
- ρ_{nw} = nonwetting-phase (DNAPL) density
- ρ_w = wetting-phase (water) density
- g = gravitational constant
- T = thickness of the pool

DNAPL will penetrate a water-saturated, porous, or jointed medium only if the capillary pressure exceeds a threshold value known as the entry pressure. Insight to the factors affecting the entry pressure is provided by idealizing joints as the opening between parallel flat plates and by idealizing pores as cylindrical capillary tubes. Assuming that water wets the solid with zero contact angle, the entry pressures for these geometries are given by the following equations

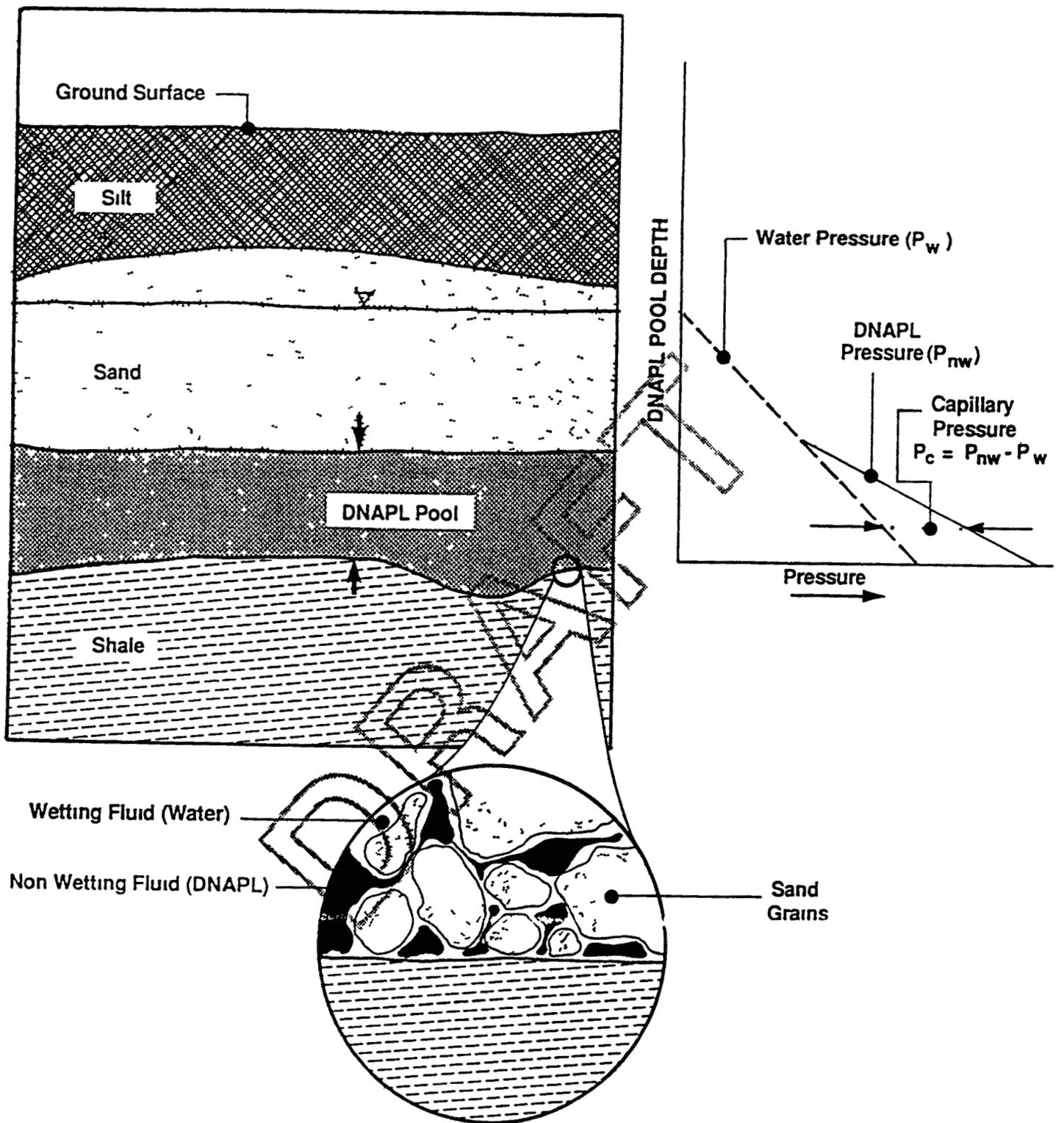
$$P_e = \frac{2\sigma}{e} \text{ (joint)} \quad (6)$$

and

$$P_e = \frac{4\sigma}{e} \text{ (pore throat)} \quad (7)$$

where

- P_e = entry pressure
- σ = interfacial tension between DNAPL and groundwater
- e = joint aperture or tube diameter



(After Kueper and McWhorter 1991)

Figure 3-1 Illustration of DNAPL Occurrence in the Alluvium and Definition of Capillary Pressure

These equations illustrate that entry pressures are directly proportional to the interfacial tension and inversely proportional to the size of the pore throat or joint aperture. Of course, real porous and jointed media contain openings with a wide variety of sizes and do not conform to these idealized geometries. For this reason, entry pressures are most reliably determined by direct measurement. Nevertheless, the fundamental dependence of entry pressure on interfacial tension and the size of openings remains as expressed above.

By putting the capillary pressure (P_c) equal to the entry pressure (P_e) in Equation 5, one can compute the critical thickness, T_c , of a static DNAPL pool required to achieve entry into a stratum with any prescribed entry pressure.

$$T_c = \frac{P_e}{(\rho_{nw} - \rho_w)g} \quad (8)$$

This approach, when applied to the IHSS 110 and 118.1 sites, can yield theoretical critical thickness values for use in assessing the potential for DNAPL migration into the UHSU at the Site. At IHSS 110, the underlying UHSU bedrock consists, at least in part, of relatively clean, fine to medium grained Arapahoe Formation sandstone. Representative pore diameters for medium-grained sandstones were not recovered from the literature, however, a maximum approximate pore diameter of 0.008 cm (80 μ m) was estimated from a uniform sand grain size of 0.05 cm (upper range of medium-grained sand) and cubic closest packing arrangement. For an interfacial tension value of 34.5 dynes/cm and pore diameter of 0.008 cm, a TCE pool thickness of at least 38.3 cm (1.3 feet) would be required to achieve DNAPL entry into the porous matrix of the Arapahoe Formation sandstone. The results of this analysis suggest that a significant thickness of DNAPL would have to pool above the sandstone before entry would occur. Chemical analyses from a nearby downgradient well, 3687, have indicated the occurrence of high concentrations of TCE/PCE that are consistent with DNAPL presence in the sandstone. If DNAPL has invaded the sandstone, it is possible that locally thick pooling may be the responsible mechanism as DNAPL presence outside of the trench has not been observed in surrounding boreholes. Alternatively, DNAPL entry via fractures could be accomplished with a lower critical

thickness, and remains a possible pathway that could explain the apparent presence of DNAPL in the sandstone near well 3687

At the IHSS 118 1 site, the analysis yields a critical thickness value of 15.5 cm (0.5 feet) for CT for a hypothetical 0.01 cm (100 μm) fracture opening and an interfacial tension value of 45 dynes/cm (see Table 3-2). Using a fracture aperture of 0.0014 cm (14 μm) calculated for the LHSU confining layer claystone, the critical thicknesses for CT becomes 111 cm (3.6 feet). Considering that an estimated one foot CT DNAPL thickness was observed in borehole 01994 at IHSS 118 1, it is entirely plausible for DNAPL to have migrated into the UHSU claystone bedrock at this locality given the probable openness of weathered bedrock fractures compared to the calculated LHSU fracture aperture value. The following discussion describes a mechanism which limits the ultimate extent of DNAPL in a fractured porous media.

Diffusive Disappearance of DNAPL from Fractures

Parker et al (1996) have recently investigated the fate of DNAPLs in fractured porous media. Their research has shown that DNAPL has a potential for relatively rapid disappearance from fractures into the adjacent porous matrix. This transfer occurs by DNAPL dissolution along fracture surfaces and subsequent diffusion and storage in the matrix as depicted in Figure 3-2. The disappearance time, t_D , for complete disappearance of DNAPL from a single fracture can be calculated from the following equation:

$$t_D = \frac{\pi\rho^2}{16S_w^2\phi_m^2D_eR}(2b)^2 \quad (9)$$

where

t_D = DNAPL disappearance time

ρ = DNAPL density

S_w = aqueous solubility of DNAPL

ϕ_m = matrix porosity

D_e = effective diffusion coefficient

R = retardation factor

$2b$ = fracture aperture

and

$$R = 1 + \frac{\rho_b}{\phi_m} K_d \quad (10)$$

where

ρ_b = bulk dry density of rock (g/cm^3)

K_d = distribution coefficient (ml/g)

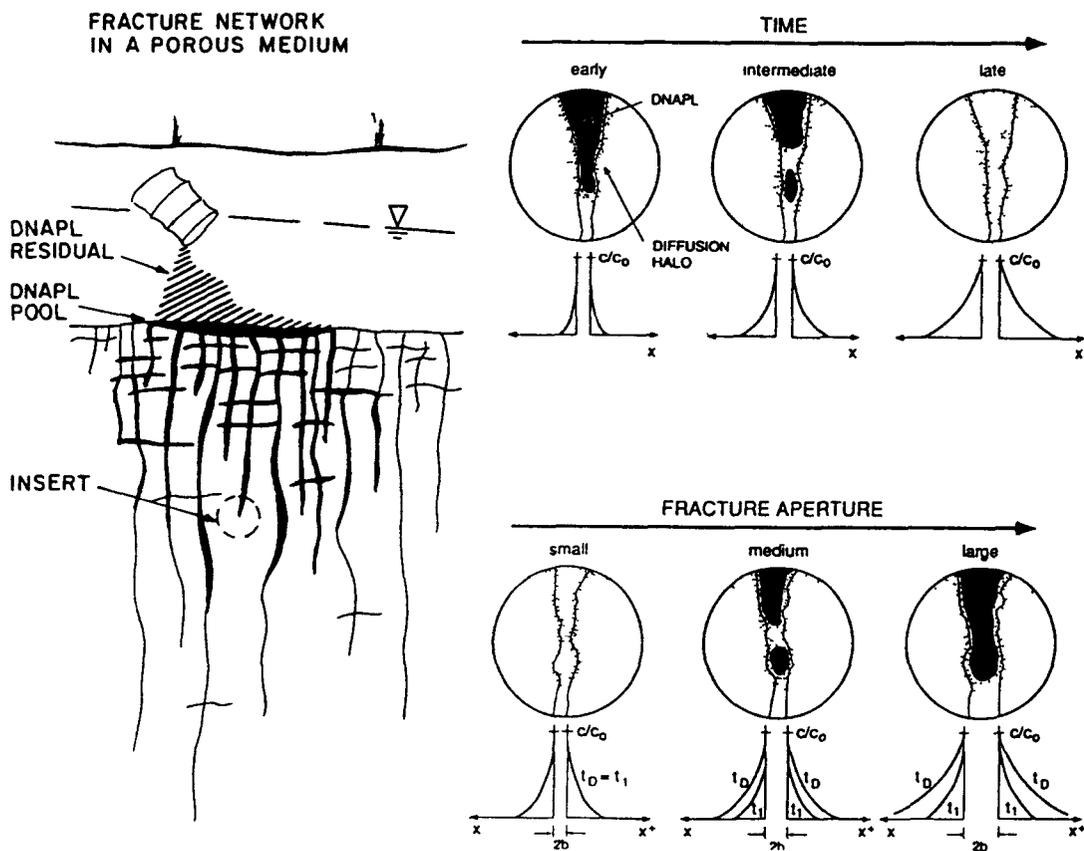


Figure 3-2 Conceptualization of DNAPL persistence and distribution with DNAPL mass loss due to diffusion in water-saturated fractures in a porous medium (such as a fractured clay till or sedimentary rock) as a function of a) time, and b) fracture size (aperture) (from Pankow and Cherry, 1996)

The distribution coefficient, K_d , is commonly predicted from listings of published partition coefficients and the organic carbon fraction measured from site samples using the equation

$$K_d = K_{oc} f_{oc} \quad (11)$$

where

K_{oc} = partition coefficient for compound of interest

f_{oc} = organic carbon fraction

For values of f_{oc} , K_{oc} , ρ_b , and ϕ_m reported previously in Section 2.0, K_d and R values for CT, TCE and PCE have been calculated as presented in Table 3-3

**Table 3-3
DNAPL Fracture Disappearance Time and Retardation Factor Calculations**

	Hydrostratigraphic Unit	FOC (%)	K_d (mL/g)	ρ_b (g/cm ³)	ϕ_m (%)	R	Fracture Aperture (cm)	Disappearance Time, T_D	
								(days)	(yrs)
CT	UHSU	0.0017	0.746	2.03	0.248	7.11	0.01	1,450	3.97
	LHSU	0.0103	4.522	2.07	0.222	43.16	0.0014	5.6	2.2×10^3
TCE	UHSU	0.0017	0.214	2.03	0.248	2.75	0.01	789	2.16
	LHSU	0.0103	1.300	2.07	0.222	13.12	0.0014	4.05	1.1×10^2
PCE	UHSU	0.0017	0.619	2.03	0.248	6.07	0.01	20,560	56.54
	LHSU	0.0103	3.749	2.07	0.222	35.96	0.0014	85.2	2.3×10^1

Substituting the CT values of R for weathered and unweathered bedrock into Equation 9, together with the appropriate values of physical and chemical properties from Table 3-2, yields disappearance times of 1,450 and 5.6 days for fracture apertures of 0.01 and 0.0014 cm, respectively. Similar results are obtained for TCE, which has a greater solubility, but lower retardation factor. Of the three compounds, PCE has the greatest disappearance time and thus can be expected to persist the longest as a non-aqueous phase liquid. Even so, the disappearance time for PCE in unweathered bedrock is relatively fast compared to the sluggishness of vertical

groundwater flow through the confining layer (see Table 3-1) Moreover, the 3-dimensional (3-D) nature of the fracture network at the Site will result in even shorter disappearance times than calculated above for the 1-D case due to an increase in the surface area to volume ratio (Parker, 1996) The disappearance of DNAPL from a fracture will continue until the diffusive flux across the fracture surface equals 0, i e when the matrix mass storage capacity is reached

The maximum amount of DNAPL that can be dissolved and sorbed per unit volume of unfractured matrix, M_m , is given by the contaminant mass storage capacity expressed as (Parker, et al , 1996)

$$M_m = \phi_m S_w R \quad (12)$$

For values of unweathered bedrock R given above, the mass storage capacity of bedrock is estimated at 7 65 kg/m³ for CT, 4 56 kg/m³ for TCE, and 1 92 kg/m³ for PCE These capacities, when calculated for the entire thickness of the unweathered bedrock, translate to approximately 1,400 kg/m² (232 gal/m²) CT, 834 kg/m² (151 gal/m²) TCE, and 351 kg/m² (57 gal/m²) PCE Converted to an alluvial pool thickness value, these volumes correspond to thicknesses of 9 6 ft , 6 2 ft , and 2 4 ft , respectively, for an assumed alluvial total porosity of 0 30 It is clear from these calculations that the unweathered bedrock is capable of storing quantities of DNAPL that greatly exceed the probable volumes released to the environment The total mass storage capacities (fractures and matrix) of the bedrock are actually expected to be greater than these calculated amounts because the estimates neglect the potentially important sorption properties of clay-rich rocks (Karickhoff, 1984) and the mass storage capacity associated with fractures

These calculations predict that once DNAPL penetrates into the fractured bedrock, it will be assimilated relatively rapidly as a dissolved or sorbed phase into the bedrock matrix Given the mass storage capacity available in the bedrock, the threat of downward DNAPL migration into the Laramie-Fox Hills aquifer is remote and unsupportable given the long travel times required for transport through the confining layer compared to the relatively short disappearance times predicted above

3 3 3 *Solute Transport and Fate*

Once a DNAPL compound enters the aqueous dissolved phase, it will be advectively and diffusively transported as a solute in groundwater depending on the average groundwater flow velocity and retardation characteristics of the media. According to Desaulniers, et al., (1981), diffusion can be an important or even dominant transport process at average groundwater flow velocities of less than about 0.7 cm/yr. From consideration of the seepage velocities presented in Table 3-1, this condition is assumed to exist when the vertical hydraulic conductivity approaches a value of about 1.0×10^{-8} cm/sec or less. The profile of decreasing hydraulic conductivity with depth shown in Figure 2-4 indicates that advection dominates in the upper half of the LHSU confining layer and suggests that diffusion may become more important in the lower half of the LHSU. For purposes of this analysis, advection coupled with dispersion is assumed to be the dominant transport mechanism operating throughout the confining layer because it is the more conservative approach of the two. The vertical movement and fate of DNAPL-derived dissolved organic contaminants will now be examined with consideration given to the hydrologic and geochemical properties of the claystone, as presented in the previous sections of the report.

3 3 3 1 Hydrodynamic Dispersion

Hydrodynamic dispersion refers to the tendency for a solute to spread out from a flow path and cause dilution of the solute (Freeze and Cherry, 1979). This phenomenon is caused by a combination of mechanical mixing during advective flow and diffusion of solute ions or molecules in groundwater environments which exhibit concentration gradients - a condition that is satisfied by the existence of a contaminant plume. Dispersion acts to spread a plume both longitudinally (direction parallel to groundwater flow) and transversely (direction normal to groundwater flow). The primary effects of neglecting hydrodynamic dispersion in transport analyses involves a prediction of maximum contaminant concentrations and minimum plume cross-sectional areas for flux calculations. Plume spreading will occur in three dimensions (3-D) unless limited by a hydrologic boundary such as the water table surface or impermeable layer. For vertical transport through a confining layer, it is expected that contaminant migration will be

three dimensional due to a lack of vertical boundaries that would limit lateral transport. Analysis of 3-D transport is beyond the scope of this white paper, however, satisfactory results can be obtained using 2-D techniques which incorporate longitudinal and transverse dispersion into the analysis. The analytical solution for a 2-D source areas, as presented in Domenico and Schwartz (1990) and Attachment B, will be used for estimating contaminant concentrations and travel times from an UHSU source to the Laramie-Fox Hills aquifer.

3.3.3.2 Contaminant Retardation

It is commonly observed in laboratory experiments and natural field conditions that the rate of solute contaminant movement is often retarded relative to the groundwater flow velocity. This reduction in contaminant velocity is caused by an interaction of the physical, chemical, and biological properties of the dissolved contaminant, media solids, and the aqueous solution. The principal agents for retardation of organic contaminants along a flow path include sorption and biotic or abiotic transformation reactions. Each of these processes and their effects will be discussed individually as they relate to vertical contaminant migration at the Site.

Sorption

The uptake of an aqueous contaminant by a geologic media without reference to a specific mechanism is a property referred to as sorption (Allen-King, et al, 1996). The sorption of different compounds can vary widely for the same geologic material depending on the physical and chemical properties of the compound. For organic contaminants, the sorption properties of a geologic media are strongly dependent on the amount of organic carbon present in the material. As groundwater containing organic solutes passes through an organic carbon-bearing geologic material, transfer of contaminant mass from the dissolved phase to organic carbon occurs reducing the concentration of the contaminant in solution. This process results in a retardation of contaminant velocity that causes the contaminant plume to move at a slower rate than the advective groundwater flow velocity. The equation describing this type of retardation, referred to as the retardation factor (R), has already been given in Subsection 3.3.1.2.

Retardation factors calculated from organic carbon-derived K_d values have been shown to underestimate sorption when compared to measured values determined from field experiments (Allen-King et al , 1996) In addition, there is evidence that sorption to mineral surfaces, such as clays, may contribute to or possibly dominate sorption at swelling clay fraction to organic carbon fraction ratios of approximately 25 to 60 (Karickhoff, 1984) The clay content of upper Laramie Formation LHSU claystones and siltstones averages 62 percent (Table 6-10 from DOE, 1995a) Compared to 1.03 percent organic carbon, it seems probable that clay sorption will further retard contaminant migration beyond that calculated by the organic carbon fraction alone The R values used in this analysis may, therefore, be conservative estimates that will result in the calculation of faster contaminant velocities than otherwise expected from a consideration of field experience presented in the literature

Transformation Reactions

Organic contaminants released to the groundwater environment have the potential to be transformed or degraded by natural geochemical or biochemical reactions The potential importance of these reactions to remediation planning and design at sites contaminated with chlorinated hydrocarbons have received a considerable amount of attention in recent years, especially stemming from the work of Gillham and O'Hannesin (1992) Transformation processes in groundwater have the net result of reducing the concentration of the parent contaminants in solution while, at the same time, producing chemical by-products that can be either more or less hazardous than the original parent compound Abiotic reaction rates for CT, PCE and TCE are available in the published literature, but vary considerably between investigators and have only a limited application to field problems For this discussion, it is assumed that abiotic reactions will dominate over biotic reactions in the confining layer given that the pore size distribution of claystone is expected to be unfavorably small for microbial transport and growth

Butler and Barker (1996) report that two abiotic transformation reactions - nucleophilic substitution by reduced sulfur and reductive dehalogenation - have been shown to be significant processes in groundwater. In both cases, environmental conditions that promote transformation include a low redox level, presence of Fe^{2+} and/or HS^- , alkaline pH, and presence of Fe^{2+} -rich mineral phases, such as pyrite, marcasite, biotite, and organic matter (Butler and Barker, 1996). For example, accelerated, aerobic and anaerobic transformation of CT to chloroform, CO_2 , CS_2 , and other intermediate reaction products in the presence of pyrite has been demonstrated in laboratory experiments conducted by Kriegman-King and Reinhard (1994). PCE and TCE are also known to abiotically transform in groundwater under reducing conditions, however, the reaction pathway includes by-products such as vinyl chloride which are more hazardous and mobile than the original reactants. From vinyl chloride, the reaction pathway proceeds and terminates with the production of ethylene.

The upper Laramie Formation LHSU confining layer has many geochemical characteristics that favor the potential for abiotic transformation reactions of chlorinated hydrocarbons, especially CT, in groundwater. For example, the deposit is inferred to consist of largely Fe^{2+} -bearing to Fe^{2+} -rich claystones and siltstones as indicated by the prevalent olive-gray to grayish-black color and organic carbon content using the $\text{Fe}^{2+}/\text{Fe}^{3+}$ mole fraction relationship suggested by Potter et al (1980). Visible pyrite has been observed in core samples collected at the Site and is presumed to increase in abundance deeper in the formation due to the presence of coal seams. Reliable measurements of redox conditions are unavailable for groundwater in the unweathered zone, however, a low dissolved oxygen content is expected based on the presence of mineral phases that readily react with oxygen (i.e. organic matter and pyrite). Chloroform, which has been found in significant concentrations in UHSU groundwater at boreholes 02595 and 02995 located near IHSS 1181, may be a reaction by-product of CT transformation. Chemical constituents associated with PCE and TCE transformation reactions have also been detected in groundwater, but many of these compounds have alternative sources that may be unrelated to in situ degradation.

In summary, the claystones and siltstones of the upper Laramie Formation LHSU confining beds contain a significant natural geochemical attenuation capacity that has the potential to substantially retard contaminant movement. The subject of non-organic carbon sorption and abiotic transformations is clearly relevant to an analysis of long-term contaminant movement and fate in groundwater, however, the state of knowledge concerning these processes prevent their application to most contaminant migration analyses. These processes have been ignored in the following subsection which deals with an analysis of contaminant velocity. It is expected that the cumulative effect of neglecting these factors will result in overestimates of contaminant velocities which impart a conservative element to the analysis.

3.3.4 Contaminant Velocity and Travel Time

LHSU Confining Layer

As presented above, the velocity at which an organic contaminant migrates is affected to a large extent by the hydrologic properties of the geologic medium, the physical and chemical properties of the contaminant, and the organic carbon fraction of the geologic materials. Assuming that sorption is linear, reversible and rapid with respect to the flow velocity, the contaminant velocity is given by (Freeze and Cherry, 1979)

$$v_c = \frac{v_w}{R} \quad (13)$$

where v_c equals the contaminant velocity. Using the previously calculated groundwater flow velocities from Table 3-1 and retardation factors from Table 3-3, the estimated range of contaminant velocities and travel times through the LHSU to the Laramie-Fox Hills aquifer are given in Table 3-4. It is apparent that contaminant movement through the LHSU is expected to be very slow given that TCE, the fastest moving compound, requires at least 17,000 years to travel to the Laramie-Fox Hills aquifer. These calculations are based strictly on 1-D transport and do not account for the effects of hydrodynamic dispersion. A more rigorous 2-D analysis of

contaminant travel time and resulting normalized concentrations (ratio of transported contaminant concentration to original source contaminant concentration) is contained in the graphs produced for CT, PCE, and TCE found in Attachment D for the range of seepage velocities reported in Table 3-4

**Table 3-4
Vertical Contaminant Velocities and Travel Time Calculation Results
for the Upper Laramie LHSU Confining Layer**

Compound	Vertical Seepage Velocity, V_w		Retardation Factor, R	Vertical Contaminant Velocity, V_c		Travel Time to Laramie-Fox Hills Aquifer (yrs)
	(cm/sec)	(ft/yr)		(cm/sec)	(ft/yr)	
CT	4.5×10^7	0.468	43.16	1.0×10^8	1.1×10^2	54,000
	1.8×10^7	0.185		4.2×10^9	4.3×10^3	140,000
	1.0×10^7	0.108		2.3×10^9	2.5×10^3	240,000
	1.8×10^8	0.018		4.2×10^{10}	4.2×10^4	1,400,000
	5.0×10^{10}	5.4×10^{-4}		1.2×10^{-4}	1.3×10^5	46,000,000
TCE	4.5×10^7	0.468	13.12	3.4×10^8	3.6×10^2	17,000
	1.8×10^7	0.185		1.4×10^8	1.4×10^2	43,000
	1.0×10^7	0.108		7.6×10^9	8.2×10^3	73,000
	1.8×10^8	0.018		1.4×10^9	1.4×10^3	440,000
	5.0×10^{10}	5.4×10^{-4}		3.8×10^{11}	4.1×10^5	15,000,000
PCE	4.5×10^7	0.468	35.96	1.3×10^8	1.3×10^2	46,000
	1.8×10^7	0.185		5.0×10^9	5.1×10^3	120,000
	1.0×10^7	0.108		2.8×10^9	3.0×10^3	200,000
	1.8×10^8	0.018		5.0×10^{10}	5.0×10^4	1,200,000
	5.0×10^{10}	5.4×10^{-4}		1.4×10^{11}	1.5×10^5	40,000,000

Laramie-Fox Hills Aquifer

Assuming that contamination ultimately reaches the Laramie-Fox Hills aquifer, the movement of groundwater and associated contaminants will change from a predominantly vertical direction to a lateral direction in compliance with the local potentiometric distribution. An estimate of contaminant velocity and travel time for the Laramie-Fox Hills aquifer from IHSS 110 to the eastern boundary (Indiana Street) can be made from the groundwater flux value of 7.2×10^7 cm/sec (from Subsection 3.2.2), an average effective porosity of 0.10, R values calculated for the

LHSU (Table 3-3), and a distance of 8,600 feet. These assumptions result in contaminant velocities for CT, TCE, and PCE of 0.56, 1.83, and 0.67 ft/yr, respectively, or travel times of 15,400, 4,700, and 12,800 years to reach the east site boundary. Additional time will be required to travel beyond the boundary to the nearest receptor well.

3.3.5 *Contaminant Mass Flux*

It has been shown that contaminant migration will, on average, proceed very slowly through the upper Laramie Formation LHSU confining beds. Corollary to this approach is the consideration of contaminant mass flux into the Laramie-Fox Hills aquifer. Once a contaminant plume is intercepted by a natural hydrologic boundary such as a stream or deeper aquifer, it will mix with water at the boundaries often resulting in a substantial decrease in concentration. This concentration will further decrease in a downgradient direction away from plume entry point as additional groundwater is added to the system from the overlying confining beds. In certain circumstances, the contaminant flux may be small enough relative to the clean water flux that mixing improves the water quality such that it meets drinking water standards. This possibility will be examined using the estimated groundwater fluxes and calculated concentration levels reported in Attachment D.

Calculation of the contaminant mass flux requires assumptions about the size of the source area and mixing conditions in the aquifer. In the case of DNAPL contamination for a vertical flow problem, the source area is defined by the areal extent of the DNAPL pool or resulting DNAPL diffused zone. The dimensions of the DNAPL source zones for IHSSs 110 and 118.1 are unknown and cannot be estimated with any degree of certainty. Therefore, it is necessary to treat the size of these zones hypothetically in order to evaluate the potential significance of mixing on contaminant levels in the Laramie-Fox Hills aquifer. Mixing is assumed to be both instantaneous and complete, although in reality, this condition will only exist at a well which fully penetrates the aquifer.

At both sites, a 100 by 100 foot square area oriented parallel to the groundwater flow direction in the Laramie-Fox Hills aquifer will be assumed to simplify calculations. The cross-sectional area for horizontal flow in the Laramie-Fox Hills aquifer is assumed to be 100 feet wide by 200 feet thick (20,000 ft²). This assumed source area and a unit horizontal flux rate of 7.2×10^7 cm/sec (see Subsection 3.2.2) yield a total horizontal flux of 13.38 cm³/sec. Given these parameters and the groundwater flux determined from Site hydrologic conditions, the TCE and CT vertical mass flux into the Laramie-Fox Hills aquifer and resulting concentrations in the aquifer are predicted in Table 3-5.

**Table 3-5
Contaminant Mass Flux and Predicted Laramie-Fox Hills Aquifer Concentrations for
IHSS 110 and 118.1 Based on Maximum Concentrations**

Ky	Unit Vertical Flux	Vertical Flux Area	Vertical Flux	Horizontal(1) to Vertical Flux Ratio	Normalized Maximum TCE Concentration	TCE(2) Concentration in Laramie-Fox Hills Aquifer	Normalized Maximum CT Concentration	CT(3) Concentration in Laramie-Fox Hills Aquifer
(cm/sec)	(cm/sec)	(cm ²)	(cm ³ /sec)		(ratio)	(mg/L)	(ratio)	(mg/L)
2.5×10^7	1.0×10^7	9.3×10^6	0.93	14.4	0.94	102.2	0.94	52.1
1.0×10^7	4.0×10^8	9.3×10^6	0.37	36.2	0.88	38.1	0.88	19.4
5.8×10^8	2.3×10^8	9.3×10^6	0.21	63.7	0.80	19.7	0.80	10.0
1.0×10^8	4.0×10^9	9.3×10^6	0.04	335	0.35	1.6	0.35	0.8
2.8×10^{10}	1.1×10^{10}	9.3×10^6	0.001	13,380	0.01	0.001	0.01	0.0006

(1) Horizontal flux is equal to 13.68 cm³/sec
(2) From IHSS 110 at travel times given in Table 3-4
(3) From IHSS 118 a at travel times given in Table 3-4

The results indicate that, under the assumed conditions, mixing of contaminated leakage water from the confining layers into the Laramie-Fox Hills aquifer will theoretically yield contaminant levels that exceed drinking water standards in most cases following the average travel time periods shown in Table 3-4. This condition exists mainly as a result of the relatively low hydraulic conductivity of the Laramie-Fox Hills aquifer and illustrates a worst case scenario. In reality, contaminant concentrations in most field situations are often observed far below saturation (Johnson and Kueper, 1996). If it is assumed that contaminant concentrations entering the LHSU are at 1% of solubility - a criterion that is often used to indicate DNAPL presence in the subsurface (Feenstra and Cherry, 1996) - the predicted contaminant concentrations reported

in Table 3-5 will be overestimated by two orders of magnitude. In addition, it is expected that the source concentrations will not remain continuous for the estimated transport times to the Laramie-Fox Hills aquifer. This conclusion is derived from the fact that the matrix has a high mass contaminant storage capacity. Contaminant degradation caused by in situ abiotic transformation reactions have the potential to significantly reduce contaminant levels. Assuming a conservative contaminant half life of 100 years, calculations performed for PCE transport (see Attachment D) indicate that PCE contamination will never reach the Laramie-Fox Hills aquifer. The same results can be obtained for the other parameters considered under this report.

In view of information presented above and the expectation that the average vertical hydraulic conductivity occupies the lower part of the range, it seems highly improbable that contaminant concentrations in excess of current regulatory limits will be released from the Site via the Laramie-Fox Hills aquifer. As groundwater moves deeper into the claystone, the dominant transport process is expected to convert from an advection-dominated transport system to a diffusion-dominated transport system when vertical hydraulic conductivities become lower than about 1.0×10^{-8} cm/sec. The conversion to a diffusion-dominated transport system will further delay contaminant arrival times at the Laramie-Fox Hills aquifer, and will promote lateral spreading of the plume. This spreading will further reduce contaminant concentrations at the confining layer/aquifer interface causing the resulting concentrations in the Laramie-Fox Hills aquifer to become lower than presented by the advection-dispersion example above.

