



**Environmental Protection Department**  
**Environmental Restoration Division**

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**CERCLA**  
**Feasibility Study for the**  
**LLNL Livermore Site**

**December 1990**

**Including Errata of October 1991**

**Technical Editors**

**W. F. Isherwood**  
**C. H. Hall**  
**M. D. Dresen\***

**Contributing Authors**

<b>A. J. Boegel</b>	<b>R. S. Lawson*</b>
<b>J. I. Daniels</b>	<b>P. F. McKereghan*</b>
<b>R. O. Devany*</b>	<b>E. M. Nichols*</b>
<b>M. D. Dresen*</b>	<b>J. J. Nitao</b>
<b>L. C. Hall</b>	<b>D. W. Rice</b>
<b>C. H. Hall</b>	<b>J. Scott***</b>
<b>W. F. Isherwood</b>	<b>R. K. Thorpe</b>
<b>J. L. Iovenitti*</b>	<b>B. C. Toler**</b>

\*Weiss Associates, Inc., Emeryville, California

\*\*Science Applications International Corporation

\*\*\*Woodward-Clyde Consultants

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**Lawrence Livermore National Laboratory**  
**University of California Livermore, California 94551**

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## LLNL FEASIBILITY STUDY EXECUTIVE SUMMARY

This Feasibility Study (FS) was prepared for the Lawrence Livermore National Laboratory (LLNL) site in Livermore, California, to comply with the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA). Together with the previously conducted Remedial Investigation (RI) Report (Thorpe *et al.*, 1990), which characterizes the site, the FS forms the basis for evaluating and selecting alternative technologies for remediation of hazardous materials in the LLNL subsurface.

The RI identified eight volatile organic compounds (VOCs)—tetrachloroethylene (PCE), trichloroethylene (TCE), 1,1-dichloroethylene (1,1-DCE), 1,2-dichloroethylene (1,2-DCE), 1,2-dichloroethane (1,2-DCA), 1,1-dichloroethane (1,1-DCA), carbon tetrachloride, and chloroform—as well as fuel hydrocarbons (FHCs), two metals (chromium and lead), and tritium that occur in ground water at LLNL in concentrations above Federal or State drinking water standards. The only environmental media that may require remediation at LLNL are sediments and ground water.

Two EPA-approved pilot studies are being conducted at LLNL in the Offsite and Gasoline Spill Areas. In the Offsite Pilot Study, a fully screened extraction well design has proven effective in hydraulically capturing a significant part of the offsite VOC plume. Other well designs are being considered for future wells to offset some of the limitations of the fully screened design. An ultraviolet light/hydrogen peroxide (UV/H<sub>2</sub>O<sub>2</sub>) water treatment system with an aeration polishing unit and activated carbon air filter has treated over 20 million gal of water, which has been discharged to LLNL's recharge basin south of East Avenue. The aeration and activated carbon units were added to the UV/H<sub>2</sub>O<sub>2</sub> system to improve treatment efficiency for halogenated alkanes such as trichloroethane, which are not completely destroyed by the UV/H<sub>2</sub>O<sub>2</sub> process.

The liquid equivalent of over 6000 gal of FHC vapors has been removed from the vadose zone of the Gasoline Spill Area by vacuum-induced venting. Experiments suggest that hot air injection may improve recovery of the fuel. FHC vapors are destroyed by a thermal oxidizer with a better than 99.8% efficiency. An additional 100 to 150 gal of gasoline was removed by free product skimming from the top of the water table. Future work will include attempts to dewater the area with the highest FHC concentrations and remove the remaining fuel by vacuum-induced venting, possibly supplemented by steam injection.

Section 3 of the FS identifies hydraulic control over the contaminant plumes as a remedial action objective, which would comply with the State of California's nondegradation policy. State and Federal Maximum Contaminant Levels (MCLs) are identified as cleanup objectives for ambient ground water at the LLNL site. Concentration limits in LLNL's Waste Discharge Requirements are identified as treatment objectives and form the basis of treatment system design. Potential health risks that could result from remediation of ground water to MCLs are within or much lower than the range acceptable to EPA.

Three general response actions, (1) no action, (2) immediate action, and (3) deferred action, are identified and screened for potential remediation of the approximately 200 gal of VOCs and 10,000 gal of FHCs in the saturated zone, and liquid equivalent 50 gal of VOCs and 1000 gal of FHCs remaining in the unsaturated zone.

The screening process yielded three potential remedial alternatives for further evaluation: two pump and treat alternatives and the Deferred-Action Alternative. Either of the two extraction alternatives would quickly establish hydraulic control over the contaminant plumes. The first, Extraction Alternative No. 1, uses about 18 extraction locations and results in the most rapid remediation of ground water. Using this plan, the time estimated to remediate the ground water to below MCLs is about 50 y. The second, Extraction Alternative No. 2, uses about 10 extraction locations for downgradient plume margin control. This hydraulic control alternative also remediates ground water to below MCLs, but is estimated to take about 90 y. By preventing further offsite migration, both pump and treat alternatives equally reduce risk to human health from exposure to ground water.

Under the Deferred-Action Alternative, ground water is predicted to attain MCLs by natural processes in about 360 y and never exceeds MCLs at municipal drinking water supply wells in downtown Livermore. Although contaminants would migrate beyond their current range, human health is assured protection by the commitment to treat at the point-of-use if any MCLs are exceeded.

Vacuum-induced venting is identified as the most effective process for removing VOCs or FHCs from the vadose zone at LLNL.

For each potential remedial alternative, a wide range of technologies was evaluated for treating VOCs, FHCs, chromium, and lead in ground water. These include:

- Granular activated carbon (GAC).
- Air stripping with GAC treatment of the vapor phase.
- UV/oxidation.
- Biological treatment.
- Precipitation.
- Ion exchange.
- Ultrafiltration.

The first four technologies are primarily for VOCs and/or FHCs, and the last three are primarily for metals.

Potential disposal alternatives for treated ground water include:

- Recharge via the existing LLNL recharge basin.
- Recharge via drainage ditches, arroyos, and the onsite drainage retention basin, with the potential for re-use.
- Recharge wells.

Potential technologies for treating VOCs and/or FHCs in vapor are:

- GAC.
- Thermal oxidation.
- Catalytic oxidation.

The screening process resulted in the development of three or more treatment options (combination of technologies) for remediation of five possible situations regarding hazardous materials in ground water, as summarized below.

Situation	Treatment option
<i>Immediate action</i>	
Ground water with VOCs or FHCs	<ol style="list-style-type: none"> <li>1. GAC treatment of the liquid phase.</li> <li>2. Air stripping with GAC treatment of the vapor phase.</li> <li>3. UV/oxidation with aeration polishing and GAC treatment of the vapor phase.</li> </ol>
Ground water with VOCs and chromium	<ol style="list-style-type: none"> <li>1. Same as (1) above with ion exchange.</li> <li>2. Same as (2) above with ion exchange.</li> <li>3. Same as (3) above with ion exchange.</li> </ol>
Ground water with VOCs, FHCs, and lead	<ol style="list-style-type: none"> <li>1. GAC treatment of the liquid phase.</li> <li>2. Air stripping with GAC treatment of the vapor phase and additional GAC treatment of the liquid phase.</li> <li>3. UV/oxidation with additional GAC treatment of the liquid phase.</li> <li>4. <i>In situ</i> bioremediation.</li> </ol>
Vadose zone with FHCs or VOCs	<ol style="list-style-type: none"> <li>1. GAC treatment of the vapor phase.</li> <li>2. Thermal oxidation of the vapor phase.</li> <li>3. Catalytic oxidation of the vapor phase.</li> </ol>
<i>Deferred action</i>	
Ground water with low VOC concentrations at point-of-distribution	<ol style="list-style-type: none"> <li>1. GAC treatment of the liquid phase.</li> <li>2. Air stripping of the liquid phase.</li> <li>3. UV/oxidation of the liquid phase.</li> </ol>

Each of these treatment options was evaluated in detail for each remedial alternative and situation against the criteria provided in EPA guidance. *In situ* bioremediation has no proven track record in circumstances equivalent to those at LLNL, and consequently has greater uncertainty of success than the other technologies, even for FHCs, where it is potentially applicable. The application of catalytic oxidation is also limited to FHCs, but it is potentially applicable to vapor extraction from the vadose zone at the Gasoline Spill Area. Each of the other treatment options can be designed to meet or substantially exceed all of the EPA criteria. The noneconomic differences among them involve aesthetics, and possibly the need to transport and regenerate GAC. UV/oxidation processes minimize waste requiring further treatment or disposal by destroying the VOCs or FHCs. The most significant difference among the treatment options is cost, which varies by factors of at least two for each treatment situation.

The lowest costs of the evaluated technologies for each treatment situation are generally those using air stripping as the primary treatment technology, as summarized below.

Situation	Lowest cost treatment option
<i>Immediate action</i>	
Ground water with VOCs or FHCs	Air stripping with GAC treatment of the vapor phase.
Ground water with VOCs and chromium	Air stripping with ion exchange and GAC treatment of the vapor phase.
Ground water with VOCs, FHCs, and lead	UV/oxidation with GAC treatment of the liquid phase.
Vadose zone with FHCs or VOCs	Thermal oxidation.
<i>Deferred action</i>	
Ground water with low VOC concentrations at point-of-distribution	Air stripping.

Using the available treatment options, the three remedial alternatives provide a spectrum of costs and effectiveness. Extraction Alternative No. 1 (complete capture and treatment of affected ground water), Extraction Alternative No. 2 (downgradient plume margin control), and the Deferred-Action Alternative are all fully protective of human health. The Deferred-Action Alternative allows continued migration of contaminants beyond their present extent as they undergo slow natural degradation, but is by far the least expensive—even if VOC concentrations greater than MCLs were to reach municipal supply wells. Extraction Alternative No. 2 costs somewhat less than and differs from Extraction Alternative No. 1 in that fewer extraction locations are employed and a much longer time is predicted before attaining MCLs than for Extraction Alternative No. 1. Extraction Alternative No. 1 most expeditiously remediates ground water by siting extraction wells in all of the areas of high VOC concentration, minimizing the time necessary to complete remediation.

LLNL will recommend preferred alternatives in the Proposed Remedial Action Plan, following regulatory acceptance of the FS.

# 1. INTRODUCTION

## 1.1. PURPOSE AND ORGANIZATION OF REPORT

Lawrence Livermore National Laboratory (LLNL) is a government-owned research facility operated by the University of California for the Department of Energy (DOE). Previous government owners of the site include the U.S. Navy and DOE predecessors. The LLNL site was added to the Environmental Protection Agency's (EPA) National Priorities List (NPL) in July 1987, based on the presence of volatile organic compounds (VOCs) in ground water. In November 1988, DOE, EPA, the California Department of Health Services (DHS), and the Bay Area Regional Water Quality Control Board (RWQCB) signed a Federal Facility Agreement (FFA) to facilitate compliance with the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), the Superfund Amendments and Reauthorization Act of 1986 (SARA), and applicable State environmental laws.

The history and characterization of the site, including the subsurface distribution of hazardous materials, are presented in detail in the *Remedial Investigations Report* (RI) (Thorpe *et al.*, 1990). This report was submitted to the FFA signatories and is available for public comment. The RI and this Feasibility Study (FS) provide the basis for selection of strategies for remediating contaminants at LLNL and those that have migrated from the LLNL site. The RI includes the *Baseline Public Health Assessment* (BPHA) (modified from Layton, 1989), which concludes that the only media of concern are ground water and sediments. The contaminants of concern fall into three categories—VOCs, fuel hydrocarbons (FHCs), and metals. Low concentrations of tritium have also been detected in ground water, but are shown to be of little concern.

### 1.1.1. Purpose

The purpose of the FS report is to screen available technologies and present feasible alternatives and associated costs for remediating contaminants in ground water and sediments beneath and adjacent to the LLNL site. The RI characterizes the physical and chemical aspects of the study area and describes in detail the distribution and concentration of contaminants. Because of varying site conditions, optimal cleanup will consist of a combination of remediation technologies, each designed to achieve specific goals.

This FS provides conceptual approaches to remediation and is a decision management tool; it is not a fully engineered remediation plan. Although the RI presents details of the distribution, fate, and potential migration of contaminants at the LLNL site, no such study can specify all parameters with complete certainty. We recognize that further information will be gained as the investigation and remediation efforts continue. We therefore provide as much flexibility as possible, in order to accommodate changes in conditions which may be found or anticipated as the project progresses. Potential remedial alternatives are described with respect to their applicability, along with the factors to be evaluated in deciding when a particular remediation technology should be applied.

The identification of Applicable or Relevant and Appropriate Requirements (ARARs) and the initial screening of remedial alternatives were begun in the RI. The FS continues with both the resolution of ARARs and screening of remedial alternatives building upon the discussions in

the RI. The FS uses the results and methodology of the BPHA to evaluate the health benefits of prospective remedial measures.

The RI and FS form the basis for the Proposed Remedial Action Plan (PRAP), which will be prepared following review and acceptance of this document. The PRAP will be subject to formal public review and comment, and will lead to a Record of Decision. Schedules and engineering design will follow in the Remedial Implementation Plan and Remedial Design.

### 1.1.2. Report Organization

- Section 1 of the FS describes physical characteristics of the LLNL site and vicinity and summarizes from the RI the nature and extent of contamination.
- Section 2 summarizes the Pilot Studies for the Offsite and Gasoline Spill Areas.
- Section 3.2 develops remedial action objectives, based on ARARs and on potential risks to human health identified in the BPHA. Specific contaminants and areas requiring remediation are identified (e.g., FHCs in sediment and ground water beneath the Gasoline Spill Area).
- Section 3.3 explores protective measures or general response actions for the media and contaminants of concern, and identifies and evaluates specific remediation technologies.
- Sections 3.4 through 3.7 address potential remedial alternatives, assemble viable technologies into potential treatment options, and complete a screening evaluation.
- Section 4 analyzes in detail remedial alternatives and treatment options that passed the screening evaluation and compares resulting strategies.
- Section 5 presents an Environmental Assessment of remedial alternatives that pass the screening for compliance with the National Environmental Policy Act (NEPA).
- Appendices provide backup materials to support the text.

## 1.2. SUMMARY OF REMEDIAL INVESTIGATIONS REPORT

### 1.2.1. Site Description and History

LLNL is an 800-ac research facility located about 40 mi east of San Francisco, approximately 3 mi east of downtown Livermore (Figure 1-1). The land surface slopes gently northwestward and is underlain by alluvial sediments to a depth of about 1000 ft. Two intermittent streams, Arroyo Seco and Arroyo Las Positas, traverse the area. The climate is semiarid, with an average precipitation of about 14 in./y. Commercial, industrial, and agricultural land uses dominate the immediate vicinity, but residential development is proceeding immediately west of the site.

The LLNL site was converted from agricultural use in 1942 by the U.S. Navy to an aviation training base. Activities such as aircraft maintenance and servicing used VOCs, which were disposed of onsite (Thorpe *et al.*, 1990). In 1950, the property was transferred to the Atomic Energy Commission (AEC) and, in 1952, the University of California began management of LLNL under contract with the AEC. In 1975, responsibility for LLNL was transferred to the Energy Research and Development Agency (ERDA) and, in 1977, to the DOE, its present owner agency. Various hazardous materials, including VOCs, metals, and tritium, were used and released at the site in the post-Navy era.

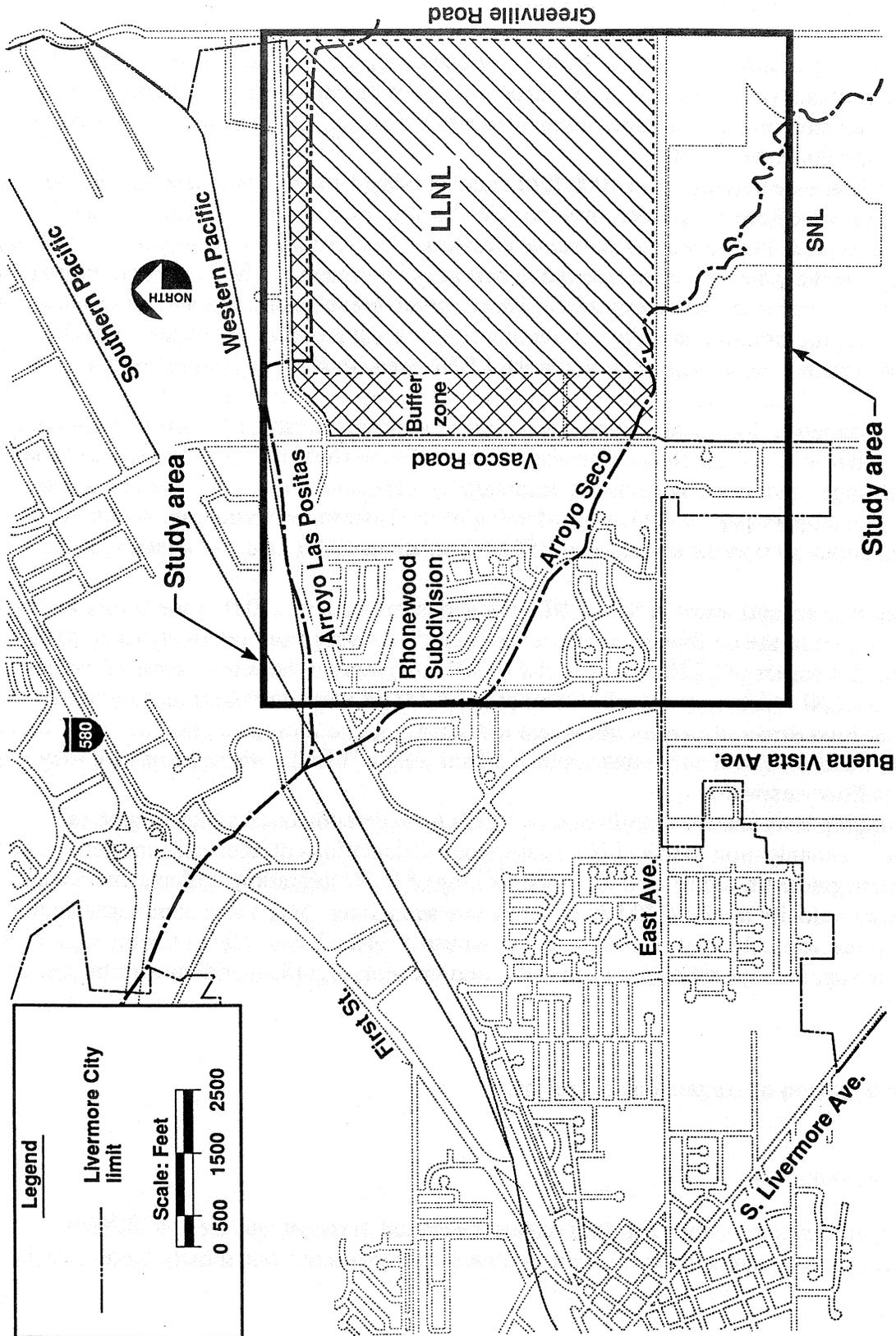


Figure 1-1. The LLNL site and surrounding area.

## 1.2.2. Summary of Geology and Hydrogeology

LLNL is partially within the Mocho I and Spring hydrologic subbasins (CDWR, 1974). The only significant beneficial use of the surface water in the study area is for ground water recharge. The major existing and/or potential beneficial uses of ground water are agricultural, municipal, and domestic supply.

LLNL is underlain by up to 1000 ft of unconsolidated sediments of late Tertiary to Holocene age, which are subdivided into the Plio-Pleistocene Livermore Formation and undifferentiated late Pleistocene to Holocene alluvium. Unconsolidated sedimentary materials above or below the water table are referred to herein as "sediment." The Livermore Formation is divided into an upper member composed of interfingering gravel, sand, silt, and clay, and a lower member consisting of more laterally continuous layers of silt and clay with lesser gravel beds.

Two ground water systems underlie the LLNL area—a shallow system composed predominantly of heterogeneous alluvial deposits, and a deeper system composed of fluvial and lacustrine sediments. Regional ground water flow is generally westward, locally stratified, and primarily horizontal, but the flow paths deepen gradually westward toward the center of the basin. The upper and lower systems are separated by a regional confining layer that slopes westward in the upper part of the Lower Member of the Livermore Formation, which varies in depth from about 60 ft in the eastern part of LLNL to about 400 ft near the western LLNL boundary.

Depth to ground water in the LLNL area varies from about 110 ft in the southeast corner of LLNL to 30 ft in the northwest. Ground water gradients vary from relatively steep (0.02 ft/ft) in the northeast corner of LLNL to fairly flat (0.001 ft/ft) toward the west. Some of the ground water in the LLNL vicinity eventually flows about 1-1/2 mi west-northwest to Arroyo Las Positas near First Street in Livermore, where it discharges, and through a possible "gap" between the Mocho I and Mocho II subbasins about 1-1/2 mi west of LLNL, where some of it may continue to flow westward.

Pumping tests and the distribution of VOCs have demonstrated a high degree of horizontal communication in the LLNL subsurface. Calculations of hydraulic conductivity and ground water gradients, along with history matching of VOC migration, indicate an average ground water velocity of about 70 ft/y in permeable sediments. Much less communication is observed in the vertical direction. Although downward vertical hydraulic gradients exist over much of the site, the layered nature of the alluvium prevents significant downward migration of VOCs.

## 1.2.3. Distribution of Hazardous Materials

### 1.2.3.1. Surface Water

Chromium is the only hazardous material detected in recent analyses of LLNL's intermittent surface waters in concentrations above its Maximum Contaminant Level (MCL).

### 1.2.3.2. VOCs in Unsaturated Sediment and Ground Water

Present data indicate that total VOC concentrations exceeding 1 part per million (ppm) in unsaturated sediment occur in only one area, near Building 518 in the southeast corner of LLNL, where a maximum total VOC concentration of about 6 ppm was measured in sediments from a depth of about 20 ft. Soil samples from other potential source areas contained total VOC concentrations ranging from <5 parts per billion (ppb) to <500 ppb, with most containing less than 100 ppb. Notable exceptions are the East Taxi Strip and the East Traffic Circle in eastern LLNL, where total VOCs in the vadose zone have been reported in concentrations up to 300 ppb and 800 ppb, respectively.

Eight chlorinated solvents, perchloroethylene (PCE), trichloroethylene (TCE), 1,1-dichloroethylene (1,1-DCE), 1,2-dichloroethylene (1,2-DCE), 1,2-dichloroethane (1,2-DCA), 1,1-dichloroethane (1,1-DCA), carbon tetrachloride, and chloroform, have been detected in ground water in the LLNL area in concentrations exceeding Federal or State action levels or MCLs. TCE is the most abundant VOC and occurs in eastern LLNL in concentrations exceeding 1 ppm. PCE occurs mainly in the southwest part of LLNL and the adjacent offsite area to the west, but is also present in eastern LLNL where it is subordinate to TCE. Freon 113 has been sporadically reported above its MCL in one well (MW-501); its presence will be considered in the design of the treatment system for that area.

The VOCs in ground water in the LLNL vicinity occur in relatively large but diffuse plumes that underlie about 85% of the LLNL site and a total area of about 1.4 mi<sup>2</sup> (Figure 1-2). The calculated volume of VOCs in ground water is less than 200 gal. The plumes are about 30 ft to 100 ft thick, and VOCs are seldom found below a depth of 200 ft. VOCs have migrated offsite in two areas: (1) about 2500 ft west of Vasco Road onto private property, and (2) about 800 ft south of southeastern LLNL onto DOE property administered by Sandia National Laboratories (SNL). Chemical and hydraulic data strongly indicate that a TCE plume northwest of LLNL originates on private property. That plume is currently under investigation by the RWQCB and property owners in that area.

### 1.2.3.3. Fuels and Aromatic Hydrocarbons

Significant concentrations of FHCs occur only in the Gasoline Spill Area, where about 17,000 gal of leaded gasoline was lost prior to 1979. Up to 11,000 ppm total FHCs and 4800 ppm total aromatic hydrocarbons occur in the vadose zone in this area. Total aromatic hydrocarbon concentrations above 1 ppm in the vadose zone are limited to an area less than about 30 to 35 ft from the leak point, and diminish to 0.1 ppm within 40 to 45 ft of the leak point.

Total fuel hydrocarbon (TFH) concentrations exceeding 10 ppm in ground water are restricted to the immediate vicinity of the gasoline leak point and decrease significantly in all directions. TFH concentrations ranging from 0.001 to 100 ppm are confined to a roughly oval-shaped area extending from the leak point about 350 ft to the north and to the south, about 400 ft to the east, and about 500 ft to the west. Benzene concentrations above the 0.001 ppm State MCL are restricted to an area within about 300 ft of the leak point. FHCs in ground water are not present below a depth of about 150 ft. The only other FHC reported in concentrations exceeding an MCL is ethylene dibromide, which recent analyses suggest to be present in five monitor wells in the immediate vicinity of the gasoline leak point.

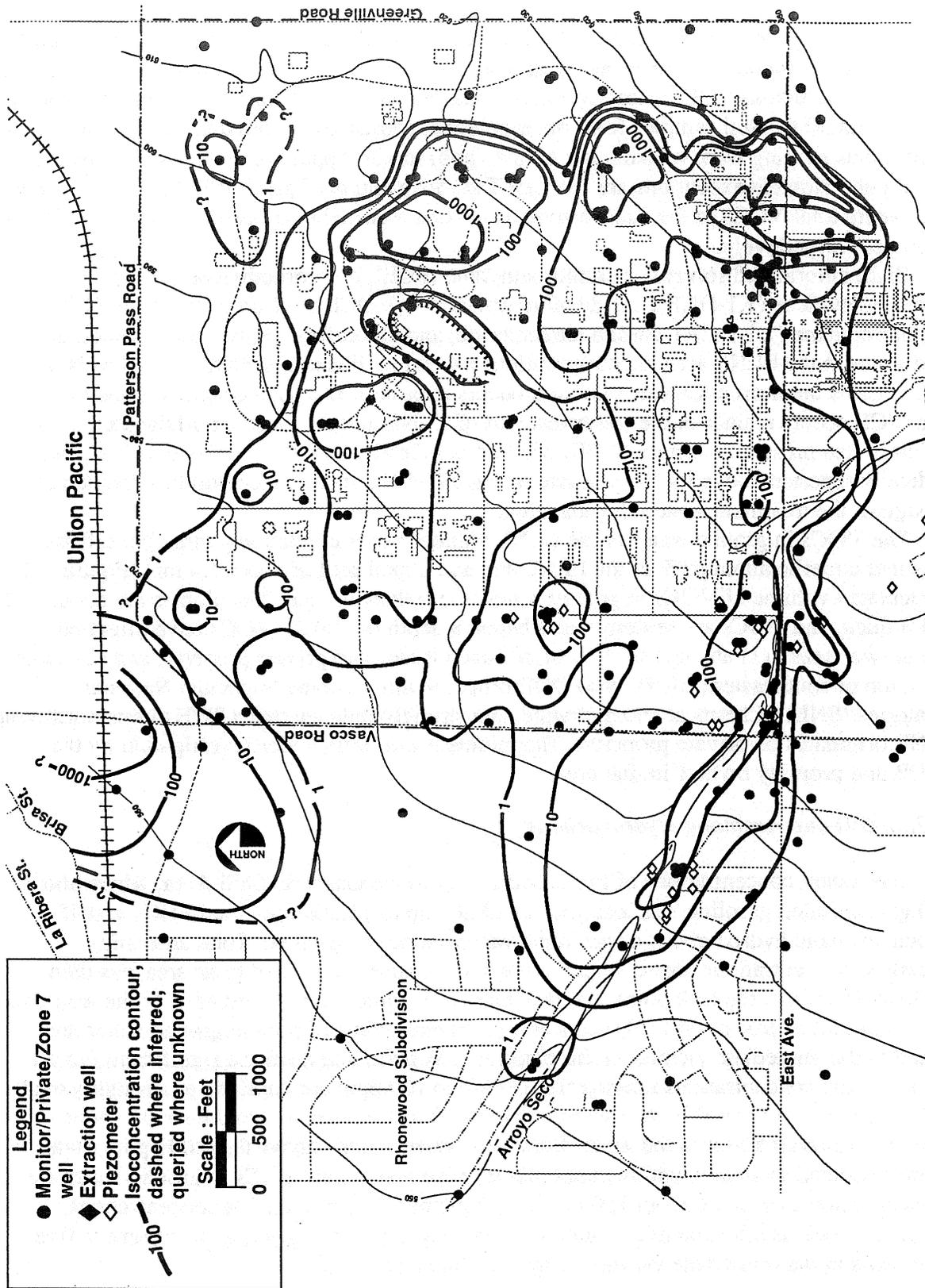


Figure 1-2. Isoconcentration contour map of total VOCs in ground water. Data from all wells within plumes contoured without regard to depth.

#### 1.2.3.4. Radiological Parameters

Tritium is the only radiological parameter present in ground water in concentrations above an MCL. In the southeast part of LLNL, MW-206 contains tritium slightly above the MCL of 20,000 pCi/L. At the time of the RI, only three other LLNL monitor wells contained detectable concentrations of tritium. Investigations subsequent to the RI have detected tritium in four other monitor wells in concentrations from 911 to 1500 pCi/L. The natural 12.3-y half-life for tritium and slow movement of ground water ensure that the observed tritium will have decayed to well below the MCL long before migrating offsite.

Tritium, if present in unsaturated sediments, is contained in the water phase within interstitial pore spaces. At LLNL, water typically represents 5 to 20% of the unsaturated sediments by weight. The amount of tritium present is dependent on the percent moisture within the unsaturated sediments, and the reported concentrations are not directly comparable to measurements derived from ground water. To make this distinction, tritium measurements from unsaturated sediments are now reported in picocuries per liter of soil moisture (pCi/L<sub>sm</sub>).

Data collected for the RI indicate that tritium is present in unsaturated sediment in concentrations significantly above the LLNL background level of about 3500 pCi/L<sub>sm</sub> in the Building 514 Area in southeastern LLNL. Followup investigations subsequent to the RI have detected tritium in the unsaturated sediment in the Building 514 Area as high as  $2.68 \times 10^6$  pCi/L<sub>sm</sub> in shallow soil. The investigation of the Building 514 Area is fully described in Isherwood *et al.* (1990). Tritium has now also been detected above LLNL background levels in four additional areas. In the Building 292 Area, located in the northeastern part of LLNL, a maximum concentration of  $2.2 \times 10^8$  pCi/L<sub>sm</sub> was reported adjacent to an underground tank that failed its annual leak test. This area is now under detailed investigation, the results of which will be reported as part of LLNL's underground tank program. In the other three areas, the highest tritium concentrations reported were  $9.4 \times 10^4$ ,  $9.7 \times 10^4$ , and  $1.4 \times 10^5$  pCi/L<sub>sm</sub>, respectively, in soil moisture at the Eastern Landing Mat, West Traffic Circle, and Old Salvage Yard Areas. These areas will be the subject of discussions in future Monthly Progress Reports.

No specific concentration standards currently exist for tritium in soil; however, concentration limits can be derived from exposure standards. Federal regulations (40 CFR 61.92) forbid emissions that would cause any member of the public to receive in any one year a maximum effective dose equivalent of more than 10 millirem per year (mrem/y). Screening level calculations, using the standard EPA code AIRDOSEPA, indicate that no pathways exist from any of the measured tritium concentrations in soil that could exceed 0.01% of this standard. These calculations will be presented in a future Monthly Progress Report.

#### 1.2.3.5. Metals

Ground water samples from most wells monitored by LLNL have been analyzed for antimony, arsenic, barium, beryllium, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, and zinc. Of these, only total chromium and lead occur at levels above MCLs. Lead concentrations exceed the MCL in two wells, both in the Gasoline Spill Area. As reported in the RI, total chromium concentrations exceeded the MCL in 12 wells in the study area. Data collected subsequent to the RI indicate total chromium is present in concentrations above the MCL in a total of 19 monitor wells.

No metals have been detected in unsaturated sediment in concentrations exceeding the State Soluble Threshold Limit Concentrations (STLCs). Sediments were removed at two locations where analyses indicated that metals had accumulated in surficial soils. Screening analyses for the remaining soils indicate no significant health risk.

#### **1.2.3.6. Baseline Public Health Assessment**

We used a two-dimensional analytical flow and transport model to predict the movement of VOCs from the LLNL site toward municipal and domestic water-supply wells, assuming no VOC remediation were to occur. Input parameters were assigned based on the available data and on our conceptual model of the local hydrogeology. Uncertainties in the parameter values associated with VOC transport were addressed by using "best-estimate" (average) and "health-conservative" (worst case) values.

Under best-estimate transport conditions, the maximum incremental risk of developing cancer is  $2 \times 10^{-7}$  from a 70-y (lifetime) exposure to calculated concentrations of VOCs in water obtained from wells in downtown Livermore. Under a health-conservative transport scenario, involving exposure to VOCs by domestic use of water from a hypothetical monitor well drilled 250 ft west of LLNL, the incremental risk of developing cancer is estimated to be  $2 \times 10^{-3}$ . No members of the public are currently exposed to VOCs from the use of wells near LLNL.

## 2. OFFSITE AND GASOLINE SPILL PILOT STUDIES

LLNL is currently conducting two EPA-approved pilot studies within the context of the CERCLA process. The Offsite Pilot Study is evaluating the effectiveness of a test extraction well design, an ultraviolet light/hydrogen peroxide (UV/H<sub>2</sub>O<sub>2</sub>) water treatment system, and a basin to recharge treated ground water. The Gasoline Spill Pilot Study, in the southern part of LLNL, is evaluating the feasibility of venting FHCs from the vadose zone and from a portion of the saturated zone after it is dewatered by pumping. In addition, we are testing a thermal oxidizer for destruction of extracted fuel vapors, and we plan to test a UV/H<sub>2</sub>O<sub>2</sub> unit in the future for treatment of water containing relatively high concentrations of FHCs. Data from these pilot studies were used in the analysis of remedial alternatives in Sections 3 and 4.

### 2.1. OFFSITE PILOT STUDY

The Offsite Pilot Study (Dresen *et al.*, 1987a) was begun in 1988 to:

1. Evaluate the effectiveness of a fully screened and sand-packed extraction well design to hydraulically capture the full vertical thickness of the offsite VOC plume.
2. Compare actual capture areas with those predicted by analytical modeling.
3. Evaluate methods to treat and recharge the extracted ground water.

The goals of the pilot remediation efforts are to:

1. Completely capture all VOCs originating at LLNL and migrating offsite in concentrations above MCLs.
2. Reduce total VOC concentrations in the treated water to less than 5 ppb and below MCLs for individual VOCs.
3. Release no VOCs to the atmosphere from treatment facilities.
4. Demonstrate a system that can reduce residual VOC concentrations in ground water below MCLs.

#### 2.1.1. Test Extraction Well EW-415 Design

Test extraction well EW-415, located in the southwestern part of LLNL (Figure 2-1), was installed in August 1988. We collected sediment samples from a pilot borehole for chemical and grain-size analyses before installing the well. Geologic, geophysical, and grain-size data were then used to design the well. Based on the the grain-size analyses, we selected the optimum filter pack and screen size for the formation materials. Drilling, construction, and development of EW-415 are described in Dresen *et al.* (1988a) and Yukic *et al.* (1988), and construction details are shown in Figure 2-2.

Extraction well EW-415 is continuously screened and sand-packed over six water-bearing zones, from 79 to 179 ft (Figure 2-2), and draws water from the entire thickness of the VOC plume in the area (Dresen *et al.*, 1988a). We employed this design because VOCs occur in sediment of all grain sizes in the local area, and because of the difficulty associated with installing relatively thin grout seals between permeable water-bearing zones in a well with multiple screened intervals.



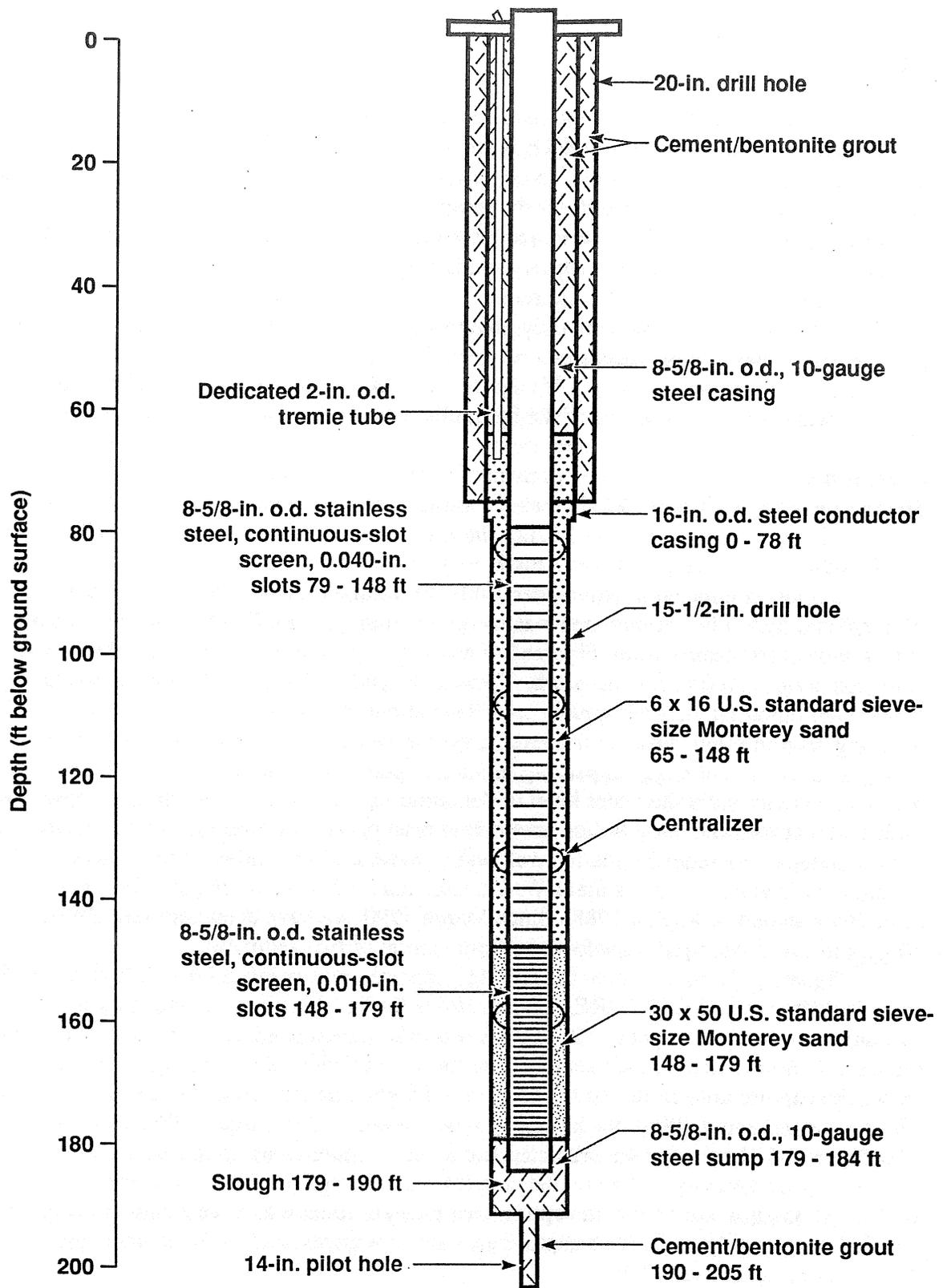


Figure 2-2. Construction details for test extraction well EW-415.

### 2.1.2. Capture Area Analysis

To prevent cross-contamination of water-bearing zones, we pumped EW-415 intermittently while the pilot UV/H<sub>2</sub>O<sub>2</sub> water treatment unit at Treatment Facility A (TFA), described below, was being tested. In September 1989, we began evaluating the hydraulic performance of EW-415 by continuously pumping the well at flow rates ranging from 10 to 80 gallons per minute (gpm). The extracted water was treated at TFA and discharged to LLNL's recharge basin located on DOE property south of East Avenue (Figure 2-1).

Because of maintenance requirements, performance evaluations, and some problems with the TFA control systems, we were only able to pump EW-415 at rates greater than 50 gpm for as long as 7 to 10 days on two occasions between September 1989 and March 1990. A network of over 30 observation wells within a 1500-ft radius was monitored for piezometric data while EW-415 was pumped. Analysis of the hydraulic data from these two high flow tests indicates that we can define hydraulic capture areas (i.e., regions from which water would eventually flow towards the well) for two main depth intervals: 80 to 130 ft and 130 to 185 ft. Pumping at about 50 gpm for 1 wk in October 1989 created capture zones that extended about 500 ft west, 600 ft north, and 450 ft south of EW-415 in the shallow zone; and about 350 ft west, 600 ft north, and 650 ft south in the deeper zone (Figures 2-3 and 2-4).

In a test conducted in November 1989, we pumped EW-415 at about 65 gpm for 9 days. The induced hydraulic capture area was larger, extending about 700 ft west in the upper zone and 500 ft west in the deeper zone (Figures 2-5 and 2-6). In both depth intervals, the capture zone extended about 700 ft north and south. Toward the end of this 9-day pumping period, the water level in the pumping well fell rapidly to a depth about 90 ft below the original level. The resulting drop in water pressure triggered a system shutdown at TFA. Prior to the shutdown, fine-grained sediment began appearing in the pumped water, and one nearby observation well began to recover while the water level in the pumping well was still dropping. These data indicated that the sand pack and/or screen in at least part of the well may have become plugged with sediment. We redeveloped the well and re-evaluated its efficiency in January 1990. Preliminary analysis indicates that EW-415 was more efficient in January 1990 than when initially evaluated in August 1988. Since March 1990, we have been pumping EW-415 at about 50 gpm to avoid the rapid drawdown and production of fine sediment.

Figures 2-7 and 2-8 show the EW-415 capture areas predicted by the two-dimensional analytical flow model CAPTURE. This model is further described in Appendix B. The hydraulic conductivity input to CAPTURE was determined from hydraulic tests on EW-415. Figure 2-7 shows the predicted capture area for an extraction rate of 50 gpm, and Figure 2-8 shows the capture area predicted for 65 gpm. The predicted 50-gpm capture area extends about 450 ft west and about 600 ft north and south of EW-415. Comparison of Figures 2-3 and 2-4 with Figure 2-7 shows that the predicted and actual capture areas agree remarkably well, despite the geologic complexity and given the simplifying assumption of homogeneity of the CAPTURE model. At 65 gpm, the predicted capture area extends about 600 ft west and 750 ft north and south of the pumping well. This capture area also compares well to the actual capture areas shown in Figures 2-5 and 2-6.

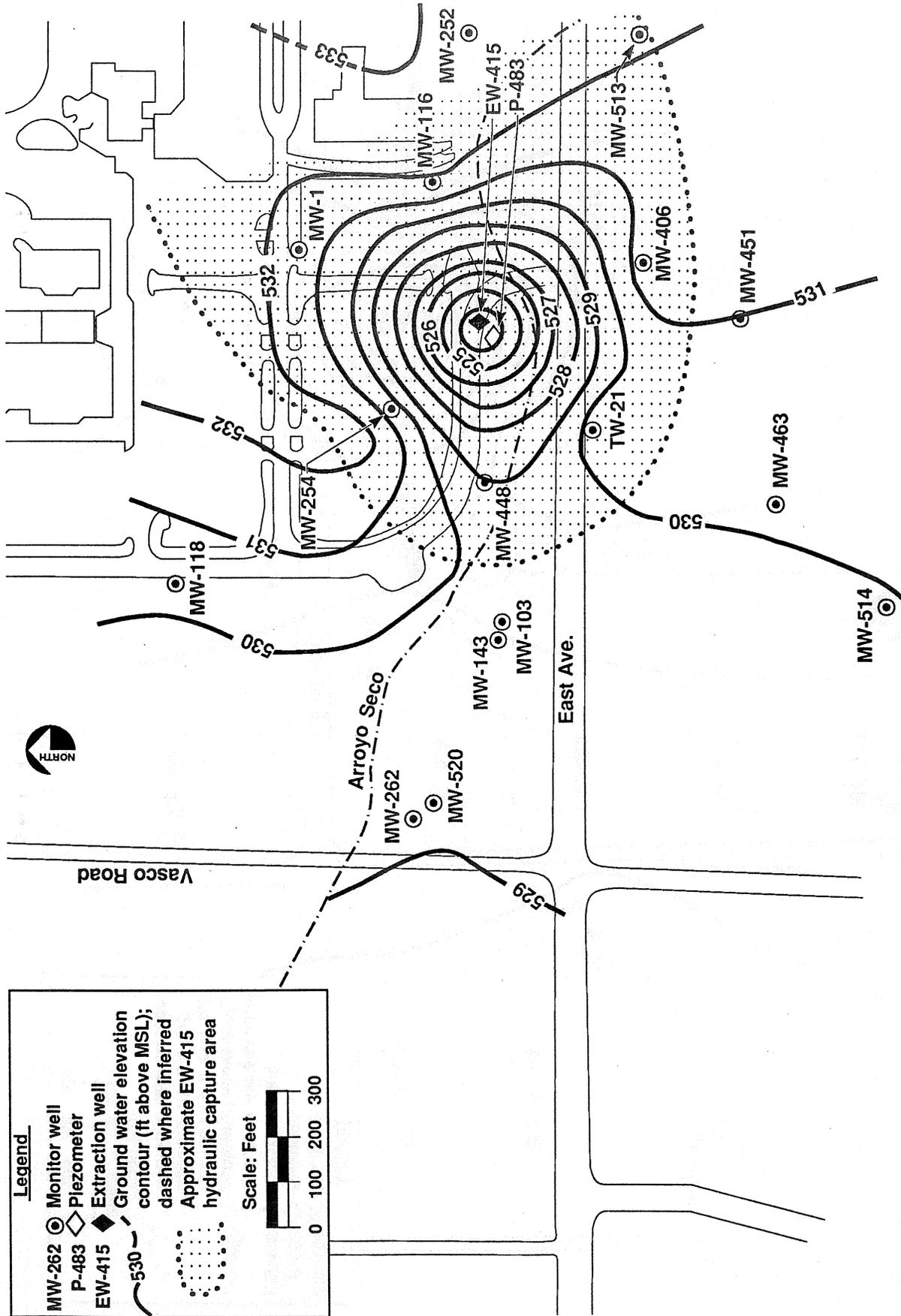


Figure 2-3. Hydraulic capture area for the 50-gpm EW-415 pumping test, September 1989; wells screened between 80- and 130-ft depth.

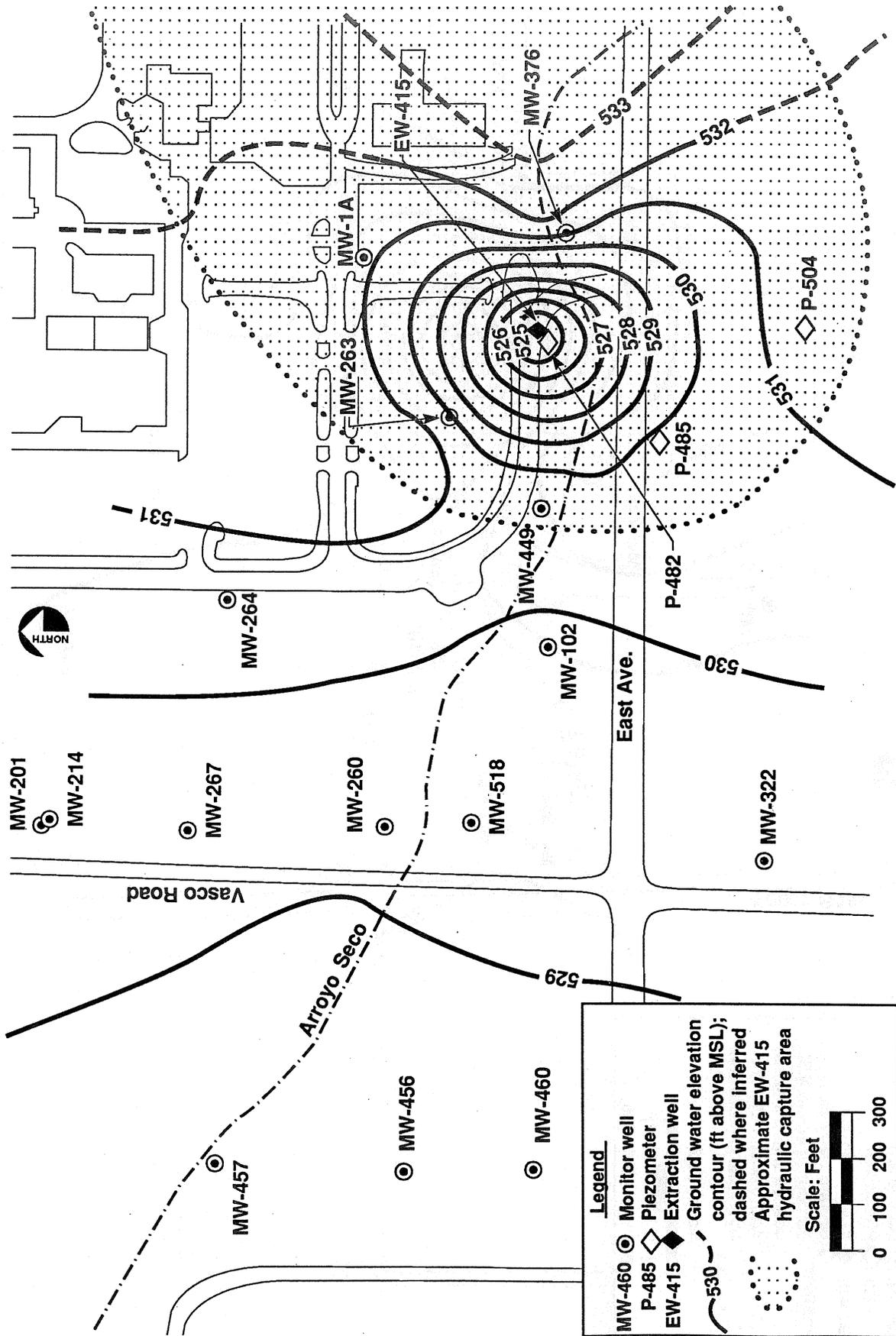


Figure 2-4. Hydraulic capture area for the 50-gpm EW-415 pumping test, September 1989; wells screened between 130- and 185-ft depth.

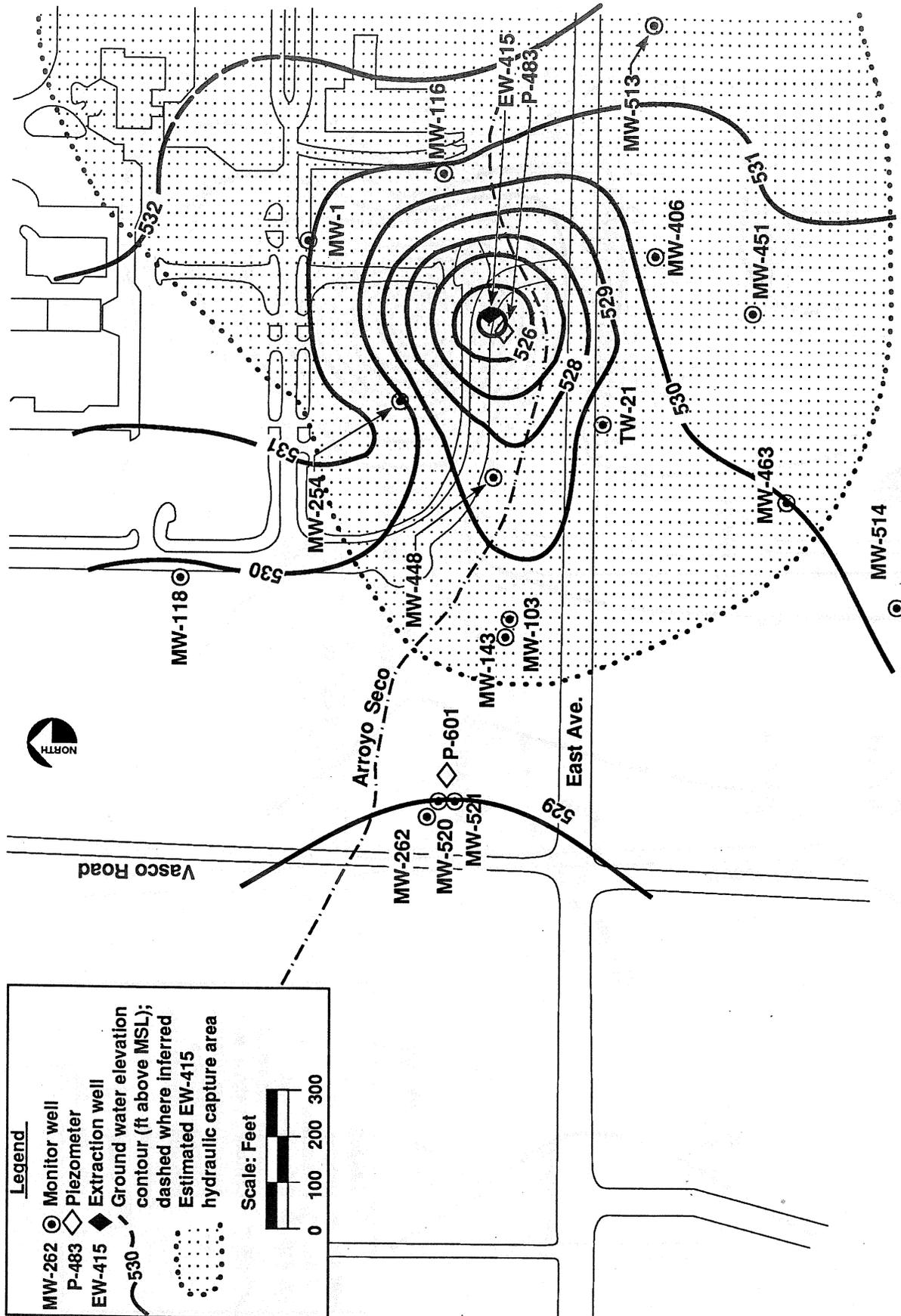


Figure 2-5. Hydraulic capture area for the 65-gpm EW-415 pumping test, November 1989; wells screened between 80- and 130-ft depth.

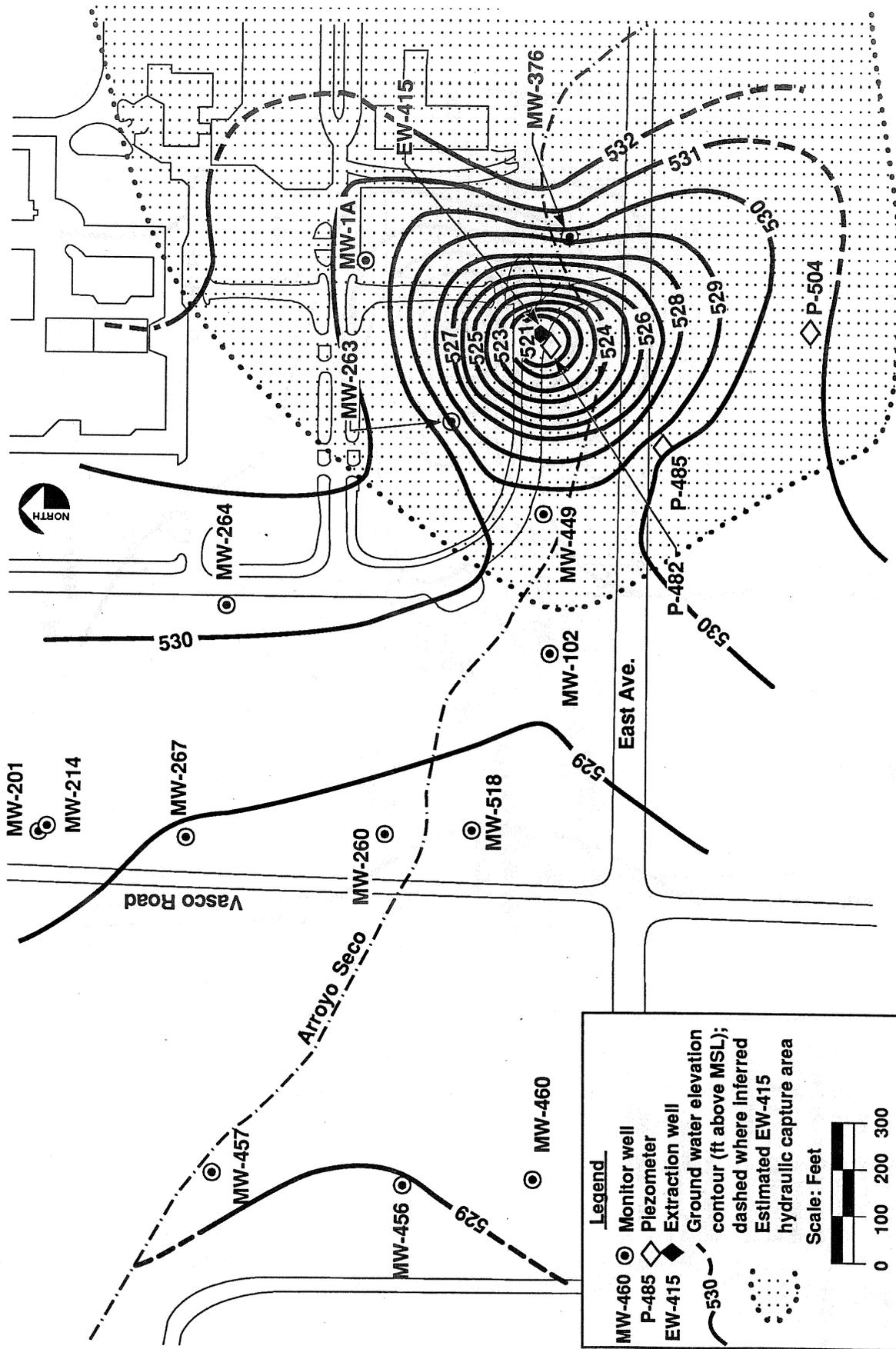


Figure 2-6. Hydraulic capture area for the 65-gpm EW-415 pumping test, November 1989; wells screened between 130- and 185-ft depth.





### 2.1.3. Future Extraction Wells

Data collected thus far indicate that EW-415 can effectively capture a significant portion of the VOCs in the Southwest Corner/Offsite Area. Compared to wells screened only in permeable zones, its fully screened and filter-packed design is probably more effective in removing VOCs from both coarse- and fine-grained sediment, a condition present near source areas at LLNL (Thorpe *et al.*, 1990). However, the fully screened and sand-packed design of this well has limitations that were recognized before the well was installed, including:

1. Inability to pump a zone, or zones, selectively and/or at different flow rates.
2. Difficulty in assessing the flow and VOC-mass removal rates for individual zones.
3. The potential to produce fine-grained sediment in water pumped from the screened silts and clays, which could clog the well screen.

In view of these limitations, we are considering alternative designs for future pilot study extraction wells. Analyses of saturated sediment and ground water indicate that VOCs are present in all sediments within the plume within several hundred feet of a source area (Thorpe *et al.*, 1990). However, at greater distances from the source, VOCs are limited to the more permeable sediments (Rice *et al.*, 1990). In such areas, we may install a single well in each interval requiring remediation. This approach offers maximum flexibility for assessing VOC-mass removal from each zone, and enables the pumping of each zone at an optimum flow rate and/or different flow rates over time. In addition, the shutdown of one well in the cluster would not result in cessation of all extraction at that location. We are currently testing this extraction approach at a cluster of wells just south of TFA, near MW-262 (Figure 2-1).

An alternative approach is to install a single well completed in all permeable zones, with grout seals installed in the well annulus adjacent to selected intervals (Figure 2-9). This design would allow isolation of an individual zone, or zones, with packers for selective pumping and sampling for VOCs. However, it does not provide the same degree of flexibility as would individual, single-zone wells. Our experience with test vent/extraction well GSW-16 in the LLNL Gasoline Spill Area shows that it is difficult to install multiple grout seals in a single well without risk of grouting portions of the well screen, especially where the distance between screens is less than 5 to 10 ft.

A third approach is to install wells completed in more than one zone with grout seals between permeable zones, but limiting each well to two or perhaps three screens (Figure 2-10). In these wells, grout seals would be installed only when the minimum thickness of grout is about 7 to 10 ft. These measures would reduce the risk of grouting portions of the well screen and would provide additional flexibility compared to the fully screened and sand-packed single-well design.

For future pilot study extraction wells, we will be evaluating the advantages and disadvantages of these designs with respect to plume thickness, vertical distribution of VOCs, number of permeable zones requiring remediation, and proximity to VOC source areas.

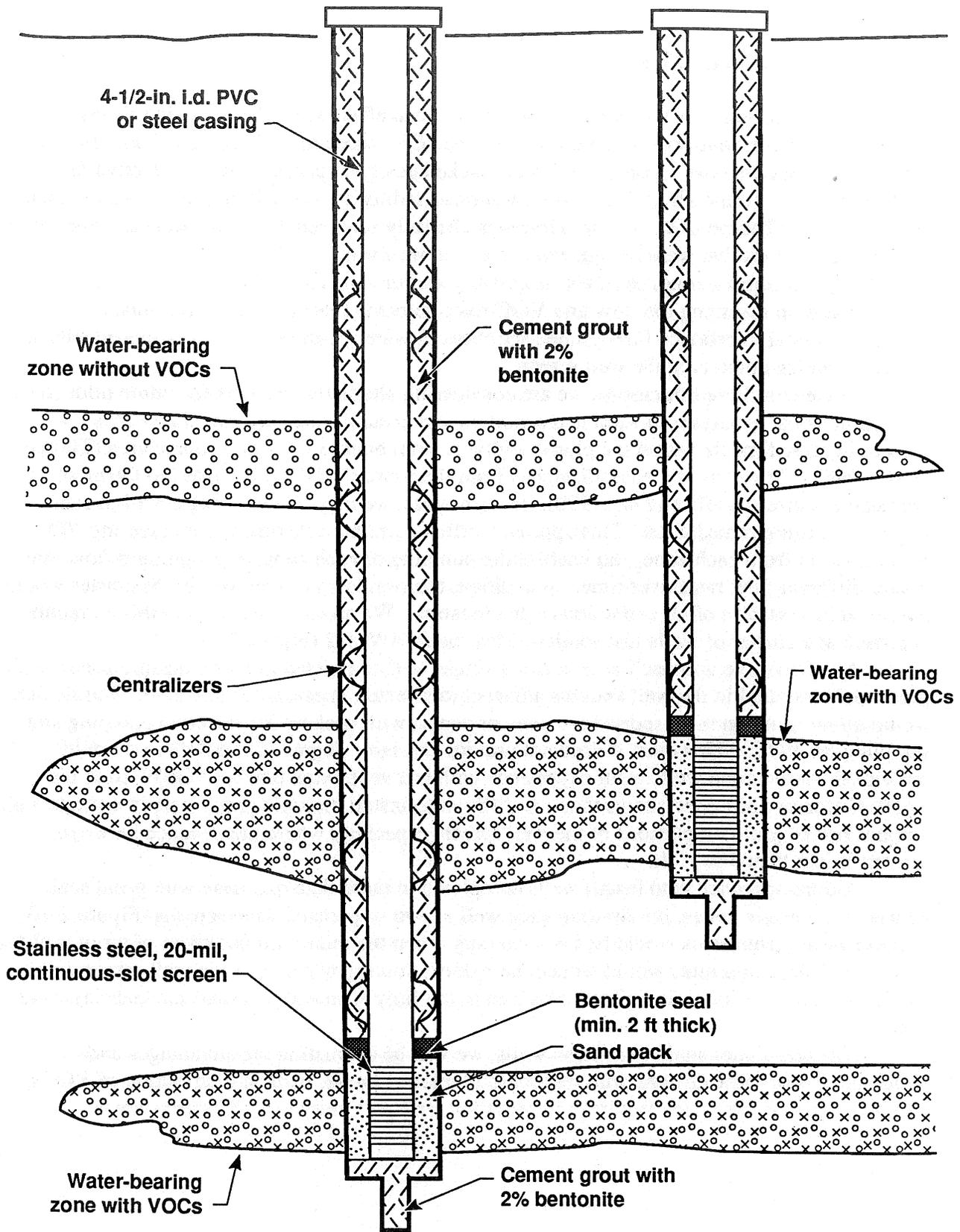


Figure 2-9. Schematic diagram of single-zone extraction wells.

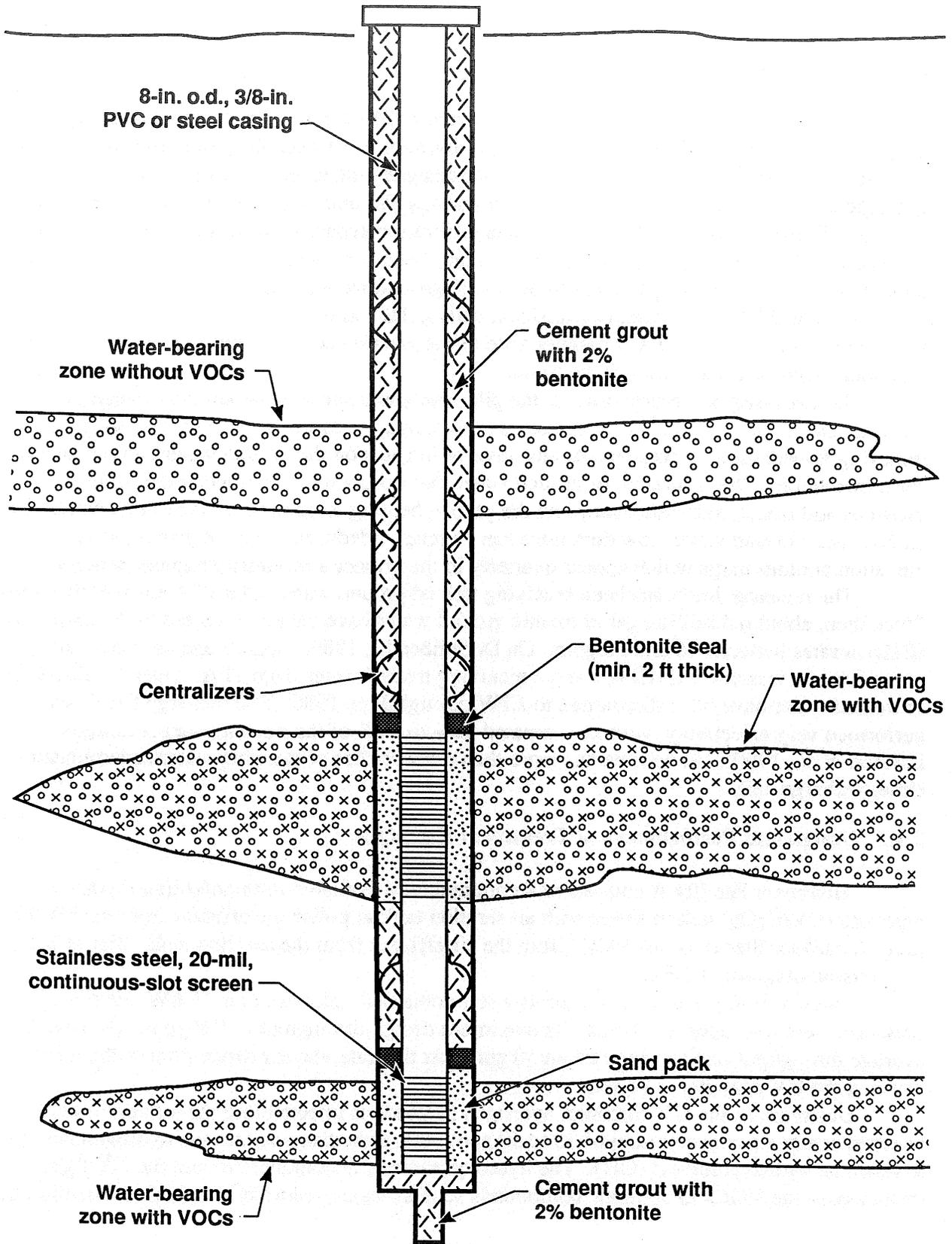


Figure 2-10. Schematic diagram of extraction well completed in multiple zones.

#### 2.1.4. LLNL Recharge Basin

In 1988, LLNL constructed a recharge basin south of East Avenue on DOE property administered by Sandia National Laboratory to investigate the feasibility of conserving the local ground water resource by surface recharge. We designed the recharge basin on the basis of geologic and hydraulic data from exploratory borings and trenches, as reported in Dresen *et al.* (1988b). These data indicate that the average infiltration capacity of the local alluvial sediments is approximately 1.9 ft/day. Incorporating a safety factor of 5 yielded a design infiltration rate of about 0.4 ft/day. To recharge 100 gpm of treated ground water, a recharge area of 500 ft by 100 ft was required. Therefore, two adjacent cells (E1E and E1W) of this size were constructed to allow for periodic resting and maintenance of the inactive cell. Figures 2-11 and 2-12 show plan and cross-sectional views of the basin.

As discussed in the proposal for the pilot study and subsequent Monthly Progress Reports, the recharge basin was constructed in a clean area, south of the region identified as requiring remediation. This prevents any adverse impacts on the ground water capture necessary for remediation. The mounding of ground water that occurs with recharge in the basin also provides additional hydraulic control on the plume, helping to contain contaminants within the LLNL site. Ground water flow directions can be readily deduced from the ground water elevation contour maps which appear quarterly in the project's Monthly Progress Reports.