A review of the available information on bedrock geologic and hydrogeologic conditions at the Site has been presented in this report. Based on this review, an updated analysis of the vertical contaminant migration potential to the deep Laramie-Fox Hills aquifer has been performed using simple, 1- and 2-dimensional analytical techniques. The major conclusions of this white paper are summarized as follows:

- (1) A thick, laterally continuous, low-permeability confining layer underlies the Site and serves to effectively restrict vertical groundwater flow and contaminant movement to the underlying deep Laramie-Fox Hills aquifer,
- (2) Fractures observed in unweathered bedrock strata appear to close and become no more permeable than porous media with depth based on vertical conductivity profiling and observed claystone lithologic characteristics,
- (3) Fault zones present in bedrock strata at the Site, despite an increased incidence of fracturing, have an inferred low permeability due to closure of fractures with depth caused by lithostatic stress and claystone bedrock ductility,
- (4) Groundwater sampling and analysis of LHSU wells installed at source areas indicates that VOC migration into the upper Laramie confining layer is limited mainly to the top five feet of the unit. The detection of trace VOC concentrations in one LHSU well, completed at a depth of 24 feet below the base of the UHSU, indicates that a potential exists for transport in isolated, open fractures occurring in the uppermost part of this unit. VOC and radionuclide cross-contamination of deep well completion zones with shallow contaminated groundwater or soils is suspected in the case of several LHSU wells based on consideration of well construction practices and the trend plots of individual well contaminant concentrations,

- (5) In general, DNAPL compounds have the potential to enter fractured bedrock, diffuse into the bedrock matrix, and provide a long term source of dissolved contamination for subsequent vertical migration. However, in this case, fracture transport of DNAPLs to the Laramie-Fox Hills aquifer is not considered to be a threat given the rapid disappearance times calculated for each DNAPL,
- (6) Vertical contaminant movement is predicted to be very slow with travel times to the Laramie-Fox Hills aquifer estimated to be on the order of tens of millennia or greater,
- (7) Conditions favorable for contaminant transformation or degradation exist in the confining layer which may, to a significant degree, naturally attenuate contaminant levels given the long calculated residence times. Contaminant species with short to moderately long half lives have the potential to completely degrade prior to arrival at the deep aquifer, and
- (8) Mixing calculations for the maximum estimated vertical contaminant fluxes in the confining layer and lateral groundwater flux in the Laramie-Fox Hills aquifer suggest that, under worst case conditions, even small vertical fluxes are sufficiently large to cause MCL exceedences in the deep aquifer shortly after arrival. This scenario is, however, considered to be extremely unlikely given the amount of conservatism built into the analysis for certain parameters, i.e., contaminant source life, contaminant retardation, and contaminant stability in a relatively reactive geologic media. It is proffered that a more realistic view of these assumptions will result in contaminant concentrations that are below levels of concern for the deep aquifer.

It is concluded from this review and analysis that the upper Laramie Formation confining beds have a sufficient amount of hydrologic and geochemical integrity to provide long-term protection

of the Laramie-Fox Hills aquifer. This analysis validates the previous conclusions reached by earlier investigators that the confining layer adequately restricts the vertical movement of shallow groundwater to deeper aquifers. There does not appear to be an immediate or long term vertical migration threat associated with potential DNAPL invasion into bedrock materials. Monitoring of vertical contaminant migration at potential bedrock source areas, rather than remediation, appears to be the most prudent and cost effective option for protection of the Laramie-Fox Hills aquifer given the apparent robust geochemical nature of unweathered bedrock materials underlying the Site.

5.0 REFERENCES

- Allen-King, R M , R W Gillham, and D M Mackay, 1996, "Sorption of Dissolved Chlorinated Solvents to Aquifer Materials" *in* Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Bredehoeft, J D , C E Nuezil, and P C D Milly, 1983, Regional Flow in the Dakota Aquifer A Study of the Role of Confining Layers, U S Geological Survey Water-Supply Paper 2237
- Butler, B J and J F Barker, 1996, "Chemical and Microbiological Transformations and Degradation of Chlorinated Solvent Compounds" *in* Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Cohen, R M and J W Mercer, 1993, DNAPL Site Evaluation, C K Smoley/CRC Press, Boca Raton, Florida
- Desaulniers, D E , J A Cherry, and P Fritz, 1981, "Origin, Age, and Movement of Pore Water in Argillaceous Quaternary Deposits at Four Sites in Southwestern Ontario", *Journal of Hydrology*, 50, 231-257
- Domenico, P A and F W Schwartz, 1990, Physical and Chemical Hydrogeology, John Wiley and Sons
- DOE, 1992a, Final Historical Release Report for the Rocky Flats Plant, U S Department of Energy, Golden, Colorado ER Program June
- DOE, 1992b, Phase II Geologic Characterization - Data Aquisition, Surface Geologic Mapping of the Rocky Flats Plant and Vicinity, Jefferson and Boulder Counties, Colorado
- DOE, 1993, Final Phase III RI/RFI Report, Rocky Flats Plant, 881 Hillside Area (Operable Unit 1), November
- DOE, 1994, Phase 1 RFI/RI Work Plan for Operable Unit No 8, 700 Area, Environmental Restoration Program, Rev 0, October 18th
- DOE, 1995a, Geologic Characterization Report for the Rocky Flats Environmental Technology Site, Sitewide Geoscience, Characterization Study, Volume 1, U S Department of Energy, March 1995
- DOE, 1995b, Hydrogeologic Characterization Report for the Rocky Flats Environmental Technology Site, Sitewide Geoscience, Characterization Study, Volume 2, U S Department of Energy, April 1995

- DOE, 1995c, Groundwater Geochemistry Report for the Rocky Flats Environmental Technology Site, Sitewide Geoscience, Characterization Study, Volume 3, U S Department of Energy, January 1995
- DOE, 1995d, 1994 Well Evaluation Report for the Rocky Flats Environmental Technology Site - Final, March 1995
- DOE, 1995e, OU4 Solar Evaporation Ponds Interim Measure/Interim Remedial Action Environmental Assessment Decision Document, Part II, proposed February 1995
- DOE, 1995f, Final Technical Memorandum No 4, Site Model for Hydrogeologic/Contaminant Distribution for Trench T-3, IHSS 110, OU-2, OU-2 Subsurface IM/IRA Soil Vapor Extraction Pilot Test, Site No 1, Volume 1, May
- DOE, 1995g, Draft Final, Phase II RFI/RI Report , 903 Pad, Mound, and East Trenches Area, Operable Unit NO 2, Volume 1, Sections 1 0, 2 0, and 3 0, RF/ER-95-0079 UN, May 1995
- Doty and Associates, 1992, OU8 IHSS Descriptions, prepared for Advanced Sciences, Inc (Appendix B of DOE, 1994)
- EG&G, 1990, First Draft Phase 1 RFI/RI Work Plan, Operable Unit No 5 prepared for the U S Department of Energy, Rocky Flats Plant, Golden, Colorado, July
- EG&G, 1991a, Rocky Flats Sitewide Quality Assurance Project Plan for CERCLA RI/FS and RFI/CMS Activities EG&G Rocky Flats, Inc , Golden, Colorado May 1991
- EG&G, 1991b, General Radiochemistry and Routine Analytical Services Protocol EG&G Rocky Flats, Inc , Golden, Colorado
- EG&G, 1992, Phase II Geologic Characterization - Data Aquisition, Surface Geologic Mapping of the Rocky Flats Plant and Vicinity, Jefferson and Boulder Counties, Colorado, Final Report, March
- EPA, 1988a, Laboratory Data Validation Functional Guidelines for Evaluating Organics Analyses, U S Environmental Protection Agency Data Review Work Group, February 1988
- EPA, 1988b, Laboratory Data Validation Functional Guidelines for Evaluating Inorganics Analyses, U S Environmental Protection Agency Data Review Work Group, February 1988

- Feenstra, S and J A Cherry, 1996, "Diagnosis and Assessment of DNAPL Sites" in Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Feenstra, S and N Guiguer, 1996, "Dissolution of Dense Non-aqueous Phase Liquids (DNAPLs) in the Subsurface" in Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Feenstra, S , J A Cherry, and B L Parker, 1996, "Conceptual Models for the Behavior of Dense Non-aqueous Phase Liquids (DNAPLs) in the Subsurface" in Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Freeze, R A and J A Cherry, 1979, Groundwater, Prentice-Hall, Inc , Englewood Cliffs, N J
- Geomatrix Consultants Inc , 1995, Final Report - Evaluation of the Capability of Inferred Faults in the Vicinity of Building 371, Rocky Flats Environmental Technology Site, Colorado prepared for EG&G Rocky Flats, Inc , February
- Gillham, R W and S F O'Hannesin, 1992, Metal-catalysed abiotic degradation of halogenated organic compounds IAH Conference "Modern trends in hydrogeology," Hamilton Ontario, May 10-13
- Hurr, R T , 1976, Hydrology of a Nuclear Processing Plant, Rocky Flats, Jefferson County, Colorado, U S Geological Survey Open-File Report 76-268
- Illsley, C T , 1976, Letter to Jerry Lackey of EG&G, Analyses of Waters from Deep Wells, January 9th
- Karickhoff, S W , 1984, "Organic Pollutant Sorption in Aquatic Systems", *J Hydraulic Eng* , 110, 707-735
- Kriegman-King, M R and M Reinhard, 1994, "Transformation of Carbon Tetrachloride by Pyrite in Aqueous Solution", *Environmental Science and Technology*, Vol 28, No 4, 692-700
- Johnson, R L and Kueper, B H , 1996, "Experimental Studies of the Movement of Chlorinated Solvent Compounds and other DNAPLs in the Vadous, Capillary, and Groundwater Zones" in Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Kueper, B H and D B McWhorter, 1991, "The Behavior of Dense, Nonaqueous Phase Liquids in Fractured Clay and Rock", *Groundwater*, v 29, pp 716-728

- Kurt, C E and R C Johnson, 1982, Permeability of Grout Seals Surrounding Thermoplastic Well Casing, *Groundwater*, v 20, n 4, pp 415-419
- Litaor, M L , M L Thompson, G R Barth, and P C Molzer, 1994, Plutonium-239+240 in Soils East of Rocky Flats, Colorado, *Jour of Environmental Quality*, v 23, n 6, pp 1231-1239
- McKay, L D , R W Gillham, and J A Cherry, 1993, Field Experiments in a Fractured Clay Till 2 Solute and Colloid Transport, *Water Resources Research*, Vol 29, No 12, pp-3879-3890
- Mudge, M R and R F Brown, 1952, Geology and Groundwater of the Rocky Flats Area, Golden, Colorado U S Geological Survey Special Report for the Atomic Energy Commission
- Pankow, J F and J A Cherry (eds), 1996, Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Pankow, J F , S Feenstra, J A Cherry, and M C Ryan, 1996, Dense Chlorinated Solvents in Groundwater Background and History of the Problem in Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Parker, B L , J A Cherry, and R W Gillham, 1996, "The Effects of Molecular Diffusion on DNAPL Behavior in Fractured Porous Media" in Pankow, J F and J A Cherry eds , Dense Chlorinated Solvents and Other DNAPLs in Groundwater, Waterloo Press, Portland, Oregon
- Potter, P E , J B Maynard, and W A Pettyjohn, 1980, Sedimentology of Shale, Springer-Verlag, New York
- Robson, S G , 1983, Hydraulic Characterization of the Principal Bedrock Aquifers in the Denver Basin, Colorado, U S Geological Survey Hydrological Investigations Atlas HA-659
- Robson, S G , 1987, Bedrock Aquifers in the Denver Basin, Colorado - A Quantitative Water Resources Appraisal, U S Geological Survey Professional Paper 1257
- Robson, S G and E R Banta, 1987, Geology and Hydrology of Deep Bedrock Aquifers in Eastern Colorado, U S Geological Survey Water Resources Investigations Report 85-4240
- Robson, S G , 1989, Alluvial and Bedrock Aquifers of the Denver Basin Eastern Colorado's Dual Ground-Water Resource, U S Geological Survey Water-Supply Paper 2302

- Rockwell International, 1989, ER Program Quality Assurance/Quality Control Plan, Rockwell International January 1989
- Romero, J C , 1976, Groundwater Resources of the Bedrock Aquifers of the Denver Basin, Colorado, Colorado Department of Natural Resources, Denver Division of Water Resources, Planning and Investigations
- Sale, T , D B McWhorter, and K Piontek, 1992, "Analysis of DNAPL Migration at a Former Wood-Treating Facility", Proceedings of the 1992 Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water Prevention, detection, and Restoration, November 4-6, 1992, Houston, Texas, National Ground Water Association
- Schneider, P A , 1980, Water-Supply Assessment of the Laramie-Fox Hills Aquifer in Parts of Adams, Boulder, Jefferson, and Weld Counties, U S Geological Survey Open-File Report 80-327
- Spencer, F D , 1961, Bedrock Geology of the Louisville Quadrangle, Colorado, U S Geological Survey Geologic Quadrangle Map GC-151
- Spencer, F D , 1986, Local Geology and Coal, Oil and Gas Resources of the Erie and Frederick Quadrangles, Boulder and Weld Counties, Colorado, U S Geological Survey Bulletin 1619
- Weast, R C (ed), 1984, CRC Handbook of Chemistry and Physics, 65th Edition, CRC Press, Boca Raton, Florida
- Wells, J D, 1967, Geology of the Eldorado Springs Quadrangle, Boulder and Jefferson Counties, Colorado, U S Geological Survey Bulletin 1221-D
- Zeff, Congorno, and Sealy, Inc , 1974, Report of Subsurface Studies for U S Atomic Energy Commission Sanitary Landfill Renovations, Rocky Flats Plant, Golden, Colorado

Fracture Data for Borehole 01193

(Depth to Bedrock = 9 6 ft)

Depth (ft)	Fracture Dip	Fracture Spacing (ft)	Comments
15 8			microfractures
17 7		1 9	microfractures
27 1	25	9 4	
27 2	25	0 1	
27 6	30	0 4	
28 1	35	0 5	
30 1	25	2	
30 2	40	0 1	
32 8	60	2 6	
33 5		0 7	microfractures
34 4	60	0 9	
36 5	40	2 1	
43	45	6 5	
44	40	1	
44 3	50	0 3	
45	35	0 7	
46 4	70	1 4	
52 1	20	5 7	
54 7	40	2 6	
54 7	30	0	
54 7	50	0	
61 5	80	6 8	
62 2	35	0 7	
67 5	35	5 3	
69 9	30	2 4	
74 5	65	4 6	
74 5	65	0	
76 5	25	2	
77 5	30	1	
79 5	25	2	
83 3	30	3 8	
84 5	55	1 2	
85	30	0 5	
90 5	20	5 5	
91	20	0 5	
95	0	4	
95	10	0	
97 8	15	2 8	
97 8	15	0	
99 8	15	2	
99 8	15	0	
102 8	15	3	
110 4	50	7 6	
115 8	40	5 4	
118 9		3 1	

Fracture Data for Borehole 01193

(Depth to Bedrock = 9 6 ft)

Depth (ft)	Fracture Dip	Fracture Spacing (ft)	Comments
119 9	30	1	
122	30	2 1	
122 4	40	0 4	
123 7	45	1 3	
127 8		4 1	
128 1	34	0 3	
129 2		1 1	
129 5		0 3	
131 2	60	1 7	
132 3	65	1 1	
137 6	20	5 3	
137 8	20	0 2	
137 8		0	abundant to 142 5
140 3	85	2 5	
145 9	60	5 6	
151 5	60	5 6	
154 5	50	3	
158 3	60	3 8	
164 7	65	6 4	
166		1 3	fracture zone
170 5		4 5	fracture zone to 171
171 9	75	1 4	
172 4	60	0 5	
173 3	55	0 9	
174 4	75	1 1	
177 6	70	3 2	fracture zone to 178
178	70	0 4	
179	0	1	
179	10	0	
181	0	2	
181	5	0	
202 5	75	21 5	
202 6	5	0 1	
207		4 4	fracture zone to 208
208	80	1	
208 5	80	0 5	
208 7	25	0 2	
213 2	53	4 5	
220	50	6 8	
224 6	35	4 6	
225 4	35	0 8	
228 4	60	3	
241 3	75	12 9	
247 2	80	5 9	
249 4	55	2 2	
249 4	60	0	

Fracture Data for Borehole 01193

(Depth to Bedrock = 9 6 ft)

Depth (ft)	Fracture Dip	Fracture Spacing (ft)	Comments
252 5	80	3 1	
259 2	30	6 7	
260 6	30	1 4	
261 1	45	0 5	
263 8	40	2 7	
264 3	15	0 5	
267 7	85	3 4	
268 8	10	1 1	
268 9	65	0 1	
270 3	10	1 4	fracture zone to 271 3
271 3	10	1	
278 6	20	7 3	
280 2	30	1 6	
281 2	70	1	
284 9	40	3 7	
290 3	60	5 4	
290 7	20	0 4	
297 7	40	7	
298	50	0 3	
301 3	60	3 3	
301 7	20	0 4	
303 8	15	2 1	
307 6	15	3 8	
308 2	55	0 6	
309 6	65	1 4	
310 7	45	1 1	
311 4	22	0 7	
311 5	10	0 1	
312 4	0	0 9	
314 4	45	2	
316	55	1 6	
321 2	65	5 2	
322 3	60	1 1	
327 7	75	5 4	
331 8	80	4 1	
333 2	35	1 4	
343 6		10 4	
346 3		2 7	
347 2		0 9	
349 8		2 6	
354 9	40	5 1	
356 5	0	1 6	
358	65	1 5	
360 8	65	2 8	
365 5	50	4 7	
369 8	15	4 3	

Fracture Data for Borehole 01193
(Depth to Bedrock = 9 6 ft)

Depth (ft)	Fracture Dip	Fracture Spacing (ft)	Comments
373 8	90	4	
375	40	1 2	
375 6	55	0 6	
375 9	40	0 3	
376 7	90	0 8	
377	35	0 3	
377 8	15	0 8	
377 9	15	0 1	
380	90	2 1	
391 7	25	11 7	
392	35	0 3	
392 4	0	0 4	
395	23	2 6	
396 7	18	1 7	
396 9	20	0 2	
397 1	35	0 2	
397 3	0	0 2	
399 4		2 1	
400 6	25	1 2	
400 8	20	0 2	
402 7	10	1 9	
403 1	15	0 4	
403 2	60	0 1	
404 4	15	1 2	
406 6		2 2	
408 4	30	1 8	
409 7	60	1 3	
410 5	65	0 8	
410 6	0	0 1	
412	10	1 4	
412 8	60	0 8	
413 6	0	0 8	
416 7	25	3 1	
416 9	35	0 2	
417 9	18	1	
418 2	10	0 3	
418 3	10	0 1	
418 7	50	0 4	
419 6	70	0 9	
419 9	0	0 3	
420 1	90	0 2	
424 3	15	4 2	
424 3	45	0	
430 7	60	6 4	
431 4	70	0 7	
442	35	10 6	

Fracture Data for Borehole 01193
(Depth to Bedrock = 9 6 ft)

Depth (ft)	Fracture Dip	Fracture Spacing (ft)	Comments
442	65	0	
451 9	0	9 9	
452 2	20	0 3	
454 4	0	2 2	
455	20	0 6	
455	30	0	
460 5	15	5 5	
461 2	15	0 7	
464 3	20	3 1	
468 8	50	4 5	
469 8	5	1	
471 5	35	1 7	
471 8	20	0 3	
473 4	10	1 6	
474 1	10	0 7	
474 8	35	0 7	
476 8	35	2	
476 8	90	0	
480 9	20	4 1	
486 4	50	5 5	
486 9	40	0 5	
491 2	15	4 3	
491 2	45	0	
492	35	0 8	
497 3	40	5 3	
498 6	65	1 3	