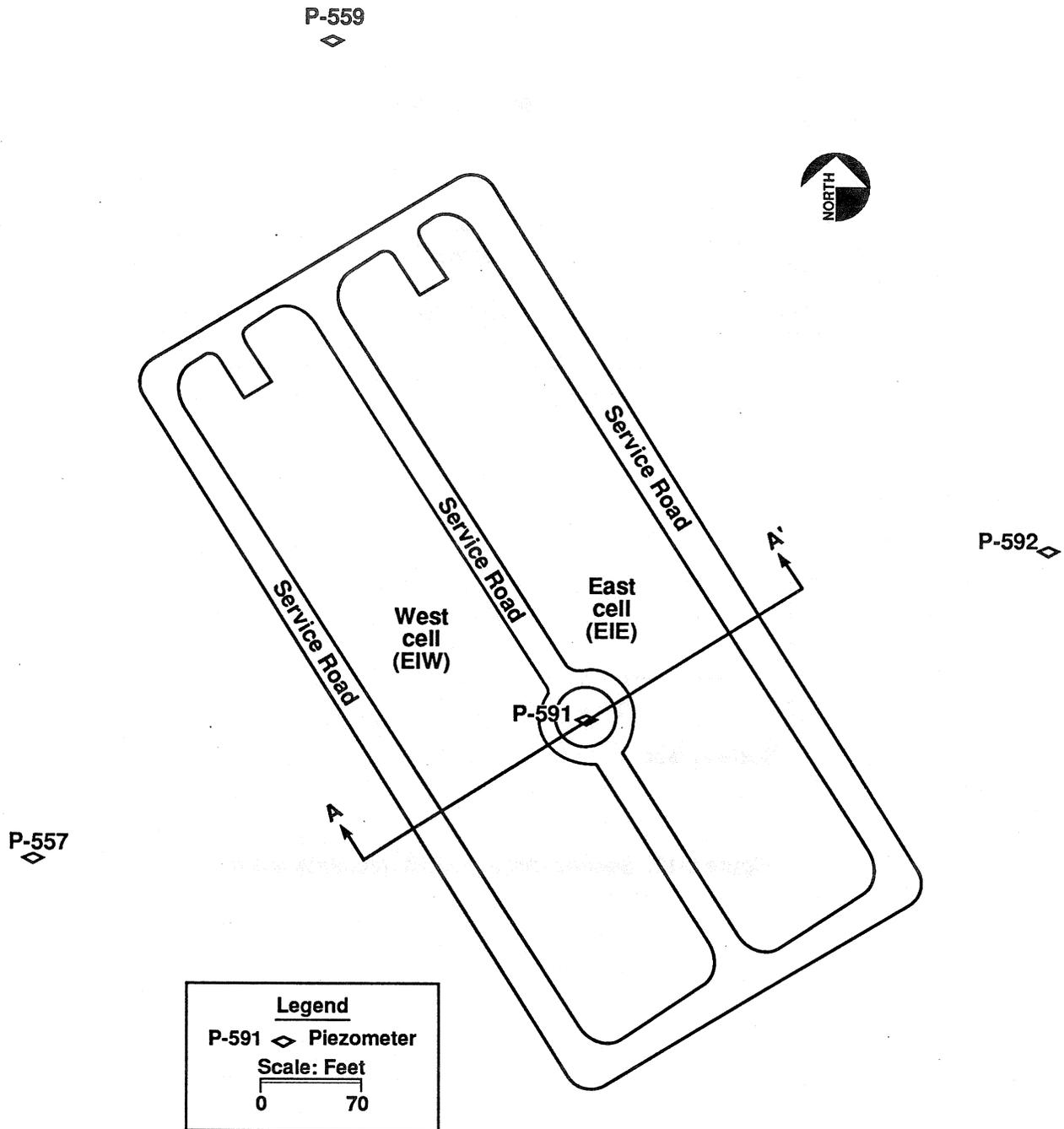
The recharge basin has been receiving treated ground water from TFA since early 1989. Since then, about 6.5 million gal of treated ground water have been discharged to the eastern cell (E1E) at rates between 20 and 70 gpm. On December 12, 1989, roughly one year from start of operation, the western cell (E1W) began receiving treated water from TFA. Over 6 million gal of treated water have been discharged to E1W through May 1990. The recharge basin has performed very effectively, with an estimated 92% to 98% of the treated water recharged (see Lawson *et al.*, 1990). At no time has more than a few inches of standing water accumulated in either recharge cell.

#### 2.1.5. Design and Performance of Treatment Facility A

Treatment Facility A consists of a commercially available ultraviolet light/hydrogen peroxide (UV/H<sub>2</sub>O<sub>2</sub>) unit in series with an aeration tank to polish the effluent from the UV/H<sub>2</sub>O<sub>2</sub> unit. A carbon filter removes VOCs from the air effluent from the aeration tank. Figure 2-13 is a schematic diagram of TFA.

The UV/H<sub>2</sub>O<sub>2</sub> treatment system is a self-contained unit with four 15-kW, medium pressure, mercury-vapor UV bulbs. Its maximum design throughput is 100 gpm. To date, the average throughput rate has been about 50 gpm. At this rate, the residence time of the influent water in the UV chamber is 90 sec.

Upstream of the UV chamber, hydrogen peroxide is injected into the influent ground water to achieve a concentration of 30 to 50 ppm. UV light disassociates the hydrogen peroxide to form the hydroxyl radical (OH). The hydroxyl radical, in conjunction with the UV light, decomposes the VOCs to nontoxic compounds such as water, chloride ions, and carbon dioxide.



Note: See Figure 2-1 for location of recharge basin

Figure 2-11. Plan view of LLNL recharge basin.

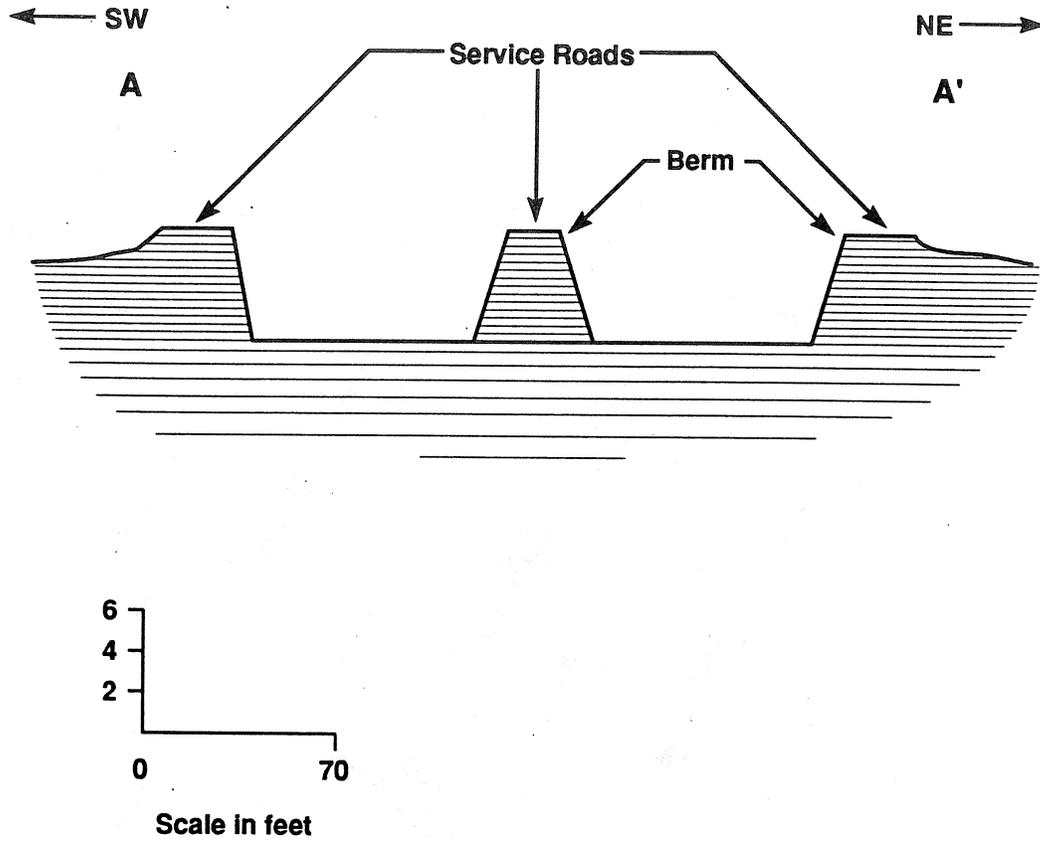


Figure 2-12. Section through LLNL recharge basin.

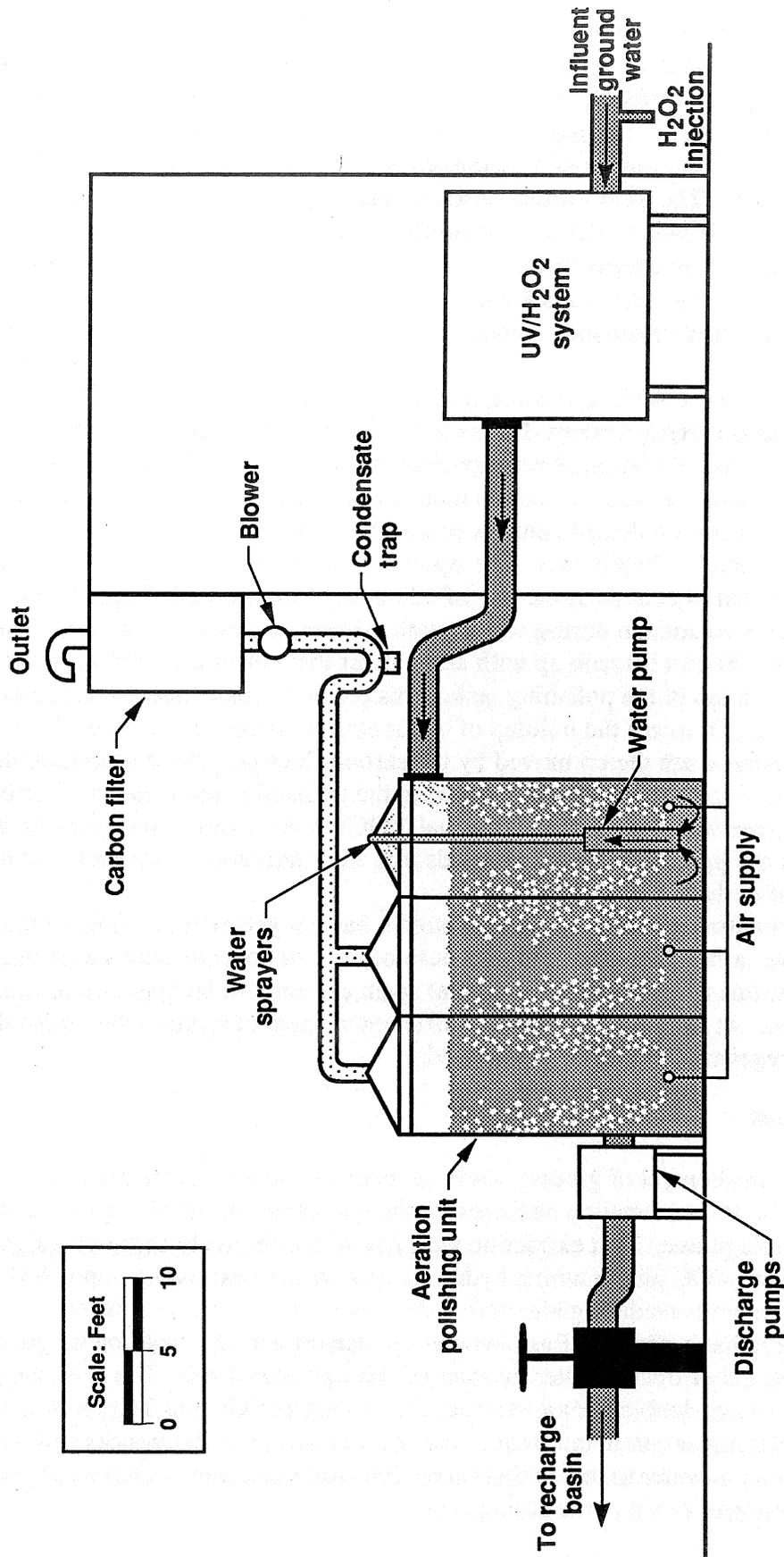


Figure 2-13. Schematic diagram of Treatment Facility A.

The UV/H<sub>2</sub>O<sub>2</sub> treatment unit efficiently destroys PCE and TCE. These compounds have a double carbon bond that is photoreactive and readily broken under the influence of UV radiation and the hydroxyl radical. We have obtained destruction efficiencies of 97% to 98% with the double-carbon-bonded compounds (haloalkenes). Since the start of operation, the influent PCE concentrations have decreased from an initial value of about 800 ppb to about 150 ppb (Figure 2-14). The TFA influent also contains the incidental compounds 1,1,1-trichloroethane (1,1,1-TCA), 1,1-DCA, chloroform, and Freon-113 individually below their MCLs, but cumulatively in excess of LLNL's discharge limit. Analyses of treated water from the UV/H<sub>2</sub>O<sub>2</sub> unit show that the haloalkanes 1,1,1-TCA and 1,1-DCA, with their single carbon bonds, are not completely destroyed. Table 2-1 summarizes TFA destruction efficiencies for various VOCs.

Because we were unable to achieve total destruction of the haloalkanes, we added an aeration tank to the UV/H<sub>2</sub>O<sub>2</sub> system (Figure 2-13) in order to meet the water discharge limits required by our National Pollution Discharge Elimination System (NPDES) permit; this permit limits our treated discharge water to <5 ppb total VOCs and less than MCLs for individual VOCs. The aeration system design consists of a baffled 1400-gal tank that receives the effluent water directly from the UV/H<sub>2</sub>O<sub>2</sub> unit. The water is then subjected to intense aeration using a centrifugal blower that injects air at the rate of 150 cfm. Another centrifugal blower extracts the air, including VOCs volatilized during the aeration process, at a rate of 250 cfm. This air flow rate differential of 100 cfm is made up with ambient air that enters the exhaust-air stream through screened vents at the top of the polishing tank. This prevents volatilized VOCs from escaping to the atmosphere and minimizes the buildup of condensation in the carbon filter. Any volatilized VOCs in the air exhaust are then removed by the carbon filter prior to atmospheric discharge. The concentration of total VOCs in water entering the polishing tank is about 10 ppb, and the aeration process generally reduces these residual VOCs in the water to less than the analytic detection limit of 0.5 ppb. The carbon filter adsorbs all volatilized VOCs such that no detectable VOCs are emitted to the air from TFA.

Regular monitoring of the exhaust air stream has not yet indicated breakthrough of any VOCs through the carbon filter, no doubt because of the low concentrations entering the aeration polishing unit. At this time it is anticipated that spent carbon will be disposed of rather than regenerated onsite. At such time as there is sufficient volume of spent carbon from this and other facilities, onsite regeneration will be considered.

### 2.1.6. Conclusions

Almost 20 million gal of ground water has been extracted, treated, and discharged through May 1990. Pilot extraction has arrested the movement of the highest concentration portion of the offsite plume. Test extraction well EW-415 effectively captures a significant portion of the offsite VOC plume with a hydraulic capture area extending about 600 ft from the well. However, we are considering alternative designs for future pilot study extraction wells. The LLNL recharge basin south of East Avenue has performed very well, recharging about 95% of the 12.5 million gal of treated water discharged through May 1990. The UV/H<sub>2</sub>O<sub>2</sub> treatment system at TFA destroys double carbon bonded VOCs such as PCE and TCE with a 97% to 98% efficiency. A polishing aeration unit with a carbon filter successfully reduces residual VOC concentrations in water to below discharge limits of 5 ppb total VOCs and prevents discharge of volatilized VOCs to the atmosphere.

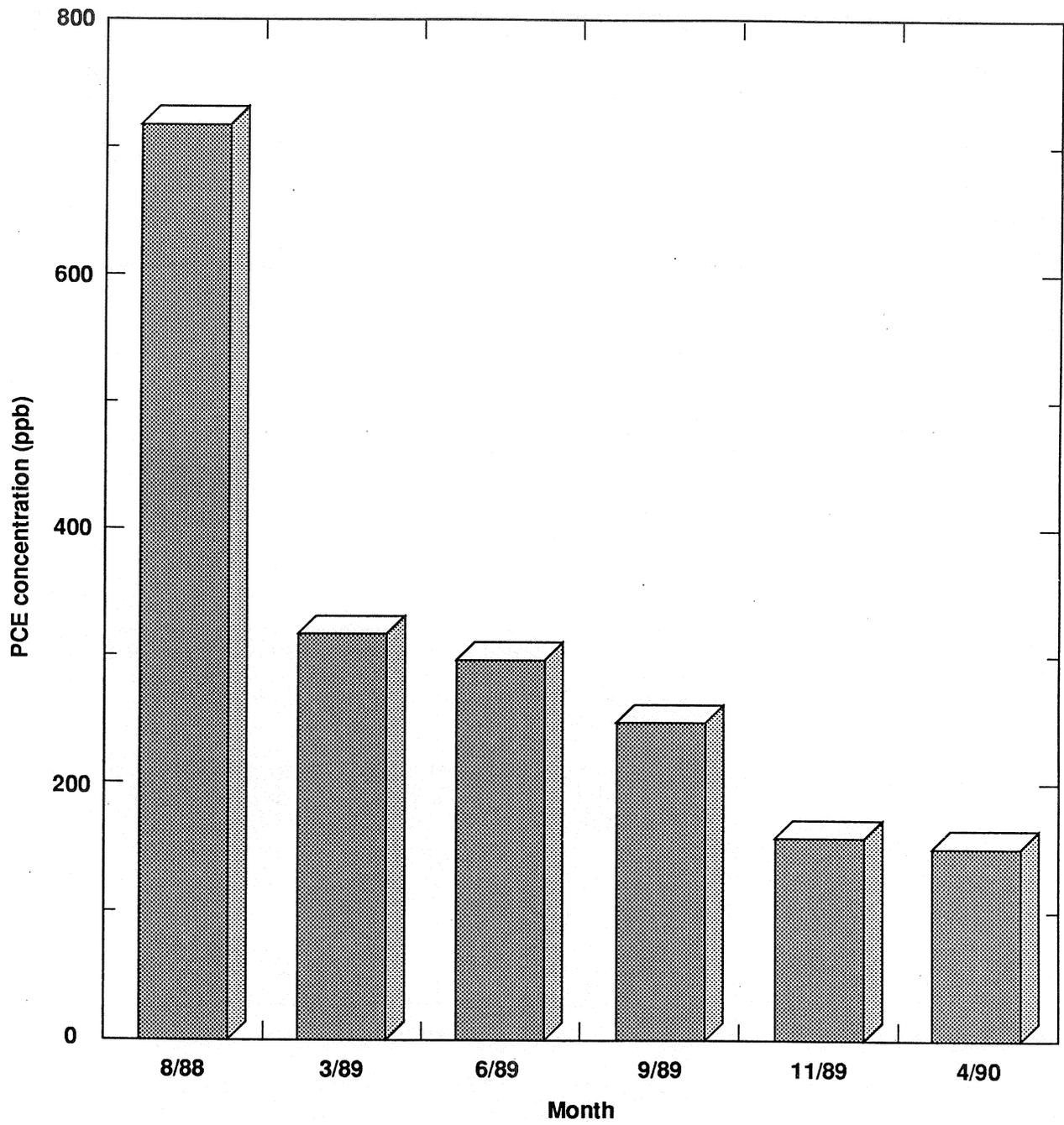


Figure 2-14. Average monthly PCE concentrations from EW-415 (influent to Treatment Facility A).

Table 2-1. Treatment Facility A performance results (typical data set, August 16, 1989).

	UV/H <sub>2</sub> O <sub>2</sub> unit		Polishing system	Air discharge at carbon-filter outlet (ppb <sub>v/v</sub> )
	Influent (ppb)	Effluent (ppb)	water Effluent (ppb)	
PCE	140	4	<0.5	<1
TCE	4	<1	<0.5	<1
1,1-DCE	13	<1	<0.5	<1
1,1-DCA	4	2	<0.5	<1
1,1,1-TCA	9	8	<0.5	<1
Chloroform	2	2	<0.5	<1
Freon 113	7	6	<0.5	<1

## 2.2. GASOLINE SPILL PILOT STUDY

As discussed in Dresen *et al.* (1986), Nichols *et al.* (1988), and Thorpe *et al.* (1990), about 17,000 gal of leaded gasoline were lost from a U.S. Navy-era underground tank between 1952 and 1979 in the Gasoline Spill Area. Because the water table in this area is about 100 ft deep, conventional excavation techniques and aboveground venting are not feasible in this area for remediation of FHCs. Therefore, *in situ* vacuum-induced venting is being evaluated to remove FHCs from the subsurface. We are testing a thermal oxidizer for destruction of gasoline vapor, and plan to test a UV/H<sub>2</sub>O<sub>2</sub> water treatment unit as well.

To evaluate the effectiveness of vacuum-induced venting for cleanup of the FHCs, we designed and installed a combination ground water and vapor extraction well, GSW-16, near the fuel leak site in the Gasoline Spill Area. This well is designed to allow:

- Venting of hydrocarbons from the vadose zone.
- Dewatering of the saturated zone containing the highest concentrations of FHCs.
- Venting of the newly dewatered zone. (Trapped free product exists below the present water table because of water table rise.)
- Skimming of any free product from the water surface.

The components of the pilot system are shown schematically in Figure 2-15 and include:

1. Combination vapor and ground water extraction well GSW-16.
2. Two gasoline skimmers, one below ground and the other above ground.
3. A thermal oxidizer for destroying FHC vapors.
4. A UV/H<sub>2</sub>O<sub>2</sub> water treatment system.

Although the complete system, including the UV/H<sub>2</sub>O<sub>2</sub> unit described above, is not yet operational, we have intermittently tested a gasoline skimmer, the vapor extraction well, and a thermal oxidizer since September 1988. We calculate that about 6000 gal liquid equivalent of gasoline vapor has been removed from the subsurface between September 1988 and October 1990. This quantity was calculated using the concentration and mass flow rate data for the FHC vapor removed through vacuum extraction. An additional 100 to 150 gal of hydrocarbons has been removed by skimming free product from the top of the water table.

The concentration of the extracted FHC vapor has averaged between 2500 ppm and 4000 ppm, and the flow rate has been 50 to 60 cfm. FHC vapor concentrations from the uppermost screened interval (23- to 28-ft depth, Figure 2-16) have decreased significantly relative to the initial concentration of about 2500 ppm. Because vapor concentrations from this uppermost interval are now less than 100 ppb and have reached a point of diminishing returns, vacuum-induced venting is now performed only on the deeper vadose zone screens, which still yield higher concentrations of FHCs.

### 2.2.1. Ground Water and Vapor Extraction

Test vent/extraction well GSW-16, was installed near the center of the gasoline spill to vent hydrocarbon vapors and extract ground water containing gasoline components. As ground water pumping progresses, FHC vapors will be extracted by vacuum-induced venting from both the unsaturated zone and the newly dewatered zone within GSW-16. The vacuum system will be designed to produce flow rates up to 300 cfm.

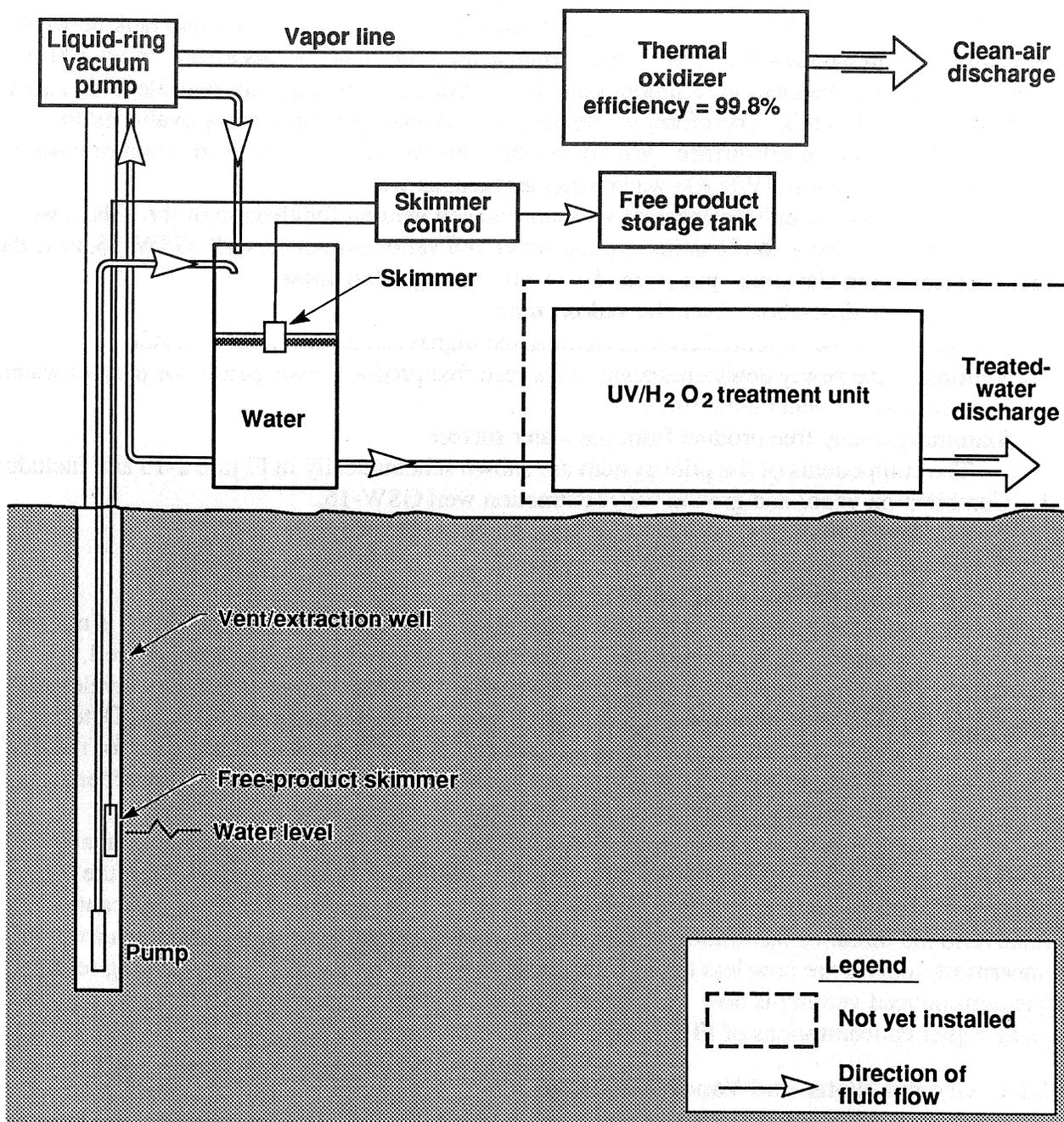


Figure 2-15. Pilot treatment system at the Gasoline Spill Area.

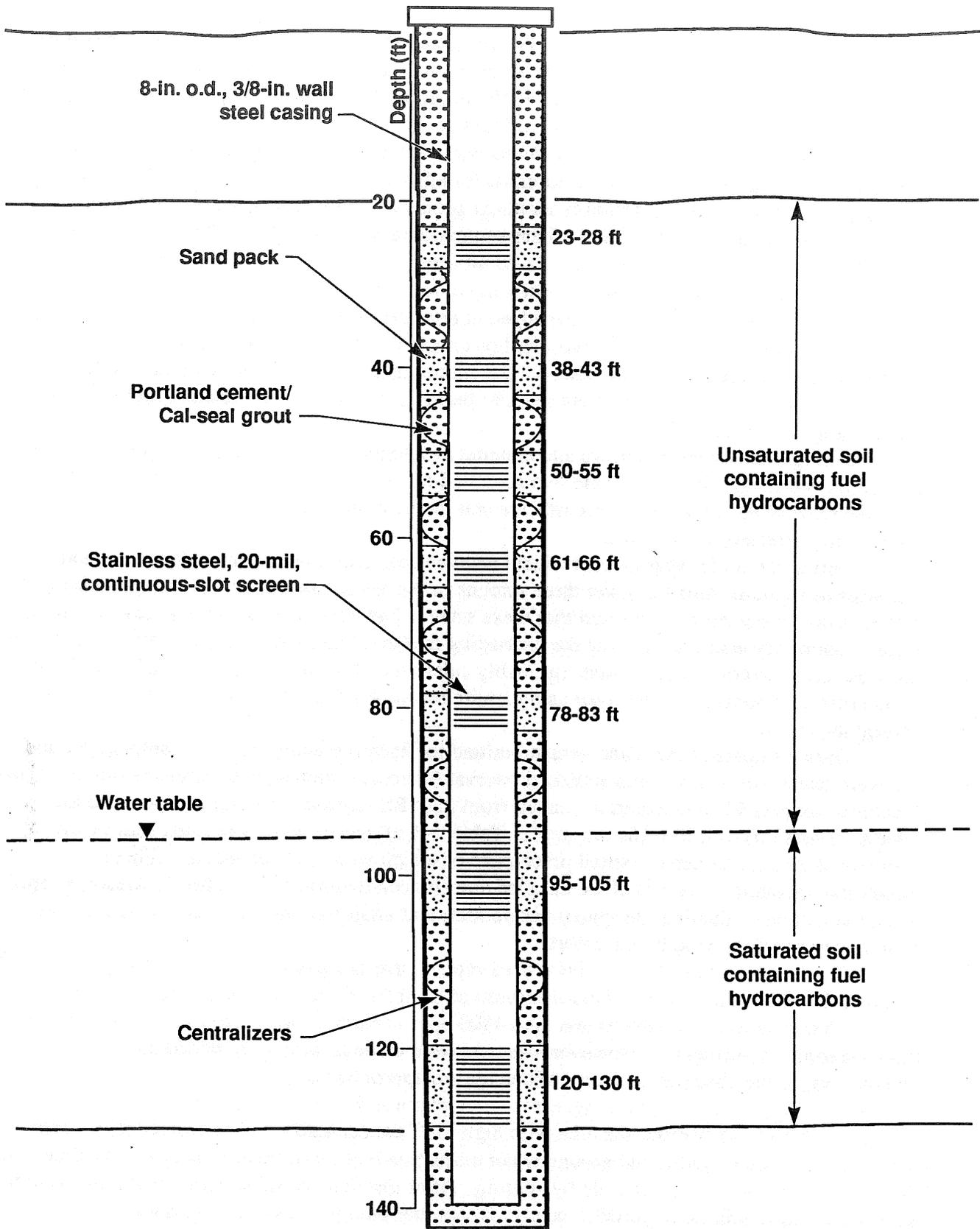


Figure 2-16. Schematic diagram of test vent/extraction well GSW-16.

In the fall of 1987, we installed GSW-16, using an air-rotary casing hammer system to minimize formation damage in the vadose zone. Construction details are shown in Figure 2-16. The 8-in. casing size was chosen to allow sufficient room for a pump discharge line, a downhole skimmer, and packers for isolating zones of interest.

The GSW-16 screened intervals were chosen based on soil hydrocarbon analyses of sediment and lithologic data from the borehole for adjacent monitor well GSW-15, which has similar screened intervals and virtually identical geology. The lithology and hydrocarbon distribution in the borehole for GSW-15 are summarized in Figure 2-17. The vadose zone screens in GSW-15 and GSW-16 were placed adjacent to intervals with the highest concentrations of FHCs, which occur mostly in silt and clay (Figure 2-17). To prevent "short circuiting" or preferential flow from the adjacent coarse-grained layers, cement grout seals were installed between intervals of high hydrocarbon concentration in the vadose zone. The two screens in the saturated zone were placed adjacent to the more permeable sediments to facilitate dewatering. Below the water table, these more permeable sediments correlate with the higher concentrations of FHCs.

During well construction, we encountered problems installing the grout seals; some grout entered the well, partially coating the two saturated-zone screens. A wire brush effectively removed most of the grout, and tests indicate that the hydraulic efficiency of the well has not been greatly affected by the grout.

During the initial year of intermittent test venting, decreases in vapor flow rates and increases in vacuum from the lower three screens in the unsaturated zone were noted (see Figure 2-18). A downhole camera revealed that these screens had developed a slight to heavy coating of scale. Laboratory tests showed that the encrusting material had high hydrocarbon concentrations and was composed of mineral matter (probably calcium carbonate, in part) and bacteria. When the encrusting material was removed using a wire brush, vacuums and vapor flow rates returned to original levels.

Three samples of the scale were submitted for bacterial analysis. Two samples, B1 and B2, were taken from the seventh screened interval (deepest saturated zone screen) (Figure 2-16). The third sample, S2, was material scraped from the fifth screened interval (deepest vadose screen, 78 to 83 ft) of GSW-16. As seen in Table 2-2, all the samples contained significant numbers of aerobic bacteria, a small percentage of which were methanotrophs (able to metabolize methane). As part of the detailed site characterization planned for the Gasoline Spill Area, we will be evaluating the spatial distribution and vitality of the bacteria population and how they may affect remediation efforts.

Concentrations of FHCs in the vented vapors have decreased over time, as shown in Figure 2-19. Concentrations of TFH measured at the inlet of the thermal oxidizer decreased from 16,000 ppm in early 1989 to less than 4000 ppm in early 1990. (See discussion on "Vadose Zone Heating Experiment.") However, changes were made in sampling procedures over this time period, so the absolute measures of change are approximate.

A 5-day continuous pumping test is being planned for mid- to late-1990 to evaluate the ability of GSW-16 to dewater the area with high FHC concentrations. The results of that test will indicate whether additional ground water extraction wells will be necessary to remediate the FHCs below the current water table by venting. After installation of the water treatment system, additional testing will be required to determine optimal pumping and vacuum rates for

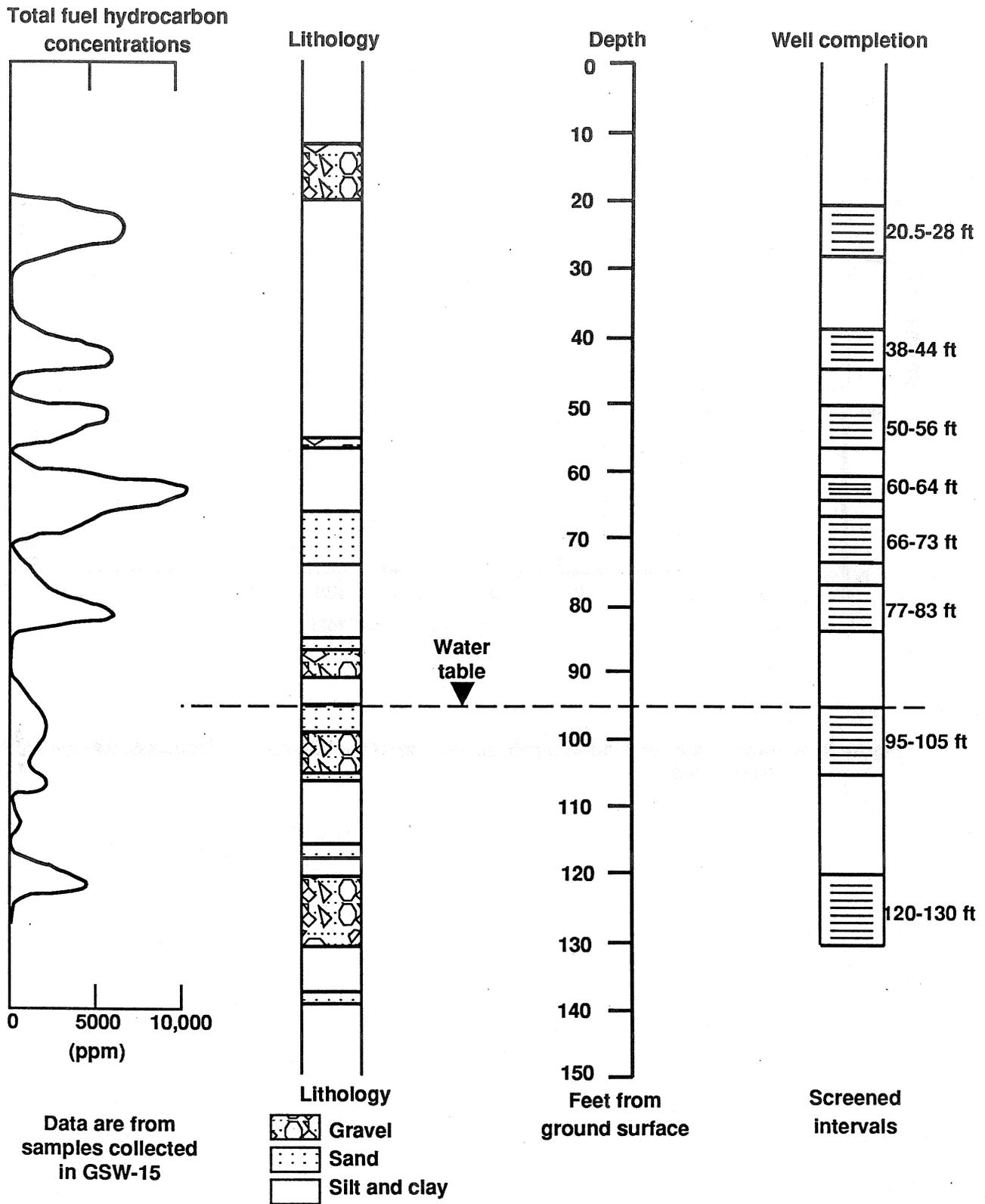


Figure 2-17. Total fuel hydrocarbons in sediment, generalized borehole stratigraphy, and screened intervals in monitor well GSW-15.

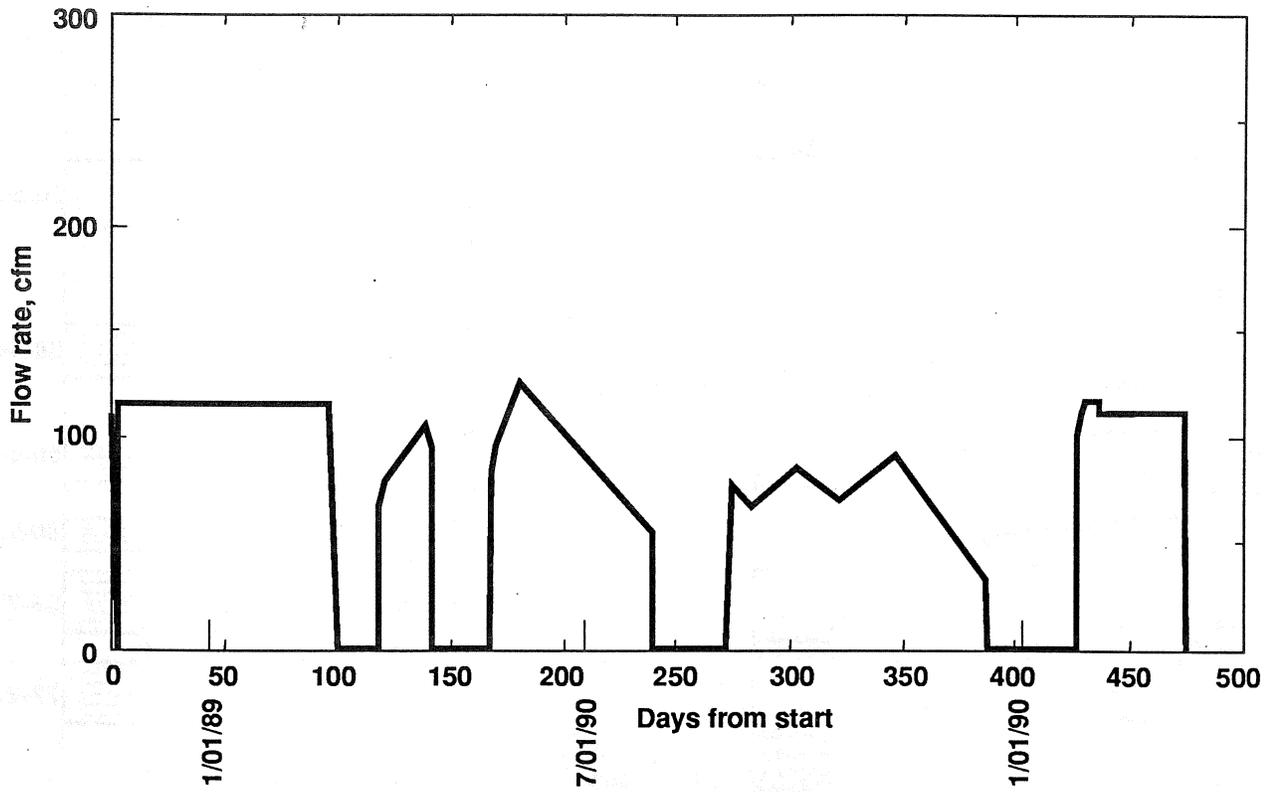


Figure 2-18. Flow rate from vacuum-induced venting of well GSW-16, December 1988 through March 1990.

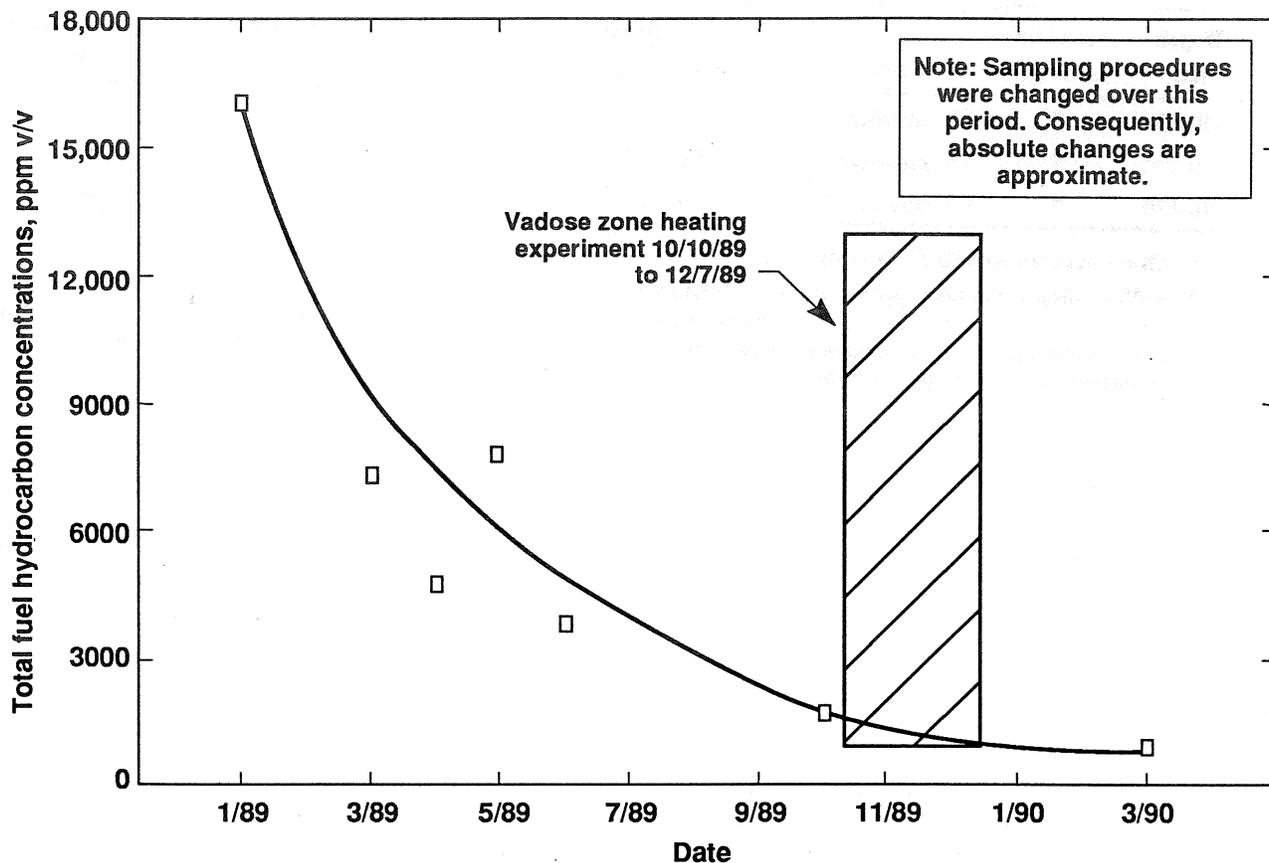


Figure 2-19. Vapor concentrations of fuel hydrocarbons during vacuum-induced venting.

Table 2-2. Bacteria analyses from scale coating GSW-16 screen.

Depth (ft)	Screened interval	Sample	LB medium <sup>a</sup> (colonies/g of sample)	NMS medium <sup>b</sup> (colonies/g of sample)	Methanotrophs <sup>c</sup> (%)
78-83	5	S2, unsaturated	$3.0 \times 10^9$	$1.6 \times 10^7$	0.5
120-130	7	B1, saturated	$2.3 \times 10^5$	$8.4 \times 10^3$	4
120-130	7	B2, saturated	$1.0 \times 10^6$	$1.4 \times 10^5$	14

<sup>a</sup> LB = Luria (an enriched medium) broth.

<sup>b</sup> NMS = Nitrate minimum salts (a minimal medium).

<sup>c</sup> One set of samples was plated and incubated in air. A second set was plated and incubated in a one-to-one mixture of air to methane. The air-methane incubation colony counts minus the air incubation colony counts equals the number of methanotrophs present.

dewatering. Additional monitor well clusters are planned for installation in the vadose zone by mid-1990 to monitor the radius of influence of the GSW-16 vapor extraction. A soil vapor survey will be used to assist in the siting of these clusters.

### 2.2.2. Treatment of Gasoline Vapor and Ground Water

As shown in Figure 2-15, the vacuum extraction system in the Gasoline Spill Area uses a liquid ring vacuum pump as the vacuum source. Vacuum is applied to any combination of the five screened areas in the vadose zone by using packers to isolate zones of interest. During routine operation, the vacuum extraction system operates at about 15 in. of mercury with a flow rate of about 60 cfm. The hydrocarbons in the vapor are destroyed in the thermal oxidizer at an efficiency of greater than 99% (Table 2-3). These FHCs oxidize to CO<sub>2</sub> and H<sub>2</sub>O. The data in Table 2-3 reflect two different sets of data used to determine the efficiency of the thermal oxidizer. The first set of data represents source tests performed by the Bay Area Air Quality Management District and LLNL in June 1989. Efficiency was calculated based on total fuel hydrocarbon concentrations. The second set of data is representative of tests regularly performed during operation of the thermal oxidizer. These weekly efficiencies are calculated based on total BETX concentrations. Propane is used as supplemental fuel to ensure that the destruction is efficient and complete.

Free-product gasoline (i.e., separate-phase nondissolved gasoline) floating on top of the water table constitutes a small fraction of the total gasoline volume. Our first attempts to remove free product were terminated when the membrane-type commercial skimmer failed. Our present system uses an air-driven pump with its intake at the top, which is manually adjusted to follow the gasoline-water interface. The skimming system is shut off and removed from the well when the color of the liquid product visibly changes, indicating that more water is being removed than free product. Maintaining the pump intake at the gasoline-water interface is also difficult when the layer of free product is thin. From 3 to 5 gal of free product can be removed from the water in a skimming episode, after which it commonly takes about 2 to 3 wk for recoverable quantities to accumulate again. To date, the skimming has been performed without depressing the water table. As of June 1990, between 100 and 150 gal of free product has been removed by skimming from GSW-15 and GSW-16. The removed gasoline was disposed of as hazardous waste.

The rate at which FHCs can be removed by vacuum-induced extraction depends on the permeability of the surrounding sediment and the degree of sorption of the hydrocarbon molecules to the surrounding sediment. We are currently experimenting with a process that may enhance volatilization and reduce hydrocarbon sorption to soil. In this experiment, we are evaluating the feasibility of increasing the rate of *in situ* volatilization by heating the air drawn into the vadose zone.

To conduct the experiment, we fabricated a heat exchanger and placed it at the third deepest vadose screen of GSW-15. This zone was packed off in GSW-15 and GSW-16, isolating the interval between 50 and 55 ft. The first week of the experiment involved only vacuum extraction from GSW-16. Vapor concentrations averaged about 3500 ppm of fuel hydrocarbons during this week. We followed this with a second week of ambient air injection in GSW-15, with continued vacuum extraction from GSW-16. The fuel hydrocarbon concentrations this week averaged about 7500 ppm. We then introduced hot air into the vadose zone for 2 wk at 170°F, 1.5 to 2.0 psi at 4 cfm. During this 2-wk interval, fuel hydrocarbon concentrations

**Table 2-3. Efficiency of hydrocarbon destruction in thermal oxidizer at the Gasoline Spill Area.**

Test	Influent (ppm <sub>v/v</sub> )	Effluent (ppm <sub>v/v</sub> )	Efficiency (%)
<b>Based on total fuel hydrocarbons</b>			
BAAQMD <sup>a</sup>	30,000	200	99.3
LLNL <sup>b</sup>	17,000	30	99.8
<b>Based on total BETX</b>			
LLNL <sup>c</sup>	243	0.110	99.95
LLNL <sup>c</sup>	287	0.104	99.96

<sup>a</sup> Bay Area Air Quality Management Board source test, June 13, 1989 (memorandum from D. Armstrong to J. Steenhoven).

<sup>b</sup> LLNL Environmental Restoration Division source test, June 13, 1989 (memorandum from D. Armstrong to J. Steenhoven).

<sup>c</sup> Representative LLNL operational monitoring tests October 8, 1990, and October 16, 1990, as documented in field log books.

increased to an average of 8500 ppm. The 2-wk period of heating was followed by 1 wk of vacuum extraction only. During this week, the fuel hydrocarbon concentrations averaged 10,000 to 12,000 ppm.

The experiment was repeated twice using the same protocol. In both experiments, the hydrocarbon concentrations collected during the week following hot air injection were almost two times greater than during the hot air injection.

Results from one of these vadose zone heating experiments are shown in Figure 2-20. This figure presents the FHC vapor concentrations as a function of the different phases of the experiment. As shown, the average concentration of FHCs following the hot air injection sequence is two to three times higher than when the test began. We are investigating this technique in more detail.

Several cleanup options are currently being evaluated for ground water in the Gasoline Spill Area. Those options are discussed in Section 3.4 and in more detail in Appendix D.

### 2.2.3. Conclusions

The Gasoline Spill Pilot Study has demonstrated that venting is a viable process for the remediation of gasoline hydrocarbons within the unsaturated zone. Approximately 6000 gal liquid equivalent of FHCs has been removed from the vadose zone with test vent/extraction well GSW-16. The thermal oxidizer destroys FHCs at approximately 99.8% efficiency. Preliminary analysis suggests that heating the vadose zone may increase FHC recovery. Between 100 and 150 gal of free-phase gasoline has been skimmed from the water table through June 1990.

We have planned additional work that includes:

1. Installing and testing a water treatment system.
2. Conducting tests to evaluate the feasibility of dewatering and venting of the newly dewatered zone.
3. Determining the extent of vapor extraction possible using GSW-16.
4. Evaluating the need for additional vapor and ground water extraction wells.
5. Skimming free-phase fuel from the water table under pumping conditions.
6. Developing numerical models to analyze results and design additional remediation strategies.

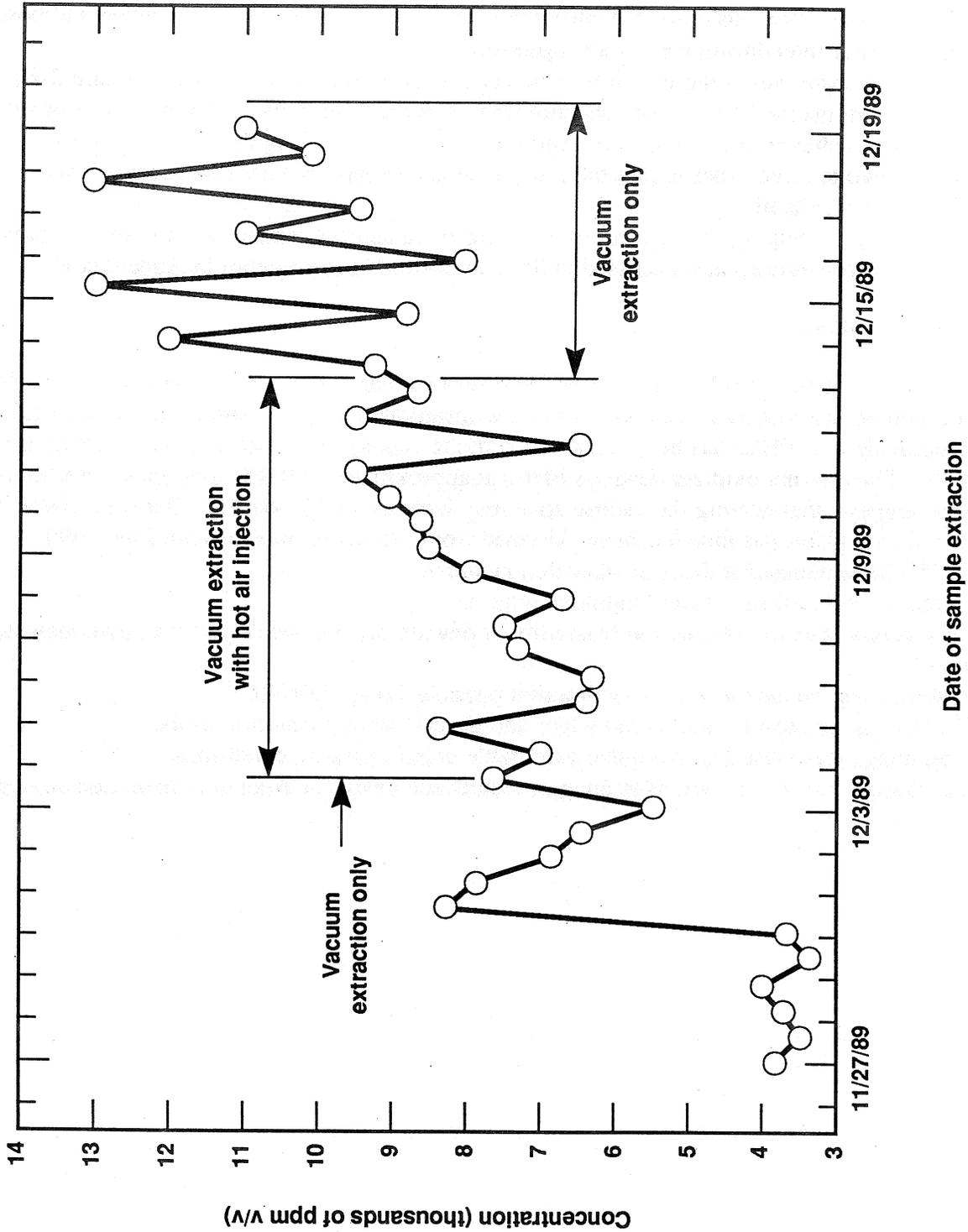


Figure 2-20. Results of vadose zone heating test, using the fifth screened interval of GSW-16.

### 3. IDENTIFICATION AND SCREENING OF TECHNOLOGIES, REMEDIAL ALTERNATIVES, AND TREATMENT OPTIONS

#### 3.1. INTRODUCTION

##### 3.1.1. Purpose

The purpose of identifying and screening remediation technologies and remedial alternatives is to provide decisionmakers with a range of possible alternatives for remediating the LLNL site. This process is designed to evaluate a wide range of technologies, alternatives, and treatment options that can be evaluated against practical, site-specific criteria.

##### 3.1.2. Overview of Design and Evaluation Process

The EPA has designed a process for systematically examining possible methods of hazardous material extraction, treatment, disposal, and source control for remediation. Remedial alternatives are evaluated to identify those that best meet design, cost, and other objectives and constraints (U.S. EPA, 1988). This process is intended to provide continuity among activities carried out in the Remedial Investigation (RI) and the Feasibility Study (FS).

The RI (Thorpe *et al.*, 1990) provides a foundation for the FS. RI activities pertinent to the FS included:

- Site characterization.
- Source characterization.
- Determining the nature and extent of contamination.
- Hydrogeologic modeling, to estimate the fate and transport of compounds.
- The Baseline Public Health Assessment (BPHA).

The conclusions of the BPHA are fundamental to the first step in the FS: determining preliminary remedial action objectives. The BPHA has identified the media of concern at LLNL: ground water and unconsolidated sedimentary materials (referred to herein as "sediment") above the water table. In Section 3.2, we identify preliminary remedial action objectives for each medium subject to remediation. These objectives are generally stated either in terms of residual concentrations following remediation or as treated ground water discharge limits. The residual concentrations are limits promulgated by Federal or State agencies that constitute the ARARs (Applicable or Relevant and Appropriate Requirements). The remedial action objectives may be refined to reflect health risk-based concentrations that take into account various possible pathways and chemicals (U.S. EPA, 1986).

In Section 3.3, we identify a set of general response actions for each medium (Figures 3-1a and 3-1b). These include:

- No action.
- Immediate action, i.e., containment, extraction, treatment (surface or *in situ*), and disposal.
- Deferred action, i.e., administrative/institutional measures with treatment as necessary at the point of use.

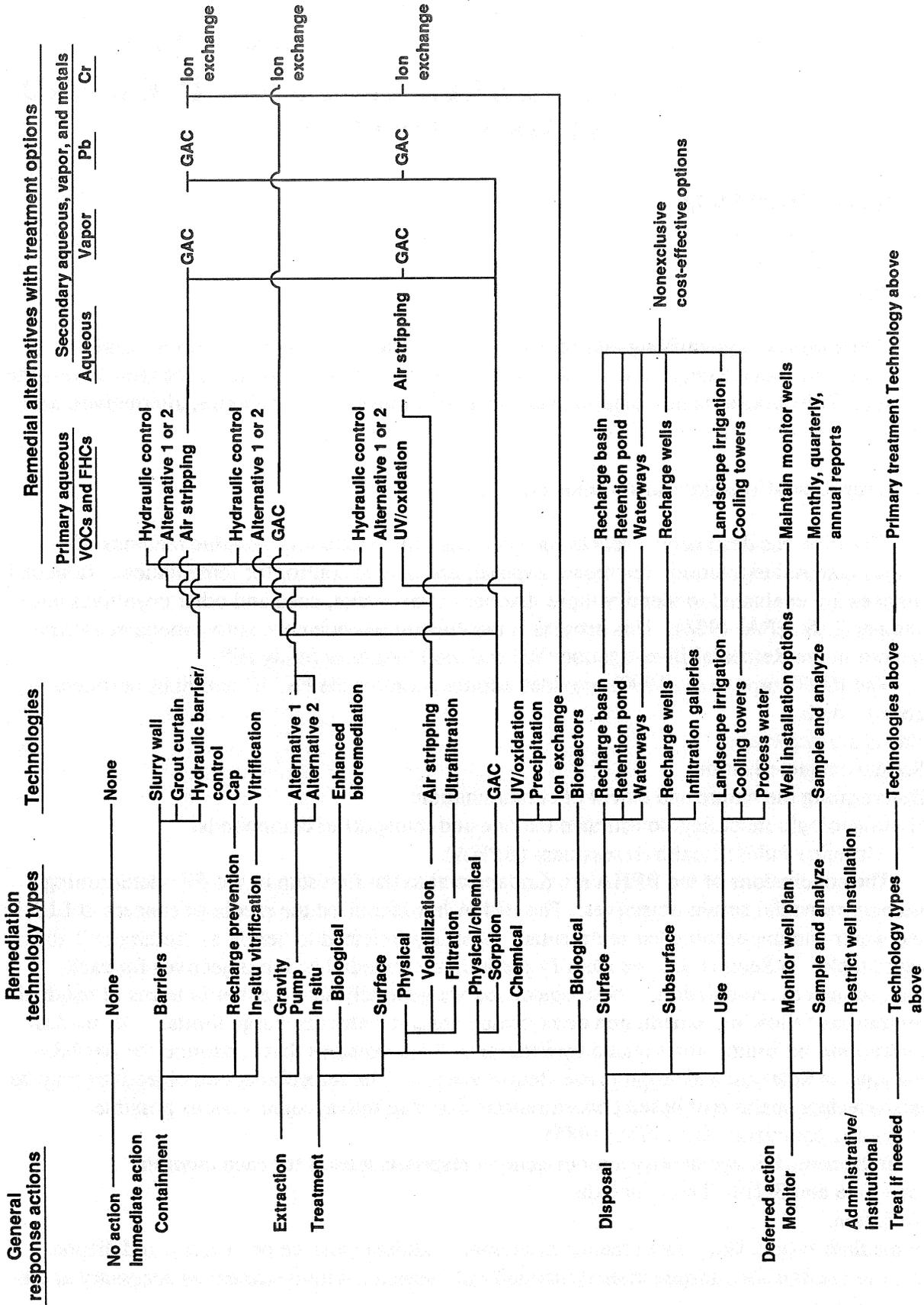


Figure 3-1a. Preliminary screening process for ground water.

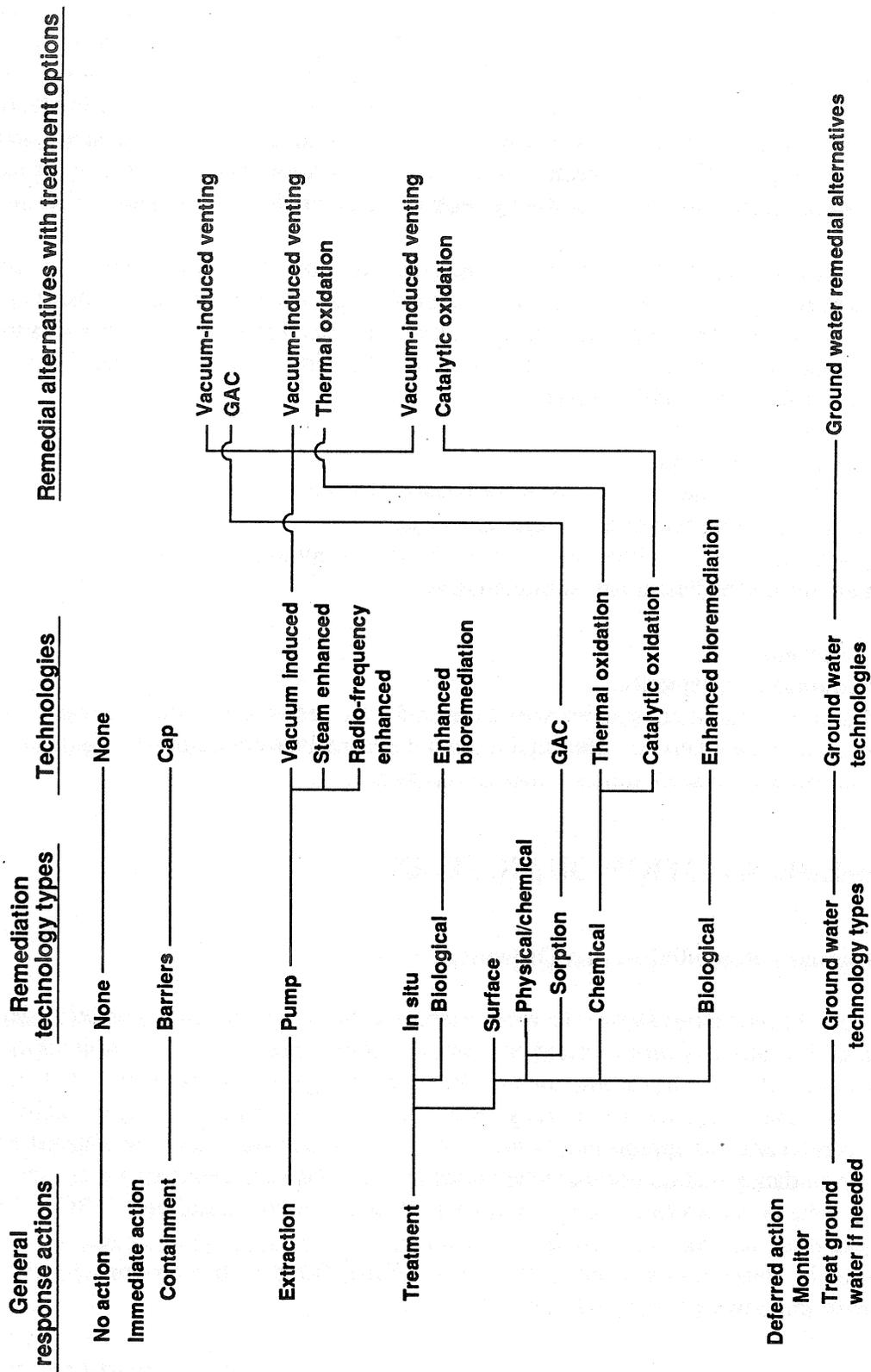


Figure 3-1b. Preliminary screening process for the vadose zone.

The volumes of hazardous materials within each medium and area of interest have been calculated based primarily on the monitoring program and hydrogeologic models. Under each of these general response actions, a set of more specific technology types is identified for each class of contaminants in each medium. These technologies are screened on the basis of the remedial action objectives and technical implementability. At each screening or evaluation, the option is either retained for further evaluation, or is eliminated from further consideration. For each technology type retained for further consideration, a representative technology is identified. These are evaluated in more detail for their effectiveness, technical implementability, and relative cost.

Technologies that pass this screening are grouped into either contaminant-specific or sitewide treatment options. The right-hand columns of Figure 3-1 illustrate treatment options assembled from a number of technologies applied to remedial alternatives. These treatment options and remedial alternatives are evaluated in detail against nine criteria, the first two of which are threshold, "go/no go" criteria:

1. Protection of human health and the environment.
2. Compliance with ARARs.
3. Short-term (through the completion of remediation) effectiveness.
4. Long-term (following remediation) effectiveness.
5. Reduction in toxicity, mobility, and volume of the compounds of interest.
6. Implementability (technical and administrative).
7. Cost.
8. State acceptance.
9. Local community acceptance.

Criteria (8) and (9) will be considered after State and local responses to the Proposed Remedial Action Plan have been received. The final remedial alternatives are compared against one another to facilitate final selection of remedial measures.

## **3.2. REMEDIAL ACTION OBJECTIVES**

### **3.2.1 Preliminary Remedial Action Objectives**

Table 3-1a lists those standards, requirements, criteria, or limitations under Federal environmental law and any promulgated standards, requirements, criteria, or limitations under State environmental or facility siting law that are more stringent than those provided under Federal law that the signatories to LLNL's Federal Facility Agreement consider legally applicable or relevant and appropriate to the LLNL site. In addition, nonpromulgated criteria advisories or guidance that do not meet the definition of ARARs but that may assist in determining what is necessary to be protective are listed as to be considered (TBC). Some of these apply to remediation activities, such as discharges from treatment facilities, whereas others form the basis for determining when cleanup is complete. Table 3-1b is a summary comparison of alternatives and corresponding ARARs.

*Text continues on page 3-21.*

Table 3-1a. Potential Federal and State and local ARARs.

Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
<b>Federal Chemical-Specific Requirements</b>				
Safe Drinking Water Act (SDWA) [42 USCA 300] [40 CFR 141.11-141.16; 141.50-141.51]	GW 1 and 2 GW 3 VZ 2 <sup>c</sup>	X <sup>b</sup>	X <sup>b</sup> X <sup>b</sup>	
This law establishes treatment standards for current potential drinking water sources by setting Maximum Contaminant Levels (MCLs) and non-zero Maximum Contaminant Level Goals (MCLGs), which are used as cleanup standards. The remedial action objectives for ground water remediation are given for compounds of concern at LLNL (see Table 3-2). The standards in the columns of Federal and State drinking water MCLs and Federal non-zero MCLGs become remedial action objectives for ambient ground water (i.e., ground water left in place after remediation), whereas the discharge limits given in the last column apply to discharge of treated water under LLNL's NPDES Permit. Ground water in the LLNL plume is a potential, not a current, drinking water source. Because GW 1 and 2 preclude any contaminated ground water from reaching drinking wells, MCLs and MCLGs are RAR. GW 3, which treats contaminants prior to use at Livermore wells, triggers the SDWA requirements. VZ 1 prevents contaminants above MCLs from reaching ground water; therefore, the SDWA requirements do not apply.				

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.

GW 2—Pump and treat; downgradient plume margin control.

GW 3—Deferred action; treat at point of use, if necessary.

VZ 1—Vacuum-induced venting.

VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

<sup>c</sup> Because VZ 2 contemplates no action and potentially allows contaminants to migrate to the ground water, it relies on GW 1 and 2 for remediation, if necessary. Therefore, ARARs triggered by GW 1 and 2 may eventually be ARARs for VZ 2.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
Clean Air Act (CAA) [42 USCA 7401-7642] [40 CFR 50-69]	National primary and secondary ambient air quality standards (NAAQS) are defined under Section 109 of the CAA and are listed in 40 CFR 50. Treatment processes GW 1 and 2 employ air stripping as primary or secondary treatment of ground water. VZ 1 treats vapor with a thermal oxidizer. The only contaminant of concern at LLNL, regulated under NAAQS, is lead. All treatment alternatives prevent dispersion of lead to the atmosphere, and, thus, comply with this ARAR. The NAAQ standard for lead is 1.5 micrograms per cubic meter.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
Clean Air Act [42 USCA 7412] [40 CFR 61.92]	National Emission Standards for Hazardous Air Pollutants (NESHAPs) are specific to industrial emissions. 40 CFR 61.92 limits emissions of radionuclides to those amounts that would cause any member of the public to receive, in any one year, a maximum effective dose equivalent of 10 millirems per year (mrem/y). Treatment processes GW 1 and 2 employ air stripping as primary or secondary treatment of ground water. VZ 1 treats vapor with a thermal oxidizer. These NESHAPs are, therefore, applicable. No treatment alternative will emit hazardous levels of tritium to the atmosphere. Screening level calculations using AIRDOSEPA indicate that none of the considered remediations would exceed 0.01% of the NESHAP standard.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.  
<sup>b</sup> CAA requirements only apply to treatment options with atmospheric discharges.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
<b>Federal Action-Specific Requirements</b>					
<i>Action: Closure</i>					
Resource Conservation Recovery Act (RCRA) 42 USCA 6901 [40 CFR 264.111]	Requires that the facility be closed in a manner which minimizes the need for further maintenance and is protective of human health and the environment. Applicable to hazardous waste management facilities.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
RCRA [40 CFR 264.178]	Requires removal of all hazardous waste and waste residues from containment systems. Although the treatment facilities and thermal system are not considered containment systems, this closure requirement will be considered RAR.	GW 1-3 VZ 1 and 2		X <sup>b</sup> X <sup>b</sup>	
<i>Action: Pump and Treat</i>					
RCRA [40 CFR 264.190-192]	Design and operating standards for tank systems. Tank systems may be used for pump and treat alternatives.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
RCRA [40 CFR 264.601-602]	Design, monitoring, and performance standards for miscellaneous treatment units.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.  
<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
Land Disposal Restrictions (LDRs) RCRA [40 CFR 268]	Any waste placed in land-disposal units must comply with LDRs by either attaining specific performance or technology-based standards. This is applicable to untreated soil or debris from the CERCLA cleanup. Generated waste for GW 1-3 includes granular-activated carbons (GAC) and ion-exchange resins. For VZ 1, there is no waste (to be transported) because all contaminants are destroyed by thermal oxidation.	GW 1-3 VZ 2	X <sup>b</sup> X <sup>b</sup>		
<i>Action: Thermal Treatment</i>					
RCRA [40 CFR 265.373-381]	These regulations apply to owners or operators of facilities that thermally treat hazardous waste in devices other than enclosed devices that use controlled flame combustion. VZ 1 triggers these requirements because it uses auxiliary fuel to thermally oxidize contaminants in vapor.	VZ 1	X <sup>b</sup>		
<i>Action: Transportation</i>					
Transportation of Hazardous Waste RCRA [40 CFR 263]	Transporters must be licensed hazardous waste haulers. In the event of a discharge during transportation, the transporter must take immediate action to protect human health and the environment (263.30) and clean up the discharge such that it no longer presents a hazard (263.31). Generated waste being transported to an offsite disposal facility would be subject to this requirement. Generated waste for GW 1-3 includes granular-activated carbons (GAC) and ion-exchange resins. For VZ 1, there is no waste (to be transported) because all contaminants are destroyed by thermal oxidation.	GW 1-3 VZ 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

Action	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
<p><b>Action: Reinjection of Treated Ground Water</b></p>					
<p><b>Safe Drinking Water Act Underground Injection Control Program</b></p>	<p>These regulations consist of inventory and monitoring requirements for reinjection of treated ground water.</p>	<p>GW 1-3 VZ 2</p>	<p>X<sup>b</sup> X<sup>b</sup></p>		
<p><b>[40 CFR 144.26-27]</b></p>					
<p><b>Action: Discharge of Treatment System Effluent</b></p>					
<p><b>Clean Water Act</b></p>	<p>Both onsite and offsite discharges from CERCLA sites to surface waters are required to meet the substantive CWA limitations, monitoring requirements [40 CFR 122.41(i); 40 CFR 136.1; 40 CFR 136.4], and best management practices [40 CFR 125.100].</p>	<p>GW 1 and 2 VZ 2</p>	<p>X<sup>c</sup> X<sup>c</sup></p>		
<p><b>[33 USCA 1251-1376]</b></p>					
<p><b>National Pollutant Discharge Elimination System (NPDES)</b></p>					
<p><b>[40 CFR 122-125]</b></p>					
<p><b>Action: Air Stripping</b></p>					
<p><b>OSWER Directive 9355.0-28</b></p>	<p>Establishes guidance on the control of air emissions from air strippers used at Superfund sites for ground water treatment. This is a nonpromulgated directive and is, therefore, TBC.</p>	<p>GW 1-3 VZ 2</p>			<p>X<sup>d</sup> X<sup>d</sup></p>
<p><b>General Action-Specific ARARs</b></p>					
<p><b>DOE Order 5400.4</b></p>	<p>Prescribes conduct of operations on DOE facilities for compliance with CERCLA, and provides for the integration of NEPA and CERCLA documentation for DOE. This is a nonpromulgated regulation and is, therefore, TBC.</p>	<p>GW 1-3 VZ 1 and 2</p>			<p>X<sup>d</sup> X<sup>d</sup></p>

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

<sup>c</sup> Only offsite CERCLA discharges to surface waters must be NPDES-permitted.

<sup>d</sup> Factors TBC are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
29 USC 651 <i>et seq.</i> Occupational Safety and Health Act (OSHA)	OSHA requirements under 29 CFR 1910.120 are applicable to worker exposures during response actions at CERCLA sites; 29 CFR 1926 construction standards apply during construction phase of treatment facilities.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
29 CFR 1910 <i>et seq.</i> Noise Control Act of 1972, as amended by the Quiet Communities Act of 1978 [40 CFR 204, 205, 211]	Construction and transportation equipment noise levels (e.g., portable air compressors, and medium and heavy trucks), process equipment noise levels, and noise levels at the property boundaries of the project are regulated under this Act. State or local agencies typically enforce these levels.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
<i>State and Local Chemical-Specific Requirements</i>					
Hazardous Waste Control Act (Health and Safety Code, Section 25100-25395), CCR, Title 22, ch. 30: Minimum Standards for Management of Hazardous and Extremely Hazardous Wastes	HCWA controls hazardous wastes from their point of generation through accumulation, transportation, treatment, storage, and ultimate disposal. All potentially hazardous materials are handled in accordance with standard chain-of-custody procedures. These requirements are, therefore, applicable to all treatment alternatives.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
Criteria for Identifying Hazardous Wastes [Title 22, 66693-66776]	Tests for identifying hazardous characteristics are set forth in these regulations. If a chemical is either listed or tested and found hazardous, then remedial actions must comply with Title 22 requirements. All treatment alternatives use these criteria.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		

a GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

b All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
Persistent and Bioaccumulative Toxic Substances [Title 22, 66699]	Total Threshold Limit Concentrations (TTLCs) and Soluble Threshold Limit Concentrations (STLCs) have been established for selected toxics to be used in establishing whether waste is hazardous. If a chemical is either listed or tested and found hazardous, then remedial actions must comply with the hazardous waste requirements under Title 22. All treatment alternatives use these criteria.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
Porter-Cologne Water Quality Control Act [WC13000-13806], as administered by the State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Board (RWQCB) under CCR Title 23, subch. 15, 1050-2836.	Establishes authority for State and Regional Water Boards to determine site-specific discharge requirements and to regulate disposal of waste to land (see Table 3-2). All ground water treatment alternatives use these criteria.	GW 1-3 VZ 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.

VZ 1—Vacuum-induced venting.

VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

State Water Resources Control Board's Resolution 68-16	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
	<p>The State Board's policy on maintaining the high quality of California's waters implies that ground water cleanup should continue below MCLs if it can be shown that it is technically feasible and cost effective to do so. The resolution also allows alternative cleanup levels if LLNL can demonstrate that MCLs cannot be practically achieved and that the alternative is protective of human health and the environment. LLNL's health risk assessment, presented in the RI/FS, demonstrates that there is no significant health benefit to setting cleanup goals lower than MCLs. In the process of achieving MCLs for the contaminants of primary concern (e.g., PCE, TCE, carbon tetrachloride, and benzene), the concentrations of co-contaminants, such as chloroform and xylenes, will be reduced to far below their MCLs. LLNL aggressively pursues new technologies with the potential to affect cleanup faster, cheaper, or more completely, and would expect to utilize the best available technologies. The issue of the technical feasibility of further cleanup will be on the agenda at each of the scheduled 5-year reviews.</p>	<p>GW 1-3 VZ 1 and 2</p>	<p>X<sup>b</sup> X<sup>b</sup></p>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
California Safe Drinking Water Act, Health and Safety Code, Section 2549.5	Regulations and standards for public water systems; MCLs and secondary MCLs (SMCLs), which are enforceable in California; requirements for water quality analyses and laboratories (see Table 3-2). Ground water in the LLNL plume is not a drinking water source. Because GW 1-2 preclude use of any contaminated ground water from reaching drinking wells, MCLs and MCLGs are RAR. GW 3, which treats contaminants prior to use at Livermore wells, triggers the SDWA requirements. VZ 1 prevents contaminants above MCLs from reaching ground water; therefore, the SDWA requirements do not apply.	GW 1-3 VZ 2		X <sup>b</sup> X <sup>b</sup>	
<i>State and Local Action-Specific Requirements</i>					
<i>Action: General Treatment of Hazardous Waste</i>					
Hazardous Waste Control Act, Health and Safety Code (HCWA), Sections 25100-25395 [22 CCR 67100-67195]	Requirements for general operations of interim status and permitted facilities [67100-67108], including preparedness and prevention [67120-67126], contingency plans and emergency procedures [67140-67145], and manifesting and monitoring requirements [67180-67195].	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.

VZ 1—Vacuum-induced venting.

VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
Hazardous Waste Control Act Land-Disposal Restrictions [22 CCR 66900]	This law requires that certain hazardous wastes meet minimum treatment standards prior to disposal at a landfill. Generated waste for GW 1-3 includes regeneration of granular-activated carbons (GAC) and ion-exchange resins. For VZ 1, there is no waste (to be transported) because all contaminants are destroyed by thermal oxidation.	GW 1-3 VZ 2	X <sup>b</sup> X <sup>b</sup>		
Hazardous Materials Release Response Plans and Inventory [H&SC, Div. 20, ch. 6.95] [19 CCR, ch. 3, subch. 3]	This law requires businesses handling hazardous materials to plan for emergency response actions.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
<i>Action: Closure</i>					
Hazardous Waste Control Act Closure Requirements, Sections 25100-25395 [22 CCR 67210-67220]	A facility shall be closed in a manner that minimizes the need for future maintenance. If hazardous wastes are left in place, postclosure care must continue for 30-y.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
<i>Action: Transportation</i>					
Hazardous Waste Control Act Hauler Registration Requirements [22 CCR 66420-66465] and Requirements for Transporters of Hazardous Waste [22 CCR 66530-66564]	Hazardous wastes must be transported by a hauler registered with the State of California. Generated waste for GW 1-3 includes regeneration of granular-activated carbons (GAC) and ion-exchange resins. For VZ 1, there is no waste (to be transported) because all contaminants are destroyed by thermal oxidation.	GW 1-3 VZ 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.  
<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
Requirements for Generators of Hazardous Waste [Title 22 66470-66515]	Owners or operators who ship hazardous waste from a Transport, Storage, or Disposal (TSD) facility shall comply with the generator standards in these regulations. These standards include keeping of manifests [66481], submission of manifest to CDHS within 30 days of shipment [66484(f)], preparation of a biennial report [66493(a)], and a maximum 90-day accumulation time [66508(a)]. These regulations are applicable to transportation and offsite disposal of hazardous waste. Generated waste for GW 1-3 includes regeneration of granular-activated carbons (GAC) and ion-exchange resins. For VZ 1, there is no waste (to be transported) because all contaminants are destroyed by thermal oxidation.	GW 1-3 VZ 2	X <sup>b</sup> X <sup>b</sup>		
<i>Action: Discharge of Treatment System Effluent</i>					
Porter-Cologne Water Quality Control Act [WC 13000-13806], as administered by the State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Board (RWQCB) under CCR Title 23, subch. 15, 1050-2836	Establishes authority for State and Regional Water Boards to determine site-specific discharge requirements and to regulate disposal of waste to land (see Table 3-2).	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> All ARARs are the same for all treatment options contemplated under this treatment alternative.

Table 3-1a. (Continued)

	Comments	Alternative No. <sup>a</sup>	Applicable (A)	Relevant and Appropriate (RAR)	To be considered (TBC)
Fish and Game Regulations on Pollution	Prohibits water pollution with any substance or material deleterious to fish, plant, or bird life.	GW 1-3 VZ 1 and 2	X <sup>c</sup> X <sup>c</sup>		
<i>Action: Air Stripping</i>					
Air Resources Act (Health and Safety Code, section 3900 <i>et. seq.</i> )	Establishes allowable discharge standards for point sources within each air pollution control district, and establishes ambient air quality standards. Treatment processes GW 1 and 2 employ air stripping as primary or secondary treatment of ground water. VZ 1 treats vapor with a thermal oxidizer. These requirements are, therefore, applicable.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		
Bay Area Air Quality Management District [Regulation 8, Rule 47]	Requires permitting of VOC air discharges (e.g., from an air-stripping unit). Treatment processes GW 1 and 2 employ air stripping as primary or secondary treatment of ground water. VZ 1 treats vapor with a thermal oxidizer. These requirements are, therefore, applicable.	GW 1-3 VZ 1 and 2	X <sup>b</sup> X <sup>b</sup>		

<sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.

GW 2—Pump and treat; downgradient plume margin control.

GW 3—Deferred action; treat at point of use, if necessary.

VZ 1—Vacuum-induced venting.

VZ 2—Deferred action; treat ground water as necessary.

<sup>b</sup> Unless otherwise indicated, all ARARs are the same for all treatment options contemplated under each treatment alternative.

<sup>c</sup> Applies only to treatment options with surface discharges.

Table 3-1b. Summary comparison of corresponding ARARs and factors to be considered.

	Alternative				
	GW 1	GW 2	GW 3	VZ 1	VZ 2
<b><i>Federal Chemical-Specific Requirements</i></b>					
Safe Drinking Water Act (SDWA) [42 USCA 300] [40 CFR 141.11-141.16; 141.50-141.51]	RAR	RAR	A	**	RAR
Clean Air Act (CAA) [42 USCA 7401-7642] [40 CFR 50-69]	A	A	A	A	A
Clean Air Act [42 USCA 7412] [40 CFR 61.92]	A	A	A	A	A
<b><i>Federal Action-Specific Requirements</i></b>					
<b><i>Action: Closure</i></b>					
RCRA 42 USCA 6901 [40 CFR 264.111]	A	A	A	A	A
RCRA [40 CFR 264.178]	RAR	RAR	RAR	RAR	RAR
<b><i>Action: Pump and Treat</i></b>					
RCRA [40 CFR 264.190-192]	A	A	A	A	A
RCRA [40 CFR 264.601-602]	A	A	A	A	A
Land Disposal Restrictions (LDRs) RCRA [40 CFR 268]	A	A	A	**	A
<b><i>Action: Thermal Treatment</i></b>					
RCRA [40 CFR 265.373-381]	**	**	**	A	**
<b><i>Action: Transportation</i></b>					
Transportation of Hazardous Waste RCRA [40 CFR 263]	A	A	A	**	A

- <sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

A = Applicable.

RAR = Relevant and Appropriate.

TBC = To be considered.

\*\* = Not ARAR or TBC.

Table 3-1b. (Continued)

	Alternative <sup>a</sup>				
	GW 1	GW 2	GW 3	VZ 1	VZ 2
<i>Action: Reinjection of Treated Ground Water</i>					
Safe Drinking Water Act Underground Injection Control Program [40 CFR 144.26-27]	A	A	A	**	A
<i>Action: Discharge of Treatment System Effluent</i>					
Clean Water Act [33 USCA 1251-1376] National Pollutant Discharge Elimination System (NPDES) [40 CFR 122-125]	A	A	A	**	A
<i>Action: Air Stripping</i>					
OSWER Directive 9355.0-28	TBC	TBC	TBC	**	TBC
DOE Order 5400.4	TBC	TBC	TBC	TBC	TBC
Occupational Safety and Health Act (OSHA)	A	A	A	A	A
Noise Control Act of 1972, as amended by the Quiet Communities Act of 1978 [40 CFR 204, 205, 211]	A	A	A	A	A
<i>State and Local Chemical-Specific Requirements</i>					
Hazardous Waste Control Act (Health and Safety Code, Section 25100-25395), CCR, Title 22, ch. 30: Minimum Standards for Management of Hazardous and Extremely Hazardous Wastes	A	A	A	A	A
Criteria for Identifying Hazardous Wastes [Title 22, 66693-66776]	A	A	A	A	A
Persistent and Bioaccumulative Toxic Substances [Title 22, 66699]	A	A	A	A	A

- <sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

A = Applicable.

RAR = Relevant and Appropriate.

TBC = To be considered.

\*\* = Not ARAR or TBC.

Table 3-1b. (Continued)

	Alternative <sup>a</sup>				
	GW 1	GW 2	GW 3	VZ 1	VZ 2
Porter-Cologne Water Quality Control Act [WC13000-13806], as administered by the State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Board (RWQCB) under CCR Title 23, subch. 15, 1050-2836.	A	A	A	**	A
State Water Resources Control Board's Resolution 68-16	A	A	A	A	A
California Safe Drinking Water Act Health and Safety Code, Section 2549.5	RAR	RAR	RAR	**	RAR
<i>State and Local Action-Specific Requirements</i>					
<i>Action: General Treatment of Hazardous Waste</i>					
Hazardous Waste Control Act, Health and Safety Code, Sections 25100-25395 [22 CCR 67100-67195]	A	A	A	A	A
Hazardous Waste Control Act Land-Disposal Restrictions [22 CCR 66900]	A	A	A	**	A
Hazardous Materials Release Response Plans and Inventory [H&SC, Div. 20, ch. 6.95] [19 CCR, ch. 3, subch. 3]	A	A	A	A	A
<i>Action: Closure</i>					
Hazardous Waste Control Act Closure Requirements, Sections 25100-25395 [22 CCR 67210-67220]	A	A	A	A	A
<i>Action: Transportation</i>					
Hazardous Waste Control Act Hauler Registration Requirements [22 CCR 66420-66465] and Requirements for Transporters of Hazardous Waste [22 CCR 66530-66564]	A	A	A	**	A

- <sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

A = Applicable.

RAR = Relevant and Appropriate.

TBC = To be considered.

\*\* = Not ARAR or TBC.

Table 3-1b. (Continued)

	Alternative <sup>a</sup>				
	GW 1	GW 2	GW 3	VZ 1	VZ 2
Requirements for Generators of Hazardous Waste [Title 22 66470-66515] <i>Action: Discharge of Treatment System Effluent</i>	A	A	A	**	A
Porter-Cologne Water Quality Control Act [WC13000-13806], as administered by the State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Board (RWQCB) under CCR Title 23, subch. 15, 1050-2836.	A	A	A	A	A
Fish and Game Regulations on Pollution <i>Action: Air Stripping</i>	A <sup>b</sup>	A <sup>b</sup>	A <sup>b</sup>	A <sup>b</sup>	A <sup>b</sup>
Air Resources Act (Health and Safety Code, section 3900 <i>et seq.</i> )	A	A	A	A	A
Bay Area Air Quality Management District [Regulation 8, Rule 47]	A	A	A	A	A

- <sup>a</sup> GW 1—Pump and treat; complete capture with source remediation.  
 GW 2—Pump and treat; downgradient plume margin control.  
 GW 3—Deferred action; treat at point of use, if necessary.  
 VZ 1—Vacuum-induced venting.  
 VZ 2—Deferred action; treat ground water as necessary.

- <sup>b</sup> Applies only to treatment options with surface discharges.

A = Applicable.

RAR = Relevant and Appropriate.

TBC = To be considered.

\*\* = Not ARAR or TBC.

There are three general kinds of ARARs: chemical-specific, location-specific, and action-specific. Chemical-specific ARARs usually result in health- or risk-based concentration limits. *CERCLA Compliance with Other Laws Manual* (U.S. EPA, 1988a) contains a nonexhaustive list of potential chemical-specific ARARs from which LLNL has drawn to ensure that no ARAR is overlooked.

The chemical-specific concentrations proposed as remedial action objectives for ground water remediation are given for the compounds of concern at LLNL in Table 3-2. The standards in the columns of Federal and State drinking water MCLs and Federal non-zero MCLGs become remedial action objectives for ambient ground water (i.e., ground water left in place after remediation), whereas the discharge limits given in the last column apply to discharges of treated water under LLNL's NPDES permit. The most stringent concentration limit (*italic*) is the governing ARAR for each chemical of concern.

San Francisco Bay Area Regional Water Quality Control Board's Basin Plan ("Basin Plan") taste and odor objectives are not considered an ARAR for this proposal because acceptable numerical expressions of these objectives are not available at the present time. There is no methodology for enforcement of these objectives and consequently they have not been enforced by the State. We, therefore, cannot use the Basin Plan's taste and odor objectives to establish a cleanup level for compliance purposes. If in the future a method is established for measurement and achievement of the Basin Plan's taste and odor objectives and achievement of those objectives is determined to be applicable or relevant and appropriate and necessary to ensure that the remedy is protective of human health and the environment, then LLNL will consider the objectives applicable to the cleanup. 40 CFR §300.430 (F) (1) (ii) (B) (1).

If any additional hazardous substances are found in the ground water environment at levels of concern in the future, standards for those will be requested and agreed upon with EPA and DHS and can be added to those listed in Table 3-2.

Resource Conservation Recovery Act (RCRA) Section 3020 bans hazardous disposal by underground injection into or above a source of drinking water unless the reinjection involves treated ground water from a CERCLA response action. This section does not apply if certain conditions are met. At LLNL, proposed injection is a CERCLA response action intended to clean up contamination; the contaminated ground water will be treated to substantially reduce hazardous constituents prior to such injection; and the response action will be sufficient to protect human health and the environment upon completion. LLNL thus meets the conditions for exemption and is not subject to the ban.

Whereas specific ARARs do not appear to exist as cleanup standards for vadose zone sediments, LLNL considers health protection (at a  $10^{-6}$  risk) to be a remedial action objective. Based on results of the Baseline Public Health Assessment (BPHA), ground water constitutes the only significant pathway of exposure from vadose zone contaminants. The BPHA demonstrates that, if ground water concentrations are at MCLs or below, the health risk is well below  $10^{-6}$ . Therefore, because the MCL limit is more stringent, we propose the chemical-specific limits on Table 3-2 as the maximum concentrations that would be allowed to migrate to ground water.

Unsaturated sediment cleanup concentrations will be based on the mobility of specific contaminants in the sediment at the LLNL site. We have examined the potential for hazardous substances in the sediments of the unsaturated zone to migrate to ground water (Appendix G). The preliminary results of our investigation indicate that the potential for affecting the ground water depends on the mass, concentration, and distribution of contaminants in the vadose zone.

Table 3-2. Potential chemical-specific ARARs for compounds of concern in ground water at the LLNL site.<sup>a</sup>

Constituent	Primary remedial action objective (ppb)			
	Concentration limit for drinking water <sup>ab</sup>			
	Non-zero Federal MCLG	Federal MCL	CA MCL	Discharge limit <sup>c</sup>
PCE	—	5 <sup>d</sup>	5	4
TCE	—	5	5	5
1,1-DCE	7	7	6	5
cis-1,2-DCE	70 <sup>d</sup>	70 <sup>d</sup>	6	5 (total)
trans-1,2-DCE	100 <sup>d</sup>	100 <sup>d</sup>	10	5 (total)
1,1-DCA	—	—	5	5
1,2-DCA	—	5	0.5	5
Carbon tetrachloride	—	5	0.5	5
Total THM <sup>e</sup>	—	100 <sup>e</sup>	100 <sup>e</sup>	5
Benzene	—	5	1.0	0.7
Toluene	2,000 <sup>d</sup>	2,000 <sup>d</sup>	100 <sup>d</sup>	5
Xylenes (total)	10,000 <sup>d</sup>	10,000 <sup>d</sup>	1,750	5
Ethylene dibromide	—	0.05 <sup>d</sup>	0.02	5
Total VOCs	—	—	—	5
Chromium <sup>+3 f</sup>	100 <sup>d</sup> (total)	50 <sup>g</sup> (total)	50 (total)	2,500
Chromium <sup>+6 f</sup>	100 <sup>d</sup> (total)	50 <sup>g</sup> (total)	50 (total)	11
Lead	—	50	50	5.6
Tritium <sup>g</sup>	—	20,000 pCi/L	20,000 pCi/L	—

<sup>a</sup> Human receptor.

<sup>b</sup> The more stringent concentration limits are shown in *italic* to illustrate that the most stringent requirements are followed.

<sup>c</sup> From NPDES Permit No. CA0029289 (revised 8/1/90) and RWQCB order No. 88-075.

<sup>d</sup> Proposed MCL or MCLG.

<sup>e</sup> Total trihalomethanes, includes chloroform, bromoform, chlorodibromomethane, and bromodichloromethane (California Drinking Water Requirement).

<sup>f</sup> National Interim Primary Drinking Water Regulation for chromium (total) is 50 ppb.

<sup>g</sup> Thorpe *et al.* (1990) show that ground water in the one well that currently exceeds the MCL will be naturally remediated long before it migrates offsite.

Note: Because non-zero Federal MCLGs are equal to Federal MCLs in all cases above, these are referred to simply as MCLs throughout this document.

For the areas of greatest potential concern at LLNL, we conclude that the dominant transport mechanism for migration to the ground water is vapor diffusion. The model illustrated in Appendix G provides a basis for deciding which, if any, areas at LLNL may warrant vadose zone remediation.

Based on the findings of the BPHA section of the RI (Thorpe *et al.*, 1990) that no surficial soils at LLNL constitute a potential health threat, we have not suggested cleanup standards for surficial soils.

Location-specific ARARs are restrictions placed on the concentration of chemicals or conduct of operations based on the location of a site. Potential location-specific ARARs include the protection of:

- Wetlands.
- Floodplains.
- Historic landmarks.
- Coastal zones.
- Coastal barriers.
- Rare and endangered species.
- Cultural resources.

The LLNL site contains no wetlands, floodplains, historic landmarks, coastal zones, or coastal barriers. A review of the LLNL site for rare and endangered species was performed as part of the site Environmental Impact Report (EIR), and none have been found [list of species shown in University of California (1986)]. No contemplated action will have an impact beyond those discussed in Section 5 of this report. LLNL does not believe that significant cultural resources will be impacted, because (1) there is no source of water on the site to sustain early cultures, and (2) virtually the entire site has been subject to intense development over the last 50 y. No excavation is contemplated that would disturb sites to depths greater than they may have already been disturbed.

California's Alquist-Priolo Special Studies Zones Act of 1972 (California Public Resource Code, Section 2621, *et seq.*) provides constraints on the building of residences within 50 ft of an active fault. RCRA 40 CFR Section 264.18(a) prohibits new treatment, storage, or disposal facilities within 200 ft of a Holocene fault. There are no active faults within 200 ft of LLNL, and construction of residences is not permitted onsite; therefore, these two requirements are not ARARs. All treatment facilities will comply with local construction codes as applied by LLNL's Plant Engineering Department.

Action-specific ARARs are usually technology- or activity-based limitations on actions taken with respect to hazardous wastes. These requirements are triggered by the particular remedial activities that are selected to accomplish a remedy. Since there are usually several alternative actions for any remedial site, different requirements can be triggered. Action-specific ARARs may indicate or influence how a selective alternative is implemented. For instance, for discharge of treatment system effluents, the discharge limits given in Table 3-2, air permit requirements, and proper operation and maintenance of the treatment system are all action-specific ARARs.

### 3.2.2. Assessment of Potential Health Risks from Baseline (Unremediated) and Remediated Concentrations of Hazardous Materials in Ground Water

In this section, we summarize our assessment of potential health risks from hazardous materials in unremediated and remediated ground water and from compounds in the vadose zone. Details of these assessments are presented in the BPHA section of the RI (Thorpe *et al.*, 1990) and Appendix A of this report. The BPHA uses a risk-based assessment methodology that incorporates a description of the source term, fate and transport, exposure from the major pathways, the dose resulting from the predicted exposure, and potential health risk. This process is further described in U.S. EPA (1986). The screening in the BPHA considers all possible pathways and concludes that ground water is the only viable pathway of exposure. That conclusion remains valid in light of continued investigations and findings subsequent to the RI (Section 1.2.3.4). Therefore, the RI/FS calculates potential risks from exposure to and use of ground water.

#### 3.2.2.1. Methodology for Estimating Health Risk

There are many uncertainties in predicting potential health risks. Judgments must be made with regard to the physical and chemical mechanisms that affect the movement and distribution (fate and transport) of chemicals in ground water. These include:

1. Advection (transport by bulk movement of water).
2. Dispersion (transport by mechanical spreading and molecular diffusion).
3. Retardation (sorption by aquifer materials).
4. Degradation (biological or abiotic chemical transformation).

To address the uncertainties, we used two different exposure scenarios. One, the "best-estimate" case, represents our best professional judgment for each factor. It assumes no human exposure to the compounds until they reach currently used municipal supply wells in downtown Livermore because there are no other current potential receptors. Administrative controls exist that prevent domestic well installation into a contaminated zone. The "best-estimate" scenario estimates the effects of retardation and degradation of the chemical compounds, and mixing with other water at the point of probable extraction in downtown Livermore. The other, a "health-conservative" case, assumes no retardation or transformation and no mixing with other water, the fastest transport rate, hypothetical receptor wells very near the LLNL site directly in the path of the plume, and the highest possible source concentrations. Both scenarios assume that contaminants migrate directly toward the target wells and that individuals use well water as their sole source of domestic water for a continuous period of 70 y.

VOCs present in ground water at LLNL could pose a (very low) potential public health risk if no cleanup or remediation activities take place. As described in the RI, an estimated 91% of the mass of VOCs dissolved in ground water is comprised of TCE, PCE, and chloroform. The remaining 9% of the VOC mass is comprised of several chlorinated solvents (i.e., "other VOCs"), including 1,1-DCE and carbon tetrachloride; 1,1-DCE is the principal component, comprising roughly 60% of the "other VOCs."

#### 3.2.2.2. Estimation of Potential Health Effects from Unremediated Ground Water

An exposure and risk assessment described in the RI used procedures developed at LLNL to quantify the potential incremental cancer risks to the public associated with exposure to

unremediated concentrations of TCE, PCE, and chloroform in ground water. Incremental cancer risks to the public from carbon tetrachloride in ground water were also calculated. Carbon tetrachloride was used as an indicator compound to evaluate the carcinogenic potential of the "other VOCs," and 1,1-DCE was used as an indicator compound to estimate noncarcinogenic hazard. Results obtained using standard EPA procedures are also presented in the RI for comparison. The risk assessment calculations are summarized in Table 3-3 and further described in Appendix A.

The conclusions of the potential health effects from untreated ground water are:

1. The maximum incremental risk of developing cancer associated with the "best-estimate" (most likely) case for the combined 70-y exposure to VOCs (all pathways, all VOCs) from municipal supply wells in downtown Livermore is calculated to be two in ten million ( $2 \times 10^{-7}$ ).
2. The maximum incremental risk of developing cancer associated with the "health-conservative" (unlikely) case for the combined 70-y exposure to VOCs (all pathways, all VOCs) from municipal-supply wells in downtown Livermore is calculated to be one in one thousand ( $1 \times 10^{-3}$ ).
3. The maximum incremental risk of developing cancer associated with the health-conservative (unlikely) case for the combined 70-y exposure to VOCs (all pathways, all VOCs) from a postulated well 250 ft west of the LLNL Livermore site is calculated to be two in one thousand ( $2 \times 10^{-3}$ ).
4. Tritium occurs in a concentration slightly above the MCL in one well onsite. Natural decay will reduce the concentration to below the MCL in a few years, long before the affected ground water could migrate offsite (Thorpe *et al.*, 1990).

To determine if exposure to a chemical with noncarcinogenic properties may pose a hazard to human health, a hazard index (HI) was calculated. The HI for a chemical is the ratio of the chemical-specific exposure (in mg/kg-d) to the reference dose (RfDs in mg/kg-d), which is the estimated maximum chronic daily intake of the chemical that is not expected to produce adverse health effects. If the quotient of this ratio exceeds unity, then exposure may potentially result in adverse health effects. The HI values calculated by LLNL (Thorpe *et al.*, 1990) were based on 1,1-DCE exclusively. Accordingly, using the RfD for 1,1-DCE of 0.009 mg/kg-d (U.S. EPA, 1989b and 1990), neither the estimated exposure for the best-estimate scenario nor the two estimated exposures for the health-conservative scenario exceeded the RfD and the calculated HI was less than one. However, as explained in the RI, if an uncertainty factor of 10 is applied to the RfD to account for contradictory data regarding the carcinogenic potential of 1,1-DCE (i.e., reducing the RfD value from  $9 \times 10^{-3}$  mg/kg-d to a value of  $9 \times 10^{-4}$  mg/kg-d), then the maximum exposures estimated for the health-conservative scenario would exceed the adjusted RfD, i.e., the resulting HIs would range from 1.4 to 1.8.

The EPA methodology (U.S. EPA, 1989a) for estimating the noncarcinogenic health hazard differs from the approach taken by LLNL because the EPA guidance stipulates that HIs, which are derived with respect to the noncarcinogenic properties of a chemical, be calculated for all contaminants of concern (i.e., both carcinogens and noncarcinogens). Calculation of HIs for all contaminants of concern identified in the RI and derived using EPA methodology appear in Appendix S of that report. The maxima of these HIs are presented in Table 3-4 and range from  $1.6 \times 10^{-3}$  (best-estimate) to 1.0 (health-conservative).

**Table 3-3. The baseline risk of cancer from untreated ground water compared with the risk of cancer from remediated ground water at LLNL.**

Scenario	Highest 70-y average concentration of total VOCs (ppb)	Time to maximum concentration (y)	Risk of cancer	
			Based on LLNL method	Based on EPA method
<b>Unremediated ground water</b>				
Best estimate <sup>a</sup>	0.15	270	$2 \times 10^{-7}$	$7 \times 10^{-7}$
Health-conservative <sup>a</sup>	440	110	$1 \times 10^{-3}$	$1 \times 10^{-3}$
Health-conservative <sup>b</sup>	584	35	$2 \times 10^{-3}$	$2 \times 10^{-3}$
<b>Remediated ground water</b>				
Best estimate <sup>a</sup>	0.006	265	$9 \times 10^{-9}$	$5 \times 10^{-8}$
Health-conservative <sup>a</sup>	3.0	98	$9 \times 10^{-6}$	$1 \times 10^{-5}$
Health-conservative <sup>b</sup>	3.4	22	$1 \times 10^{-5}$	$2 \times 10^{-5}$

<sup>a</sup> Based on receptor wells in downtown Livermore.

<sup>b</sup> Based on hypothetical receptor wells 250 ft west of LLNL.

**Table 3-4. Hazard-index values for unremediated scenario derived from LLNL and EPA methodologies.**

Unremediated scenario (from RI Predecisional Final)	Highest 70-y average concentration of total VOCs (ppb)	Arrival time of maximum concentration (y)	Hazard index (HI) <sup>a</sup>	
			Based on LLNL method <sup>b</sup>	Based on EPA method <sup>c</sup>
Best estimate <sup>d</sup>	0.15	270	$8.7 \times 10^{-5}$	$1.6 \times 10^{-3}$
Health conservative <sup>d</sup>	440	110	$1.4 \times 10^{-1}$	$1.0 \times 10^0$
Health conservative <sup>e</sup>	584	35	$1.8 \times 10^{-1}$	$1.0 \times 10^0$

<sup>a</sup> Sum of the ratios of chemical-specific exposures (mg/kg-d) to their reference maximum chronic daily doses that are not expected to produce adverse health effects; a value above unity indicates that exposure may potentially result in adverse health effects

<sup>b</sup> For 1,1-DCE only.

<sup>c</sup> See Appendix A.

<sup>d</sup> Based on receptor wells in downtown Livermore.

<sup>e</sup> Based on a potential monitor well drilled 250 ft west of LLNL.

### 3.2.2.3. Estimation of Potential Health Effects from Remediated Ground Water

As part of this FS, an assessment using the same methodologies as those in the RI was performed to assess potential risks posed by remediated ground water. Details are provided in Appendix A. The basis for the calculations is that ground water will be remediated to the standards for ambient ground water in Table 3-2 and then allowed to migrate under natural conditions. The conclusions of this assessment are:

1. The maximum incremental risk of developing cancer associated with the best-estimate (most likely) case for the combined 70-y exposure to VOCs (all pathways, all VOCs) from municipal supply wells in downtown Livermore is calculated to be nine in a billion ( $9 \times 10^{-9}$ ).
2. The maximum incremental risk of developing cancer associated with the health-conservative (unlikely) case for the combined 70-y exposure to VOCs (all pathways, all VOCs) from municipal supply wells in downtown Livermore is calculated to be nine in a million ( $9 \times 10^{-6}$ ).
3. The maximum incremental risk of developing cancer associated with the health-conservative (unlikely) case for the combined 70-y exposure to VOCs (all pathways, all VOCs) from a postulated well 250 ft west of the LLNL site is calculated to be one in one hundred thousand ( $1 \times 10^{-5}$ ).

As seen in Table 3-3, the estimated risk levels are significantly lower for the remediated case. In all scenarios, the estimated incremental cancer risk is reduced by more than a factor of 10. The estimated maximum HIs for remediated ground water (Table 3-5) are also reduced compared to the unremediated case (Table 3-4) by more than a factor of 10. The low HIs for the remediated case indicate that the potential for noncarcinogenic adverse health effects is insignificant.

A screening level evaluation was made of potential risks that could result from dispersing any tritium that might be present in ground water during the remediation process. Only one monitor well has measured tritium concentrations greater than the drinking water standard of 20,000 pCi/L (MW-206), and that has decreasing concentrations that are likely to be below standards by the time remediation can begin in that area.

Although MW-206 cannot produce more than about 0.5 gpm of water, we examined the risk of 30 gpm of water at 20,000 pCi/L being extracted and put through surface treatment units. The maximum exposure would come from breathing moisture laden air in which air moisture contained tritiated water. Calculations show that an air stripping operation could transfer at most about 0.1% of the tritium extracted into the air, or less than 3000 pCi/min. Other technologies would have lesser air emissions. Using the standard EPA code, AIRDOSEPA, for screening level calculations, the maximum human exposure would be less than 0.000005 mrem/y, compared to the EPA standard of 10 mrem/y. Exposures to the public would be reduced even further by air dispersal.

Because of the extremely low exposures from this worst case scenario, we conclude that the method of treatment need not consider tritium unless monitoring values show an extraordinary increase in the future.

**Table 3-5. Maximum hazard-index values for remediated scenario derived from LLNL and EPA methodologies.**

Remediated scenario	Highest 70-y average concentration of total VOCs (ppb)	Arrival time of maximum concentration (y)	Hazard index (HI)	
			Based on LLNL method <sup>a</sup>	Based on EPA method <sup>b</sup>
Best estimate <sup>c</sup>	0.006	265	$6.9 \times 10^{-6}$	$1.7 \times 10^{-5}$
Health conservative <sup>c</sup>	3.0	97.5	$1.6 \times 10^{-3}$	$6.1 \times 10^{-3}$
Health conservative <sup>d</sup>	3.4	22	$2.3 \times 10^{-3}$	$9.1 \times 10^{-3}$

<sup>a</sup> For 1,1-DCE only.

<sup>b</sup> See Appendix A.

<sup>c</sup> Based on receptor wells in downtown Livermore.

<sup>d</sup> Based on a potential monitor well drilled 250 ft west of LLNL.

#### 3.2.2.4. Risk Assessment of Compounds in the Vadose Zone

The conclusions of the BPHA with respect to the vadose zone are:

1. The only potentially significant pathway for human exposure to contaminants in the vadose zone at LLNL is via ground water.
2. The relatively low concentration of VOCs and FHCs in the vadose zone and the mechanics of soil-water transfer are such that concentrations of the chemicals in the ground water are not expected to exceed their current values. FHCs at the Gasoline Spill Area persist in concentrations likely to migrate to ground water if unremediated. In other areas, contaminant concentrations are sufficiently low that migration from the vadose zone is unlikely to cause ARARs to be exceeded in ground water even without active remediation.
3. The public is not directly exposed to contaminated soils; soil samples taken from offsite arroyos draining the LLNL site do not contain any chemicals of concern. The only potential soil-based exposure pathway for the public is through the inhalation of VOCs volatilized from sediment onsite, which is insignificant.
4. People onsite exposed to VOCs and other organic compounds in sediments will not be at significant risk of adverse health effects. Screening calculations suggested that concentrations of some inorganic substances in a few unoccupied portions of the site posed a possibly higher than desirable potential risk of cancer; consequently, sediment from these locations has been removed and appropriately disposed of. Remaining sediments do not pose a significant health risk.
5. Thorpe *et al.* (1990) and subsequent screening calculations (Section 1.2.3.4) show that radionuclide concentrations detected in the vadose zone do not present a health hazard to adults onsite or to the public offsite.

### 3.3. IDENTIFICATION AND SCREENING OF GENERAL RESPONSE ACTIONS

General response actions are the most inclusive class of remedial actions. These can be divided into (1) no action, (2) immediate action, and (3) deferred action. Immediate action responses include containment, *in situ* treatment, extraction with treatment and disposal, and excavation and disposal. Deferred action responses are similar, but include monitoring to observe any change in conditions and responding if certain conditions are met. Deferred action responses depend upon institutional and administrative controls and natural degradation processes.

#### 3.3.1. Estimate of Areas, Volumes, and Mass of Hazardous Materials

To evaluate general response actions that may meet remedial action objectives, we have estimated the areas, volumes, and masses of VOCs and FHCs in the unsaturated and saturated zones. We also estimated the area and mass of chromium in the saturated zone in excess of the MCL of 50 ppb. These estimates are adequate for comparing general response actions, but will be refined as additional data become available. Because existing data on chromium in

unsaturated sediments generally reflect background concentrations and show no concentrations above either Total Threshold Limit Concentrations (TTLCs) or STLCs, we have not calculated the amount of chromium in unsaturated sediments. The other metal of potential concern, lead, is limited to the Gasoline Spill Area, where only one recent measurement showed a concentration above the 50 ppb MCL. Because recent data do not confirm earlier measured concentrations and recent data are limited, we have not calculated the area and amount of lead, but may estimate them in the future if additional data warrant such an effort.

#### 3.3.1.1. Saturated Zone

Our most recent estimates of the area and volume of VOC-bearing ground water and sediments, and the total mass of VOCs within these media are shown in Table 3-6. These estimates are more refined than those presented in the RI, having been calculated using the interactive volume modeling (IVM) software developed by Dynamic Graphics, Inc. (1989). These estimates vary by less than 2% from earlier estimates. Saturated zone sediment and ground water chemical data were processed using a grid and contour model. The volumes of specified contour intervals were calculated by IVM from the gridded data. VOC masses were derived from the volumes by assuming a porosity of 30% and a retardation factor of 1.5. We estimated the VOC volume and mass where ground water concentrations exceeded 5 ppb (Figure 3-2), approximating the State or Federal MCLs or action levels for all plumes, since they are predominantly composed of TCE and PCE (MCL = 5 ppb). For comparison, we also estimated the volume and mass of VOCs in ground water exceeding 1 ppb (Figure 3-3). For these calculations, we omitted VOCs that do not originate from the LLNL site, i.e., northwest of the Patterson Pass–Vasco Road intersection (Figure 3-3). The plume in that area is being investigated separately by the RWQCB and property owners.

The estimated volume of ground water containing gasoline and the total gasoline mass are also shown in Table 3-6. The ground water volume estimates were calculated by multiplying the area of benzene concentrations greater than 1 ppb (Figure 3-4) by an average fuel plume thickness of 25 ft and a porosity of 30%. The mass of FHCs in the saturated zone was modified from Nichols *et al.* (1988).

The estimated volume of ground water containing chromium above the 50 ppb MCL and the total mass of chromium in excess of the MCL are shown in Table 3-6. For these calculations, we omitted chromium that does not originate from the LLNL site, i.e., northwest of the Patterson Pass–Vasco Road intersection (Figure 3-5). The ground water volume estimates were calculated by multiplying the area of chromium concentrations above 50 ppb (Figure 3-5) by an assumed porosity of 30% and an average chromium plume thickness between 8 and 13.5 ft, depending on the specific area. The mass of chromium was estimated by using the mean concentration of chromium in excess of 50 ppb for each area and a retardation factor of 11 (Selim *et al.*, 1989).

#### 3.3.1.2. Unsaturated Zone

The estimated volumes of unsaturated VOC-bearing sediment and the mass of VOCs in unsaturated sediment are shown in Table 3-7. Because remedial action objectives for unsaturated soil are based upon their potential to migrate to ground water, we have provided volume and mass estimates for several concentration ranges. These estimates were calculated using the IVM (Dynamic Graphics, Inc., 1989). Unsaturated chemical data were processed by the IVM,

Table 3-6. Estimated areas, volumes, and masses of VOCs, gasoline, and chromium in the saturated zone.

Unit <sup>a</sup>	Approximate area (thousands ft <sup>2</sup> )	Estimated pore volume <sup>b</sup> (thousands gal)	Estimated mass dissolved in ground water <sup>c</sup> (kg)	Estimated volume dissolved in ground water (gal)	Estimated total mass (kg)	Estimated total volume (dissolved and sorbed) (gal)
<b>VOCs:</b>						
>5 ppb	21,000	2,878,000	879	166 <sup>d</sup>	1,319 <sup>e</sup>	249
>1 ppb	38,800	4,820,000	890	168 <sup>d</sup>	1,335 <sup>e</sup>	252
Gasoline	477	26,800	237 <sup>f</sup>	85	31,400 <sup>f</sup>	11,200
<b>Chromium</b>						
>50 ppb	1,410	40,800	6 <sup>g</sup>	—	67 <sup>e</sup>	—

<sup>a</sup> Areas are shown in Figures 3-2, 3-3, 3-4, and 3-5, respectively.

<sup>b</sup> Amount of water that contains VOCs or fuel within bounds of unit. VOC pore volumes calculated using IVM by Dynamic Graphics, Inc., Berkeley, California. Fuel pore volume is the product of unit area, average plume thickness of 25 ft, and an assumed porosity of 30%. Chromium pore volume is the product of unit area, average plume thickness (8 to 13.5 ft), and an assumed porosity of 30%.

<sup>c</sup> Product of pore volume and geometric mean of VOC concentration.

<sup>d</sup> This compares to 183 gal estimated by Thorpe *et al.* (1990, Table 5.2-13), using less sophisticated techniques.

<sup>e</sup> Equals mass in ground water plus mass sorbed, assuming a retardation factor of 1.5 for VOCs and 11 for chromium.

<sup>f</sup> From Nichols *et al.* (1988). Gasoline mass estimates (dissolved, sorbed, and free product) are based on the product of unit area, ground water and saturated sediment concentrations, average plume thickness, and an assumed porosity of 30%.

<sup>g</sup> Product of pore volume and mean chromium concentration in excess of 50 ppb.

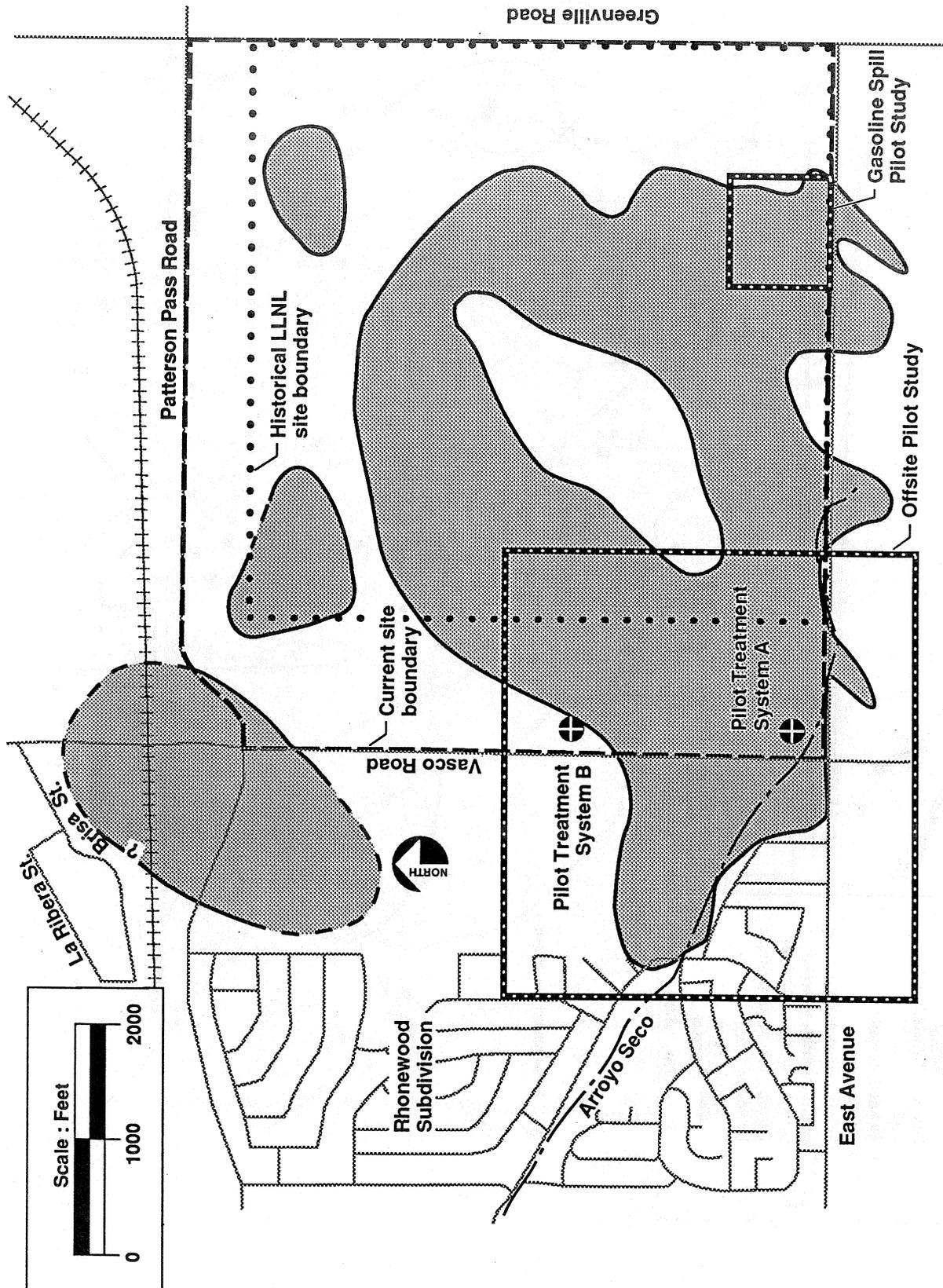


Figure 3-2. Area where one or more VOCs in ground water equals or exceeds Federal or California maximum contaminant levels (MCLs).

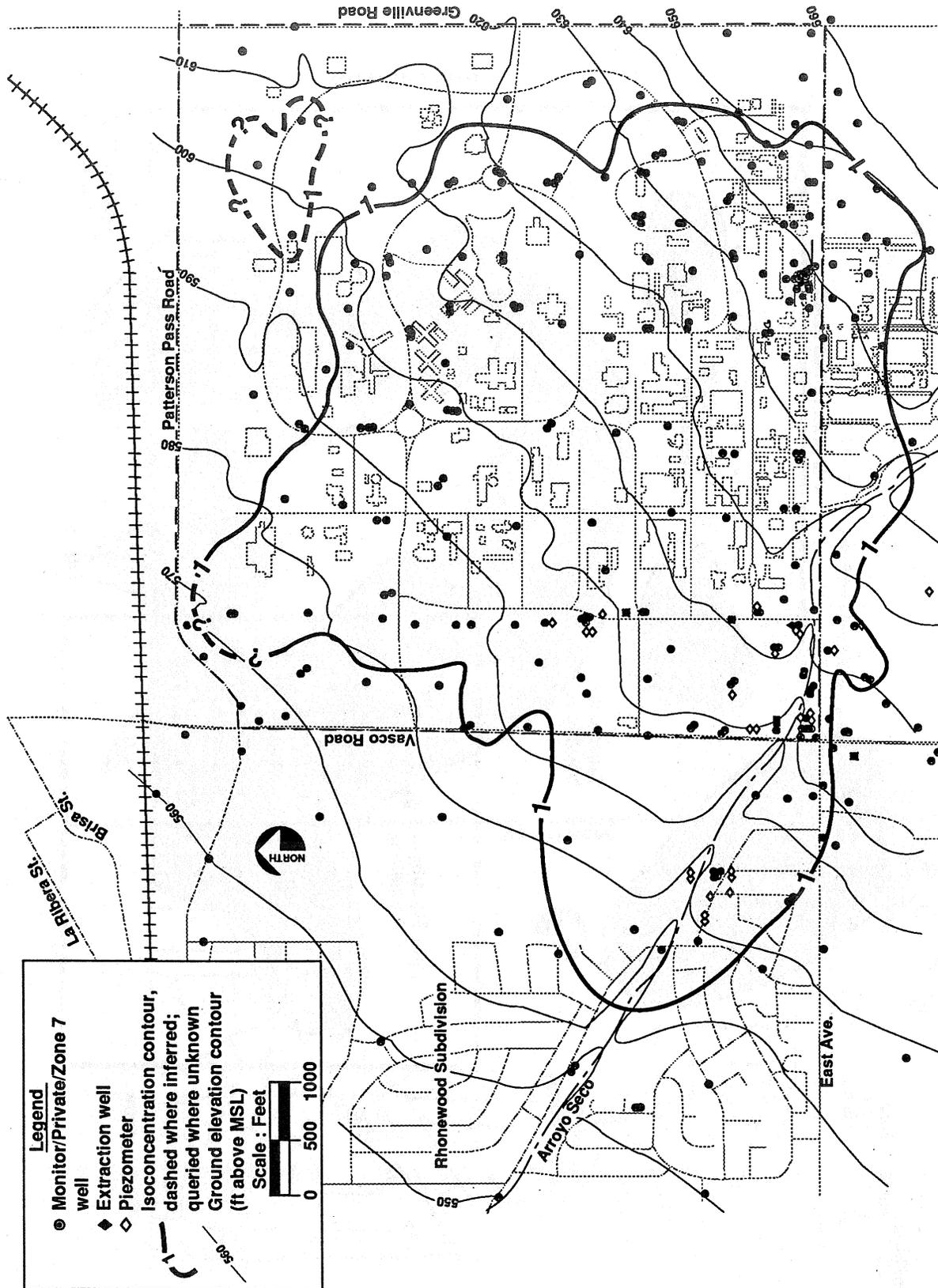


Figure 3-3. 1 ppb Isoconcentration boundary for total VOCs in ground water originating on the LLNL site.



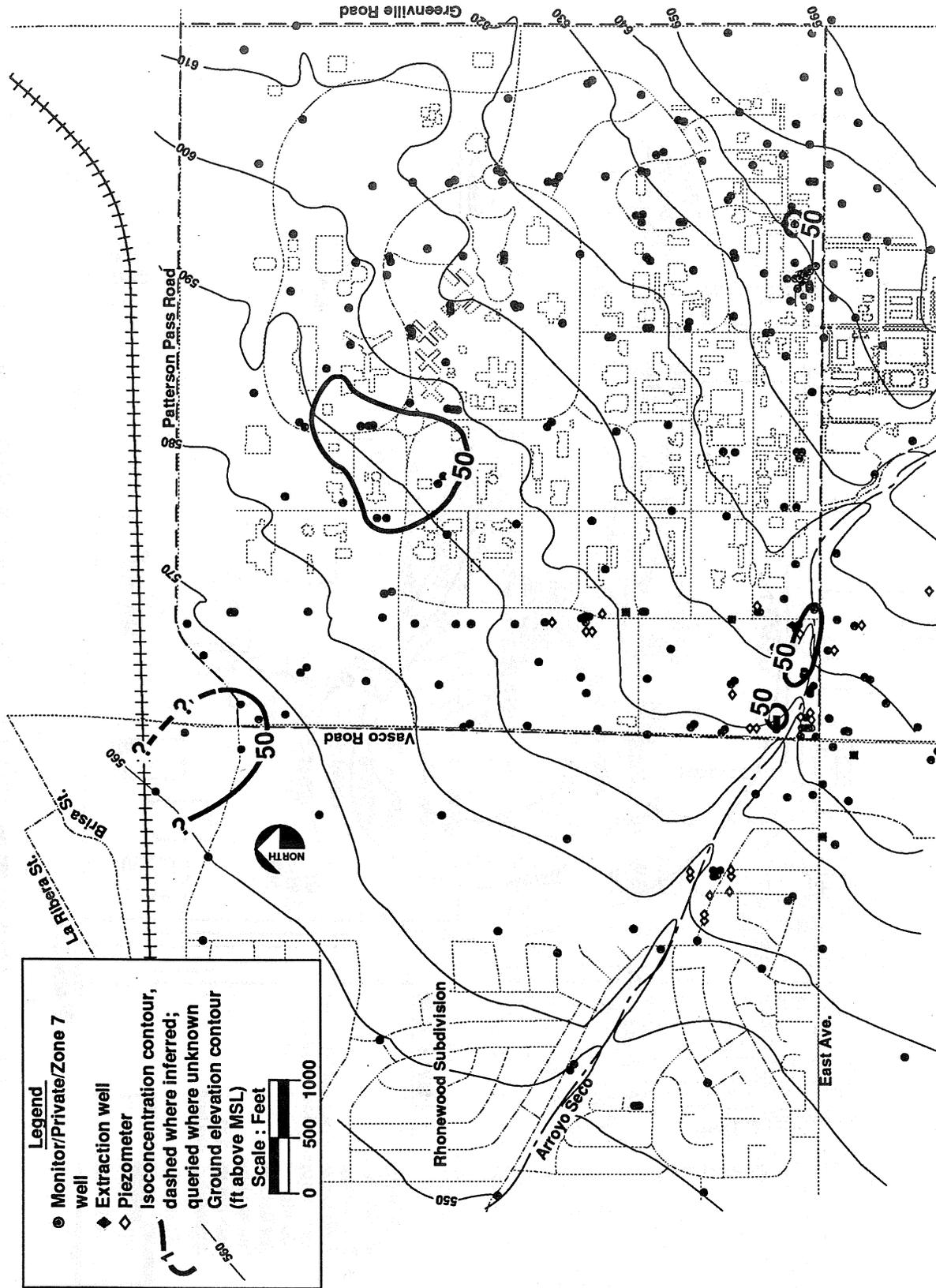


Figure 3-5. 50 ppb isoconcentration contour map of total chromium in ground water.

Table 3-7. Estimated volume and mass of VOCs in unsaturated sediment.

Concentration range (ppb)	Estimated sediment volume <sup>a</sup> (yd <sup>3</sup> )	Estimated total VOC mass <sup>b</sup> (kg)	Estimated total VOC volume (gal)
10-100	2,330,000	92.0	17.3
100-1,000	605,000	164	30.9
1,000-10,000	8,780	32.6	6.14
>10,000	0	0	0
Totals <sup>c</sup>	2,940,000	289	54.3

<sup>a</sup> Calculated using interactive volume modeling by Dynamic Graphics Incorporated, Berkeley, California.

<sup>b</sup> Calculated assuming a dry bulk density of 120 lb/ft<sup>3</sup> and 15% moisture by weight.

<sup>c</sup> Rounded to three significant figures.

producing a grid and contour model. This three-dimensional contour model was evaluated statistically and visually. When necessary, additional gridding was performed to refine the model. The volumes of specified contour intervals were calculated by the IVM using this grid. Masses were derived from volume by assuming a dry bulk density of 120 lb/ft<sup>3</sup> and a moisture content of 15% by weight.

We estimated the VOC volume and mass for all 14 RI source investigation areas. Figure 3-6 shows the investigation areas and the approximate areal extent of total VOCs exceeding 10 ppb at one or more depths. The volumes and masses shown in Table 3-7 were calculated for these areas.

We have conducted an evaluation of VOC migration through the vadose zone in the Building 518 and 511 Areas (Figures 3-6 and G-1). These areas were chosen for study because they contain the highest concentrations of vadose zone VOCs reported by Thorpe *et al.* (1990). The Building 518 Area is the only site at LLNL where VOC concentrations exceed 1 ppm. At Building 511, the highest concentration of vadose zone VOCs was nearly 1 ppm in a single borehole, at a depth of 10 ft. The objective of the study was to assess the possible impact of vadose zone VOCs in these two areas on local ground water, focusing on the dominant VOC constituent in each area: TCE at Building 518 and 1,2-DCE at Building 511. Appendix G contains details of this study.

We conclude that gaseous diffusion is the most important mechanism transporting vadose zone VOCs to the ground water, given the low infiltration rates and relatively low concentrations in the study areas. To evaluate the migration of a VOC mass in the vadose zone quantitatively, we solved a three-dimensional, radially symmetric diffusion equation which includes first-order degradation of VOCs. Using this model, we calculated the VOC concentration at the top of the capillary fringe that would result from migration through the vadose zone. We then solved a three-dimensional, steady-state ground water transport equation semi-analytically, using the VOC mass and concentration from the diffusion model as input. This allowed for the calculation of the transport of VOCs from the top of the capillary fringe to the water table, and the downgradient transport of VOCs in ground water.

Our calculations yield a maximum aqueous TCE concentration at the water table at Building 518 of about 17 ppb, roughly 60 y from the present. The TCE concentration falls off fairly rapidly from the water table beneath the source region to less than 5 ppb about 100 ft away. The peak aqueous 1,2-DCE concentration at the water table under the Building 511 Area was calculated to be 0.04 ppb, 75 y from present, which is far below the 6 ppb MCL.

We also conducted an extensive sensitivity analysis which identified VOC mass and distribution, degradation half-life, and soil anisotropy as key parameters strongly affecting peak VOC concentrations in the ground water. Reducing the peak TCE concentration from 6.1 to 2.5 ppm lowers the maximum aqueous concentration from 17 ppb to about 7 ppb. Decreasing the degradation half-life of TCE from 50 to 10 y lowers the peak concentration in the Building 518 Area from 17 to 4 ppb. The presence of thin sediment layers with high liquid saturation (80%) increases the vertical anisotropy and promotes lateral spreading, which also significantly reduces peak ground water concentrations.

Because of limitations of field data, and the sensitivity of the results to some of the hydrological parameters, we consider our results preliminary and subject to future refinement. The LLNL Ground Water Project will continue field monitoring to compare future VOC movement with model predictions and to calibrate the model. Nevertheless, work to date

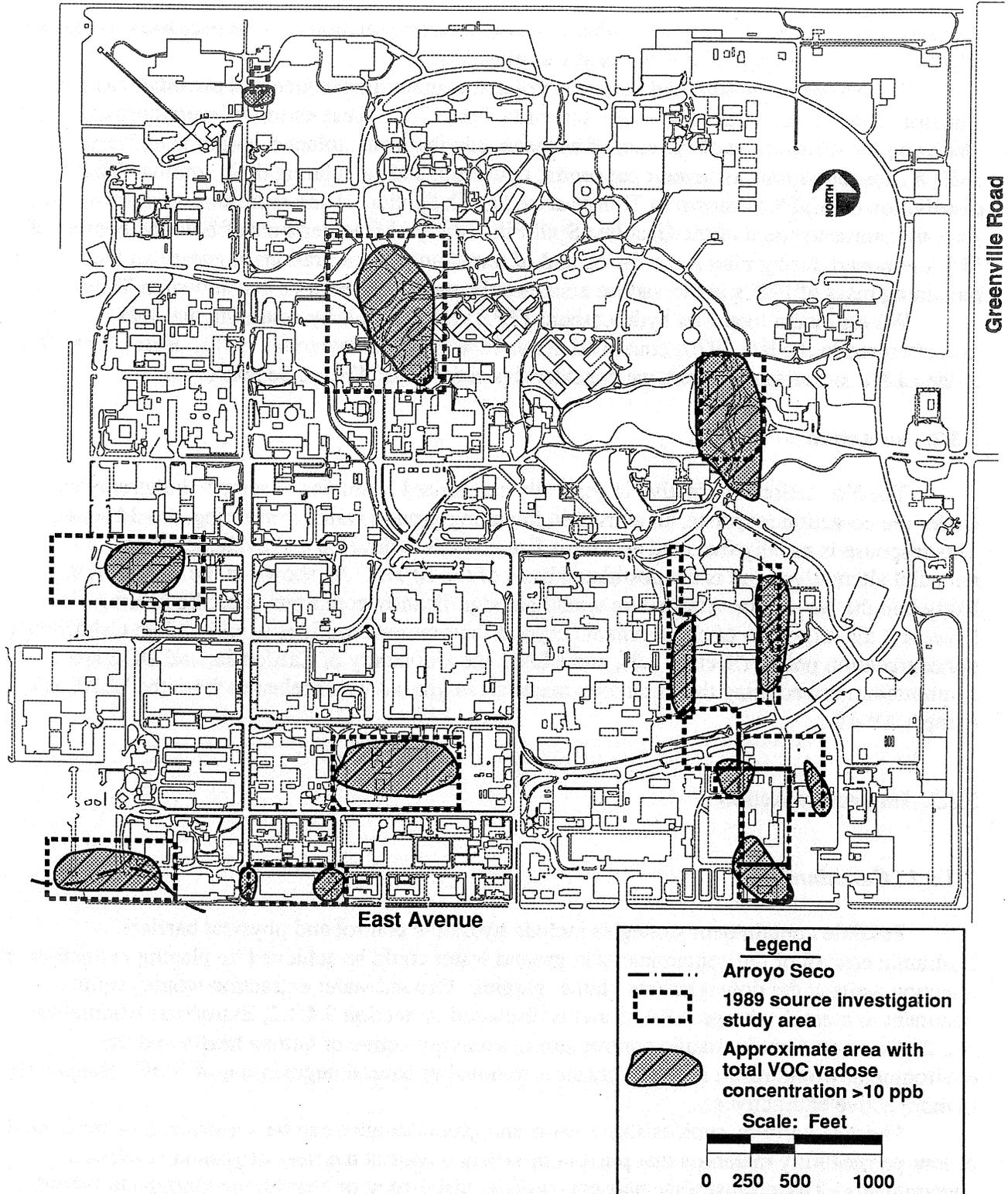


Figure 3-6. Areas within source investigation study areas at LLNL where total VOC concentrations exceed 10 ppb in the unsaturated zone.

suggests that, at most, the only area where vadose zone remediation may be necessary to prevent VOCs from impacting ground water is at Building 518.

The estimated unsaturated sediment volume containing gasoline and the total mass of gasoline in the Gasoline Spill Area are shown in Table 3-8. These estimates were prepared by idealizing the distribution of the sum of benzene, ethylbenzene, toluene, and total xylenes (BETX) concentrations as several concentric cylinders, and calculating their volume. This distribution of BETX is shown in Thorpe *et al.* (1990, Section 4) and represents concentrations prior to commencement of the Gasoline Spill Pilot Study. Measurements of both the amount of FHCs removed during pilot remediation and of remaining concentrations suggest that the remaining mass of FHCs in the vadose zone is only about one-tenth of that shown in Table 3-8.

We estimated total fuel hydrocarbons (TFH) from BETX by assuming that fuel manufactured in the late 1970s contained about 16% BETX (Mayrsohn, 1978). Because the fuel in the LLNL subsurface is aged, we consider this estimate of TFH to be conservative.

### 3.3.2. No Action

The No-Action Alternative is generally considered in studies of remedial alternatives. Under the no-action response, all activities, including ground water monitoring, would cease. This response is usually included as a basis from which to develop and evaluate proactive remedial alternatives and is the postulated basis of the BPHA. As shown in the BPHA, it is likely that the No-Action Alternative would not significantly compromise public health. However, the migration of contaminants beyond their current confines would violate California's nondegradation policy (Section 3.2), and LLNL, the University of California, and DOE are committed to remediating the hazardous materials in ground water released from the LLNL site to meet ARARs.

### 3.3.3. Immediate Action

#### 3.3.3.1. Containment

Possible containment strategies include hydraulic control and physical barriers. Hydraulic control of the contaminants in ground water could be achieved by placing extraction or injection wells at the downgradient plume margins. Ground water extraction would require treatment to meet discharge ARARs and is discussed in Section 3.4.1.2, Extraction Alternative No. 2. Downgradient hydraulic control alone, while protective of human health and the environment, would result in relatively slow removal or natural degradation of VOCs compared to more active alternatives.

Physical barriers, such as slurry walls and grout curtains, can be constructed belowground of low-permeability materials that prevent or severely restrict the flow of ground water and contaminants. These subsurface barriers could be installed at or near plume margins to inhibit further migration of contaminants. However, the relatively great depth (about 200 ft) and large areal extent of the VOC plumes in the study area severely limit the practicality of slurry walls and grout curtains.

**Table 3-8. Estimated area, volume, and mass of FHCs in unsaturated sediment.**

Concentration	Estimated area (ft <sup>2</sup> )	Average thickness (ft)	Estimated sediment volume (yd <sup>3</sup> )	Estimated total gasoline mass <sup>a</sup> (kg)	Estimated total FHCs volume <sup>a</sup> (gal)
Above 100,000 ppb TFH <sup>b</sup>	1,500	80	4,500	16,500	5,900
Above 100 ppb BETX	3,700	80	11,200	17,000	6,100

<sup>a</sup> After Nichols *et al.* (1988) and concentrations prior to pilot extraction. Assumes a dry bulk density of 120 lb/ft<sup>3</sup> and 15% moisture by weight.

<sup>b</sup> Estimated from sediment BETX concentrations, assuming a 16% BETX fraction in gasoline.