38 4010417 2 321153846

Attachment B

Detected VOCs and Radionuclides in LHSU Wells

Attachment B

**Detected Concentrations of VOCs/SVOCs in
LHSU Wells**

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
01891	GW02872IT	05/13/92	VOA502 2	CHLOROMETHANE	0 290	UG/L	0 10	J		1
01891	GW02872IT	05/13/92	VOA502 2	METHYLENE CHLORIDE	6 700	UG/L	0 01			1
01891	GW01754GA	11/11/94	VOA524 2	METHYLENE CHLORIDE	0 100	UG/L	0 20	J	A	1
01891	GW02509IT	02/27/92	VOA502 2	TETRACHLOROETHENE	0 100	UG/L	0 02		JA	1
01891	GW01213WC	08/24/93	VOA524 2	TETRACHLOROETHENE	0 100	UG/L	0 10		V	1
0387	GW01253IT	05/14/91	VOACL P	CARBON TETRACHLORIDE	8 000	UG/L	5 00		JA	1
0387	G03870290001	02/16/90	VOACL P	METHYLENE CHLORIDE	5 000	UG/L	5 00	B		1
0387	GW00984IT	03/14/91	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
0387	GW01253IT	05/14/91	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	J	A	1
0886	GW03592IT	10/16/92	VOACL P	1 1 1 TRICHLOROETHANE	9 000	UG/L	5 00	B		1
0886	GW03592IT	10/16/92	VOACL P	1 1 DICHLOROETHENE	2 000	UG/L	5 00	J		1
0886	GW00010IT	07/17/90	VOACL P	ACETONE	4 000	UG/L	10 00	J		1
0886	GW03592IT	10/16/92	VOACL P	ACETONE	13 000	UG/L	10 00	B		1
0886	G08860190001	01/31/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
0886	GW00010IT	07/17/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	BJ		1
0886	GW01243IT	05/29/91	VOACL P	METHYLENE CHLORIDE	5 000	UG/L	5 00	B		1
0886	GW01470IT	07/11/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J		1
0886	GW03592IT	10/16/92	VOACL P	METHYLENE CHLORIDE	19 000	UG/L	5 00	B		1
0886	GW01386WC	10/11/93	VOACL P	METHYLENE CHLORIDE	10 000	UG/L	5 00		V	1
0886	GW00636IT	11/06/90	VOACL P	TOLUENE	2 000	UG/L	5 00	J	A	1
0886	GW03592IT	10/16/92	VOACL P	TOLUENE	4 000	UG/L	5 00	J		1
0887	GW00024IT	09/11/90	VOACL P	4 METHYL 2 PENTANONE	25 000	UG/L	10 00			1
0887	GW01675IT	09/19/91	VOACL P	4 METHYL 2 PENTANONE	1 000	UG/L	10 00	J		1
0887	GW01267IT	05/10/91	VOACL P	ACETONE	6 000	UG/L	10 00	J	A	1
0887	G08870290001	02/15/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
0887	GW00983IT	03/14/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
0887	GW01267IT	05/10/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
0986	G09860390001	03/14/90	VOACL P	ACETONE	5 000	UG/L	10 00	JB		1
0986	GW00942IT	03/13/91	VOACL P	ACETONE	22 000	UG/L			V	1
0986	GW03203IT	09/22/92	VOACL P	ACETONE	24 000	UG/L	10 00			1
0986	GW01448WC	11/04/93	VOACL P	ACETONE	5 000	UG/L	10 00	J	A	1
0986	GW02760GA	07/31/95	VOA524 2	BENZENE	2 000	UG/L	0 50		V1	1
0986	G09860390001	03/14/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
0986	GW00175IT	07/27/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	BJ		1
0986	GW03203IT	09/22/92	VOACL P	METHYLENE CHLORIDE	9 000	UG/L	5 00			1
0986	GW03587IT	10/16/92	VOACL P	TOLUENE	5 000	UG/L	5 00		JA	1
0986	GW01559GA	10/12/94	VOA524 2	TRICHLOROETHENE	0 670	UG/L	0 50		V	1
1686	GW00137WC	02/02/93	VOACL P	4 METHYL 2 PENTANONE	3 000	UG/L	10 00	J	A	1
1686	G16860511020845	05/11/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
1686	GW00366IT	09/25/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	BJ		1
1686	GW00556IT	10/23/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
1686	GW00974IT	03/15/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
1686	GW00556WC	04/23/93	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	J	A	1
1686	GW01450WC	10/29/93	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
1686	GW02697GA	07/12/95	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	1 00	J	V1	1
1686	GW00137WC	02/02/93	VOACL P	TOTAL XYLENES	1 000	UG/L	5 00	J	A	1
1686	GW00137WC	02/02/93	VOACL P	TRICHLOROETHENE	1 000	UG/L	5 00	J	A	1
1687	GW03443IT	09/03/92	VOACL P	1 2 DICHLOROETHENE	0 500	UG/L	5 00	J	A	1
1687	GW03443IT	09/03/92	VOACL P	CARBON TETRACHLORIDE	14 000	UG/L	5 00		V	1
1687	GW02648GA	06/19/95	VOA524 2	CARBON TETRACHLORIDE	0 300	UG/L	0 50	J	Y	1
1687	GW03443IT	09/03/92	VOACL P	CHLOROFORM	0 400	UG/L	5 00	J	A	1
1687	G16870390001	03/17/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
1687	GW00853IT	01/09/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
1687	GW01645IT	09/05/91	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
1687	GW03443IT	09/03/92	VOACL P	TETRACHLOROETHENE	2 000	UG/L	5 00	J	A	1
1687	GW00791GA	06/27/94	VOA524 2	TETRACHLOROETHENE	0 200	UG/L	0 20	J	A	1
1687	GW01154GA	08/22/94	VOA524 2	TETRACHLOROETHENE	0 200	UG/L	0 20		Z	1
1687	GW01771GA	11/22/94	VOA524 2	TETRACHLOROETHENE	0 598	UG/L	0 50		Y	1
1687	GW02648GA	06/19/95	VOA524 2	TETRACHLOROETHENE	0 400	UG/L	0 50	J	Y	1
1687	GW02913IT	05/19/92	VOACL P	TRICHLOROETHENE	1 000	UG/L	5 00	J	A	1
1687	GW03443IT	09/03/92	VOACL P	TRICHLOROETHENE	2 000	UG/L	5 00	J	A	1
1687	GW00791GA	06/27/94	VOA524 2	TRICHLOROETHENE	0 100	UG/L	0 20	J	A	1
1887	GW01295GA	08/24/94	VOA524 2	1 1 1 TRICHLOROETHANE	0 500	UG/L	0 20		V	1
1887	GW00558IT	10/23/90	VOACL P	ACETONE	6 000	UG/L	10 00	BJ		1
1887	GW01295GA	08/24/94	VOA524 2	CARBON TETRACHLORIDE	4 000	UG/L	0 30		V	1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
1887	GW01762GA	11/14/94	VOA524 2	CARBON TETRACHLORIDE	1 000	UG/L	0 30		V	1
1887	GW02218GA	03/20/95	VOA524 2	CARBON TETRACHLORIDE	0 500	UG/L	0 30		Y	1
1887	GW02847IT	04/30/92	VOACL P	CHLOROFORM	1 000	UG/L	5 00	BJ		1
1887	GW01295GA	08/24/94	VOA524 2	CHLOROFORM	3 000	UG/L	0 20		V	1
1887	GW01762GA	11/14/94	VOA524 2	CHLOROFORM	2 000	UG/L	0 20		V	1
1887	GW02218GA	03/20/95	VOA524 2	CHLOROFORM	0 900	UG/L	0 20		Y	1
1887	G18870390001	03/08/90	VOACL P	METHYLENE CHLORIDE	5 000	UG/L	5 00	B		1
1887	GW00558IT	10/23/90	VOACL P	METHYLENE CHLORIDE	5 000	UG/L	5 00	B		1
1887	GW01629WC	12/02/93	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
1887	GW00761GA	05/19/94	VOA524 2	METHYLENE CHLORIDE	0 800	UG/L	0 20		V	1
1887	GW01295GA	08/24/94	VOA524 2	METHYLENE CHLORIDE	0 400	UG/L	0 20		V	1
1887	GW01762GA	11/14/94	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	0 20		V	1
1887	GW00406GA	03/10/94	VOA524 2	TETRACHLOROETHENE	0 200	UG/L	0 20	J	A	1
1887	GW00761GA	05/19/94	VOA524 2	TETRACHLOROETHENE	0 200	UG/L	0 20		V	1
1887	GW01295GA	08/24/94	VOA524 2	TETRACHLOROETHENE	5 000	UG/L	0 20		V	1
1887	GW01762GA	11/14/94	VOA524 2	TETRACHLOROETHENE	4 000	UG/L	0 20		V	1
1887	GW02218GA	03/20/95	VOA524 2	TETRACHLOROETHENE	2 000	UG/L	0 20		Y	1
1887	G18870390001	03/08/90	VOACL P	TRICHLOROETHENE	4 000	UG/L	5 00	J		1
1887	G18870604021315	06/05/90	VOACL P	TRICHLOROETHENE	28 000	UG/L	5 00			1
1887	GW01295GA	08/24/94	VOA524 2	TRICHLOROETHENE	0 200	UG/L	0 20		V	1
2087	G20870290001	02/13/90	VOACL P	ACETONE	5 000	UG/L	10 00	J	A	1
2087	G20870521021125	05/22/90	VOACL P	ACETONE	9 000	UG/L	10 00	JB		1
2087	GW00645IT	11/08/90	VOACL P	ACETONE	4 000	UG/L		J		1
2087	GW00977IT	03/21/91	VOACL P	ACETONE	3 000	UG/L	10 00	J		1
2087	GW02426IT	02/25/92	VOACL P	ACETONE	4 000	UG/L	10 00	BJ	JA	1
2087	GW03302IT	08/07/92	VOACL P	BENZENE	0 700	UG/L	5 00	J	A	1
2087	GW00764GA	05/11/94	VOA524 2	BENZENE	0 100	UG/L	0 20	J	A	1
2087	GW03302IT	08/07/92	VOACL P	CARBON DISULFIDE	5 000	UG/L	5 00		V	1
2087	G20870521021125	05/22/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
2087	GW00112IT	07/27/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
2087	GW01262IT	05/10/91	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	J	A	1
2087	GW03302IT	08/07/92	VOACL P	STYRENE	2 000	UG/L	5 00	J	A	1
2087	G20870290001	02/13/90	VOACL P	TETRACHLOROETHENE	91 000	UG/L	5 00		A	1
2087	G20870521021125	05/22/90	VOACL P	TETRACHLOROETHENE	1 000	UG/L	5 00	J		1
2087	GW00645IT	11/08/90	VOACL P	TETRACHLOROETHENE	11 000	UG/L				1
2087	GW00977IT	03/21/91	VOACL P	TETRACHLOROETHENE	1 000	UG/L	5 00	J		1
2087	GW01664IT	08/15/91	VOACL P	TETRACHLOROETHENE	4 000	UG/L	5 00	J	A	1
2087	GW02075IT	12/07/91	VOACL P	TETRACHLOROETHENE	2 000	UG/L	5 00	J	A	1
2087	GW02426IT	02/25/92	VOACL P	TETRACHLOROETHENE	6 000	UG/L	5 00		V	1
2087	GW02965IT	05/29/92	VOACL P	TETRACHLOROETHENE	2 000	UG/L	5 00	J	A	1
2087	GW03302IT	08/07/92	VOACL P	TETRACHLOROETHENE	1 000	UG/L	5 00	J	A	1
2087	GW03825IT	11/04/92	VOACL P	TETRACHLOROETHENE	0 900	UG/L	5 00	J	A	1
2087	GW00764GA	05/11/94	VOA524 2	TETRACHLOROETHENE	0 700	UG/L	0 20		V	1
2087	GW03302IT	08/07/92	VOACL P	TOLUENE	0 400	UG/L	5 00	J	A	1
2087	GW00764GA	05/11/94	VOA524 2	TOLUENE	0 700	UG/L	0 20		V	1
2087	G20870290001	02/13/90	VOACL P	TRICHLOROETHENE	3 000	UG/L	5 00	J	A	1
2087	GW02075IT	12/07/91	VOACL P	TRICHLOROETHENE	5 000	UG/L	5 00		V	1
2087	GW02426IT	02/25/92	VOACL P	TRICHLOROETHENE	3 000	UG/L	5 00	J	A	1
2087	GW02965IT	05/29/92	VOACL P	TRICHLOROETHENE	1 000	UG/L	5 00	J	A	1
2087	GW03302IT	08/07/92	VOACL P	TRICHLOROETHENE	0 800	UG/L	5 00	J	A	1
2087	GW03825IT	11/04/92	VOACL P	TRICHLOROETHENE	0 700	UG/L	5 00	J	A	1
2087	GW00764GA	05/11/94	VOA524 2	TRICHLOROETHENE	0 200	UG/L	0 20		V	1
2186	GW03560IT	10/07/92	VOACL P	1 1 2 TRICHLOROETHANE	0 600	UG/L	5 00	J		1
2186	GW00059IT	08/02/90	VOACL P	ACETONE	8 000	UG/L	10 00	BJ		1
2186	GW01637IT	08/09/91	VOACL P	ACETONE	7 000	UG/L	10 00	J		1
2186	GW03560IT	10/07/92	VOACL P	BENZENE	0 400	UG/L	5 00	J		1
2186	GW03560IT	10/07/92	VOACL P	BROMODICHLOROMETHANE	0 200	UG/L	5 00	J		1
2186	GW03560IT	10/07/92	VOACL P	BROMOFORM	0 900	UG/L	5 00	J		1
2186	GW00109GA	02/07/94	VOA524 2	CARBON TETRACHLORIDE	0 100	UG/L	0 20	J	A	1
2186	GW03560IT	10/07/92	VOACL P	CHLOROFORM	0 200	UG/L	5 00	J		1
2186	G21860290001	02/28/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
2186	GW00059IT	08/02/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J		1
2186	GW01379IT	06/04/91	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	BJ		1
2186	GW03560IT	10/07/92	VOACL P	METHYLENE CHLORIDE	0 800	UG/L	5 00	J		1
2186	GW03560IT	10/07/92	VOACL P	TETRACHLOROETHENE	0 500	UG/L	5 00	J		1
2186	GW03560IT	10/07/92	VOACL P	TOLUENE	0 700	UG/L	5 00	J		1
2186	GW03560IT	10/07/92	VOACL P	TOTAL XYLENES	1 000	UG/L	5 00	J		1
2186	GW03560IT	10/07/92	VOACL P	TRICHLOROETHENE	1 000	UG/L	5 00	J		1
22093	GW00413GA	03/15/94	VOA524 2	TRICHLOROETHENE	0 500	UG/L	0 20		V	1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
22093	GW00744GA	06/02/94	VOA524 2	TRICHLOROETHENE	1 000	UG/L	0 20	V		1
22093	GW01270GA	09/14/94	VOA524 2	TRICHLOROETHENE	0 300	UG/L	0 20	V		1
22093	GW01598GA	11/28/94	VOA524 2	TRICHLOROETHENE	0 600	UG/L	0 20	V		1
22093	GW02092GA	02/21/95	VOA524 2	TRICHLOROETHENE	0 200	UG/L	0 20	V		1
22293	GW01179WC	08/17/93	VOA524 2 4	ISOPROPYLTOLUENE	0 200	UG/L	0 20	V		1
22393	GW00746GA	05/19/94	VOA524 2	METHYLENE CHLORIDE	1 000	UG/L	0 20	V		1
22593	GW01464WC	11/09/93	VOA524 2	TETRACHLOROETHENE	0 100	UG/L	0 10	JA		1
22593	GW01464WC	11/09/93	VOA524 2	TRICHLOROETHENE	7 000	UG/L	0 10	JA		1
22593	GW00416GA	03/16/94	VOA524 2	TRICHLOROETHENE	2 000	UG/L	0 20	V		1
22593	GW00629GA	05/05/94	VOA524 2	TRICHLOROETHENE	0 600	UG/L	0 20	V		1
22593	GW01274GA	08/25/94	VOA524 2	TRICHLOROETHENE	0 300	UG/L	0 20	V		1
22593	GW02096GA	02/15/95	VOA524 2	TRICHLOROETHENE	4 000	UG/L	0 20	V		1
22593	GW02420GA	04/18/95	VOA524 2	TRICHLOROETHENE	1 640	UG/L	0 50	Y		1
2287	G22870290001	02/08/90	VOACL P	ACETONE	2 000	UG/L	10 00	JB		1
2287	GW03567IT	10/13/92	VOACL P	BENZENE	0 300	UG/L	5 00	J	A	1
2287	GW02799GA	08/02/95	VOA524 2	BENZENE	1 000	UG/L	0 50		V1	1
2287	GW03567IT	10/13/92	VOACL P	CARBON DISULFIDE	0 400	UG/L	5 00	J	A	1
2287	GW03567IT	10/13/92	VOACL P	CHLOROFORM	0 080	UG/L	5 00	J	A	1
2287	G22870290001	02/08/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	JB		1
2287	GW02648IT	04/16/92	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
2287	GW03567IT	10/13/92	VOACL P	TETRACHLOROETHENE	0 200	UG/L	5 00	J	A	1
2287	GW03567IT	10/13/92	VOACL P	TOLUENE	0 400	UG/L	5 00	J	A	1
2287	GW03567IT	10/13/92	VOACL P	TOTAL XYLENES	0 600	UG/L	5 00	J	A	1
2287	GW03567IT	10/13/92	VOACL P	TRICHLOROETHENE	0 200	UG/L	5 00	J	A	1
23193	GW00417GA	03/16/94	VOA524 2	METHYLENE CHLORIDE	0 200	UG/L	0 20	V		1
23193	GW00628GA	04/25/94	VOA524 2	METHYLENE CHLORIDE	0 100	UG/L	0 20	J	A	1
23193	GW00628GA	04/25/94	VOA524 2	TETRACHLOROETHENE	0 600	UG/L	0 20	V		1
23193	GW00924WC	06/08/93	VOA524 2	TRICHLOROETHENE	10 000	UG/L	0 10	V		1
23193	GW00417GA	03/16/94	VOA524 2	TRICHLOROETHENE	7 000	UG/L	0 20	V		1
23193	GW00628GA	04/25/94	VOA524 2	TRICHLOROETHENE	8 000	UG/L	0 20	V		1
23193	GW01155GA	08/08/94	VOA524 2	TRICHLOROETHENE	7 600	UG/L	0 50	V		1
23193	GW01603GA	10/24/94	VOA524 2	TRICHLOROETHENE	6 030	UG/L	0 50	Y		1
23193	GW02097GA	02/15/95	VOA524 2	TRICHLOROETHENE	6 000	UG/L	0 20	V		1
23193	GW02421GA	04/18/95	VOA524 2	TRICHLOROETHENE	3 110	UG/L	0 50	Y		1
23293	GW00915GA	06/21/94	VOA524 2	METHYLENE CHLORIDE	2 000	UG/L	0 20	V		1
23293	GW00915GA	06/21/94	VOA524 2	TRICHLOROETHENE	2 000	UG/L	0 20	V		1
23293	GW01275GA	08/22/94	VOA524 2	TRICHLOROETHENE	0 500	UG/L	0 20	V		1
23293	GW02098GA	02/13/95	VOA524 2	TRICHLOROETHENE	1 100	UG/L	0 50	V		1
2386	G23860524020910	05/25/90	VOACL P	ACETONE	12 000	UG/L	10 00	B		1
2386	GW03527IT	10/07/92	VOACL P	ACETONE	30 000	UG/L	10 00			1
2386	GW03527IT	10/07/92	VOACL P	BENZENE	5 000	UG/L	5 00			1
2386	GW03527IT	10/07/92	VOACL P	ETHYLBENZENE	1 000	UG/L	5 00	J		1
2386	G23860524020910	05/25/90	VOACL P	METHYLENE CHLORIDE	5 000	UG/L	5 00	B		1
2386	GW01364IT	05/31/91	VOACL P	METHYLENE CHLORIDE	7 000	UG/L	5 00			1
2386	GW03527IT	10/07/92	VOACL P	TOLUENE	24 000	UG/L	5 00			1
2386	GW03527IT	10/07/92	VOACL P	TOTAL XYLENES	23 000	UG/L	5 00			1
2386	GW00616IT	11/14/90	VOACL P	TRICHLOROETHENE	6 000	UG/L	5 00	V		1
2386	GW02684GA	08/14/95	VOA524 2	TRICHLOROETHENE	0 100	UG/L	0 30	J	Y	1
2386	GW02335GA	04/24/95	VOA524 2	c1s 1 2 DICHLOROETHENE	1 200	UG/L	0 50	Y		1
2586	GW03529IT	10/13/92	VOACL P	1 1 2 TRICHLOROETHANE	0 300	UG/L	5 00	J	A	1
2586	GW00471IT	10/11/90	VOACL P	2 BUTANONE	4 000	UG/L	10 00	BJ		1
2586	G25860524021140	05/25/90	VOACL P	ACETONE	11 000	UG/L	10 00	B		1
2586	GW00471IT	10/11/90	VOACL P	ACETONE	7 000	UG/L	10 00	BJ		1
2586	GW02267IT	01/23/92	VOACL P	ACETONE	2 000	UG/L	10 00	J		1
2586	GW00471IT	10/11/90	VOACL P	BENZENE	1 000	UG/L	5 00	J		1
2586	GW03529IT	10/13/92	VOACL P	CARBON DISULFIDE	0 900	UG/L	5 00	J	A	1
2586	G25860290001	02/22/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
2586	G25860524021140	05/25/90	VOACL P	METHYLENE CHLORIDE	7 000	UG/L	5 00	B		1
2586	GW00471IT	10/11/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	BJ		1
2586	GW00847IT	01/08/91	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J		1
2586	GW01442WC	10/22/93	VOACL P	METHYLENE CHLORIDE	9 000	UG/L	5 00			1
2586	GW03529IT	10/13/92	VOACL P	TETRACHLOROETHENE	0 300	UG/L	5 00	J		1
2586	GW00471IT	10/11/90	VOACL P	TOTAL XYLENES	2 000	UG/L	5 00	J		1
2586	GW03529IT	10/13/92	VOACL P	TRICHLOROETHENE	0 400	UG/L	5 00	J		1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
2586	GW00471IT	10/11/90	VOACL P	cis 1 3 DICHLOROPROPENE	1 000	UG/L	5 00	J		1
2786	G27860290001	02/13/90	VOACL P	ACETONE	4 000	UG/L	10 00	J		1
2786	GW00014WC	02/10/93	VOACL P	ACETONE	4 000	UG/L	10 00	J	A	1
2786	G27860290001	02/13/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
2786	G27860514020928	05/14/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
2786	GW00092IT	08/03/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
2786	GW02232IT	01/27/92	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
2786	GW02662IT	04/14/92	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
2786	GW03541IT	10/16/92	VOACL P	TOLUENE	6 000	UG/L	5 00		JA	1
2786	GW00664IT	11/13/90	VOACL P	TRICHLOROETHENE	2 000	UG/L	5 00	J	A	1
2887	GW01379GA	09/14/94	VOA524 2	1 1 1 TRICHLOROETHANE	0 300	UG/L	0 20		JA	1
2887	GW01379GA	09/14/94	VOA524 2	1 1 DICHLOROETHANE	0 200	UG/L	0 20		V	1
2887	GW00412IT	09/19/90	VOACL P	2 BUTANONE	8 000	UG/L			BJ	1
2887	GW00412IT	09/19/90	VOACL P	4 METHYL 2 PENTANONE	9 000	UG/L			BJ	1
2887	GW00412IT	09/19/90	VOACL P	ACETONE	7 000	UG/L			BJ	1
2887	GW03445IT	09/01/92	VOACL P	BENZENE	0 200	UG/L	5 00	J	A	1
2887	GW00412IT	09/19/90	VOACL P	CARBON DISULFIDE	12 000	UG/L				1
2887	GW01379GA	09/14/94	VOA524 2	CHLOROFORM	2 000	UG/L	0 20		JA	1
2887	GW01785GA	11/14/94	VOA524 2	CHLOROFORM	0 500	UG/L	0 20		V	1
2887	G28870625021055	06/26/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00		JB	1
2887	GW00412IT	09/19/90	VOACL P	METHYLENE CHLORIDE	8 000	UG/L			B	1
2887	GW01785GA	11/14/94	VOA524 2	METHYLENE CHLORIDE	0 400	UG/L	0 20		V	1
2887	GW00811GA	05/12/94	VOA524 2	TETRACHLOROETHENE	0 100	UG/L	0 20	J	A	1
2887	GW01379GA	09/14/94	VOA524 2	TETRACHLOROETHENE	0 800	UG/L	0 20		JA	1
2887	GW01785GA	11/14/94	VOA524 2	TETRACHLOROETHENE	0 400	UG/L	0 20		V	1
2887	GW02661GA	06/14/95	VOA524 2	TETRACHLOROETHENE	0 300	UG/L	0 50	J	V1	1
2887	GW00412IT	09/19/90	VOACL P	TOLUENE	10 000	UG/L			B	1
2887	GW03445IT	09/01/92	VOACL P	TOLUENE	0 400	UG/L	5 00	J	A	1
2887	GW02427IT	02/25/92	VOACL P	TRICHLOROETHENE	1 000	UG/L	5 00	J	A	1
2887	GW01379GA	09/14/94	VOA524 2	TRICHLOROETHENE	63 000	UG/L	0 20	E	Z	1
2887	GW01785GA	11/14/94	VOA524 2	TRICHLOROETHENE	43 000	UG/L	0 20	E	Z	1
2887	GW02661GA	06/14/95	VOA524 2	TRICHLOROETHENE	19 000	UG/L	0 50		V1	1
3087	G30870530020930	05/30/90	VOACL P	METHYLENE CHLORIDE	13 000	UG/L	5 00			1
3087	GW00045IT	07/23/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
3087	GW01272IT	05/10/91	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00		V	1
3087	GW01751GA	11/10/94	VOA524 2	METHYLENE CHLORIDE	0 100	UG/L	0 20	J	A	1
3187	GW00413IT	09/18/90	VOACL P	2 BUTANONE	5 000	UG/L	10 00	BJ		1
3187	GW01273WC	08/31/93	VOACL P	2 HEXANONE	5 000	UG/L	10 00	J	A	1
3187	GW01273WC	08/31/93	VOACL P	4 METHYL 2 PENTANONE	4 000	UG/L	10 00	J	A	1
3187	G31870626020840	06/27/90	VOACL P	ACETONE	5 000	UG/L			JB	1
3187	GW00413IT	09/18/90	VOACL P	ACETONE	5 000	UG/L	10 00	BJ		1
3187	GW03878IT	12/14/92	VOACL P	BROMOFORM	0 900	UG/L	5 00	J	A	1
3187	GW03446IT	09/09/92	VOACL P	CHLOROBENZENE	0 500	UG/L	5 00	J	A	1
3187	GW00413IT	09/18/90	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J		1
3187	GW01643IT	09/10/91	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
3187	GW01641WC	12/02/93	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
3187	GW01784GA	11/14/94	VOA524 2	METHYLENE CHLORIDE	0 400	UG/L	0 20		V	1
3187	GW03446IT	09/09/92	VOACL P	STYRENE	2 000	UG/L	5 00	J	A	1
3187	GW00739IT	11/21/90	VOACL P	TOLUENE	1 000	UG/L	5 00	J	A	1
3187	GW03446IT	09/09/92	VOACL P	TOTAL XYLENES	3 000	UG/L	5 00	J	A	1
3286	G32860621020900	06/21/90	VOACL P	ACETONE	5 000	UG/L			JB	1
3286	GW01351IT	05/31/91	VOACL P	ACETONE	5 000	UG/L	10 00	J		1
3286	GW02353IT	03/05/92	VOACL P	ACETONE	5 000	UG/L	10 00	J	A	1
3286	G32860621020900	06/21/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L			B	1
3286	GW00294IT	08/31/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
3286	GW01351IT	05/31/91	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	J		1
3286	GW02353IT	03/05/92	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
3286	GW01001GA	08/04/94	VOA524 2	METHYLENE CHLORIDE	0 610	UG/L	0 50	B	Z	1
3486	GW00116IT	07/30/90	VOACL P	1 1 1 TRICHLOROETHANE	1 000	UG/L	5 00	BJ		1
3486	G34860521021434	05/21/90	VOACL P	ACETONE	13 000	UG/L	10 00			1
3486	GW00116IT	07/30/90	VOACL P	ACETONE	5 000	UG/L	10 00	BJ		1
3486	G34860521021434	05/21/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	JB		1
3486	GW00116IT	07/30/90	VOACL P	METHYLENE CHLORIDE	12 000	UG/L	5 00	B		1
3486	GW00975IT	03/14/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
3486	GW02199IT	01/10/92	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	BJ		1
3486	GW03827IT	12/11/92	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
3486	GW01700WC	12/14/93	VOACL	METHYLENE CHLORIDE	6 000	UG/L	10 00	J	Y	1
3486	GW01181IT	04/22/91	VOACL	TETRACHLOROETHENE	2 000	UG/L	5 00	J	A	1
3487	G34870390001	03/19/90	VOACL	ACETONE	4 000	UG/L	10 00	J		1
3487	GW00416IT	09/18/90	VOACL	CARBON TETRACHLORIDE	7 000	UG/L			V	1
3487	G34870390001	03/19/90	VOACL	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
3487	G34870625021258	06/26/90	VOACL	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
3487	GW00873IT	01/15/91	VOACL	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
3487	GW01638WC	12/02/93	VOACL	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
3487	GW00814GA	05/17/94	VOA524 2	METHYLENE CHLORIDE	0 500	UG/L	0 20		V	1
3487	GW01781GA	11/15/94	VOA524 2	METHYLENE CHLORIDE	0 800	UG/L	0 20		V	1
3487	G34870390001	03/19/90	VOACL	TRICHLOROETHENE	2 000	UG/L	5 00	J		1
3487	GW00416IT	09/18/90	VOACL	TRICHLOROETHENE	1 000	UG/L		J	A	1
3987	GW00473IT	12/18/90	VOACL	2 BUTANONE	6 000	UG/L	10 00	J	A	1
3987	GW00473IT	12/18/90	VOACL	4 METHYL 2 PENTANONE	3 000	UG/L	10 00	J	A	1
3987	GW00238IT	08/16/90	VOACL	ACETONE	7 000	UG/L	10 00	BJ		1
3987	GW00473IT	12/18/90	VOACL	ACETONE	74 000	UG/L	10 00		V	1
3987	GW01561IT	07/31/91	VOACL	ACETONE	19 000	UG/L	10 00			1
3987	GW01445WC	10/26/93	VOACL	ACETONE	5 000	UG/L	10 00	J		1
3987	GW01063WC	07/28/93	VOACL	CARBON TETRACHLORIDE	6 000	UG/L	5 00		V	1
3987	G39870621020940	06/22/90	VOACL	METHYLENE CHLORIDE	4 000	UG/L	5 00	JB		1
3987	GW00238IT	08/16/90	VOACL	METHYLENE CHLORIDE	1 000	UG/L	5 00	BJ		1
3987	GW01376IT	06/05/91	VOACL	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
3987	GW02213IT	01/10/92	VOACL	METHYLENE CHLORIDE	1 000	UG/L	5 00	BJ		1
3987	GW00051WC	02/04/93	VOACL	METHYLENE CHLORIDE	4 000	UG/L	5 00	J	A	1
3987	GW00536WC	04/22/93	VOACL	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
3987	GW00238IT	08/16/90	VOACL	TRICHLOROETHENE	1 000	UG/L	5 00	J		1
3987	GW00473IT	12/18/90	VOACL	VINYL ACETATE	5 000	UG/L	10 00	J	A	1
4086	GW01783GA	11/14/94	VOA524 2	1 1 DICHLOROETHENE	0 300	UG/L	0 20		V	1
4086	G40860290001	02/19/90	VOACL	ACETONE	2 000	UG/L	10 00	J		1
4086	GW01783GA	11/14/94	VOA524 2	CARBON TETRACHLORIDE	1 000	UG/L	0 30		V	1
4086	GW01783GA	11/14/94	VOA524 2	CHLOROFORM	0 900	UG/L	0 20		V	1
4086	GW02304GA	03/27/95	VOA524 2	CHLOROFORM	0 500	UG/L	0 20		Y	1
4086	G40860626020915	06/27/90	VOACL	METHYLENE CHLORIDE	4 000	UG/L	5 00	JB		1
4086	GW00866IT	01/11/91	VOACL	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
4086	GW01783GA	11/14/94	VOA524 2	METHYLENE CHLORIDE	0 400	UG/L	0 20		V	1
4086	GW00604GA	04/28/94	VOA524 2	TETRACHLOROETHENE	0 100	UG/L	0 20	J	A	1
4086	GW01783GA	11/14/94	VOA524 2	TETRACHLOROETHENE	0 300	UG/L	0 20		V	1
4086	GW01783GA	11/14/94	VOA524 2	TRICHLOROETHENE	0 500	UG/L	0 20		V	1
4086	GW01783GA	11/14/94	VOA524 2	cis 1 2 DICHLOROETHENE	0 700	UG/L	0 20		V	1
4187	GW00279IT	08/22/90	VOACL	CHLOROENZENE	1 000	UG/L	5 00	J		1
4187	G41870290001	02/05/90	VOACL	METHYLENE CHLORIDE	6 000	UG/L	5 00		A	1
4187	GW00279IT	08/22/90	VOACL	METHYLENE CHLORIDE	2 000	UG/L	5 00	BJ		1
4187	GW00631IT	10/31/90	VOACL	METHYLENE CHLORIDE	7 000	UG/L	5 00	B		1
4187	GW01242IT	05/07/91	VOACL	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
4187	GW02771IT	04/28/92	VOACL	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
4187	GW01563GA	10/17/94	VOA524 2	METHYLENE CHLORIDE	0 200	UG/L	0 20	J	A	1
4187	GW00279IT	08/22/90	VOACL	TOLUENE	1 000	UG/L	5 00	J		1
4187	GW00631IT	10/31/90	VOACL	TOLUENE	1 000	UG/L	5 00	J		1
4187	GW00090WC	03/01/93	VOACL	TOTAL XYLENES	1 000	UG/L	5 00	J	A	1
4587	G45870612020830	06/12/90	VOACL	ACETONE	3 000	UG/L	10 00	JB		1
4587	G45870390001	03/15/90	VOACL	METHYLENE CHLORIDE	5 000	UG/L	5 00	B		1
4587	G45870612020830	06/12/90	VOACL	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
4587	GW02097IT	12/11/91	VOA502 2	TETRACHLOROETHENE	0 100	UG/L	0 02		V	1
4587	GW00226GA	03/09/94	VOA524 2	TETRACHLOROETHENE	0 100	UG/L	0 20	J	A	1
4587	GW02097IT	12/11/91	VOA502 2	TRICHLOROETHENE	0 100	UG/L	0 03		V	1
46692	GW01674WC	12/09/93	VOA524 2	CARBON TETRACHLORIDE	0 900	UG/L	0 20		Y	1
46692	GW03525IT	09/24/92	VOA524 2	CHLOROFORM	0 500	UG/L	0 20		V	1
46692	GW01674WC	12/09/93	VOA524 2	CHLOROFORM	1 000	UG/L	0 10		Y	1
46692	GW00315GA	02/23/94	VOA524 2	METHYLENE CHLORIDE	0 500	UG/L	0 20		V	1
46692	GW01825GA	11/16/94	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	0 20		V	1
46692	GW01674WC	12/09/93	VOA524 2	TETRACHLOROETHENE	0 700	UG/L	0 10		Y	1
46692	GW00349WC	03/04/93	VOA524 2	TRICHLOROETHENE	2 000	UG/L	0 10		V	1
46692	GW00776WC	05/11/93	VOA524 2	TRICHLOROETHENE	0 200	UG/L	0 10		V	1
46692	GW01674WC	12/09/93	VOA524 2	TRICHLOROETHENE	78 000	UG/L	0 10	E	Y	1
46692	GW00315GA	02/23/94	VOA524 2	TRICHLOROETHENE	0 200	UG/L	0 20	JA		1
46692	GW00851GA	05/19/94	VOA524 2	TRICHLOROETHENE	0 200	UG/L	0 20		V	1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
46792	GW03971IT	12/16/92	VOA524 2	METHYLENE CHLORIDE	0 500	UG/L	0 20		V	1
46792	GW00865GA	06/20/94	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	0 20		V	1
46792	GW01231GA	08/17/94	VOA524 2	METHYLENE CHLORIDE	0 500	UG/L	0 20		V	1
46792	GW03971IT	12/16/92	VOA524 2	TOLUENE	4 000	UG/L	0 20		V	1
46792	GW00350WC	03/03/93	VOA524 2	TOLUENE	4 000	UG/L	0 10		V	1
46792	GW00350WC	03/03/93	VOA524 2	TRICHLOROETHENE	1 000	UG/L	0 10		V	1
4686	GW01083IT	04/08/91	VOA524 2	ACETONE	21 000	UG/L	10 00		V	1
4686	GW01545IT	07/22/91	VOA524 2	ACETONE	7 000	UG/L	10 00	J		1
4686	GW01185WC	08/17/93	VOA524 2	ACETONE	7 000	UG/L	10 00	J	A	1
4686	GW00024WC	01/27/93	VOA524 2	CARBON DISULFIDE	0 100	UG/L	5 00	J	A	1
4686	G46860390001	03/21/90	VOA524 2	METHYLENE CHLORIDE	3 000	UG/L		JB		1
4686	GW00394IT	09/14/90	VOA524 2	METHYLENE CHLORIDE	7 000	UG/L		B		1
4686	GW01380IT	06/04/91	VOA524 2	METHYLENE CHLORIDE	1 000	UG/L	5 00	BJ		1
4686	GW02979IT	06/03/92	VOA524 2	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
4686	GW00024WC	01/27/93	VOA524 2	METHYLENE CHLORIDE	0 400	UG/L	5 00	J	A	1
4686	GW02803GA	08/07/95	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	1 00	J	Y	1
4686	GW00024WC	01/27/93	VOA524 2	TETRACHLOROETHENE	0 400	UG/L	5 00	J	A	1
4686	GW00756GA	06/13/94	VOA524 2	TETRACHLOROETHENE	0 500	UG/L	0 20		V	1
4686	GW00024WC	01/27/93	VOA524 2	TOLUENE	0 200	UG/L	5 00	J	A	1
4686	GW00024WC	01/27/93	VOA524 2	TOTAL XYLENES	0 500	UG/L	5 00	J	A	1
46892	GW00351WC	03/03/93	BNACL	DIETHYL PHTHALATE	9 000	UG/L	10 00	J	A	1
46892	GW00852GA	05/19/94	VOA524 2	METHYLENE CHLORIDE	0 500	UG/L	0 20	B	Z	1
46892	GW00351WC	03/03/93	VOA524 2	TRICHLOROETHENE	1 000	UG/L	0 10		V	1
4886	GW02803IT	04/30/92	VOA524 2	CHLOROFORM	1 000	UG/L	5 00	BJ		1
4886	G48860290001	02/26/90	VOA524 2	METHYLENE CHLORIDE	3 000	UG/L		JB		1
4886	GW00311IT	08/30/90	VOA524 2	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
4886	GW00631WC	04/22/93	VOA524 2	METHYLENE CHLORIDE	3 000	UG/L	5 00	J	A	1
4886	GW01077WC	08/03/93	VOA524 2	METHYLENE CHLORIDE	23 000	UG/L	5 00	JA		1
4886	GW00510GA	04/12/94	VOA524 2	METHYLENE CHLORIDE	0 800	UG/L	0 20		V	1
4886	GW02707GA	07/13/95	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	1 00	J	V1	1
4886	GW03659IT	10/16/92	VOA524 2	TOLUENE	6 000	UG/L	5 00	JA		1
4886	GW00921IT	03/07/91	VOA524 2	TRICHLOROETHENE	3 000	UG/L	5 00	J	A	1
53094	GW02024GA	01/24/95	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	2 000	UG/L	10 00	J	A	1
53094	GW02024GA	01/24/95	BNACL	BUTYL BENZYL PHTHALATE	1 000	UG/L	10 00	J	A	1
5486	GW01718IT	08/28/91	VOA524 2	ACETONE	6 000	UG/L	10 00	BJ	JA	1
5486	GW03342IT	08/19/92	VOA524 2	BENZENE	0 400	UG/L	5 00	J	A	1
5486	G54860290001	02/21/90	VOA524 2	METHYLENE CHLORIDE	4 000	UG/L	5 00	JB		1
5486	GW00047IT	07/25/90	VOA524 2	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
5486	GW02950IT	05/26/92	VOA524 2	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
5486	GW03342IT	08/19/92	VOA524 2	STYRENE	0 400	UG/L	5 00	J	A	1
5486	GW02450IT	02/10/92	VOA524 2	TOLUENE	2 000	UG/L	5 00	J	A	1
57594	GW02352GA	04/11/95	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	1 000	UG/L	10 00	J	Y	1
57594	GW02352GA	04/11/95	BNACL	DI n BUTYL PHTHALATE	1 000	UG/L	10 00	J	Y	1
59894	GW02201GA	03/07/95	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	2 000	UG/L	10 00	J	A	1
59894	GW02525GA	05/15/95	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	2 000	UG/L	10 00	BJ	Y	1
59894	GW02525GA	05/15/95	BNACL	DI n BUTYL PHTHALATE	0 600	UG/L	10 00	J	Y	1
59894	GW02201GA	03/07/95	BNACL	DIETHYL PHTHALATE	5 000	UG/L	10 00	J	A	1
59894	GW02525GA	05/15/95	BNACL	DIETHYL PHTHALATE	1 000	UG/L	10 00	J	Y	1
70293	GW00635GA	04/21/94	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	2 000	UG/L	10 00	J	A	1
70293	GW00640WC	04/28/93	BNACL	DI n BUTYL PHTHALATE	5 000	UG/L	10 00	J	A	1
70593	GW01141WC	08/04/93	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	24 000	UG/L	10 00		V	1
70593	GW01593WC	11/19/93	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	3 000	UG/L	10 00	J	A	1
70593	GW01593WC	11/19/93	BNACL	DI n BUTYL PHTHALATE	4 000	UG/L	10 00	J	A	1
70893	GW00645WC	04/27/93	VOA524 2	ACETONE	36 000	UG/L	10 00		JA	1
70893	GW00997WC	06/15/93	BNACL	BIS(2 ETHYLHEXYL)PHTHALATE	4 000	UG/L	10 00	J	A	1
70893	GW01510WC	11/12/93	BNACL	DIETHYL PHTHALATE	3 000	UG/L	10 00	J	A	1
70893	GW01143WC	07/29/93	BNACL	NAPHTHALENE	2 000	UG/L	10 00	J	A	1
8203789	G32890290001	02/21/90	VOA524 2	ACETONE	2 000	UG/L	10 00	J		1
8203789	G32890290	02/21/90	VOA524 2	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
8203789	GW00339IT	08/30/90	VOA524 2	METHYLENE CHLORIDE	2 000	UG/L	5 00	BJ		1
8203789	GW02980IT	06/03/92	VOA524 2	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
B203789	GW03787IT	10/29/92	VOACL P	TOLUENE	1 000	UG/L	5 00	J	A	1
B203789	GW03787IT	10/29/92	VOACL P	TOTAL XYLENES	1 000	UG/L	5 00	J	A	1
B203789	GW03266IT	08/19/92	VOACL P	TRICHLOROETHENE	1 000	UG/L	5 00	J	A	1
B203889	GW01065IT	04/05/91	VOACL P	ACETONE	10 000	UG/L	10 00		JA	1
B203889	G33890390001	03/05/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L		B		1
B203889	GW00340IT	08/30/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	BJ		1
B203989	GW02536IT	03/03/92	VOACL P	ACETONE	6 000	UG/L	10 00	J	A	1
B203989	G34890618021250	06/18/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
B203989	GW00341IT	09/14/90	VOACL P	METHYLENE CHLORIDE	12 000	UG/L		B		1
B203989	GW01020IT	03/21/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B203989	GW01340IT	05/28/91	VOACL P	METHYLENE CHLORIDE	17 000	UG/L	5 00	B		1
B203989	GW02978IT	06/05/92	VOACL P	TOTAL XYLENES	1 000	UG/L	5 00	JX	A	1
B204089	GW00607IT	10/30/90	VOACL P	2 BUTANONE	1 000	UG/L	10 00	J		1
B204089	GW02121IT	12/12/91	VOACL P	ACETONE	9 000	UG/L	10 00	J	A	1
B204089	G35890390001	03/05/90	VOACL P	METHYLENE CHLORIDE	5 000	UG/L		B		1
B204089	G35890619021055	06/20/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	JB		1
B204089	GW00607IT	10/30/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
B204089	GW02121IT	12/12/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B204089	G35890619021055	06/20/90	VOACL P	TOTAL XYLENES	7 000	UG/L	5 00			1
B204189	GW00604IT	10/30/90	VOACL P	ACETONE	2 000	UG/L	10 00	BJ		1
B204189	G36890390001	03/05/90	VOACL P	METHYLENE CHLORIDE	8 000	UG/L		B		1
B204189	G36890618020945	06/19/90	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	JB		1
B204189	GW00604IT	10/30/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
B204189	GW02122IT	12/13/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B204189	GW01003IT	03/19/91	VOACL P	TETRACHLOROETHENE	1 000	UG/L	5 00	J		1
B206289	GW00114WC	02/02/93	VOACL P	4 METHYL 2 PENTANONE	6 000	UG/L	10 00	J	A	1
B206289	LF0389BR0531021010	06/01/90	VOACL P	ACETONE	28 000	UG/L	10 00	B		1
B206289	GW00204IT	08/07/90	VOACL P	ACETONE	4 000	UG/L	10 00	J		1
B206289	GW03606IT	10/06/92	VOACL P	BENZENE	0 200	UG/L	5 00	J	A	1
B206289	GLF03890390001	03/09/90	VOACL P	BROMOFORM	1 000	UG/L	5 00	J		1
B206289	LF0389BR0531021010	06/01/90	VOACL P	METHYLENE CHLORIDE	20 000	UG/L	5 00	B		1
B206289	GW00204IT	08/07/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
B206289	GW03606IT	10/06/92	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
B206289	GW00520WC	04/08/93	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B206289	GW01960IT	10/31/91	VOACL P	TOLUENE	1 000	UG/L	5 00	J	A	1
B206289	GW03606IT	10/06/92	VOACL P	TOLUENE	0 400	UG/L	5 00	J	A	1
B206289	GW03606IT	10/06/92	VOACL P	TOTAL XYLENES	0 400	UG/L	5 00	J	A	1
B206289	GLF03890390001	03/09/90	VOACL P	TRICHLOROETHENE	2 000	UG/L	5 00	J		1
B206289	GW00504GA	04/11/94	VOA524 2	TRICHLOROETHENE	0 100	UG/L	0 20	J	A	1
B206589	LF06890611020900	06/12/90	VOACL P	ACETONE	4 000	UG/L	10 00	JB		1
B206589	GW03609IT	10/06/92	VOACL P	ACETONE	10 000	UG/L	10 00		JA	1
B206589	GLF06890390001	03/12/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L	5 00	JB		1
B206589	LF06890611020900	06/12/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	JB		1
B206589	GW01233IT	05/03/91	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B206589	GW03609IT	10/06/92	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	JA	1
B206589	GW01579GA	10/17/94	VOA524 2	METHYLENE CHLORIDE	0 200	UG/L	0 20	J	A	1
B206589	GW01961IT	10/31/91	VOACL P	TOLUENE	1 000	UG/L	5 00	J	A	1
B206589	GW03609IT	10/06/92	VOACL P	TOLUENE	2 000	UG/L	5 00	J	JA	1
B206589	GW03609IT	10/06/92	VOACL P	TOTAL XYLENES	0 900	UG/L	5 00	J	JA	1
B207089	LF12890612020830	06/13/90	VOACL P	ACETONE	3 000	UG/L	10 00	JB		1
B207089	GW03584IT	10/14/92	VOACL P	ACETONE	8 000	UG/L	10 00	JB		1
B207089	GW03584IT	10/14/92	VOACL P	BENZENE	0 100	UG/L	5 00	J		1
B207089	GLF12890290001	02/07/90	VOACL P	METHYLENE CHLORIDE	8 000	UG/L	5 00	B		1
B207089	LF12890612020830	06/13/90	VOACL P	METHYLENE CHLORIDE	12 000	UG/L	5 00	B		1
B207089	GW02769IT	04/28/92	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	J	A	1
B207089	GW01099WC	08/13/93	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B207089	GW03584IT	10/14/92	VOACL P	TOLUENE	0 200	UG/L	5 00	J		1
B207189	LF13890614021610	06/15/90	VOACL P	ACETONE	13 000	UG/L		B		1
B207189	GW00243IT	08/17/90	VOACL P	ACETONE	8 000	UG/L	10 00	BJ		1
B207189	GW00600IT	10/30/90	VOACL P	ACETONE	10 000	UG/L	10 00	B		1
B207189	GW00950IT	03/12/91	VOACL P	ACETONE	7 000	UG/L		J	A	1
B207189	GW02305IT	02/20/92	VOACL P	ACETONE	7 000	UG/L	10 00	J	A	1
B207189	GLF13890290001	02/06/90	VOACL P	METHYLENE CHLORIDE	11 000	UG/L	5 00	B		1
B207189	LF13890614021610	06/15/90	VOACL P	METHYLENE CHLORIDE	7 000	UG/L				1

Attachment B

Detected Concentrations of VOCs/SVOCs in LHSU Wells

LOCATION	SAMPLE	SDATE	GROUP	ANALYTE	RESULT	UNITS	DETECT	QUAL	VAL	HIT
B207189	GW00243IT	08/17/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00	BJ		1
B207189	GW00600IT	10/30/90	VOACL P	METHYLENE CHLORIDE	7 000	UG/L	5 00	B		1
B207189	GW01240IT	05/07/91	VOACL P	METHYLENE CHLORIDE	8 000	UG/L	5 00		V	1
B207189	LF13890614021610	06/15/90	VOACL P	TOLUENE	2 000	UG/L		J		1
B217289	GW03377IT	09/18/92	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B217289	GW01602WC	12/10/93	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00	J	A	1
B217289	GW01121GA	08/10/94	VOA524 2	METHYLENE CHLORIDE	0 300	UG/L	0 20		JA	1
B217289	GW01834GA	11/28/94	VOA524 2	TRICHLOROETHENE	0 300	UG/L	0 20		V	1
B217689	GW03966IT	12/15/92	VOA524 2	METHYLENE CHLORIDE	0 500	UG/L	0 20		V	1
B304289	GW01021IT	03/21/91	VOACL P	1 2 DICHLOROETHENE	3 000	UG/L	5 00	J	A	1
B304289	GW01306IT	05/20/91	VOACL P	ACETONE	6 000	UG/L	10 00	J	A	1
B304289	G37890390001	03/02/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L			JB	1
B304289	G37890620021059	06/20/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00		JB	1
B304289	GW00342IT	08/30/90	VOACL P	METHYLENE CHLORIDE	2 000	UG/L	5 00		BJ	1
B304989	G41890531020930	06/01/90	VOACL P	ACETONE	18 000	UG/L	10 00	B		1
B304989	GW00212IT	08/17/90	VOACL P	ACETONE	6 000	UG/L	10 00	BJ		1
B304989	GW01342IT	05/29/91	VOACL P	ACETONE	5 000	UG/L	10 00	BJ		1
B304989	G41890290001	02/05/90	VOACL P	METHYLENE CHLORIDE	7 000	UG/L	5 00	B		1
B304989	G41890531020930	06/01/90	VOACL P	METHYLENE CHLORIDE	17 000	UG/L	5 00	B		1
B304989	GW00212IT	08/17/90	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	BJ		1
B304989	GW01342IT	05/29/91	VOACL P	METHYLENE CHLORIDE	11 000	UG/L	5 00	B		1
B304989	G41890290001	02/05/90	VOACL P	TOLUENE	3 000	UG/L	5 00	J		1
B304989	G41890290001	02/05/90	VOACL P	TRICHLOROETHENE	2 000	UG/L	5 00	J		1
B405289	GW03739IT	10/22/92	VOACL P	ACETONE	2 000	UG/L	10 00	J		1
B405289	GW03739IT	10/22/92	VOACL P	CARBON DISULFIDE	0 200	UG/L	5 00	J		1
B405289	G43890390001	03/02/90	VOACL P	METHYLENE CHLORIDE	3 000	UG/L			JB	1
B405289	GW00100IT	08/01/90	VOACL P	METHYLENE CHLORIDE	6 000	UG/L	5 00	B		1
P208889	GW01064GA	08/02/94	VOA524 2	1 2 3 TRICHLOROBENZENE	0 523	UG/L	0 50		Y	1
P208889	GW01064GA	08/02/94	VOA524 2	1 2 4 TRICHLOROBENZENE	0 534	UG/L	0 50		Y	1
P208889	GW01064GA	08/02/94	VOA524 2	1 2 DICHLOROETHANE	0 877	UG/L	0 50		Y	1
P208889	GSEP16890290001	02/05/90	VOACL P	ACETONE	14 000	UG/L	10 00	B		1
P208889	SEP16890621021115	06/22/90	VOACL P	ACETONE	10 000	UG/L			B	1
P208889	GW00237IT	08/16/90	VOACL P	ACETONE	7 000	UG/L	10 00	BJ		1
P208889	GW01446WC	10/25/93	VOACL P	ACETONE	3 000	UG/L	10 00	J		1
P208889	GW03558IT	10/06/92	VOACL P	BENZENE	0 200	UG/L	5 00	J	A	1
P208889	GW01064GA	08/02/94	VOA524 2	HEXACHLOROBUTADIENE	0 582	UG/L	0 50		Y	1
P208889	GSEP16890290001	02/05/90	VOACL P	METHYLENE CHLORIDE	4 000	UG/L	5 00		JB	1
P208889	SEP16890621021115	06/22/90	VOACL P	METHYLENE CHLORIDE	7 000	UG/L				1
P208889	GW00237IT	08/16/90	VOACL P	METHYLENE CHLORIDE	1 000	UG/L	5 00	BJ		1
P208889	GW03558IT	10/06/92	VOACL P	METHYLENE CHLORIDE	0 800	UG/L	5 00	J	A	1
P208889	GW02758GA	07/24/95	VOA524 2	METHYLENE CHLORIDE	0 100	UG/L	1 00	J	V1	1
P208889	GW01064GA	08/02/94	VOA524 2	NAPHTHALENE	0 523	UG/L	0 50		Y	1
P208889	GW03558IT	10/06/92	VOACL P	TOLUENE	0 800	UG/L	5 00	J	A	1
P208889	GW03558IT	10/06/92	VOACL P	TOTAL XYLENES	0 600	UG/L	5 00	J	A	1
P416989	GW02053GA	02/23/95	VOA524 2	1 2 DICHLOROETHANE	0 514	UG/L	0 50		Y	1
P416989	GW00203GA	02/21/94	VOA524 2	CARBON TETRACHLORIDE	0 200	UG/L	0 30	J	A	1
P416989	GW00203GA	02/21/94	VOA524 2	CHLOROFORM	0 200	UG/L	0 20	J	A	1
P416989	GW02931GA	11/08/95	VOA524 2	METHYLENE CHLORIDE	0 200	UG/L	1 00	BJ	Y	1
P416989	GW00203GA	02/21/94	VOA524 2	TETRACHLOROETHENE	0 100	UG/L	0 20	J	A	1

Attachment B

**Dissolved Radionuclides > Background Mean
+ 2SD in LHSU Groundwater**

Attachment B

Dissolved Radionuclides > Background Mean+ 2SD inLHSU Groundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
0887	GW00024IT	09/11/90	GROSS BETA	13 730	PCI/L	3 3700		4 0000	A
0887	GW00568IT	11/09/90	GROSS BETA	10 920	PCI/L	3 6200		4 0000	A
0887	GW01675IT	09/19/91	GROSS BETA	11 310	PCI/L	3 5300		4 9000	A
0887	GW02019IT	11/14/91	GROSS BETA	9 959	PCI/L	4 5500		7 3000	A
0986	GW00096WC	02/12/93	GROSS ALPHA	16 510	PCI/L	5 7500		3 3000	A
0986	GW00566GA	04/18/94	URANIUM 235	0 201	PCI/L	0 1832		0 1450	V
0986	GW01559GA	10/12/94	URANIUM 235	0 270	PCI/L	0 2460		0 1948	Y
1686	GW02639IT	04/08/92	GROSS BETA	11 030	PCI/L	7 9000		15 0000	A
1686	GW03189IT	07/22/92	GROSS BETA	10 320	PCI/L	3 8200		5 8000	A
1686	GW01452GA	10/06/94	GROSS BETA	12 900	PCI/L	6 8863	C	10 6606	Y
1686	GW01943GA	01/16/95	GROSS BETA	9 000	PCI/L	5 2000		8 1000	V
1686	GW03629IT	10/13/92	URANIUM 235	0 210	PCI/L	0 1813		0 1118	A
1686	GW01450WC	10/29/93	URANIUM 235	0 305	PCI/L	0 2453		0 1377	V
1687	G16870390001	03/17/90	URANIUM 235	0 180	PCI/L	0 2358		0 2790	
1687	GW00757WC	05/21/93	URANIUM 235	0 280	PCI/L	0 1984		0 0964	A
1687	GW01154GA	08/22/94	URANIUM 235	0 279	PCI/L	0 2382		0 1876	V
2186	GW00059IT	08/02/90	GROSS ALPHA	19 830	PCI/L	7 4400		2 0000	
2186	GW02468GA	04/27/95	URANIUM 235	0 263	PCI/L	0 1433		0 1013	Y
22093	GW01178WC	08/17/93	GROSS BETA	13 000	PCI/L	2 5000		3 1000	V
22093	GW00413GA	03/15/94	GROSS BETA	9 300	PCI/L	2 6000		3 4000	V
22093	GW00744GA	06/02/94	GROSS BETA	10 000	PCI/L	6 0000		7 0000	V
22093	GW01461WC	11/09/93	URANIUM 235	0 475	PCI/L	0 2836		0 1171	Y
22093	GW01598GA	11/28/94	URANIUM 235	0 326	PCI/L	0 2625		0 2035	Y
22293	GW02094GA	02/21/95	GROSS BETA	23 238	PCI/L	4 3452	C	5 1112	V
22293	GW01179WC	08/17/93	URANIUM 235	0 180	PCI/L	0 1800	J	0 0640	V
22293	GW02094GA	02/21/95	URANIUM 235	0 303	PCI/L	0 1622		0 1035	A
22393	GW02407GA	05/16/95	URANIUM 233 234	8 859	PCI/L	1 0271		0 1548	Y
22393	GW02407GA	05/16/95	URANIUM 235	0 744	PCI/L	0 2781		0 1457	Y
22593	GW01602GA	10/24/94	URANIUM 235	0 165	PCI/L	0 1622	Y	0 1486	Y
2287	G22870290001	02/08/90	CESIUM 137	1 600	PCI/L	0 7300		1 0000	
2287	GW01402IT	06/10/91	GROSS BETA	9 618	PCI/L	2 3700		2 9000	A
2287	GW03567IT	10/13/92	GROSS BETA	9 304	PCI/L	2 6000		3 3000	A
2287	GW00540WC	04/16/93	GROSS BETA	10 000	PCI/L	10 0000	U	16 0000	V
2287	GW02799GA	08/02/95	GROSS BETA	14 430	PCI/L	4 1000		6 0200	Y
2287	GW01198IT	04/24/91	STRONTIUM 89 90	5 530	PCI/L	2 0300		1 0000	
2287	GW01927IT	10/16/91	URANIUM 235	0 697	PCI/L	0 3050		0 1400	A
2287	GW00703GA	05/03/94	URANIUM 235	0 501	PCI/L	0 2775		0 1361	V
2287	GW01654GA	10/31/94	URANIUM 235	0 182	PCI/L	0 1945		0 1942	Y
2287	GW02547GA	05/09/95	URANIUM 235	0 181	PCI/L	0 1240		0 1127	Y
23193	GW00628GA	04/25/94	URANIUM 235	0 607	PCI/L	0 3405		0 1823	V
23193	GW01603GA	10/24/94	URANIUM 235	0 211	PCI/L	0 1849	Y	0 1622	Y
23193	GW02097GA	02/15/95	URANIUM 235	0 344	PCI/L	0 1779		0 1099	A
2586	GW00471IT	10/11/90	GROSS ALPHA	27 690	PCI/L	35 8000		2 0000	
2586	GW00471IT	10/11/90	GROSS BETA	30 630	PCI/L	11 1000		4 0000	
2586	GW01600IT	07/24/91	GROSS BETA	9 804	PCI/L	4 0900		6 4000	A
2586	GW01909IT	10/16/91	GROSS BETA	10 920	PCI/L	5 2800		8 8000	A
2586	GW02267IT	01/23/92	GROSS BETA	10 540	PCI/L	4 7700		7 7000	A
2586	GW03018IT	06/09/92	GROSS BETA	10 790	PCI/L	4 6400		7 2000	A
2586	GW03158IT	07/22/92	GROSS BETA	15 000	PCI/L	10 0000		15 0000	V
2586	GW00004WC	02/05/93	GROSS BETA	11 480	PCI/L	4 8600		7 5000	A
2586	GW00488GA	04/15/94	GROSS BETA	9 000	PCI/L	2 8000		4 2000	V
2586	GW00999GA	07/20/94	GROSS BETA	9 500	PCI/L	2 4000		3 7000	V
2586	GW01455GA	10/06/94	GROSS BETA	11 961	PCI/L	9 7427	C	15 8252	Y
2586	GW02359GA	04/20/95	GROSS BETA	18 106	PCI/L	10 2281	C	15 9885	Y
2586	GW02686GA	07/12/95	GROSS BETA	12 990	PCI/L	4 7800		7 8400	Y
2586	GW00847IT	01/08/91	URANIUM 235	0 159	PCI/L	0 0874	J	0 6000	
2586	GW00004WC	02/05/93	URANIUM 235	0 230	PCI/L	0 23 0	J	0 1500	A
2586	GW00529WC	04/13/93	URANIUM 235	0 560	PCI/L	0 14 0		0 0280	A
2586	GW01046WC	07/16/93	URANIUM 235	0 190	PCI/L	0 03 0	BJ	0 0120	
2586	GW00006GA	01/31/94	URANIUM 235	0 220	PCI/L	0 15 0		0 1310	V
2586	GW01455GA	10/06/94	URANIUM 235	0 332	PCI/L	0 15 0	J	0 0429	Y

Attachment B

Dissolved Radionuclides > Background Mean+ 2SD inLHSU Groundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
2586	GW01903GA	01/11/95	URANIUM 235	0 906	PCI/L	0 2910	F	0 1560	V
2887	GW02009IT	11/22/91	GROSS BETA	11 630	PCI/L	3 5100		4 7000	A
2887	GW02661GA	06/14/95	GROSS BETA	9 290	PCI/L	4 5192	C	6 8970	Y
2887	GW007411T	11/28/90	URANIUM 233 234	9 242	PCI/L	2 0400		0 0000	A
2887	GW008741T	01/15/91	URANIUM 233 234	9 993	PCI/L	1 1100		0 6000	V
2887	GW010981T	04/17/91	URANIUM 233 234	9 251	PCI/L	1 9900		0 6000	
2887	GW007411T	11/28/90	URANIUM 235	0 400	PCI/L	0 3440	J	0 1440	A
2887	GW010981T	04/17/91	URANIUM 235	0 426	PCI/L	0 3480	J	0 6000	
3087	G30870290001	02/09/90	CESIUM 137	1 030	PCI/L	0 5400		0 7500	
3087	GW00407WC	03/22/93	GROSS BETA	9 290	PCI/L	4 7600		7 1800	
3187	GW004131T	09/18/90	GROSS ALPHA	44 730	PCI/L	11 2000		2 0000	A
3187	GW004131T	09/18/90	GROSS BETA	9 567	PCI/L	1 8500		4 0000	A
3187	GW01784GA	11/14/94	URANIUM 235	0 232	PCI/L	0 2192		0 1890	Y
3286	GW02754GA	07/27/95	CESIUM 137	0 825	PCI/L	0 7140	J	1 2300	Y
3286	GW01444WC	11/03/93	URANIUM 235	0 168	PCI/L	0 1653	Y	0 1512	A
3286	GW00540GA	04/19/94	URANIUM 235	0 414	PCI/L	0 2714		0 1247	V
3486	GW011811T	04/22/91	GROSS BETA	24 720	PCI/L	5 6200		6 8000	A
3486	GW018211T	10/07/91	GROSS BETA	12 930	PCI/L	4 5300		6 8000	A
3486	GW038271T	12/11/92	GROSS BETA	10 900	PCI/L	11 6000	UC	18 0000	V
3486	GW00261WC	03/05/93	GROSS BETA	9 700	PCI/L	8 4400	UC	13 8000	V
3486	GW00694WC	05/06/93	GROSS BETA	13 000	PCI/L	5 0000		6 9000	V
3486	GW01243WC	09/22/93	GROSS BETA	11 000	PCI/L	4 1000		5 7000	V
3486	GW02134GA	02/14/95	GROSS BETA	9 100	PCI/L	1 8000		2 7000	V
3486	GW02805GA	08/29/95	GROSS BETA	14 820	PCI/L	3 5500		5 3900	Y
3486	GW01836GA	11/29/94	URANIUM 235 234	0 194	PCI/L	0 2321		0 2486	Y
3487	GW007381T	11/28/90	URANIUM 233 234	9 457	PCI/L	1 9200		0 1690	V
3487	GW00784WC	05/18/93	URANIUM 235	0 206	PCI/L	0 0900		0 0600	A
3487	GW01638WC	12/02/93	URANIUM 235	0 435	PCI/L	0 2716		0 1178	Y
3487	GW00814GA	05/17/94	URANIUM 235	0 549	PCI/L	0 3083		0 1650	V
3487	GW01376GA	09/09/94	URANIUM 235	0 696	PCI/L	0 3426		0 1178	V
3487	GW01781GA	11/15/94	URANIUM 235	0 193	PCI/L	0 2184		0 2232	Y
3987	GW012031T	04/29/91	GROSS BETA	17 960	PCI/L	4 0100		4 8000	A
4187	GW01093WC	08/10/93	GROSS ALPHA	16 000	PCI/L	3 1000		1 7000	V
4187	GW006311T	10/31/90	GROSS BETA	13 190	PCI/L	4 8500		4 0000	
4187	GW019201T	10/17/91	GROSS BETA	14 040	PCI/L	5 4700		8 3000	A
4187	GW035791T	10/13/92	GROSS BETA	15 780	PCI/L	4 7600		7 2000	A
4187	GW00544WC	04/20/93	GROSS BETA	16 270	PCI/L	11 9800		18 6600	
4187	GW01093WC	08/10/93	GROSS BETA	15 000	PCI/L	9 5000		14 0000	V
4187	GW02745GA	07/24/95	GROSS BETA	10 370	PCI/L	4 8200		8 5700	Y
4587	GW023771T	02/22/92	GROSS BETA	14 690	PCI/L	2 4800		2 2000	A
4587	GW005921T	10/25/90	URANIUM 233 234	60 750	PCI/L	8 2100		0 0950	V
4587	GW01364GA	09/12/94	URANIUM 233 234	55 605	PCI/L	4 3579		0 2650	V
4587	GW005921T	10/25/90	URANIUM 235	1 372	PCI/L	0 5290		0 0000	V
4587	GW01364GA	09/12/94	URANIUM 235	6 518	PCI/L	1 1942		0 1834	V
4587	GW005921T	10/25/90	URANIUM 238	39 270	PCI/L	5 5400		0 0000	V
4587	GW01364GA	09/12/94	URANIUM 238	61 360	PCI/L	4 6726		0 2506	V
46692	GW035251T	09/24/92	URANIUM 235	0 390	PCI/L	0 3449		0 2109	A
46692	GW01427GA	09/12/94	URANIUM 235	0 170	PCI/L	0 1700	J	0 1100	Y
46692	GW01825GA	11/16/94	URANIUM 235	0 206	PCI/L	0 1874		0 1645	Y
46792	GW039711T	12/16/92	URANIUM 233 234	9 100	PCI/L	1 4751		0 1781	A
46792	GW00350WC	03/03/93	URANIUM 233 234	8 657	PCI/L	2 1000		0 4735	A
46792	GW039711T	12/16/92	URANIUM 235	0 161	PCI/L	0 1741	U	0 1673	A
46792	GW00350WC	03/03/93	URANIUM 235	0 381	PCI/L	0 3630		0 3508	A
46792	GW00865GA	06/20/94	URANIUM 235	0 350	PCI/L	0 2500	J	0 1800	V
46792	GW01826GA	11/29/94	URANIUM 235	0 191	PCI/L	0 1876		0 1718	Y
4686	GW036431T	10/20/92	GROSS BETA	9 300	PCI/L	3 2000	UE	4 5000	V
4686	GW029791T	06/03/92	URANIUM 235	0 280	PCI/L	0 0020	U	0 1500	A
4686	GW036431T	10/20/92	URANIUM 235	0 189	PCI/L	0 2631	U	0 2558	A
4686	GW00629WC	04/21/93	URANIUM 235	0 280	PCI/L	0 2900	J	0 0590	A
4686	GW02576GA	05/22/95	URANIUM 235	0 204	PCI/L	0 1649		0 1569	Y
46892	GW01676WC	12/14/93	URANIUM	0 190	PCI/L	0 1797		0 1546	Y

Attachment B

Dissolved Radionuclides > Background Mean+ 2SD in LHSU Groundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
46892	GW01428GA	09/14/94	URANIUM 235	0 230	PCI/L	0 2100	J	0 1900	Y
4886	GW01455WC	11/09/93	URANIUM 235	0 158	PCI/L	0 1628		0 1438	Y
53094	GW02554GA	06/20/95	GROSS ALPHA	24 403	PCI/L	12 6756	C	14 5588	Y
53094	GW01875GA	12/15/94	GROSS BETA	15 880	PCI/L	3 7600		5 7700	Y
53094	GW02554GA	06/20/95	GROSS BETA	19 314	PCI/L	9 1342	C	13 7840	Y
53094	GW01875GA	12/15/94	URANIUM 235	0 248	PCI/L	0 1450		0 1680	Y
5486	GW00047IT	07/25/90	GROSS BETA	10 870	PCI/L	2 4200	X	4 0000	
59894	GW02201GA	03/07/95	CESIUM 137	0 949	PCI/L	0 7170	J	1 2700	V
70293	GW02500GA	05/09/95	GROSS BETA	108 733	PCI/L	7 5119		2 8756	Y
70293	GW70015ST	03/27/93	URANIUM 235	0 334	PCI/L	0 2880		0 2540	A
70293	GW00640WC	04/28/93	URANIUM 235	0 290	PCI/L	0 2100	J	0 0520	A
70293	GW01138WC	07/30/93	URANIUM 235	0 180	PCI/L	0 1800	BJ	0 0360	A
70293	GW01229GA	08/22/94	URANIUM 235	0 468	PCI/L	0 3402		0 2322	V
70293	GW02105GA	02/13/95	URANIUM 235	0 426	PCI/L	0 2176		0 1198	Y
70293	GW02500GA	05/09/95	URANIUM 235	0 705	PCI/L	0 3233	F	0 1788	Y
70293	GW70015ST	03/27/93	URANIUM 238	4 196	PCI/L	1 1400		0 3160	A
70593	GW00643WC	04/29/93	GROSS BETA	11 000	PCI/L	2 3000	B	2 8000	A
70593	GW00643WC	04/29/93	URANIUM 235	0 270	PCI/L	0 2300	J	0 1000	A
70593	GW00995WC	06/16/93	URANIUM 235	0 170	PCI/L	0 1700	BJ	0 0350	A
70593	GW01628GA	10/24/94	URANIUM 235	0 303	PCI/L	0 2312		0 1761	Y
70593	GW02108GA	02/16/95	URANIUM 235	0 164	PCI/L	0 1233		0 1108	A
70893	GW01311GA	08/29/94	URANIUM 235	0 160	PCI/L	0 0500		0 0200	V
70893	GW01630GA	10/31/94	URANIUM 235	0 607	PCI/L	0 3504	F	0 2095	Y
B203889	GW01065IT	04/05/91	URANIUM 235	0 164	PCI/L	0 2330	J	0 0000	V
B203889	GW01765IT	09/19/91	URANIUM 235	0 175	PCI/L	0 1830	J	0 0750	V
B203989	GW03782IT	10/23/92	URANIUM 235	0 170	PCI/L	0 1591		0 1371	A
B204089	GW00607IT	10/30/90	GROSS ALPHA	21 820	PCI/L	8 1300		2 0000	A
B204089	GW00607IT	10/30/90	GROSS BETA	12 560	PCI/L	3 0500		4 0000	A
B204089	GW02634GA	06/06/95	GROSS BETA	11 531	PCI/L	5 7959	C	8 8845	Y
B204089	GW02634GA	06/06/95	URANIUM 235	0 488	PCI/L	0 2549		0 1419	Y
B204189	GW01003IT	03/19/91	GROSS BETA	10 090	PCI/L	2 7200		3 3000	A
B204189	GW03789IT	10/23/92	GROSS BETA	13 000	PCI/L	10 1000	UC	16 2000	V
B204189	GW00604IT	10/30/90	URANIUM 235	0 225	PCI/L	0 3200	J	0 6000	
B204189	GW02988IT	05/29/92	URANIUM 235	0 280	PCI/L	0 0030	U	0 2900	A
B204189	GW00306WC	03/22/93	URANIUM 235	0 200	PCI/L	0 0870		0 0420	JA
B206289	GW00114WC	02/02/93	URANIUM 235	0 210	PCI/L	0 1956		0 1544	A
B206289	GW00039GA	01/20/94	URANIUM 235	0 260	PCI/L	0 1010		0 0690	V
B206289	GW01965GA	01/19/95	URANIUM 235	0 214	PCI/L	0 1599		0 1347	A
B207089	GLF12890290001	02/07/90	CESIUM 137	1 100	PCI/L	0 6700		0 9700	
B207089	GW01917IT	10/18/91	GROSS BETA	12 130	PCI/L	5 2900		8 7000	A
B207089	GW02306IT	02/20/92	GROSS BETA	8 922	PCI/L	5 8900		11 0000	A
B207089	GW02769IT	04/28/92	GROSS BETA	11 530	PCI/L	5 1200		8 3000	A
B207089	GW02748GA	07/20/95	GROSS BETA	10 900	PCI/L	4 3400		7 5600	Y
B207089	GW01217IT	04/30/91	STRONTIUM 89 90	11 170	PCI/L	3 5700		0 7700	A
B207089	GW00612IT	10/30/90	URANIUM 235	0 215	PCI/L	0 2500	J	0 6000	
B207089	GW01381WC	10/12/93	URANIUM 235	0 255	PCI/L	0 2044		0 1151	A
B207089	GW00480GA	04/07/94	URANIUM 235	0 295	PCI/L	0 2371		0 1839	V
B207089	GW01927GA	01/11/95	URANIUM 235	0 326	PCI/L	0 1555		0 0978	V
B207089	GW02512GA	05/11/95	URANIUM 235	0 323	PCI/L	0 1851		0 1341	Y
B207189	GW00243IT	08/17/90	GROSS BETA	15 410	PCI/L	4 8300		4 0000	
B207189	GW02305IT	02/20/92	GROSS BETA	9 083	PCI/L	5 1600		8 9000	A
B207189	GW02770IT	04/ 9/92	GROSS BETA	9 873	PCI/L	4 5000		7 2000	A
B217289	GW01602WC	2/ 0 93	URANIUM 235	0 264	PCI/L	0 2185		0 1574	Y
B217589	GW03965IT	12 5/92	URANIUM 235	0 220	PCI/L	0 2049		0 1793	A
B217689	GW03966IT	12/15/92	URANIUM 235	0 176	PCI/L	0 1895	U	0 1821	A
B217689	GW00451WC		URANIUM 235	0 180	PCI/L	0 1500		0 1210	JA

Attachment B

Dissolved Radionuclides > Background Mean+ 2SD in LHSU Groundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
B304989	GW03751IT	10/27/92	URANIUM 235	0 370	PCI/L	0 2424		0 1112	A
B405289	GW00100IT	08/01/90	GROSS ALPHA	36 650	PCI/L	13 5000		2 0000	A
B405289	GW00688IT	11/13/90	GROSS ALPHA	26 110	PCI/L	12 3000		2 0000	A
B405289	GW00100IT	08/01/90	GROSS BETA	13 800	PCI/L	3 6600		4 0000	A
B405289	GW00100IT	08/01/90	URANIUM 233 234	13 850	PCI/L	3 5200		0 6000	
B405289	GW00688IT	11/13/90	URANIUM 233 234	15 330	PCI/L	2 5300		0 6000	V
B405289	GW00688IT	11/13/90	URANIUM 235	0 231	PCI/L	0 2090	J	0 6000	V
B405289	GW00100IT	08/01/90	URANIUM 238	8 010	PCI/L	2 4100		0 6000	
B405289	GW00688IT	11/13/90	URANIUM 238	7 714	PCI/L	1 5300		0 6000	V
P208889	SEP16890621021115	06/22/90	GROSS BETA	11 000	PCI/L	2 8000		4 0000	
P416989	GW01572WC	11/23/93	URANIUM 233 234	26 000	PCI/L	2 7142		0 1593	
P416989	GW02931GA	11/08/95	URANIUM 233 234	13 230	PCI/L	3 5500		0 5910	Y
P416989	GW01572WC	11/23/93	URANIUM 235	1 300	PCI/L	0 4320		0 0971	
P416989	GW00697GA	05/03/94	URANIUM 235	0 337	PCI/L	0 2451		0 1834	V
P416989	GW02931GA	11/08/95	URANIUM 235	0 359	PCI/L	0 3900	J	0 4770	Y
P416989	GW01572WC	11/23/93	URANIUM 238	29 000	PCI/L	2 8894		0 1453	
P416989	GW02931GA	11/08/95	URANIUM 238	10 070	PCI/L	2 8700		0 6140	Y

**Total Radionuclides > Background Mean
+ 2SD in LHSU Groundwater**

Attachment B

Total Radionuclides > Background Mean +2SD in LHSUGroundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
0887	GW00983IT	03/14/91	CESIUM 137	1 16	PCI/L	0 755		1 130	A
0986	GW01050GA	08/07/94	RADIUM 226	2 10	PCI/L	0 130	B	0 083	V
1686	GW01452GA	10/06/94	AMERICIUM 241	0 05	PCI/L	0 018		0 005	Y
1687	GW03443IT	09/03/92	AMERICIUM 241	0 04	PCI/L	0 015		0 000	A
1687	GW01622WC	11/29/93	AMERICIUM 241	0 03	PCI/L	0 011		0 006	Y
1687	GW00791GA	06/27/94	AMERICIUM 241	0 07	PCI/L	0 016		0 005	V
1687	GW00409IT	09/18/90	PLUTONIUM 239/240	0 14	PCI/L	0 034		0 007	A
1687	GW00853IT	01/09/91	PLUTONIUM 239/240	0 02	PCI/L	0 009		0 010	
1687	GW01095IT	04/16/91	PLUTONIUM 239/240	0 07	PCI/L	0 019		0 010	
1687	GW01645IT	09/05/91	PLUTONIUM 239/240	0 03	PCI/L	0 012		0 000	V
1687	GW02423IT	02/25/92	PLUTONIUM 239/240	0 04	PCI/L	0 016		0 006	A
1687	GW00394WC	03/10/93	PLUTONIUM 239/240	0 12	PCI/L	0 020		0 002	A
1687	GW01622WC	11/29/93	PLUTONIUM 239/240	0 22	PCI/L	0 025		0 002	Y
1687	GW00791GA	06/27/94	PLUTONIUM 239/240	0 42	PCI/L	0 054		0 012	V
1687	GW01154GA	08/22/94	PLUTONIUM 239/240	0 13	PCI/L	0 063	Y	0 067	A
1687	GW01771GA	11/22/94	PLUTONIUM 239/240	0 02	PCI/L	0 016	U	0 022	Y
1687	GW02648GA	06/19/95	PLUTONIUM 239/240	0 02	PCI/L	0 010		0 003	Y
1687	G16870625021115	06/26/90	URANIUM 233 234	3 05	PCI/L	0 880		0 080	A
1687	G16870625021115	06/26/90	URANIUM 238	1 10	PCI/L	0 510		0 080	A
2186	GW00109GA	02/07/94	URANIUM 235	0 09	PCI/L	0 130	U	0 120	A
2186	GW01656GA	10/31/94	URANIUM 235	0 10	PCI/L	0 154		0 197	Y
2186	G21860290001	02/28/90	URANIUM 238	0 92	PCI/L	0 446		0 163	
2186	GW00109GA	02/07/94	URANIUM 238	1 00	PCI/L	0 450	B	0 190	A
22093	GW02092GA	02/21/95	RADIUM 226	1 50	PCI/L	0 180		0 140	Y
22093	GW02092GA	02/21/95	URANIUM 233 234	2 60	PCI/L	0 940		0 500	V
22093	GW02417GA	04/17/95	URANIUM 233 234	2 36	PCI/L	0 446		0 165	Y
22093	GW02417GA	04/17/95	URANIUM 235	0 17	PCI/L	0 130		0 126	Y
22093	GW02092GA	02/21/95	URANIUM 238	1 60	PCI/L	0 680		0 270	V
22093	GW02417GA	04/17/95	URANIUM 238	1 53	PCI/L	0 363		0 180	Y
22193	GW02418GA	04/17/95	AMERICIUM 241	0 03	PCI/L	0 013		0 013	Y
22193	GW02418GA	04/17/95	PLUTONIUM 239/240	0 42	PCI/L	0 055		0 017	Y
22193	GW01177WC	08/16/93	RADIUM 226	1 60	PCI/L	0 440		0 086	V
22193	GW00627GA	06/23/94	RADIUM 226	3 30	PCI/L	0 180		0 074	V
22193	GW01271GA	08/23/94	RADIUM 226	1 60	PCI/L	0 140	B	0 068	Y
22193	GW02093GA	02/21/95	RADIUM 226	4 20	PCI/L	0 390		0 330	Y
22193	GW00918WC	06/02/93	URANIUM 238	1 84	PCI/L	0 710		0 262	V
22293	GW01179WC	08/17/93	CESIUM 137	3 70	PCI/L	1 200	B	1 400	A
22293	GW01463WC	11/05/93	GROSS ALPHA	69 00	PCI/L	5 600		2 600	V
22293	GW01463WC	11/05/93	GROSS BETA	46 00	PCI/L	5 600		5 500	V
22293	GW00992WC	06/14/93	RADIUM 226	7 80	PCI/L	0 260	B	0 140	A
22293	GW02419GA	05/30/95	RADIUM 226	1 60	PCI/L	0 065	B	0 054	Y
22293	GW01463WC	11/05/93	URANIUM 233 234	3 40	PCI/L	0 520	B	0 120	A
22293	GW01463WC	11/05/93	URANIUM 235	0 12	PCI/L	0 088	J	0 087	A
22293	GW01463WC	11/05/93	URANIUM 238	2 70	PCI/L	0 450	B	0 170	A
22593	GW01274GA	08/25/94	RADIUM 226	1 68	PCI/L	0 518		0 346	V
22593	GW01274GA	08/25/94	URANIUM 233 234	4 38	PCI/L	0 870		0 218	Y
22593	GW01274GA	08/25/94	URANIUM 235	0 23	PCI/L	0 199		0 157	Y
22593	GW01274GA	08/25/94	URANIUM 238	1 88	PCI/L	0 557		0 157	Y
2287	GW00143IT	08/14/90	AMERICIUM 241	0 03	PCI/L	0 024		0 000	
2287	GW00756IT	12/12/90	PLUTONIUM 239/240	0 02	PCI/L	0 013		0 010	V
2287	G22870524021410	05/25/90	URANIUM 233 234	2 71	PCI/L	0 770		0 077	A
2287	GW00143IT	08/14/90	URANIUM 233 234	2 69	PCI/L	0 590		0 000	
2287	GW00143IT	08/14/90	URANIUM 235	0 36	PCI/L	0 200		0 000	
2287	G22870524021410	05/25/90	URANIUM 238	1 38	PCI/L	0 530		0 077	A
23193	GW00924WC	06/08/93	RADIUM 226	1 70	PCI/L	0 110	B	0 080	A
23193	GW00417GA	03/16/94	RADIUM 226	2 60	PCI/L	0 170	B	0 090	V
23193	GW01155GA	08/08/94	RADIUM 226	1 50	PCI/L	0 190		0 120	Y
23193	GW02421GA	04/18/95	URANIUM 235	0 19	PCI/L	0 128		0 100	Y
2386	GW03156IT	07/28/92	TRITIUM	2973 00	PCI/L	410 000		660 000	V
2386	G23860524020910	05/25/90	URANIUM 233 234	1 98	PCI/L	0 580		0 050	A
2386	G23860390001	03/22/90	URANIUM 238	1 48	PCI/L	0 740		0 600	