Capping is another kind of physical barrier that can be used to limit exposure of humans and wildlife to chemicals in soil and to minimize infiltration of surface water and leaching into the ground water. It is a passive technology that does not treat the hazardous materials in soil. Capping consists of grading the ground surface to establish drainage away from the contaminated area and covering the surface with a layer of low-permeability material. A variety of cap designs and capping materials are available, including asphalt, clay, and synthetic liners. A surface cover may be added to protect the cap and to facilitate surface water drainage. The principal drawback to capping is the fact that the hazardous materials in the soil are not removed. Capping can, however, greatly increase the time available for natural degradation to reduce concentrations of hazardous materials. At the LLNL site, direct infiltration of rain water to the water table is limited to areas of ponding (drainage retention basins) and concentrated runoff (arroyos). Hence, capping would have little effect on much of the site.

*In situ* vitrification has been proposed as an alternative process for containing subsurface hazardous wastes. Because this technology is considered experimental, is very energy intensive, and is not likely to have any advantages at LLNL, we will not consider it further.

### 3.3.3.2. In Situ Treatment

Biological treatment technologies have been shown in some circumstances to be applicable *in situ*. These rely on the metabolic destruction of organic compounds by microbes that convert the organic compounds present in the ground water to less toxic compounds. The biological process requires sufficient material to support sustained biological growth. In addition, sufficient concentrations of other nutrients (e.g., nitrogen and phosphorus) must be present. The biological destruction of petroleum hydrocarbons has been demonstrated, but chlorinated solvents are less amenable to biological destruction, and efficient destruction has not yet been shown for halogenated compounds. A major problem for large, diffuse plumes, such as at LLNL, is the dispersal of microbes and nutrients. Because of these problems, *in situ* bioremediation of VOCs is not considered further at this time. If the state-of-the-art advances sufficiently during remediation, its applicability will be evaluated further.

Bioremediation of the gasoline spill is potentially more viable than for VOCs because of the limited extent of FHCs and the more advanced state-of-the-art. Nonetheless, the depth of FHCs at LLNL and the sensitivity of microorganisms to *in situ* conditions that are difficult to control introduce substantial uncertainties in the applicability of *in situ* bioremediation at LLNL.

### 3.3.3.3. Extraction with Treatment and Disposal

Surface treatment of ground water involves extraction, usually by pumping wells, conveyance to a treatment system, treatment, and discharge of the treated effluent. The following extraction, treatment, and disposal alternatives have been considered:

- |             |  |
|-------------|--|
| Extraction: | Pumping for optimal capture (ground water)                   |
|             | Pumping for downgradient plume margin control (ground water) |
|             | Excavation (vadose zone or ground water)                     |
|             | Vacuum-induced venting (vadose zone or dewatered zone)       |
| Treatment:  | Granular activated carbon (ground water or vapor)            |
|             | Air stripping (ground water)                                 |

- UV/oxidation (ground water)
- Thermal oxidation (vapor)
- Catalytic oxidation (vapor)
- Surface biological reactors (ground water)
- Precipitation (ground water)
- Ion exchange (ground water)
- Ultrafiltration (ground water)

Disposal :

- Recharge basin (treated ground water)
- Recharge via surface drainages (treated ground water)
- Used for LLNL landscape irrigation (treated ground water)
- Recharge wells (treated ground water)

These alternatives are discussed in more detail in Section 3.4.

### 3.3.4. Deferred Action

A potential Deferred-Action Alternative would involve treatment, if necessary, at the point of use. To assure protection of health, periodic sampling and analyses—with the installation of additional monitor wells between LLNL and the municipal supply wells in downtown Livermore—would be required. Monitoring would continue until the physical and chemical processes of dilution, sorption, dispersion, and degradation reduce the concentrations of VOCs to insignificant levels, or until monitoring demonstrates that further action is required. If VOCs in concentrations representing a significant health risk were to reach an in-use domestic or agricultural supply well, LLNL would either install a point-of-use treatment system or supply an alternative source of water to the affected user. No more than five supply wells are likely ever to be affected.

Institutional/administrative responses, such as permit restrictions on well installation and land use restrictions, may in fact be as protective of human health and the environment as other alternatives. Natural decay, dispersion, and adsorption would eventually reduce the concentration of compounds that may enter aquifers used for domestic or irrigation water to acceptable levels in terms of health risk. Institutional/administrative controls would require that no ground water containing hazardous materials in concentrations exceeding MCLs would be used for drinking.

If VOCs in concentrations representing a significant health risk were to reach the municipal supply wells in downtown Livermore, LLNL would install point-of-distribution treatment facilities. Administrative and institutional controls would be recommended as part of this option to reduce the likelihood that a new well would be installed into a contaminant plume.

This approach would be the most cost effective remediation alternative. Although this alternative is technically feasible and protective of human health and the environment, it would allow ground water degradation for a much longer time period, over which physical and chemical processes would slowly reduce the concentrations of VOCs. Therefore, this approach is not acceptable to DOE, LLNL, and the regulatory agencies, and is presented only as a baseline for comparison with more aggressive, immediate response actions.

### 3.4. IDENTIFICATION AND SCREENING OF REMEDIAL ALTERNATIVES AND REMEDIATION TECHNOLOGIES

Ground water can be extracted for treatment via extraction wells or trenches. Extraction trenches are not technically or economically feasible at LLNL because the VOC plumes extend as deep as 200 ft below the surface. In addition, VOCs are present only in discrete water-bearing zones in many parts of the study area, and extraction wells are the most efficient way to remove ground water containing VOCs from distinct intervals.

Presented below are two extraction alternatives, each utilizing a different array of extraction wells.

#### 3.4.1. Ground Water Extraction

Conceptual locations of extraction wells and ground water treatment facilities are discussed below for two alternatives. Under Alternative No. 1, extraction wells would be placed to intercept and hydraulically control ground water originating from LLNL with VOCs in concentrations exceeding the ARARs in Table 3-2. To expedite cleanup, extraction wells would also be located in areas where VOC concentrations in ground water exceed 100 ppb. Under Alternative No. 2, extraction wells would be located to intercept and hydraulically control offsite migration of VOCs in concentrations exceeding ARARs in the downgradient (western and southern) areas only.

##### 3.4.1.1. Extraction Alternative No. 1—Complete Capture and Source Area Extraction

Using the parameter value discussed in Appendix A, we estimate that VOCs in concentrations above MCLs in ground water that originate at LLNL can be hydraulically captured and source area cleanup can be initiated by extracting ground water at about 18 locations. The hypothetical initial locations for extraction and simulated capture flow lines for this alternative are shown superimposed on an isoconcentration contour map of VOCs in Figure 3-7. The actual capture areas would probably differ from those in Figure 3-7, depending on the local distribution and orientation of interconnected high conductivity sediments. Additional extraction wells would subsequently be phased in to shorten the time required for remediation. Water would be pumped from these locations using current extraction wells, existing monitor wells, and new extraction wells. As shown in Figure 3-7, the analytical model CAPTURE (Appendix B) predicts that pumping at these 18 locations will effectively intercept VOC plumes and control ground water flow in all but one area where VOC concentrations exceed ARARs, i.e., northwest of LLNL (Figure 3-7). Extraction wells are not planned for this area because the VOCs appear to have a source unrelated to LLNL (Thorpe *et al.*, 1990).

At each of the extraction locations, ground water would be extracted via one or more wells. The number of extraction wells at each location will depend upon the chosen extraction well design. Presently, the following three extraction well design alternatives (discussed in Section 2) are being considered:

1. One extraction well continuously screened and sand-packed over all water-bearing zones containing VOCs at that location (EW-415 design, Figure 2-2).

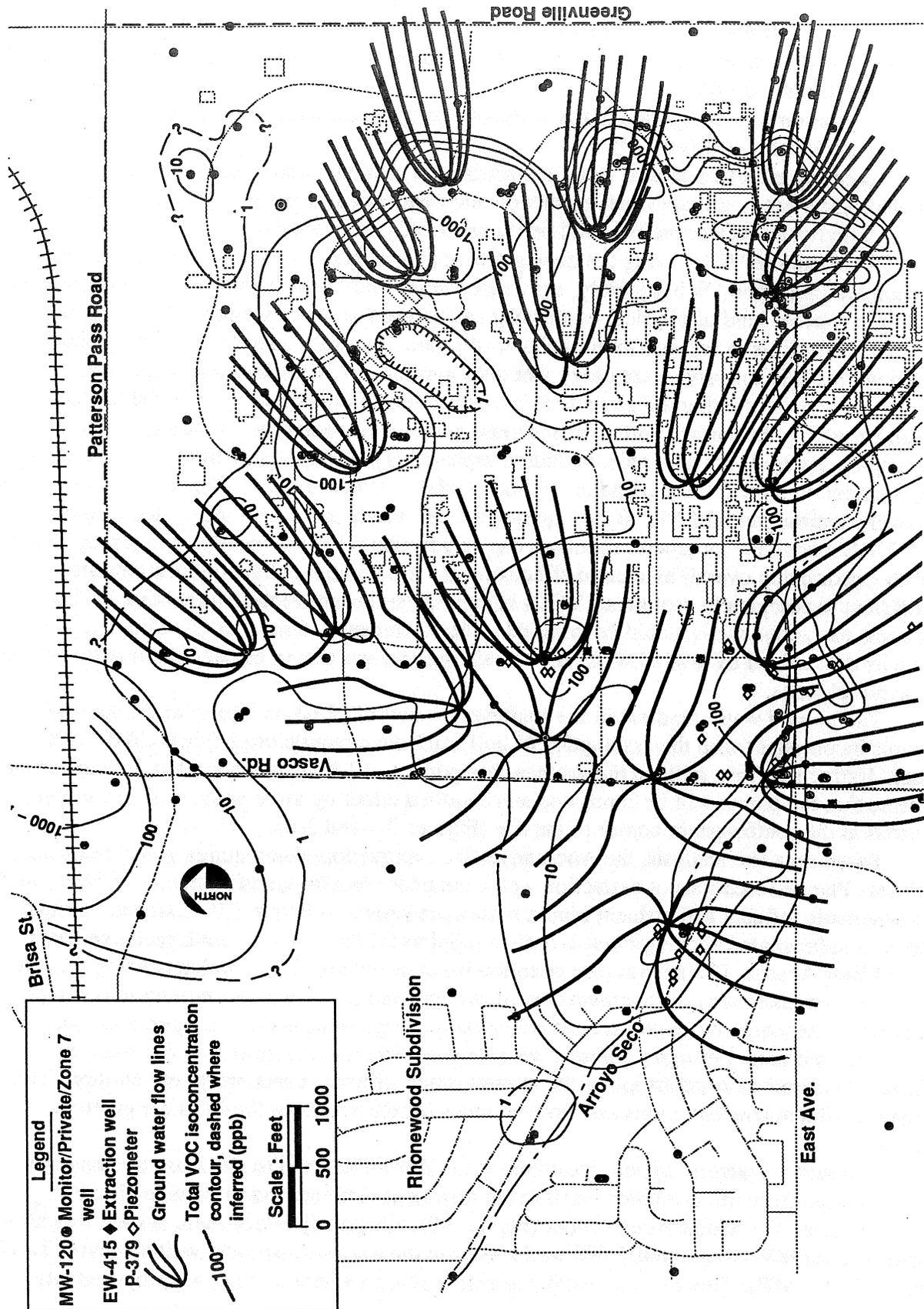


Figure 3-7. Capture plot for Extraction Alternative No. 1—Complete Capture and Source Remediation.

2. One or two multiply completed extraction wells per location, with grout seals between each permeable zone screened. Each well would be limited to two or perhaps three screened intervals (Figure 2-10).
3. One extraction well completed in each water-bearing zone containing VOCs at each extraction location (Figure 2-9).

To ensure effective ground water extraction and cleanup in the heterogeneous LLNL hydrogeologic system, ground water extraction and treatment systems would be installed in phases. Initially, extraction wells would be installed and pumped at the ten locations shown in Figure 3-8 to capture VOCs along the downgradient plume margins and halt further westward and southern migration. Subsequently, extraction wells would be installed at locations near VOC Capping is another kind of physical barrier that can be used to limit exposure of humans and wildlife to chemicals in soil and to minimize infiltration of surface water and leaching into the ground water. It is a passive technology that does not treat the hazardous materials in soil. Capping consists of grading the ground surface to establish drainage away from the contaminated area and covering the surface with a layer of low-permeability material. A variety of cap designs and capping materials are available, including asphalt, clay, and synthetic liners. A surface cover may be added to protect the cap and to facilitate surface water drainage. The principal drawback source areas throughout LLNL. By comparing actual capture areas with those predicted by the CAPTURE model, the parameter estimates can be adjusted for subsequent planning proposes, thereby maximizing overall extraction effectiveness. If the initial extraction locations are insufficient to completely capture all VOCs in concentrations above their respective MCLs, additional extraction wells would be installed. The placement and number of additional wells would be determined by ground water flow modeling and analysis of actual capture areas created by the initial wells.

The ground water gradient in the southeastern part of LLNL is locally to the southwest, which is inconsistent with the assumption of uniform flow direction used by the CAPTURE model. Extraction from wells in the southeastern portion of LLNL will alter that flow direction to assure that the plume will be controlled and captured either by those wells or at extraction locations at the southwestern corner of the site (Figures 3-7 and 3-8).

Based on a site analysis, the Alternative No. 1 extraction plan requires seven treatment facilities. Planned locations of extraction wells, treatment facilities, and recharge facilities, along with schematic influent and effluent piping routes, are shown in Figure 3-9. Extracted ground water would be treated above ground and discharged to (1) the existing LLNL recharge basin south of East Avenue, (2) the drainage retention basin in central LLNL, which is being lined to prevent further dispersing contaminants by infiltration, and (3) to ditches draining into Arroyo Las Positas. Recharge of treated ground water via recharge wells is also being considered.

For preliminary design purposes, we have used data from existing monitor wells to estimate the chemical composition of the ground water influent to each treatment facility. The estimated influent concentrations and flow volumes for the treatment facilities are given in Table 3-9.

The seven treatment system locations (A to G) were selected to minimize the length of piping required from the extraction wells to the treatment facilities and to provide efficient discharge routes for treated ground water (Figure 3-9). Originally, a treatment system was also planned for the MW-108/109/407/408 well cluster in the Rhonewood Subdivision, west of LLNL (Dresen *et al.*, 1987). However, to avoid placement of a treatment facility in a proposed city

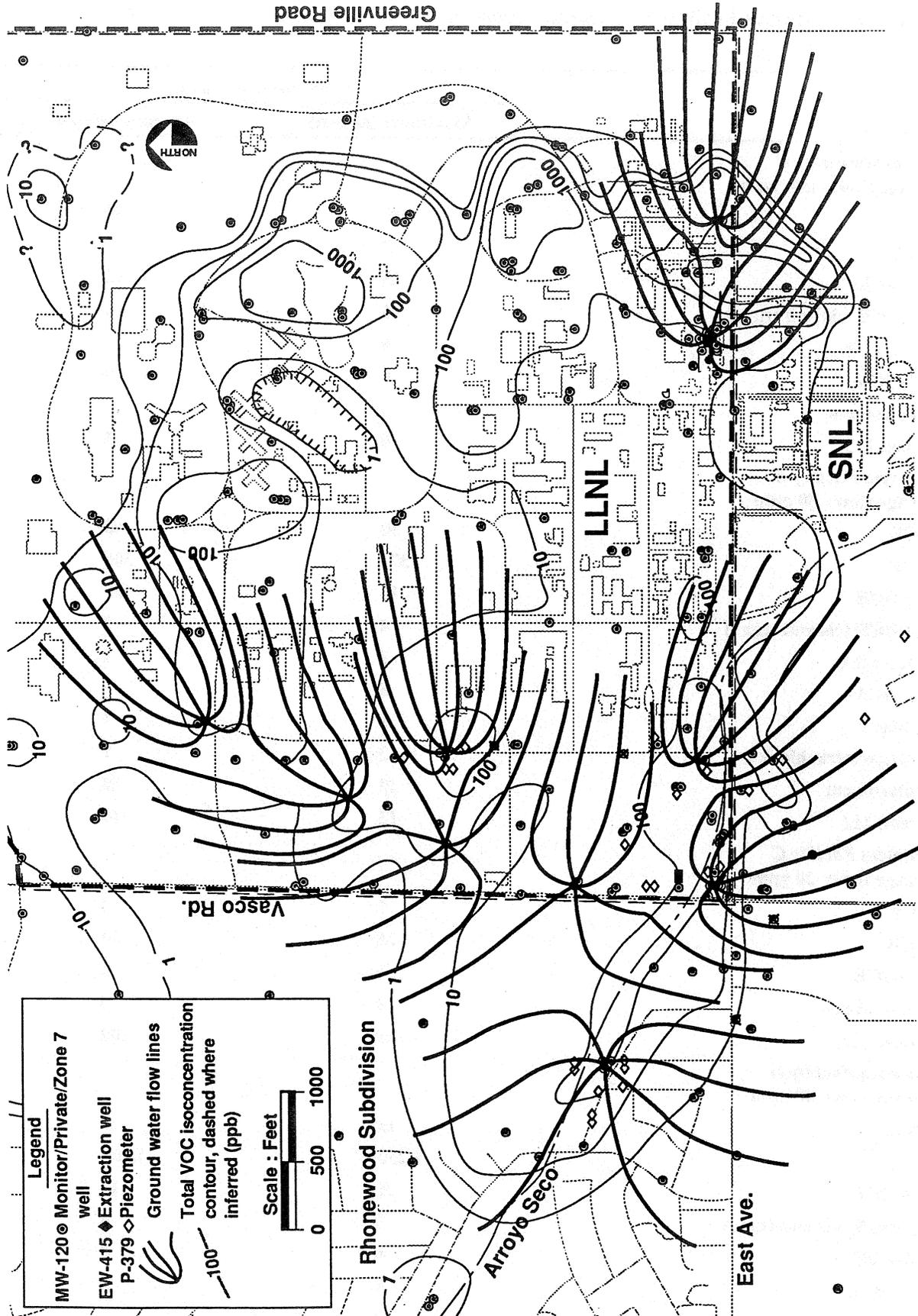


Figure 3-8. Capture plot for Extraction Alternative No. 2—Downgradient Plume Margin Control, with Southeast Corner Extraction.

Table 3-9. Estimated influent concentrations for seven postulated ground water treatment facilities.

Constituents	Concentration (ppb)	
	Maximum influent	Average influent
<i>Treatment Facility A</i>		
Average flow: 150 gpm		
PCE	350	280
TCE	9	7
1,1-DCE	15	12
1,2-DCE (cis and trans)	5	4
1,1,1-TCA	6	5
1,1-DCA	6	5
Chloroform	13	10
Freon 113	6	5
<i>Treatment Facility B</i>		
Average flow: 50 gpm		
PCE	50	40
TCE	375	300
1,1-DCE	13	10
1,2-DCE (cis and trans)	4	3
1,1,1-TCA	1	1
1,1-DCA	6	5
1,2-DCA	1	1
Carbon tetrachloride	3	2
Chloroform	13	10
Freon 113	13	10
<i>Treatment Facility C</i>		
Average flow: 20 gpm		
PCE	6	5
TCE	25	20
1,1-DCE	3	2
Chloroform	4	3
Freon 113	125	100
<i>Treatment Facility D</i>		
Average flow: 30 gpm		
PCE	13	10
TCE	1,250	1,000
1,1-DCE	21	17
1,2-DCE (cis and trans)	5	4
1,1,1-TCA	4	3
1,1-DCA	4	3

Table 3-9. (Continued)

Constituents	Concentration (ppb)	
	Maximum influent	Average influent
<i>Treatment Facility D (continued)</i>		
1,2-DCA	26	21
Carbon tetrachloride	38	30
Chloroform	162	130
Freon 113	4	3
Chromium	63	50
<i>Treatment Facility E</i>		
Average flow: 30 gpm		
PCE	313	250
TCE	3,500	2,800
1,1-DCE	44	35
1,2-DCE (cis and trans)	0	0
1,1,1-TCA	34	27
1,1-DCA	0	0
1,2-DCA	13	10
Carbon tetrachloride	13	10
Chloroform	125	100
Freon 113	13	10
<i>Treatment Facility F</i>		
Average flow: 30 gpm		
PCE	13	10
TCE	250	200
1,1-DCE	13	10
1,1,1-TCA	4	3
1,2-DCA	163	130
Carbon tetrachloride	13	10
Chloroform	25	20
Freon 113	13	10
Benzene	25,000	20,000
Toluene	38,000	30,000
Xylenes	19,000	15,000
Lead	38	30

Table 3-9. (Continued)

Constituents	Concentration (ppb)	
	Maximum influent	Average influent
<i>Treatment Facility G</i>		
Average flow: 50 gpm		
PCE	13	10
TCE	125	100
1,1-DCE	13	10
1,2-DCE (cis and trans)	1	0.5
1,1,1-TCA	25	20
Carbon tetrachloride	6	5
Chloroform	25	20
Freon 113	13	10
Constituents	Health conservative	Best estimate
<i>Downtown Livermore production wells</i>		
<i>point of distribution</i>		
Average flow: 470 gpm		
PCE	460	0.02
TCE	900	0.10
1,1-DCE	42	0.01
1,2-DCE (cis and trans)	4.2	0.001
1,1,1-TCA	4.2	0.001
1,1-DCA	8.4	0.002
1,2-DCA	8.4	0.002
Carbon tetrachloride	8.4	0.002
Chloroform	120	0.20

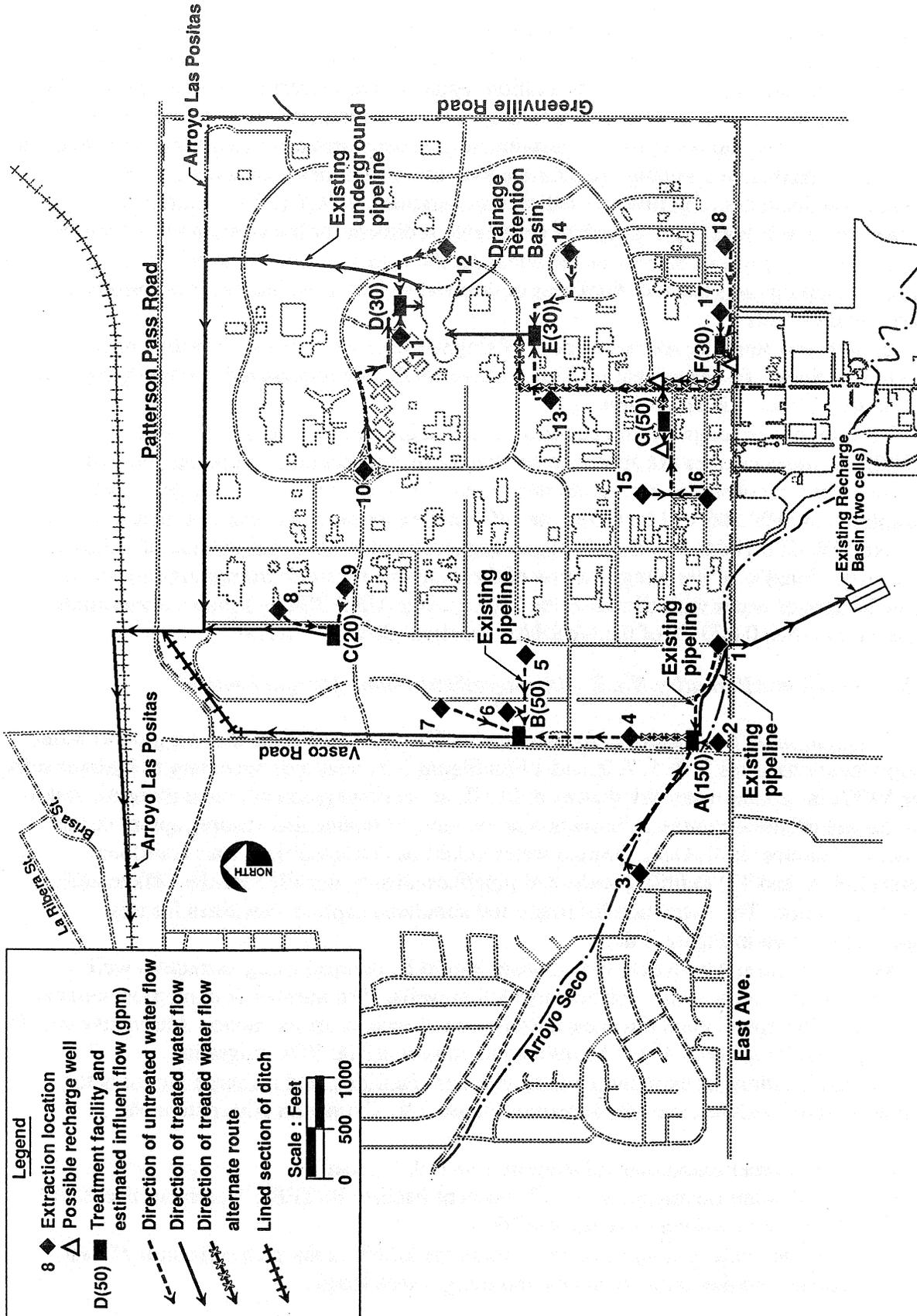


Figure 3-9. Preliminary ground water extraction and treatment facility locations.

park area, extracted ground water from this area will be piped along the north side of Arroyo Seco to Treatment Facility A (TFA) (Figure 3-9). Selection of the final locations of treatment facilities will depend on piping costs, installation logistics, and recharge well feasibility. The estimated influent flow rate is shown in parentheses at each treatment facility location in Figure 3-9. This flow rate is the sum of sustainable pumping rates estimated for each extraction location. The sustainable pumping rates for the extraction locations were estimated by multiplying the thickness of permeable sediments containing VOCs at that location (as determined from well logs) by 1 gpm/ft of permeable sediment for the western two-thirds of LLNL, and by 0.5 gpm/ft of permeable sediment for the eastern third. These estimates of sustainable pumping rates per foot thickness of permeable sediments are based on results of sitewide pumping tests.

As with any pumping scenario, zones of stagnation could possibly develop under constant pumping conditions. To ensure that all VOCs above MCLs are remediated, the pumping rates and locations will be varied over time.

We note that although tritium currently exists at greater than the MCL at one well onsite (MW-206), its presence does not appear to be a factor in the selection of a pump and treat alternative. First, the observed rate of decline in the tritium concentrations suggests that concentrations in MW-206 will be below the MCL before extraction could commence in that area. Next, MW-206 yields less than 0.5 gpm, suggesting that the actual volume of affected water is small. Finally, a screening analysis of the exposure resulting from pumping and air stripping 30 gpm of water with tritium at the MCL (using AIRDOSEPA) shows a maximum exposure of less than 0.0001% of the NESHAP standard (Section 3.2.2.3).

#### **3.4.1.2. Extraction Alternative No. 2—Downgradient Plume Margin Control**

Using the same parameters as for Alternative No. 1, we conclude that six ground water extraction locations (sites 2, 3, 5, 7, 9, and 17 on Figure 3-9) would be necessary to hydraulically capture VOCs in ground water originating at LLNL at the downgradient plume margins, and to prevent further offsite migration. Extraction at location 17 would also ensure capture of the FHCs at the Gasoline Spill Area. Ground water would be extracted from four additional locations (1, 4, 6, and 18) to utilize wells and pipelines already installed for the Offsite and Gasoline Spill Pilot. The extraction locations and simulated capture flow lines for this alternative are shown in Figure 3-8.

As in Extraction Alternative No. 1, water would be pumped using extraction well EW-415, existing monitor wells, and new extraction wells. The number of extraction wells at each location will depend upon the chosen design, as discussed for Extraction Alternative No. 1. If necessary, additional wells would be utilized to control offsite VOC migration.

Planned locations of extraction wells, treatment facilities, and recharge facilities for Extraction Alternative No. 2 are also shown in Figure 3-9. Extraction Alternative No. 2 consists of:

- Ground water extraction at locations 1 to 7, 9, 17, and 18.
- Ground water treatment at TFA, Treatment Facility B (TFB), Treatment Facility C (TFC), and Treatment Facility G (TFG).
- Recharge to the drainage retention basin, the LLNL recharge basin south of East Avenue, and the drainage ditch paralleling Vasco Road.

### 3.4.1.3. Estimated Cleanup Time

The length of time necessary to achieve the remedial action objectives for the LLNL VOC plumes using a pump and treat approach was estimated using the following assumptions:

1. The plumes are uniformly mixed and contain two reservoirs of VOC mass: VOCs dissolved in ground water and VOCs sorbed in saturated soil.
2. All sources of VOCs within the vadose zone have been (or will be) removed so that there will be no new leaching of VOCs from the vadose zone to the saturated zone.
3. The concentrations of VOCs within the soil and ground water are in equilibrium, based on linear partitioning coefficients ( $K_{ds}$ ).
4. The extraction locations are:
  - a. distributed uniformly throughout the plumes (Alternative No. 1), or
  - b. located only at the western and southern margins of the plumes (Alternative No. 2).
5. The VOCs undergo natural first-order degradation with a half-life of 50 y (Thorpe *et al.*, 1990).

Using these assumptions, an analytical expression was derived to predict the average concentration of total VOCs in the ground water over time. This expression is discussed in more detail in Appendix C. Using estimates of existing total VOC mass and extraction pumping rates, the average concentrations of VOCs in the ground water were predicted over time and are shown in Figure 3-10 for both extraction alternatives.

For Extraction Alternative No. 1, the decline in average VOC concentration is exponential with a half-life of 13 y. As shown in Figure 3-10, the length of time necessary to lower the average concentration of total VOCs in ground water to less than 5 ppb is about 53 y. Because the calculation does not account for the extraction at the highest concentration locations and continued optimization of the extraction network, cleanup may proceed somewhat faster.

For Extraction Alternative No. 2, the decline in average total VOC concentration has a half-life of 22 y. As shown in Figure 3-10, the length of time necessary to lower the average concentration of VOCs in the ground water to less than 5 ppb is about 87 y. Because the calculation does not consider the time necessary for contaminants to migrate from the eastern portion of the site to the extraction wells near the western boundary, actual cleanup may take longer.

If active ground water remediation were not implemented, the VOC plume would slowly disperse and degrade by natural processes. The transport model PLUME was used (In-Situ, Inc., 1986) to estimate the time necessary for the concentration of each VOC to fall below its MCL. The model and the "best-estimate" parameters used for the simulations are discussed in the RI report (Thorpe *et al.*, 1990). The compounds simulated included PCE, TCE, chloroform and "other VOCs," which represent compounds such as carbon tetrachloride and 1,1-DCE. The simulations indicated that, of these VOCs, the concentration of TCE takes the longest time to diminish to its MCL of 5 ppb. This is predicted to occur after about 360 y. These best-estimate simulations predict that all concentrations of VOCs within the plume fall below MCLs before the plume has migrated more than about 6500 ft west of LLNL.

Several of the assumptions and parameter values affect this cleanup time. Conditions that may increase or decrease the time required for remediation are discussed in Appendix C. Candidate treatment options that can be used in conjunction with either extraction alternative are discussed later in this section.

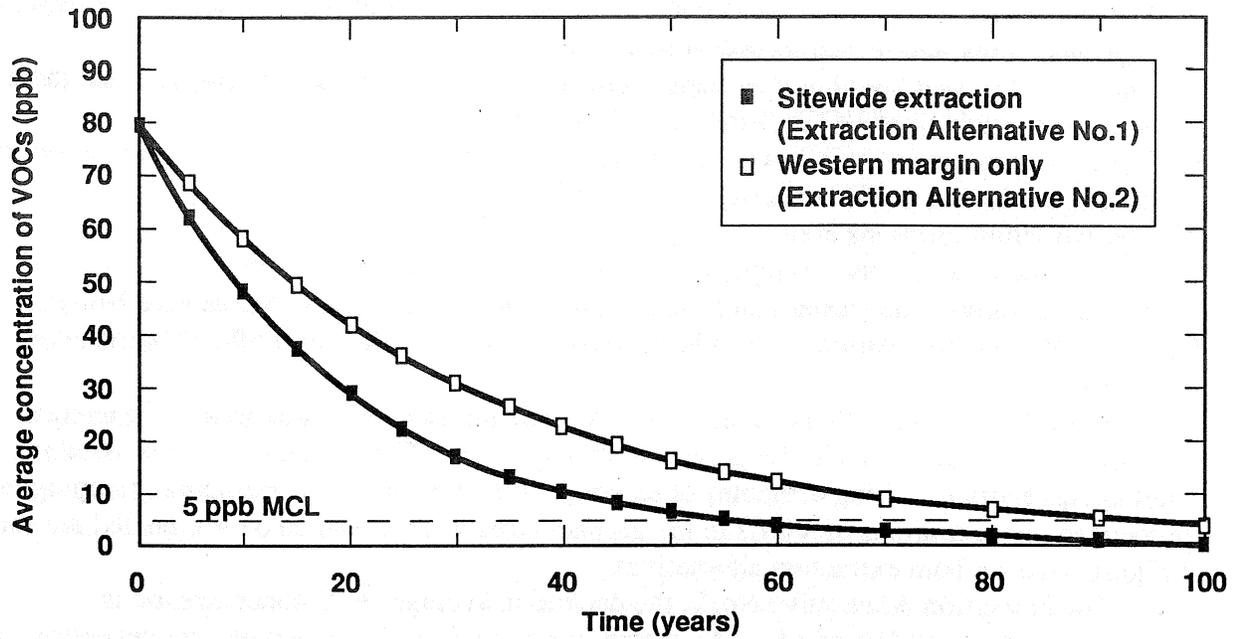


Figure 3-10. Estimate of average VOC concentration vs time for Extraction Alternatives Nos. 1 and 2, includes a 50-y natural degradation half-life (see Thorpe *et al.*, 1990).

Remediation of unsaturated sediments containing VOCs at LLNL is expected to consist of:

1. Excavation in limited areas if local concentrations exceed designated limits, with subsequent treatment and/or disposal of the excavated material.
2. Soil vapor extraction in locations where concentrations are less than designated limits and/or where excavation is impractical, coupled with treatment of the vapors by carbon adsorption, thermal oxidation, or other potential methods.

The length of time necessary to reduce VOC concentrations in the unsaturated zone to a particular level will depend on many factors, such as:

- Spacing, depth, and design of vapor extraction wells.
- Initial concentration and volatility of contaminants in sediments.
- Volume removed by excavation (if any).
- Rate of local infiltration.
- Ability of the local sediments to transmit vapor.

Many of the factors affecting removal rates are expected to vary considerably across the LLNL site. Details of vadose zone remediation system(s) will be presented in the proposed Remedial Action Plan.

Although the time required to remediate the vadose zone is difficult to predict, it is expected to be more rapid than for ground water for the following reasons:

1. The rate of mass removal is typically much more rapid for soil vapor extraction than for ground water extraction. For instance, our pilot vapor extraction study at the Gasoline Spill Area has already removed most of the estimated hydrocarbons from the vadose zone in the first 1.5 y of operation. The VOCs in the vadose zone at LLNL are as volatile and, in some cases, more volatile (based on vapor pressures) than most constituents of gasoline, and should, therefore, be as rapidly removed.
2. Except for the Gasoline Spill Area, the estimated mass of VOCs contained in the vadose zone is significantly less than in ground water.
3. The presence of fresh air increases rates of aerobic degradation, natural volatilization, and transport by diffusion in the unsaturated zone.

#### **3.4.1.4. Other Extraction Options**

Extraction by *in situ* heating and volatilization has been suggested, but not yet demonstrated. Electromagnetic and other energy sources are being researched for this purpose, but we will not discuss these technologies here.

#### **3.4.1.5. Removal by Skimming**

Where nonaqueous phase liquid (NAPL) is present in ground water and that liquid is lighter than water, skimming may be used to facilitate remediation. Skimming is most effective, where a significant accumulation of floating NAPL exists. Floating NAPL has been found only at the Gasoline Spill Area at the LLNL site.

Skimming is facilitated by two pumps set within an extraction well that has a screen that intersects the water table. The lower pump extracts ground water and causes a cone of depression to form around the well. Floating NAPL accumulates within this cone. A second pump is positioned such that the intake selectively withdraws the floating NAPL. Ground water

is separately treated by one of the processes discussed in Section 4; the NAPL is commonly collected for recycling or disposal as a hazardous waste.

### 3.4.2. Vadose Zone Extraction

#### 3.4.2.1. Excavation and Fixation

Excavation is a common method of removing near-surface contaminated sediment using conventional earth moving equipment. In some cases, excavation is the only practical technology, particularly for small volumes of soil that contain contaminants such as polychlorinated biphenyls (PCBs) or metals that cannot be treated *in situ*. Excavated materials can be treated onsite or transported to an appropriate waste landfill. Alternatively, fixation has been applied commercially to sediments contaminated with metals. Fixation involves physical or chemical immobilization of the contaminants in the sediment, after which the sediment may be returned to its original location.

Depending on the quantity of material to be excavated and the depth of excavation, different types of equipment can be used. The methods used for excavation are not greatly affected by the types of contaminants present. Determination of the extent of material to be excavated is one of the most difficult aspects of this technology. In most cases, collection and analysis of sediment samples are required during the excavation, adding considerably to the cost. Transport and disposal of excavated material can be very costly if large volumes are involved.

#### 3.4.2.2. Vacuum-Induced Venting

Vacuum-induced venting consists of applying a vacuum to one or more extraction wells screened in the vadose zone. The vacuum induces a flow of air through the unsaturated sediment. Volatile compounds are vaporized into this air flow and removed from the sediment. This technology is only applicable to compounds of sufficient volatility to allow a reasonable rate of removal by evaporation into the soil gas. Industry experience indicates that this process is very effective for chlorinated solvents and the volatile FHCs.

The properties of the vadose zone sediment, such as permeability and moisture content, and the areal extent and depth of contamination determine the design of a vacuum-induced venting system. The extracted gas may be treated to prevent release of hazardous materials to the atmosphere. Treatment options include thermal or catalytic oxidation and granular-activated carbon, described in the next section. Drawbacks to the venting technology are the uncertainty in predicting the time required to achieve the remedial objectives and difficulties extracting all hazardous materials in a heterogeneous subsurface environment. The control of air emissions can also be a significant expense of operation.

Variations of the vacuum-induced venting process include venting of dewatered sediments and venting in conjunction with steam flooding beneath the water table. Although experimental at this time, these techniques show promise for accelerating cleanup of high concentrations below the static water table.

Remediation of unsaturated sediments containing VOCs at LLNL is expected to consist of:

1. Excavation in limited areas if local concentrations exceed designated limits, with subsequent treatment and/or disposal of the excavated material.

2. Vacuum-induced venting in locations where concentrations are greater than designated limits but excavation is impractical, coupled with treatment of the vapors by carbon absorption, thermal oxidation, or catalytic oxidation, if necessary to meet air discharge requirements.

Technologies in the research stage, such as microwave soil heating and steam flooding, may develop to decrease cleanup times, but will not be discussed here.

### 3.4.3. Remediation Technologies

#### 3.4.3.1. VOCs and FHCs in Ground Water

In the following discussion, remediation technologies are first considered individually. Following the discussion of individual technologies, we describe the specific treatment options, comprised of combinations of technologies. This is a slight modification of the EPA design and evaluation process that suggests they be considered sequentially as increasingly narrow and specific definitions of the remediation approach. We combined some of the EPA steps because research conducted at the LLNL site, particularly the pilot studies, has provided much data about the characteristics of the site sediments, the compounds of interest, and the strengths and limitations of available remediation methods.

Each potential treatment facility would be designed to treat a slightly different suite of compounds. In general, treatment options for facilities A, B, C, E, and G need to treat primarily VOCs (see Table 3-7). However, treatment options for Treatment Facility D (TFD) may need to treat chromium, as well as VOCs. Treatment options for Treatment Facility F (TFF) will need to address VOCs, FHCs, and possibly lead.

**3.4.3.1.1. Granular Activated Carbon Treatment of the Liquid Phase.** Granular activated carbon (GAC) adsorption is a well-established technology for ground water treatment that is generally effective for removing high molecular weight compounds, chlorinated solvents, petroleum hydrocarbons, and some inorganic ions.

Activated carbon removes contaminants from water by adsorbing them onto its surface. GAC units are made from a variety of carbonaceous materials by dehydrating and carbonizing the raw material. This is followed by the activation procedure in which the grain structure of the solid is increased to yield high surface area for adsorption and potential sorption sites are freed of competing substances. GACs generally have surface areas of 500 to 1400 m<sup>2</sup>/g.

A GAC adsorption system consists of a packed column with a system to distribute the water evenly over the bed of carbon. Organic compounds adsorb onto the surface of the GAC as the water flows through the fixed bed. Initially, almost all adsorption takes place at the end of the column nearest the water inlet. With time, the GAC becomes saturated and the zone of maximum adsorption moves down the bed. This continues until "breakthrough" occurs in which some organic compounds pass through the bed without being adsorbed.

The usual configuration uses two beds in series. Therefore, when the GAC in the first bed becomes saturated, the system is shut down and the spent material in that bed is removed and replaced. The system is then restarted with the flow direction changed such that the order of the beds is reversed. The spent GAC may be thermally regenerated by heating the carbon in a natural gas-fired furnace. This results in the complete desorption of the organic compounds from the surface of the GAC. The compounds can then be thermally oxidized or driven off and

collected for reuse. In thermal oxidation, the FHCs are converted to carbon dioxide and water; the chlorinated compounds are converted to carbon dioxide, water, and hydrogen chloride. Lead is converted to lead oxide, which vaporizes at the temperatures used. After regeneration, the GAC is no longer considered a hazardous waste.

GAC technology for treating the liquid phase is effective for a broad range of organic compounds. When operated properly, complete removal of organic compounds can be achieved, regardless of the influent concentrations or flow rate. The amount of GAC required, however, is dependent on concentration, because the loading efficiency is greater at high concentrations. Some disadvantages of applying GAC to the liquid phase include:

- Influent water must be free of suspended solids and free-phase hydrocarbons to prevent fouling of the bed.
- Capital investment costs for these GAC systems are relatively high.
- Replacement and thermal regeneration of the adsorbent are relatively expensive and labor intensive.

**3.4.3.1.2. Packed-Tower Counter-Flow Air stripping.** Packed-tower air stripping is a well established technology for the removal of VOCs and FHCs from ground water. It has been successfully used for treatment of VOCs and volatile FHCs.

Treatment is achieved by contacting the water with a flow of air in a vertical tower containing a high surface-area packing medium which facilitates contact between the water and air. The volatile compounds are transferred (stripped) from the water to the air as the water flows down over the packing material countercurrent to the air, which is blown upwards through the packing material. To prevent release to the atmosphere of the compounds that have been transferred to the air, removal of the VOCs or FHCs from the exhaust air stream by adsorption onto GAC can be added as supplemental treatment.

The ability of air stripping to remove organic compounds from ground water is based on the volatility of the compound expressed as the Henry's law constant. The Henry's law constant is the ratio at equilibrium between the concentration of the compound in the water and the concentration in the air in contact with the water. A high Henry's law constant indicates that the compound will be easily removed by air stripping.

Alternative configurations are feasible for air stripping. As described in Section 2, the Offsite Pilot Study has successfully employed an aeration bubbling tank. The aeration tank has a low profile and is adequate for the low concentrations of VOCs exiting the UV/H<sub>2</sub>O<sub>2</sub> unit.

LLNL has made a policy decision not to construct ground water remediation systems that produce measurable emissions of contaminants to the atmosphere. Consequently, we analyze air stripping technology for the LLNL site only in conjunction with treatment of the exhaust air stream.

**3.4.3.1.3. Air stripping with GAC Treatment of the Vapor Phase.** The operation of a GAC system to treat the vapor phase for removal of organic compounds from air is very similar to that for GAC treatment of the liquid phase. The air stream containing contaminants is forced through a fixed bed of dry GAC. When the capacity of the GAC to adsorb the chemicals is exhausted, the GAC is removed and replaced. The spent GAC can be thermally regenerated at a commercial facility, which results in the complete desorption of the organic compounds from the surface of the GAC. The compounds can then be thermally oxidized or driven off and collected for reuse. The advantage of air stripping compounds from the water followed by vapor-phase adsorption onto GAC over direct liquid-phase adsorption onto GAC is that the capacity of GAC (expressed as pounds of chemical adsorbed per pound of GAC) for vapor is generally much

greater than that of GAC for liquid. This results in less frequent replacement of the GAC and, hence, lower operating costs for GAC replacement. This is somewhat offset by the more complex operation required for the air stripping system with vapor phase compared to a GAC system for treating the liquid phase.

The advantages of air stripping are relatively simple operation and low capital costs. The necessity for control of air emissions using GAC results in significant operating costs for spent GAC replacement and thermal regeneration. However, this cost is much lower than for GAC used to treat the liquid phase. The disadvantages of air stripping are that the system must be designed for the maximum anticipated flow rate and concentrations of organic compounds and is not adaptable to significant changes in either. Air stripping is also not effective for nonvolatile compounds or inorganics.

The cost consequences of treating the air stream are presented in Appendix D and in Section 4 of the text.

**3.4.3.1.4. UV/Oxidation.** This process involves the destruction of organic compounds using a strong oxidizing agent, usually hydrogen peroxide or ozone. The process employs ultraviolet light to increase the rate of oxidation, which both creates hydroxyl radicals and breaks bonds in the organic molecules. In theory, organic compounds in an aqueous medium can be completely destroyed by chemical oxidation. The process has been shown to be most effective on double bonded halocarbons (ethylenes). Pilot testing of a UV/oxidation system at LLNL has shown that a system sized for destruction of PCE and TCE is not necessarily sufficient to destroy all VOCs of concern. However, refinements in this relatively new technology still hold considerable promise for increasing destruction efficiencies and reducing costs.

UV/oxidation is carried out by the addition of sufficient quantities of hydrogen peroxide to oxidize all oxidizable material in the water stream. The stream is then passed through a chamber in which the water is exposed to UV radiation, with the effectiveness proportional to residence time.

The main advantage of UV/oxidation is that virtually immediate destruction of many organic compounds occurs with production of innocuous byproducts. This minimizes waste requiring further treatment or disposal. The disadvantages are that large units with high energy demands are necessary to destroy all compounds of concern at LLNL, and so for efficiency, must often be coupled with another technology. The process can be adapted to lower-than-design flow rates or concentrations by simply turning off unnecessary UV lamps.

**3.4.3.1.5. Biological Treatment.** Biological treatment can be conducted above ground on extracted ground water, as well as *in situ*, as discussed previously. There are a number of different aboveground biological treatment technology designs.

One design, an activated sludge process, consists of an aeration tank in which biodegradation occurs, followed by a settling tank. The aeration tank contains biomass that is provided with nutrients and oxygen to continuously consume organic compounds supplied by the influent stream. The settling tank is used to remove biomass from the effluent stream, part of which is recycled back to the aeration tank.

A second design consists of a rotating biological contactor system comprised of a series of partially submerged disks covered with a film of biomass. The disks are rotated to alternately expose the biomass to the water containing the organic compounds and to the oxygen in the atmosphere. Biomass routinely sloughs off the disks and must be removed from the effluent water.

A third design, a trickling filter, consists of a bed of highly permeable media to which biomass is attached and through which influent water is percolated. The water passes through the bed in the form of a film flowing over the media covered with biomass. Oxygen is supplied by a countercurrent flow of air rising by natural convection. Biomass routinely sloughs off and must be removed from the effluent water.

Biological technology is potentially applicable to treatment of ground water containing organic compounds. However, the technology may not be suitable for the treatment of chlorinated solvents. The technology is also sensitive to upsets in influent water quality and organic compound concentrations and requires careful operator attention. Hazardous compounds that are not destroyed may be absorbed by the sludge, making it a hazardous waste. This technology is not considered further due to the operational complexity relative to other proven technologies for the compounds of concern at LLNL.

**3.4.3.1.6. Precipitation.** Chemical precipitation technology is well proven for the removal of dissolved metals from ground water. The process includes adjusting the pH of the water and adding reagents to form insoluble compounds with the metals of concern, followed by sedimentation and/or filtration to remove the precipitated solids. The total reduction in concentration of a metal is determined by the solubility of the compound precipitated and the efficiency of solids removal. Usually, simple treatment testing is required to determine the optimum pH, and the type and concentration of reagents, to achieve the optimum reduction in concentration of metals.

Several variations are possible for treatment of water containing chromium, as illustrated in Figure 3-11. First, the chromium oxidation state is reduced from +6 to +3, if necessary. Common reagents used to achieve this reduction are sulfur dioxide and sodium bisulfite. The trivalent chromium is then precipitated as chromium hydroxide by adjusting the pH. The precipitated chromium is separated from the liquid and the sludge is dewatered in a filter press. The recovered liquid is then stored and slowly metered into an ion-exchange treatment system (see below). The dewatered sludge can be disposed of at a hazardous waste landfill if the solid waste passes the Toxicity Characteristic Leaching Procedure (TCLP) criteria for chromium. If the sludge does not pass the TCLP criteria without further treatment, solidification and stabilization may be achieved by adding chemical fixation agents. The stabilized material could then be disposed of at a hazardous waste landfill. Dewatered chromium sludge could theoretically be sent to a chromium ore processing facility for high temperature recovery. Alternatively, the chromium could be removed from the liquid by plating it out in an electrolytic cell. In this way, essentially pure chromium metal is recovered.

The main advantage of chemical precipitation is that it is a well-proven technology applicable to most metals. A major disadvantage is that the process produces a sludge containing the metals, which may be considered hazardous and require further treatment prior to disposal. Because of the complexity of the precipitation options and the need to couple them with additional waste treatment, precipitation is not considered further.

The final processing alternatives could be carried out at LLNL or, alternatively, the waste could be sent to a hazardous waste treatment facility.

**3.4.3.1.7. Ion Exchange.** Ion exchange is a proven process for the removal of metal salts from water. Ion exchange can be applied to the removal of cations (principally metals) or anions from water.

In ion exchange, water is pumped through a fixed bed of ion-exchange resin. The ionic species to be removed are exchanged for nonhazardous ions bound to the resin. When the

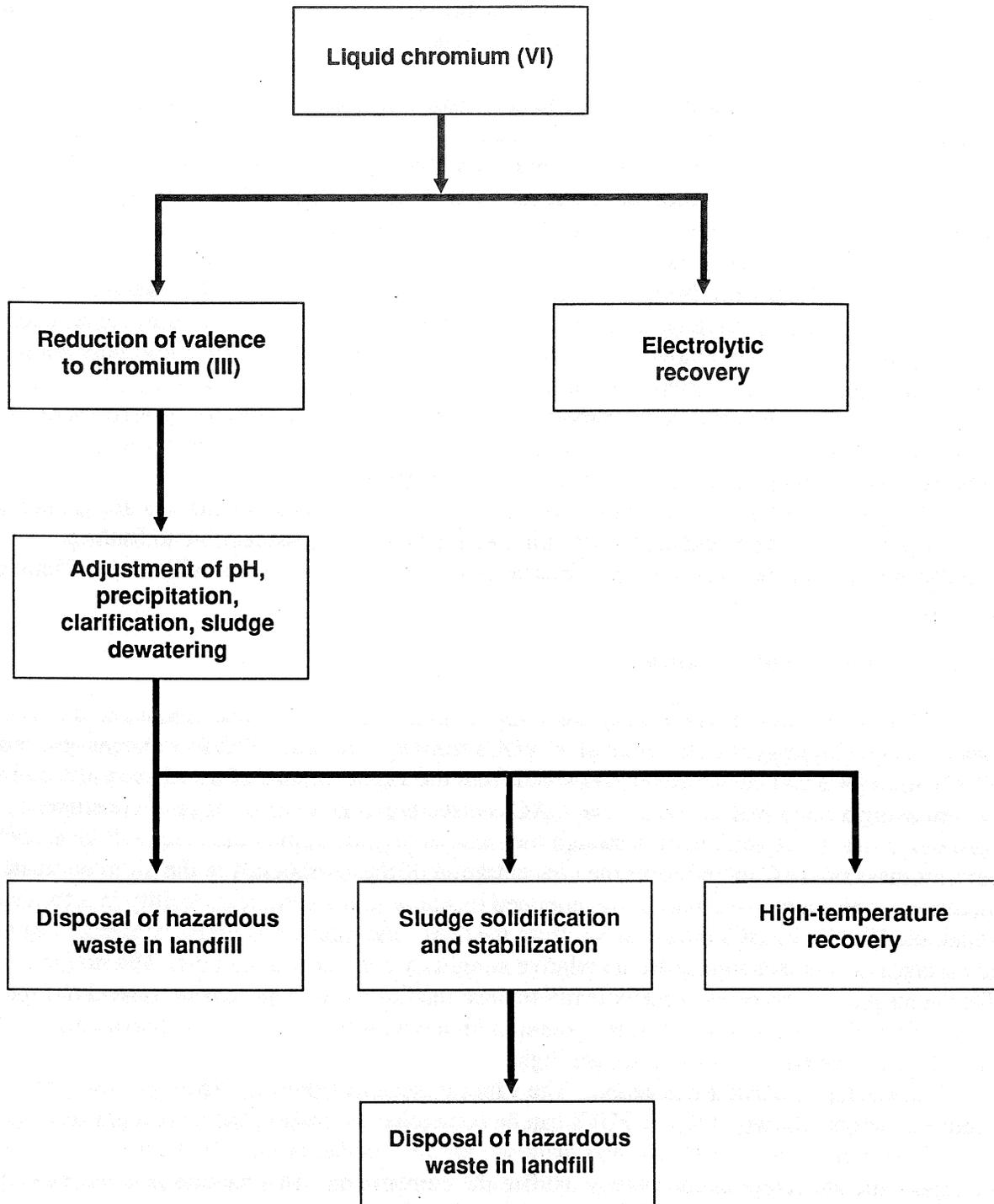


Figure 3-11. Possible treatment options for liquid chromium waste.

ion-exchange resin approaches equilibrium with the influent stream, it is regenerated by passing a concentrated solution of a nonhazardous salt through the columns. The ions adsorbed during the treatment cycle are replaced by the regeneration salt ions. The regeneration waste solution contains the hazardous ions removed from the ground water and may require further treatment or disposal as a hazardous waste.

The primary advantage of ion exchange is that it is a simple technology that can achieve very low effluent concentrations. A disadvantage is that only chemicals that are in ionic form are removed. Also, other ions of the same charge may compete for ion-exchange sites, which can necessitate frequent regeneration of the resin. Treatment testing is normally required to demonstrate the practicality of the process. The process also produces a waste regeneration solution that may be hazardous.

**3.4.3.1.8. Ultrafiltration.** Ultrafiltration is a process for removal of insoluble particles of approximately 1  $\mu\text{m}$  or more from water. The process is very effective for removal of insoluble compounds, but does not remove dissolved compounds. This technology is normally applied as a polishing step following another technology, such as precipitation. However, sufficient treatment can often be achieved by removing suspended materials from the ground water. In such cases, ultrafiltration may be applied alone. However, larger suspended material would have to be removed to prevent fouling of the ultrafiltration media.

The disadvantages of this technology are that (1) only contaminants that are greater than about 1  $\mu\text{m}$  are removed, and (2) the filtration membrane is also susceptible to fouling. Ultrafiltration could be used in conjunction with another technology, but will not be discussed further.

### **3.4.3.2. Vadose Zone Treatment**

**3.4.3.2.1. GAC Treatment of the Vapor Phase.** The use of GAC treatment is a well-established technology for the removal of VOCs from air streams. With few exceptions, most VOCs and FHCs can be effectively removed from the vapor exhaust of a soil vacuum venting system using a fixed bed of GAC. The GAC is effective over a broad range of constituent concentrations in the air stream, although the mass of organic compounds that will be adsorbed per unit mass of GAC increases as the concentration of the compounds in the air to be treated increases. The spent GAC may be regenerated onsite or at a commercial facility in a furnace in which the VOCs or FHCs are desorbed from the GAC and then completely oxidized. The major advantages of this technology are its relative simplicity and low capital cost. The major disadvantages are the need to periodically replace the GAC, the requirement to send the spent GAC offsite for regeneration, and the potential high operating cost for GAC replacement if the quantities of vented VOCs or FHCs are high.

**3.4.3.2.2. Thermal Oxidation.** The vapor emissions from the vacuum venting of the vadose zone containing VOCs or FHCs can be controlled by passing the vented gas through a thermal oxidation unit. In the thermal oxidizer, the air containing the organic vapors is heated to a temperature sufficient to completely oxidize the compounds. This technique is most easily applied to mixtures of air and FHCs in which the oxidation products will consist of water and carbon dioxide. Chlorinated solvents may also be thermally oxidized, although additional treatment of the exhaust gas from the thermal oxidation unit may be required to remove the hydrogen chloride produced. In most cases, the concentrations of organic compounds in the emissions from the venting operations will not be sufficient to maintain combustion. An

auxiliary source of fuel, such as propane or natural gas, must be supplied to the thermal oxidizer to produce sufficient heat to sustain thermal combustion. The major advantage of this system is that almost complete destruction (over 99%) of the VOCs or FHCs is achieved onsite. In addition, this technology may be more economical than GAC treatment of the vapor phase for large quantities of vapor vented over extended periods. The disadvantages are the capital cost for the thermal oxidation system, and the expense associated with the need for an auxiliary fuel supply.

**3.4.3.2.3. Catalytic Oxidation.** Catalytic oxidation is similar to the thermal oxidation process except that the oxidation occurs in the presence of a catalyst, commonly platinum or palladium metal, that allows the oxidation to occur at much lower temperatures. This has the advantage of reducing the quantity of auxiliary fuel required for the oxidation unit. However, the catalyst is susceptible to fouling and poisoning, particularly in the presence of chlorinated solvents. The capital cost for installation can be weighed against the lower operational costs for thermal oxidation. Close operator attention or automated protection is generally required to prevent catalyst damage.

#### **3.4.4. Disposal of Treated Ground Water**

The discharge of treated ground water from the seven treatment facilities under Extraction Alternative No. 1, or the four treatment facilities under Extraction Alternative No. 2, would be designed to return a large proportion of the treated ground water to the ground water subbasin (Mocho I or Spring) from which it was extracted, without adversely affecting remediation efforts. To accomplish this, we are currently recharging treated ground water by surface infiltration using the LLNL recharge basin south of East Avenue and drainage ditches along the west LLNL perimeter that flow to Arroyo Las Positas for our Offsite Pilot Study. Other alternatives under consideration include subsurface recharge using recharge wells and discharge into a lined retention basin, from which irrigation water could be drawn, with excess entering the Arroyo Las Positas channel along the northern portion of the site. Each of these is discussed below. Some of the treated ground water could be used onsite for irrigation or other purposes.

##### **3.4.4.1. Recharge Basin**

As part of the Offsite Pilot Study discussed in Section 2, the LLNL recharge basin located south of the VOC plumes has been receiving treated ground water from TFA since early 1989. Under both Extraction Alternatives Nos. 1 and 2, additional ground water would be treated by TFA and discharged to the recharge basin (Figure 3-9). The design and performance of the recharge basin are discussed in Section 2.

##### **3.4.4.2. Drainage Ditches, Arroyos, and Drainage Retention Basin**

Under Extraction Alternative No. 1, treated ground water from TFD and Treatment Facility E (TFE), and possibly TFF and TFG, could be discharged to the drainage retention basin (Figure 3-9). Under both Extraction Alternatives Nos. 1 and 2, effluent from TFB and TFC would be discharged to drainage ditches paralleling Vasco Road. Recharge from unlined sections of drainage ditches and Arroyo Las Positas are estimated to be between about 0.5 and 1.2 ft/day, respectively, based on an infiltration study conducted in June 1988 (Dresen *et al.*, 1988a).

To maintain hydraulic control over the VOC plumes, treated ground water would not be recharged by surface infiltration to any area containing ground water with VOC concentrations exceeding an MCL. If recharge were to occur within this area, capture areas would decrease and additional extraction wells would be necessary. Partly for this reason, the drainage retention basin, located in the central part of LLNL (Figure 3-9), is being lined to prevent recharge in that area. The LLNL Plant Engineering Department estimates that up to 300,000 gal per day could be used for landscape watering or cooling tower makeup at LLNL during the summer. To prevent recharge in other areas underlain by VOCs, a section of the north-flowing drainage ditch paralleling Vasco Road has been lined with concrete. The lined section is shown with a hatched pattern in Figure 3-9.

#### 3.4.4.3. Possible Recharge Wells

Recharge through recharge wells has several potential advantages:

- Reduced piping distances and costs.
- More effective hydrologic control of VOC plumes.
- Possible reversal of downward vertical gradients.
- Higher extraction rates and shorter cleanup times.

Under Extraction Alternative No. 1, the locations of TFF and TFG in the southern part of LLNL would require long piping routes to convey treated water to the drainage retention basin or the recharge basin. Therefore, deep recharge wells are being considered for these facilities. One design approach is to discharge treated ground water from both TFG and TFF to a centrally located recharge well between the facilities (Figure 3-9). A second alternative is to drill separate recharge wells for each facility, which would minimize the length of discharge piping required.

Recharge well(s) for TFF and TFG would probably be 300 to 400 ft deep. They would be screened below the regional confining layer (Thorpe *et al.*, 1990) because VOC plumes extend to the top of the confining layer (about 200 ft deep) in this area. Alternatively, shallow recharge wells along the eastern boundary of the site might facilitate cleanup by increasing hydraulic gradient and pore water exchange, even though more extraction wells might be necessary. Shallow recharge wells may also minimize dewatering of sediments containing VOC plumes. We are currently investigating the technical and regulatory feasibility of using recharge wells at LLNL, and the logistical constraints of siting recharge wells.

### 3.5. DEVELOPMENT OF TREATMENT OPTIONS

#### 3.5.1. Ground Water

Currently, we believe "pump and treat," using the conceptual approach of either extraction alternative, will comply best with the requirements of DOE, LLNL, and the regulatory agencies. Because the two extraction alternatives differ primarily in scale, all treatment options described below assume that ground water will be extracted and conveyed to treatment systems as discussed for Alternative No. 1. The only difference under Alternate No. 2 is that only Treatment Facilities A, B, C, and F are installed.

The compounds in the ground water can be divided into three categories:

1. Ground water containing only VOCs. Current data indicate only VOCs will be influent to Treatment Facilities A, B, C, E, and G (see Figure 3-9).
2. Ground water containing VOCs and chromium. Treatment Facility D may require treatment of chromium, as well as VOCs.
3. Ground water containing VOCs, FHCs, and possibly lead. Treatment Facility F may require treatment of lead, as well as organic compounds.

Treatment technologies will be combined as necessary for each of the three categories of influent to meet the effluent discharge requirements (Table 3-2). These are illustrated in Figures 3-12, 3-13, and 3-14.

#### **3.5.1.1. VOCs and FHCs Only**

Three treatment options are available that will successfully remove VOCs and FHCs from the ground water and leave essentially zero emissions in the aqueous or vapor effluent. These are described in detail in Appendix D. The first is GAC treatment of the liquid phase, shown in schematic form in Figure 3-12A. In this option, aqueous influent is directed through a bed of activated carbon, treated water is released to one of several disposition alternatives (e.g., recharge basin, wells, or drainage ditches), and the organic compounds adsorbed onto the GAC can be oxidized to nonharmful compounds or collected for reuse (recycling) in the carbon regeneration process.

The second treatment option for ground water containing only VOCs and/or FHCs is a combination of packed-column, counter-flow air stripping and GAC treatment of the vapor phase, shown in Figure 3-12B. In this alternative, the ground water treatment is by air stripping. Although the treatment facilities could possibly meet local air discharge requirements without additional treatment of the air stream, GAC treatment of the vapor phase has been added to the design to completely eliminate vapor-phase emissions from the air stripper. The organic compounds adsorbed onto the GAC can be oxidized to nonharmful compounds or collected for reuse (recycling) in the thermal regeneration process.

The third treatment option consists of primary treatment by UV/oxidation followed by secondary treatment of the aqueous medium by air stripping (aeration); the vapor effluent is treated by GAC. This system is shown in Figure 3-12C. Design and sizing of the UV/oxidation units may obviate the necessity for secondary treatment by aeration and GAC treatment of the vapor phase, in some circumstances. UV/oxidation processes minimize waste requiring further treatment or disposal by destroying the VOCs or FHCs.

#### **3.5.1.2. VOCs and Chromium**

Treatment options for ground water containing both VOCs and chromium, which may be influent to TFD, are shown in schematic form in Figure 3-13 and are described in detail in Appendix D.

The first treatment options that is effective in achieving the remedial action objectives (Table 3-2) is GAC and ion exchange (Figure 3-13A). Influent water is fed through a bed of activated carbon, where VOCs are removed, leaving chromium in the aqueous medium. The VOC-free water is next fed through an ion-exchange chamber in which the chromium is extracted from the water.

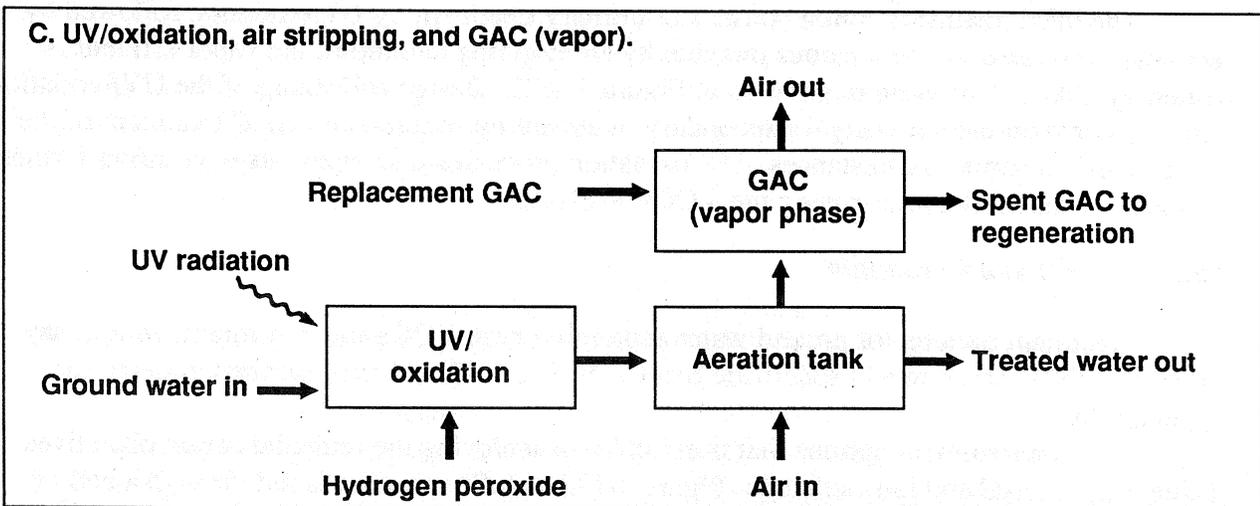
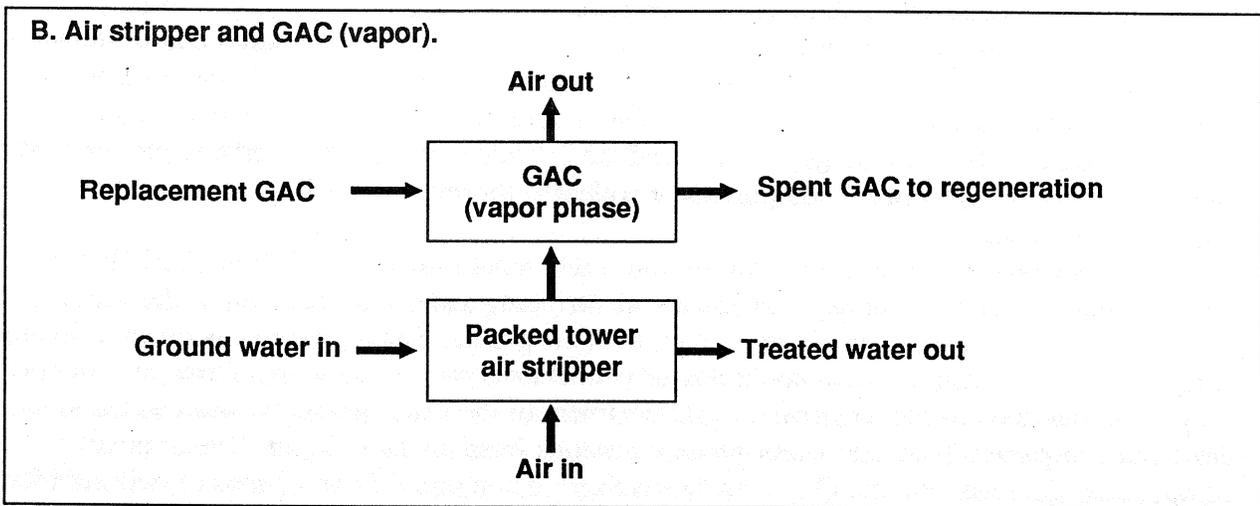
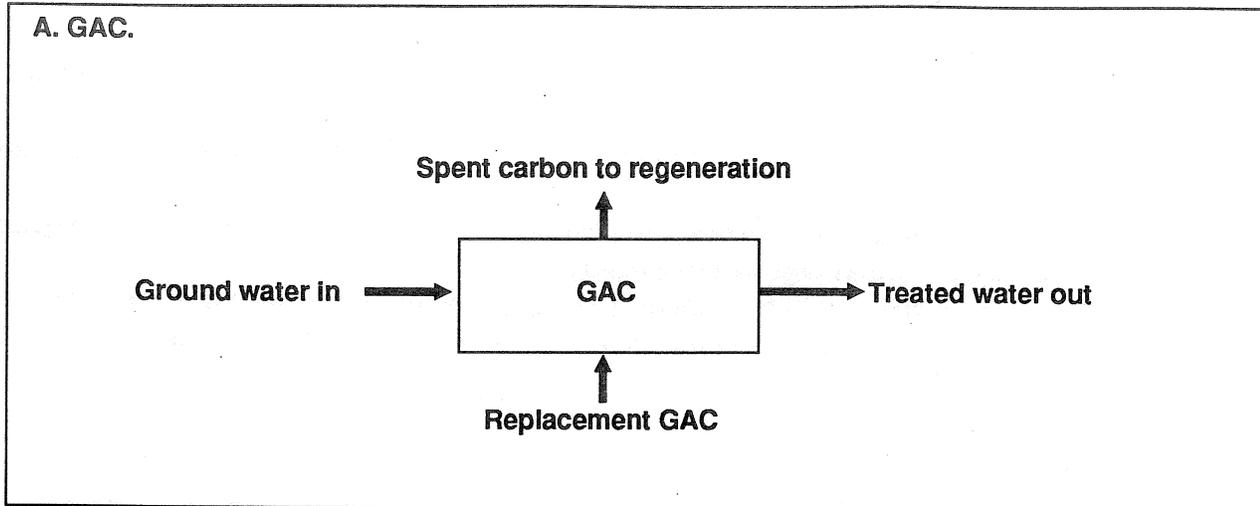


Figure 3-12. Alternatives for remediating VOCs and FHCs in ground water (Treatment Facilities A, B, C, E, and G).