Attachment B

Total Radionuclides > Background Mean +2SD in LHSUGroundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
2386	G23860524020910	05/25/90	URANIUM 238	1 06	PCI/L	0 410		0 050	A
2586	G25860290001	02/22/90	PLUTONIUM 239/240	0 03	PCI/L	0 010		0 006	
2586	G25860290001	02/22/90	URANIUM 233 234	5 76	PCI/L	1 540		0 061	
2586	G25860524021140	05/25/90	URANIUM 233 234	5 15	PCI/L	1 060		0 060	A
2586	GW002931T	08/28/90	URANIUM 233 234	5 22	PCI/L	0 920		0 000	
2586	G25860290001	02/22/90	URANIUM 235	0 15	PCI/L	0 152		0 104	
2586	G25860524021140	05/25/90	URANIUM 235	0 13	PCI/L	0 140		0 000	A
2586	GW002931T	08/28/90	URANIUM 235	0 18	PCI/L	0 137		0 000	
2586	G25860290001	02/22/90	URANIUM 238	1 84	PCI/L	0 685		0 061	
2586	G25860524021140	05/25/90	URANIUM 238	1 01	PCI/L	0 420		0 000	A
2586	GW002931T	08/28/90	URANIUM 238	1 36	PCI/L	0 400		0 000	
2786	G27860290001	02/13/90	URANIUM 235	0 10	PCI/L	0 300		0 400	A
2887	G28870390001	03/12/90	URANIUM 233 234	6 76	PCI/L	1 400		0 200	A
2887	G28870625021055	06/26/90	URANIUM 233 234	9 77	PCI/L	1 900		0 000	A
2887	G28870625021055	06/26/90	URANIUM 235	0 19	PCI/L	0 230		0 100	A
2887	G28870390001	03/12/90	URANIUM 238	2 87	PCI/L	0 840		0 160	A
2887	G28870625021055	06/26/90	URANIUM 238	2 66	PCI/L	0 880		0 100	A
3087	G30870530020930	05/30/90	URANIUM 235	0 11	PCI/L	0 130		0 050	A
3187	GW00789WC	05/14/93	PLUTONIUM 239/240	0 04	PCI/L	0 010		0 010	V
3187	GW01641WC	12/02/93	PLUTONIUM 239/240	0 04	PCI/L	0 012		0 007	Y
3187	G31870626020840	06/27/90	STRONTIUM 89 90	0 64	PCI/L	0 270		0 310	A
3187	G31870626020840	06/27/90	URANIUM 233 234	2 42	PCI/L	0 880		0 110	A
3286	GW00535WC	04/23/93	AMERICIUM 241	0 08	PCI/L	0 017		0 010	A
3286	GW01483GA	10/12/94	AMERICIUM 241	0 08	PCI/L	0 035		0 019	Y
3286	G32860390001	03/12/90	URANIUM 235	0 35	PCI/L	0 310		0 160	A
3487	G34870625021258	06/26/90	URANIUM 233 234	2 73	PCI/L	0 810		0 150	A
4086	G40860626020915	06/27/90	URANIUM 233 234	3 37	PCI/L	0 910		0 080	A
4086	G40860626020915	06/27/90	URANIUM 238	1 37	PCI/L	0 550		0 000	A
4187	G41870618020930	06/19/90	RADIUM 226	1 50	PCI/L	0 250		0 500	
4187	G41870290001	02/05/90	URANIUM 233 234	3 24	PCI/L	0 830		0 140	A
4187	G41870290001	02/05/90	URANIUM 235	0 08	PCI/L	0 130		0 060	A
4187	G41870290001	02/05/90	URANIUM 238	1 20	PCI/L	0 480		0 130	A
46692	GW035251T	09/24/92	AMERICIUM 241	0 03	PCI/L	0 000	UY	0 028	Z
46692	GW01674WC	12/09/93	AMERICIUM 241	0 13	PCI/L	0 021		0 010	Y
46692	GW035251T	09/24/92	PLUTONIUM 239/240	0 07	PCI/L	0 027		0 007	A
46692	GW01674WC	12/09/93	PLUTONIUM 239/240	0 97	PCI/L	0 092		0 004	Y
46692	GW00315GA	02/23/94	PLUTONIUM 239/240	0 06	PCI/L	0 022		0 005	V
46792	GW00316GA	02/23/94	AMERICIUM 241	0 08	PCI/L	0 032		0 023	V
46792	GW01675WC	12/13/93	PLUTONIUM 239/240	0 04	PCI/L	0 016		0 013	Y
46792	GW00316GA	02/23/94	PLUTONIUM 239/240	0 53	PCI/L	0 098		0 008	V
46892	GW01428GA	09/14/94	AMERICIUM 241	0 08	PCI/L	0 068	UX	0 081	Y
46892	GW01676WC	12/14/93	PLUTONIUM 239/240	0 02	PCI/L	0 008		0 002	Y
46892	GW00317GA	02/24/94	PLUTONIUM 239/240	0 08	PCI/L	0 018		0 009	V
46892	GW01428GA	09/14/94	PLUTONIUM 239/240	0 48	PCI/L	0 080		0 021	Y
4886	GW003111T	08/30/90	AMERICIUM 241	0 06	PCI/L	0 023		0 000	
4886	GW01459GA	10/19/94	AMERICIUM 241	0 05	PCI/L	0 062	Y	0 098	Y
4886	GW003111T	08/30/90	CESIUM 137	0 61	PCI/L		U	0 600	A
4886	GW009211T	03/07/91	CESIUM 137	1 20	PCI/L	0 721	J	1 600	A
4886	GW031181T	07/28/92	PLUTONIUM 239/240	0 03	PCI/L	0 008	B	0 003	A
4886	GW005851T	10/26/90	TRITIUM	868 00	PCI/L	250 000	X	400 000	A
4886	GW003111T	08/30/90	URANIUM 235	0 24	PCI/L	0 165		0 000	
70293	GW01229GA	08/22/94	RADIUM 226	1 60	PCI/L	0 354		0 172	V
B203889	G33890390001	03/05/90	URANIUM 233 234	3 89	PCI/L	0 780		0 143	
B203889	G33890621021120	06/22/90	URANIUM 233 234	3 98	PCI/L	0 560		0 050	A
B203889	G33890390001	03/05/90	URANIUM 235	0 15	PCI/L	0 146		0 173	
B203889	G33890390001	03/05/90	URANIUM 238	0 95	PCI/L	0 375		0 143	
B203889	G33890621021120	06/22/90	URANIUM 238	1 02	PCI/L	0 250		0 000	A

Attachment B

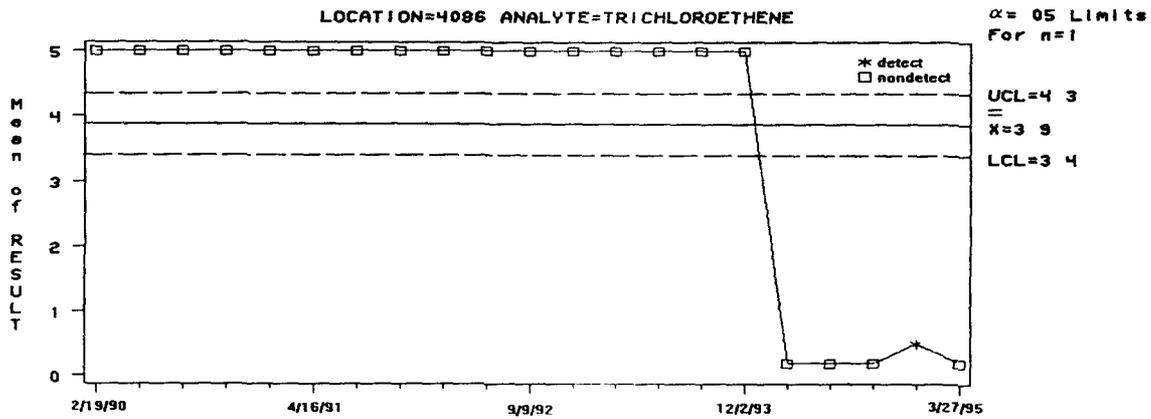
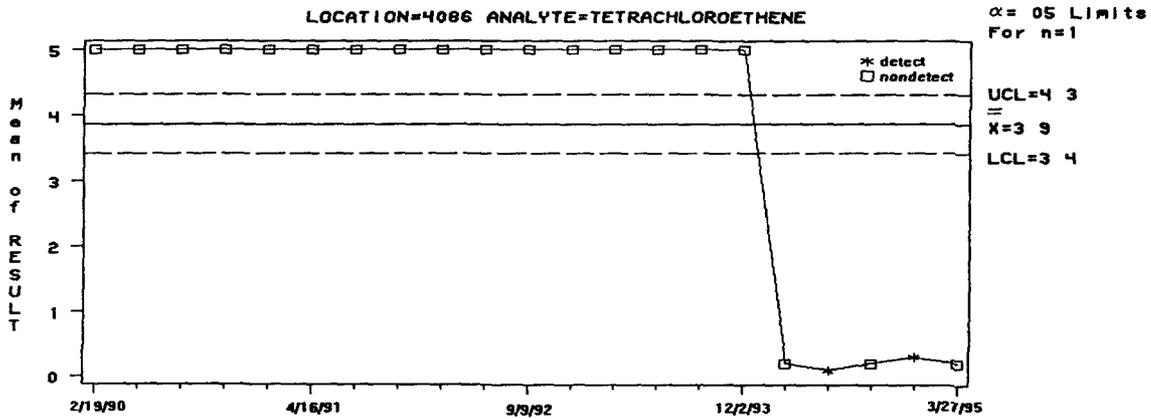
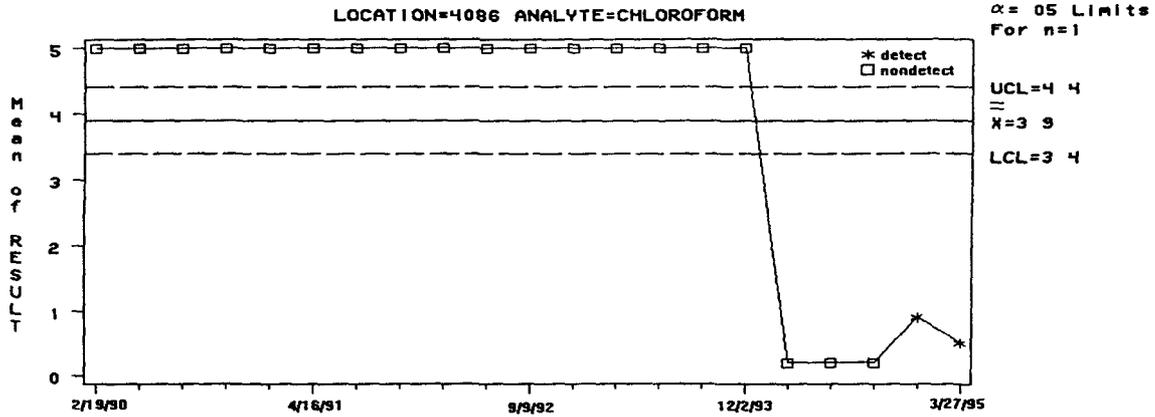
Total Radionuclides > Background Mean +2SD in LHSUGroundwater

LOCATION	SAMPLE	SDATE	ANALYTE	RESULT	UNITS	ERROR	QUAL	DETECT	VAL
B204189	GW00306WC	03/22/93	AMERICIUM 241	0 47	PCI/L	0 076		0 046	A
B204189	GW00310IT	09/05/90	CESIUM 137	0 63	PCI/L		U	0 650	A
B204189	G36890618020945	06/19/90	GROSS ALPHA	44 90	PCI/L	13 000		8 000	A
B204189	G36890618020945	06/19/90	GROSS BETA	39 20	PCI/L	10 800		11 300	A
B204189	GW00306WC	03/22/93	PLUTONIUM 239/240	10 32	PCI/L	0 140		0 008	A
B206289	LF0389BR0531021010	06/01/90	CESIUM 137	0 88	PCI/L	0 440		0 590	A
B206289	LF0389BR0531021010	06/01/90	STRONTIUM 89 90	1 00	PCI/L	0 320		0 380	A
B206289	GLF03890390001	03/09/90	URANIUM 233 234	32 89	PCI/L	4 320		0 170	A
B206289	GW00204IT	08/07/90	URANIUM 233 234	3 49	PCI/L	0 660			
B206289	GLF03890390001	03/09/90	URANIUM 235	0 94	PCI/L	0 460		0 080	A
B206289	LF0389BR0531021010	06/01/90	URANIUM 235	0 11	PCI/L	0 160		0 000	A
B206289	GW00204IT	08/07/90	URANIUM 235	0 38	PCI/L	0 193			
B206289	GLF03890390001	03/09/90	URANIUM 238	21 11	PCI/L	3 040		0 130	A
B206289	GW00204IT	08/07/90	URANIUM 238	0 89	PCI/L	0 296			
B207089	GW01927GA	01/11/95	PLUTONIUM 239/240	0 03	PCI/L	0 013		0 010	V
B207089	GW00236IT	08/15/90	URANIUM 233 234	4 25	PCI/L	1 020		0 000	
B207089	GW00236IT	08/15/90	URANIUM 235	0 35	PCI/L	0 330		0 000	
B207089	GW00236IT	08/15/90	URANIUM 238	1 58	PCI/L	0 570		0 000	
B217789	GW00452WC	03/21/93	AMERICIUM 241	0 04	PCI/L	0 024		0 030	A
B217789	GW00452WC	03/21/93	PLUTONIUM 239/240	0 14	PCI/L	0 028		0 010	A
B304289	GW03402IT	09/11/92	AMERICIUM 241	0 10	PCI/L	0 025		0 000	A
B304289	GW03402IT	09/11/92	PLUTONIUM 239/240	0 05	PCI/L	0 020		0 000	A
B304289	G37890190001	01/24/90	URANIUM 235	0 08	PCI/L	0 090		0 000	A
B304989	GW00212IT	08/17/90	CESIUM 137	0 61	PCI/L		U	0 000	
B304989	GW00425WC	03/21/93	PLUTONIUM 239/240	0 03	PCI/L	0 011		0 006	A
B304989	GW00212IT	08/17/90	TRITIUM	1350 00	PCI/L	250 000		0 000	
B405289	G43890190001	01/31/90	GROSS ALPHA	51 60	PCI/L	7 000		4 300	V
P208889	GW00237IT	08/16/90	URANIUM 235	0 16	PCI/L	0 240		0 000	
P416989	GW01701GA	10/31/94	URANIUM 235	0 19	PCI/L	0 183		0 173	Y

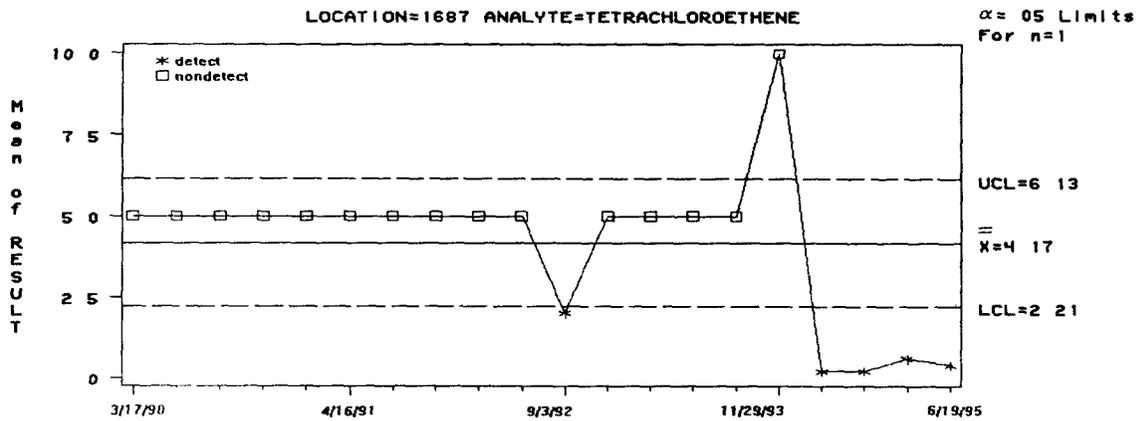
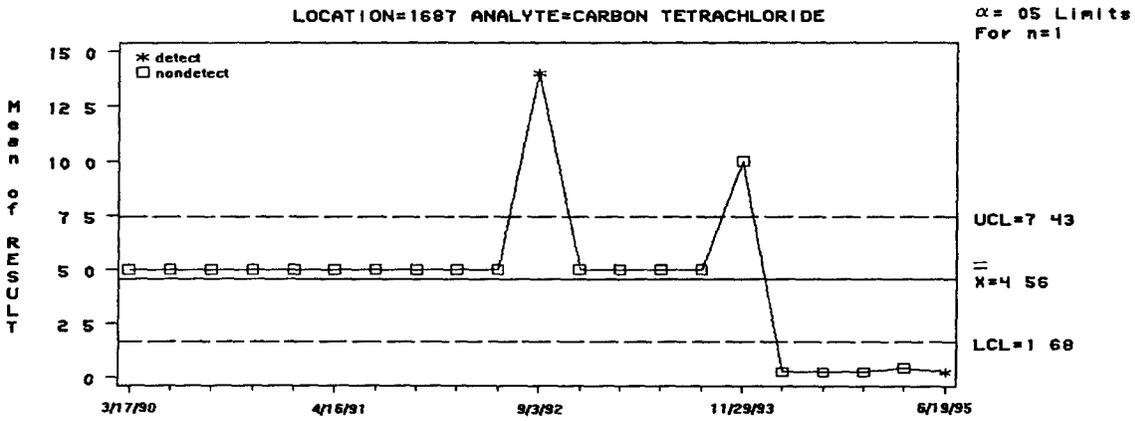
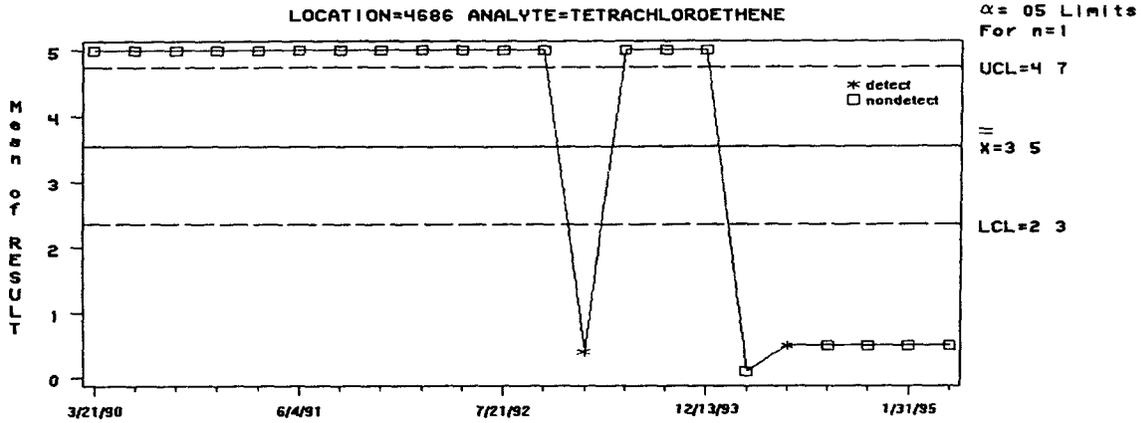
Appendix C

Shewhart Control Charts and Time-Series Plots for Selected LHSU Groundwater Monitoring Wells With Detectable VOC and Radionuclide Contaminants (excluding laboratory-related contaminants)

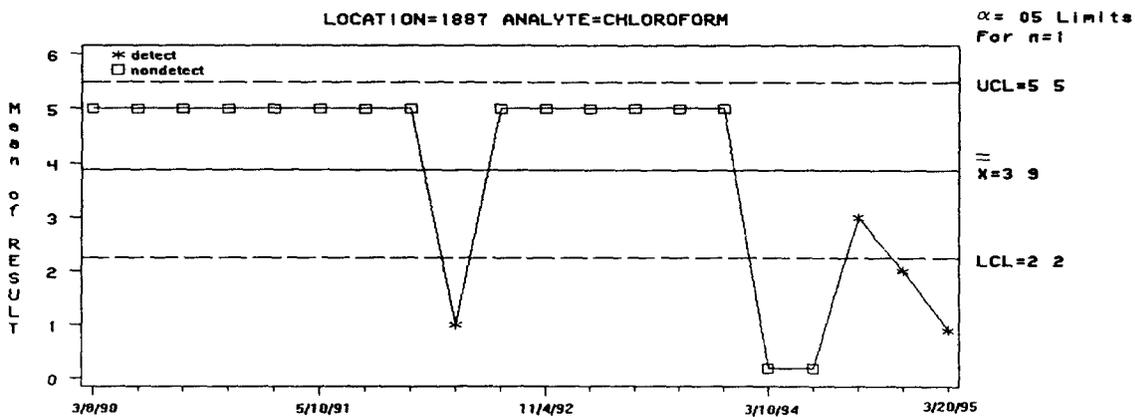
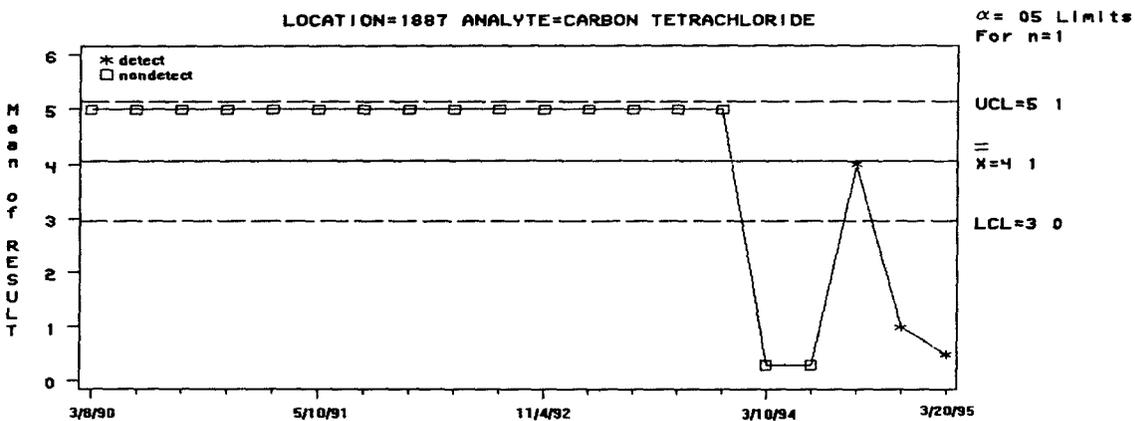
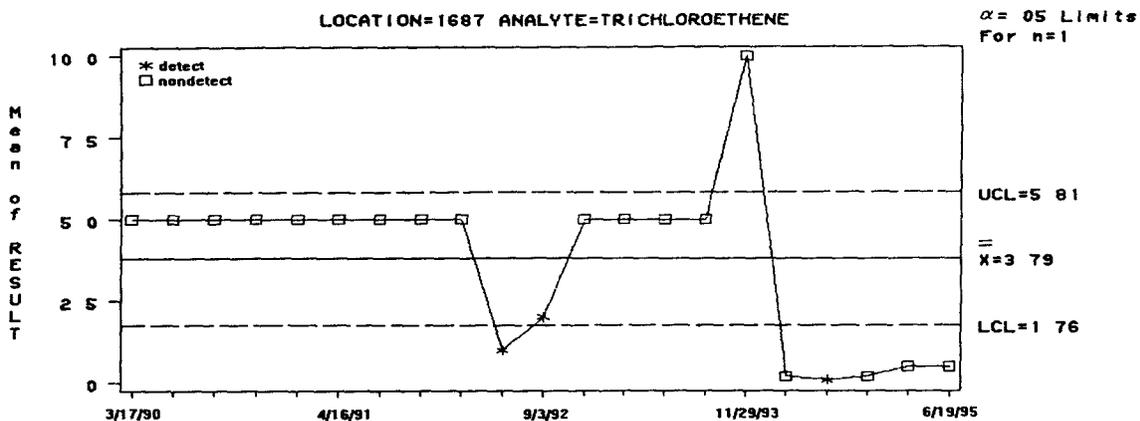
Attachment C



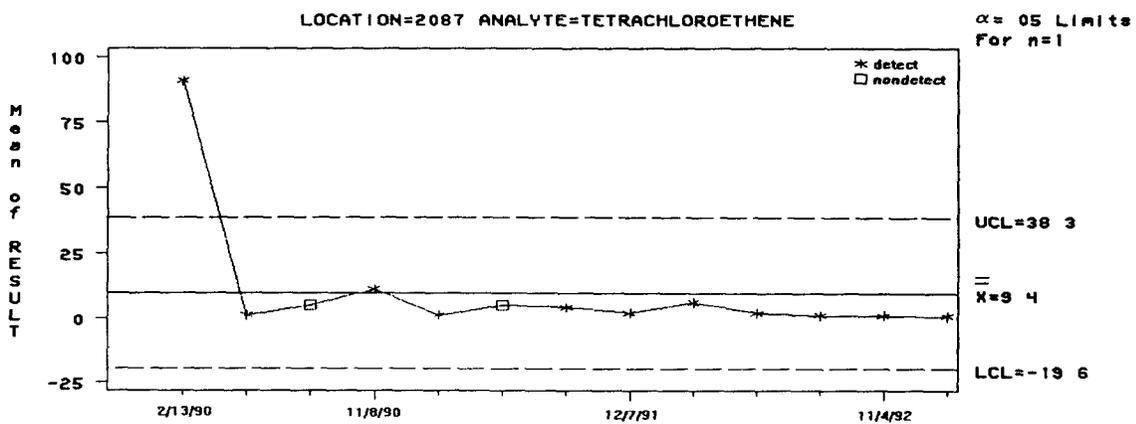
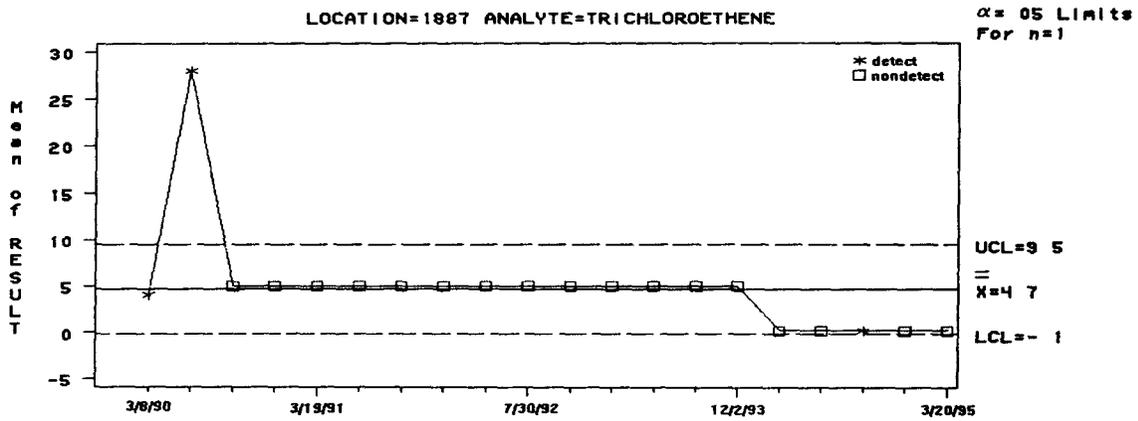
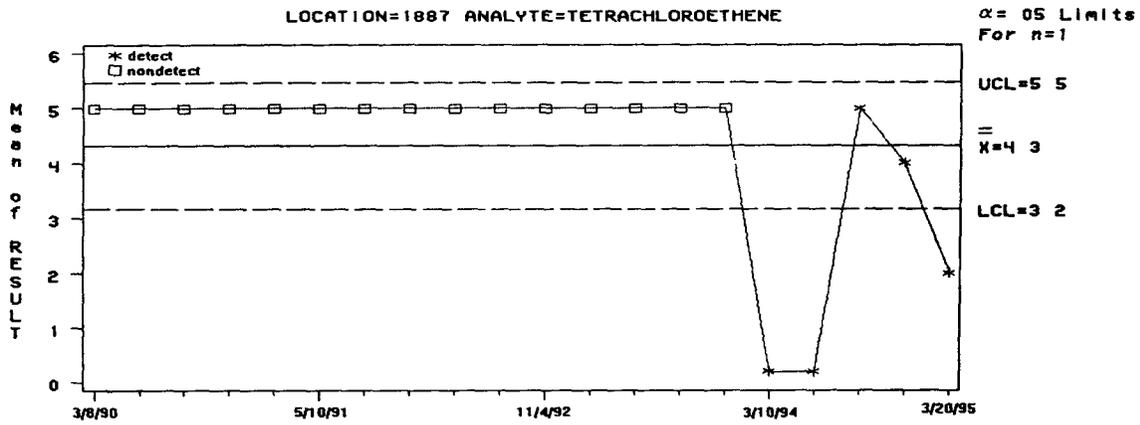
Attachment C



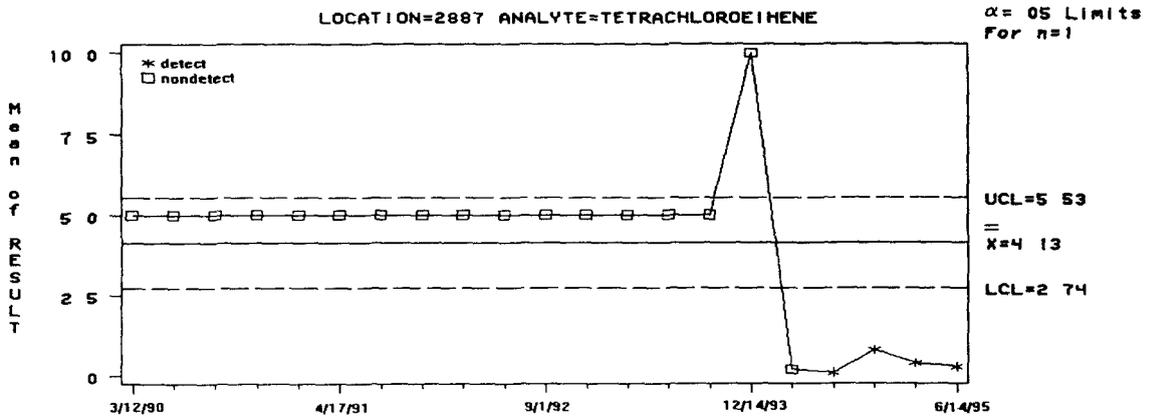
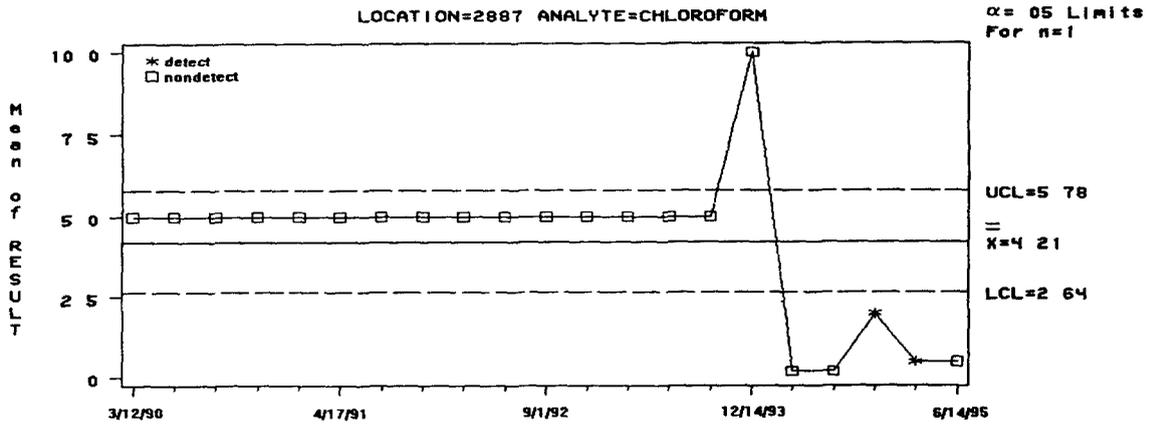
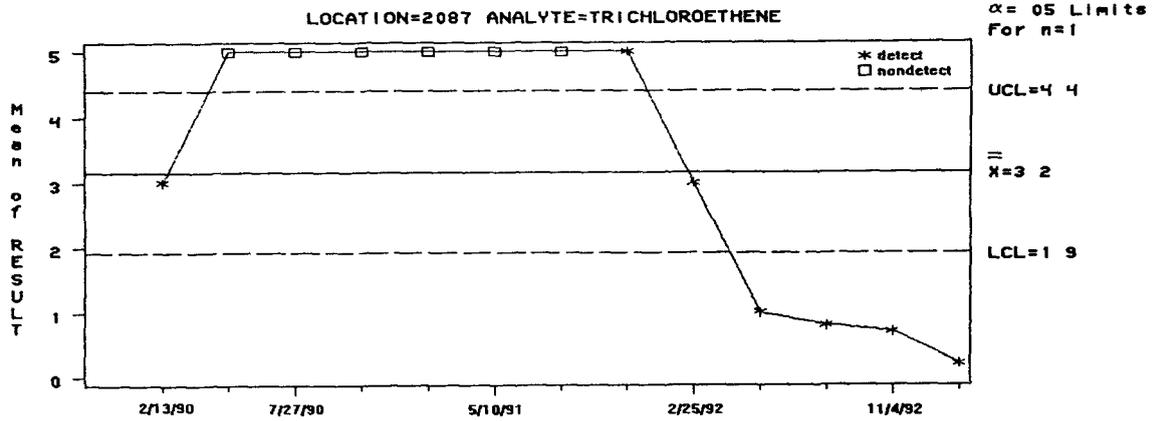
Attachment C



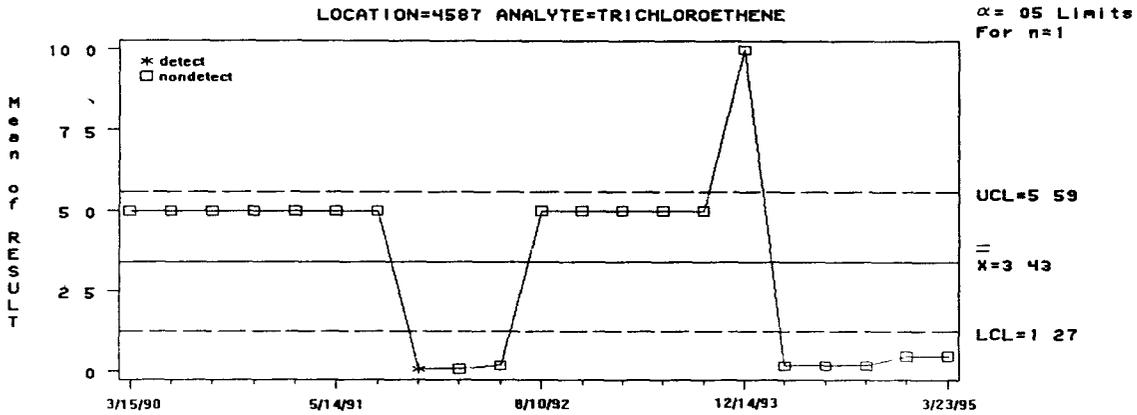
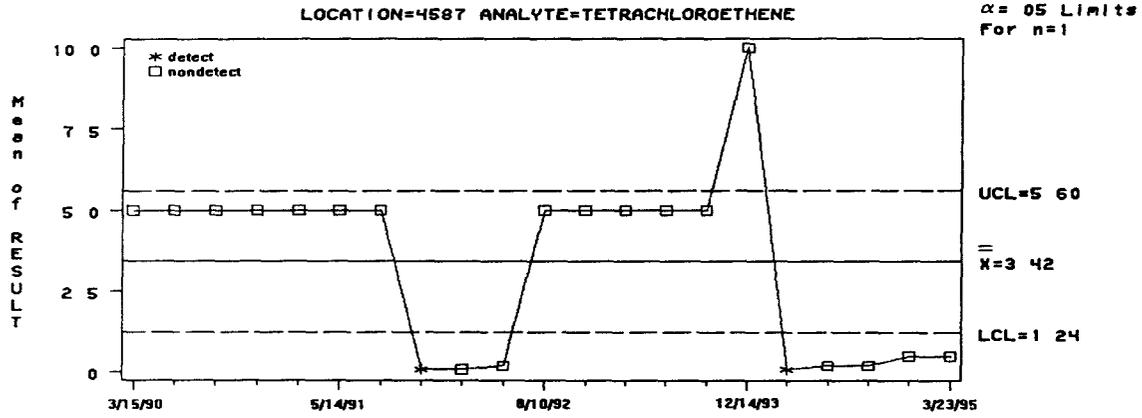
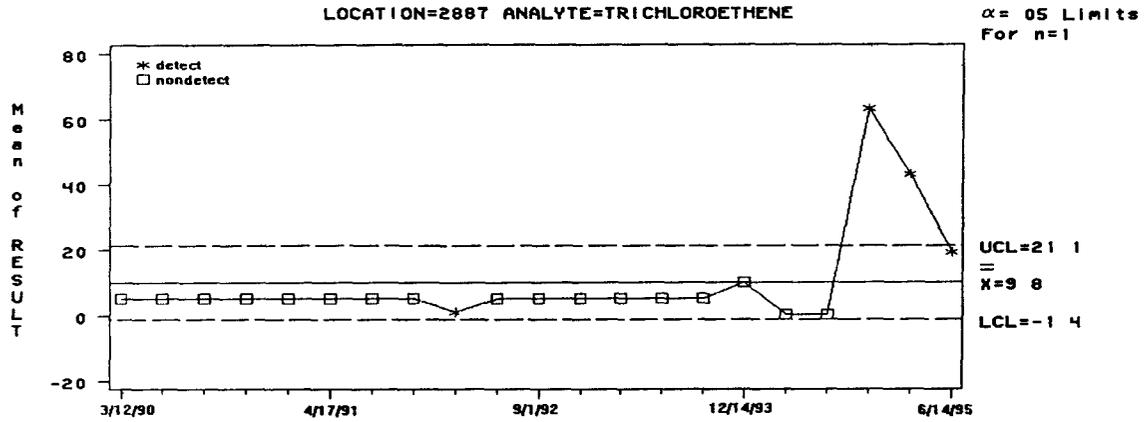
Attachment C



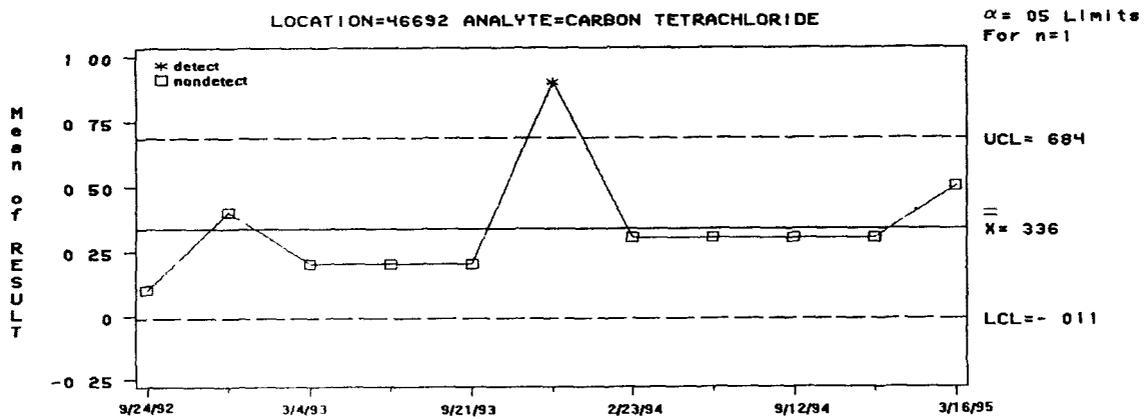
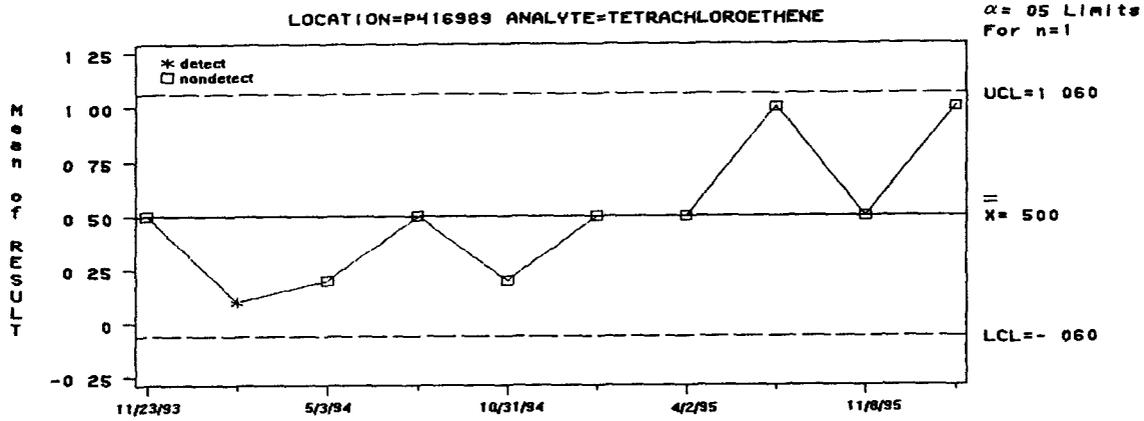
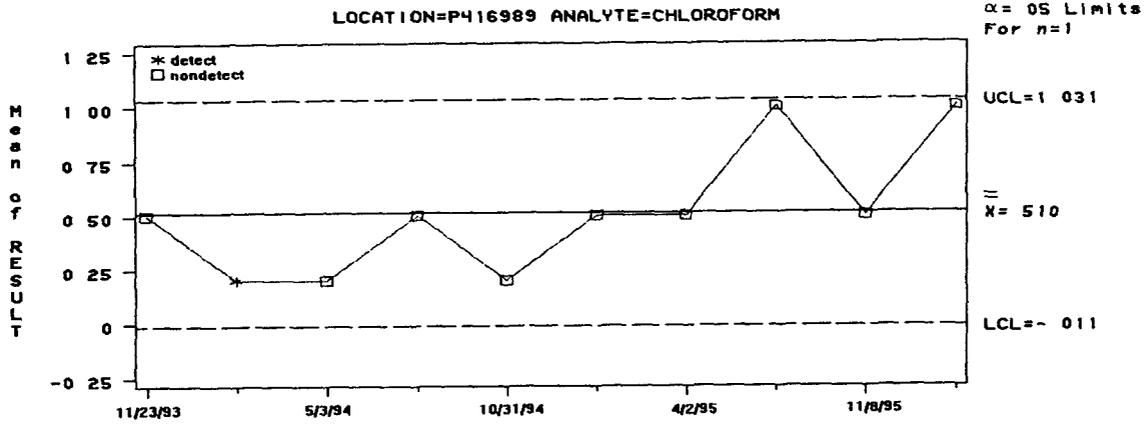
Attachment C



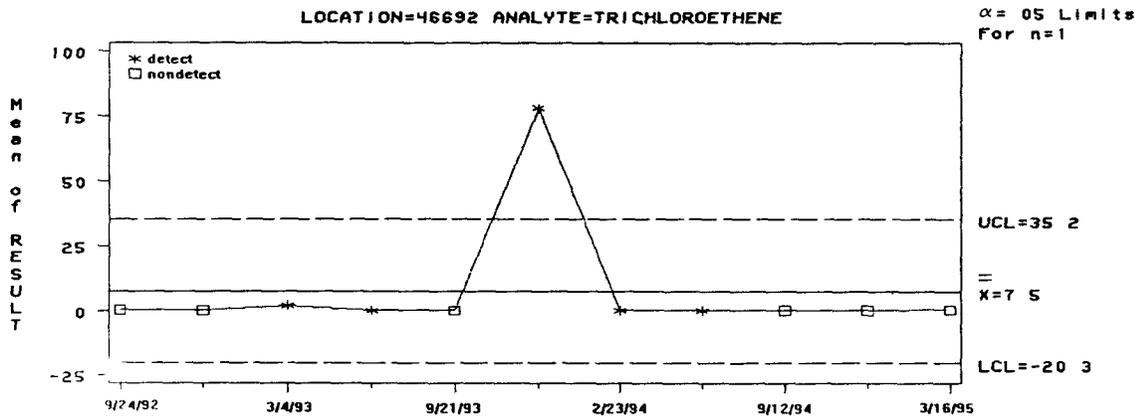
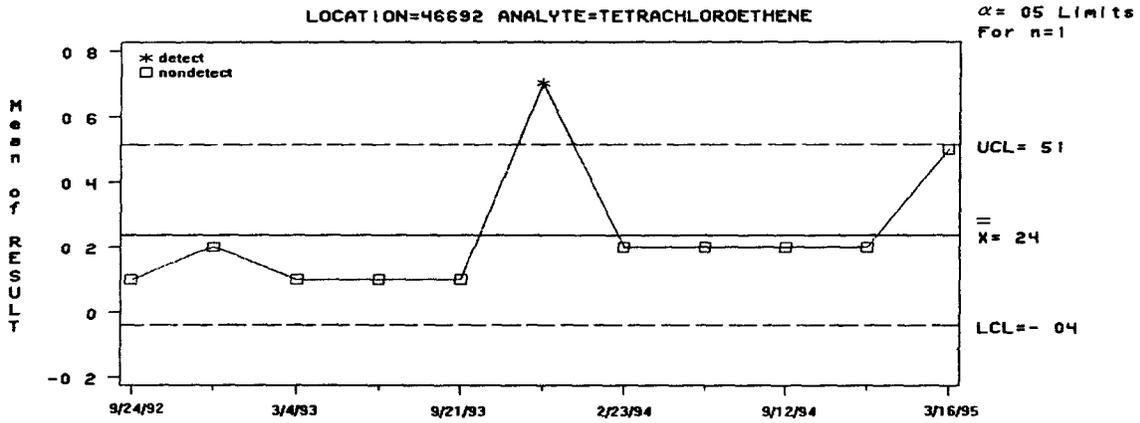
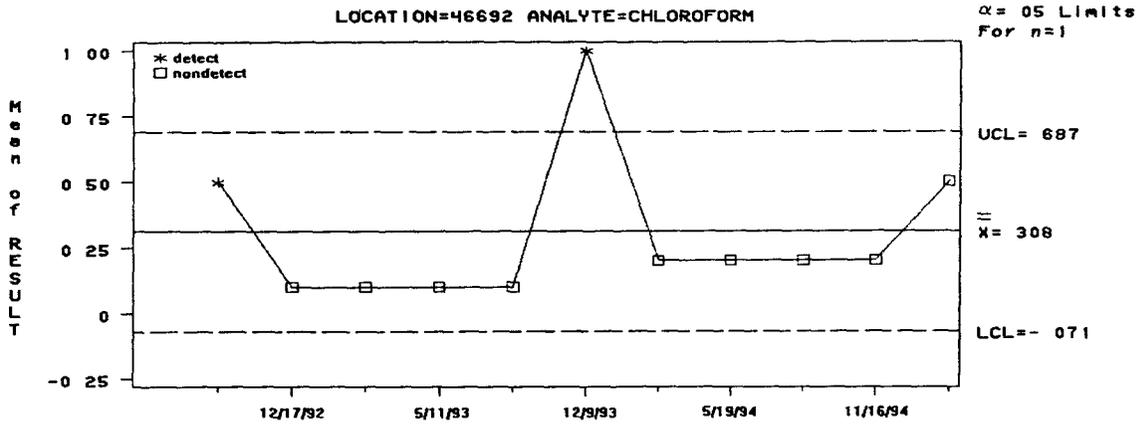
Attachment C



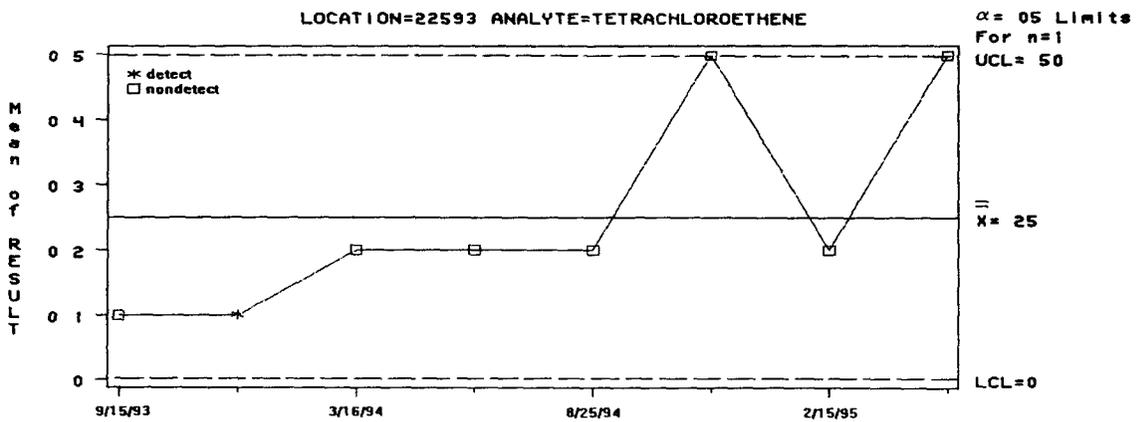
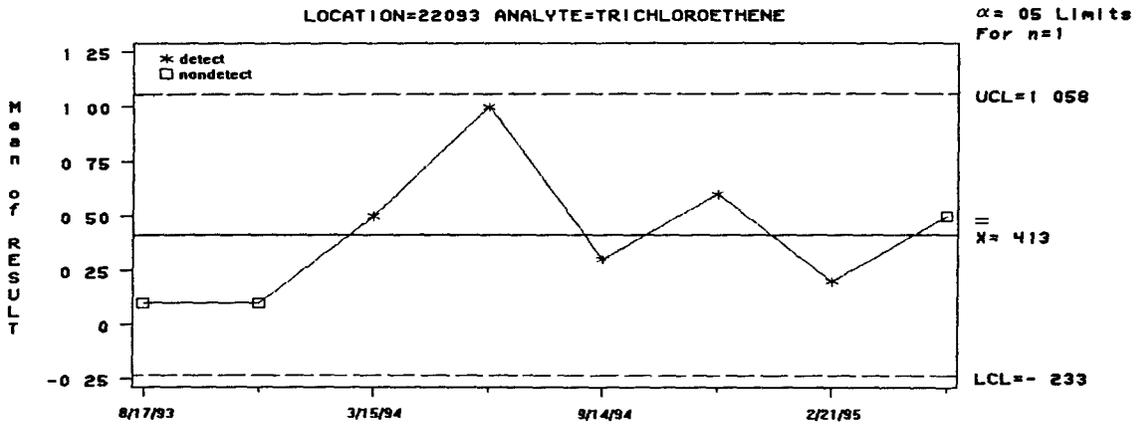
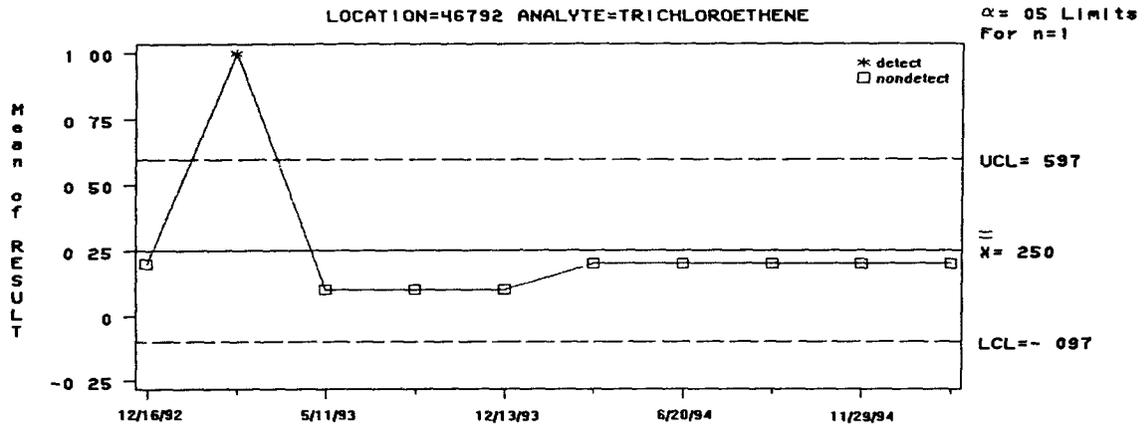
Attachment C



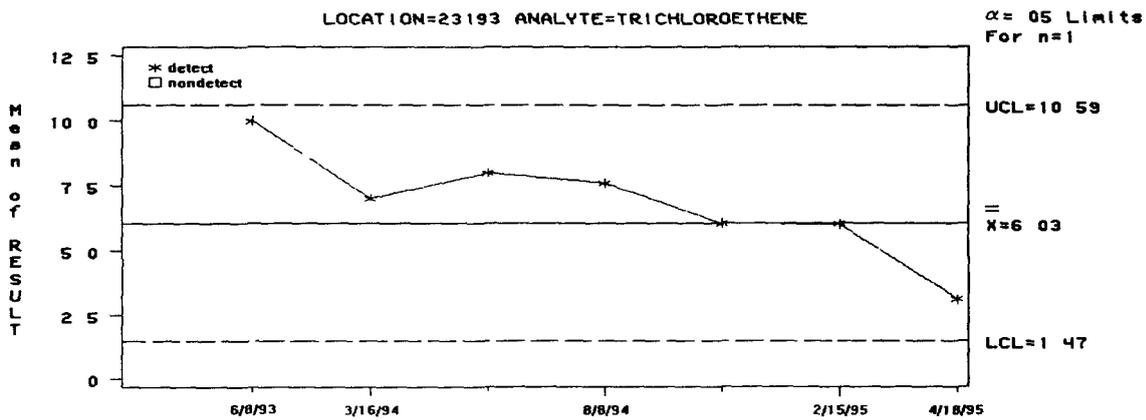
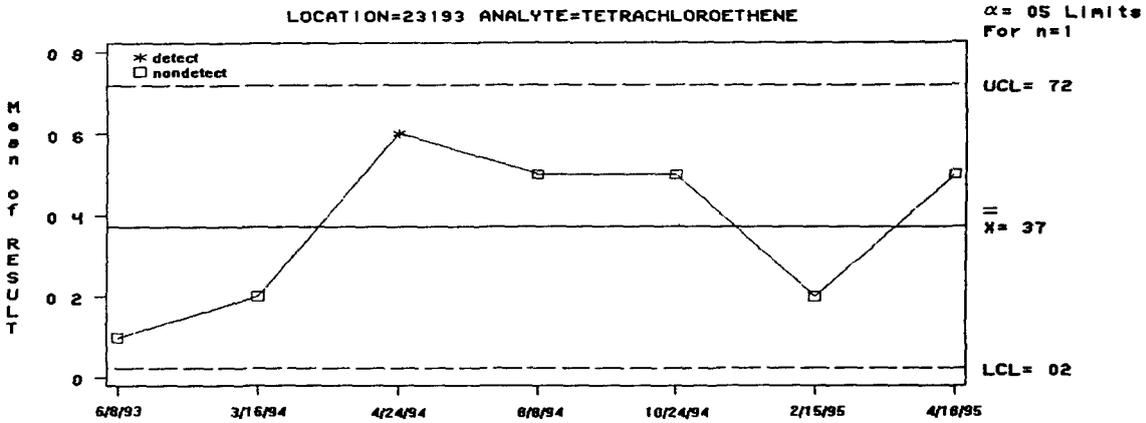
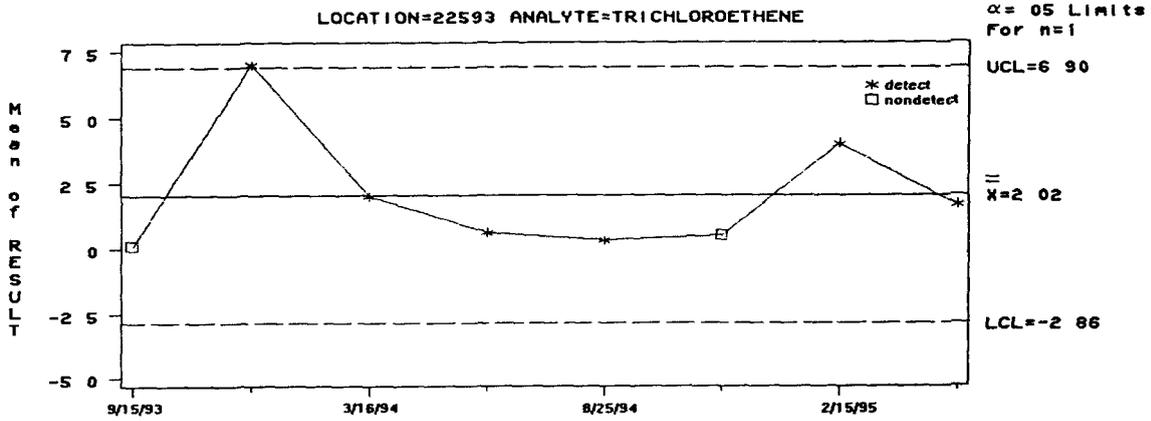
Attachment C



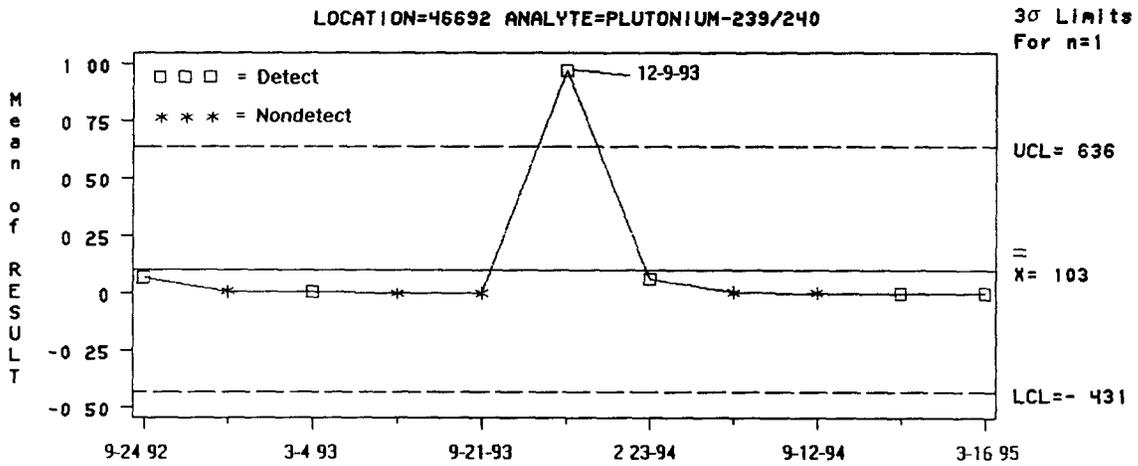
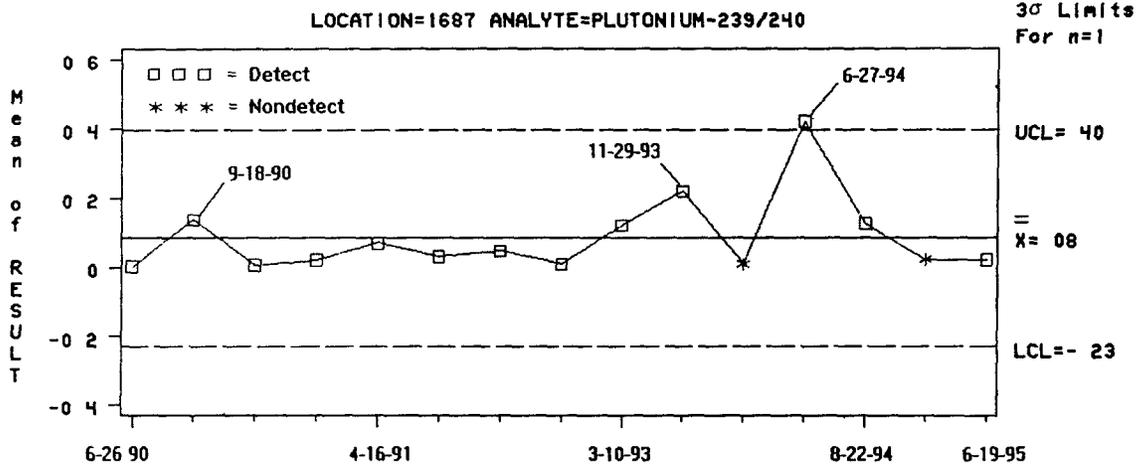
Attachment C



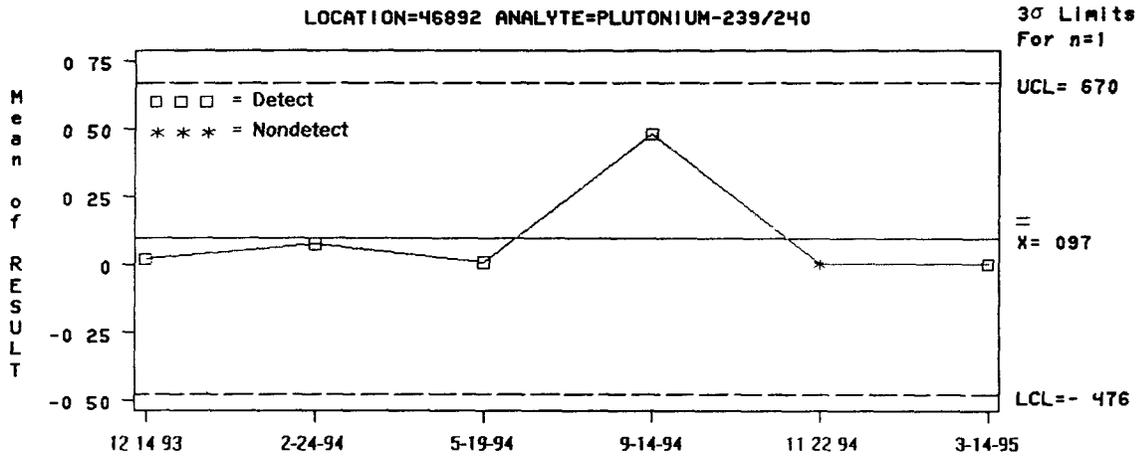
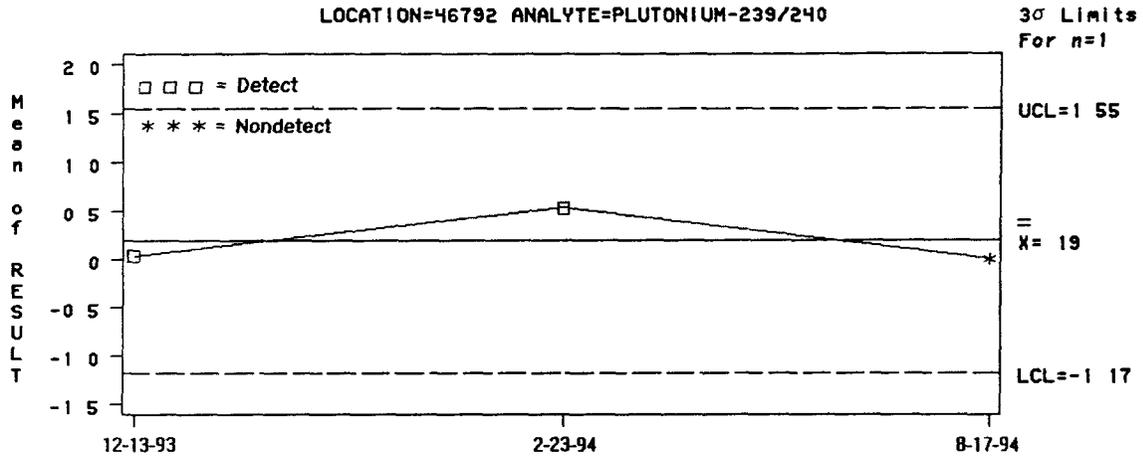
Attachment C



Attachment C



Attachment C



CTET

A) Consider a NAPL pool (Carbon Tetrachloride) 100 ft by 100 ft as a source in the UHSU. Evaluate 1-D (downward) transport to the Laramie Fox Hills Aquifer considering retardation, transverse dispersion, and longitudinal dispersion under the condition of steady uniform flow. The rate of mass release on this plane is constant and equal to pure phase aqueous solubility multiplied by the source area and Darcy flux.