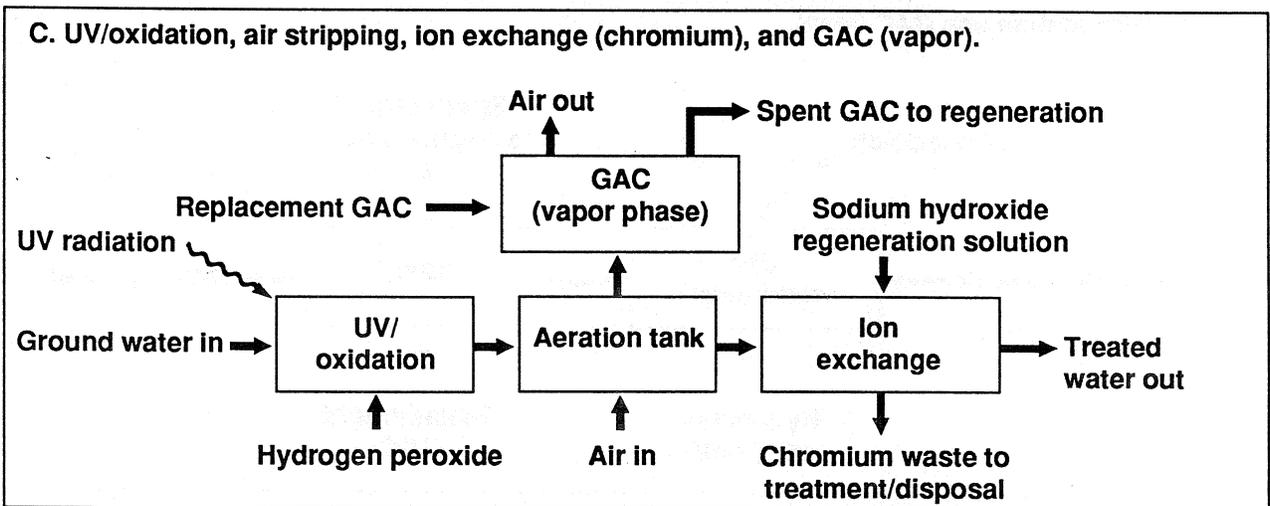
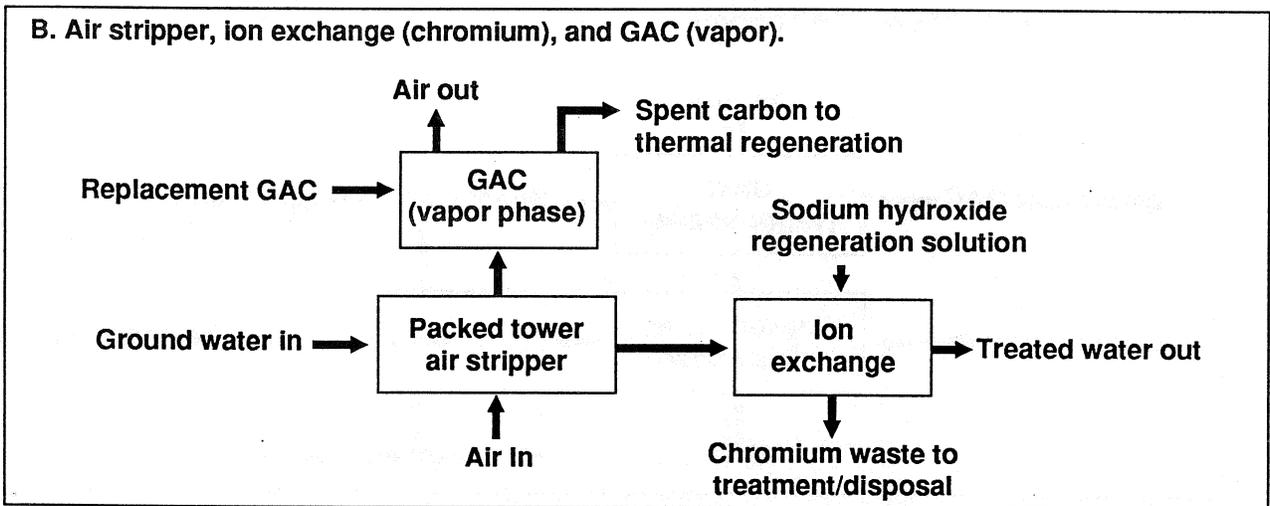
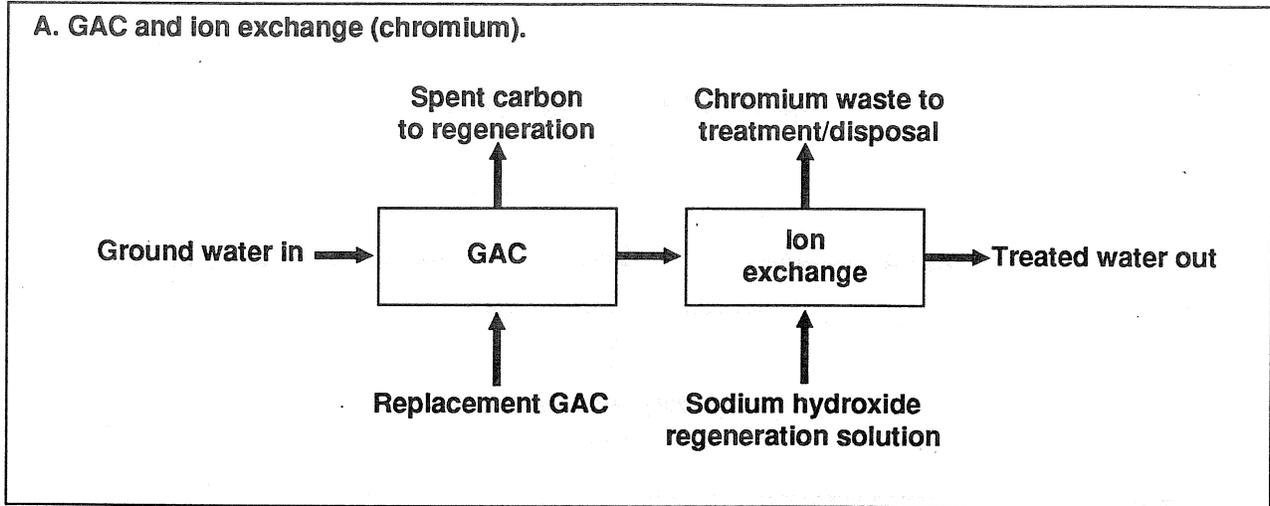


Figure 3-13. Treatment options for remediating VOCs and chromium in ground water (Treatment Facility D).

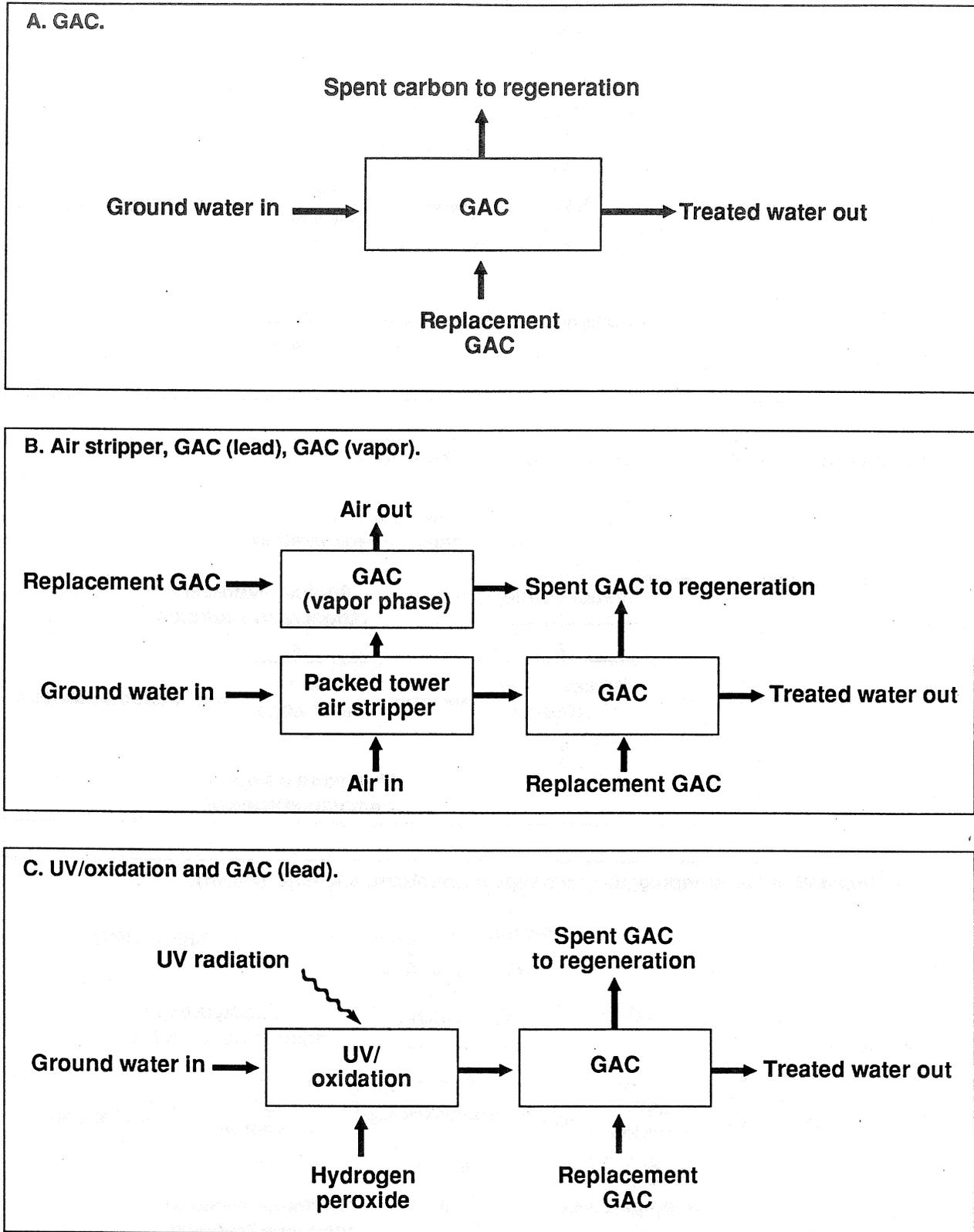


Figure 3-14. Treatment options for remediating VOCs, FHCs, and lead in ground water (Treatment Facility F).

The second treatment option is packed-tower counter-flow air stripping, which removes VOCs, followed by ion exchange for removal of chromium (Figure 3-13B). The vapor effluent from air stripping is then treated by GAC.

The third treatment option is UV/oxidation, followed by secondary treatment of the aqueous medium by aeration (air stripping), followed by ion exchange; the vapor effluent is treated by GAC. This system is shown in Figure 3-13C. Improved UV/oxidation chambers may obviate the necessity for secondary treatment by aeration and GAC treatment of the vapor, in some circumstances. Regardless, the VOC-free water is then treated by ion exchange to remove chromium.

### **3.5.1.3. VOCs, FHCs, and Lead**

Water containing VOCs, FHCs, and possibly lead will be influent to TFF. As noted in Table 3-9, concentrations of lead are expected to be below the MCL of 50 ppb. However, lead concentrations will be monitored and, if they approach regulatory limits, additional treatment may be necessary, as described below. Treatment options for the TFF area are shown in Figure 3-14, and are described in greater detail in Appendix D.

The first treatment option that is effective in achieving the remedial action objectives (Table 3-2) is shown in Figure 3-14A. In this process, extracted ground water is directed through a bed of activated carbon, treated water is released to one of several disposition alternatives, and the captured VOCs and FHCs are oxidized to nonharmful compounds or collected for reuse in the carbon regeneration process. The lead is converted to lead oxide, which vaporizes at the high temperatures used in the thermal regeneration of GAC.

The second treatment option is a combination of air stripping followed by GAC treatment for the aqueous phase, augmented by GAC treatment of the vapor phase. This system is shown in Figure 3-14B. In this process, the primary treatment is by air stripping. GAC treatment of the vapor phase is used to treat the vapor effluent from the air stripper. GAC treatment of the liquid phase is used to adsorb the lead and any remaining VOCs or FHCs from the water. The VOCs and FHCs adsorbed on GAC from the vapor and liquid stream are oxidized to nonharmful compounds or collected for reuse in the carbon regeneration process. The lead is converted to lead oxide, which vaporizes at the high temperatures used in the thermal regeneration of GAC.

The third treatment option consists of primary treatment by UV/oxidation followed by secondary treatment of the aqueous medium by GAC. In this system, most of the VOCs and FHCs are destroyed in the oxidation process. Any remaining organics and lead are adsorbed onto the carbon. The adsorbed VOCs and FHCs are oxidized to nonharmful compounds or collected for reuse in the carbon regeneration process. The lead is converted to lead oxide, which vaporizes at the high temperatures used in the thermal regeneration of GAC. This system is shown in Figure 3-14C.

### **3.5.1.4. VOCs in Downtown Livermore**

Treatment options for the Deferred-Action Alternative are considered as a baseline for comparison purposes. This alternative relies on monitoring the VOCs in the plume without attempting to control their migration. Administrative and institutional measures would be employed to prevent human contact with the ground water containing contaminants originating from the LLNL site. If monitoring of the municipal supply wells demonstrated the need for

treatment, three treatment options would be effective in removing VOCs from this water. These are shown in Figure 3-15 and are described more fully in Appendix D. The difference between these options and those described previously for onsite VOC treatment result from the very low concentrations expected.

The first treatment option is GAC treatment of the liquid phase, shown in Figure 3-15A. In this option, aqueous influent is directed through a bed of GAC. Treated water is released for distribution in the municipal supply system, and the adsorbed VOCs are oxidized to nonharmful compounds or collected for reuse in the thermal regeneration process.

The second treatment option consists only of an air stripper. This system is shown schematically in Figure 3-15B. In this system, influent from the municipal supply wells is fed into a stripping tower or other aeration unit into which air is forced under pressure. The treated water is discharged to the municipal supply system. The stripping tower discharges the extremely low concentrations of VOCs with the effluent air stream. This would be permissible under current Bay Area Air Quality Management District (BAAQMD) rules.

A third effective option for treatment at the point of distribution in downtown Livermore consists of a UV/oxidation system. This system is shown in Figure 3-15C. In this system, VOC concentrations are reduced to below drinking water standards by the oxidation process, without secondary air stripping.

### 3.5.2. Vadose Zone

LLNL's Gasoline Spill Pilot Study, described in Section 2, is now in operation using vacuum-induced venting to extract vapors containing FHCs from the vadose zone. The FHCs in the vadose zone are as deep as 100 ft below the surface, making excavation impractical. The compounds of interest are sufficiently volatile for extraction by conventional vacuum-induced venting. This same process has been successful elsewhere for VOCs.

A schematic flow diagram of treatment options that would be effective in the treatment of vapors extracted from the vadose zone is shown in Figure 3-16.

The first option is GAC treatment of the vapor phase, shown schematically in Figure 3-16A. Vapors from the vent well are routed through a chamber containing a fixed bed of GAC. The VOCs and FHCs are adsorbed onto the carbon, and treated vapor (air) is exhausted to the atmosphere. The carbon bed is exchanged for a new one as required, and the spent carbon is regenerated, as described earlier.

The second treatment option is similar to the pilot program currently in operation and under evaluation for treatment of vapors extracted from the vadose zone in the Gasoline Spill Area. This system, shown in Figure 3-16B, uses thermal oxidation to transform the FHCs to carbon dioxide and water. When used for chlorinated compounds, hydrogen chloride is also formed. Vapor from the vent well is introduced to the thermal oxidation chamber where it is ignited with the assistance of a heat source such as combusted propane. The resulting gases are then vented to a stack.

The third treatment option for extracted vapors is catalytic oxidation. In this process, vapors are heated and passed through a catalytic oxidizer (Figure 3-16C) where VOCs and/or FHCs are similarly converted to their oxidation products. Destruction efficiencies are not as high as with thermal oxidation; however, they may be adequate when vapor concentrations are relatively low. Since chlorinated compounds and lead can poison the catalyst, this alternative

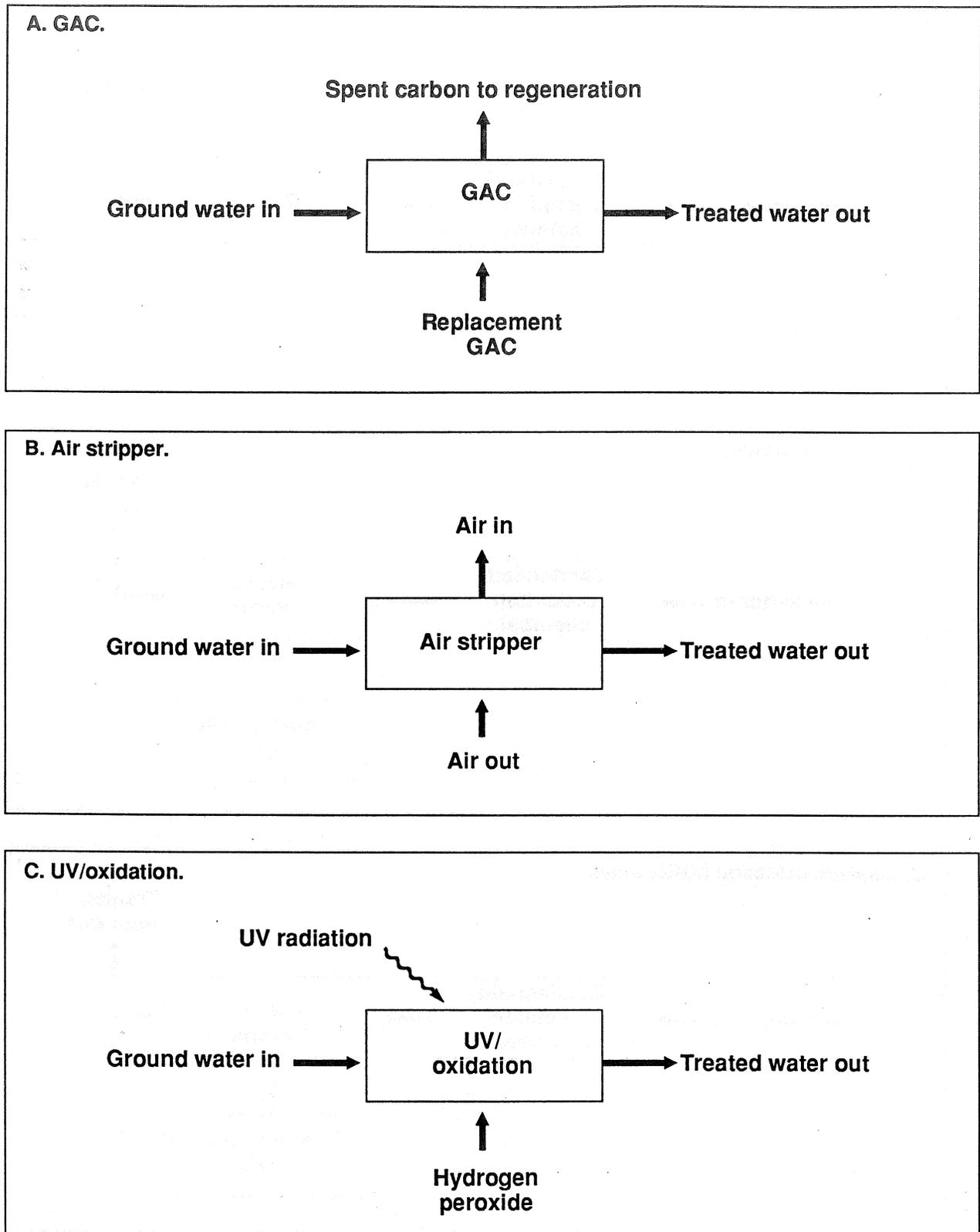


Figure 3-15. Treatment options for remediating low concentrations of VOCs in ground water (at the point of distribution, downtown Livermore).

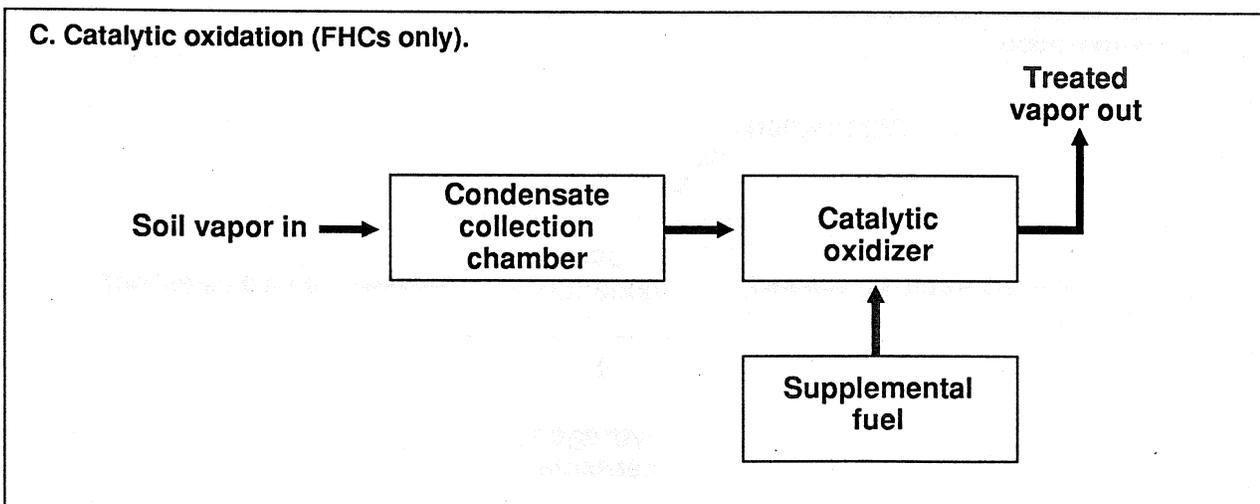
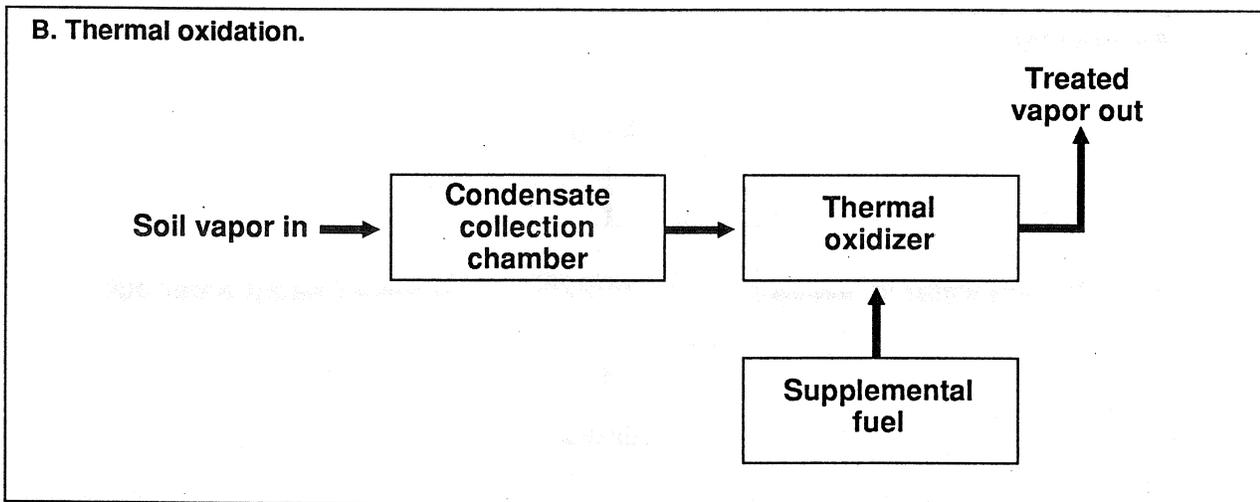
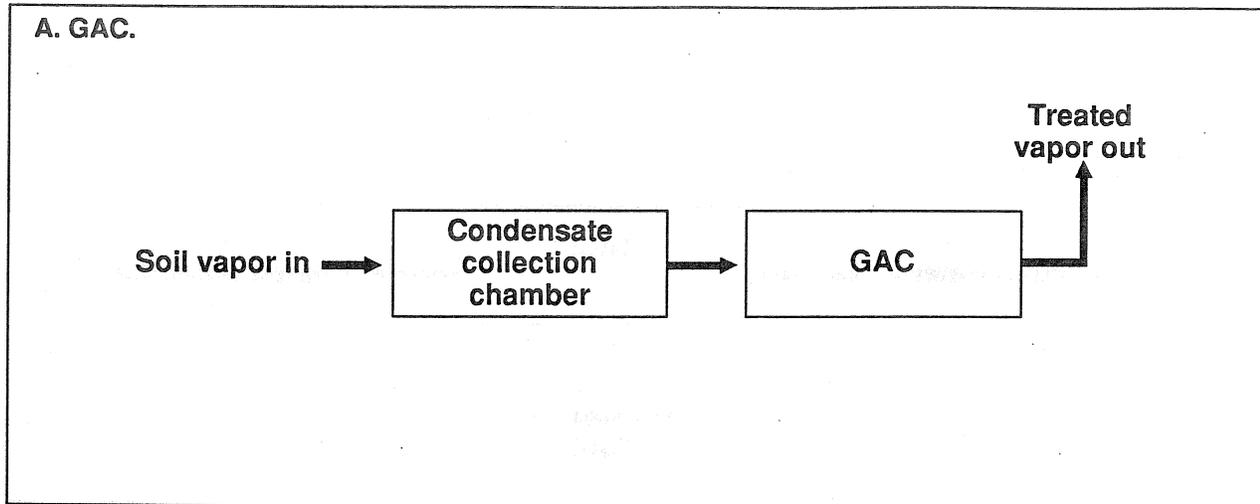


Figure 3-16. Treatment options for remediating VOCs and FHCs from the vadose zone.

may be more applicable as a follow-up process after chlorinated compounds and lead are reduced to low levels by other methods, or as a second-stage treatment to polish vapor effluent from thermal oxidation.

Vacuum-induced venting readily extracts the VOCs and FHCs. The lead in the vadose zone associated with the leaked gasoline is in an organic form that readily sorbs on soil particles. It is not volatile and will not be drawn into the vapor stream.

### **3.6. SUMMARY OF SCREENING PROCESS**

Tables 3-10 and 3-11 summarize the screening and evaluation of the general response actions, technology types, technologies, and treatment options available for the remedial alternatives for ground water and the vadose zone at the LLNL site.

Table 3-10 addresses treatment options for ground water and vadose zone sediments. The remedial action objectives (Table 3-2) apply to all treatment options and remedial alternatives. For the vadose zone, the objective is to preclude migration of contaminants to the ground water that would prevent meeting ambient ground water objectives. General response actions, shown in the first column, are general classes of actions that may achieve the remedial objectives. We have selected for detailed evaluation only active remediation measures that lead to positive, permanent removal of the constituents of interest from the ground water and the vadose zone. Of the several technologies available for treatment of chromium, ion exchange was chosen as representative because it is a proven technology that is about equal in cost to the alternatives it represents. The proven technologies of air stripping, GAC treatment of both the vapor and liquid phases, and UV/oxidation are viable to remediate VOCs and FHCs. Table 3-11 assembles the technologies into treatment options potentially suitable to the LLNL site.

#### **3.6.1. No Action**

It is very likely that the compounds of interest will, through the processes of natural decay, degradation, and sorption, be reduced in concentration to the point that no exposure would occur that would significantly increase the risk of adverse health effects. The No-Action Alternative, while likely protective of human health, does allow continued water quality degradation and migration of the compounds in the ground water. Furthermore, there is great uncertainty as to the rate and secondary products of natural transformation and the rate of adsorption of the compounds in sediments in the LLNL vicinity. Therefore, it is not possible to predict health effects of the No-Action Alternative with certainty. As a result, a monitoring program would have to be carried out, eliminating the possibility of the No-Action Alternative. To the extent that expedient remediation is desired, the No-Action Alternative is not acceptable.

#### **3.6.2. Immediate Action**

##### **3.6.2.1. Containment**

Although it may be protective of human health, containment by itself does not quickly restore the ground water to concentrations specified in the ARARs. In the form of hydraulic

Table 3-10. Summary of screening process, showing general process options.

General response action	Remediation technology type	Technology (process option)	Screening comments	
<b>GROUND WATER</b>				
<i>No action</i>	<b>No action</b>			
	Natural degradation, dispersion, adsorption	No action	Not acceptable to LLNL, DOE, and the regulatory agencies	
<i>Immediate action</i>				
<b>Containment</b>	<b>Vertical barrier</b>	Slurry wall	Not practical at LLNL	
		Grout curtain	Not practical at LLNL	
		Hydraulic barrier	Applicable in conjunction with treatment	
	<b>Capping</b>	Asphalt cover	Practical in conjunction with extraction	
<b>Extraction</b>	<b>Pump</b>	Electric pump	Applicable	
	<b>Gravity</b>	French drains	Not practical at LLNL	
	<b>Excavation</b>	Physical removal	Limited to shallow depths	
<b>Treatment</b>	<i>In situ</i> treatment			
	<b>Bioremediation</b>	Enhanced bioremediation	Not applicable to VOCs Applicable to FHCs	
	Surface treatment			
	Physical transfer:			
		Volatilization	Air stripping	Applicable
		Sorption	GAC (liquid or vapor)	Applicable
			Ultrafiltration	Applicable to nondissolved compounds as small as 1 $\mu\text{m}$
		<b>Chemical transformation</b>	UV/oxidation	Applicable
			Precipitation	Applicable
			Ion exchange	Applicable
<b>Disposal</b>	<b>Surface</b>	Recharge basin	Applicable	
		Retention pond	Applicable	
		Surface water ways	Applicable	
	<b>Subsurface</b>	Recharge wells	Applicable	
		Infiltration galleries	Applicable but complex	

Table 3-10. (Continued)

Effectiveness	Preliminary evaluation	
	Implementability	Cost <sup>a</sup>
<b>GROUND WATER</b>		
Does not immediately remediate ground water or vadose zone. Is probably protective of human health	Not acceptable to LLNL, DOE, and the regulatory agencies	None
Dropped	Dropped	Dropped
Dropped	Dropped	Dropped
Not evaluated separately	Not evaluated separately	Not evaluated separately
Prevents surface recharge	Implementable	Low
Effective	Implementable	(b)
Dropped	Dropped	Dropped
Effective	Dropped	Dropped
Not effective for VOCs	Dropped for VOCs	Dropped
Possibly effective for FHCs	Implementable for FHCs	Medium to high
Effective technology for VOCs and FHCs	Implementable; transfers compounds to air	Medium
Effective technology for VOCs, FHCs, lead, not for chromium	Implementable; transfers compounds to carbon	Medium to high
Effective for nondissolved compounds over 1 $\mu\text{m}$ in size	Dropped	Dropped
Effective technology for VOCs and FHCs	Implementable in combination with other technologies	Medium to high
Effective for chromium	Dropped	Dropped
Effective for chromium	Implementable; hazardous residue	Medium
Effective	Implementable; permit obtained	Medium
Effective	Implementable; permit obtained	High
Effective	Implementable; permit obtained	Low
Effective	Implementable; permit required	Medium
Dropped	Dropped	Dropped

Table 3-10. (Continued)

General response action	Remediation technology type	Technology (process option)	Screening comments
	Use	Landscape irrigation	Applicable
		Cooling towers, other process water	Applicable
<i>Deferred action</i>			
Monitor and treat if necessary at the point of use	Monitor (treat), administrative/institutional measures	Same as for immediate treatment, if necessary. Restrict well development	Technically feasible; least expensive remediation measure; fully protective of human health
<b>VADOSE ZONE</b>			
<i>No action</i>			
No action	No action		
	Natural degradation, dispersal, adsorption	No action	Acceptability dependent upon initial concentrations
<i>Immediate action</i>			
Containment	Horizontal barrier (capping)	Asphalt cover	Applicable
Extraction	Extraction technologies:		
	Excavation	Soil removal	Applicable if compounds not too deep
	Vent	Vacuum-induced vent	Applicable
		Steam-enhanced vent	Heat not required
		RF-enhanced vent	Heat not required
Treatment	Treatment technologies:		
	Extract and treat:		
	Physical transfer	GAC	Applicable
	Chemical transformation	Thermal oxidation	Applicable
		Catalytic oxidation	Applicable
	Biological	Bioreactor	Complex operations
	<i>In situ</i> treatment	Enhanced bioremediation	Difficult distribution of nutrients Experimental for VOCs
<i>Deferred action</i>			
Monitor and treat as necessary	Monitor migration and desorption processes	Treat compounds that desorb and leach to ground water	Technically feasible; compounds would be treated with other ground water contaminants

<sup>a</sup> Cost ranges defined in Tables 4-8 through 4-12; Appendix D provides actual cost breakdowns.

<sup>b</sup> Costs for various treatment options applied to individual treatment facilities provided in Tables 4-8 through 4-12.

Table 3-10. (Continued)

Effectiveness	Preliminary evaluation	
	Implementability	Cost <sup>a</sup>
Effective use of treated water	Implementable	Very low
Effective use of treated water	Implementable	Very low
Effective in protecting human health. Allows continued migration; natural degradation reduces volume and toxicity; does not reduce mobility; does not fully meet ARARs	Requires Zone 7 participation in administrative/institutional control measures. No new supply wells anticipated	Very, very low or none
<b>VADOSE ZONE</b>		
Does not immediately remediate vadose zone. Ground water remediation assures health protection	Implementable	None
Retards leaching from soil. Does not remediate soil. Can supplement other means	Implementable	Low
Effective in limited situations	Situation dependent	Dependent on situation
Effective	Implementable	Low to medium
Dropped	Dropped	Dropped
Dropped	Dropped	Dropped
Effective technology for VOCs and FHCs	Implementable; regeneration an issue	Medium
Effective technology for VOCs and FHCs	Implementable	Low
Effective technology for FHCs	Implementable	Low
Dropped	Dropped	Dropped
Dropped	Dropped	Dropped
Does not result in immediate remediation of vadose zone. Ground water remediation assures health protection	Implementable	Very, very low

Table 3-11. Summary of screening process, showing treatment options technically and administratively implementable at LLNL.

Treatment options: media-specific, sitewide, implementability	Screen alternatives	
	Effectiveness	Cost <sup>a</sup>
<b>GROUND WATER</b>		
<b>Extraction:</b>		
Pump	Effective	(b)
<b>Surface treatment:</b>		
AS + GAC(V)	Effective for VOCs and FHCs	Low
AS + GAC(V) + IX	Effective for VOCs, FHCs, and chromium	Low-medium
AS + GAC(V) + GAC(L)	Effective for VOCs, FHCs, and lead	Very high
GAC(L)	Effective for VOCs, FHCs, and lead	Very high
GAC(L) + IX	Effective for VOCs, FHCs, and chromium	High
UV/Ox + AS + GAC(V)	Effective for VOCs and FHCs	Medium
UV/Ox + AS + GAC(V) + IX	Effective for VOCs, FHCs, and chromium	Medium
UV/Ox + GAC(L)	Effective for VOCs, FHCs, and lead	Medium
<b>Disposal</b>		
Recharge basin	All disposition alternatives are considered effective; complementary options to be used as cost effectiveness and hydraulic control needs require	Medium
Retention pond		High
Surface waterings		Low
Recharge wells		Medium
Irrigation		Very low
Cooling towers		Very low
<b>Deferred-action:</b>		
Administrative controls	Effective at prevention of exposure	Very, very low
GAC	Effective for low concentrations of VOCs	Very, very low
AS	Effective for low concentrations of VOCs	Very, very low
UV/Ox	Effective for low concentrations of VOCs	Very, very low
<b>VADOSE ZONE</b>		
GAC(V)	Effective for VOCs and FHCs	Medium to high
ThmOx	Effective for VOCs and FHCs	Low
CatOx	Effective for FHCs	Low

<sup>a</sup> Cost ranges defined in Tables 4-8 through 4-12; Appendix D provides actual cost breakdowns.

<sup>b</sup> Costs for various treatment options applied to individual treatment facilities provided in Tables 4-8 through 4-12.

AS = Air stripping    UV/Ox = Ultraviolet light oxidation

GAC(V) = GAC applied to vapor phase

ThmOx = Thermal oxidation

GAC(L) = GAC applied to liquid phase

CatOx = Catalytic oxidation

IX = Ion exchange

control of ground water movement, it would most reasonably be used in conjunction with more active measures to remediate VOCs, FHCs, and metals, such as described in Extraction Alternative No. 2.

### **3.6.2.2. Extraction/Excavation**

**3.6.2.2.1. Ground Water.** Of the alternatives for ground water, the site hydrogeology and current state of technology dictate an active technology such as pump and treat.

There are two general strategies for extracting ground water using wells. Extraction Alternative No. 1 results in complete VOC and FHC plume capture and remediation of sources of hazardous material in the ground water originating from the LLNL site. Extraction Alternative No. 2 results in hydraulic control and remediation by extraction wells along the downgradient plume margins only. Alternative No. 1 would result in more rapid and complete remediation of the ground water.

Hydraulic control of all VOCs originating at LLNL in concentrations above their MCLs is assumed in all active alternatives selected for further evaluation.

**3.6.2.2.2. Vadose Zone.** For the vadose zone, vacuum-induced venting is the extraction alternative chosen for detailed evaluation because it is compatible with available treatment options for the vadose zone and with the characteristics and limitations of the subsurface materials. Supplemental excavation could be used if appropriate conditions are found.

### **3.6.2.3. Treatment**

#### **3.6.2.3.1. Ground Water**

**3.6.2.3.1.1. Natural Degradation.** VOCs, FHCs, and tritium are all subject to natural degradation. This process will proceed regardless of our intervention. In the one area containing tritium in excess of MCLs, natural decay will decrease tritium concentrations below MCLs within 2 or 3 y even without our action. The VOCs and FHCs will be remediated using more active means; nevertheless, they will simultaneously undergo natural degradation. It is probable that natural degradation of the VOCs and FHCs, in combination with administrative and institutional controls, would be fully protective of human health.

**3.6.2.3.1.2. Air Stripping.** Packed-column, counter-flow air stripping is an applicable, effective, implementable, and medium-cost method to remove VOCs and FHCs by physical means from aqueous streams. This technology does not effectively remove metals.

**3.6.2.3.1.3. Adsorption.** This technology, using GAC, is an applicable, effective, implementable, and medium- to high-cost method to remove VOCs and FHCs from either an aqueous or vapor medium. In addition, GAC effectively treats many metals.

**3.6.2.3.1.4. UV/oxidation.** Chemical oxidation using an oxidizing agent, such as hydrogen peroxide or ozone, and ultraviolet light as an agent to augment the dissociation of the oxidizing agent to a hydroxyl radical, is an applicable, effective, implementable, and medium- to high-cost method to treat VOCs and FHCs in ground water. UV/oxidation processes minimize waste requiring further treatment or disposal by destroying the VOCs or FHCs. This technology does not effectively remove metals.

**3.6.2.3.1.5. Enhanced Bioremediation.** Bioremediation, either *in situ* or in surface reactor vessels, is possibly effective in remediating FHCs. However, *in situ* treatment of halogenated hydrocarbons is still experimental. Surface reactors require careful control of conditions and constant operator attention and produce a biomass sludge that may be considered hazardous and require treatment or disposal. This technology has been eliminated from further consideration for VOCs at this time because implementation is complex and the *in situ* technology is still experimental for VOCs. Bioremediation for FHCs is implementable, but considerable uncertainty remains about actual effectiveness and cost.

**3.6.2.3.1.6. Ultrafiltration.** Ultrafiltration can be used to remove insoluble particles of approximately 1  $\mu\text{m}$  or larger from ground water. It would be effective in removing nondissolved metals such as lead, but not VOCs, FHCs, or dissolved metals such as chromium. The process is generally used as secondary treatment and is not evaluated in further detail.

**3.6.2.3.1.7. Precipitation.** Chemical precipitation is a well-proven technology for removing dissolved metals from ground water. It produces a sludge residue containing the metals that may be considered hazardous and require further treatment prior to disposal. Chemical conditions in the influent stream must be carefully controlled. We have not chosen to evaluate precipitation in more detail because ion exchange is a better-defined process for the ground water at LLNL.

**3.6.2.3.1.8. Ion Exchange.** This technology effectively removes metals from ground water. The ionic species to be removed are exchanged for nonhazardous ions bound to the resin. The resin is regenerated, leaving a hazardous waste solution that may require further treatment prior to disposal. This process is being used to represent all nonadsorption technologies for the removal of chromium in our detailed evaluation.

### **3.6.2.3.2. Vadose Zone**

**3.6.2.3.2.1. Thermal Oxidation.** This technology effectively transforms VOCs and FHCs to nonhazardous compounds, but requires more fuel to initiate and maintain the oxidation process than the catalytic oxidation method.

**3.6.2.3.2.2. Catalytic Oxidation.** This process removes FHCs from vapor effluent recovered from vacuum-induced soil venting of the Gasoline Spill Area. We do not consider it further for VOCs because halogenated compounds destroy the catalyst.

**3.6.2.3.2.3. GAC.** GAC treatment of the vapor phase is an applicable, effective, implementable, and medium- to high-cost method to physically remove VOCs and FHCs from vapors extracted from the vadose zone. The current pilot project in the Gasoline Spill Area uses thermal oxidation for the transformation of FHCs to nonhazardous compounds, but GAC would also be effective.

### **3.6.3. Deferred Action**

The Deferred-Action Alternative, in conjunction with administrative/institutional controls, is protective of human health and is the lowest cost alternative. It involves allowing the compounds of interest to continue migrating with the ground water, while undergoing natural degradation and adsorption. All wells in the pathway of the plume would be monitored and, if concentrations of VOCs above ARARs or other health risk-based levels were detected, alternate supplies of water or point-of-use treatment would be provided. This alternative would not result

in as-rapid-as-possible reduction of the compounds in the ground water to ARAR concentrations, and would allow migration of contaminants, violating the State's nondegradation policy. Therefore, it will not be recommended by LLNL and will not be investigated further except as a baseline case for cost comparison purposes.

#### **3.6.4. Conclusion**

This screening process has resulted in the development of a set of technically feasible, effective remedial alternatives using a variety of treatment options, described in some detail in the previous part of this section and in Appendix D. These are analyzed in greater detail in Section 4.

## 4. DETAILED EVALUATION OF REMEDIAL ALTERNATIVES

### 4.1. CRITERIA AND EVALUATION PROCESS

Having identified and screened technology types and individual technologies, and performed a preliminary evaluation of the most promising remedial alternatives, we now conduct a detailed analysis and comparison of treatment options and remedial alternatives. EPA (1988b) has identified nine criteria to be used in the detailed analysis of alternatives:

1. Overall protection of human health and the environment.
2. Compliance with ARARs.
3. Long-term effectiveness and permanence.
4. Reduction of toxicity, mobility, or volume.
5. Short-term effectiveness.
6. Implementability.
7. Cost.
8. State acceptance.
9. Community acceptance.

Remedial alternatives, technology types, and treatment options are intended to be medium-specific. At LLNL, the medium of most interest is ground water within complexly interfingering alluvial sediments. The associated vadose zone, particularly in source areas, is the other medium of concern. Surface water and air were not affected by the original releases of hazardous materials, but are considered in the selection of remedial alternatives.

In this section, we evaluate treatment options and remedial alternatives against the first seven of these criteria. The evaluation of State and community acceptance will be completed after State and local review and response to this document.

Three or more treatment options are evaluated for each possible situation at LLNL that may require remediation. These situations are based on current knowledge of the distribution of the hazardous materials in the subsurface at LLNL. The situations and corresponding technologies are:

<b>Situation</b>	<b>Treatment option</b>
<i>Immediate action</i>	
Ground water with VOCs or FHCs	<ol style="list-style-type: none"> <li>1. GAC treatment of the liquid phase.</li> <li>2. Air stripping with GAC treatment of the vapor phase.</li> <li>3. UV/oxidation with aeration polishing and GAC treatment of the vapor phase.</li> </ol>
Ground water with VOCs and chromium	<ol style="list-style-type: none"> <li>1. Same as (1) above with ion exchange.</li> <li>2. Same as (2) above with ion exchange.</li> <li>3. Same as (3) above with ion exchange.</li> </ol>

Situation	Treatment option
Ground water with VOCs, FHC, and lead	<ol style="list-style-type: none"> <li>1. GAC treatment of the liquid phase.</li> <li>2. Air stripping with GAC treatment of both the vapor phase and liquid phase.</li> <li>3. UV/oxidation with GAC treatment of the liquid phase.</li> <li>4. <i>In situ</i> bioremediation (FHCs only).</li> </ol>
Vadose zone with FHCs or VOCs	<ol style="list-style-type: none"> <li>1. Thermal oxidation.</li> <li>2. Catalytic oxidation (FHCs only).</li> <li>3. GAC treatment of the vapor phase.</li> </ol>
<b>Deferred action</b>	
Ground water with low VOC concentration at point-of-distribution	<ol style="list-style-type: none"> <li>1. GAC treatment of the liquid phase.</li> <li>2. Air stripping.</li> <li>3. UV/oxidation.</li> </ol>

Evidence is not yet definitive regarding the need for chromium and lead remediation. We are currently collecting and evaluating additional sediment and water samples to further characterize chromium and lead in the subsurface. These data will be reported in our Monthly Progress Reports. Should the new data indicate that treatment of chromium and/or lead is necessary, the treatment technologies described herein would be available.

## 4.2. DETAILED ANALYSIS OF ALTERNATIVES FOR REMEDIATION OF GROUND WATER

For purposes of this FS, the LLNL site is defined as one operable unit. Within this unit, the various original sources of contamination varied in composition, leaving residual plumes of different chemical makeup in different areas dispersed throughout the site. As discussed in the RI (Thorpe *et al.*, 1990), these plumes are now intermingled. To address these composite plumes efficiently, LLNL would install up to seven treatment systems at locations that permit optimization of ground water conveyance in pipelines over relatively short distances and flexibility in choosing treatment options applicable to the specific local conditions.

Each treatment facility would be served by a number of extraction wells, pipelines to the facility, and a disposal system also requiring a pipeline to the point of disposition. Two remedial alternatives for ground water extraction were considered during the identification and screening process (see Section 3). Both extraction options, Alternative No. 1, complete capture and treatment of all ground water affected by contaminants originating from the LLNL site, and Alternative No. 2, downgradient plume margin control, survived the screening. Conceptual extraction sites have been chosen to effectively intercept and hydraulically control contaminant plumes and to minimize the estimated time to complete remediation.

There are several options for disposal of the treated ground water. These are not viewed as competing alternatives, but as complementary options to be used on the basis of logistics, usefulness for hydraulic control and expedited cleanup, conserving the ground water resource, and cost effectiveness of and demand for the beneficial use of treated ground water onsite.

The results of the detailed analysis of treatment options and remedial alternatives for ground water are presented in a number of formats, the first of which is provided in Tables 4-1 through 4-4 for ground water. The evaluation presented in these tables is organized into four categories of treatment options designed to treat:

1. VOCs and/or FHC only [to be used at proposed Treatment Facilities A, B, C, E, and G (Table 4-1)].
2. VOCs and chromium, if necessary [Treatment Facility D (Table 4-2)].
3. VOCs plus FHC and lead, if necessary [Treatment Facility F (Table 4-3)].
4. VOCs in downtown Livermore [deferred action (Table 4-4)].

Both of the pump and treat alternatives are equally protective of human health and the environment because the treatment options (Tables 4-1 through 4-3) are designed to meet the same treatment criteria. Each is designed to reduce the concentration of VOCs, FHCs, and metals to discharge requirement levels, and can be designed to accommodate the necessary flow rates. The Deferred-Action Alternative (Table 4-4) is also fully protective of human health, but does allow further degradation of ground water until natural processes reduce concentrations below ARARs. Some portion of the ground water is predicted to exceed remedial action objectives for as long as 360 y, if no active remediation is undertaken. The estimated time of operation required to meet ambient ground water ARARs is discussed in Section 3.4 and Appendix C.

Each of the treatment options, except *in situ* bioremediation, is equally effective in the short term and the long term. Bioremediation is only effective on a portion of the problems at TFF. Each of the others equally reduces the toxicity, mobility, and volume of the compounds. Each is equally technically implementable. The treatment options involving air stripping towers may be somewhat less appealing to local citizens as a result of the greater visual impact of the towers and their associated noise. However, this effect will be minimal in the general setting of LLNL, a highly developed research facility. Somewhat greater concern may be raised over the visual impact of a tower in close proximity to Vasco Road or East Avenue, such as where Treatment Facility A is currently located.

Treatment options involving GAC may require either transport or onsite regeneration of spent carbon and appropriate environmental controls to ensure complete destruction of toxic compounds, which could cause some concern. However, the compounds to be removed from ground water at the Livermore site can easily be completely destroyed or transformed to nonharmful constituents.

The treatment options for the Deferred-Action Alternative are described in Table 4-4. This alternative, consisting of implementing administrative/institutional measures to prevent new wells from being developed in the path of the migrating plume, ground water monitoring, and as-needed treatment at the point of distribution, is as protective of human health as the immediate-action alternatives. It does allow the compounds to continue to migrate with the movement of the ground water. Much of this material will degrade, adsorb, and disperse, and the small amount that might reach a municipal or domestic well will be considerably reduced in concentration (toxicity) and volume. If treatment is required to meet ARARs, the amount of treatment necessary will be much less than if the ground water is treated immediately. This alternative would ensure that concentrations are below ARARs for water delivered for consumption. In the short-term, this approach does not reduce mobility and allows degradation

*Text continues on page 4-14*

Table 4-1. Detailed evaluation of treatment options for VOCs or FHCs in ground water to concentrations below detection limits (Facilities A, B, C, E, and G).

Assessment factor	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction with air stripping and GAC treatment (vapor phase)	Ground water extraction with UV/oxidation plus air stripping with GAC treatment (vapor phase)
Overall protection of human health and the environment	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water. No air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water or air emissions.
Compliance with ARARs	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.
Long-term effectiveness and permanence	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until concentrations in ground water meet ARARs. UV/oxidation destroys most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.
Reduction in toxicity, mobility, or volume	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. UV/oxidation destroys most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants.

Table 4-1. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction with air stripping and GAC treatment (vapor phase)	Ground water extraction with UV/oxidation plus air stripping with GAC treatment (vapor phase)
Short-term effectiveness	Minimal impact to community during construction. No impact to community during operation. Possible exposure of workers during construction of extraction wells, piping, and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. Use of GAC for control of air emissions from stripper will prevent impact on community. Possible exposure of workers during construction of extraction wells, piping, and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. Use of GAC for control of air emissions from stripper will prevent impact on community. Possible exposure of workers during construction of extraction wells, piping, and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.
Implementability	GAC is proven for treatment of VOCs and FHCs in ground water. Services and materials for system construction, operation and maintenance, and for disposal or regeneration of GAC are readily available, but may involve shipment offsite. Permit required for discharge of treated water.	Air stripping is proven for treatment of VOCs and FHCs in ground water. Stripping towers may have visual impacts. GAC is proven for control of air emissions. Services and materials for system construction, operation and maintenance, and for disposal or regeneration of GAC are readily available, but may involve shipment offsite. Permits required for discharge of treated water and operation of air stripper.	Onsite pilot testing has shown that combination of UV/oxidation and air stripping will achieve required treatment of ground water. GAC is proven for control of air emissions. Services and materials for system construction, operation, and maintenance. Minimizes waste requiring further treatment or disposal. Permits required for discharge of treated water or any air emissions.
Cost <sup>a</sup>	Ranges from \$2.2 million (medium) for TFG to \$6.3 million (very high) for TFA.	Ranges from \$1.6 million (low) for TFC and \$2.2 million (medium) for TFB.	Ranges from \$2.7 million (medium) for TFC to \$4.0 million (high) for TFA.
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> See Table 4-8 for definition of cost ranges.

Table 4-2. Detailed evaluation of treatment options for VOCs and chromium in ground water to concentrations below detection limits (Facility D).

Assessment factor	Ground water extraction with GAC treatment (liquid phase) plus ion-exchange treatment	Ground water extraction and air stripping (vapor phase) plus ion-exchange treatment	Ground water extraction with UV/oxidation and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment
Overall protection of human health and the environment	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water. No air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public from system operation and discharged treated water or air emissions.
Complies with ARARs	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.
Long-term effectiveness and permanence	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Ion-exchange residues properly disposed of. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Ion-exchange residues properly disposed of. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until concentrations in ground water meet ARARs. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Ion-exchange residues properly disposed of. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.

Table 4-2. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase) plus ion-exchange treatment	Ground water extraction and air stripping (vapor phase) plus ion-exchange treatment	Ground water extraction with UV/oxidation and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment
Reduction in toxicity, mobility, or volume	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants. Stabilized sludge containing metals from ion exchange may require disposal at a hazardous waste landfill.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants. Stabilized sludge containing metals from ion exchange may require disposal at a hazardous waste landfill.	Volume and toxicity of contaminants reduced by ground water by extraction and treatment. Mobility reduced by hydraulic control. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Stabilized sludge containing metals from ion exchange may require disposal at a hazardous waste landfill.
Short-term effectiveness	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y estimated to achieve remedial objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y estimated to achieve remedial objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y estimated to achieve remedial objectives.
Implementability	GAC is proven technology for removal of VOCs and FHCs, and ion exchange is proven for removal of chromium from ground water. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Air stripping is proven technology for removal of VOCs and FHCs, and ion exchange is a proven technology for removal of chromium from ground water. Stripping towers may have visual impacts. GAC is proven for removal of VOCs and FHCs from air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permits required for discharge of treated water and operation of air stripper.	Onsite pilot testing for over a year has shown UV/oxidation in combination with air stripping with GAC treatment of vapor as reliable for removal of VOCs from ground water. Ion exchange is proven technology for removal of chromium from ground water. Services, materials, and equipment are readily available. Minimizes waste requiring further treatment or disposal. Permits required for discharge of treated water or any air emissions.

Table 4-2. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase) plus ion-exchange treatment	Ground water extraction and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment	Ground water extraction with UV/oxidation and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment
Cost <sup>a</sup>	\$4.4 million (high).	\$2.5 million (medium).	\$3.6 million (high).
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> See Table 4-9 for definition of cost ranges.

Table 4-3. Detailed evaluation of treatment options for VOCs, FHCs, and lead in ground water to concentrations below detection limits (Facility F).

Assessment factor	Ground water extraction and air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)		Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)		<i>In situ</i> bioremediation
	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction and air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	
Overall protection of human health and the environment	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water. No air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public.	Risk to human health and the environment is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public.
Compliance with ARARs	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	No aboveground effluents. ARARs for FHCs in ambient ground water likely achievable, but not suitable for VOCs or lead.
Long-term effectiveness and permanence	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until concentrations in ground water meet ARARs. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Experience limited on cleanup completeness. Microbes destroy FHCs, but may not be effective for VOCs or lead. Would have to be used in conjunction with other techniques. Bioorganisms are sensitive to the presence of inorganic compounds and other <i>in situ</i> conditions that are difficult to control.

Table 4-3. (Continued)

Assessment factor	Ground water extraction and air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)		Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)		<i>In situ</i> bioremediation
	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction and air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	
Reduction in toxicity, mobility, or volume	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants, except lead, which volatilizes as lead oxide.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants, except lead, which volatilizes as lead oxide.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants, except lead, which volatilizes as lead oxide.	Volume and toxicity of FHCs reduced by biodegradation. Most FHCs would be destroyed, but not effective for VOCs or lead.	
Short-term effectiveness	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment mitigates risk. Period of about 50 to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment mitigates risk. Period of about 50 to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment mitigates risk. Period of about 50 to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	No impact to employees or public during operation. Possible exposure of employees during installation of emplacement wells. Use of protective procedures, clothing, and equipment mitigates risk. Time estimates for remediation of FHCs not available; not feasible for VOCs or lead. No cleanup time estimate possible.	

Table 4-3. (Continued)

Assessment factor	Ground water extraction and air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)		Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)		<i>In situ</i> bioremediation
	Ground water extraction with GAC treatment (liquid phase)	air stripping is proven for removal of VOCs and FHCs, and GAC treatment of the liquid phase is proven for removal of lead from ground water. Stripping tower may have visual impacts. GAC is proven for removal of these constituents from an air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Ground water extraction with GAC treatment (liquid phase)	Onsite pilot testing for over a year has established UV/oxidation in combination with air stripping with GAC treatment of the vapor as reliable for removal of VOCs from ground water. GAC treatment of the liquid phase is proven for removal of lead from ground water. Services, materials, and equipment are readily available. Minimizes waste requiring further treatment or disposal. Permit required for discharge of treated water.	
Implementability	GAC treatment of the liquid phase is proven for removal of VOCs, FHCs, and lead from ground water. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Air stripping is proven for removal of VOCs and FHCs, and GAC treatment of the liquid phase is proven for removal of lead from ground water. Stripping tower may have visual impacts. GAC is proven for removal of these constituents from an air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Onsite pilot testing for over a year has established UV/oxidation in combination with air stripping with GAC treatment of the vapor as reliable for removal of VOCs from ground water. GAC treatment of the liquid phase is proven for removal of lead from ground water. Services, materials, and equipment are readily available. Minimizes waste requiring further treatment or disposal. Permit required for discharge of treated water.	Implementable for localized FHC problem only. No practical way to disburse microbes and nutrients to entire VOC plume in the area. Services for bioremediation are readily available.	
Cost <sup>a</sup>	\$9.1 million (extremely high).	\$5.3 million (high).	\$4.5 million (high).	Not comparable because only FHCs treated; costs for FHCs medium to high; estimated in the range of \$4 million for 10 y of treatment.	
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.	
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.	

<sup>a</sup> See Table 4-10 for definition of cost ranges.

Table 4-4. Detailed evaluation of treatment options for low concentrations of VOCs in ground water at point of distribution in downtown Livermore.

Assessment factor	GAC treatment	Air stripping	UV/oxidation
Overall protection of human health and the environment	Risk to human health and the environment reduced, if necessary, by treatment at point of use. Ground water quality reduced until MCLs met via natural degradation.	Risk to human health and the environment reduced, if necessary, by treatment at point of use. Ground water quality reduced until MCLs met via natural degradation.	Risk to human health and the environment reduced, if necessary, by treatment at point of use. Ground water quality reduced until MCLs met via natural degradation.
Compliance with ARARs	ARARs for ambient ground water met by natural degradation in an estimated 360 y. Nondegradation policy violated.	ARARs for ambient ground water met by natural degradation in an estimated 360 y. Nondegradation policy violated.	ARARs for ambient ground water met by natural degradation in an estimated 360 y. Nondegradation policy violated.
Long-term effectiveness and permanence	Treatment system will be operated until concentrations in supply well water meet or are lower than ARARs.	Treatment system will be operated until concentrations in supply well water meet or are lower than ARARs.	Treatment system will be operated until concentrations in supply well water meet or are lower than ARARs.
Reduction in toxicity, mobility, or volume	Toxicity and volume of compounds area reduced by natural degradation. If monitoring indicates treatment is required, toxicity and volume would be reduced by treatment at the point of withdrawal from the aquifer and the treated water. Thermal regeneration of spent GAC completely destroys or recycles contaminants.	Toxicity and volume of compounds area reduced by natural degradation. If monitoring indicates treatment is required, toxicity and volume would be reduced by treatment at the point of withdrawal from the aquifer and the treated water. Operation of treatment system transfers small volumes of contaminants from ground water to the atmosphere.	Toxicity and volume of compounds area reduced by natural degradation. If monitoring indicates treatment is required, toxicity and volume would be reduced by treatment at the point of withdrawal from the aquifer and the treated water. UV/oxidation results in complete destruction of contaminants.
Short-term effectiveness	This alternative does not result in immediate remediation of the ground water. Administrative/institutional measures have no anticipated adverse impact on the public. Treatment is assumed to require 10 to 50 y from time of commencement, estimated to be over 200 y from now.	This alternative does not result in immediate remediation of the ground water. Administrative/institutional measures have no anticipated adverse impact on the public. Treatment is assumed to require 10 to 50 y from time of commencement, estimated to be over 200 y from now.	This alternative does not result in immediate remediation of the ground water. Administrative/institutional measures have no anticipated adverse impact on the public. Treatment is assumed to require 10 to 50 y from time of commencement, estimated to be over 200 y from now.

Table 4-4. (Continued)

Assessment factor	GAC treatment	Air stripping	UV/oxidation
Implementability	GAC treatment of the liquid phase is proven for treatment of VOCs in ground water. Services, materials, and equipment for construction are readily available, but may involve transshipment of hazardous waste. Alternative may not be acceptable to regulatory agencies because it delays remediation an estimated 200 y.	Air stripping is a well-proven technology for treatment of VOCs in ground water. Stripping towers may have visual impacts. Services, materials, and equipment for construction are readily available. Alternative may not be acceptable to regulatory agencies because it delays remediation an estimated 200 y.	UV/oxidation alone should achieve required treatment of ground water. Services, materials, and equipment for construction are readily available. Alternative may not be acceptable to regulatory agencies because it delays remediation an estimated 200 y.
Cost <sup>a</sup>	\$0.3 million (very low).	\$0.03 million (extremely low).	\$0.2 million (very low).
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> Assumes treatment would take place at municipal water supply wells. See Table 4-11 for definition of cost ranges.

of ground water quality; however, it avoids the risks and impacts associated with activities such as drilling and construction. The analysis is based on the assessment in the RI that concludes that no contaminants other than VOCs reach municipal or domestic supply wells west of LLNL. The best-estimate calculation suggests that VOCs reaching the municipal supply wells will be well below MCLs; however, if actual concentrations exceed drinking water standards, treatment would be required.

The estimated present worth of the life-cycle cost of each treatment option for each of the onsite treatment facilities and treatment at the point of distribution is shown in Table 4-5. All treatment systems are costed on the basis of a design that will treat ground water to concentrations below detection limits (0.5 ppb) for organics. For information purposes, the costs of the nominal extraction-pipeline-disposal alternative are also shown for each facility, although they do not vary among options at each facility. These data summarize the cost analyses presented in Appendices D (ground water treatment), E (vadose zone treatment), and F (extraction, pipeline, and disposal alternatives). Capital, installation, operation, and maintenance costs are itemized in the Appendices, but are combined for comparison here. Assumptions on which the cost estimates are based are discussed in the Appendices.

In general, air stripping with GAC treatment of the vapor phase is the least expensive ground water treatment option for most situations, followed by UV/oxidation and then by GAC applied to the liquid phase. These cost patterns are a function of the treatment system influent concentration, the power requirements for UV/oxidation, and the cost of carbon for the GAC-based systems. For example, the high concentrations of FHC at TFF drive the cost of GAC treatment of the liquid phase to a very high level, and low concentrations of VOCs at TFG result in relatively low costs for GAC. These cost comparisons are based on current prices, some of which may change as technologies evolve. In particular, the UV/oxidation technologies are still relatively new and appear to have significant potential for increasing efficiencies and lowering costs.

### **4.3. DETAILED ANALYSIS OF ALTERNATIVES FOR REMEDIATION OF THE VADOSE ZONE**

One remedial alternative with three treatment options survived screening and is evaluated for remediating organic vapors extracted from the vadose zone: GAC, thermal oxidation, and catalytic oxidation. The detailed analysis of these treatment options appears in Appendix E and is summarized in Table 4-6. All rely on vacuum-induced venting to extract organic vapors and are designed to reduce concentrations below ARARs. For GAC, the captured FHCs are oxidized to nonhazardous compounds or collected for reuse during carbon regeneration. The thermal and catalytic oxidation alternatives transform the FHCs directly to nonhazardous compounds. The cost analysis of these systems, shown in Table 4-7, indicates that thermal and catalytic oxidation are more cost effective than GAC for FHCs.

If vadose zone remediation becomes necessary for VOCs, either to reach cleanup standards or to reduce ground water cleanup times, vacuum-induced venting would also be applicable. Based on current information, no treatment of the low concentration vented vapors would be necessary to meet BAAQMD discharge limitations. Table 4-6 shows a comparison of GAC and thermal oxidation cost, for background, if vapor treatment of VOCs were ever deemed necessary.

**Table 4-5. Summary costs for treatment options and remedial alternatives for ground water at the LLNL site (millions of 1990 dollars).**

Treatment facility	Remediation alternative	Capital costs	Present worth of 30-y operating and maintenance costs	Total present worth	Present worth of complete remediation system
Treatment Facility A	Extraction and disposal	0.34	0.14	0.48	
	GAC	0.73	5.06	5.79	6.27
	AS(L), GAC(V)	0.21	1.39	1.60	2.09
	UV(L), AS(L), GAC(V)	0.49	3.03	3.53	4.01
Treatment Facility B	Extraction and disposal	0.50	0.20	0.70	
	GAC	0.45	3.05	3.50	4.20
	AS(L), GAC(V)	0.18	1.36	1.55	2.24
	UV(L), AS(L), GAC(V)	0.37	1.96	2.33	3.02
Treatment Facility C	Extraction and disposal	0.39	0.15	0.51	
	GAC	0.45	1.80	2.25	2.76
	AS(L), GAC(V)	0.14	0.95	1.09	1.60
	UV(L), AS(L), GAC(V)	0.36	1.80	2.16	2.68
Treatment Facility D	Extraction and disposal	0.65	0.26	0.91	
	GAC, IX(Cr)	0.56	2.97	3.53	4.44
	AS(L), GAC(V), IX(Cr)	0.26	1.59	1.85	2.76
	UV(L), AS(L), GAC(V), IX(Cr)	0.47	2.22	2.69	3.60
Treatment Facility E	Extraction and disposal	0.44	0.17	0.61	
	GAC	0.45	2.69	3.14	3.75
	AS(L), GAC(V)	0.18	1.36	1.54	2.15
	UV(L), AS(L), GAC(V)	0.36	1.84	2.21	2.82
Treatment Facility F	Extraction and disposal	0.42	0.17	0.59	
	GAC	1.33	7.15	8.48	9.07
	AS(L), GAC(V), GAC(Pb)	0.36	4.39	4.75	5.33
	UV(L), GAC(Pb)	0.64	3.28	3.92	4.51

Table 4-5. (Continued)

Treatment facility	Remediation alternative	Capital costs	Present worth of 30-y operating and maintenance costs	Total present worth	Present worth of complete remediation system
Treatment Facility G	Extraction and disposal	0.43	0.17	0.60	
	GAC	0.25	1.34	1.58	2.18
	AS(L), GAC(V)	0.15	1.07	1.22	1.82
	UV(L), AS(L), GAC(V)	0.37	1.91	2.28	2.88
<i>Summary:</i>					
<i>Immediate action</i>					
Combination of all seven TFs; Extraction Alternative No. 1 <sup>a</sup>	Extraction and disposal	3.15	1.26	4.40	
	Lowest cost	1.77	10.74	12.50	16.90
	Highest cost	4.33	24.63	28.96	33.37
Combination of TFA, TFB, TFC, and TFF; Extraction Alternative No. 2 <sup>b</sup>	Extraction and disposal	1.65	0.77 <sup>b</sup>	2.41 <sup>b</sup>	
	Lowest cost	1.17	8.57 <sup>b</sup>	9.75 <sup>b</sup>	12.14 <sup>b</sup>
	Highest cost	2.87	19.26 <sup>b</sup>	22.13 <sup>b</sup>	24.54 <sup>b</sup>
<i>Summary:</i>					
<i>Deferred action</i>					
Treatment facility at point of distribution <sup>c</sup>	Extraction and disposal	NA	NA	NA	NA
	GAC(L)	0.01	0.26	0.28	0.28
	AS(L)	0.01	0.02	0.03	0.03
	UV(L)	0.02	0.16	0.18	0.18
<i>No action</i>					
No action	No treatment	0.00	0.00	0.00	0.00

<sup>a</sup> Thirty years of O & M costs are discounted at 5% to the present.

<sup>b</sup> Costs adjusted to reflect operating expense for 87 y and discounted at 5% to the present, to account for the longer time necessary to complete remediation.