B) Input Parameters

General $\phi = 0.222$ $\alpha_L = 1 \text{ m}$ $\alpha_T = 0.1 \text{ m}$ $L_2 = 50 \text{ ft}$ $L_3 = 50 \text{ ft}$

CTET Specific $R = 43.16 \frac{\text{cm}}{\text{cm}}$ $\mu = 0.00 \text{ yr}^{-1}$ $\rho_s = 798 \frac{\text{mg}}{\text{liter}}$ $D_e = 1.42 \cdot 10^{-6} \frac{\text{cm}^2}{\text{sec}}$

C) Simplifying Calculations

$$D_L(V_1) = V_1 \alpha_L + D_e$$

$$D_T(V_1) = V_1 \alpha_T + D_e$$

D) Governing Equations

$$f_1(x_1, t, V_1) = \frac{1}{2 \left(\frac{\pi D_L(V_1) t}{R} \right)^{\frac{1}{2}}} \exp \left[\frac{\left(x_1 - \frac{V_1 t}{R} \right)^2}{4 D_L(V_1) \frac{t}{R}} - \mu t \right]$$

$$F_2(x_2, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_2 + L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{x_2 - L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] \right]$$

$$F_3(x_3, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_3 + L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{x_3 - L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] \right]$$

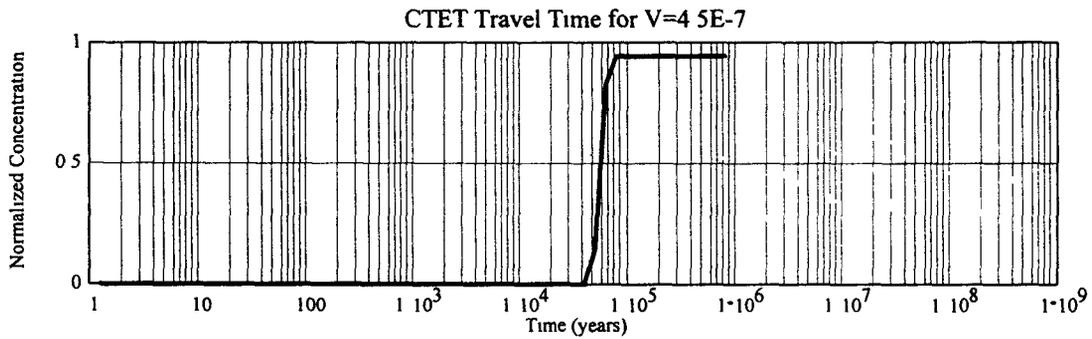
$$\rho\rho_0(x_1, x_2, x_3, t, V_1) = \frac{V_1}{R} \int_{0 \text{ sec}}^{t - 1 \text{ day}} f_1(x_1, t - \tau, V_1) F_2(x_2, t - \tau, V_1) F_3(x_3, t - \tau, V_1) d\tau$$

$$\rho\rho_0 \left(x_1, 0 \text{ m}, 0 \text{ m}, t_j, 4.5 \cdot 10^{-7} \frac{\text{cm}}{\text{sec}} \right)$$

E) Calculations

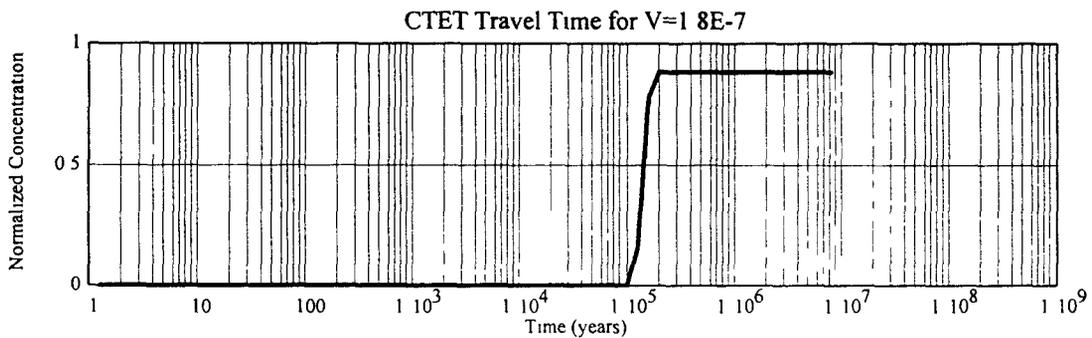
$$x_1 = 600 \text{ ft} \quad N = 59$$

$$J = 1 \text{ N} \quad t_j = 10^{01} \text{ yr}$$



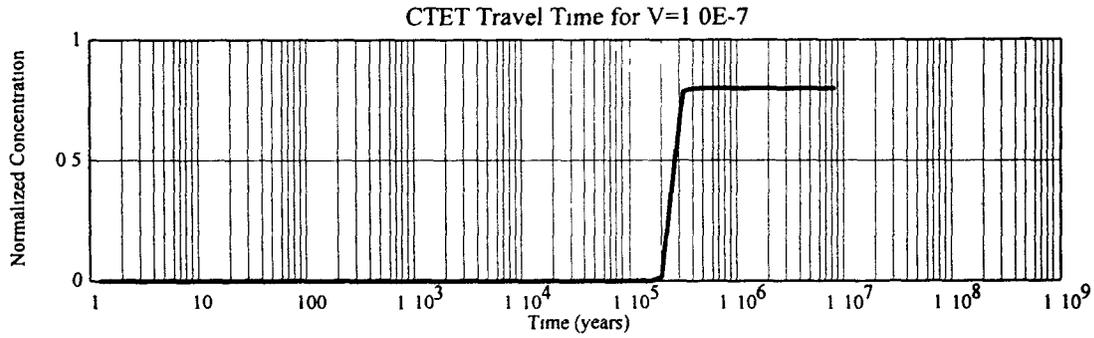
$$x_1 = 600 \text{ ft} \quad N = 69$$

$$J = 1 \text{ N} \quad t_j = 10^{01} \text{ yr}$$



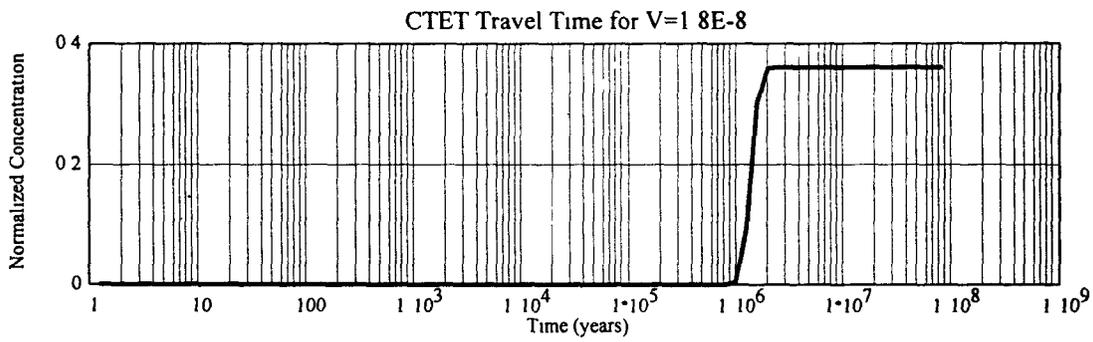
$x_1 = 600$ ft $N = 69$

$J = 1$ N $t_j = 10^{0.1}$ yr



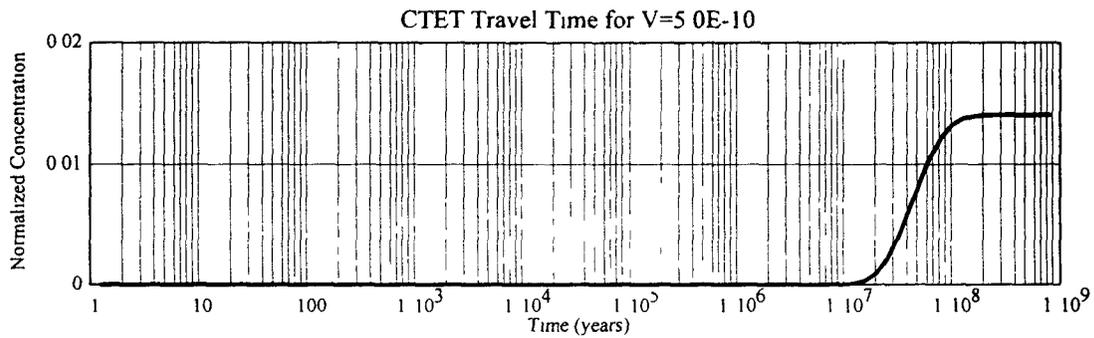
$x_1 = 600$ ft $N = 79$

$J = 1$ N $t_j = 10^{0.1}$ yr



$x_1 = 600$ ft $N = 89$

$J = 1$ N $t_j = 10^{0.1}$ yr



TCE

A) Consider a NAPL pool (Trichloroethene) 100 ft by 100 ft as a source in the UHSU. Evaluate 1-D (downward) transport to the Laramie Fox Hills Aquifer considering retardation, transverse dispersion, and longitudinal dispersion under the condition of steady uniform flow. The rate of mass release on this plane is constant and equal to pure phase aqueous solubility multiplied by the source area and Darcy flux.

B) Input Parameters

General $\phi = 0.222$ $\alpha_L = 1 \text{ m}$ $\alpha_T = 0.1 \text{ m}$ $L_2 = 50 \text{ ft}$ $L_3 = 50 \text{ ft}$

TCE Specific $R = 13.12 \frac{\text{cm}}{\text{cm}}$ $\mu = 0.00 \text{ yr}^{-1}$ $D_e = 1.48 \cdot 10^{-6} \frac{\text{cm}^2}{\text{sec}}$

C) Simplifying Calculations

$$D_L(V_1) = V_1 \alpha_L + D_e$$

$$D_T(V_1) = V_1 \alpha_T + D_e$$

D) Governing Equations

$$f_1(x_1, t, V_1) = \frac{1}{2 \left(\frac{\pi D_L(V_1) t}{R} \right)^{\frac{1}{2}}} \exp \left[\frac{\left(x_1 - \frac{V_1 t}{R} \right)^2}{4 D_L(V_1) \frac{t}{R}} - \mu t \right]$$

$$F_2(x_2, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_2 + L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{x_2 - L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] \right]$$

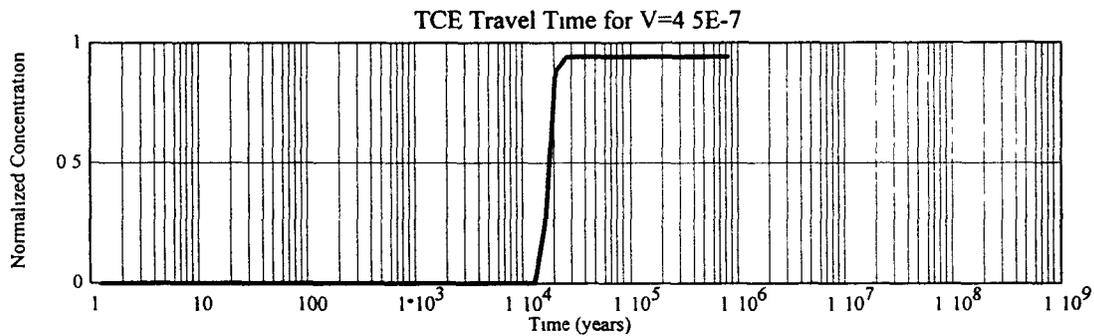
$$F_3(x_3, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_3 + L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{1/2}} \right] - \operatorname{erf} \left[\frac{x_3 - L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{1/2}} \right] \right]$$

$$pp_o(x_1, x_2, x_3, t, V_1) = \frac{V_1}{R} \int_{0 \text{ sec}}^{t - 1 \text{ day}} f_1(x_1, t - \tau, V_1) F_2(x_2, t - \tau, V_1) F_3(x_3, t - \tau, V_1) d\tau$$

E) Calculations

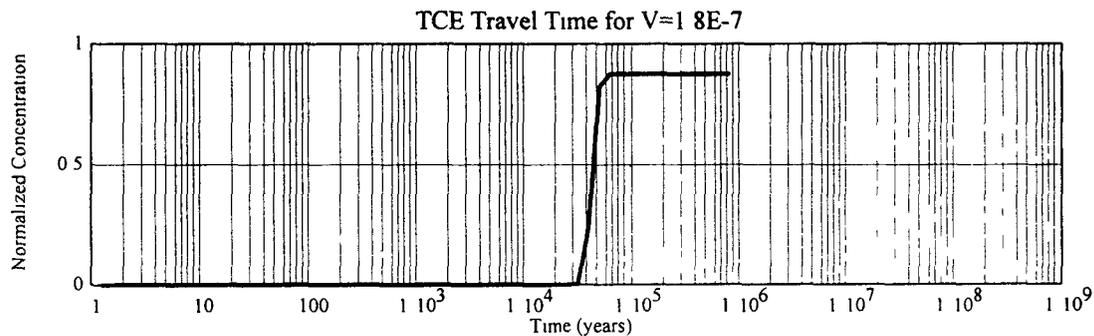
$$x_1 = 600 \text{ ft} \quad N = 59$$

$$j = 1 \quad N \quad t_j = 10^{0.01} \text{ yr}$$



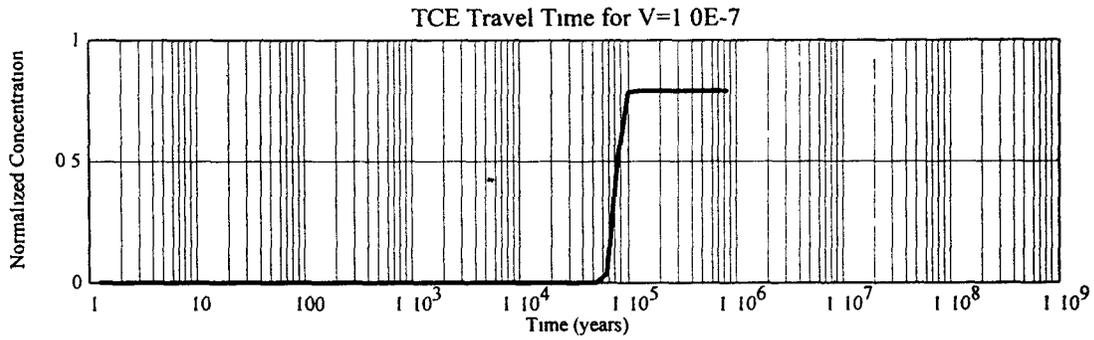
$$x_1 = 600 \text{ ft} \quad N = 59$$

$$j = 1 \quad N \quad t_j = 10^{0.01} \text{ yr}$$



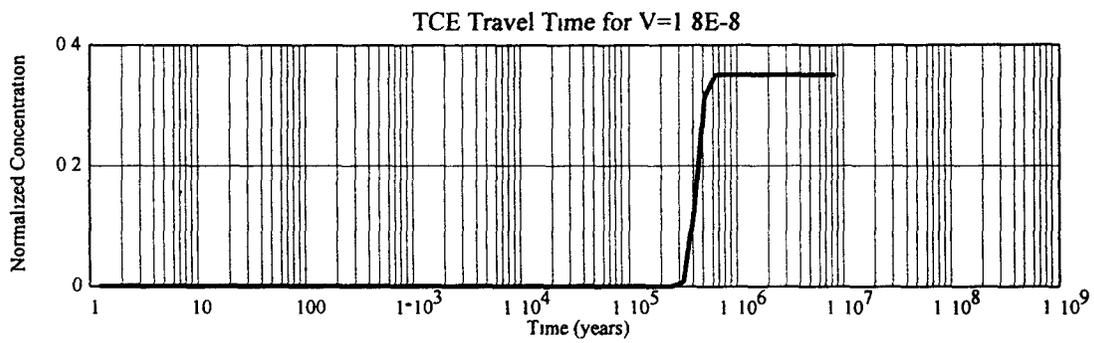
$x_1 = 600$ ft $N = 59$

$J = 1$ N $t_j = 10^{0.1}$ yr



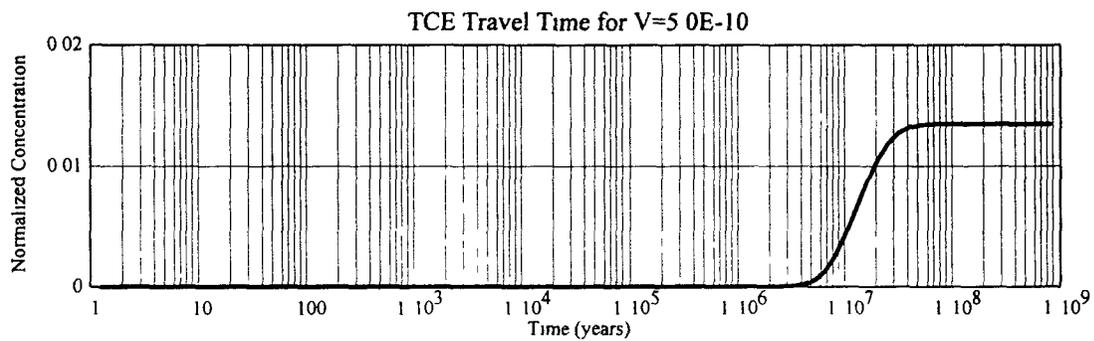
$x_1 = 600$ ft $N = 69$

$J = 1$ N $t_j = 10^{0.1}$ yr



$x_1 = 600$ ft $N = 89$

$J = 1$ N $t_j = 10^{0.1}$ yr



PCE

A) Consider a NAPL pool (Tetrachloroethylene) 100 ft by 100 ft as a source in the UHSU. Evaluate 1-D (downward) transport to the Laramie Fox Hills Aquifer considering retardation, transverse dispersion and longitudinal dispersion under the condition of steady uniform flow. The rate of mass release on this plane is constant and equal to pure phase aqueous solubility multiplied by the source area and Darcy flux.

B) Input Parameters

General $\phi = 0.222$ $\alpha_L = 1 \text{ m}$ $\alpha_T = 0.1 \text{ m}$ $L_2 = 50 \text{ ft}$ $L_3 = 50 \text{ ft}$

TCE Specific $R = 35.96 \frac{\text{cm}}{\text{cm}}$ $\mu = 0.00 \text{ yr}^{-1}$ $D_e = 1.36 \cdot 10^{-6} \frac{\text{cm}^2}{\text{sec}}$

C) Simplifying Calculations

$$D_L(V_1) = V_1 \alpha_L + D_e$$

$$D_T(V_1) = V_1 \alpha_T + D_e$$

D) Governing Equations

$$f_1(x_1, t, V_1) = \frac{1}{2 \left(\frac{\pi D_L(V_1) t}{R} \right)^{\frac{1}{2}}} \exp \left[\frac{\left(x_1 - \frac{V_1 t}{R} \right)^2}{4 D_L(V_1) \frac{t}{R}} - \mu t \right]$$

$$F_2(x_2, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_2 + L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{x_2 - L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] \right]$$

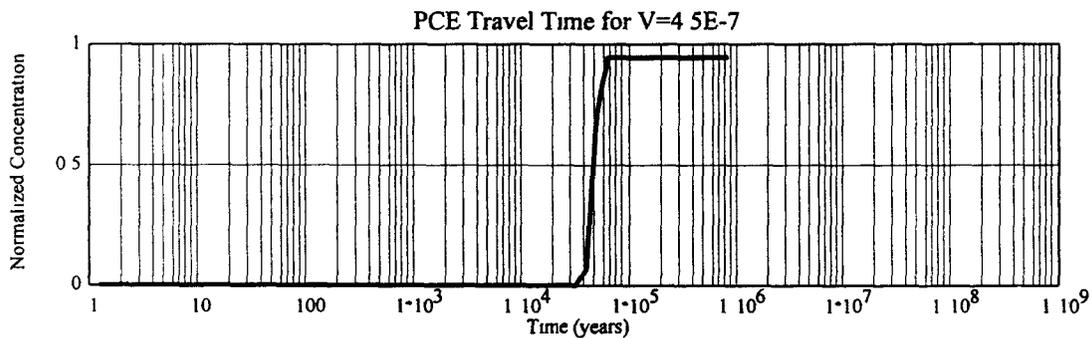
$$F_3(x_3, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_3 + L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{1/2}} \right] - \operatorname{erf} \left[\frac{x_3 - L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{1/2}} \right] \right]$$

$$pp_o(x_1, x_2, x_3, t, V_1) = \frac{V_1}{R} \int_{0 \text{ sec}}^{t - 1 \text{ day}} f_1(x_1, t - \tau, V_1) F_2(x_2, t - \tau, V_1) F_3(x_3, t - \tau, V_1) d\tau$$

E) Calculations

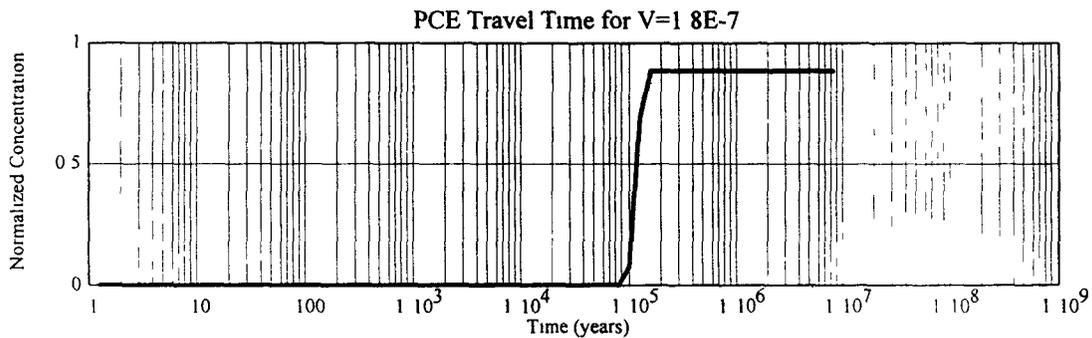
$$x_1 = 600 \text{ ft} \quad N = 59$$

$$J = 1 \text{ N} \quad t_j = 10^{01} \text{ yr}$$



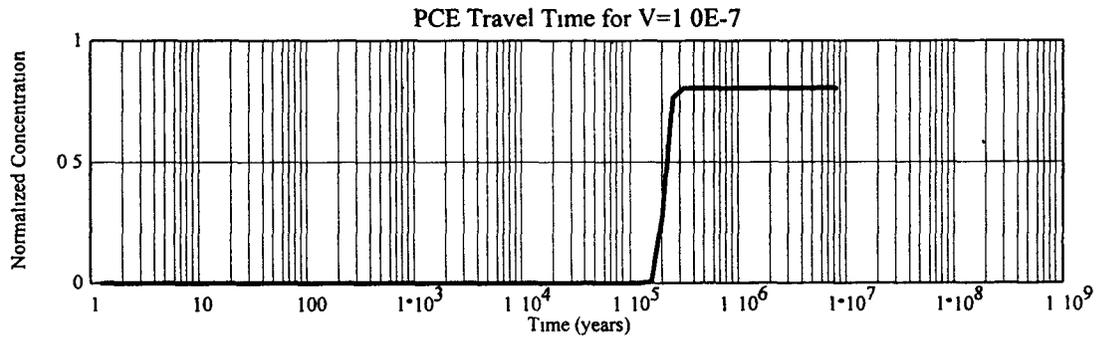
$$x_1 = 600 \text{ ft} \quad N = 69$$

$$J = 1 \text{ N} \quad t_j = 10^{01} \text{ yr}$$



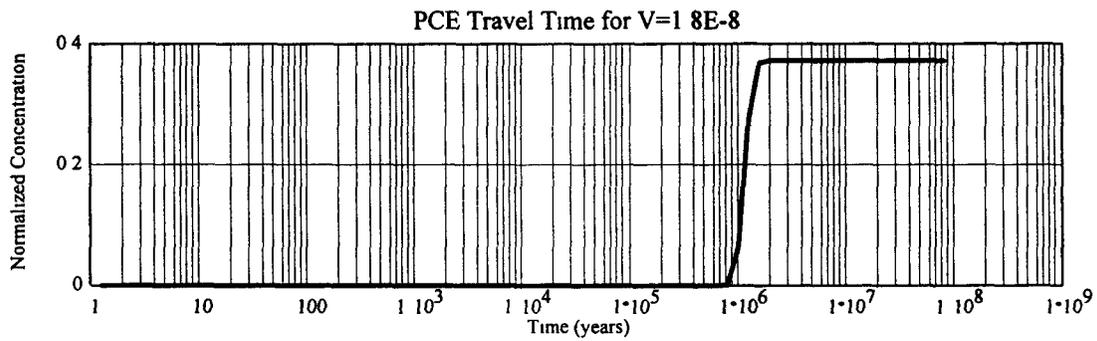
$x_1 = 600$ ft $N = 69$

$J = 1$ N $t_j = 10^{01}$ yr



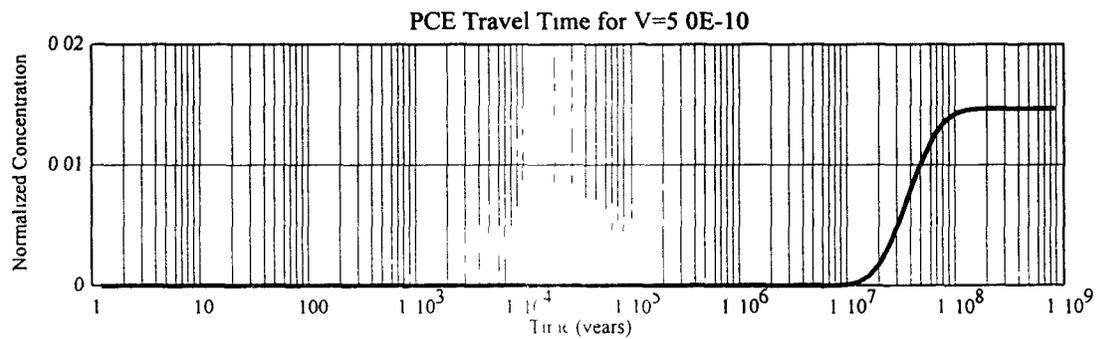
$x_1 = 600$ ft $N = 79$

$J = 1$ N $t_j = 10^{01}$ yr



$x_1 = 600$ ft $N = 89$

$J = 1$ N $t_j = 10^{01}$ yr



Consider PCE With a Conservative Half Life of 100 years

A) Consider a NAPL pool (Tetrachloroethylene) 100 ft by 100 ft as a source in the UHSU. Evaluate 1-D (downward) transport to the Laramie Fox Hills Aquifer considering retardation, transverse dispersion, and longitudinal dispersion under the condition of steady uniform flow. The rate of mass release on this plane is constant and equal to pure phase aqueous solubility multiplied by the source area and Darcy flux.

B) Input Parameters

General $\phi = 0.222$ $\alpha_L = 1 \text{ m}$ $\alpha_T = 0.1 \text{ m}$ $L_2 = 50 \text{ ft}$ $L_3 = 50 \text{ ft}$

TCE Specific $R = 35.96 \frac{\text{cm}}{\text{cm}}$ $\mu = 0.01 \text{ yr}^{-1}$ $D_e = 1.36 \cdot 10^{-6} \frac{\text{cm}^2}{\text{sec}}$

C) Simplifying Calculations

$$D_L(V_1) = V_1 \alpha_L + D_e$$

$$D_T(V_1) = V_1 \alpha_T + D_e$$

D) Governing Equations

$$f_1(x_1, t, V_1) = \frac{1}{2 \left(\frac{\pi D_L(V_1) t}{R} \right)^{\frac{1}{2}}} \exp \left[\frac{\left(x_1 - \frac{V_1 t}{R} \right)^2}{4 D_L(V_1) \frac{t}{R}} - \mu t \right]$$

$$F_2(x_2, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_2 + L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{x_2 - L_2}{2 \left(\frac{D_T(V_1) t}{R} \right)^{\frac{1}{2}}} \right] \right]$$

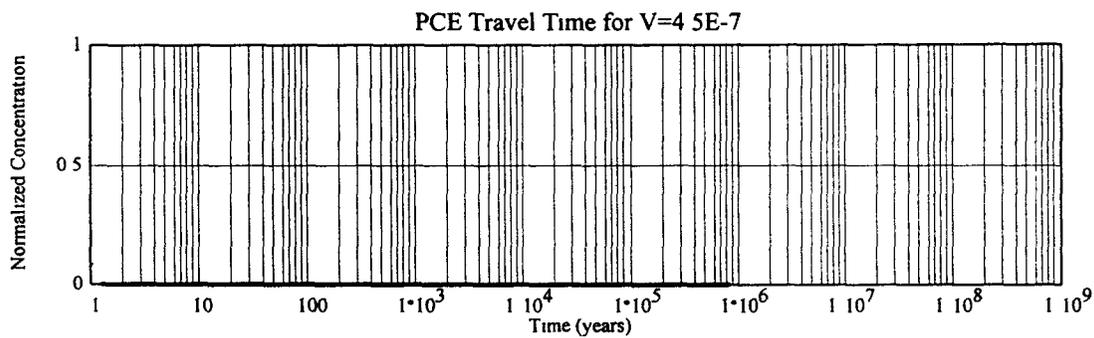
$$F_3(x_3, t, V_1) = \frac{1}{2} \left[\operatorname{erf} \left[\frac{x_3 + L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{1/2}} \right] - \operatorname{erf} \left[\frac{x_3 - L_3}{2 \left(\frac{D_T(V_1) t}{R} \right)^{1/2}} \right] \right]$$

$$pp_0(x_1, x_2, x_3, t, V_1) = \frac{V_1}{R} \int_{0 \text{ sec}}^{t - 1 \text{ day}} f_1(x_1, t - \tau, V_1) F_2(x_2, t - \tau, V_1) F_3(x_3, t - \tau, V_1) d\tau$$

E) Calculations

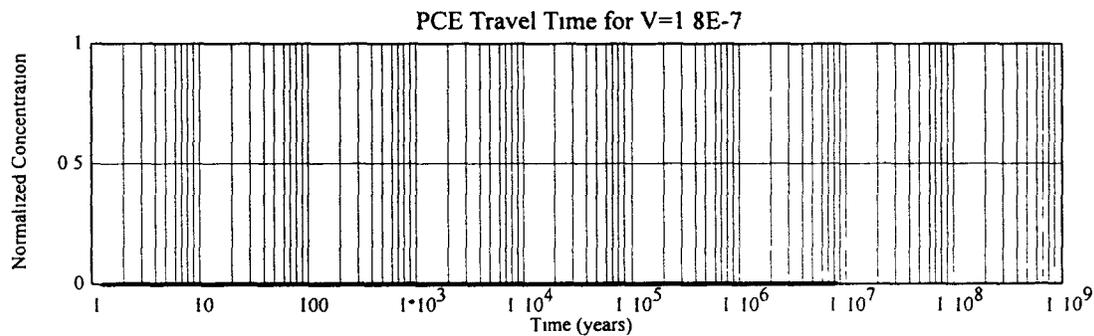
$$x_1 = 600 \text{ ft} \quad N = 59$$

$$j = 1 \text{ N} \quad t_j = 10^{0.1} \text{ yr}$$



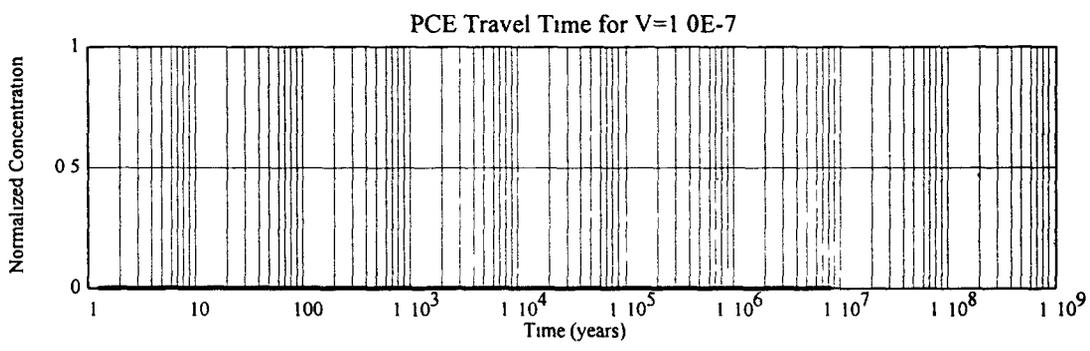
$$x_1 = 600 \text{ ft} \quad N = 69$$

$$j = 1 \text{ N} \quad t_j = 10^{0.1} \text{ yr}$$



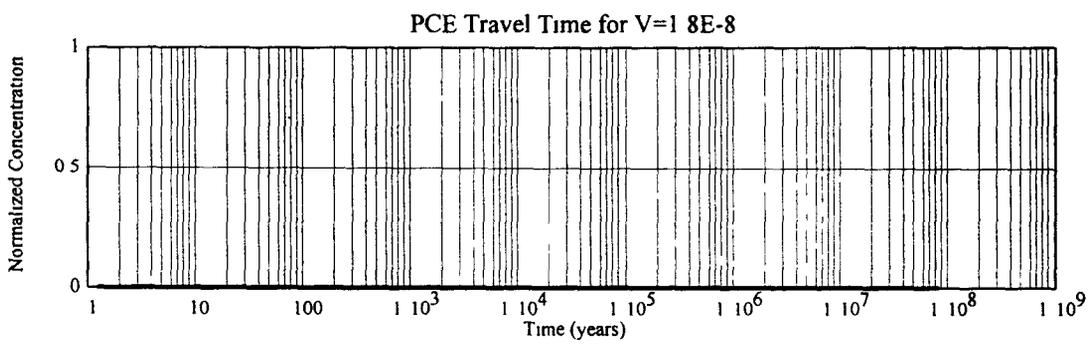
$x_1 = 600$ ft $N = 69$

$j = 1$ N $t_j = 10^{0.1}$ yr



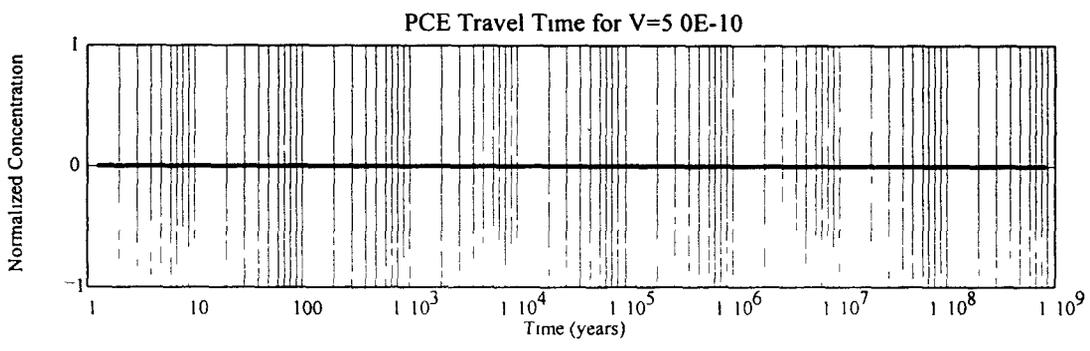
$x_1 = 600$ ft $N = 79$

$j = 1$ N $t_j = 10^{0.1}$ yr



$x_1 = 600$ ft $N = 89$

$j = 1$ N $t_j = 10^{0.1}$ yr



solids concentrations ranging from 200 to 714 mg/L (DOE, 1995b). With one exception, sulfate concentrations were less than 10 mg/L. These data were obtained in 1976 and showed an increase in concentration from west to east. The results are consistent with the results of Robson (1989). In addition, these wells, with the exception of the Wind Site well, were sampled and analyzed for Site-related radionuclides, including plutonium, uranium, and tritium. The results of testing indicated that there was no difference between up and downgradient water quality and that the wells were free of radionuclide contaminants (Illsley, 1976). The available water quality data indicate that the Laramie-Fox Hills aquifer in the Rocky Flats area is generally potable and suitable for most uses.