<sup>c</sup> Thirty years of operation and maintenance (O & M) costs are discounted at 5% to the beginning of operation, assumed to be 200 y in the future; then, the capital and discounted O & M costs are discounted from 200 y in the future to 1990 at 2%.

L = For treatment of liquid phase.

V = For treatment of vapor phase.

GAC = Granular activated carbon.

AS = Air stripping.

UV = Ultraviolet light, hydrogen peroxide.

IX = Ion exchange.

Cr = Chromium.

Pb = Lead.

NA = Not applicable.

Table 4-6. Detailed evaluation of alternatives for treatment of FHCs and VOCs in the vadose zone.

Assessment factor	Vacuum-induced venting with GAC treatment	Vacuum-induced venting with thermal oxidation	Vacuum-induced venting with catalytic oxidation
Overall protection of human health and the environment	Risk to human health and the environment from these constituents is reduced by this alternative. Results in negligible risk to employees, the public, and the environment from system operation and treated vapor emissions. Reduces concentrations of constituents in vadose zone below ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants.	Risk to human health and the environment from these constituents is reduced by this alternative. Results in negligible risk to employees, the public, and the environment from system operation and treated vapor emissions. Reduces concentrations of constituents in vadose zone below ARARs. Air discharge requirements met.	Risk to human health and the environment from these constituents is reduced by this alternative. Results in negligible risk to employees, the public, and the environment from system operation and treated vapor emissions. Reduces concentrations of constituents in vadose zone below ARARs. Air discharge requirements met.
Compliance with ARARs	Reduces concentrations of constituents in vadose zone below ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants.	Reduces concentrations of constituents in vadose zone below ARARs. Air discharge requirements met.	Reduces concentrations of constituents in vadose zone below ARARs. Air discharge requirements met.
Long-term effectiveness and permanence	Extraction and treatment of soil vapors prevent further migration of constituents. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent new sources.	Extraction and treatment of soil vapors prevent further migration of constituents. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent new sources.	Extraction and treatment of soil vapors prevent further migration of constituents. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent new sources.
Reduction in toxicity, mobility, or volume	Constituents removed from soil are transformed to nonharmful compounds or collected for reuse in the carbon regeneration process. Placement and design of vent wells prevent migration of the constituents to the ground water.	Constituents removed from soil are transformed to nonharmful compounds in the oxidation process. Placement and design of vent wells prevent migration of the constituents to the ground water.	Constituents removed from soil are transformed to nonharmful compounds in the oxidation process. Placement and design of vent wells prevent migration of the constituents to the ground water.

Table 4-6. (Continued)

Assessment factor	Vacuum-induced venting with GAC treatment	Vacuum-induced venting with thermal oxidation	Vacuum-induced venting with catalytic oxidation
Short-term effectiveness	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of up to 10 y estimated to achieve remedial action objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of up to 10 y estimated to achieve remedial action objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of up to 10 y estimated to achieve remedial action objectives.
Implementability	Vacuum-induced venting effectively removes volatile constituents from subsurface. GAC treatment of the vapor phase is proven for removal of FHCs and VOCs from an air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated air.	Vacuum-induced venting effectively removes volatile constituents from subsurface. Thermal oxidation is proven for removal of FHCs and VOCs from an air stream. Services, materials, and equipment are readily available. Permit required for discharge of treated air.	Vacuum-induced venting effectively removes volatile constituents from subsurface. Catalytic oxidation is a proven technology for removal of FHCs from an air stream, but not for VOCs. Services, materials, and equipment are readily available. Permit required for discharge of treated air.
Cost	\$2.5 million (medium).	\$1.5 million (low).	\$0.8 million (FHCs only) (low).
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

**Table 4-7. Summary cost comparison of the estimated present value of treatment options for the remediation of the vadose zone at the LLNL site (millions of 1990 dollars).**

Treatment facility	Remediation alternative	Capital costs	Present worth of 30-y operating and maintenance costs	Total present value	Present worth of complete remediation system
Gasoline Spill Area (FHC)	Extraction	0.131	0.056	0.187	
	GAC	0.082	2.066	2.148	2.335
	Thermal oxidation	0.250	0.740	0.990	1.177
	Catalytic oxidation	0.259	0.506	0.765	0.952
Building 518 Area (VOCs) <sup>a</sup>	Extraction	0.102	0.045	0.148	
	GAC	0.065	0.312	0.377	0.525
	Thermal oxidation	0.245	0.304	0.549	0.696
Total vadose zone <sup>b</sup>	Extraction	0.233	0.102	0.335	
	GAC	0.147	2.378	2.525	2.860
	Thermal oxidation	0.495	1.044	1.539	1.874
	Catalytic oxidation	0.259	0.506	0.765	0.952

<sup>a</sup> Catalytic oxidation technology is not feasible in the presence of halogenated compounds.

<sup>b</sup> Assumes one system at the Gasoline Spill Area and one system at the Building 518 Area.

#### 4.4. SUMMARY OF DETAILED ANALYSIS AND COMPARATIVE EVALUATION OF ALTERNATIVES FOR REMEDIATION OF GROUND WATER AND THE VADOSE ZONE

The characteristics of each treatment option for each of the facilities are evaluated in Tables 4-8 through 4-13 according to the nine EPA evaluation criteria. The most significant distinguishing feature among the options is cost (see Table 4-7), which varies by factors of at least two for all treatment facilities. Noneconomic differences among the technologies may arise over concerns for aesthetics and the transport and ultimate disposal or regeneration of carbon and resin regeneration solutions.

The close proximity of the gasoline spill to areas that require ground water treatment for VOCs would allow the use of a single treatment system (TFF) for both problems. Further studies would be required to determine the feasibility of bioremediation at LLNL. It is not currently practical for VOCs. Therefore, we do not consider *in situ* bioremediation as practical as an overall remediation for that area. If additional remediation is required for the FHC after the VOCs have been cleaned up, *in situ* bioremediation will again be considered as a final cleanup process.

Each of the treatment technologies for ground water is considered in three remedial alternatives (Table 4-12); pump and treat with Extraction Alternative No. 1, pump and treat with Extraction Alternative No. 2, and the Deferred-Action Alternative. The Deferred-Action Alternative protects human health, but allows contaminants to migrate beyond their current extent, violating the State's nondegradation policy. Both of the pump and treat alternatives meet ARARs. The major differences are that Extraction Alternative No. 1 entails higher initial expenditures and results in the most rapid remediation, while Extraction Alternative No. 2 entails lower capital expenditures but requires operation of treatment facilities for a much longer time period. The longer operation is reflected in greater overall operating expenses for treatment facilities operated, which are portrayed on Table 4-5 by using operating expenses for 87 y. Because only four facilities are employed and the additional time of operation is in the distant future, the total present worth is somewhat less. (Dollars expended between 50 and 80 y in the future have little value under today's accepted accounting practices.)

The costs of these systems are shown graphically in Figures 4-1 through 4-3.

Ground Water	Threshold Factors				Balancing Factors						Modifying Factors			
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implement-ability	Cost	State Acceptance	Local Acceptance	TBD	TBD	TBD	TBD	TBD
GAC	●	●	●	●	●	●	●	●	●	L-VH	TBD	TBD	TBD	TBD
AS + GAC(V)	●	●	●	●	●	●	●	●	●	L	TBD	TBD	TBD	TBD
UV + AS + GAC(V)	●	●	●	●	●	●	●	●	●	M	TBD	TBD	TBD	TBD
Extraction, transport, disposal	●	●	●	●	●	●	●	●	●	H	TBD	TBD	TBD	TBD

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
**Treatment**  
 L < 2.0    2.0 < M < 3.5    H > 3.5    VH > 5.0  
**Extraction/disposition**  
 L < 0.3    0.3 < M < 0.5    H > 0.5

Table 4-8. Comparative evaluation of treatment options for ground water containing VOCs at Treatment Facilities A, B, C, E, and G. (AS= air stripping, V= vapor.)

Ground Water	Threshold Factors		Balancing Factors				Modifying Factors		Local Acceptance
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	
GAC + IX	●	●	●	●	●	●	H	TBD	TBD
AS + IX + GAC(V)	●	●	●	●	●	●	L	TBD	TBD
UV/OX + AS + IX + GAC(V)	●	●	●	●	●	●	M	TBD	TBD
Extraction, transport, disposal	●	●	●	●	●	●	H	TBD	TBD

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 L < 2.0 L < 0.3  
 2.0 < M < 3.5 0.3 < M < 0.5  
 H > 3.5 H > 0.5  
 VH > 5.0

Table 4-9. Comparative evaluation of treatment options for ground water containing VOCs and chromium at Treatment Facility D. (IX= ion exchange, AS= air stripping, V= vapor.)

Ground Water	Threshold Factors		Balancing Factors						Modifying Factors	
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance	
GAC	●	●	●	●	●	●	VH	TBD	TBD	
AS + GAC + GAC(V)	●	●	●	●	●	●	VH	TBD	TBD	
UV/OX + GAC	●	●	●	●	●	●	H	TBD	TBD	
Bioremediation <sup>a</sup>	●	●	●	●	●	●	H	TBD	TBD	
Extraction, transport, disposal	●	●	●	●	●	●	H	TBD	TBD	

<sup>a</sup> Implementable for FHCs, but not for VOCs.

Cost ranges (millions of dollars)

Treatment	Extraction/disposition
L > 2.0 <M <3.5	L > 0.3
H > 3.5 <H <5.0	0.3 <M < 0.5
VH > 5.0	H > 0.5
VVH < 7.0	

● = Alternative fully satisfies criterion  
○ = Alternative fails to satisfy criterion  
TBD = To be determined

Table 4-10. Comparative evaluation of treatment options for ground water containing VOCs, FHCs, and lead at Treatment Facility F. (AS= air stripping, V= vapor.)

Ground Water	Threshold Factors			Balancing Factors						Modifying Factors	
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance		
GAC	●	○	●	○	●	●	VVL	TBD	TBD		
AS	●	○	●	○	●	●	VVL	TBD	TBD		
UV/OX	●	○	●	○	●	●	VVL	TBD	TBD		

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 VVL < 0.5 N/A

Table 4-11. Comparative evaluation of treatment options for ground water containing VOCs at the point of distribution in Livermore, Deferred-Action Alternative. (AS= air stripping.)

Ground Water	Threshold Factors			Balancing Factors						Modifying Factors		
	Protect Human Health & the Environment	Comply with ARARS	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance	TBD	TBD	TBD
Immediate action:	●	●	●	●	●	●	M-H	TBD	TBD	TBD		
Extraction Alternative No.1	●	●	●	●	●	●	M-H	TBD	TBD	TBD		
Extraction Alternative No.2	●	●	●	●	●	●	M-H	TBD	TBD	TBD		
Delayed action	●	◐	●	◐	◐	◐	VWL	TBD	TBD	TBD		

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 VWL < 0.5 N/A  
 M > 15.0  
 H > 15.0

Table 4-12. Comparative evaluation of remedial alternatives for the combined remediation of ground water at LLNL.

Ground Water	Threshold Factors				Balancing Factors						Modifying Factors		
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance	TBD	TBD	TBD	TBD
GAC	●	●	●	●	●	●	M	TBD	TBD	TBD	TBD	TBD	TBD
THM/OX	●	●	●	●	●	●	L	TBD	TBD	TBD	TBD	TBD	TBD
CAT/OX	●	●	●	●	●	● <sup>a</sup>	L	TBD	TBD	TBD	TBD	TBD	TBD
Extraction	●	●	●	●	●	●	L	TBD	TBD	TBD	TBD	TBD	TBD

<sup>a</sup> Implementable for FHCs, but not for VOCs.

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment  
 L < 2.0  
 M > 2.0 < M < 3.5  
 H > 3.5  
 VH > 5.0

Extraction/disposition  
 L < 0.3  
 0.3 < M < 0.5  
 H > 0.5

Table 4-13. Comparative evaluation of treatment options for vadose zone vapor containing VOCs and/or FHCs.

Present worth (millions of 1990 dollars)

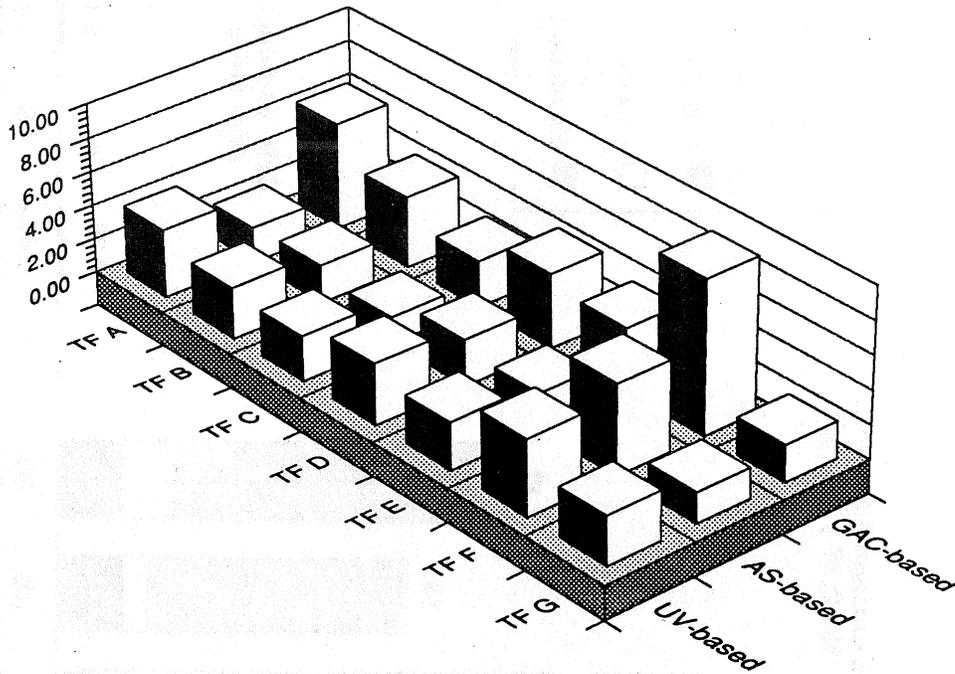


Figure 4-1. Extraction Alternative No. 1: Comparison of present worth of costs for three different treatment options for each of the seven potential LLNL treatment facilities. Analysis based on 30-y operation. (AS = air stripping.)

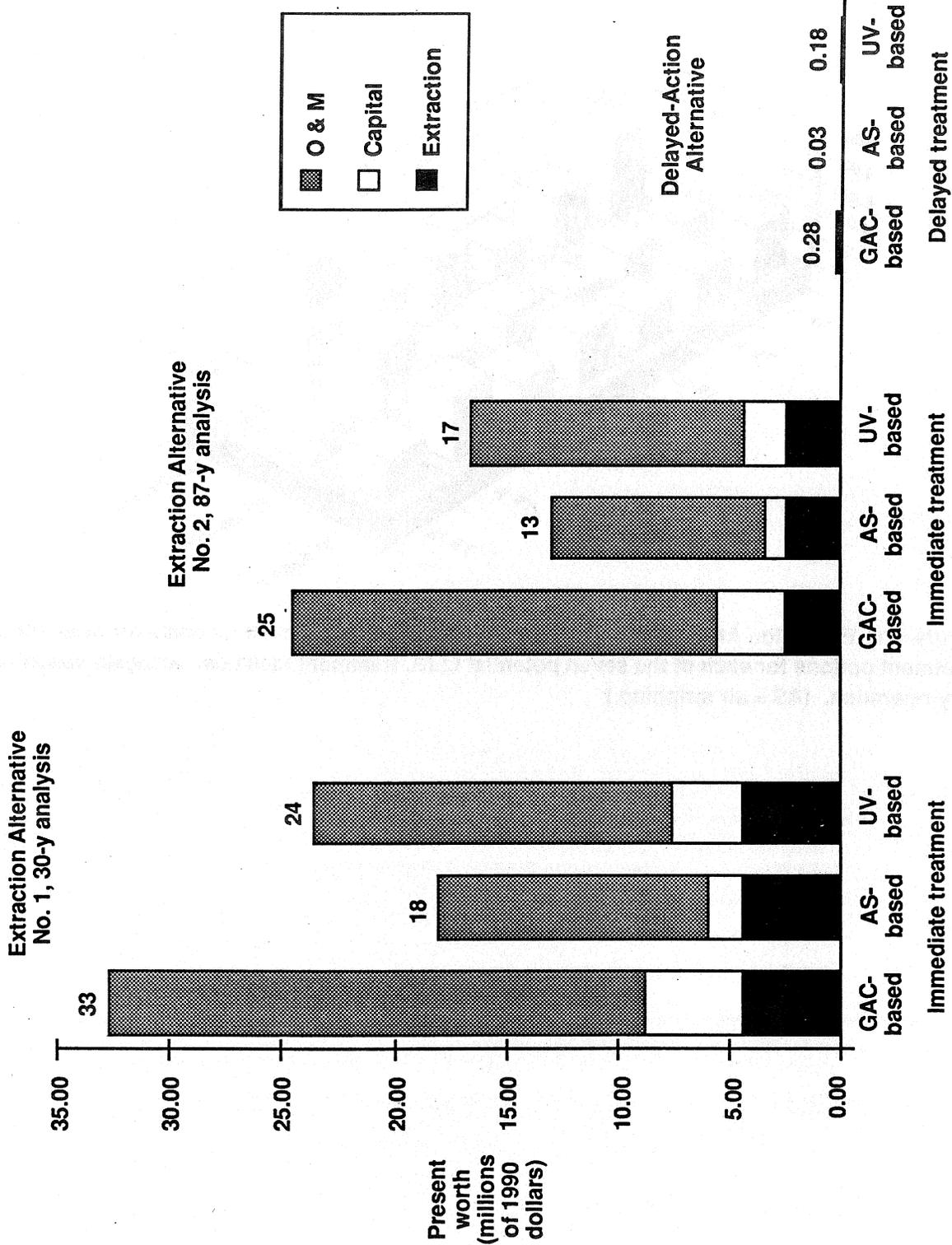


Figure 4-2. A comparison among ground water remedial alternatives for the LLNL Livermore site, assuming the same technologies for all treatment facilities (technologies will be chosen for each facility separately).

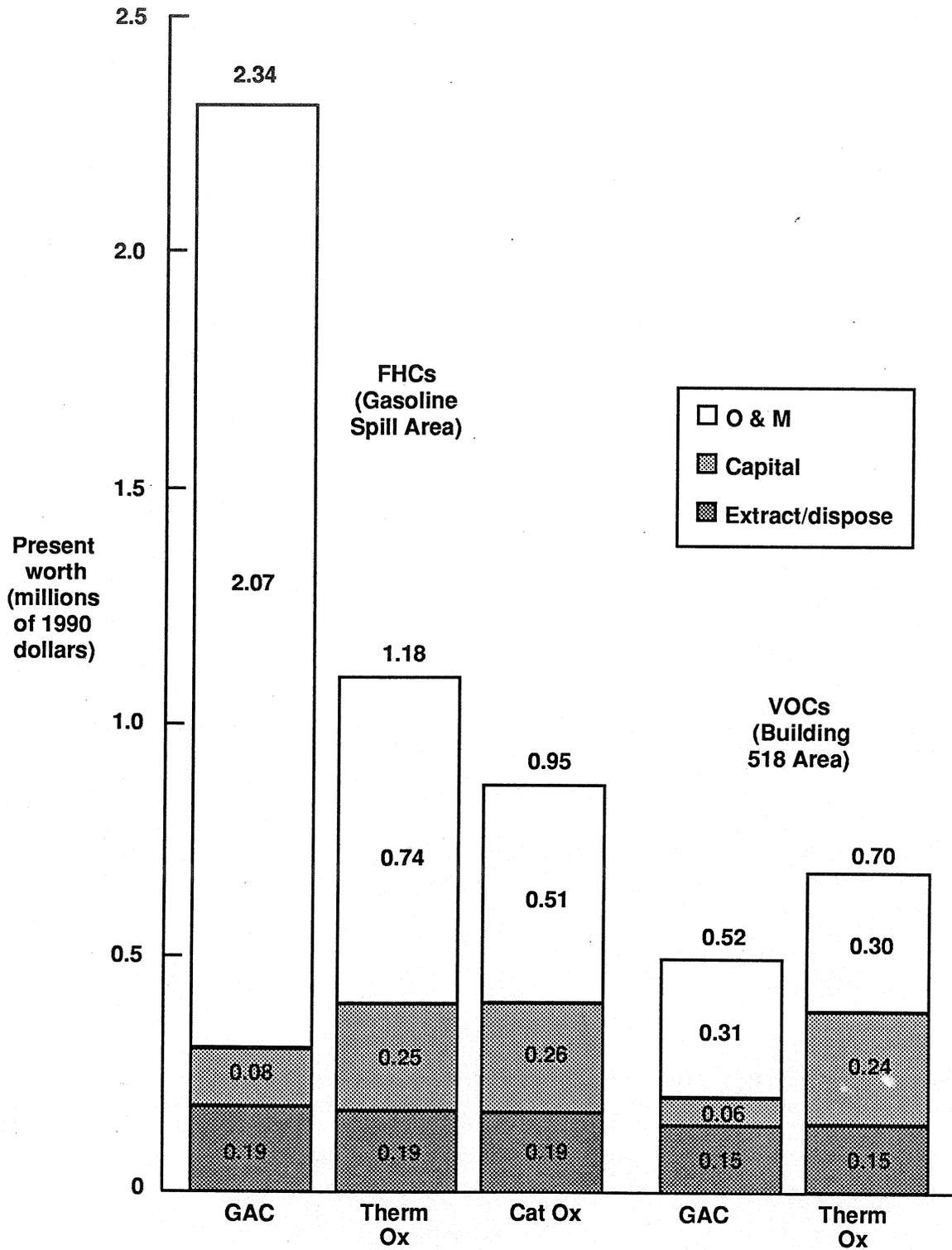


Figure 4-3. Vadose zone treatment options for FHCs and VOCs for the Livermore site.

## 5. ENVIRONMENTAL ASSESSMENT

### 5.1 . PURPOSE AND NEED FOR THE PROPOSED PROJECT

The evaluation of proposed remedial actions and subsequent performance of remediation are required under CERCLA. Each of the alternatives considered in detail is designed to restore environmental conditions as specified in the applicable laws and regulations, and described in Section 3.

This Section evaluates the potential for environmental impacts for each of the evaluated remedial alternatives and is provided to meet the requirements of the National Environmental Policy Act (NEPA). Some redundancies exist between the potential impacts discussed in this analysis and the potential impacts discussed in the analysis using the CERCLA evaluation criteria in Section 4. Section 5 presents an inclusive discussion of the potential environmental impacts to be taken into consideration when selecting a final alternative for site cleanup.

### 5.2. RELATIONSHIP OF THE PROPOSED REMEDIAL ALTERNATIVES TO OTHER ACTIVITIES AT LLNL

The LLNL Site Ground Water Project is closely tied to the proposed Drainage Retention Basin redevelopment project and to the construction of the improved drainage ditch that runs north along Vasco Road. The Drainage Retention Basin project involves lining the existing storm water basin so that infiltration of the collected storm water will not disperse contaminants or inhibit ground water remediation efforts in the East Traffic Circle Landfill Area of the LLNL site. Lining the basin will prevent infiltration, while at the same time creating a potential storage area for treated ground water. Retention of natural storm water and treated ground water will combine to form an artificial lake. The water stored in the retention basin could potentially be used for landscape irrigation at the LLNL site. The improved drainage ditch, newly constructed to accommodate runoff from western portions of the LLNL site in conjunction with widening Vasco Road, is proposed as the surface drainage to receive treated effluent from Treatment Facilities B and C.

### 5.3. SUMMARY OF LLNL ENVIRONMENTAL SETTING

A brief description of the LLNL site environmental setting is presented in this Section. As referenced in the following text, more detailed descriptions for many of the environmental setting categories can be found in the LLNL site Remedial Investigation (RI) Report (Thorpe *et al.*, 1990) or in Section 1 of this document.

#### 5.3.1. Location and Physiography

LLNL is located about 80 km (50 mi) east of San Francisco and approximately 3 mi east of the downtown area of Livermore, in the Livermore Valley in southern Alameda County (Figure 5-1). The site occupies approximately 800 ac and overlies a land surface of low relief that slopes approximately 1% from southeast to northwest. Elevations at the site range from a high of 675 ft (206 m) above sea level at the southeast corner of the site to a low of 570 ft (174 m) at the northwest corner. Slopes at the site generally do not exceed 3%, except for

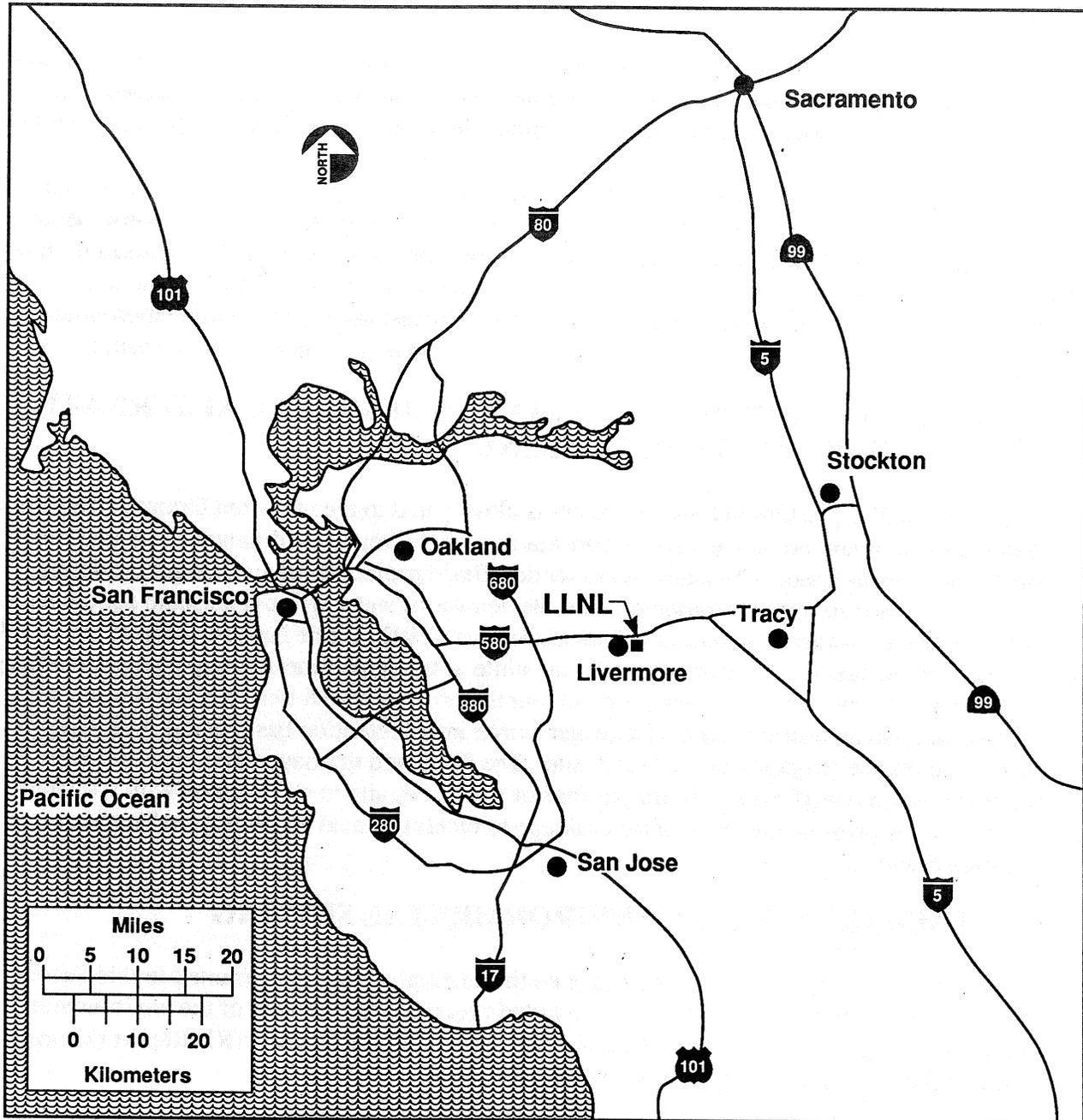


Figure 5-1. Regional setting of LLNL Livermore site (from Webster-Scholten and Hall, 1989).

stream banks on the sides of drainage ditches, which have an average slope of 50% (Carpenter *et al.*, 1984). Refer to Section 3.1 of the RI for a more detailed discussion.

### 5.3.2. Geology and Soils

LLNL is located in the central part of the Coast Range province of California. In the Livermore region, the Coast Ranges consist of north- to northwest-trending mountain ranges and valleys bounded by faults, as shown in Figure 5-2. Most of the faults in the region are north- to northwest-trending right-lateral strike-slip faults of the San Andreas Fault system. The Livermore Valley is an east-west topographic and structural depression that cuts across the predominant structural and physiographic grain of the region. The fault zones and geology of the Livermore site are shown in Figure 5-3.

Soils in the Livermore Valley are composed principally of alluvial material eroded from local hills and mountains. The region is within the Rincon-San Ysidro Association, which is characterized by nearly level, shallow-to-deep soils (U.S. Department of Agriculture, 1966).

At the Livermore site, the soils vary in texture from clayey to sandy loams or mixed gravels. The soils tend to be high in sodium, calcium, magnesium, iron, chlorine, and sulfur, and low in organic matter, nitrate, phosphates, and potassium.

Three soil series are found at the Livermore site. They are the San Ysidro Series, the Zamora Series, and the Rincon Series (Tonnessen and Tewes, 1982). The San Ysidro Series is found in the northeastern corner of the site, in and northeast of Arroyo Las Positas. It is a pale brown loam, which is hard when dry and plastic when wet. This type of soil has a low permeability. The Zamora Series soils, found in the southwest corner of the Livermore site, are well-drained, deep, loamy soils with relatively low permeability, found on nearly level flood plains. The Rincon Series, found in the central part of LLNL, is a loam with a brown surface and dark-brown subsurface. This soil has a high water-retention capacity. Figure 5-4 is a map depicting the soils present at the Livermore site and surrounding area. Refer to Section 3.4 of the RI Report for a detailed discussion of regional and local geology, and Section 3.5 of the RI Report for more detailed information on surficial soils.

### 5.3.3. Climate, Meteorology, and Air Quality

The climate of the Livermore Valley is characterized by mild, rainy winters and warm, dry summers. The mean annual temperature is 12.5°C (59°F). The normal seasonal temperature range is defined by nighttime winter lows in the vicinity of 0°C (32°F), and summer daytime highs around 38°C (100°F).

Prevailing winds are from the west and southwest from April through September; during the remainder of the year, wind directions are variable. The average annual rainfall is approximately 14 in. (36 cm) and occurs between October and April.

Measurements by the BAAQMD have determined that, for the years 1984 through 1986, the Livermore Valley region has met all ambient air quality standards except those for ozone, which were occasionally exceeded each year (BAAQMD, 1987).

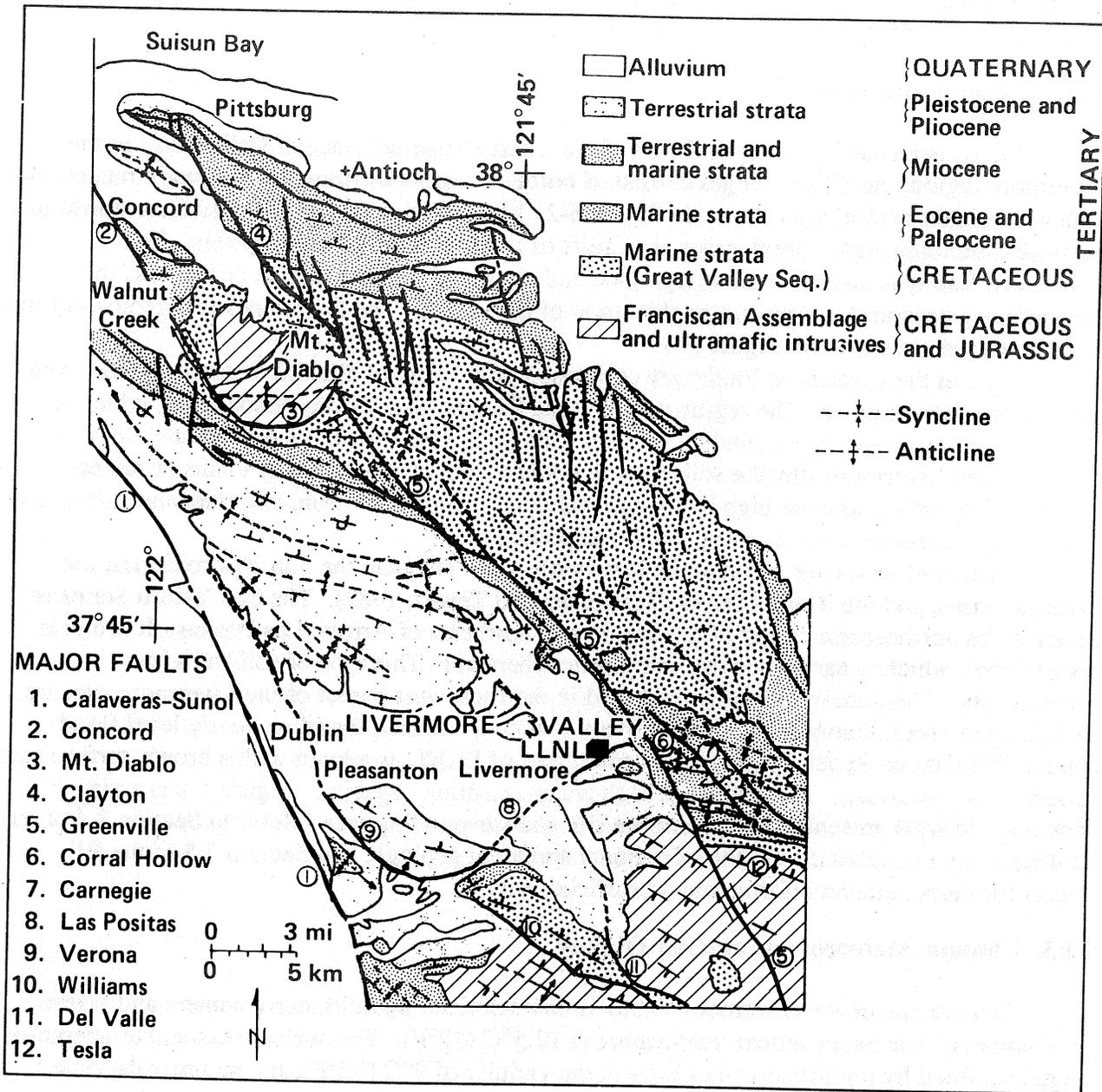


Figure 5-2. Major structural features of the Livermore and San Ramon Valleys (from Carpenter *et al.*, 1984).

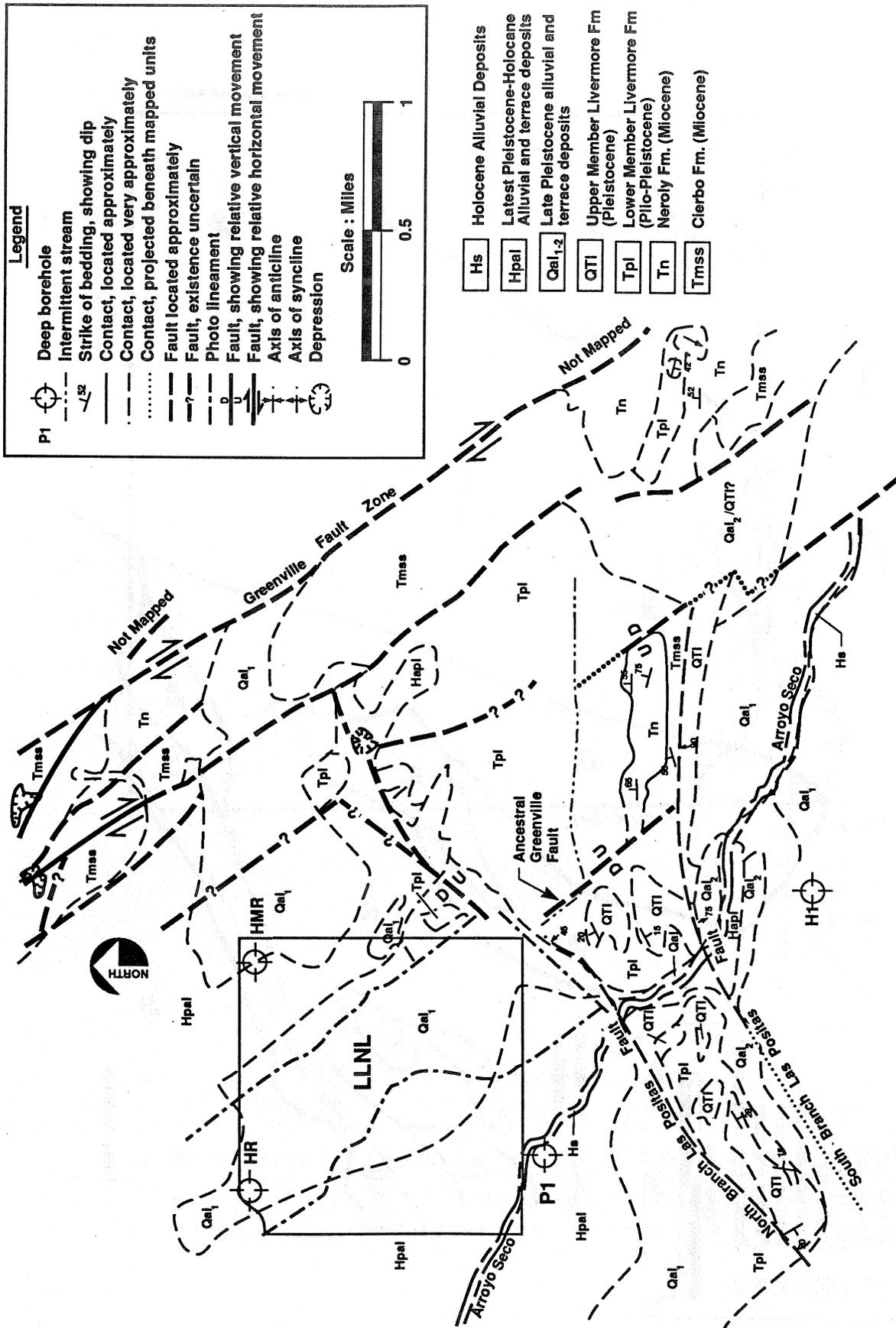


Figure 5-3. Geologic map of southeastern Livermore Valley (modified from Carpenter *et al.*, 1984).

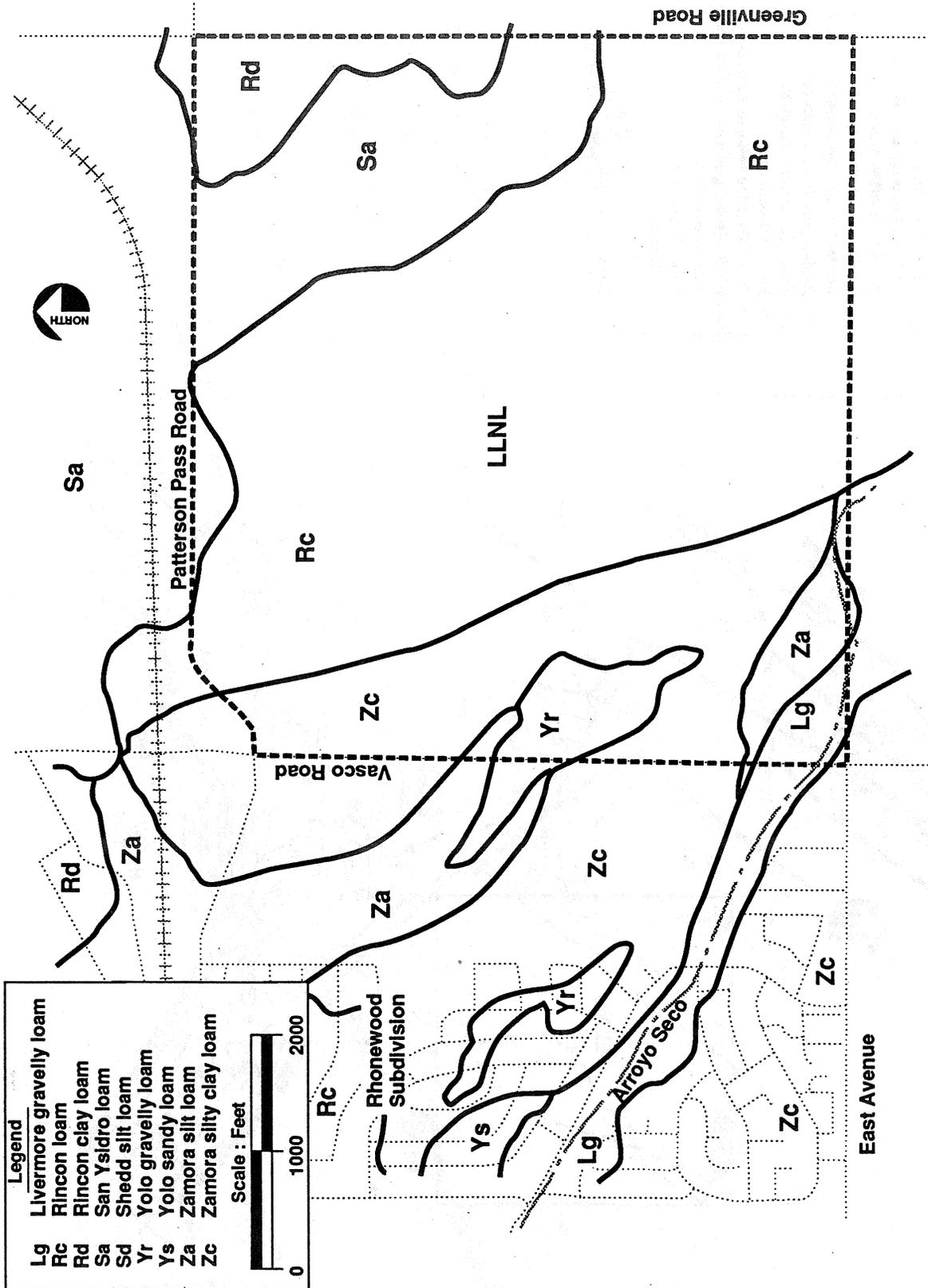


Figure 5-4. Soil distribution at the LLNL site and in the surrounding area (after USDA Soil Conservation Service, 1966).

The Livermore site is considered by the BAAQMD to be a single source for emission calculations, i.e., all facility emissions are cumulative. If the cumulative release of a regulated pollutant such as a nonprecursor organic compound (e.g., chlorofluorocarbons; 1,1,1-trichloroethane; and methylene chloride) exceeds a threshold of 25 tons/year, emission controls are required to minimize emissions from new sources. The Livermore site has exceeded the nonprecursor organic compound threshold and now uses Best Available Control Technology (BACT) to minimize emissions from new sources. Section 3.2 of the RI report provides more detailed information on the meteorology of the LLNL site.

#### 5.3.4. Surface Water Hydrology

The major drainages in the Livermore Valley are Arroyo Las Positas, Arroyo Mocho, Arroyo Seco, Cottonwood Creek, and Tassajara Creek (Figure 5-5). These streams are all intermittent, and flow gently to the west, with the exception of Tassajara and Cottonwood Creeks, which flow south. Only Arroyo Las Positas and Arroyo Seco cross the Livermore site. Arroyo Seco crosses the southwest corner of the Livermore site and receives a minor amount of site runoff. Arroyo Las Positas, which is dry most of the year, enters the Livermore site from the east and flows across the axis of the Valley and then in a generally westward direction. Arroyo Seco and Arroyo Las Positas merge in the west end of the valley to form the southward-flowing Arroyo de la Laguna, a tributary to the Alameda Creek drainage system.

Winter flows that have not been captured as ground water recharge flow out of the southwestern corner of the valley, eventually entering San Francisco Bay by way of Alameda Creek. Surface water bodies near the site include the South Bay Aqueduct, the treatment tanks and reservoir of the Patterson Pass water treatment facility, Lake Del Valle, Lake Isabel, and the lake at Shadow Cliffs Regional Park. LLNL normally receives its treated water supply from the Hetch Hetchy Aqueduct, which also supplies San Francisco.

Refer to Section 3.3 of the RI Report for more surface water hydrology information.

#### 5.3.5. Hydrogeology

The Livermore Valley has been divided into a series of ground water subbasins (State of California, 1974; Sorenson *et al.*, 1985). The Livermore site is located primarily within the Spring subbasin, with the southwestern corner located in the Mocho I subbasin. Within the Spring and Mocho I subbasins, ground water occurs in the valley-fill materials in unconfined conditions and in the underlying Livermore Formation under some degree of confinement (State of California, 1974; Sorenson *et al.*, 1985). The aquifers are locally recharged by percolation through the Valley alluvium and by infiltration via Altamont Creek, Arroyo Seco, and Arroyo Las Positas. Ground water below the Livermore site flows to the west or west-northwest (Thorpe *et al.*, 1990), as shown in Figure 5-6. This information agrees with an earlier California Department of Water Resources (1974) report on ground water resources in the Livermore Valley.

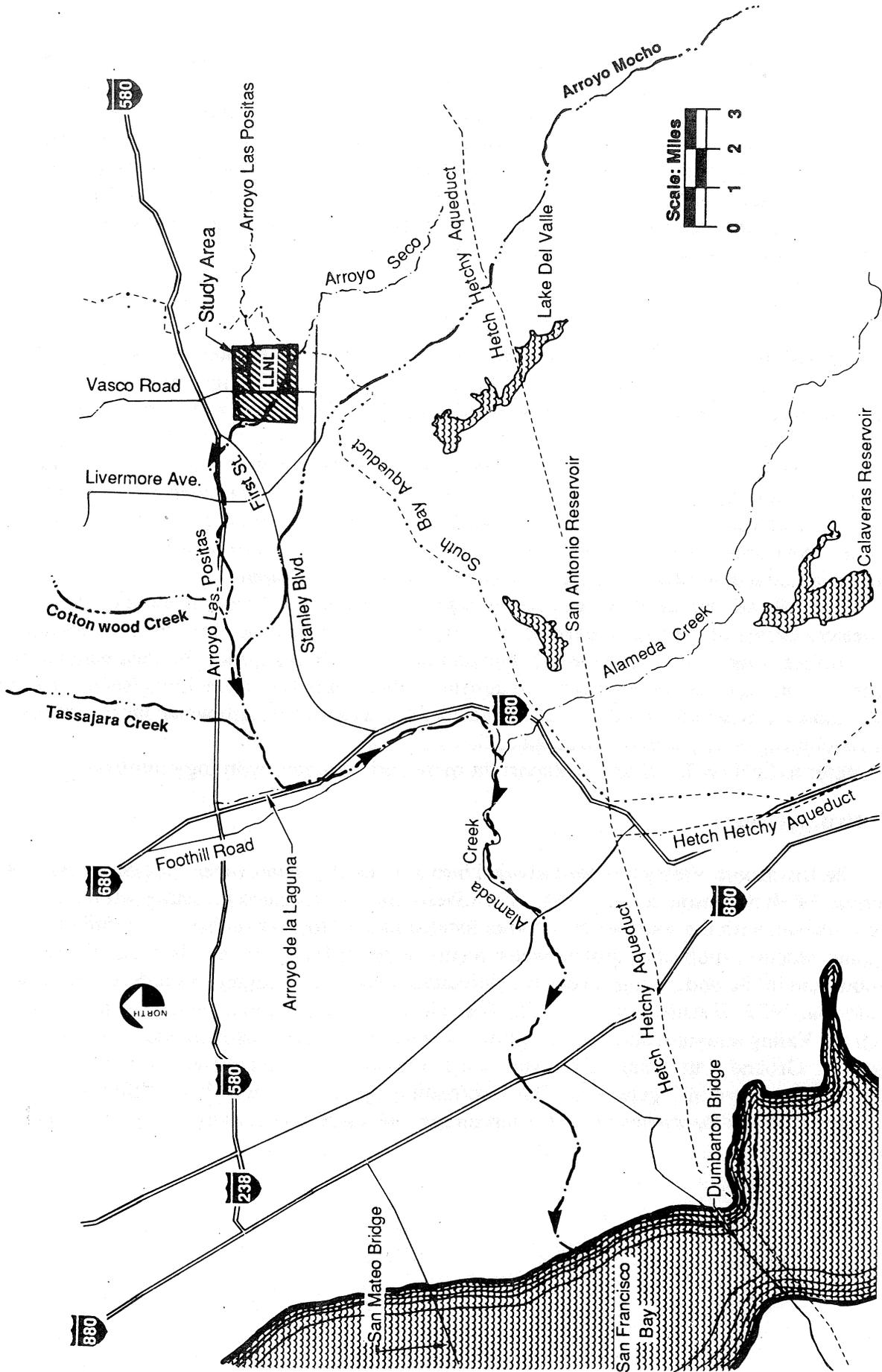


Figure 5-5. Map of Alameda Creek Watershed, showing relative location of LLNL ground water study area.

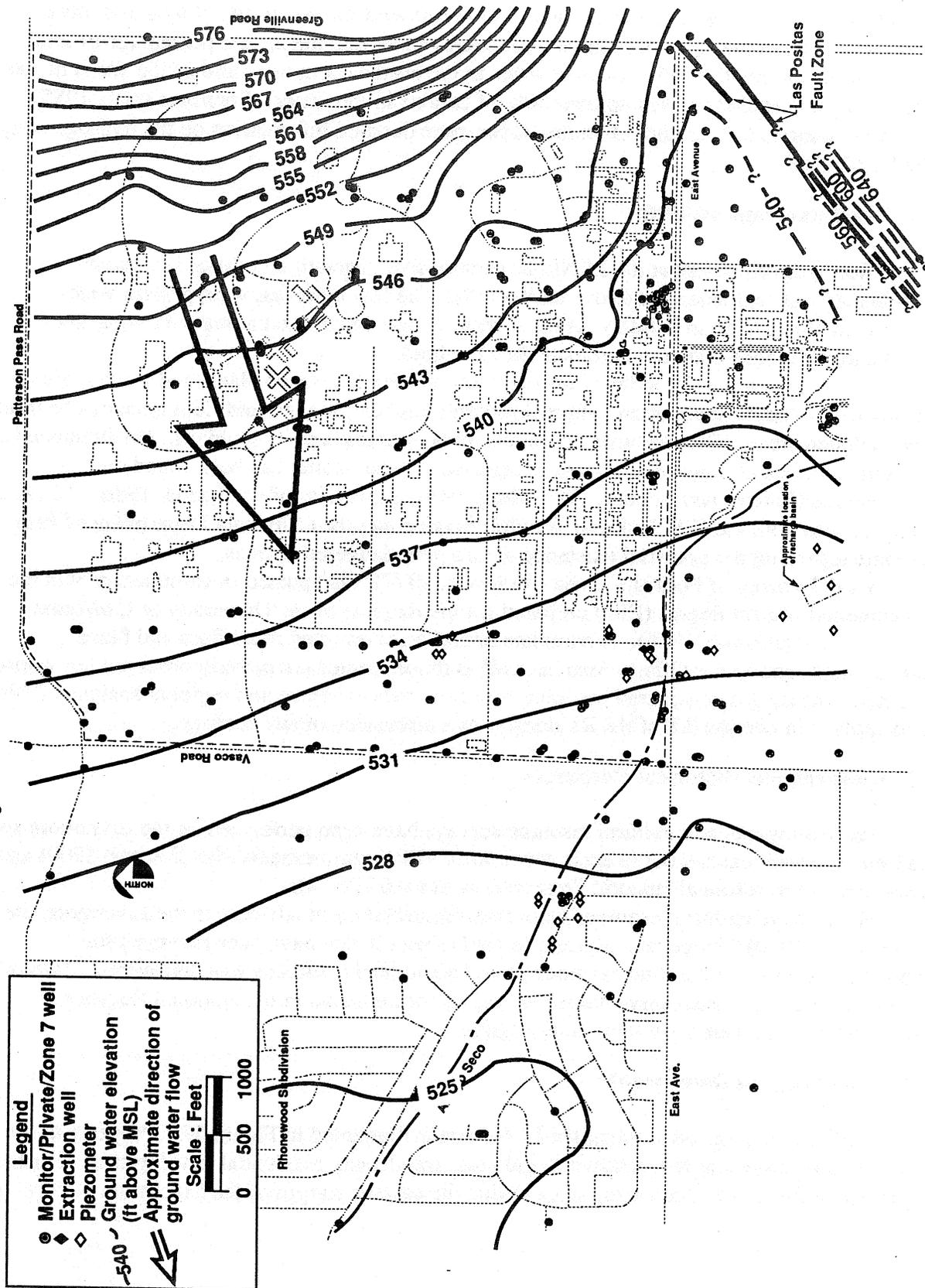


Figure 5-6. Ground water elevation contour map, March 1989, LLNL and vicinity.

Ground water quality in the Livermore Valley ranges from poor to excellent, with most in the good-to-excellent range. Ground water in the southwestern two-thirds of the Livermore site is of the sodium-calcium type (i.e., these two species constitute the largest percentage of total cations) (Sorenson *et al.*, 1985). Ground water in the northeastern one-third of the site is of the sodium type (i.e., sodium makes up over 50% of cations in the water) (Sorenson *et al.*, 1985).

See Sections 1.2.3.3 and 3.6 in the RI for more detailed information on the hydrogeology of the LLNL site.

### 5.3.6. Vegetation and Wildlife

Prior to development at the LLNL Livermore site, vegetation consisted of native California grasses that extended to the nearby hills. The few trees that were present were concentrated along riparian habitats. Annual wild oat was introduced along with nongrass annuals and perennials that now dominate the grassland.

Vegetation on the site today is made up of common landscape plants and weedy species. Jack rabbits are the most common mammal present; gophers, snakes, and field mice can be found in undeveloped areas. The site hosts numerous birds, reptiles, and amphibians. No threatened or endangered species of plant or animal or designated critical habitat has been found on the Livermore site (Leitner and Leitner, 1986; Bing, 1986; University of California, 1986). LLNL is consulting with both the U.S. Fish and Wildlife Service and the California Department of Fish and Game regarding the potential existence of rare or endangered species.

A 1977 survey of flora and fauna (McIntyre, 1977) was updated in conjunction with the Environmental Impact Report (EIR) prepared for the Regents of the University of California (University of California, 1986). A complete listing was compiled of all flora and fauna observed onsite and in the Offsite Area, as well as those species not directly observed but whose existence in the area is considered probable based on trace evidence and regional analysis. This listing appears in Section 3.8 of the RI along with a discussion of site ecology.

### 5.3.7. Cultural and Historical Resources

Archaeological and cultural resource surveys have been performed on the Livermore site. These surveys were carried out in accordance with NEPA requirements (40 CFR part 1500) and Section 106 of the National Historic Preservation Act (16 USC 4).

No sensitive cultural resources have been identified on or adjacent to the Livermore site (Thorpe *et al.*, 1990). Properties adjacent to the Livermore site have been surveyed for archaeological resources, and no evidence of archaeological resources was discovered. Two of the site buildings have been surveyed for eligibility for inclusion in the National Register of Historic Places, and were found not to be eligible.

### 5.3.8. Land Use and Demography

Land-use zoning surrounding the LLNL site is illustrated in Figure 5-7. Property to the east of the Livermore site is agricultural land with low-density residential development. Farther east, the foothills of the intercoastal range define the eastern margin of the Livermore Valley. A

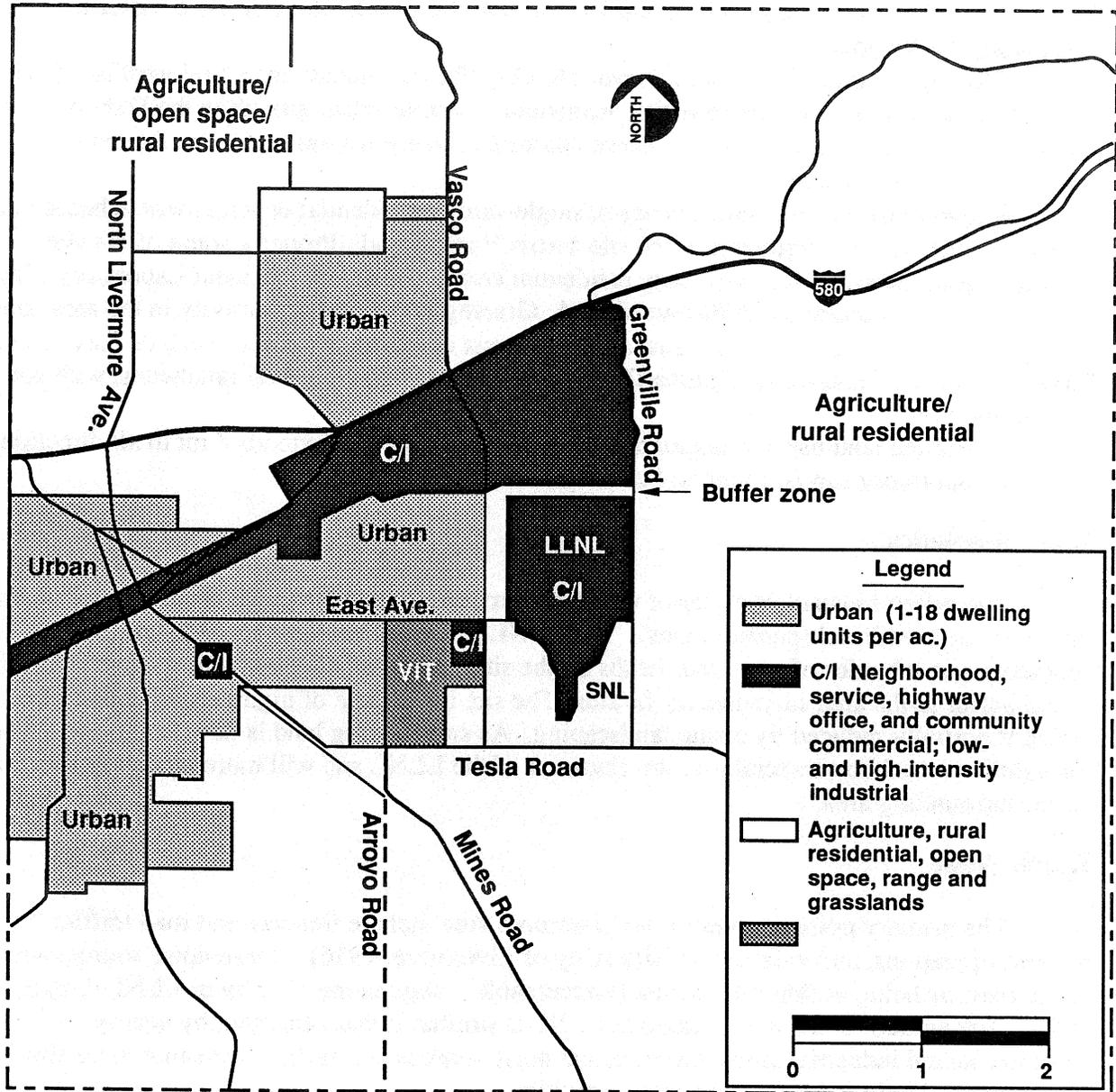


Figure 5-7. The LLNL demographic/land use study area and current land use.

287-ac parcel of open space and agricultural land northeast of the LLNL site has recently been rezoned to allow development of a center for heavy industry.

During the last 30 y, the City of Livermore has grown to the point where residential, industrial, and commercial development are occurring on parcels adjacent to the once isolated LLNL site. DOE has acquired additional land around the LLNL site to act as a buffer in preserving site security.

The population of Livermore is over 56,000. The city limits, once 3 mi west of LLNL, now reach the western and northern site perimeters. Despite urban growth in the Dublin-Pleasanton-Livermore area, most of eastern Alameda County is rural and is dominated by agriculture and open space.

A low-density (three units per acre), single-family residential development is being built adjacent to the western perimeter of the site across Vasco Road. Property south of the site includes agricultural areas, low-density residential areas, and Sandia National Laboratory (SNL), which is also surrounded by DOE-owned land. Grazing is the primary activity in the area south of the site, and orchards and vineyards are grown west of Vasco Road and south of East Avenue. Property south of Tesla Road is primarily open space scattered with rural ranchettes, with some agricultural use.

A detailed land use and demography study of the area that extends 4 mi in all directions from the Laboratory can be found in Section 3.7 of the RI.

### 5.3.9. Aesthetics

The general visual character of the area surrounding the LLNL site is a mixture of light industrial and semirural (pasture lands). The LLNL site itself has a highly industrial visual character with a border of trees and shrubs on the site perimeter. These plantings form a partial visual buffer to the area surrounding the site. The site is a source of nighttime light and glare, which is partially reduced by onsite landscaping. As surrounding land is developed, particularly for light industrial/commercial use, the character of the LLNL site will more closely match that of the surrounding area.

### 5.3.10. Noise

The primary noise sources in the Livermore area include freeway and road traffic, railroad operations, and aviation activity (City of Livermore, 1976). These noise sources are categorized as being within the "normally acceptable" range in the vicinity of LLNL (Ungo, 1986). The amount of noise generated at LLNL is similar to that generated by nearby commercial and industrial areas; the principal noise sources are traffic onsite and on nearby roads and occasional noises from construction activities.

## 5.4. POTENTIAL ENVIRONMENTAL IMPACTS OF THE PROPOSED REMEDIAL ALTERNATIVES ON THE ENVIRONMENT AND PROPOSED MITIGATION MEASURES

### 5.4.1. Impacts of Ground Water Contamination Remedial Alternatives

#### 5.4.1.1. Impacts of the No-Action Alternative

Under this alternative, no action would be employed to intercept and clean up the contaminated ground water plumes. This implies that the ground water extraction/treatment pilot scale activities now in progress at Treatment Units A and B would be discontinued, and the ground water monitoring would cease. A further description of this remedial alternative is presented in Section 3.3. The no-action response is not under serious consideration due to commitment by LLNL, DOE, and the University of California to remediating the hazardous materials in ground water released from the LLNL site. The no-action response is included, as a requirement of CERCLA and NEPA, and serves as a basis from which to develop and evaluate proactive remediation alternatives as well as the postulated basis of the BPHA. The no-action response would have no impacts on air quality, surface water, earth resources, biological resources, cultural resources, noise and traffic, natural resources, socioeconomics, or aesthetics, and there is no risk of upset.

**5.4.1.1.1. Human Health.** The public would be unlikely to be exposed to significant potential health hazards if the contaminated ground water plume were allowed to continue to migrate toward water supply wells. According to ground water models used in the RI, at an average ground water velocity of 70 ft/y, the closest water supply wells (municipal supply wells located in downtown Livermore, approximately 2 mi west of the plume's present location) would not be impacted for approximately 270 y. Under the "best estimate" case, consisting of private and municipal wells as receptors and the most probable hydrogeologic, chemical, and source parameters, the maximum cancer risk associated with the best-estimate case for the combined 70-y maximum exposure to VOCs at a municipal supply well in downtown Livermore is calculated to be  $2 \times 10^{-7}$  (an additional 2 in 10 million chance of developing cancer over a lifetime of exposure). This is well within what is considered "acceptable health risk" ( $10^{-4}$  to  $10^{-6}$ ) by EPA. It should be stressed that even these risks would not begin to occur for over 200 y, and no members of the public are currently exposed to VOCs derived from the use of wells near the LLNL site.

**5.4.1.1.2. Ground Water.** Continued degradation of the Livermore area ground water would occur as the plume(s) continue to migrate. This could inhibit future beneficial uses of increasingly greater portions of the aquifer. Over time, reduction in chemical concentrations would occur by natural attenuation processes, including biodegradation, dispersion, and abiotic degradation. Assuming a 50-y half-life, that no new contamination sources contribute chemicals to the ground water, and no action is taken to clean up the ground water, the maximum concentration after 270 y is predicted to be 1.5 ppb total VOCs in ground water.

**5.4.1.1.3. Socioeconomic Impacts.** If contaminated ground water were to reach municipal wells, economic impacts associated with the loss of a valuable water resource would result to water consumers. Municipalities now supplying water pumped from municipal wells to

its constituents would be forced either to treat the contaminated water source or purchase water from other sources, thus resulting in increased water costs. This would certainly not be of concern in the foreseeable future, in that the RI estimates the plume will not reach supply wells for 270 y and that by the time it did, it is likely that the contaminants would naturally degrade and diffuse to concentrations below drinking water standards.

#### 5.4.1.2. Impacts of the Immediate-Action Alternatives—Pump and Treat

These alternatives include ground water monitoring and ground water extraction and treatment for:

1. VOCs and FHCs via air stripping, GAC treatment of the liquid phase, and/or UV/oxidation of the liquid phase.
2. FHCs and organic lead (if necessary) via air stripping, GAC treatment of the liquid phase and/or UV/oxidation of the liquid phase, or *in situ* biodegradation.
3. Treatment of chromium (if necessary) via ion exchange.

Because the potential impacts are similar for both pump and treat options, they are discussed together. Treated water would be disposed of in the recharge basin, the retention basin (where a portion would likely be used for irrigation), recharge wells, or surface drainages, or otherwise be beneficially used onsite.

All pump and treat strategies require:

1. The drilling and completion of extraction wells and construction of pipelines and treatment facilities either on the LLNL site or offsite.
2. The extraction of ground water.
3. The treatment of the ground water to meet ARARs.
4. The appropriately permitted disposal of treated water to recharge basins, the retention basin, recharge wells, or surface drainages.

The two pump and treat remediation scenarios are described in Section 3.4.1, with treatment facility and extraction well locations shown on Figure 3-7. No. 2 employs Treatment Facilities A, B, C, and F, which provide hydraulic control over the ground water containing VOCs and FSCs. Alternative No. 1 adds Treatment Facilities D, E, and G, and will employ at least 18 extraction wells to shorten the time required for remediation. Treatment and extraction facilities can be made similar in physical appearance, with the exception of the height requirements of air stripping towers. That is, other treatment system components can be placed in a small building.

- Treatment Facility A (TFA). At least three extraction wells will supply water to TFA. To keep all treatment facilities on DOE property, extracted ground water from the offsite Rhonewood Subdivision area, west of LLNL, will be piped along the north side of Arroyo Seco to TFA. The pipe will be buried, double-contained, and have a leak-detection system. Total treated ground water flows of approximately 150 gpm will be discharged to the existing recharge basin located south of LLNL.
- Treatment Facility B (TFB). At least four extraction wells will supply water to TFB. Total treated ground water flows of approximately 50 gpm will be discharged to the partially unlined ditch that runs north along Vasco Road and flows into Arroyo Las Positas.
- Treatment Facility C (TFC). At least two extraction wells will supply water to TFC. Total treated ground water flows of approximately 20 gpm will be discharged to the partially unlined ditch that runs north along Vasco Road and flows into Arroyo Las Positas.

- Treatment Facility D (TFD). At least three extraction wells will supply water to TFD. Total treated ground water flows of approximately 30 gpm will be discharged to the Drainage Retention Basin. Water flowing into the Drainage Retention Basin will either be used for site irrigation or will be discharged to Arroyo Las Positas.
- Treatment Facility E (TFE). At least two extraction wells will supply water to TFE. Total treated ground water flows of approximately 30 gpm will be discharged to the Drainage Retention Basin.
- Treatment Facility F (TFF). At least two extraction wells will supply water to TFF. Total treated ground water flows of approximately 30 gpm will be discharged either to recharge wells or to the Drainage Retention Basin.
- Treatment Facility G (TFG). At least two extraction wells will supply water to TFG. Total treated ground water flows of approximately 50 gpm will be discharged to either recharge wells or the Drainage Retention Basin.

The suites of compounds in the ground water fall into three categories. The first includes a variety of VOCs. Extraction wells will be used to feed influent water containing only VOCs to TFA, TFB, TFC, TFE, and TFG (Figure 3-7). Extraction wells feeding influent to TFD, could also contain chromium. The extraction wells in the Gasoline Spill Area, which feed influent water to TFF, will carry VOCs, FHCs, and, possibly, lead.

Hazardous wastes could be generated from some of the water remediation technologies employed. These wastes would be in the form of:

- Spent activated carbon from activated carbon treatment of the liquid phase.
- Spent activated carbon from vapor-phase air scrubbers.
- Petroleum waste separated by skimming free product at the Gasoline Spill Area.
- Ion-exchange resins and resin regeneration solutions.

Except for skimmed free product, only a few pounds of these materials will be generated per year. These (including any free product recovered) will be either recycled or disposed of (regenerated) offsite in a permitted waste disposal facility. The spent GAC may be thermally regenerated by heating the carbon in a natural gas-fired furnace. After regeneration, the GAC is no longer considered a hazardous waste.

**5.4.1.2.1. Human Health.** No adverse impacts to human health would occur as a result of these alternatives. Human consumption of ground water containing contaminants would not occur because the plumes would be intercepted and cleaned up before they reached water-supply wells. Emissions of hydrocarbons to the air would result in air concentrations far below health-based and environmental regulatory standards (less than 1 lb/day, satisfying the conditions of BAAQMD Regulation 8: Organic Compounds Rule 47, Air Stripping and Soil Vapor Extraction Operations, 8-47-402).

**5.4.1.2.2. Ground Water.** The ground water plume will be intercepted and cleaned up to health-based ARARs, eventually allowing beneficial use of those areas where ground water is already affected and preventing loss of beneficial uses elsewhere that would have been degraded if no action had been taken.

Extraction of ground water will cause local aquifer drawdown in the area surrounding the extraction wells. Because the methods of disposal of treated water will return a significant fraction of the treated ground water through recharge (recharge basins and wells, stream channels, or landscape irrigation) and no water supply wells are currently located in the remediation areas, no significant impacts on water supply wells are anticipated.

**5.4.1.2.3. Risk of Upset.** There is the potential for release of hydrogen peroxide from storage tanks and untreated ground water from pipelines located at or near treatment facilities. Adequate secondary containment (350-gal capacity for a 200-gal tank) will be provided for the hydrogen peroxide storage facilities, virtually eliminating chances for release to the environment. Potential release of untreated ground water to the environment is minimized by providing double-walled pipelines with leak detection systems wherever the pipeline is buried, and regular inspections of aboveground piping. If release of untreated ground water to the environment did occur, it would not present serious impacts to human health or the environment due to the low concentrations (<1 ppm) of the contaminants in the water. Most of the VOCs would vaporize upon contact with air. Emission levels would not be a health problem for short-term exposure during repair, and the water would evaporate or infiltrate back into the ground.

Eyewash and other safety equipment as required by OSHA will be supplied to mitigate potential human health hazards, e.g., associated with an accidental release of hydrogen peroxide at treatment facilities.

As discussed earlier in this report, TFD may be outfitted with an ion-exchange system to remove chromium. Regeneration of the system's resin bed would be performed *in situ* with basic and/or acid solutions. If a base is required, the most likely choice would be sodium hydroxide in solution. This form would be most convenient for handling, because burn hazards to personnel would be minimized. If an acid solution were required, sulfuric acid would probably be chosen. This solution would be doubly contained, and personnel would be required to wear the proper protective clothing during handling. Because of the low concentration of chromium, we anticipate that the frequency of resin bed regeneration would be low and the amounts of acid or base onsite would be small. Any rinsate containing chromium would be handled as a hazardous waste and properly stored in a waste accumulation area until disposed of by LLNL's Hazardous Waste Management Division.

Similarly, TFF could be outfitted with GAC to remove lead. Any carbon containing lead, once loaded, would be handled and disposed of as a hazardous material per the appropriate handling procedures.

**5.4.1.2.4. Air Quality.** Air emissions may occur from ground water extraction, piping, and treatment facilities. All systems, i.e., "pump and treat" and vacuum extraction (Section 5.4.2), would be designed to ensure that the release of total hydrocarbons to air from the LLNL Ground Water Project would not exceed 1 lb/day and that no risk to workers and/or the public would occur. Hydrocarbon air emissions would be limited either administratively (i.e., quantitative treatment limits would be set) or by technical control with best available technology (activated carbon). This would result in air pollutant concentrations in the atmosphere far below any health-based or environmental regulatory standards. The LLNL Ground Water Project has an expressed goal of limiting air emissions to below measurable quantities (nondetectable for VOCs). To keep VOC air emissions within the 1 lb/day limit, emission control will be accomplished either administratively (limiting the amount of water to be treated) or with best available technology (most likely with carbon adsorption units for VOCs, or thermal or catalytic oxidizers for FHCs).

During construction of treatment facilities and pipelines, disruption of the soil could generate dust. Standard dust control techniques, such as watering, would be employed when necessary.

**5.4.1.2.5. Surface Water.** Treated ground water will be discharged to the existing recharge basin or onsite cooling towers (an estimated 150 gpm from TFA), to the partially

unlined ditch that runs north along Vasco Road to the Arroyo Las Positas (an estimated 70 gpm from TFB and TFC), and to the Drainage Retention Basin (an estimated 140 gpm from TFD and TFE, and possibly TFF and TFG) where some of it may be used for irrigation or for cooling tower makeup water, and the remainder will be discharged to Arroyo Las Positas. Figure 3-9 shows the treatment facilities and points of surface discharge. These flows could be less, depending on whether recharge wells are employed.

The discharge of treated ground water from TFA to the existing recharge basin north of LLNL is designed to allow as much water as possible to return to the affected ground water subbasin (Mocho I), while avoiding interference with ground water capture. We anticipate that most of the treated water discharged from TFB and TFC into the unlined ditch along Vasco Road will infiltrate into the ground before reaching the Arroyo Las Positas. However, some of this water may reach the Arroyo, particularly during the winter months and certainly during wet weather flow.

The retention basin is designed to store treated ground water and storm water runoff. Much of this water will likely be used in onsite cooling towers or for site irrigation. An undetermined amount of retention basin overflow will be released downstream into the Arroyo Las Positas, resulting in increased volumes of surface runoff. If irrigation or other onsite uses are not employed, this flow could be as much as 140 gpm. Such a flow could expand wetlands within the arroyo channel downstream from LLNL.

This increased runoff could result in near perennial flow in a stream that is now intermittent, as well as increased year-round flow volumes. Because of treatment plant downtime and other onsite uses of treated water, flows will not be continuous. The consequent intermittent drying of the Arroyo channel will likely preclude any establishment of fish populations. Experience indicates that most of the increased flow will infiltrate into the unlined channel of the Arroyo, contributing to ground water recharge. The channel is located in a region of uncontaminated ground water where infiltration would be beneficial in maintaining ground water storage. Both discharges into the Arroyo Las Positas (retention basin overflow and flow from the unlined ditch) will be closely monitored by LLNL to determine if the increased flows result in significant contributions of surface water to the Arroyo.

Water will be tested before release to surface water or use as prescribed for the LLNL site by National Pollution Discharge Elimination System (NPDES) permit (No. CA0029289) and State of California Regional Water Quality Control Board (RWQCB) Waste Discharge Requirements to assure quality levels and, therefore, would not be chemically harmful to the downstream environment or ground water resources. There is concern that the ground water may contain slightly elevated levels of boron, as do the natural ground waters of the region and as evidenced by boron levels as high as 2.5 ppm in one well in the area of proposed remediation (Thorpe *et al.*, 1990). High levels of boron can be toxic to vegetation and aquatic life, although no Federal criteria for protection of aquatic life have been adopted for boron. The current NPDES permit for TFA, TFB, and Gasoline Spill Area discharges stipulates an allowable boron concentration of 7.0 ppm. Use of treated ground water for irrigation and perhaps for release to downstream habitats may require some dilution of salts. By mixing treated ground water with runoff water, and perhaps Hetch Hetchy Reservoir water when necessary, hardness and boron will be maintained at levels suited to supporting aquatic life, irrigation, and other purposes that will not be harmful to downstream habitats.

Although unlikely because of the anticipated small flows, increased sediment loading caused by soil erosion is a potentially adverse impact. If close visual monitoring shows that

significant flows are occurring in Arroyo Las Positas, stream gauging stations will be constructed to allow the surface discharges and recharge volumes to be adequately estimated. The stations could also help locate the proper sites for downgradient sediment traps (if necessary) that would control erosion and loss of sediment to drainageways and streams, thereby preventing water quality deterioration and channel erosion.

The Alameda County Flood Control and Conservation District, Zone 7, maintains maps of flood plains in the county surrounding LLNL. These have been reviewed, and we note that no flood plains have been identified in any areas of proposed treatment facilities or extraction wells. In the event of impending flood conditions, treatment facilities would be shut down to preclude exacerbation of high water levels.

**5.4.1.2.6. Earth Resources.** Construction-related disruption of the soil will occur during construction of treatment facilities, pipelines, and monitor or extraction wells. This could result in short-term increased wind and water erosion. Disturbed areas will be revegetated to match the condition prior to construction to prevent erosion and negative visual impacts.

**5.4.1.2.7. Biological Resources.** Freshwater discharges into Arroyo Las Positas may impact certain biota that occupy downstream wetland habitats. A biological field survey was conducted on May 9, 1990, by Biosystems Analysis, Inc., to assess the potential biological and botanical impacts of potential freshwater discharges into Arroyo Las Positas. The onsite channel of Arroyo Las Positas was surveyed, with special attention given to the presence of sensitive species. The survey found no sensitive plant or wildlife species along the stream channel. It also determined that no habitat suitable to support rare plants exists within the project vicinity.

A marginal potential habitat for the tiger salamander (*Ambystoma rigrinum californiense*) and red-legged frog (*Rana aurora*), two Federal candidate species of special concern, exists along the westernmost portion of Arroyo Las Positas. This habitat consists of minor sections of aquatic vegetation and standing water found primarily where culverts discharge small volumes of water to the creek. Pacific tree frogs (*Hyla regilla*) were found in one ponded area (both tadpoles and adults). The portion of Arroyo Las Positas immediately downstream of the LLNL site was visually inspected and found to be a poor-quality habitat due to its disturbed condition (e.g., channelization, rock rip rap on the side slopes, and possible vegetation maintenance).

The overall impacts of any potential release of water into the Arroyo Las Positas should be beneficial to both plants and wildlife as long as the treated water is of good quality for aquatic plants and animals. It is not likely that significant flows will reach the Arroyo from TFB and TFC because most of the water is expected to infiltrate before reaching the Arroyo. As mentioned in the surface water impacts section, this water may contain somewhat elevated levels of boron, as do the natural ground waters of the region. Neither water quality data nor hydrologic flow/infiltration data regarding TFB and TFC will be fully known until the systems become operational. Discharged water will probably reach the Arroyo Las Positas only during wet weather flows. If so, the water would likely be well-diluted naturally by the time it reached the Arroyo. Hence, potential negative impacts to plants and animals inhabiting Arroyo Las Positas would not occur.

Flows will be discharged to the onsite section of Arroyo Las Positas from TFD and TFE, and possibly TFF and TFG, via the retention basin. The amount of flow depends on whether the treated water is used for irrigation or other onsite uses. As mentioned in the surface water impacts section, a maximum of 140 gpm (without any onsite use) would be discharged into the Arroyo year-round and much of this total is expected to infiltrate into the stream bed before leaving the site. During winter, and particularly during wet weather, infiltration into the stream

beds would be greatly inhibited. If a high concentration of boron is encountered and discharged undiluted, boron could be above levels tolerable to downstream plants and animals. Even so, waters discharged to any channel entering Arroyo Las Positas will meet discharge requirements of the NPDES permit, which includes standards on boron. Hence, no negative impacts are anticipated to plants and animals inhabiting Arroyo Las Positas. If dilution of the extracted ground water proves necessary to reduce boron concentrations for onsite irrigation, this dilution would be carefully monitored. LLNL will monitor closely all flows to Arroyo Las Positas and is prepared to implement alternative disposal options if any situation arises which could result in potentially significant impacts on resident plants or animals.

If new perennial flows are created, the riparian components of Arroyo Las Positas will likely be increased. An increase in the diversity of species and numbers of individuals within species may occur. If flows are not too swift, the tiger salamander and red-legged frog could inhabit the Arroyo. There are known populations of these species within a mile of LLNL. If flows were to become perennial, fish could be introduced naturally and possibly become established in the Arroyo. However, exigencies of operating treatment systems and opportunities to beneficially use treated water onsite will no doubt result in intermittent flows, at most, in the Arroyo Las Positas channel. Tricolored blackbirds (*Agelaius tricolor*), a Federal candidate species, may nest in this area if cattails substantially increase in density.

Adverse impacts to newly established biota, should they exist, may occur upon discontinuance of the ground water remediation activities and, thus, surface water flows. LLNL will monitor by field investigation (annual surveys) the establishment of riparian vegetation and possible colonization by sensitive species. Routine flood control maintenance activities, such as keeping the stream channel free of blockage and riparian vegetation, would likely inhibit colonization by sensitive species.

A suggested biotic monitoring program would include monitoring changes in vegetation and faunal components of Arroyo Las Positas that may occur as a result of added water to the drainage. Monitoring of changes in riparian vegetation would involve:

1. Determination of the extent of riparian vegetation on false-color infrared aerial photographs at 5-y intervals throughout the project lifespan.
2. Characterization of vegetation conditions in the affected stream reaches (including estimation of cover by species) at 5-y intervals throughout the project lifespan.
3. Photography from easily relocated points (e.g., every 100 ft down Arroyo Las Positas) at 5-y intervals throughout the project lifespan.

Monitoring of changes in wildlife would involve:

1. Biannual (one wet season, one dry season) visits to Arroyo Las Positas by a wildlife biologist who will walk the drainage until it leaves LLNL property, recording all species observed; special attention would be given to locating sensitive species.
2. Seining surveys of the creek in the spring during the wet season for larvae of sensitive amphibian species (provided there is enough water in the creek to seine).
3. Photography from easily relocated points, taken on each biannual survey (e.g., every 100 ft down Arroyo Las Positas).

Baseline data would be collected prior to any ground water release using the same methods described above. This monitoring program can easily be combined with monitoring suggested for the retention basin development project.

**5.4.1.2.8. Cultural Resources.** Archaeological surveys have been conducted onsite (DOE, 1982) and in the area where TFA is located, i.e., the area east of Vasco Road and south of

Mesquite Way (DOE, 1984). On May 25, 1990, an archaeological survey was also conducted at the offsite area of the proposed ground water pumping facility pipeline and at TFB. Surveys were carried out in accordance with the requirements of NEPA and Section 106 of the National Historic Preservation Act (NHPA). No significant resources were recorded as a result of any of the surveys. Before construction of facilities in an area that has not been surveyed, an archaeological survey would be performed.

**5.4.1.2.9. Noise and Traffic.** During construction of treatment facilities, extraction wells, and pipelines, there will be a short-term increase in noise levels due to standard construction practices. There may also be some disruption of traffic patterns both on the Livermore site and on adjacent roads during construction. Construction will be planned so as to minimize traffic impacts. These impacts will be short-term and are not considered significant.

The blowers at the treatment facilities generate noise [up to 85 dba, the Occupational Safety and Health Administration (OSHA) permissible exposure limit] in the immediate vicinity. They will be housed in buildings or otherwise muffled to reduce the noise, reducing the level to about 50 dba.

**5.4.1.2.10. Natural Resources/Energy.** Ground water, a valuable resource in the arid region of California in which LLNL is located, will be cleaned up and reclaimed as a result of the proposed project. The project will also prevent further compromise of ground water resources.

The UV/hydrogen peroxide treatment process is energy intensive. Each treatment system uses about 100 kW. However, energy use and its resultant use of fossil fuels, a nonrenewable resource, during the course of the cleanup activities is not considered significant.

**5.4.1.2.11. Socioeconomic Impacts.** Implementation of the restoration project would result in the short-term (construction related, 60 days or less) employment of a maximum of 30 workers, and in the long-term (up to 50 y, the time required for the completion of the project) employment of a maximum of 20 workers. The regional employment base is approximately 30,000 (from the city of Livermore), so this project should result in no significant short-term or long-term impacts on the local labor force, social structure, or economic base.

**5.4.1.2.12. Aesthetics.** There is concern that TFA and TFB maintain an inoffensive appearance, as they are exposed to public view from Vasco Road. To mitigate offensive visual impacts, the number of new separate structures will be minimized, one style of architecture and color scheme will be employed, and screen fences or walls will be used when necessary. Size and height of all required structures will also be kept to a minimum. Air strippers would, by necessity, be about 25 ft in height.

**5.4.1.2.13. Cumulative Impacts.** Each of the impacts considered separately above has some minor cumulative effect, because of its being added to an already industrialized site. The pump and treat options add no measurable contaminants to either the air or surface waters. However, water discharges add to existing flows in storm drains; even the combined effect is unlikely to sustain continuous flow in arroyo channels. We do not consider contributions to noise, energy consumption, and socioeconomic impacts significant.

#### **5.4.1.3. Impacts of the Deferred-Action Alternative—Administrative Controls, Ground Water Monitoring, and Treatment at the Point of Use, if Necessary**

This alternative would not attempt to intercept and clean up the plume, but would rely on the following:

1. Implementation of institutional/administrative controls through local water agencies (e.g., permit restrictions, land use restrictions) to prevent well drilling and ground water usage in affected areas.
2. Ground water monitoring to track the plume to ensure that ground water posing any health concern is not consumed. This monitoring would continue indefinitely until the physical and chemical processes of dilution, adsorption, dispersion, and degradation reduce the concentrations of VOCs to insignificant levels or until monitoring demonstrates that further action is required.
3. Where domestic drinking water is imminently threatened, if ever, an alternative drinking water source (bottled water or municipal drinking water) would be supplied. If VOCs in concentrations representing a significant health risk were to reach an in-use municipal, domestic, or agricultural supply well, LLNL would either install a point-of-use treatment system or contract for the supply of alternative water to the affected user. No more than five wells would be affected, and most likely none will be affected.

A detailed description of the Deferred-Action Alternative is presented in Section 3.3.4. The Deferred-Action Alternative would have no impacts on surface water, earth resources, biological resources, noise and traffic, or natural resources, and has no risk of upset.

**5.4.1.3.1. Human Health.** No negative impacts on human health would occur, because monitoring, administrative control, and supply of alternative water sources would prevent public exposure to the ground water contaminants.

Hazardous waste in the form of soil cuttings may be generated from the drilling and installation of monitor wells. Cuttings would be characterized, and approved Standard Operating Procedures would be followed for their disposal.

**5.4.1.3.2. Ground Water.** As with the No-Action Alternative, increasingly larger portions of the Livermore area ground water would become affected as the plume migrates and expands, inhibiting the beneficial uses of the local ground water. Over time, reduction in chemical concentrations would occur by natural attenuation processes, including biodegradation, dispersion, and abiotic degradation.

**5.4.1.3.3. Air Quality.** Drilling and installation of monitor wells may result in temporary VOC air emissions and dust. However, emissions would be at extremely low levels (<1 ppm) and short-term, and thus are not considered to be significant.

**5.4.1.3.4. Noise and Traffic.** Drilling and installation of monitor wells may result in temporary noise and, depending on the location, possibly traffic; however, these impacts would be moderate and short-term and are not considered to be significant.

**5.4.1.3.5. Socioeconomic Impacts.** It is likely that contaminants would decompose and diffuse to within drinking water standards long before they reached any water supply wells. Treatment at the point-of-use, paid for by LLNL, would preclude expense to well owners in the event that any wells encounter contaminated ground water.

Owners of properties overlying ground water perceived to be contaminated could be economically impacted. This could be reflected in property values, even though all potentially affected areas have city water available and have no reason to rely on ground water. LLNL has and will continue to work with local realty agents and lending institutions to provide accurate information about actual conditions in the subsurface and put hypothetical health risks and liabilities into perspective.

**5.4.1.3.6. Cultural Resources.** Depending on the location of monitor wells, currently unknown, cultural historical/archaeological resources could be impacted. Before surface disturbance in an area that has not been surveyed, an archaeological survey would be performed.

**5.4.1.3.7. Cumulative Impacts.** If other, currently unknown, ground water contamination were to arrive at the municipal water wells in the same time period as water from the LLNL site, the effects could be additive. Because of the very low predicted concentrations of contaminants from the LLNL site by the time such waters would arrive at the municipal water wells, this addition is not considered significant.

## **5.4.2. Impacts of the Proposed Vadose Zone Contamination Remedial Alternatives**

### **5.4.2.1. Impacts of the No-Action Alternative**

Under this alternative, no action would be employed to remove or isolate vadose zone contamination. A detailed description of the No-Action Alternative for the vadose zone is presented in Section 3.3.2. The No-Action Alternative would have no impact on earth resources, biological resources, cultural resources, noise and traffic, natural resources, socioeconomics, or aesthetics, and has no risk of upset.

**5.4.2.1.1. Human Health.** After 8 y of observation there is no evidence that new contaminants are contributing to the ground water via percolation or to the air via volatilization. The BPHA determined that the only potential soil-based exposure pathway for the public and people onsite is through the inhalation of VOCs volatilized from soil onsite, which is insignificant. The unsaturated soil is not currently creating any measurable adverse impacts on human health. The No-Action Alternative does not control future access by humans to the contaminants. Where contaminants have been found in the vadose zone, the maximum concentrations are 20 to 50 ft below the surface, making the potential for their future disturbance unlikely.

**5.4.2.1.2. Ground Water.** As long as contaminants remain in the soil and the ground surface remains unprotected, the potential for contaminants to percolate down to the ground water exists. However, the relatively low concentrations of VOCs and FHCs in the soil, and the mechanics of soil-water transfer, are such that concentrations of the chemicals in the ground water are not expected to exceed their current values. Ground water quality will improve as the chemicals naturally degrade and desorb from the sediments until the remedial action objectives are reached.

**5.4.2.1.3. Surface Water.** Contamination does not exist in surface soils, so potential adverse impacts to surface water are not a consideration.

**5.4.2.1.4. Air Quality.** There is no potential for significant adverse air quality impacts from VOCs or particulates due to the depth of contamination.

### **5.4.2.2. Impacts of the Deferred-Action Alternative—Capping, Administrative Control, and Ground Water Monitoring**

Capping is used to prevent exposure to humans and wildlife and to minimize leaching of chemicals into the ground water. It is a passive technology, as is administrative control (well drilling restrictions, land use restrictions), in that it does not treat the hazardous materials in the

soil. Capping consists of grading the ground surface to establish drainage away from areas of concern and then covering the surface with a layer of low-permeability material. This alternative involves capping the areas with an impermeable, weather-proof asphalt cap. The Deferred-Action Alternative would have no impact on biological resources, cultural resources, natural resources, or socioeconomics, and has no risk of upset.

**5.4.2.2.1. Human Health.** No negative impacts on human health would occur due to the implementation of this alternative. Capping, as well as administrative controls, would prevent disturbance by humans and any related potential adverse human health impacts. Capping would minimize the release of VOCs volatilized from the soil, already established to be insignificant by the BPHA.

**5.4.2.2.2. Ground Water.** Capping will reduce the transport of contaminants from the unsaturated zone to the water table by not allowing infiltration and percolation of rain water down through the soil. Ground water monitoring will allow detection of measurable transport of contaminants.

**5.4.2.2.3. Surface Water.** Capping will not allow infiltration of rain water, therefore creating more surface runoff. The runoff will be channelized to the existing storm water system.

**5.4.2.2.4. Air Quality.** During cap construction, temporary impacts on air quality may result due to the generation of dust. Mitigation measures, such as watering, can be employed to minimize dust generation. Capping would prevent the release of VOCs, already not considered a significant air quality problem.

**5.4.2.2.5. Earth Resources.** Disruption of the soil that occurs during cap construction could result in short-term increased wind and water erosion. Construction during dry weather and watering of soil would mitigate these potential impacts.

**5.4.2.2.6. Noise and Traffic.** During cap construction, there will be a short-term increase in noise levels due to standard construction practices. These impacts will be short-term and are not considered significant. The areas of potential cap construction are not located near any roads; therefore, no disruption of traffic would occur.

**5.4.2.2.7. Aesthetics.** The cap would likely be constructed of asphalt and located in an industrial, nonaesthetic area of LLNL. The impact on aesthetics is considered minimal.

### **5.4.2.3. Impacts of the Immediate-Action Alternative—Vacuum-Induced Soil Venting, Ground Water Monitoring, and Air Monitoring**

This alternative involves employing soil gas extraction technology on contaminated soil and sediments to remove VOCs and FHCs. VOCs in the gaseous phase would be monitored to assure compliance with BAAQMD discharge requirements. It is unlikely that sitewide extraction could reach BAAQMD's 1 lb/day minimum permitting threshold. FHCs in the gaseous phase would be thermally or catalytically oxidized. The Immediate-Action Alternative would have no impact on surface water, biological resources, cultural resources, natural resources, socioeconomics, or aesthetics.

**5.4.2.3.1. Human Health.** No impacts from VOCs on human health are anticipated in that the gaseous contaminants are treated to health-based and/or environmental regulatory standards (less than 1 lb/day of VOCs emitted to the air for all the treatment processes onsite—see Section 5.4.1.3). The potential health hazard due to possible accidental emissions releases is miniscule. Onsite ambient air monitoring and the use of personal protective equipment will ensure that no health risk occurs.

Hazardous waste could be generated in the form of used carbon that would be regenerated at either an approved offsite facility or at a future onsite facility. Soil cuttings generated from the drilling and installation of the vapor extraction wells would be characterized and handled according to approved Standard Operating Procedures.

**5.4.2.3.2. Ground Water.** Soil gas extraction would greatly reduce or totally eliminate VOCs from the soil, reducing any potential for further impact on the ground water.

**5.4.2.3.3. Risk of Upset.** Potential for accidental release exists. Automatic shut-down mechanisms can be put in place to minimize the magnitude of the release. Workers would be equipped with the appropriate protective and emergency equipment.

**5.4.2.3.4. Air Quality.** The potential for emissions exists with soil gas extraction technology. As previously stated, the VOCs in the gaseous phase are minimal and are likely to approach BAAQMD standards, even without control. The FHCs in the gaseous phase would be thermally oxidized. This has been proven to be 99.8% effective in pilot tests.

During extraction well installation, the potential for release of VOCs exists. However, VOC levels are so low (generally <10 ppb in drilling fluids) that potential impacts on air quality are considered insignificant.

**5.4.2.3.5. Earth Resources.** Installation of the extraction wells will result in a minor amount of disruption and displacement of soil. This is not considered a significant impact.

**5.4.2.3.6. Noise and Traffic.** Vacuum pumps used for vapor extraction generate noise levels of approximately 70 dba in their immediate vicinity. They can be housed in buildings or otherwise muffled to reduce the noise to a level below 50 dba.

**5.4.2.3.7. Cumulative Impacts.** Each of the impacts considered separately above has some minor cumulative effect because of its being added to an already industrialized site. Vacuum-induced venting could add small, but measurable, amounts of VOCs and/or FHCs to the air. Air permitting requirements of the Bay Area Air Quality Management District will be followed to assure no significant impact. Contributions to noise, energy consumption, and socioeconomic impacts are not considered significant.

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## GLOSSARY

1,1-DCA	1,1-dichloroethane
1,1-DCE	1,1-dichloroethylene, also 1,1-dichloroethene
1,2-DCA	1,2-dichloroethane
1,2-DCE	1,2-dichloroethylene, also 1,2-dichloroethene
1,1,1-TCA	1,1,1-trichloroethane
AEC	Atomic Energy Commission
ARAR	Applicable or Relevant and Appropriate Requirement
BAAQMD	Bay Area Air Quality Management District
BACT	Best Available Control Technology
BETX	sum of benzene, ethylbenzene, toluene, and xylene isomers
BPHA	Baseline Public Health Assessment
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
cfs	cubic feet per second
DHS	California Department of Health Services
diam	diameter
DOE	U.S. Department of Energy
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EPD	Environmental Protection Department
ERD	Environmental Restoration Division
ERDA	Energy Research and Development Agency
EW	extraction well
FFA	Federal Facility Agreement
FHC	fuel hydrocarbon
Fm	Formation
FS	Feasibility Study
GAC	granular activated carbon
gal	gallon(s)
gpm	gallons per minute
HI	hazards index
hp	horsepower
IRIS	Integrated Risk Information System

IVM	interactive volume modeling
L	liter(s)
LB	Luria broth
LDR	land-disposal restriction
LLNL	Lawrence Livermore National Laboratory
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
min	minute(s)
mrem/y	millirems per year
MSL or m.s.l.	mean sea level
MW	monitor well
NA	information not available
NAPL	nonaqueous phase liquid
NEPA	National Environmental Policy Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NHPA	National Historic Preservation Act
NMS	nitrate minimum salts
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
OH	hydroxyl radical
OSHA	Occupational Safety and Health Administration
PCB	polychlorinated biphenyl
PCE	tetrachloroethylene, also tetrachloroethene
pCi	picocuries
pCi/L <sub>sm</sub>	picocuries per liter of soil moisture
PDF	pathway dose factor
PEF	pathway-exposure factor
POTW	publicly owned treatment works
ppb	parts per billion
ppm	parts per million
PRAP	Proposed Remedial Action Plan
psi	pounds per square inch
PVC	polyvinylchloride
RCRA	Resource Conservation Recovery Act
RfD	reference dose
RI	Remedial Investigation

RWQCB	California Regional Water Quality Control Board
s	second
SARA	Superfund Amendments and Reauthorization Act
SMCL	secondary MCL
SNL	Sandia National Laboratories
STLC	Soluble Threshold Limit Concentration
TBC	“to be considered”
TCE	trichloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
TFA	Treatment Facility A
TFB	Treatment Facility B
TFC	Treatment Facility C; Total Field Cost
TFD	Treatment Facility D
TFE	Treatment Facility E
TFF	Treatment Facility F
TFG	Treatment Facility G
TFH	total fuel hydrocarbons
TTLC	Total Threshold Limit Concentration
UV	ultraviolet
UV/H <sub>2</sub> O <sub>2</sub>	ultraviolet light/hydrogen peroxide
VOC	volatile organic compound
y	year

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**APPENDIX A**

**ASSESSMENT OF RISK REDUCTION**

# APPENDIX A

## ASSESSMENT OF RISK REDUCTION

### A-1. DATA PRESENTATIONS

Data used to calculate exposure, incremental cancer risk, and noncarcinogenic hazard indices discussed in Section 3 of this report for the remediated case are presented in this Appendix. As described in Section 3, the estimates of exposure, risk, and hazard were derived using predicted concentrations of contaminants at receptor wells following treatment of ground water at the LLNL site. The tables herein that contain values of incremental carcinogenic risk and noncarcinogenic hazard index were prepared using the methodologies described in Section 6 (LLNL method) and Appendix S (EPA method) respectively of the RI report (Thorpe *et al.*, 1990). The PLUME model, described in detail in the RI report, was used to simulate migration of residual concentrations of the contaminants of concern at receptor wells following remediation, as described later in this Appendix. Tables A-1 and A-2 contain the estimates of the concentrations of the contaminants of concern at the receptor wells in the near-, mid-, and far-field for the best-estimate and health-conservative cases, respectively. Many of the chemical-specific concentrations are listed as "ND" (i.e., not detectable with analytical methods currently available), indicating that the predicted concentration was less than 0.1 µg/L (ppb). Nevertheless, to be conservative, the values in parentheses in Tables A-1 and A-2 were used to calculate incremental carcinogenic risk and noncarcinogenic hazard.

Table A-3 presents the pathway-dose factors (PDFs) for PCE, TCE, and chloroform, and the pathway-exposure factor (PEF) for 1,1-DCE for ingestion of drinking water, ingestion of fruits and vegetables irrigated with potable water, inhalation of potable water indoors, and dermal uptake of potable water during showering and bathing. The PDFs address metabolized dose and the PEFs address applied dose. These data are taken directly from Tables 6.1.1-4 (p. 6-11) and 6.1.1-7 (p. 6-15) of the RI.

Tables A-4 and A-5 contain LLNL-derived exposure values (mg/kg-d) for treated ground water at receptor wells in the far-field for the best-estimate exposure scenario and in the near-, mid-, and far-field for the health-conservative exposure scenario, respectively. Exposure is calculated as the product of the concentration of a contaminant in ground water multiplied by a PDF or a PEF. Only exposure related to far-field wells is of practical concern in the best-estimate scenario. Furthermore, PLUME-simulated concentrations for the best-estimate scenario have been adjusted by dividing each predicted value by 10 to account for in-well dilution that would occur as a municipal well draws water from both contaminated and uncontaminated zones (Thorpe *et al.*, 1990).

Tables A-6 and A-7 summarize LLNL-calculated incremental cancer risks for the best-estimate and health-conservative scenarios, respectively, for treated ground water. Incremental cancer risk for a specific carcinogenic chemical is calculated as the product of total exposure (mg/kg-d) multiplied by the cancer-potency factor (CPF; 1/[mg/kg-d]) for that chemical. The CPFs used in this calculation are discussed in Section 6 of the RI (Thorpe *et al.*, 1990). Tables A-8 and A-9 summarize the values of incremental cancer risk for the best-estimate

*Text continues on page A-22*

Table A-1. Predicted VOC concentrations and arrival times downgradient of LLNL: best estimate simulations for remediated ground water.

Observation point	Compound <sup>a</sup>	70-y average <sup>b</sup> concentration (ppb)	Maximum concentration (ppb)	Arrival time (y)
<b>Near-field</b>				
A-N	<i>Chloroform</i>	1.8	4	60
	PCE	ND (0)		
	TCE	0.48		
	Carbon tetrachloride	ND ( $6 \times 10^{-3}$ )		
	1,1-DCE	ND ( $5 \times 10^{-2}$ )		
B-N <sup>c</sup>	<i>Chloroform</i>	ND ( $6 \times 10^{-2}$ )	2	35
	PCE	ND (0)		
	<i>TCE</i>	0.94		
	Carbon tetrachloride	ND ( $7 \times 10^{-2}$ )		
	1,1-DCE	0.1		
B-N <sup>d</sup>	<i>Chloroform</i>	ND ( $6 \times 10^{-3}$ )	0.1	55
	PCE	ND ( $5 \times 10^{-3}$ )		
	TCE	0.78		
	<i>Carbon tetrachloride</i>	ND ( $8 \times 10^{-2}$ )		
	1,1-DCE	0.1		
C-N	<i>Chloroform</i>	ND ( $2 \times 10^{-7}$ )	5	0
	PCE	3.3		
	TCE	ND ( $2 \times 10^{-4}$ )		
	Carbon tetrachloride	ND ( $6 \times 10^{-5}$ )		
	1,1-DCE	0.1		
D-N	<i>Chloroform</i>	ND ( $4 \times 10^{-2}$ )	0.3	110
	PCE	ND ( $4 \times 10^{-4}$ )		
	TCE	0.17		
	Carbon tetrachloride	ND ( $2 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	0.23		
<b>Mid-field</b>				
C-M	<i>Chloroform</i>	ND ( $5 \times 10^{-2}$ )	0.1	205
	PCE	ND ( $9 \times 10^{-2}$ )		
	TCE	ND ( $1 \times 10^{-2}$ )		
	Carbon tetrachloride	ND ( $7 \times 10^{-4}$ )		
	1,1-DCE	ND ( $7 \times 10^{-3}$ )		
D-M	<i>Chloroform</i>	ND ( $1 \times 10^{-4}$ )	0.1	113
	PCE	ND ( $4 \times 10^{-3}$ )		
	TCE	ND ( $9 \times 10^{-4}$ )		
	Carbon tetrachloride	ND ( $4 \times 10^{-5}$ )		
	<i>1,1-DCE</i>	ND ( $8 \times 10^{-2}$ )		

Table A-1. (Continued)

Observation point	Compound <sup>a</sup>	70-y average <sup>b</sup> concentration (ppb)	Maximum concentration (ppb)	Arrival time (y)
<i>Far-field</i>				
A-F	<i>Chloroform</i>	ND ( $6 \times 10^{-2}$ )	ND ( $7 \times 10^{-2}$ )	265
	PCE	ND (0)		
	TCE	ND ( $2 \times 10^{-4}$ )		
	Carbon tetrachloride	ND ( $3 \times 10^{-6}$ )		
	1,1-DCE	ND ( $8 \times 10^{-5}$ )		
B-F <sup>c</sup>	Chloroform	ND ( $3 \times 10^{-3}$ )		335
	PCE	ND ( $6 \times 10^{-6}$ )		
	<i>TCE</i>	ND ( $6 \times 10^{-3}$ )	ND ( $6 \times 10^{-3}$ )	
	Carbon tetrachloride	ND ( $9 \times 10^{-4}$ )		
	1,1-DCE	ND ( $2 \times 10^{-3}$ )		
B-F <sup>d</sup>	Chloroform	ND ( $4 \times 10^{-3}$ )		330
	PCE	ND ( $5 \times 10^{-6}$ )		
	TCE	ND ( $6 \times 10^{-3}$ )		
	<i>Carbon tetrachloride</i>	ND ( $9 \times 10^{-4}$ )	ND ( $1 \times 10^{-3}$ )	
	1,1-DCE	ND ( $2 \times 10^{-3}$ )		
C-F	Chloroform	ND ( $2 \times 10^{-5}$ )		460
	PCE	ND ( $2 \times 10^{-3}$ )	ND ( $2 \times 10^{-3}$ )	
	TCE	ND ( $5 \times 10^{-3}$ )		
	Carbon tetrachloride	ND ( $1 \times 10^{-4}$ )		
	1,1-DCE	ND ( $1 \times 10^{-4}$ )		
D-F	Chloroform	ND ( $2 \times 10^{-3}$ )		250
	PCE	ND ( $6 \times 10^{-8}$ )		
	TCE	ND ( $2 \times 10^{-4}$ )		
	Carbon tetrachloride	ND ( $3 \times 10^{-5}$ )		
	<i>1,1-DCE</i>	ND ( $9 \times 10^{-3}$ )	ND ( $1 \times 10^{-2}$ )	

ND = Not detected (concentration below 0.1 ppb).

<sup>a</sup> The *italicized* compound is the compound of interest at that observation point, i.e., that observation point witnesses the highest concentration of the italicized compound for that distance (near, mid, or far).

<sup>b</sup> Values calculated from 70-y period that yielded maximum 70-y average for compound of interest.

<sup>c</sup> Concentrations predicted during the time period of the greatest 70-y average TCE concentration.

<sup>d</sup> Concentrations predicted during the time period of the greatest 70-y average carbon tetrachloride concentration.

Table A-2. Predicted VOC concentrations and arrival times downgradient of LLNL: health-conservative simulations for remediated ground water.

Observation point	Compound <sup>a</sup>	70-y average <sup>b</sup> concentration (ppb)	Maximum concentration (ppb)	Arrival time (y)
<i>Near-field</i>				
A-N	<i>Chloroform</i>	2.0	11	22
	<i>PCE</i>	ND ( $5 \times 10^{-6}$ )		
	<i>TCE</i>	1.3		
	<i>Carbon tetrachloride</i>	ND ( $8 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	ND ( $4 \times 10^{-2}$ )		
B-N <sup>c</sup>	<i>Chloroform</i>	ND ( $5 \times 10^{-9}$ )	5	35
	<i>PCE</i>	0.4		
	<i>TCE</i>	1.4		
	<i>Carbon tetrachloride</i>	0.1		
	<i>1,1-DCE</i>	ND ( $4 \times 10^{-2}$ )		
C-N	<i>Chloroform</i>	ND ( $2 \times 10^{-5}$ )	5	0
	<i>PCE</i>	1.2		
	<i>TCE</i>	1.4		
	<i>Carbon tetrachloride</i>	0.1		
	<i>1,1-DCE</i>	ND ( $4 \times 10^{-2}$ )		
D-N	<i>Chloroform</i>	ND ( $1 \times 10^{-2}$ )	1	30
	<i>PCE</i>	0.88		
	<i>TCE</i>	0.85		
	<i>Carbon tetrachloride</i>	ND ( $6 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	0.30		
<i>Mid-field</i>				
C-M	<i>Chloroform</i>	0.7	2	72.5
	<i>PCE</i>	1.1		
	<i>TCE</i>	1.3		
	<i>Carbon tetrachloride</i>	ND ( $3 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	0.1		
D-M	<i>Chloroform</i>	0.1	0.7	67
	<i>PCE</i>	0.87		
	<i>TCE</i>	0.95		
	<i>Carbon tetrachloride</i>	ND ( $6 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	0.22		
<i>Far-field</i>				
A-F	<i>Chloroform</i>	1.8	5	97.5
	<i>PCE</i>	ND ( $5 \times 10^{-3}$ )		
	<i>TCE</i>	1.1		
	<i>Carbon tetrachloride</i>	ND ( $7 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	ND ( $4 \times 10^{-2}$ )		
B-F <sup>c</sup>	<i>Chloroform</i>	ND ( $1 \times 10^{-3}$ )	4	110
	<i>PCE</i>	0.2		
	<i>TCE</i>	1.4		
	<i>Carbon tetrachloride</i>	0.1		
	<i>1,1-DCE</i>	ND ( $1 \times 10^{-2}$ )		

Table A-2. (Continued)

Observation point	Compound <sup>a</sup>	70-y average <sup>b</sup> concentration (ppb)	Maximum concentration (ppb)	Arrival time (y)
C-F	Chloroform	0.6		
	<i>PCE</i>	1.0	2	110
	TCE	1.2		
	Carbon tetrachloride	ND ( $3 \times 10^{-2}$ )		
	1,1-DCE	0.1		
D-F	Chloroform	0.16		
	PCE	0.86		
	TCE	0.95		
	Carbon tetrachloride	ND ( $6 \times 10^{-2}$ )		
	<i>1,1-DCE</i>	0.20	0.5	105

ND = Not detected (concentration below 0.1 ppb).

<sup>a</sup> The *italicized* compound is the compound of interest at that observation point.

<sup>b</sup> Values calculated from 70-y period that yielded maximum 70-y average for compound of interest.

<sup>c</sup> Under the health-conservative case, the maximum 70-y average concentrations for TCE and carbon tetrachloride occurred during the same 70-y period for this observation point.

Table A-3. Summary of the pathway dose factors for PCE, TCE, and chloroform and the pathway exposure factor for 1,1-DCE.

Contaminant	Pathway				
	Water ingestion, $F_{d1}$ (L/kg-d)	Indoor inhalation, $F_{d2}$ (L/kg-d)	Dermal absorption, $F_{d3}$ (L/kg-d)	$F_{fv}$ (L/kg-d)	Totals (L/kg-d)
PCE	0.018	0.0031	0.0035	0.0009	0.026
TCE	0.018	0.017	0.019	0.001	0.055
Chloroform	0.018	0.016	0.018	0.0007	0.053
1,1-DCE <sup>a</sup>	0.018	0.024	0.027	0.00019	0.069

<sup>a</sup> Used in the exposure assessment for 1,1-DCE and carbon tetrachloride and is applicable to other VOCs.

Table A-4. Summary of the exposures predicted for the best-estimate exposure scenario, remediated ground water.

Observation point	Chemical	Predicted concentration <sup>a</sup> ( $\mu\text{g/L}$ [ppb])	Water ingestion ( $\text{mg/kg-d}$ )	Produce ingestion ( $\text{mg/kg-d}$ )	Inhalation intake ( $\text{mg/kg-d}$ )	Dermal uptake ( $\text{mg/kg-d}$ )	Exposure totals ( $\text{mg/kg-d}$ )
A-F	Chloroform	$6.0 \times 10^{-3}$	$1.1 \times 10^{-7}$	$4.2 \times 10^{-9}$	$9.6 \times 10^{-8}$	$1.1 \times 10^{-7}$	$3.2 \times 10^{-7}$
	PCE	—	—	—	—	—	—
	TCE	$2.0 \times 10^{-5}$	$3.6 \times 10^{-10}$	$2.0 \times 10^{-11}$	$3.4 \times 10^{-10}$	$3.8 \times 10^{-10}$	$1.1 \times 10^{-9}$
	Carbon tetrachloride	$3.0 \times 10^{-7}$	$5.4 \times 10^{-12}$	$5.7 \times 10^{-14}$	$7.2 \times 10^{-12}$	$8.1 \times 10^{-12}$	$2.1 \times 10^{-11}$
	1,1-DCE	$8.0 \times 10^{-6}$	$1.4 \times 10^{-10}$	$1.5 \times 10^{-12}$	$1.9 \times 10^{-10}$	$2.2 \times 10^{-10}$	$5.5 \times 10^{-10}$
B-F(TCE <sub>max</sub> )	Chloroform	$3.0 \times 10^{-4}$	$5.4 \times 10^{-9}$	$2.1 \times 10^{-10}$	$4.8 \times 10^{-9}$	$5.4 \times 10^{-9}$	$1.6 \times 10^{-8}$
	PCE	$6.0 \times 10^{-7}$	$1.1 \times 10^{-11}$	$5.4 \times 10^{-13}$	$1.9 \times 10^{-12}$	$2.1 \times 10^{-12}$	$1.5 \times 10^{-11}$
	TCE	$6.0 \times 10^{-4}$	$1.1 \times 10^{-8}$	$6.0 \times 10^{-10}$	$1.0 \times 10^{-8}$	$1.1 \times 10^{-8}$	$3.3 \times 10^{-8}$
	Carbon tetrachloride	$9.0 \times 10^{-5}$	$1.6 \times 10^{-9}$	$1.7 \times 10^{-11}$	$2.2 \times 10^{-9}$	$2.4 \times 10^{-9}$	$6.2 \times 10^{-9}$
	1,1-DCE	$2.0 \times 10^{-4}$	$3.6 \times 10^{-9}$	$3.8 \times 10^{-11}$	$4.8 \times 10^{-9}$	$5.4 \times 10^{-9}$	$1.4 \times 10^{-8}$
B-F(CCl <sub>4max</sub> )	Chloroform	$4.0 \times 10^{-4}$	$7.2 \times 10^{-9}$	$2.8 \times 10^{-10}$	$6.4 \times 10^{-9}$	$7.2 \times 10^{-9}$	$2.1 \times 10^{-8}$
	PCE	$5.0 \times 10^{-7}$	$9.0 \times 10^{-12}$	$4.5 \times 10^{-13}$	$1.6 \times 10^{-12}$	$1.8 \times 10^{-12}$	$1.3 \times 10^{-11}$
	TCE	$6.0 \times 10^{-4}$	$1.1 \times 10^{-8}$	$6.0 \times 10^{-10}$	$1.0 \times 10^{-8}$	$1.1 \times 10^{-8}$	$3.3 \times 10^{-8}$
	Carbon tetrachloride	$9.0 \times 10^{-5}$	$1.6 \times 10^{-9}$	$1.7 \times 10^{-11}$	$2.2 \times 10^{-9}$	$2.4 \times 10^{-9}$	$6.2 \times 10^{-9}$
	1,1-DCE	$2.0 \times 10^{-4}$	$3.6 \times 10^{-9}$	$3.8 \times 10^{-11}$	$4.8 \times 10^{-9}$	$5.4 \times 10^{-9}$	$1.4 \times 10^{-8}$
C-F	Chloroform	$2.0 \times 10^{-6}$	$3.6 \times 10^{-11}$	$1.4 \times 10^{-12}$	$3.2 \times 10^{-11}$	$3.6 \times 10^{-11}$	$1.1 \times 10^{-10}$
	PCE	$2.0 \times 10^{-4}$	$3.6 \times 10^{-9}$	$1.8 \times 10^{-10}$	$6.2 \times 10^{-10}$	$7.0 \times 10^{-10}$	$5.1 \times 10^{-9}$
	TCE	$5.0 \times 10^{-4}$	$9.0 \times 10^{-9}$	$5.0 \times 10^{-10}$	$8.5 \times 10^{-9}$	$9.5 \times 10^{-9}$	$2.8 \times 10^{-8}$
	Carbon tetrachloride	$1.0 \times 10^{-5}$	$1.8 \times 10^{-10}$	$1.9 \times 10^{-12}$	$2.4 \times 10^{-10}$	$2.7 \times 10^{-10}$	$6.9 \times 10^{-10}$
	1,1-DCE	$1.0 \times 10^{-5}$	$1.8 \times 10^{-10}$	$1.9 \times 10^{-12}$	$2.4 \times 10^{-10}$	$2.7 \times 10^{-10}$	$6.9 \times 10^{-10}$

Table A-4. (Continued)

Observation point	Chemical	Predicted concentration <sup>a</sup> (µg/L [ppb])	Water ingestion (mg/kg-d)	Produce ingestion (mg/kg-d)	Inhalation intake (mg/kg-d)	Dermal uptake (mg/kg-d)	Exposure totals (mg/kg-d)
D-F	Chloroform	$2.0 \times 10^{-4}$	$3.6 \times 10^{-9}$	$1.4 \times 10^{-10}$	$3.2 \times 10^{-9}$	$3.6 \times 10^{-9}$	$1.1 \times 10^{-8}$
	PCE	$6.0 \times 10^{-9}$	$1.1 \times 10^{-13}$	$5.4 \times 10^{-15}$	$1.9 \times 10^{-14}$	$2.1 \times 10^{-14}$	$1.5 \times 10^{-13}$
	TCE	$2.0 \times 10^{-5}$	$3.6 \times 10^{-10}$	$2.0 \times 10^{-11}$	$3.4 \times 10^{-10}$	$3.8 \times 10^{-10}$	$1.1 \times 10^{-9}$
	Carbon tetrachloride	$3.0 \times 10^{-6}$	$5.4 \times 10^{-11}$	$5.7 \times 10^{-13}$	$7.2 \times 10^{-11}$	$8.1 \times 10^{-11}$	$2.1 \times 10^{-10}$
	1,1-DCE	$9.0 \times 10^{-4}$	$1.6 \times 10^{-8}$	$1.7 \times 10^{-10}$	$2.2 \times 10^{-8}$	$2.4 \times 10^{-8}$	$6.2 \times 10^{-8}$

<sup>a</sup> Predicted maximum ground water concentrations have been reduced by a factor of ten to account for in-well dilution that will occur as a municipal well draws water from both contaminated and uncontaminated zones.

Table A-5. Summary of the exposures predicted for the health-conservative exposure scenario, remediated ground water.

Observation point	Chemical	Predicted concentration ( $\mu\text{g/L}$ [ppb])	Water ingestion ( $\text{mg/kg-d}$ )	Produce ingestion ( $\text{mg/kg-d}$ )	Inhalation intake ( $\text{mg/kg-d}$ )	Dermal uptake ( $\text{mg/kg-d}$ )	Exposure totals ( $\text{mg/kg-d}$ )
<i>Near-field</i>							
A-N	Chloroform	$2.0 \times 10^0$	$3.6 \times 10^{-5}$	$1.4 \times 10^{-6}$	$3.2 \times 10^{-5}$	$3.6 \times 10^{-5}$	$1.1 \times 10^{-4}$
	PCE	$5.0 \times 10^{-6}$	$9.0 \times 10^{-11}$	$4.5 \times 10^{-12}$	$1.6 \times 10^{-11}$	$1.8 \times 10^{-11}$	$1.3 \times 10^{-10}$
	TCE	$1.3 \times 10^0$	$2.3 \times 10^{-5}$	$1.3 \times 10^{-6}$	$2.2 \times 10^{-5}$	$2.5 \times 10^{-5}$	$7.2 \times 10^{-5}$
	Carbon tetrachloride 1,1-DCE	$8.0 \times 10^{-2}$ $4.0 \times 10^{-2}$	$1.4 \times 10^{-6}$ $7.2 \times 10^{-7}$	$1.5 \times 10^{-8}$ $3.2 \times 10^{-8}$	$1.9 \times 10^{-6}$ $9.6 \times 10^{-7}$	$2.2 \times 10^{-6}$ $1.1 \times 10^{-6}$	$5.5 \times 10^{-6}$ $2.8 \times 10^{-6}$
B-N	Chloroform	$5.0 \times 10^{-9}$	$9.0 \times 10^{-14}$	$3.5 \times 10^{-15}$	$8.0 \times 10^{-14}$	$9.0 \times 10^{-14}$	$2.6 \times 10^{-13}$
	PCE	$4.0 \times 10^{-1}$	$7.2 \times 10^{-6}$	$3.6 \times 10^{-7}$	$1.2 \times 10^{-6}$	$1.4 \times 10^{-6}$	$1.0 \times 10^{-5}$
	TCE	$1.4 \times 10^0$	$2.5 \times 10^{-5}$	$1.4 \times 10^{-6}$	$2.4 \times 10^{-5}$	$2.7 \times 10^{-5}$	$7.7 \times 10^{-5}$
	Carbon tetrachloride 1,1-DCE	$1.0 \times 10^{-1}$ $4.0 \times 10^{-3}$	$1.8 \times 10^{-6}$ $7.2 \times 10^{-8}$	$1.9 \times 10^{-8}$ $3.2 \times 10^{-9}$	$2.4 \times 10^{-6}$ $9.6 \times 10^{-8}$	$2.7 \times 10^{-6}$ $1.1 \times 10^{-7}$	$6.9 \times 10^{-6}$ $2.8 \times 10^{-7}$
C-N	Chloroform	$2.0 \times 10^{-5}$	$3.6 \times 10^{-10}$	$1.4 \times 10^{-11}$	$3.2 \times 10^{-10}$	$3.6 \times 10^{-10}$	$1.1 \times 10^{-9}$
	PCE	$1.2 \times 10^0$	$2.2 \times 10^{-5}$	$1.1 \times 10^{-6}$	$3.7 \times 10^{-6}$	$4.2 \times 10^{-6}$	$3.1 \times 10^{-5}$
	TCE	$1.4 \times 10^0$	$2.5 \times 10^{-5}$	$1.4 \times 10^{-6}$	$2.4 \times 10^{-5}$	$2.7 \times 10^{-5}$	$7.7 \times 10^{-5}$
	Carbon tetrachloride 1,1-DCE	$1.0 \times 10^{-1}$ $4.0 \times 10^{-2}$	$1.8 \times 10^{-6}$ $7.2 \times 10^{-7}$	$1.9 \times 10^{-8}$ $3.2 \times 10^{-8}$	$2.4 \times 10^{-6}$ $9.6 \times 10^{-7}$	$2.7 \times 10^{-6}$ $1.1 \times 10^{-6}$	$6.9 \times 10^{-6}$ $2.8 \times 10^{-6}$
D-N	Chloroform	$1.0 \times 10^{-2}$	$1.8 \times 10^{-7}$	$7.0 \times 10^{-9}$	$1.6 \times 10^{-7}$	$1.8 \times 10^{-7}$	$5.3 \times 10^{-7}$
	PCE	$8.8 \times 10^{-1}$	$1.6 \times 10^{-5}$	$7.9 \times 10^{-7}$	$2.7 \times 10^{-6}$	$3.1 \times 10^{-6}$	$2.2 \times 10^{-5}$
	TCE	$8.5 \times 10^{-1}$	$1.5 \times 10^{-5}$	$8.5 \times 10^{-7}$	$1.4 \times 10^{-5}$	$1.6 \times 10^{-5}$	$4.7 \times 10^{-5}$
	Carbon tetrachloride 1,1-DCE	$6.0 \times 10^{-2}$ $3.0 \times 10^{-1}$	$1.1 \times 10^{-6}$ $5.4 \times 10^{-6}$	$1.1 \times 10^{-8}$ $2.4 \times 10^{-7}$	$1.4 \times 10^{-6}$ $7.2 \times 10^{-6}$	$1.6 \times 10^{-6}$ $8.1 \times 10^{-6}$	$4.2 \times 10^{-6}$ $2.1 \times 10^{-5}$

Table A-5. (Continued)

Observation point	Chemical	Predicted concentration ( $\mu\text{g/L}$ [ppb])	Water ingestion ( $\text{mg/kg-d}$ )	Produce ingestion ( $\text{mg/kg-d}$ )	Inhalation intake ( $\text{mg/kg-d}$ )	Dermal uptake ( $\text{mg/kg-d}$ )	Exposure totals ( $\text{mg/kg-d}$ )
<i>Mid-field</i>							
C-M	Chloroform	$7.0 \times 10^{-1}$	$1.3 \times 10^{-5}$	$4.9 \times 10^{-7}$	$1.1 \times 10^{-5}$	$1.3 \times 10^{-5}$	$3.7 \times 10^{-5}$
	PCE	$1.1 \times 10^0$	$2.0 \times 10^{-5}$	$9.9 \times 10^{-7}$	$3.4 \times 10^{-6}$	$3.9 \times 10^{-6}$	$2.8 \times 10^{-5}$
	TCE	$1.3 \times 10^0$	$2.3 \times 10^{-5}$	$1.3 \times 10^{-6}$	$2.2 \times 10^{-5}$	$2.5 \times 10^{-5}$	$7.2 \times 10^{-5}$
	Carbon tetrachloride	$3.0 \times 10^{-2}$	$5.4 \times 10^{-7}$	$5.7 \times 10^{-9}$	$7.2 \times 10^{-7}$	$8.1 \times 10^{-7}$	$2.1 \times 10^{-6}$
	1,1-DCE	$1.0 \times 10^{-1}$	$1.8 \times 10^{-6}$	$8.0 \times 10^{-8}$	$2.4 \times 10^{-6}$	$2.7 \times 10^{-6}$	$7.0 \times 10^{-6}$
D-M	Chloroform	$1.0 \times 10^{-1}$	$1.8 \times 10^{-6}$	$7.0 \times 10^{-8}$	$1.6 \times 10^{-6}$	$1.8 \times 10^{-6}$	$5.3 \times 10^{-6}$
	PCE	$8.7 \times 10^{-1}$	$1.6 \times 10^{-5}$	$7.8 \times 10^{-7}$	$2.7 \times 10^{-6}$	$3.0 \times 10^{-6}$	$2.2 \times 10^{-5}$
	TCE	$9.5 \times 10^{-1}$	$1.7 \times 10^{-5}$	$9.5 \times 10^{-7}$	$1.6 \times 10^{-5}$	$1.8 \times 10^{-5}$	$5.2 \times 10^{-5}$
	Carbon tetrachloride	$6.0 \times 10^{-2}$	$1.1 \times 10^{-6}$	$1.1 \times 10^{-8}$	$1.4 \times 10^{-6}$	$1.6 \times 10^{-6}$	$4.2 \times 10^{-6}$
	1,1-DCE	$2.2 \times 10^{-1}$	$4.0 \times 10^{-6}$	$1.8 \times 10^{-7}$	$5.3 \times 10^{-6}$	$5.9 \times 10^{-6}$	$1.5 \times 10^{-5}$
<i>Far-field</i>							
A-F	Chloroform	$1.8 \times 10^0$	$3.2 \times 10^{-5}$	$1.3 \times 10^{-6}$	$2.9 \times 10^{-5}$	$3.2 \times 10^{-5}$	$9.5 \times 10^{-5}$
	PCE	$5.0 \times 10^{-3}$	$9.0 \times 10^{-8}$	$4.5 \times 10^{-9}$	$1.6 \times 10^{-8}$	$1.8 \times 10^{-8}$	$1.3 \times 10^{-7}$
	TCE	$1.1 \times 10^0$	$2.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$1.9 \times 10^{-5}$	$2.1 \times 10^{-5}$	$6.1 \times 10^{-5}$
	Carbon tetrachloride	$7.0 \times 10^{-2}$	$1.3 \times 10^{-6}$	$1.3 \times 10^{-8}$	$1.7 \times 10^{-6}$	$1.9 \times 10^{-6}$	$4.8 \times 10^{-6}$
	1,1-DCE	$4.0 \times 10^{-2}$	$7.2 \times 10^{-7}$	$3.2 \times 10^{-8}$	$9.6 \times 10^{-7}$	$1.1 \times 10^{-6}$	$2.8 \times 10^{-6}$
B-F	Chloroform	$1.0 \times 10^{-3}$	$1.8 \times 10^{-8}$	$7.0 \times 10^{-10}$	$1.6 \times 10^{-8}$	$1.8 \times 10^{-8}$	$5.3 \times 10^{-8}$
	PCE	$2.0 \times 10^{-1}$	$3.6 \times 10^{-6}$	$1.8 \times 10^{-7}$	$6.2 \times 10^{-7}$	$7.0 \times 10^{-7}$	$5.1 \times 10^{-6}$
	TCE	$1.4 \times 10^0$	$2.5 \times 10^{-5}$	$1.4 \times 10^{-6}$	$2.4 \times 10^{-5}$	$2.7 \times 10^{-5}$	$7.7 \times 10^{-5}$
	Carbon tetrachloride	$1.0 \times 10^{-1}$	$1.8 \times 10^{-6}$	$1.9 \times 10^{-8}$	$2.4 \times 10^{-6}$	$2.7 \times 10^{-6}$	$6.9 \times 10^{-6}$
	1,1-DCE	$1.0 \times 10^{-2}$	$1.8 \times 10^{-7}$	$8.0 \times 10^{-9}$	$2.4 \times 10^{-7}$	$2.7 \times 10^{-7}$	$7.0 \times 10^{-7}$

Table A-5. (Continued)

Observation point	Chemical	Predicted concentration ( $\mu\text{g/L}$ [ppb])	Water ingestion ( $\text{mg/kg-d}$ )	Produce ingestion ( $\text{mg/kg-d}$ )	Inhalation intake ( $\text{mg/kg-d}$ )	Dermal uptake ( $\text{mg/kg-d}$ )	Exposure totals ( $\text{mg/kg-d}$ )
C-F	Chloroform	$6.0 \times 10^{-1}$	$1.1 \times 10^{-5}$	$4.2 \times 10^{-7}$	$9.6 \times 10^{-6}$	$1.1 \times 10^{-5}$	$3.2 \times 10^{-5}$
	PCE	$1.0 \times 10^0$	$1.8 \times 10^{-5}$	$9.0 \times 10^{-7}$	$3.1 \times 10^{-6}$	$3.5 \times 10^{-6}$	$2.6 \times 10^{-5}$
	TCE	$1.2 \times 10^0$	$2.2 \times 10^{-5}$	$1.2 \times 10^{-6}$	$2.0 \times 10^{-5}$	$2.3 \times 10^{-5}$	$6.6 \times 10^{-5}$
	Carbon tetrachloride	$3.0 \times 10^{-2}$	$5.4 \times 10^{-7}$	$5.7 \times 10^{-9}$	$7.2 \times 10^{-7}$	$8.1 \times 10^{-7}$	$2.1 \times 10^{-6}$
	1,1-DCE	$1.0 \times 10^{-1}$	$1.8 \times 10^{-6}$	$8.0 \times 10^{-8}$	$2.4 \times 10^{-6}$	$2.7 \times 10^{-6}$	$7.0 \times 10^{-6}$
D-F	Chloroform	$1.6 \times 10^{-1}$	$2.9 \times 10^{-6}$	$1.1 \times 10^{-7}$	$2.6 \times 10^{-6}$	$2.9 \times 10^{-6}$	$8.4 \times 10^{-6}$
	PCE	$8.6 \times 10^{-1}$	$1.5 \times 10^{-5}$	$7.7 \times 10^{-7}$	$2.7 \times 10^{-6}$	$3.0 \times 10^{-6}$	$2.2 \times 10^{-5}$
	TCE	$9.5 \times 10^{-1}$	$1.7 \times 10^{-5}$	$9.5 \times 10^{-7}$	$1.6 \times 10^{-5}$	$1.8 \times 10^{-5}$	$5.2 \times 10^{-5}$
	Carbon tetrachloride	$6.3 \times 10^{-2}$	$1.1 \times 10^{-6}$	$1.2 \times 10^{-8}$	$1.5 \times 10^{-6}$	$1.7 \times 10^{-6}$	$4.4 \times 10^{-6}$
	1,1-DCE	$2.0 \times 10^{-1}$	$3.6 \times 10^{-6}$	$1.6 \times 10^{-7}$	$4.8 \times 10^{-6}$	$5.4 \times 10^{-6}$	$1.4 \times 10^{-5}$

Table A-6. Summary of predicted incremental cancer risks for the best-estimate exposure scenario remediated ground water.

Observation point	Chemical	Predicted concentration <sup>a</sup> (µg/L [ppb])	Total exposure (mg/kg-d)	Cancer-potency factor (CPF) (1/[mg/kg-d])	Incremental cancer risk <sup>b</sup>
A-F	Chloroform	$6.0 \times 10^{-3}$	$3.2 \times 10^{-7}$	$2.8 \times 10^{-2}$	$8.9 \times 10^{-9}$
	PCE	$0.0 \times 10^0$	$0.0 \times 10^0$	$2.7 \times 10^{-1}$	$0.0 \times 10^0$
	TCE	$2.0 \times 10^{-5}$	$1.1 \times 10^{-9}$	$1.7 \times 10^{-2}$	$1.9 \times 10^{-11}$
	Carbon tetrachloride	$3.0 \times 10^{-7}$	$2.1 \times 10^{-11}$	$1.3 \times 10^{-1}$	$2.7 \times 10^{-12}$
			Subtotal for A-F		$8.9 \times 10^{-9}$
B-F(TCE <sub>max</sub> )	Chloroform	$3.0 \times 10^{-4}$	$1.6 \times 10^{-8}$	$2.8 \times 10^{-2}$	$4.4 \times 10^{-10}$
	PCE	$6.0 \times 10^{-7}$	$1.5 \times 10^{-11}$	$2.7 \times 10^{-1}$	$4.1 \times 10^{-12}$
	TCE	$6.0 \times 10^{-4}$	$3.3 \times 10^{-8}$	$1.7 \times 10^{-2}$	$5.6 \times 10^{-10}$
	Carbon tetrachloride	$9.0 \times 10^{-5}$	$6.2 \times 10^{-9}$	$1.3 \times 10^{-1}$	$8.1 \times 10^{-10}$
			Subtotal for B-F(TCE <sub>max</sub> )		$1.8 \times 10^{-9}$
B-F(CCl <sub>4max</sub> )	Chloroform	$4.0 \times 10^{-4}$	$2.1 \times 10^{-8}$	$2.8 \times 10^{-2}$	$5.9 \times 10^{-10}$
	PCE	$5.0 \times 10^{-7}$	$1.3 \times 10^{-11}$	$2.7 \times 10^{-1}$	$3.4 \times 10^{-12}$
	TCE	$6.0 \times 10^{-4}$	$3.3 \times 10^{-8}$	$1.7 \times 10^{-2}$	$5.6 \times 10^{-10}$
	Carbon tetrachloride	$9.0 \times 10^{-5}$	$6.2 \times 10^{-9}$	$1.3 \times 10^{-1}$	$8.1 \times 10^{-10}$
			Subtotal for B-F(CCl <sub>4max</sub> )		$2.0 \times 10^{-9}$
C-F	Chloroform	$2.0 \times 10^{-6}$	$1.1 \times 10^{-10}$	$2.8 \times 10^{-2}$	$3.0 \times 10^{-12}$
	PCE	$2.0 \times 10^{-4}$	$5.1 \times 10^{-9}$	$2.7 \times 10^{-1}$	$1.4 \times 10^{-9}$
	TCE	$5.0 \times 10^{-4}$	$2.8 \times 10^{-8}$	$1.7 \times 10^{-2}$	$4.7 \times 10^{-10}$
	Carbon tetrachloride	$1.0 \times 10^{-5}$	$6.9 \times 10^{-10}$	$1.3 \times 10^{-1}$	$9.0 \times 10^{-11}$
			Subtotal for C-F		$1.9 \times 10^{-9}$

Table A-6. (Continued)

Observation point	Chemical	Predicted concentration <sup>a</sup> ( $\mu\text{g/L}$ [ppb])	Total exposure ( $\text{mg/kg-d}$ )	Cancer-potency factor (CPF) ( $1/[\text{mg/kg-d}]$ )	Incremental cancer risk <sup>b</sup>
D-F	Chloroform	$2.0 \times 10^{-4}$	$1.1 \times 10^{-8}$	$2.8 \times 10^{-2}$	$3.1 \times 10^{-10}$
	PCE	$6.0 \times 10^{-9}$	$1.5 \times 10^{-13}$	$2.7 \times 10^{-1}$	$4.1 \times 10^{-14}$
	TCE	$2.0 \times 10^{-5}$	$1.1 \times 10^{-9}$	$1.7 \times 10^{-2}$	$1.9 \times 10^{-11}$
	Carbon tetrachloride	$3.0 \times 10^{-6}$	$2.1 \times 10^{-10}$	$1.3 \times 10^{-1}$	$2.7 \times 10^{-11}$
				Subtotal for D-F	$3.5 \times 10^{-10}$

<sup>a</sup> Predicted maximum ground water concentrations have been reduced by a factor of ten to account for in-well dilution that will occur as a municipal well draws water from both contaminated and uncontaminated zones.

<sup>b</sup> Risk calculations for the best-estimate scenario do not consider 1,1-DCE to be a carcinogenic chemical.

Table A-7. Summary of predicted incremental cancer risks for the health-conservative exposure scenario, remediated ground water.