3 0 EVALUATION OF VERTICAL MIGRATION POTENTIAL

3 1 Conceptual Model Basis and Assumptions

The analytical methods chosen for evaluating contaminant migration through aquifers and confining layers at the Site are based on simple, one-dimensional concepts which are capable of approximating, within reasonable limits, the transport and fate of DNAPLs and dissolved organic contaminants in saturated geologic media. In certain respects, the utilization of one-dimensional techniques imparts a somewhat conservative bias to the results. This bias serves to help offset some of the non-conservative assumptions that must necessarily be made due to a lack of adequate data or imprecise understanding of site conditions. One critical assumption made in the analysis is that fractures occurring in the LHSU claystones impart only a minimal enhancement to the bulk rock hydraulic conductivity. This assumption is supported by core and other observations presented in the preceding sections. Because the permeability enhancement is minimal, it is further assumed that the rock mass, on average, can effectively be treated as a porous media. This assumption is described in further detail in Section 3.3.2. Other key assumptions made including their impacts are

- (1) the LHSU confining layer acts as a homogeneous, isotropic and fully saturated geologic media based on minimal fracture/fault enhancement of hydraulic conductivity,
- (2) contaminant behavior is conservative (non-reactive) and is not subject to degradation or transformation reactions, and
- (3) groundwater flow occurs under steady state conditions

Additional assumptions are made, where necessary, as cited in the text.

3 2 Groundwater Flux, Flow Velocity and Travel Time

3 2 1 LHSU Confining Layer

The magnitude of downward vertical groundwater flow from the UHSU into the LHSU (and from the LHSU into the Laramie-Fox Hills aquifer) can be estimated using Darcy's Law and site-specific data. Assuming homogeneous, isotropic, steady-state, one-dimensional flow and full saturation, the vertical flux rate is calculated from

$$q = K_v \frac{dh}{dz} \quad (2)$$

where

q equals the vertical flux rate (cm/sec)

K_v is the vertical hydraulic conductivity (cm/sec)

dh/dz is the vertical hydraulic gradient (dimensionless)

Applying this equation, vertical flux rates for a range of possible K_v values were determined using a hydraulic gradient of 0.4 (see Section 2.3.4). The geometric mean horizontal hydraulic conductivity value of 2.5×10^{-7} cm/sec is included with these values as a possible upper bound given that fracturing, with an average dip angle of 40 degrees from horizontal, will potentially contribute almost equally to the vertical hydraulic conductivity. These results are summarized below in Table 3-1.

Using the previously stated assumptions and a mean porosity value (ϕ) of 0.22, the vertical seepage velocity, v_w , can be obtained from the Darcy flux with the following relationship

$$v_w = \frac{q}{\phi} \quad (3)$$

where the total porosity is considered equal to the effective porosity based on similar practice for clayey confining layers used by Desaulniers, et al (1981) and McKay et al (1993).

Table 3-1
Vertical Flux and Travel Time Calculation Results
for the Upper Laramie Formation LHSU Confining Layer

K_v (cm/sec)	Vertical Flux		Vertical Seepage Velocity		Travel Time to Laramie-Fox Hills Aquifer (yrs)
	(cm/sec)	(ft/yr)	(cm/sec)	(ft/yr)	
2.5×10^{-7} (1)	1.0×10^{-7}	0.104	4.5×10^{-7}	0.468	1,300
1.0×10^{-7} (2)	4.0×10^{-8}	0.041	1.8×10^{-7}	0.185	3,200 ³
5.8×10^{-8} (3)	2.3×10^{-8}	0.024	1.0×10^{-7}	0.108	5,500
1.0×10^{-8} (2)	4.0×10^{-9}	0.0041	1.8×10^{-8}	0.018	33,000
2.8×10^{-10} (4)	1.1×10^{-10}	0.00012	5.0×10^{-10}	0.00054	1,100,000

(1) geometric mean unweathered claystone/siltstone K_h (DOE 1995b)
(2) Assumed from Figure 2-4
(3) geometric mean laboratory K_v (DOE 1995b)
(4) Robson (1987)

The seepage velocity represents the advective transport rate for nonreactive contaminants. The range of calculated values presented in Table 3-1 demonstrates the relatively slow vertical movement of groundwater in the LHSU. A more meaningful presentation of the seepage velocity results involves the concept of contaminant travel time to a receptor. For an assumed LHSU confining layer thickness of 600 feet (182.9 meters) and seepage velocity results of Table 3-1, the travel times for a conservative contaminant to migrate from the UHSU to the Laramie-Fox Hills aquifer ranges from 1,300 to 1.1 million years. As shown in later sections, the hydrologic and geochemical properties of the LHSU have a substantially greater ability to attenuate DNAPL and dissolved contaminant migration and affect contaminant fluxes into the Laramie-Fox Hills aquifer than presented here.

3.2.2 Laramie-Fox Hills Aquifer

Estimated horizontal groundwater flux rates for the Laramie-Fox Hills aquifer at the Industrial Area were also determined using the Darcy equation and assuming a K_h value of 1.8×10^{-5} cm/sec and dh/dx value of 0.04 as presented previously in Subsection 2.3.4. The calculated Darcy flux of 7.2×10^{-7} cm/sec is about 7 to 6,550 times larger per unit area than the vertical flux occurring across the confining layer, depending on the assumed vertical hydraulic conductivity.

As discussed later in Subsection 3.3.4, the relative difference between aquifer and confining layer groundwater fluxes is of interest because the ultimate impact of a dissolved contaminant plume entering the Laramie-Fox Hills aquifer will depend on the mass flux at the aquifer/confining layer boundary.

3.3 Contaminant Transport and Pathway Analysis

DNAPLs or high levels of DNAPL-derived groundwater contamination indicative of DNAPL presence have been detected in various areas of the Site. These areas include the 903 Pad, Mound, Industrial Area (multiple sources), 881 Hillside (IHSS 119.1), Ryan's Pit (IHSS 109), east trenches (IHSSs 110, 111.1, etc.) and IHSS 118.1. In this section, the potential for vertical contaminant transport from two IHSS areas, 110 and 118.1, is evaluated based on the Site hydrologic conditions and concepts presented above. These areas were chosen because they are located in areas that are representative of industrial area conditions, contain documented evidence of DNAPL presence, differ in the chemical characteristics of the DNAPL source, and are the focus of current accelerated clean-up activities.

3.3.1 Site Descriptions and History

IHSS 118.1

IHSS 118.1 is related to a 5,000 gallon underground steel storage tank that contained carbon tetrachloride (CT) located adjacent to the west side of Building 730, just north of Building 776. The IHSS was originally defined as a 50- by 180-foot area between Buildings 776 and 701 (EG&G, 1990). More recent information provided by Doty and Associates (1992) has indicated that IHSS 118.1 should be redefined as a 30- by 13-foot area located adjacent to the east side of Building 701.

Engineering drawings indicate that the tank was approximately 14 feet in length (north-south) and approximately 8 feet in diameter. The south end of the tank was enclosed in a concrete

structure which provided access and encased the tank piping. The structure was approximately 6 feet wide, 12 feet long, and 12 feet deep. The structure encased only about three feet of the south end of the tank. An 18-inch square concrete sump pit, located in the southwestern corner at the bottom of the structure, provided drainage.

The tank has a history of numerous spills and leaks, as described in DOE (1994), which date back to the pre-1970's. On June 18, 1981, the tank failed, releasing carbon tetrachloride into the sump. The tank was subsequently removed following this failure (DOE, 1992a).

IHSS 110

IHSS 110 (Trench T-3) is located north of Central Avenue, east of the inner fence, and south of South Walnut Creek. An evaluation of recently collected geological and geophysical data indicate that Trench T-3 is approximately 5 to 10 feet in depth, 19 to 23 feet wide, and 135 to 140 feet long (DOE, 1995f). It is one of several trenches located in the east buffer zone that was used for waste disposal. The trench was operated sometime during the July 1965 through August 1968 time period.

According to the Historical Release Report (DOE, 1992a), the trench was primarily used for the disposal of uranium and plutonium-contaminated sanitary sewage sludge and flattened drums potentially containing uranium and waste oils. It is unknown, however, how much residual material may have remained in the drums at the time of burial. The trench has been extensively investigated in recent years as part of RCRA Facility Investigation/Remedial Investigation and Soil Vapor Extraction pilot testing activities (DOE, 1995f), and is currently being excavated for remediation of PCE and other VOCs.

3 3 2 *DNAPL Behavior in the Subsurface*

3 3 2 1 DNAPL Occurrence and Properties

Field investigations conducted in the IHSS 110 and 118 1 areas of the Site have detected the presence of chlorinated DNAPLs or dissolved chlorinated hydrocarbons in soils and groundwater. These areas have been scheduled for remediation activities that will remove or stabilize the source material and associated soils to clean-up levels established by the proposed 1996 Rocky Flats Compliance Agreement (currently released for public comment). Recovery of DNAPL below the water table is currently not planned at IHSS 110, but may be feasible at IHSS 118 1 pending further evaluation of site conditions.

At IHSS 110, field sampling programs have collected mixed phase liquid samples from inside the trench boundary. At least one sample was observed to consist of three layers: a black floating oily top layer, a yellowish brown aqueous middle layer, and a black liquid (possibly DNAPL) bottom layer. During shipment to the laboratory, the bottom layer apparently dissolved leaving only the floating and aqueous layers separated in the sample. Chemical analysis of the bulk sample using distillation procedures revealed a composition of about 48.4% water, 8.4% DNAPL, 2.7% LNAPL, 0.8% undifferentiated phase, and 39.7% residue. The DNAPL fraction consisted primarily of PCE and TCE which comprised about 60% and 10% of the total fraction, respectively. The remaining fraction of DNAPL in these samples was composed of a mixture of semivolatile and petroleum hydrocarbon compounds (DOE, 1995f). DNAPL has not been detected in soil or groundwater samples outside of the trench, however, the presence of 221 mg/L TCE in a groundwater sample from well 3687 strongly suggests that DNAPL has mobilized from one of the trenches into the underlying Arapahoe Formation sandstone. The volume, extent, and thickness of DNAPL residing in Trench T-3 and other nearby trenches and associated underlying unsaturated and saturated zones is unknown.

The CT composition of the IHSS 118 1 DNAPL is assumed from process history associated with the IHSS 118 1 underground Chlorine gas tank, and from CT detection in field screening samples by Draeger tube analysis of soil gas subspace from an adjacent tank investigation. Pooling

DNAPL was detected in the bottom of two boreholes (02695 and 02995) located at the northwest and northeast corners of tank T-9, with an estimated thickness of one foot. These boreholes are located approximately 20 feet east of IHSS 118 1. Estimates of DNAPL volume and extent are unavailable. However, depth to bedrock evidence from adjoining boreholes suggests that the lateral extent of DNAPL may be influenced by local depressions in the bedrock that were potentially made during tank installation. It is clear from the presence of CT in boreholes 02695 and 02995 that DNAPL has migrated laterally at least 20 feet from the source tank.

Selected physical and chemical properties of the principal DNAPL compounds found at IHSSs 110 and 118 1 are summarized in Table 3-2. These properties, in addition to the lithologic and hydrologic characteristics of the LHSU confining layer provided in subsections 2 3 2 and 2 3 4, will be used to evaluate the potential for vertical contaminant migration to the Laramie-Fox Hills aquifer in the next section.

**Table 3-2
Chemical and Physical Properties of Selected DNAPL Compounds**

Compound	(1) Aqueous Solubility (mg/L)	(2) K_{oc} (ml/g)	(3) DNAPL Density ρ_{DNAPL} (g/cm ³)	(4) $\rho_{DNAPL} - \rho_w$ (g/cm ³)	(5) Interfacial Tension, σ (dynes/cm)	(6) Aqueous Diffusion Coefficient, D (cm ² /sec)	(7) Effective Diffusion Coefficient, D_e (cm ² /sec)
Carbon Tetrachloride (CT)	798	439	1.59	0.59	45.0	7.1×10^{-6}	1.42×10^{-6}
Trichloroethylene (TCE)	1,566	126	1.46	0.46	34.5	7.4×10^{-6}	1.48×10^{-6}
Tetrachloroethylene (PCE)	240	364	1.63	0.63	44.4	6.8×10^{-6}	1.36×10^{-6}

(1)	Pankow and Cherry (1996) for 10°C	(5)	Mercer and Cohen (1990)
(2)	Pankow and Cherry (1996)	(6)	Pankow and Cherry (1996) for 10°C
(3)	Pankow and Cherry (1996)	(7)	Assumes tortuosity = 0.2
(4)	Assumes $\rho_w = 1 \text{ g/cm}^3$		

3 3 2 2 DNAPL Transport and Fate

DNAPL transport and fate is a complex topic that, despite over 10 years of intensive research and field experience, is still only imperfectly understood. It is known that DNAPL movement and behavior is strongly affected by subsurface conditions which are site-specific and can be highly variable and unpredictable. For DNAPL releases that are sufficiently large to sink below the water table and do not reach an impermeable bedrock surface, vertical migration of DNAPL into

the bedrock will be determined by capillary forces and pool thickness. Recent publications, including Pankow and Cherry (1996) and Cohen and Mercer (1993), have summarized the available information and approaches for evaluation of DNAPLs in groundwater. The reader is referred to these references for a more comprehensive discussion of DNAPL behavior in the subsurface environment.

The following analysis approach draws heavily from the work of Keuper and McWhorter (1991) on capillary pressures, as presented in a technical paper presented by Sale et al (1992) for the Laramie Tie Plant site in Laramie, Wyoming, and the work of Parker et al (1996) for diffusive loss of DNAPL from fractures in a fractured porous media.

Capillary Pressure Control of DNAPL Migration

From the available evidence at each IHSS site, it is assumed that DNAPL has penetrated through the alluvium to the underlying bedrock surface and formed a pool as displayed in Figure 3-1. The role of capillary pressure in controlling DNAPL migration into the bedrock is described in an excerpt from Sale et al (1992) as follows:

Water and DNAPL simultaneously occupy the pore space in the alluvium. Water has a stronger tendency to coat the solid grains and, therefore, is the wetting fluid. DNAPL is the non-wetting fluid, it occupies the portion of the pore space most remote from the solid surfaces.

Under these conditions, the pressures of the water and DNAPL increase with depth caused by the weight of the overlying fluids. Since the density of the DNAPL exceeds the density of water, the DNAPL pressure increases more rapidly with depth than does the water pressure. As a result, a pressure differential occurs between the DNAPL and water. This differential increases with depth in the DNAPL pool.

The difference between the DNAPL pressure and the water pressure, called capillary pressure, is defined as

$$P_c = P_{nw} - P_w \quad (4)$$

where

- P_c = capillary pressure
- P_{nw} = pressure of DNAPL (nonwetting)
- P_w = pressure of water (wetting)

For static conditions, the pressure variation in the two fluids is linear, as shown in Figure 3-1. At the bottom of the pool, the capillary pressure is at its maximum and is given by

$$P_c = (\rho_{nw} - \rho_w) g T \quad (5)$$

where

- P_c = capillary pressure
- ρ_{nw} = nonwetting-phase (DNAPL) density
- ρ_w = wetting-phase (water) density
- g = gravitational constant
- T = thickness of the pool

DNAPL will penetrate a water-saturated, porous, or jointed medium only if the capillary pressure exceeds a threshold value known as the entry pressure. Insight to the factors affecting the entry pressure is provided by idealizing joints as the opening between parallel flat plates and by idealizing pores as cylindrical capillary tubes. Assuming that water wets the solid with zero contact angle, the entry pressures for these geometries are given by the following equations

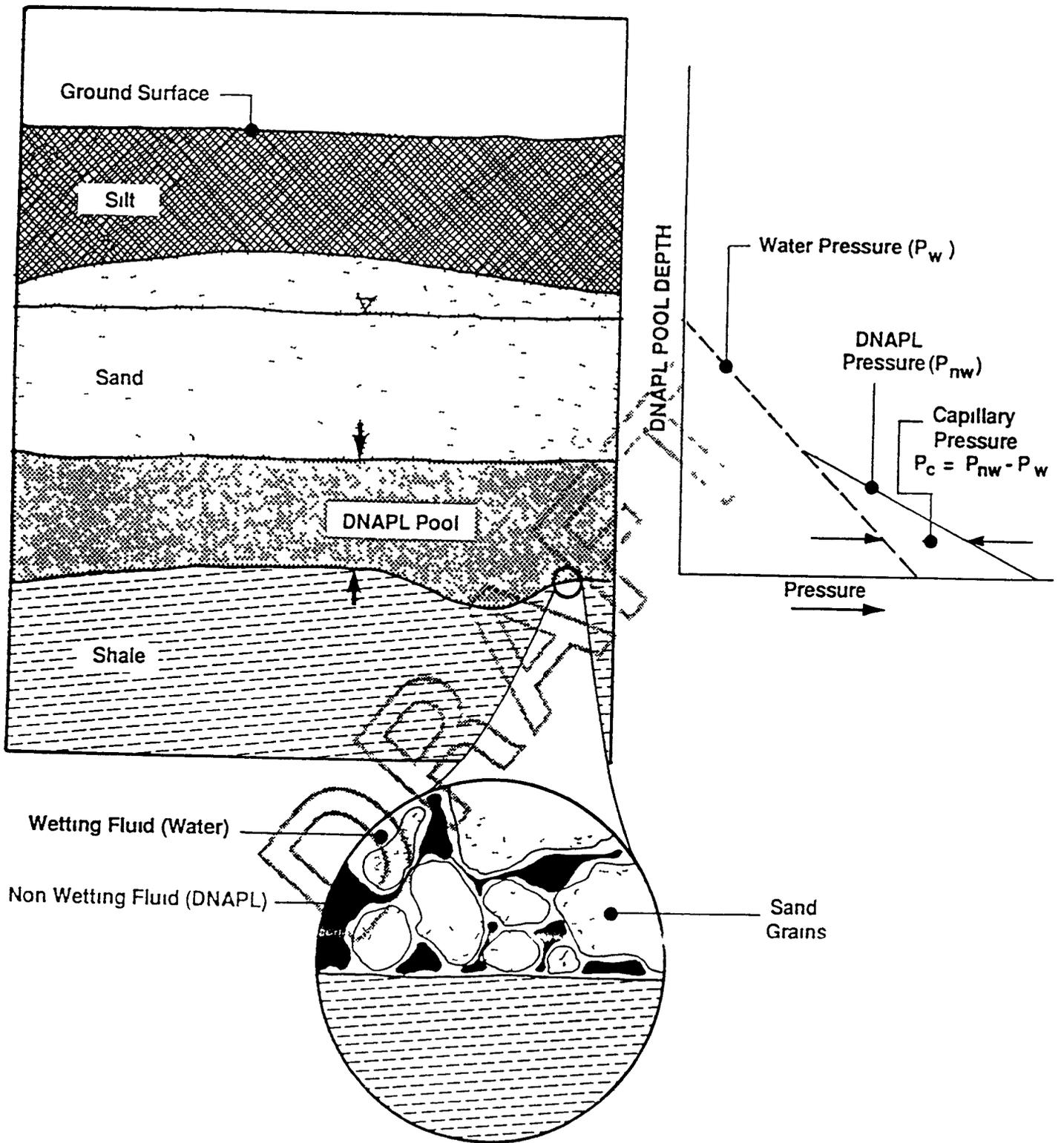
$$P_e = \frac{2\sigma}{e} \quad (\text{joint}) \quad (6)$$

and

$$P_e = \frac{4\sigma}{e} \quad (\text{pore throat}) \quad (7)$$

where

- P_e = entry pressure
- σ = interfacial tension between DNAPL and groundwater
- e = joint aperture or tube diameter



(After Kueper and McWhorter 1991)

Figure 3-1 Illustration of DNAPL Occurrence in the Alluvium and Definition of Capillary Pressure

These equations illustrate that entry pressures are directly proportional to the interfacial tension and inversely proportional to the size of the pore throat or joint aperture. Of course, real porous and jointed media contain openings with a wide variety of sizes and do not conform to these idealized geometries. For this reason, entry pressures are most reliably determined by direct measurement. Nevertheless, the fundamental dependence of entry pressure on interfacial tension and the size of openings remains as expressed above.

By putting the capillary pressure (P_c) equal to the entry pressure (P_e) in Equation 5, one can compute the critical thickness, T_c , of a static DNAPL pool required to achieve entry into a stratum with any prescribed entry pressure.

$$T_c = \frac{P_e}{(\rho_{nw} - \rho_w)g} \quad (8)$$

This approach, when applied to the IHSS 110 and 118.1 sites, can yield theoretical critical thickness values for use in assessing the potential for DNAPL migration into the UHSU at the Site. At IHSS 110, the underlying UHSU bedrock consists, at least in part, of relatively clean, fine to medium grained Arapahoe Formation sandstone. Representative pore diameters for medium-grained sandstones were not recovered from the literature, however, a maximum approximate pore diameter of 0.008 cm (80 μ m) was estimated from a uniform sand grain size of 0.05 cm (upper range of medium-grained sand) and cubic closest packing arrangement. For an interfacial tension value of 34.5 dynes/cm and pore diameter of 0.008 cm, a TCE pool thickness of at least 38.3 cm (1.3 feet) would be required to achieve DNAPL entry into the porous matrix of the Arapahoe Formation sandstone. The results of this analysis suggest that a significant thickness of DNAPL would have to pool above the sandstone before entry would occur. Chemical analyses from a nearby downgradient well, 3687, have indicated the occurrence of high concentrations of TCE/PCE that are consistent with DNAPL presence in the sandstone. If DNAPL has invaded the sandstone, it is possible that locally thick pooling may be the responsible mechanism as DNAPL presence outside of the trench has not been observed in surrounding boreholes. Alternatively, DNAPL entry via fractures could be accomplished with a lower critical

thickness, and remains a possible pathway that could explain the apparent presence of DNAPL in the sandstone near well 3687

At the IHSS 118 1 site, the analysis yields a critical thickness value of 15.5 cm (0.5 feet) for CT for a hypothetical 0.01 cm (100 μm) fracture opening and an interfacial tension value of 45 dynes/cm (see Table 3-2). Using a fracture aperture of 0.0014 cm (14 μm) calculated for the LHSU confining layer claystone, the critical thicknesses for CT becomes 111 cm (3.6 feet). Considering that an estimated one foot CT DNAPL thickness was observed in borehole 01994 at IHSS 118 1, it is entirely plausible for DNAPL to have migrated into the UHSU claystone bedrock at this locality given the probable openness of weathered bedrock fractures compared to the calculated LHSU fracture aperture value. The following discussion describes a mechanism which limits the ultimate extent of DNAPL in a fractured porous media.

Diffusive Disappearance of DNAPL from Fractures

Parker et al (1996) have recently investigated the fate of DNAPLs in fractured porous media. Their research has shown that DNAPL has a potential for relatively rapid disappearance from fractures into the adjacent porous matrix. This transfer occurs by DNAPL dissolution along fracture surfaces and subsequent diffusion and storage in the matrix as depicted in Figure 3-2. The disappearance time, t_D , for complete disappearance of DNAPL from a single fracture can be calculated from the following equation:

$$t_D = \frac{\pi \rho^2}{16 S_w^2 \phi_m^2 D_e R} (2b)^2 \quad (9)$$

where

t_D = DNAPL disappearance time

ρ = DNAPL density

S_w = aqueous solubility of DNAPL

ϕ_m = matrix porosity

D_e = effective diffusion coefficient

R = retardation factor

$2b$ = fracture aperture

and

$$R = 1 + \frac{\rho_b}{\phi_m} K_d \quad (10)$$

where

ρ_b = bulk dry density of rock (g/cm^3)

K_d = distribution coefficient (ml/g)

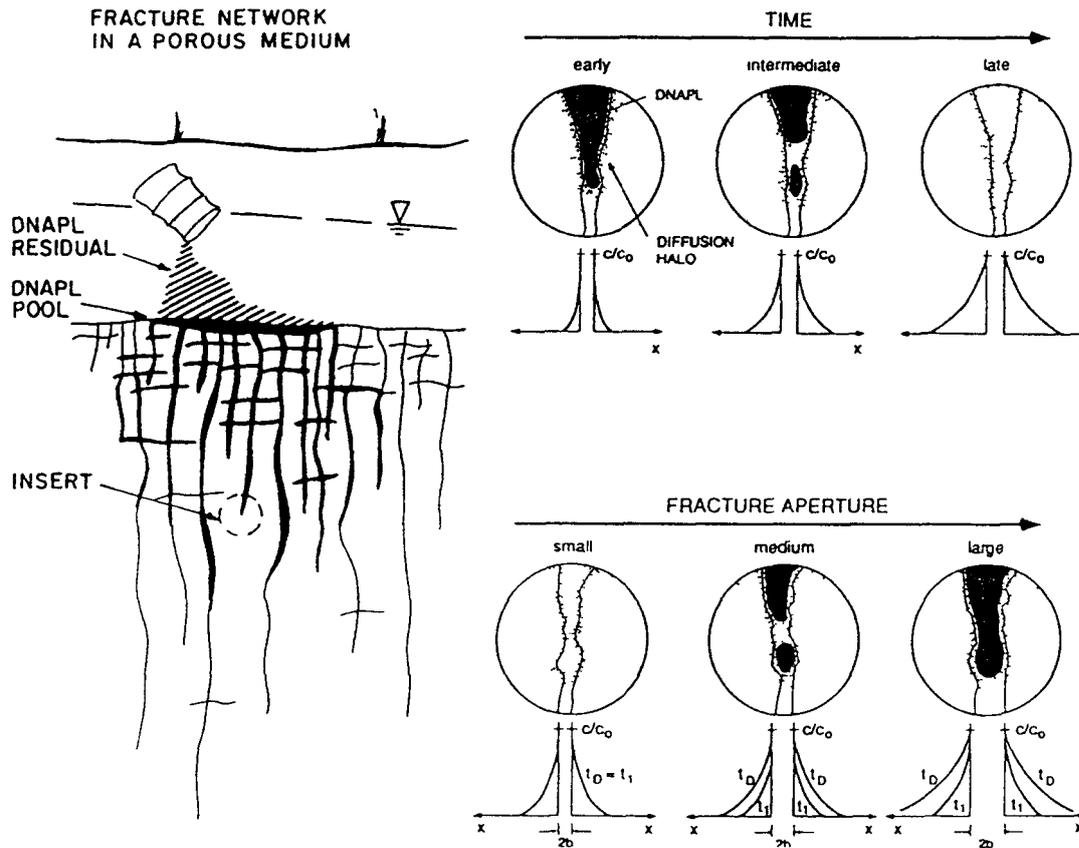


Figure 3-2 Conceptualization of DNAPL persistence and distribution with DNAPL mass loss due to diffusion in water-saturated fractures in a porous medium (such as a fractured clay till or sedimentary rock) as a function of a) time, and b) fracture size (aperture) (from Pankow and Cherry, 1996)

The distribution coefficient, K_d , is commonly predicted from listings of published partition coefficients and the organic carbon fraction measured from site samples using the equation

$$K_d = K_{oc} f_{oc} \quad (11)$$

where

K_{oc} = partition coefficient for compound of interest

f_{oc} = organic carbon fraction

For values of f_{oc} , K_{oc} , ρ_b , and ϕ_m reported previously in Section 2.0, K_d and R values for CT, TCE and PCE have been calculated as presented in Table 3-3

**Table 3-3
DNAPL Fracture Disappearance Time and Retardation Factor Calculations**

	Hydrostratigraphic Unit	FOC (%)	K_d (mL/g)	ρ_b (g/cm ³)	ϕ_m (%)	R _f	Fracture Aperture (cm)	Disappearance Time	
								(days)	(yrs)
CT	UHSU	0.0017	0.746	2.03	0.248	7.11	0.01	1,450	3.97
	LHSU	0.0103	4.522	2.07	0.222	43.16	0.0014	5.6	2.2 x 10 ³
TCE	UHSU	0.0017	0.214	2.03	0.248	2.75	0.01	789	2.16
	LHSU	0.0103	1.300	2.07	0.222	13.12	0.0014	4.05	1.1 x 10 ²
PCE	UHSU	0.0017	0.619	2.03	0.248	6.07	0.01	20,560	56.54
	LHSU	0.0103	3.749	2.07	0.222	35.96	0.0014	85.2	2.3 x 10 ¹

Substituting the CT values of R for weathered and unweathered bedrock into Equation 9, together with the appropriate values of physical and chemical properties from Table 3-2, yields disappearance times of 1,450 and 5.6 days for fracture apertures of 0.01 and 0.0014 cm, respectively. Similar results are obtained for TCE, which has a greater solubility, but lower retardation factor. Of the three compounds, PCE has the greatest disappearance time and thus can be expected to persist the longest as a non-aqueous phase liquid. Even so, the disappearance time for PCE in unweathered bedrock is relatively fast compared to the sluggishness of vertical

groundwater flow through the confining layer (see Table 3-1). Moreover, the 3-dimensional (3-D) nature of the fracture network at the Site will result in even shorter disappearance times than calculated above for the 1-D case due to an increase in the surface area to volume ratio (Parker, 1996). The disappearance of DNAPL from a fracture will continue until the diffusive flux across the fracture surface equals 0, i.e. when the matrix mass storage capacity is reached.

The maximum amount of DNAPL that can be dissolved and sorbed per unit volume of unfractured matrix, M_m , is given by the contaminant mass storage capacity expressed as (Parker, et al., 1996)

$$M_m = \phi_m S_w R \quad (12)$$

For values of unweathered bedrock R given above, the mass storage capacity of bedrock is estimated at 7.65 kg/m³ for CT, 4.56 kg/m³ for TCE, and 1.92 kg/m³ for PCE. These capacities, when calculated for the entire thickness of the unweathered bedrock, translate to approximately 1,400 kg/m² (232 gal/m²) CT, 834 kg/m² (151 gal/m²) TCE, and 351 kg/m² (57 gal/m²) PCE. Converted to an alluvial pool thickness value, these volumes correspond to thicknesses of 9.6 ft, 6.2 ft, and 2.4 ft, respectively, for an assumed alluvial total porosity of 0.30. It is clear from these calculations that the unweathered bedrock is capable of storing quantities of DNAPL that greatly exceed the probable volumes released to the environment. The total mass storage capacities (fractures and matrix) of the bedrock are actually expected to be greater than these calculated amounts because the estimates neglect the potentially important sorption properties of clay-rich rocks (Karickhoff, 1984) and the mass storage capacity associated with fractures.

These calculations predict that once DNAPL penetrates into the fractured bedrock, it will be assimilated relatively rapidly as a dissolved or sorbed phase into the bedrock matrix. Given the mass storage capacity available in the bedrock, the threat of downward DNAPL migration into the Laramie-Fox Hills aquifer is remote and unsupportable given the long travel times required for transport through the confining layer compared to the relatively short disappearance times predicted above.

3 3 3 *Solute Transport and Fate*

Once a DNAPL compound enters the aqueous dissolved phase, it will be advectively and diffusively transported as a solute in groundwater depending on the average groundwater flow velocity and retardation characteristics of the media. According to Desaulniers, et al, (1981), diffusion can be an important or even dominant transport process at average groundwater flow velocities of less than about 0.7 cm/yr. From consideration of the seepage velocities presented in Table 3-1, this condition is assumed to exist when the vertical hydraulic conductivity approaches a value of about 1.0×10^{-8} cm/sec or less. The profile of decreasing hydraulic conductivity with depth shown in Figure 2-4 indicates that advection dominates in the upper half of the LHSU confining layer and suggests that diffusion may become more important in the lower half of the LHSU. For purposes of this analysis, advection coupled with dispersion is assumed to be the dominant transport mechanism operating throughout the confining layer because it is the more conservative approach of the two. The vertical movement and fate of DNAPL-derived dissolved organic contaminants will now be examined with consideration given to the hydrologic and geochemical properties of the claystone, as presented in the previous sections of the report.

3 3 3 1 Hydrodynamic Dispersion

Hydrodynamic dispersion refers to the tendency for a solute to spread out from a flow path and cause dilution of the solute (Freeze and Cherry, 1979). This phenomenon is caused by a combination of mechanical mixing during advective flow and diffusion of solute ions or molecules in groundwater environments which exhibit concentration gradients - a condition that is satisfied by the existence of a contaminant plume. Dispersion acts to spread a plume both longitudinally (direction parallel to groundwater flow) and transversely (direction normal to groundwater flow). The primary effects of neglecting hydrodynamic dispersion in transport analyses involves a prediction of maximum contaminant concentrations and minimum plume cross-sectional areas for flux calculations. Plume spreading will occur in three dimensions (3-D) unless limited by a hydrologic boundary such as the water table surface or impermeable layer. For vertical transport through a confining layer, it is expected that contaminant migration will be

three dimensional due to a lack of vertical boundaries that would limit lateral transport. Analysis of 3-D transport is beyond the scope of this white paper, however, satisfactory results can be obtained using 2-D techniques which incorporate longitudinal and transverse dispersion into the analysis. The analytical solution for a 2-D source areas, as presented in Domenico and Schwartz (1990) and Attachment B, will be used for estimating contaminant concentrations and travel times from an UHSU source to the Laramie-Fox Hills aquifer.

3.3.3.2 Contaminant Retardation

It is commonly observed in laboratory experiments and natural field conditions that the rate of solute contaminant movement is often retarded relative to the groundwater flow velocity. This reduction in contaminant velocity is caused by an interaction of the physical, chemical, and biological properties of the dissolved contaminant, media solids, and the aqueous solution. The principal agents for retardation of organic contaminants along a flow path include sorption and biotic or abiotic transformation reactions. Each of these processes and their effects will be discussed individually as they relate to vertical contaminant migration at the Site.

Sorption

The uptake of an aqueous contaminant by a geologic media without reference to a specific mechanism is a property referred to as sorption (Allen-King, et al, 1996). The sorption of different compounds can vary widely for the same geologic material depending on the physical and chemical properties of the compound. For organic contaminants, the sorption properties of a geologic media are strongly dependent on the amount of organic carbon present in the material. As groundwater containing organic solutes passes through an organic carbon-bearing geologic material, transfer of contaminant mass from the dissolved phase to organic carbon occurs reducing the concentration of the contaminant in solution. This process results in a retardation of contaminant velocity that causes the contaminant plume to move at a slower rate than the advective groundwater flow velocity. The equation describing this type of retardation, referred to as the retardation factor (R) has already been given in Subsection 3.3.1.2.