Observation point	Chemical	Predicted concentration ( $\mu\text{g/L}$ [ppb])	Total exposure (mg/kg-d)	Cancer-potency factor (CPF) ( $1/[\text{mg}/\text{kg}\cdot\text{d}]$ )	Incremental cancer risk
<i>Near-field</i>					
A-N	Chloroform	$2.0 \times 10^0$	$1.1 \times 10^{-4}$	$2.8 \times 10^{-2}$	$3.0 \times 10^{-6}$
	PCE	$5.0 \times 10^{-6}$	$1.3 \times 10^{-10}$	$2.7 \times 10^{-1}$	$3.4 \times 10^{-11}$
	TCE	$1.3 \times 10^0$	$7.2 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.2 \times 10^{-6}$
	Carbon tetrachloride	$8.0 \times 10^{-2}$	$5.5 \times 10^{-6}$	$1.3 \times 10^{-1}$	$7.2 \times 10^{-7}$
				Subtotal for A-N	$4.9 \times 10^{-6}$
B-N	Chloroform	$5.0 \times 10^{-9}$	$2.6 \times 10^{-13}$	$2.8 \times 10^{-2}$	$7.4 \times 10^{-15}$
	PCE	$4.0 \times 10^{-1}$	$1.0 \times 10^{-5}$	$2.7 \times 10^{-1}$	$2.8 \times 10^{-6}$
	TCE	$1.4 \times 10^0$	$7.7 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.3 \times 10^{-6}$
	Carbon tetrachloride	$1.0 \times 10^{-1}$	$6.9 \times 10^{-6}$	$1.3 \times 10^{-1}$	$9.0 \times 10^{-7}$
				Subtotal for B-N	$5.0 \times 10^{-6}$
C-N	Chloroform	$2.0 \times 10^{-5}$	$1.1 \times 10^{-9}$	$2.8 \times 10^{-2}$	$3.0 \times 10^{-11}$
	PCE	$1.2 \times 10^0$	$3.1 \times 10^{-5}$	$2.7 \times 10^{-1}$	$8.3 \times 10^{-6}$
	TCE	$1.4 \times 10^0$	$7.7 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.3 \times 10^{-6}$
	Carbon tetrachloride	$1.0 \times 10^{-1}$	$6.9 \times 10^{-6}$	$1.3 \times 10^{-1}$	$9.0 \times 10^{-7}$
				Subtotal for C-N	$1.05 \times 10^{-5}$
D-N	Chloroform	$1.0 \times 10^{-2}$	$5.3 \times 10^{-7}$	$2.8 \times 10^{-2}$	$1.5 \times 10^{-8}$
	PCE	$8.8 \times 10^{-1}$	$2.2 \times 10^{-5}$	$2.7 \times 10^{-1}$	$6.1 \times 10^{-6}$
	TCE	$8.5 \times 10^{-1}$	$4.7 \times 10^{-5}$	$1.7 \times 10^{-2}$	$7.9 \times 10^{-7}$
	Carbon tetrachloride	$6.0 \times 10^{-2}$	$4.2 \times 10^{-6}$	$1.3 \times 10^{-1}$	$5.4 \times 10^{-7}$
				Subtotal for D-N	$7.4 \times 10^{-6}$

Table A-7. (Continued)

Observation point	Chemical	Predicted concentration ( $\mu\text{g/L}$ [ppb])	Total exposure (mg/kg-d)	Cancer-potency factor (CPF) ( $1/(\text{mg/kg-d})$ )	Incremental cancer risk
<i>Mid-field</i>					
C-M	Chloroform	$7.0 \times 10^{-1}$	$3.7 \times 10^{-5}$	$2.8 \times 10^{-2}$	$1.0 \times 10^{-6}$
	PCE	$1.1 \times 10^0$	$2.8 \times 10^{-5}$	$2.7 \times 10^{-1}$	$7.6 \times 10^{-6}$
	TCE	$1.3 \times 10^0$	$7.2 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.2 \times 10^{-6}$
	Carbon tetrachloride	$3.0 \times 10^{-2}$	$2.1 \times 10^{-6}$	$1.3 \times 10^{-1}$	$2.7 \times 10^{-7}$
			Subtotal for C-M		$1.0 \times 10^{-5}$
D-M	Chloroform	$1.0 \times 10^{-1}$	$5.3 \times 10^{-6}$	$2.8 \times 10^{-2}$	$1.5 \times 10^{-7}$
	PCE	$8.7 \times 10^{-1}$	$2.2 \times 10^{-5}$	$2.7 \times 10^{-1}$	$6.0 \times 10^{-6}$
	TCE	$9.5 \times 10^{-1}$	$5.2 \times 10^{-5}$	$1.7 \times 10^{-2}$	$8.9 \times 10^{-7}$
	Carbon tetrachloride	$6.0 \times 10^{-2}$	$4.2 \times 10^{-6}$	$1.3 \times 10^{-1}$	$5.4 \times 10^{-7}$
			Subtotal for D-M		$7.6 \times 10^{-6}$
<i>Far-field</i>					
A-F	Chloroform	$1.8 \times 10^0$	$9.5 \times 10^{-5}$	$2.8 \times 10^{-2}$	$2.7 \times 10^{-6}$
	PCE	$5.0 \times 10^{-3}$	$1.3 \times 10^{-7}$	$2.7 \times 10^{-1}$	$3.4 \times 10^{-8}$
	TCE	$1.1 \times 10^0$	$6.1 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.0 \times 10^{-6}$
	Carbon tetrachloride	$7.0 \times 10^{-2}$	$4.8 \times 10^{-6}$	$1.3 \times 10^{-1}$	$6.3 \times 10^{-7}$
			Subtotal for A-F		$4.3 \times 10^{-6}$

Table A-7. (Continued)

Observation point	Chemical	Predicted concentration ( $\mu\text{g/L}$ [ppb])	Total exposure (mg/kg-d)	Cancer-potency factor (CPF) ( $1/(\text{mg}/\text{kg}\cdot\text{d})$ )	Incremental cancer risk
B-F	Chloroform	$1.0 \times 10^{-3}$	$5.3 \times 10^{-8}$	$2.8 \times 10^{-2}$	$1.5 \times 10^{-9}$
	PCE	$2.0 \times 10^{-1}$	$5.1 \times 10^{-6}$	$2.7 \times 10^{-1}$	$1.4 \times 10^{-6}$
	TCE	$1.4 \times 10^0$	$7.7 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.3 \times 10^{-6}$
	Carbon tetrachloride	$1.0 \times 10^{-1}$	$6.9 \times 10^{-6}$	$1.3 \times 10^{-1}$	$9.0 \times 10^{-7}$
			Subtotal for B-F		$3.6 \times 10^{-6}$
C-F	Chloroform	$6.0 \times 10^{-1}$	$3.2 \times 10^{-5}$	$2.8 \times 10^{-2}$	$8.9 \times 10^{-7}$
	PCE	$1.0 \times 10^0$	$2.6 \times 10^{-5}$	$2.7 \times 10^{-1}$	$6.9 \times 10^{-6}$
	TCE	$1.2 \times 10^0$	$6.6 \times 10^{-5}$	$1.7 \times 10^{-2}$	$1.1 \times 10^{-6}$
	Carbon tetrachloride	$3.0 \times 10^{-2}$	$2.1 \times 10^{-6}$	$1.3 \times 10^{-1}$	$2.7 \times 10^{-7}$
			Subtotal for C-F		$9.2 \times 10^{-6}$
D-F	Chloroform	$1.6 \times 10^{-1}$	$8.4 \times 10^{-6}$	$2.8 \times 10^{-2}$	$2.4 \times 10^{-7}$
	PCE	$8.6 \times 10^{-1}$	$2.2 \times 10^{-5}$	$2.7 \times 10^{-1}$	$5.9 \times 10^{-6}$
	TCE	$9.5 \times 10^{-1}$	$5.2 \times 10^{-5}$	$1.7 \times 10^{-2}$	$8.9 \times 10^{-7}$
	Carbon tetrachloride	$6.3 \times 10^{-2}$	$4.4 \times 10^{-6}$	$1.3 \times 10^{-1}$	$5.7 \times 10^{-7}$
			Subtotal for D-F		$7.6 \times 10^{-6}$

Table A-8. Predicted cancer risks for the best-estimate exposure scenario based on EPA methodologies and comparison to LLNL results, remediated ground water.

Observation point	Chemical	Predicted concentration <sup>a</sup> (mg/L)	Oral intake (mg/kg-d)	Oral cancer-potency factor (CPF) (1/[mg/kg-d])	Oral cancer risk	Inhalation cancer-potency factor (CPF) (1/[mg/kg-d])	Inhalation cancer risk	EPA total cancer risk	LLNL total cancer risk
A-F	Chloroform	$6.0 \times 10^{-6}$	$1.7 \times 10^{-7}$	$6.1 \times 10^{-3}$	$1.0 \times 10^{-9}$	$8.1 \times 10^{-2}$	$1.4 \times 10^{-8}$	$1.5 \times 10^{-8}$	$8.9 \times 10^{-9}$
	PCE	$0.0 \times 10^0$	$0.0 \times 10^0$	$5.1 \times 10^{-2}$	$0.0 \times 10^0$	$3.3 \times 10^{-3}$	$0.0 \times 10^0$	$0.0 \times 10^0$	$0.0 \times 10^0$
	TCE	$2.0 \times 10^{-8}$	$5.7 \times 10^{-10}$	$1.1 \times 10^{-2}$	$6.3 \times 10^{-12}$	$1.7 \times 10^{-2}$	$9.7 \times 10^{-12}$	$1.6 \times 10^{-11}$	$1.9 \times 10^{-11}$
	Carbon tetrachloride	$3.0 \times 10^{-10}$	$8.6 \times 10^{-12}$	$1.3 \times 10^{-4}$	$1.1 \times 10^{-12}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-12}$	$2.2 \times 10^{-12}$	$2.7 \times 10^{-12}$
	1,1-DCE	$8.0 \times 10^{-9}$	$2.3 \times 10^{-10}$	$6.0 \times 10^{-4}$	$1.4 \times 10^{-10}$	$1.2 \times 10^0$	$2.7 \times 10^{-10}$	$4.1 \times 10^{-10}$	
			Subtotal for A-F		$1.2 \times 10^{-9}$		$1.4 \times 10^{-8}$	$1.5 \times 10^{-8}$	$8.9 \times 10^{-9}$
B-F (TCE <sub>max</sub> )	Chloroform	$3.0 \times 10^{-7}$	$8.6 \times 10^{-9}$	$6.1 \times 10^{-3}$	$5.2 \times 10^{-11}$	$8.1 \times 10^{-2}$	$6.9 \times 10^{-10}$	$7.5 \times 10^{-10}$	$4.4 \times 10^{-10}$
	PCE	$6.0 \times 10^{-10}$	$1.7 \times 10^{-11}$	$5.1 \times 10^{-2}$	$8.7 \times 10^{-13}$	$3.3 \times 10^{-3}$	$5.7 \times 10^{-14}$	$9.3 \times 10^{-13}$	$4.1 \times 10^{-12}$
	TCE	$6.0 \times 10^{-7}$	$1.7 \times 10^{-8}$	$1.1 \times 10^{-2}$	$1.9 \times 10^{-10}$	$1.7 \times 10^{-2}$	$2.9 \times 10^{-10}$	$4.8 \times 10^{-10}$	$5.6 \times 10^{-10}$
	Carbon tetrachloride	$9.0 \times 10^{-8}$	$2.6 \times 10^{-9}$	$1.3 \times 10^{-4}$	$3.3 \times 10^{-10}$	$1.3 \times 10^{-1}$	$3.3 \times 10^{-10}$	$6.7 \times 10^{-10}$	$8.1 \times 10^{-10}$
	1,1-DCE	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$6.0 \times 10^{-4}$	$3.4 \times 10^{-9}$	$1.2 \times 10^0$	$6.9 \times 10^{-9}$	$1.0 \times 10^{-8}$	
			Subtotal for B-F(TCE <sub>max</sub> )		$4.0 \times 10^{-9}$		$8.2 \times 10^{-9}$	$1.2 \times 10^{-8}$	$1.8 \times 10^{-9}$
B-F (CCl <sub>4</sub> <sub>max</sub> )	Chloroform	$4.0 \times 10^{-7}$	$1.1 \times 10^{-8}$	$6.1 \times 10^{-3}$	$7.0 \times 10^{-11}$	$8.1 \times 10^{-2}$	$9.3 \times 10^{-10}$	$1.0 \times 10^{-9}$	$5.9 \times 10^{-10}$
	PCE	$5.0 \times 10^{-10}$	$1.4 \times 10^{-11}$	$5.1 \times 10^{-2}$	$7.3 \times 10^{-13}$	$3.3 \times 10^{-3}$	$4.7 \times 10^{-14}$	$7.8 \times 10^{-13}$	$3.4 \times 10^{-12}$
	TCE	$6.0 \times 10^{-7}$	$1.7 \times 10^{-8}$	$1.1 \times 10^{-2}$	$1.9 \times 10^{-10}$	$1.7 \times 10^{-2}$	$2.9 \times 10^{-10}$	$4.8 \times 10^{-10}$	$5.6 \times 10^{-10}$
	Carbon tetrachloride	$9.0 \times 10^{-8}$	$2.6 \times 10^{-9}$	$1.3 \times 10^{-4}$	$3.3 \times 10^{-10}$	$1.3 \times 10^{-1}$	$3.3 \times 10^{-10}$	$6.7 \times 10^{-10}$	$8.1 \times 10^{-10}$
	1,1-DCE	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$6.0 \times 10^{-4}$	$3.4 \times 10^{-9}$	$1.2 \times 10^0$	$6.9 \times 10^{-9}$	$1.0 \times 10^{-8}$	
			Subtotal for B-F(CCl <sub>4</sub> <sub>max</sub> )		$4.0 \times 10^{-9}$		$8.4 \times 10^{-9}$	$1.2 \times 10^{-8}$	$2.0 \times 10^{-9}$

Table A-8. (Continued)

Observation point	Chemical	Predicted concentration <sup>a</sup> (mg/L)	Oral intake (mg/kg-d)	Oral cancer-		Inhalation			LLNL total cancer risk
				potency factor (CPF) (1/[mg/kg-d])	Oral cancer risk	potency factor (CPF) (1/[mg/kg-d])	Inhalation cancer risk	EPA total cancer risk	
C-F	Chloroform	$2.0 \times 10^{-9}$	$5.7 \times 10^{-11}$	$6.1 \times 10^{-3}$	$3.5 \times 10^{-13}$	$8.1 \times 10^{-2}$	$4.6 \times 10^{-12}$	$5.0 \times 10^{-12}$	$3.0 \times 10^{-12}$
	PCE	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$5.1 \times 10^{-2}$	$2.9 \times 10^{-10}$	$3.3 \times 10^{-3}$	$1.9 \times 10^{-11}$	$3.1 \times 10^{-10}$	$1.4 \times 10^{-9}$
	TCE	$5.0 \times 10^{-7}$	$1.4 \times 10^{-8}$	$1.1 \times 10^{-2}$	$1.6 \times 10^{-10}$	$1.7 \times 10^{-2}$	$2.4 \times 10^{-10}$	$4.0 \times 10^{-10}$	$4.7 \times 10^{-10}$
	Carbon tetrachloride	$1.0 \times 10^{-8}$	$2.9 \times 10^{-10}$	$1.3 \times 10^{-1}$	$3.7 \times 10^{-11}$	$1.3 \times 10^{-1}$	$3.7 \times 10^{-11}$	$7.4 \times 10^{-11}$	$9.0 \times 10^{-11}$
	1,1-DCE	$1.0 \times 10^{-8}$	$2.9 \times 10^{-10}$	$6.0 \times 10^{-1}$	$1.7 \times 10^{-10}$	$1.2 \times 10^0$	$3.4 \times 10^{-10}$	$5.1 \times 10^{-10}$	$1.9 \times 10^{-9}$
			Subtotal for C-F		$6.6 \times 10^{-10}$		$6.5 \times 10^{-10}$	$1.3 \times 10^{-9}$	
D-F	Chloroform	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$6.1 \times 10^{-3}$	$3.5 \times 10^{-11}$	$8.1 \times 10^{-2}$	$4.6 \times 10^{-10}$	$5.0 \times 10^{-10}$	$3.1 \times 10^{-10}$
	PCE	$6.0 \times 10^{-12}$	$1.7 \times 10^{-13}$	$5.1 \times 10^{-2}$	$8.7 \times 10^{-15}$	$3.3 \times 10^{-3}$	$5.7 \times 10^{-16}$	$9.3 \times 10^{-15}$	$4.1 \times 10^{-14}$
	TCE	$2.0 \times 10^{-8}$	$5.7 \times 10^{-10}$	$1.1 \times 10^{-2}$	$6.3 \times 10^{-12}$	$1.7 \times 10^{-2}$	$9.7 \times 10^{-12}$	$1.6 \times 10^{-11}$	$1.9 \times 10^{-11}$
	Carbon tetrachloride	$3.0 \times 10^{-9}$	$8.6 \times 10^{-11}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-11}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-11}$	$2.2 \times 10^{-11}$	$2.7 \times 10^{-11}$
	1,1-DCE	$9.0 \times 10^{-7}$	$2.6 \times 10^{-8}$	$6.0 \times 10^{-1}$	$1.5 \times 10^{-8}$	$1.2 \times 10^0$	$3.1 \times 10^{-8}$	$4.6 \times 10^{-8}$	$3.6 \times 10^{-10}$
			Subtotal for D-F		$1.5 \times 10^{-8}$		$3.1 \times 10^{-8}$	$4.7 \times 10^{-8}$	

<sup>a</sup> Predicted maximum ground water concentrations have been reduced by a factor of ten to account for in-well dilution that will occur as a municipal well draws water from both contaminated and uncontaminated zones.

Table A-9. Predicted cancer risks for the health-conservative exposure scenario based on EPA methodologies and comparison to LLNL results, remediated ground water.

Observation point	Chemical	Predicted concentration (mg/L)	Oral cancer-		Inhalation cancer-		EPA total cancer risk	LLNL total cancer risk
			intake (mg/kg-d)	potency factor (CPF) (1/[mg/kg-d])	potency factor (CPF) (1/[mg/kg-d])	cancer risk		
<i>Near-field</i>								
A-N	Chloroform	$2.0 \times 10^{-3}$	$5.7 \times 10^{-5}$	$6.1 \times 10^{-3}$	$8.1 \times 10^{-2}$	$4.6 \times 10^{-6}$	$5.0 \times 10^{-6}$	$3.0 \times 10^{-6}$
	PCE	$5.0 \times 10^{-9}$	$1.4 \times 10^{-10}$	$5.1 \times 10^{-2}$	$3.3 \times 10^{-3}$	$4.7 \times 10^{-13}$	$7.8 \times 10^{-12}$	$3.4 \times 10^{-11}$
	TCE	$1.3 \times 10^{-3}$	$3.7 \times 10^{-5}$	$1.1 \times 10^{-2}$	$1.7 \times 10^{-2}$	$6.3 \times 10^{-7}$	$1.0 \times 10^{-6}$	$1.2 \times 10^{-6}$
	Carbon tetrachloride	$8.0 \times 10^{-5}$	$2.3 \times 10^{-6}$	$1.3 \times 10^{-1}$	$1.3 \times 10^{-1}$	$3.0 \times 10^{-7}$	$5.9 \times 10^{-7}$	$7.2 \times 10^{-7}$
	1,1-DCE	$4.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$6.0 \times 10^{-1}$	$1.2 \times 10^0$	$1.4 \times 10^{-6}$	$2.1 \times 10^{-6}$	$4.9 \times 10^{-6}$
			Subtotals for A-N			$6.9 \times 10^{-6}$	$8.7 \times 10^{-6}$	
B-N	Chloroform	$5.0 \times 10^{-12}$	$1.4 \times 10^{-13}$	$6.1 \times 10^{-3}$	$8.1 \times 10^{-2}$	$1.2 \times 10^{-14}$	$1.2 \times 10^{-14}$	$7.4 \times 10^{-15}$
	PCE	$4.0 \times 10^{-4}$	$1.1 \times 10^{-5}$	$5.1 \times 10^{-2}$	$3.3 \times 10^{-3}$	$3.8 \times 10^{-8}$	$6.2 \times 10^{-7}$	$2.8 \times 10^{-6}$
	TCE	$1.4 \times 10^{-3}$	$4.0 \times 10^{-5}$	$1.1 \times 10^{-2}$	$1.7 \times 10^{-2}$	$6.8 \times 10^{-7}$	$1.1 \times 10^{-6}$	$1.3 \times 10^{-6}$
	Carbon tetrachloride	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$1.3 \times 10^{-1}$	$1.3 \times 10^{-1}$	$3.7 \times 10^{-7}$	$7.4 \times 10^{-7}$	$9.0 \times 10^{-7}$
	1,1-DCE	$4.0 \times 10^{-6}$	$1.1 \times 10^{-7}$	$6.0 \times 10^{-1}$	$1.2 \times 10^0$	$1.4 \times 10^{-7}$	$2.1 \times 10^{-7}$	$5.0 \times 10^{-6}$
			Subtotals for B-N			$1.5 \times 10^{-6}$	$2.7 \times 10^{-6}$	
C-N	Chloroform	$2.0 \times 10^{-8}$	$5.7 \times 10^{-10}$	$6.1 \times 10^{-3}$	$8.1 \times 10^{-2}$	$4.6 \times 10^{-11}$	$5.0 \times 10^{-11}$	$3.0 \times 10^{-11}$
	PCE	$1.2 \times 10^{-3}$	$3.4 \times 10^{-5}$	$5.1 \times 10^{-2}$	$3.3 \times 10^{-3}$	$1.1 \times 10^{-7}$	$1.9 \times 10^{-6}$	$8.3 \times 10^{-6}$
	TCE	$1.4 \times 10^{-3}$	$4.0 \times 10^{-5}$	$1.1 \times 10^{-2}$	$1.7 \times 10^{-2}$	$6.8 \times 10^{-7}$	$1.1 \times 10^{-6}$	$1.3 \times 10^{-6}$
	Carbon tetrachloride	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$1.3 \times 10^{-1}$	$1.3 \times 10^{-1}$	$3.7 \times 10^{-7}$	$7.4 \times 10^{-7}$	$9.0 \times 10^{-7}$
	1,1-DCE	$4.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$6.0 \times 10^{-1}$	$1.2 \times 10^0$	$1.4 \times 10^{-6}$	$2.1 \times 10^{-6}$	$1.1 \times 10^{-5}$
			Subtotals for C-N			$2.5 \times 10^{-6}$	$5.8 \times 10^{-6}$	

Table A-9. (Continued)

Observation point	Chemical	Predicted concentration (mg/L)	Oral intake (mg/kg-d)	Oral cancer-potency factor (CPF) (1/[mg/kg-d])	Oral cancer risk	Inhalation			LLNL total cancer risk
						Oral cancer-potency factor (CPF) (1/[mg/kg-d])	Inhalation cancer risk	EPA total cancer risk	
D-N	Chloroform	$1.0 \times 10^{-5}$	$2.9 \times 10^{-7}$	$6.1 \times 10^{-3}$	$1.7 \times 10^{-9}$	$8.1 \times 10^{-2}$	$2.3 \times 10^{-8}$	$2.5 \times 10^{-8}$	$1.5 \times 10^{-8}$
	PCE	$8.8 \times 10^{-4}$	$2.5 \times 10^{-5}$	$5.1 \times 10^{-2}$	$1.3 \times 10^{-6}$	$3.3 \times 10^{-3}$	$8.3 \times 10^{-8}$	$1.4 \times 10^{-6}$	$6.1 \times 10^{-6}$
	TCE	$8.5 \times 10^{-4}$	$2.4 \times 10^{-5}$	$1.1 \times 10^{-2}$	$2.7 \times 10^{-7}$	$1.7 \times 10^{-2}$	$4.1 \times 10^{-7}$	$6.8 \times 10^{-7}$	$7.9 \times 10^{-7}$
	Carbon tetrachloride	$6.0 \times 10^{-5}$	$1.7 \times 10^{-6}$	$1.3 \times 10^{-1}$	$2.2 \times 10^{-7}$	$1.3 \times 10^{-1}$	$2.2 \times 10^{-7}$	$4.5 \times 10^{-7}$	$5.4 \times 10^{-7}$
	1,1-DCE	$3.0 \times 10^{-4}$	$8.6 \times 10^{-6}$	$6.0 \times 10^{-1}$	$5.1 \times 10^{-6}$	$1.2 \times 10^0$	$1.0 \times 10^{-5}$	$1.5 \times 10^{-5}$	
				Subtotals for D-N	$6.9 \times 10^{-6}$		$1.1 \times 10^{-5}$	$1.8 \times 10^{-5}$	$7.4 \times 10^{-6}$
<i>Mid-field</i>									
C-M	Chloroform	$7.0 \times 10^{-4}$	$2.0 \times 10^{-5}$	$6.1 \times 10^{-3}$	$1.2 \times 10^{-7}$	$8.1 \times 10^{-2}$	$1.6 \times 10^{-6}$	$1.7 \times 10^{-6}$	$1.0 \times 10^{-6}$
	PCE	$1.1 \times 10^{-3}$	$3.1 \times 10^{-5}$	$5.1 \times 10^{-2}$	$1.6 \times 10^{-6}$	$3.3 \times 10^{-3}$	$1.0 \times 10^{-7}$	$1.7 \times 10^{-6}$	$7.6 \times 10^{-6}$
	TCE	$1.3 \times 10^{-3}$	$3.7 \times 10^{-5}$	$1.1 \times 10^{-2}$	$4.1 \times 10^{-7}$	$1.7 \times 10^{-2}$	$6.3 \times 10^{-7}$	$1.0 \times 10^{-6}$	$1.2 \times 10^{-6}$
	Carbon tetrachloride	$3.0 \times 10^{-5}$	$8.6 \times 10^{-7}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-7}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-7}$	$2.2 \times 10^{-7}$	$2.7 \times 10^{-7}$
	1,1-DCE	$1.0 \times 10^{-1}$	$2.9 \times 10^{-3}$	$6.0 \times 10^{-1}$	$1.7 \times 10^{-3}$	$1.2 \times 10^0$	$3.4 \times 10^{-3}$	$5.1 \times 10^{-3}$	$1.0 \times 10^{-5}$
				Subtotals for C-M	$1.7 \times 10^{-3}$		$3.4 \times 10^{-3}$	$5.1 \times 10^{-3}$	
D-M	Chloroform	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$6.1 \times 10^{-3}$	$1.7 \times 10^{-8}$	$8.1 \times 10^{-2}$	$2.3 \times 10^{-7}$	$2.5 \times 10^{-7}$	$1.5 \times 10^{-7}$
	PCE	$8.7 \times 10^{-4}$	$2.5 \times 10^{-5}$	$5.1 \times 10^{-2}$	$1.3 \times 10^{-6}$	$3.3 \times 10^{-3}$	$8.2 \times 10^{-8}$	$1.3 \times 10^{-6}$	$6.0 \times 10^{-6}$
	TCE	$9.5 \times 10^{-4}$	$2.7 \times 10^{-5}$	$1.1 \times 10^{-2}$	$3.0 \times 10^{-7}$	$1.7 \times 10^{-2}$	$4.6 \times 10^{-7}$	$7.6 \times 10^{-7}$	$8.9 \times 10^{-7}$
	Carbon tetrachloride	$6.0 \times 10^{-5}$	$1.7 \times 10^{-6}$	$1.3 \times 10^{-1}$	$2.2 \times 10^{-7}$	$1.3 \times 10^{-1}$	$2.2 \times 10^{-7}$	$4.5 \times 10^{-7}$	$5.4 \times 10^{-7}$
	1,1-DCE	$2.2 \times 10^{-4}$	$6.3 \times 10^{-6}$	$6.0 \times 10^{-1}$	$3.8 \times 10^{-6}$	$1.2 \times 10^0$	$7.5 \times 10^{-6}$	$1.1 \times 10^{-5}$	
				Subtotals for D-M	$5.6 \times 10^{-6}$		$8.5 \times 10^{-6}$	$1.4 \times 10^{-5}$	$7.6 \times 10^{-6}$

Table A-9. (Continued)

Observation point	Chemical	Predicted concentration (mg/L)	Oral intake (mg/kg-d)	Oral cancer-potency factor (CPF) (1/[mg/kg-d])	Oral cancer risk	Inhalation		EPA total cancer risk	LLNL total cancer risk
						potency factor (CPF) (1/[mg/kg-d])	Inhalation cancer risk		
<i>Far-field</i>									
A-F	Chloroform	$1.8 \times 10^{-3}$	$5.1 \times 10^{-5}$	$6.1 \times 10^{-3}$	$3.1 \times 10^{-7}$	$8.1 \times 10^{-2}$	$4.2 \times 10^{-6}$	$4.5 \times 10^{-6}$	$2.7 \times 10^{-6}$
	PCE	$5.0 \times 10^{-6}$	$1.4 \times 10^{-7}$	$5.1 \times 10^{-2}$	$7.3 \times 10^{-9}$	$3.3 \times 10^{-3}$	$4.7 \times 10^{-10}$	$7.8 \times 10^{-9}$	$3.4 \times 10^{-8}$
	TCE	$1.1 \times 10^{-3}$	$3.1 \times 10^{-5}$	$1.1 \times 10^{-2}$	$3.5 \times 10^{-7}$	$1.7 \times 10^{-2}$	$5.3 \times 10^{-7}$	$8.8 \times 10^{-7}$	$1.0 \times 10^{-6}$
	Carbon tetrachloride	$7.0 \times 10^{-5}$	$2.0 \times 10^{-6}$	$1.3 \times 10^{-1}$	$2.6 \times 10^{-7}$	$1.3 \times 10^{-1}$	$2.6 \times 10^{-7}$	$5.2 \times 10^{-7}$	$6.3 \times 10^{-7}$
	1,1-DCE	$4.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$6.0 \times 10^{-1}$	$6.9 \times 10^{-7}$	$1.2 \times 10^0$	$1.4 \times 10^{-6}$	$2.1 \times 10^{-6}$	
			Subtotals for A-F		$1.6 \times 10^{-6}$		$6.3 \times 10^{-6}$	$7.9 \times 10^{-6}$	$4.3 \times 10^{-6}$
B-F	Chloroform	$1.0 \times 10^{-6}$	$2.9 \times 10^{-8}$	$6.1 \times 10^{-3}$	$1.7 \times 10^{-10}$	$8.1 \times 10^{-2}$	$2.3 \times 10^{-9}$	$2.5 \times 10^{-9}$	$1.5 \times 10^{-9}$
	PCE	$2.0 \times 10^{-4}$	$5.7 \times 10^{-6}$	$5.1 \times 10^{-2}$	$2.9 \times 10^{-7}$	$3.3 \times 10^{-3}$	$1.9 \times 10^{-8}$	$3.1 \times 10^{-7}$	$1.4 \times 10^{-6}$
	TCE	$1.4 \times 10^{-3}$	$4.0 \times 10^{-5}$	$1.1 \times 10^{-2}$	$4.4 \times 10^{-7}$	$1.7 \times 10^{-2}$	$6.8 \times 10^{-7}$	$1.1 \times 10^{-6}$	$1.3 \times 10^{-6}$
	Carbon tetrachloride	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$1.3 \times 10^{-1}$	$3.7 \times 10^{-7}$	$1.3 \times 10^{-1}$	$3.7 \times 10^{-7}$	$7.4 \times 10^{-7}$	$9.0 \times 10^{-7}$
	1,1-DCE	$1.0 \times 10^{-5}$	$2.9 \times 10^{-7}$	$6.0 \times 10^{-1}$	$1.7 \times 10^{-7}$	$1.2 \times 10^0$	$3.4 \times 10^{-7}$	$5.1 \times 10^{-7}$	$3.6 \times 10^{-6}$
			Subtotals for B-F		$1.3 \times 10^{-6}$		$1.4 \times 10^{-6}$	$2.7 \times 10^{-6}$	
C-F	Chloroform	$6.0 \times 10^{-4}$	$1.7 \times 10^{-5}$	$6.1 \times 10^{-3}$	$1.0 \times 10^{-7}$	$8.1 \times 10^{-2}$	$1.4 \times 10^{-6}$	$1.5 \times 10^{-6}$	$8.9 \times 10^{-7}$
	PCE	$1.0 \times 10^{-3}$	$2.9 \times 10^{-5}$	$5.1 \times 10^{-2}$	$1.5 \times 10^{-6}$	$3.3 \times 10^{-3}$	$9.4 \times 10^{-8}$	$1.6 \times 10^{-6}$	$6.9 \times 10^{-6}$
	TCE	$1.2 \times 10^{-3}$	$3.4 \times 10^{-5}$	$1.1 \times 10^{-2}$	$3.8 \times 10^{-7}$	$1.7 \times 10^{-2}$	$5.8 \times 10^{-7}$	$9.6 \times 10^{-7}$	$1.1 \times 10^{-6}$
	Carbon tetrachloride	$3.0 \times 10^{-5}$	$8.6 \times 10^{-7}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-7}$	$1.3 \times 10^{-1}$	$1.1 \times 10^{-7}$	$2.2 \times 10^{-7}$	$2.7 \times 10^{-7}$
	1,1-DCE	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$6.0 \times 10^{-1}$	$1.7 \times 10^{-6}$	$1.2 \times 10^0$	$3.4 \times 10^{-6}$	$5.1 \times 10^{-6}$	$9.2 \times 10^{-6}$
			Subtotals for C-F		$3.8 \times 10^{-6}$		$5.6 \times 10^{-6}$	$9.4 \times 10^{-6}$	

Table A-9. (Continued)

Observation point	Chemical	Predicted concentration (mg/L)	Oral intake (mg/kg-d)	Oral cancer-potency factor (CPF) (1/[mg/kg-d])	Oral cancer risk	Inhalation cancer-potency factor (CPF) (1/[mg/kg-d])	Inhalation cancer risk	EPA total cancer risk	LLNL total cancer risk
D-F	Chloroform	$1.6 \times 10^{-4}$	$4.6 \times 10^{-6}$	$6.1 \times 10^{-3}$	$2.8 \times 10^{-8}$	$8.1 \times 10^{-2}$	$3.7 \times 10^{-7}$	$4.0 \times 10^{-7}$	$2.4 \times 10^{-7}$
	PCE	$8.6 \times 10^{-4}$	$2.5 \times 10^{-5}$	$5.1 \times 10^{-2}$	$1.3 \times 10^{-6}$	$3.3 \times 10^{-3}$	$8.1 \times 10^{-8}$	$1.3 \times 10^{-6}$	$5.9 \times 10^{-6}$
	TCE	$9.5 \times 10^{-4}$	$2.7 \times 10^{-5}$	$1.1 \times 10^{-2}$	$3.0 \times 10^{-7}$	$1.7 \times 10^{-2}$	$4.6 \times 10^{-7}$	$7.6 \times 10^{-7}$	$8.9 \times 10^{-7}$
	Carbon tetrachloride	$6.3 \times 10^{-5}$	$1.8 \times 10^{-6}$	$1.3 \times 10^{-1}$	$2.3 \times 10^{-7}$	$1.3 \times 10^{-1}$	$2.3 \times 10^{-7}$	$4.7 \times 10^{-7}$	$5.7 \times 10^{-7}$
	1,1-DCE	$2.0 \times 10^{-4}$	$5.7 \times 10^{-6}$	$6.0 \times 10^{-1}$	$3.4 \times 10^{-6}$	$1.2 \times 10^0$	$6.9 \times 10^{-6}$	$1.0 \times 10^{-5}$	
			Subtotals for D-F		$5.2 \times 10^{-6}$		$8.0 \times 10^{-6}$	$1.3 \times 10^{-5}$	$7.6 \times 10^{-6}$

and health-conservative scenarios, respectively, that were derived using the EPA recommended guidance (U.S. EPA, 1989a). The LLNL methodology treats 1,1-DCE as a noncarcinogen; whereas, the EPA methodology treats 1,1-DCE as a carcinogen. For comparison, Tables A-8 and A-9 also contain the risk values derived using the LLNL methodology, which originally appear in Tables A-6 and A-7.

Table A-10 summarizes the LLNL-derived hazard indices for the best-estimate and health-conservative exposure scenarios for 1,1-DCE. Tables A-11 and A-12 contain the noncarcinogenic hazard indices for the best-estimate and health-conservative exposure scenarios, respectively, that were derived according to the EPA recommended guidance (U.S. EPA, 1989a). The hazard index is the total chemical-specific exposure divided by a reference dose (RfD), which is the estimated maximum chronic daily intake of the chemical not expected to produce adverse health effects. The RfDs are taken from EPA reference material (U.S. EPA, 1989b and 1990). For comparison, Tables A-11 and A-12 also contain the hazard-index values derived by the LLNL methodology, which appear in Table A-10.

Additional details concerning the methods of calculating incremental cancer risk and noncarcinogenic hazard index for ground water contaminants can be found in Section 6 and Appendix S of the RI (Thorpe *et al.*, 1990).

## A-2. COMPARISON OF LLNL AND EPA PROCEDURES FOR ASSESSING RISK

The procedures used by LLNL for assessing exposure and estimating risk for the RI differed in certain respects from methods recommended by the EPA (U.S. EPA, 1989a). Cancer potencies for TCE, PCE, and chloroform were calculated based on metabolized rather than applied doses (see Section 6.1.2.1 and Table 6.1.2-1 in Thorpe *et al.*, 1990). Moreover, on the basis of a comprehensive review of the toxicological literature concerning 1,1-DCE, this VOC was treated as a noncarcinogenic compound (see Section 6.1.2-2 and Appendix R in Thorpe *et al.*, 1990). The LLNL approach is consistent with that adopted by the State of California Department of Health Services (DHS, 1988) concerning the potential carcinogenicity of 1,1-DCE. However, the EPA has classified 1,1-DCE as a group C carcinogen (i.e., possible human carcinogen), and has derived cancer potencies for this compound (U.S. EPA, 1989b and 1990).

In addition, the LLNL calculations of water-based exposures to the VOCs of concern include estimates of exposure from four different pathways (i.e., ingestion of drinking water, ingestion of fruits and vegetables irrigated with potable water, inhalation of potable water indoors, and dermal uptake of potable water during showering and bathing). The EPA typically considers only two of these pathways: ingestion and inhalation of potable water. Accordingly, for purposes of comparison, cancer risks were calculated using EPA methodology (U.S. EPA, 1989a) and toxicity data (U.S. EPA, 1989b and 1990). These estimates appear in Appendix S of the RI.

Table A-13 lists the maximum incremental cancer risks associated with exposure to VOCs in ground water at LLNL if no cleanup or treatment were to take place. As described in Section 3, estimates of cancer risk are presented based on both the LLNL and the EPA methodology, and on two different exposure scenarios (i.e., best estimate and health

*Text continues on page A-31*

Table A-10. Comparisons of RfD for 1,1-DCE for both best-estimate and health-conservative exposure scenarios, remediated ground water.

Well-group/monitor well	Best-estimate			Health-conservative		
	1,1-DCE exposure value (mg/kg-d)	RfD (mg/kg-d)	Ratio (Exposure/RfD)	1,1-DCE exposure value (mg/kg-d)	RfD (mg/kg-d)	Ratio (Exposure/RfD)
<i>Near-field</i>						
A-N	NA	$9.0 \times 10^{-3}$	NA	$2.8 \times 10^{-6}$	$9.0 \times 10^{-3}$	$3.1 \times 10^{-4}$
B-N	NA	$9.0 \times 10^{-3}$	NA	$2.8 \times 10^{-7}$	$9.0 \times 10^{-3}$	$3.1 \times 10^{-5}$
C-N	NA	$9.0 \times 10^{-3}$	NA	$2.8 \times 10^{-6}$	$9.0 \times 10^{-3}$	$3.1 \times 10^{-4}$
D-N	NA	$9.0 \times 10^{-3}$	NA	$2.1 \times 10^{-5}$	$9.0 \times 10^{-3}$	$2.3 \times 10^{-3}$
<i>Mid-field</i>						
C-M	NA	$9.0 \times 10^{-3}$	NA	$7.0 \times 10^{-6}$	$9.0 \times 10^{-3}$	$7.8 \times 10^{-4}$
D-M	NA	$9.0 \times 10^{-3}$	NA	$1.5 \times 10^{-5}$	$9.0 \times 10^{-3}$	$1.7 \times 10^{-3}$
<i>Far-field</i>						
A-F	$5.5 \times 10^{-10}$	$9.0 \times 10^{-3}$	$6.1 \times 10^{-8}$	$2.8 \times 10^{-6}$	$9.0 \times 10^{-3}$	$3.1 \times 10^{-4}$
B-F <sup>a</sup>	$1.4 \times 10^{-8}$	$9.0 \times 10^{-3}$	$1.6 \times 10^{-6}$	$7.0 \times 10^{-7}$	$9.0 \times 10^{-3}$	$7.8 \times 10^{-5}$
C-F	$6.9 \times 10^{-10}$	$9.0 \times 10^{-3}$	$7.7 \times 10^{-8}$	$7.0 \times 10^{-6}$	$9.0 \times 10^{-3}$	$7.8 \times 10^{-4}$
D-F	$6.2 \times 10^{-8}$	$9.0 \times 10^{-3}$	$6.9 \times 10^{-6}$	$1.4 \times 10^{-5}$	$9.0 \times 10^{-3}$	$1.6 \times 10^{-3}$

NA = Not available.

<sup>a</sup> Concentration value for 1,1-DCE is the same for B-F(TCE<sub>max</sub>) and B-F(CCl<sub>4max</sub>), therefore, only a single value is shown.

Table A-11. Calculation of the noncarcinogenic hazard index for the best-estimate exposure scenario, remediated ground water.

Observation point	Chemical	Predicted <sup>a</sup> concentration (mg/L)	Water		Oral RFD (mg/kg-d)	EPA hazard index (Exposure/RfD)	LLNL <sup>b</sup> hazard index (Exposure/RfD)
			ingestion exposure (mg/kg-d)	exposure (mg/kg-d)			
A-F	Chloroform	$6.0 \times 10^{-6}$	$1.7 \times 10^{-7}$	$1.0 \times 10^{-2}$	$1.7 \times 10^{-5}$	$1.7 \times 10^{-5}$	
	PCE	$0.0 \times 10^0$	$0.0 \times 10^0$	$1.0 \times 10^{-2}$	$0.0 \times 10^0$	$0.0 \times 10^0$	
	TCE	$2.0 \times 10^{-8}$	$5.7 \times 10^{-10}$	NA			
	Carbon tetrachloride	$3.0 \times 10^{-10}$	$8.6 \times 10^{-12}$	$7.0 \times 10^{-4}$	$1.2 \times 10^{-8}$	$1.2 \times 10^{-8}$	$6.1 \times 10^{-8}$
	1,1-DCE	$8.0 \times 10^{-9}$	$2.3 \times 10^{-10}$	$9.0 \times 10^{-3}$	$2.5 \times 10^{-8}$	$2.5 \times 10^{-8}$	$6.1 \times 10^{-8}$
			Subtotal for A-F		$1.7 \times 10^{-5}$	$1.7 \times 10^{-5}$	
B-F(TCE <sub>max</sub> )	Chloroform	$3.0 \times 10^{-7}$	$8.6 \times 10^{-9}$	$1.0 \times 10^{-2}$	$8.6 \times 10^{-7}$	$8.6 \times 10^{-7}$	
	PCE	$6.0 \times 10^{-10}$	$1.7 \times 10^{-11}$	$1.0 \times 10^{-2}$	$1.7 \times 10^{-9}$	$1.7 \times 10^{-9}$	
	TCE	$6.0 \times 10^{-7}$	$1.7 \times 10^{-8}$	NA			
	Carbon tetrachloride	$9.0 \times 10^{-8}$	$2.6 \times 10^{-9}$	$7.0 \times 10^{-4}$	$3.7 \times 10^{-6}$	$3.7 \times 10^{-6}$	$1.6 \times 10^{-6}$
	1,1-DCE	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$9.0 \times 10^{-3}$	$6.3 \times 10^{-7}$	$6.3 \times 10^{-7}$	$1.6 \times 10^{-6}$
			Subtotal for B-F(TCE <sub>max</sub> )		$5.2 \times 10^{-6}$	$1.6 \times 10^{-6}$	
B-F(CCl <sub>4</sub> max)	Chloroform	$4.0 \times 10^{-7}$	$1.1 \times 10^{-8}$	$1.0 \times 10^{-2}$	$1.1 \times 10^{-6}$	$1.1 \times 10^{-6}$	
	PCE	$5.0 \times 10^{-10}$	$1.4 \times 10^{-11}$	$1.0 \times 10^{-2}$	$1.4 \times 10^{-9}$	$1.4 \times 10^{-9}$	
	TCE	$6.0 \times 10^{-7}$	$1.7 \times 10^{-8}$	NA			
	Carbon tetrachloride	$9.0 \times 10^{-8}$	$2.6 \times 10^{-9}$	$7.0 \times 10^{-4}$	$3.7 \times 10^{-6}$	$3.7 \times 10^{-6}$	$1.6 \times 10^{-6}$
	1,1-DCE	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$9.0 \times 10^{-3}$	$6.3 \times 10^{-7}$	$6.3 \times 10^{-7}$	$1.6 \times 10^{-6}$
			Subtotal for B-F(CCl <sub>4</sub> max)		$5.5 \times 10^{-6}$	$1.6 \times 10^{-6}$	
C-F	Chloroform	$2.0 \times 10^{-9}$	$5.7 \times 10^{-11}$	$1.0 \times 10^{-2}$	$5.7 \times 10^{-9}$	$5.7 \times 10^{-9}$	
	PCE	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$1.0 \times 10^{-2}$	$5.7 \times 10^{-7}$	$5.7 \times 10^{-7}$	

Table A-11. (Continued)

Observation point	Chemical	Predicted <sup>a</sup> concentration (mg/L)	Water ingestion exposure (mg/kg-d)	Oral RFD (mg/kg-d)	EPA hazard index (Exposure/RfD)	LLNL <sup>b</sup> hazard index (Exposure/RfD)
	TCE	$5.0 \times 10^{-7}$	$1.4 \times 10^{-8}$	NA		
	Carbon tetrachloride	$1.0 \times 10^{-8}$	$2.9 \times 10^{-10}$	$7.0 \times 10^{-4}$	$4.1 \times 10^{-7}$	
	1,1-DCE	$1.0 \times 10^{-8}$	$2.9 \times 10^{-10}$	$9.0 \times 10^{-3}$	$3.2 \times 10^{-8}$	$7.7 \times 10^{-8}$
			Subtotal for C-F		$1.0 \times 10^{-6}$	$7.7 \times 10^{-8}$
D-F	Chloroform	$2.0 \times 10^{-7}$	$5.7 \times 10^{-9}$	$1.0 \times 10^{-2}$	$5.7 \times 10^{-7}$	
	PCE	$6.0 \times 10^{-12}$	$1.7 \times 10^{-13}$	$1.0 \times 10^{-2}$	$1.7 \times 10^{-11}$	
	TCE	$2.0 \times 10^{-8}$	$5.7 \times 10^{-10}$	NA		
	Carbon tetrachloride	$3.0 \times 10^{-9}$	$8.6 \times 10^{-11}$	$7.0 \times 10^{-4}$	$1.2 \times 10^{-7}$	
	1,1-DCE	$9.0 \times 10^{-7}$	$2.6 \times 10^{-8}$	$9.0 \times 10^{-3}$	$2.9 \times 10^{-6}$	$6.9 \times 10^{-6}$
			Subtotal for D-F		$3.6 \times 10^{-6}$	$6.9 \times 10^{-6}$

NA = Not available.

<sup>a</sup> Predicted concentrations have been reduced by a factor of ten to account for in-well dilution that will occur as a municipal well draws water from both contaminated and uncontaminated zones.

<sup>b</sup> Based on the methodology used in the BPHA (Layton and Daniels, 1990), the LLNL index is calculated only for 1,1-DCE, because California DHS and LLNL do not consider the data from carcinogenicity studies to support its classification as a carcinogen. Under the LLNL approach, 1,1-DCE is not considered a carcinogen.

Table A-12. Calculation of the noncarcinogenic hazards for the health-conservative exposure scenario based on EPA methodologies and comparison to LLNL results, remediated ground water.

Observation point	Chemical	Predicted concentration (mg/L)	Water ingestion (mg/kg-d)	Oral RfD (mg/kg-d)	EPA hazard index (Exposure/RfD)	LLNL <sup>a</sup> hazard index (Exposure/RfD)
<i>Near-field</i>						
A-N	Chloroform	$2.0 \times 10^{-3}$	$5.7 \times 10^{-5}$	$1.0 \times 10^{-2}$	$5.7 \times 10^{-3}$	
	PCE	$5.0 \times 10^{-9}$	$1.4 \times 10^{-10}$	$1.0 \times 10^{-2}$	$1.4 \times 10^{-8}$	
	TCE	$1.3 \times 10^{-3}$	$3.7 \times 10^{-5}$	NA		
	Carbon tetrachloride	$8.0 \times 10^{-5}$	$2.3 \times 10^{-6}$	$7.0 \times 10^{-4}$	$3.3 \times 10^{-3}$	
	1,1-DCE	$4.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$9.0 \times 10^{-3}$	$1.3 \times 10^{-4}$	$3.1 \times 10^{-4}$
			Subtotals for A-N	$9.1 \times 10^{-3}$	$3.1 \times 10^{-4}$	
B-N	Chloroform	$5.0 \times 10^{-12}$	$1.4 \times 10^{-13}$	$1.0 \times 10^{-2}$	$1.4 \times 10^{-11}$	
	PCE	$4.0 \times 10^{-4}$	$1.1 \times 10^{-5}$	$1.0 \times 10^{-2}$	$1.1 \times 10^{-3}$	
	TCE	$1.4 \times 10^{-3}$	$4.0 \times 10^{-5}$	NA		
	Carbon tetrachloride	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$7.0 \times 10^{-4}$	$4.1 \times 10^{-3}$	$3.1 \times 10^{-5}$
	1,1-DCE	$4.0 \times 10^{-6}$	$1.1 \times 10^{-7}$	$9.0 \times 10^{-3}$	$1.3 \times 10^{-5}$	$3.1 \times 10^{-5}$
			Subtotals for B-N	$5.2 \times 10^{-3}$	$3.1 \times 10^{-5}$	
C-N	Chloroform	$2.0 \times 10^{-8}$	$5.7 \times 10^{-10}$	$1.0 \times 10^{-2}$	$5.7 \times 10^{-8}$	
	PCE	$1.2 \times 10^{-3}$	$3.4 \times 10^{-5}$	$1.0 \times 10^{-2}$	$3.4 \times 10^{-3}$	
	TCE	$1.4 \times 10^{-3}$	$4.0 \times 10^{-5}$	NA		
	Carbon tetrachloride	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$7.0 \times 10^{-4}$	$4.1 \times 10^{-3}$	$3.1 \times 10^{-4}$
	1,1-DCE	$4.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$9.0 \times 10^{-3}$	$1.3 \times 10^{-4}$	$3.1 \times 10^{-4}$
			Subtotals for C-N	$7.6 \times 10^{-3}$	$3.1 \times 10^{-4}$	

Table A-12. (Continued)

Observation point	Chemical	Predicted concentration (mg/L)	Water ingestion (mg/kg-d)	Oral RfD (mg/kg-d)	EPA hazard index (Exposure/RfD)	LLNL <sup>a</sup> hazard index (Exposure/RfD)
D-N	Chloroform	$1.0 \times 10^{-5}$	$2.9 \times 10^{-7}$	$1.0 \times 10^{-2}$	$2.9 \times 10^{-5}$	
	PCE	$8.8 \times 10^{-4}$	$2.5 \times 10^{-5}$	$1.0 \times 10^{-2}$	$2.5 \times 10^{-3}$	
	TCE	$8.5 \times 10^{-4}$	$2.4 \times 10^{-5}$	NA		
	Carbon tetrachloride	$6.0 \times 10^{-5}$	$1.7 \times 10^{-6}$	$7.0 \times 10^{-4}$	$2.4 \times 10^{-3}$	
	1,1-DCE	$3.0 \times 10^{-4}$	$8.6 \times 10^{-6}$	$9.0 \times 10^{-3}$	$9.5 \times 10^{-4}$	$2.3 \times 10^{-3}$
			Subtotals for D-N	$5.9 \times 10^{-3}$	$2.3 \times 10^{-3}$	
Mid-field C-M	Chloroform	$7.0 \times 10^{-4}$	$2.0 \times 10^{-5}$	$1.0 \times 10^{-2}$	$2.0 \times 10^{-3}$	
	PCE	$1.1 \times 10^{-3}$	$3.1 \times 10^{-5}$	$1.0 \times 10^{-2}$	$3.1 \times 10^{-3}$	
	TCE	$1.3 \times 10^{-3}$	$3.7 \times 10^{-5}$	NA		
	Carbon tetrachloride	$3.0 \times 10^{-5}$	$8.6 \times 10^{-7}$	$7.0 \times 10^{-4}$	$1.2 \times 10^{-3}$	
	1,1-DCE	$1.0 \times 10^{-1}$	$2.9 \times 10^{-3}$	$9.0 \times 10^{-3}$	$3.2 \times 10^{-1}$	$7.8 \times 10^{-4}$
			Subtotals for C-M	$3.2 \times 10^{-1}$	$7.8 \times 10^{-4}$	
D-M	Chloroform	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$1.0 \times 10^{-2}$	$2.9 \times 10^{-4}$	
	PCE	$8.7 \times 10^{-4}$	$2.5 \times 10^{-5}$	$1.0 \times 10^{-2}$	$2.5 \times 10^{-3}$	
	TCE	$9.5 \times 10^{-4}$	$2.7 \times 10^{-5}$	NA		
	Carbon tetrachloride	$6.0 \times 10^{-5}$	$1.7 \times 10^{-6}$	$7.0 \times 10^{-4}$	$2.4 \times 10^{-3}$	
	1,1-DCE	$2.2 \times 10^{-4}$	$6.3 \times 10^{-6}$	$9.0 \times 10^{-3}$	$7.0 \times 10^{-4}$	$1.7 \times 10^{-3}$
			Subtotals for D-M	$5.9 \times 10^{-3}$	$1.7 \times 10^{-3}$	

Table A-12. (Continued)

Observation point	Chemical	Predicted concentration (mg/L)	Water ingestion (mg/kg-d)	Oral RFD (mg/kg-d)	EPA hazard index (Exposure/RfD)	LLNL <sup>a</sup> hazard index (Exposure/RfD)
<i>Far-field</i> A-F	Chloroform	$1.8 \times 10^{-3}$	$5.1 \times 10^{-5}$	$1.0 \times 10^{-2}$	$5.1 \times 10^{-3}$	
	PCE	$5.0 \times 10^{-6}$	$1.4 \times 10^{-7}$	$1.0 \times 10^{-2}$	$1.4 \times 10^{-5}$	
	TCE	$1.1 \times 10^{-3}$	$3.1 \times 10^{-5}$	NA		
	Carbon tetrachloride	$7.0 \times 10^{-5}$	$2.0 \times 10^{-6}$	$7.0 \times 10^{-4}$	$2.9 \times 10^{-3}$	$3.1 \times 10^{-4}$
	1,1-DCE	$4.0 \times 10^{-5}$	$1.1 \times 10^{-6}$	$9.0 \times 10^{-3}$	$1.3 \times 10^{-4}$	$3.1 \times 10^{-4}$
				Subtotals for A-F	$8.1 \times 10^{-3}$	
B-F	Chloroform	$1.0 \times 10^{-6}$	$2.9 \times 10^{-8}$	$1.0 \times 10^{-2}$	$2.9 \times 10^{-6}$	
	PCE	$2.0 \times 10^{-4}$	$5.7 \times 10^{-6}$	$1.0 \times 10^{-2}$	$5.7 \times 10^{-4}$	
	TCE	$1.4 \times 10^{-3}$	$4.0 \times 10^{-5}$	NA		
	Carbon tetrachloride	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$7.0 \times 10^{-4}$	$4.1 \times 10^{-3}$	$7.8 \times 10^{-5}$
	1,1-DCE	$1.0 \times 10^{-5}$	$2.9 \times 10^{-7}$	$9.0 \times 10^{-3}$	$3.2 \times 10^{-5}$	$7.8 \times 10^{-5}$
				Subtotals for B-F	$4.7 \times 10^{-3}$	
C-F	Chloroform	$6.0 \times 10^{-4}$	$1.7 \times 10^{-5}$	$1.0 \times 10^{-2}$	$1.7 \times 10^{-3}$	
	PCE	$1.0 \times 10^{-3}$	$2.9 \times 10^{-5}$	$1.0 \times 10^{-2}$	$2.9 \times 10^{-3}$	
	TCE	$1.2 \times 10^{-3}$	$3.4 \times 10^{-5}$	NA		
	Carbon tetrachloride	$3.0 \times 10^{-5}$	$8.6 \times 10^{-7}$	$7.0 \times 10^{-4}$	$1.2 \times 10^{-3}$	$7.8 \times 10^{-4}$
	1,1-DCE	$1.0 \times 10^{-4}$	$2.9 \times 10^{-6}$	$9.0 \times 10^{-3}$	$3.2 \times 10^{-4}$	$7.8 \times 10^{-4}$
				Subtotals for C-F	$6.1 \times 10^{-3}$	

Table A-12. (Continued)

Observation point	Chemical	Predicted concentration (mg/L)	Water ingestion (mg/kg-d)	Oral RfD (mg/kg-d)	EPA hazard index (Exposure/RfD)	LLNL <sup>a</sup> hazard index (Exposure/RfD)
D-F	Chloroform	$1.6 \times 10^{-4}$	$4.6 \times 10^{-6}$	$1.0 \times 10^{-2}$	$4.6 \times 10^{-4}$	
	PCE	$8.6 \times 10^{-4}$	$2.5 \times 10^{-5}$	$1.0 \times 10^{-2}$	$2.5 \times 10^{-3}$	
	TCE	$9.5 \times 10^{-4}$	$2.7 \times 10^{-5}$	NA		
	Carbon tetrachloride	$6.3 \times 10^{-5}$	$1.8 \times 10^{-6}$	$7.0 \times 10^{-4}$	$2.6 \times 10^{-3}$	
	1,1-DCE	$2.0 \times 10^{-4}$	$5.7 \times 10^{-6}$	$9.0 \times 10^{-3}$	$6.3 \times 10^{-4}$	$1.6 \times 10^{-3}$
				Subtotals for D-F	$6.1 \times 10^{-3}$	$1.6 \times 10^{-3}$

<sup>a</sup> Based on the methodology used in the BPHA (Layton and Daniels, 1990), the LLNL index is calculated only for 1,1-DCE, because California DHS and LLNL do not consider the data from carcinogenicity studies to support its classification as a carcinogen. Under the LLNL approach, 1,1-DCE is not considered a carcinogen.

**Table A-13. Comparison of risk values for unremediated scenario derived using the LLNL and the EPA methodologies.**

Unremediated scenario (from RI Predecisional Final)	Highest 70-y average concentration of total VOCs (ppb)	Arrival time of maximum concentration (y)	Based on LLNL method for estimating cancer risk	Based on EPA method for estimating cancer risk
Best estimate <sup>a</sup>	0.15	270	$2.0 \times 10^{-7}$	$7.0 \times 10^{-7}$
Health conservative <sup>a</sup>	440	110	$1.0 \times 10^{-3}$	$1.0 \times 10^{-3}$
Health conservative <sup>b</sup>	584	35	$2.0 \times 10^{-3}$	$2.0 \times 10^{-3}$

<sup>a</sup> Based on receptor wells in downtown Livermore.

<sup>b</sup> Based on a potential monitor well drilled 250 ft west of LLNL.

conservative; see Sections 5.3 and 6 in Thorpe *et al.*, 1990). These exposure scenarios represent alternative sets of assumptions regarding the movement, degradation, and dilution of the contaminated ground water.

The LLNL procedure for deriving incremental cancer risk results in a best-estimate value of  $2 \times 10^{-7}$  and the EPA procedure yields a best-estimate incremental cancer risk of  $7 \times 10^{-7}$ . Both risk values are for exposures for receptor wells in downtown Livermore. Under the health-conservative exposure scenario, the EPA and LLNL methods for estimating incremental cancer risk produced identical results of  $1 \times 10^{-3}$  for receptor wells in downtown Livermore, and  $2 \times 10^{-3}$  for exposure to water from a potential monitor well drilled 250 ft west of LLNL. The differences between the LLNL and EPA methodologies notwithstanding, the maximum incremental cancer risks determined using the two approaches (i.e., LLNL and EPA) are either identical (health-conservative scenario) or only slightly different (best-estimate scenario).

Table A-14 summarizes the estimated maximum incremental cancer risks for the best-estimate and health-conservative exposure scenarios associated with concentrations at receptor wells after remediation of the ground water at the LLNL site to MCLs. These values were determined using the LLNL or EPA methodologies, as noted in the table.

Under the best-estimate scenario, the maximum incremental cancer risk estimated using the LLNL method is  $9 \times 10^{-9}$  for exposure related to a receptor well in downtown Livermore; the corresponding value resulting from the use of the EPA method is  $5 \times 10^{-8}$ . Under the health-conservative scenario, the LLNL methodology yields estimates of a maximum cancer risk of  $9 \times 10^{-6}$  associated with exposure at a receptor well in downtown Livermore (far-field) and  $1 \times 10^{-5}$  for a potential monitor well drilled 250 ft west of LLNL (near-field). Using the EPA methodology, the corresponding values for maximum incremental cancer risk for exposure at near- and far-field wells are  $2 \times 10^{-5}$  and  $1 \times 10^{-5}$ , respectively. Regardless of which exposure scenario or method of calculating exposure and risk is considered, these risk levels are significantly lower than those estimated in the baseline case described in the RI.

### A-3. ANALYTICAL TRANSPORT MODELING USED FOR RISK ASSESSMENT

To calculate the risk associated with VOCs remaining in the subsurface after the proposed remedial alternatives have reduced the concentrations of VOCs to or below their MCLs, the analytical transport model PLUME (In-Situ, 1986) was used to simulate the migration of PCE, TCE, chloroform, carbon tetrachloride, and 1,1-DCE from LLNL property. Except for the initial mass input to the system, the parameters entered into PLUME were the same as those used for the Baseline Public Health Assessment (BPHA) modeling described in the RI report (Thorpe *et al.*, 1990). Modeling assumptions and verification are further discussed in that document.

For these simulations, we have assumed that areas currently containing concentrations of VOCs greater than 100 ppb (10 ppb for carbon tetrachloride) will be the only localities to contain significant VOCs, at or below MCLs, after remediation. Therefore, the locations of the source area rectangles input to PLUME were based on the present day "hot spots" of the modeled compound (Figures A-1 through A-5). The initial concentration within a source rectangle was set equal to the compound's projected concentration at the time that remedial action objectives have been met as follows: PCE = 5 ppb, TCE = 5 ppb, chloroform = 20 ppb, 1,1-DCE = 3 ppb,

*Text continues on page A-38*

**Table A-14. Comparison of maximum risk values for remediated scenario derived using the LLNL or the EPA methodologies.**

Unremediated scenario (from RI Predecisional Final)	Highest 70-y average concentration of total VOCs (ppb)	Arrival time of maximum concentration (y)	Based on LLNL method for estimating cancer risk	Based on EPA method for estimating cancer risk
Best estimate <sup>a</sup>	0.006	265	$8.9 \times 10^{-9}$	$4.7 \times 10^{-8}$
Health conservative <sup>a</sup>	3.0	97.5	$9.2 \times 10^{-6}$	$1.3 \times 10^{-5}$
Health conservative <sup>b</sup>	3.4	22	$1.1 \times 10^{-5}$	$1.8 \times 10^{-5}$

<sup>a</sup> Based on receptor wells in downtown Livermore.

<sup>b</sup> Based on a potential monitor well drilled 250 ft west of LLNL.





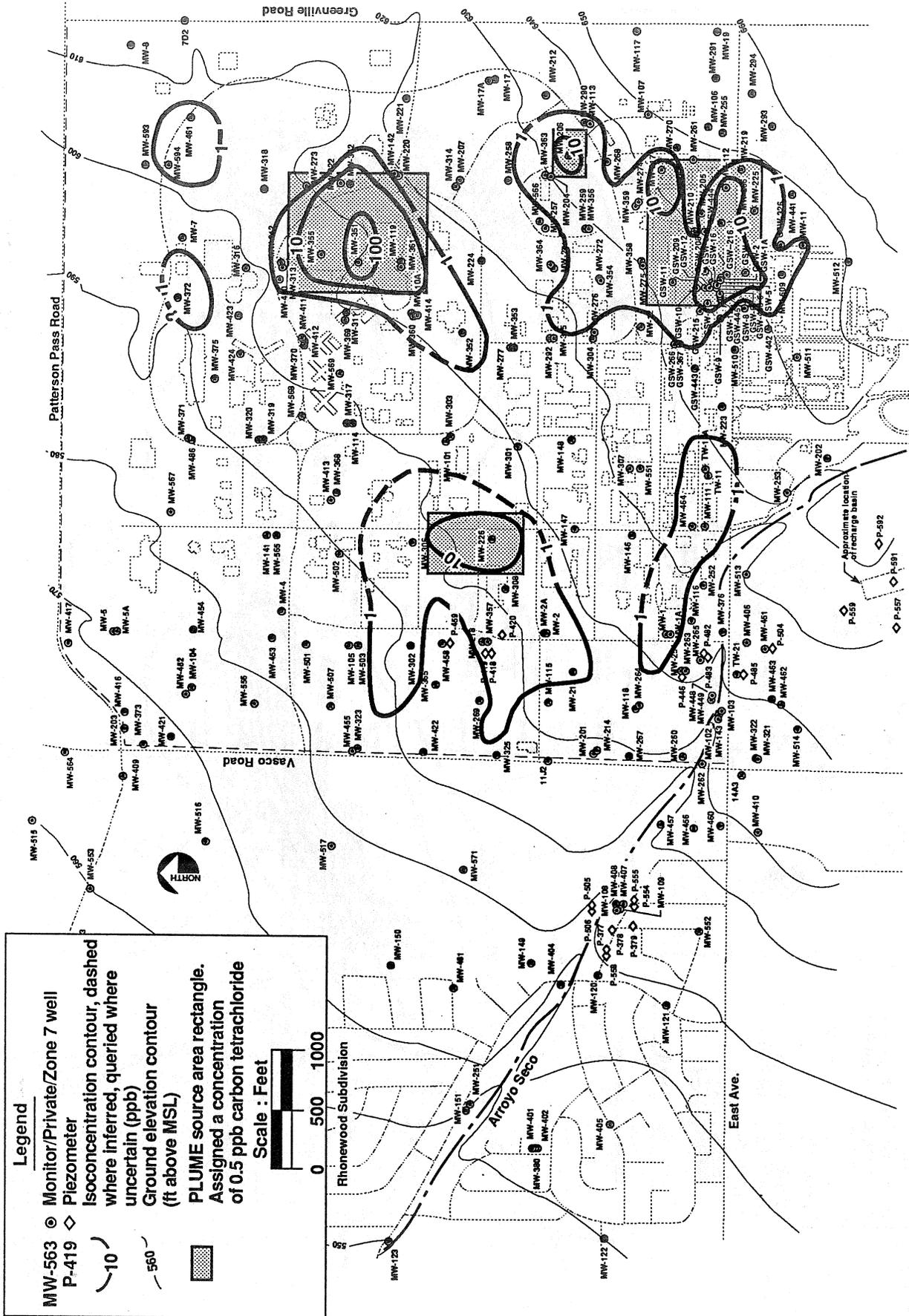


Figure A-3. Isoconcentration contour map of carbon tetrachloride in ground water (Spring 1989), showing PLUME source area rectangles.

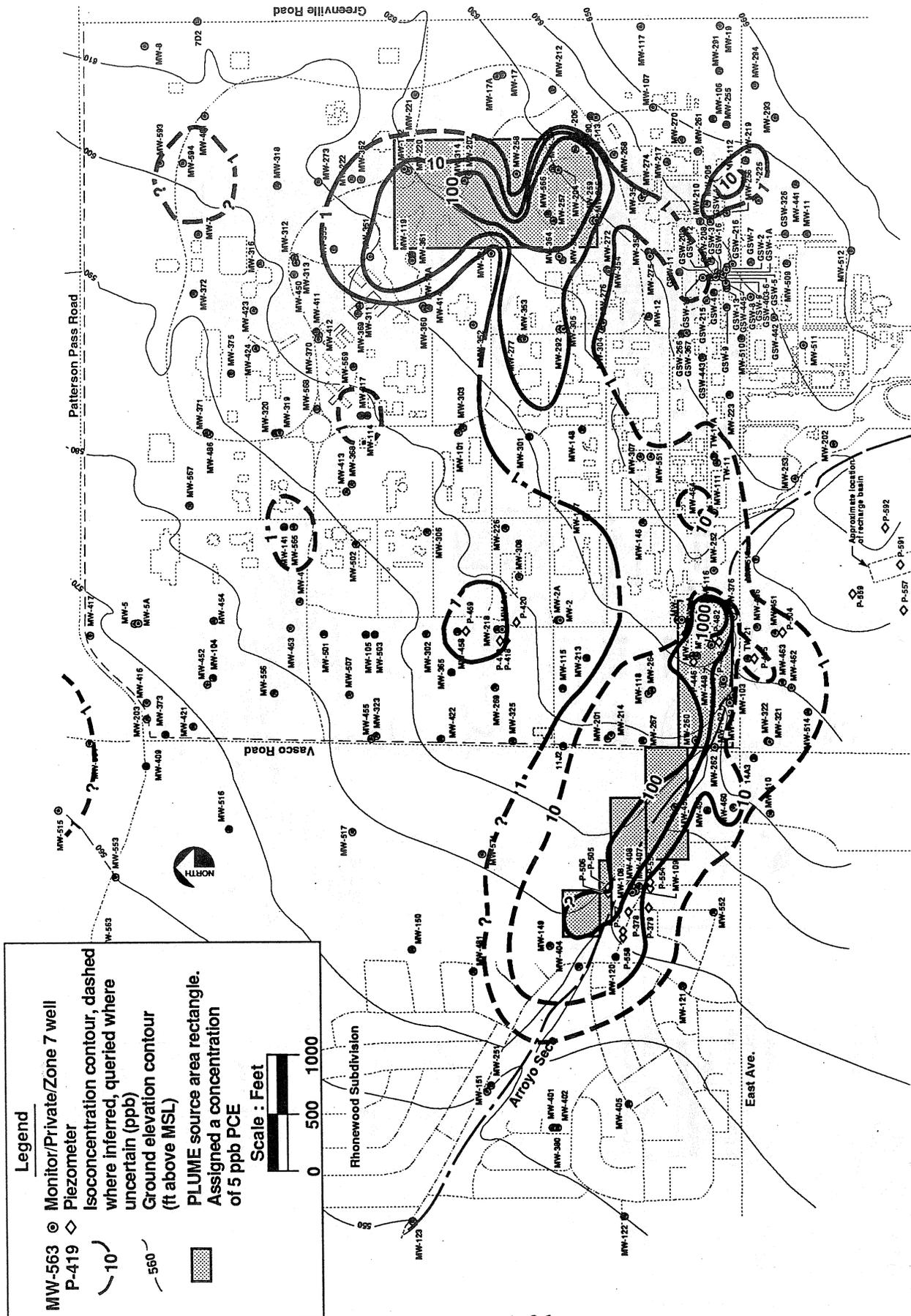


Figure A-4. Isoconcentration contour map of PCE in ground water (Spring 1989), showing PLUME source area rectangle.

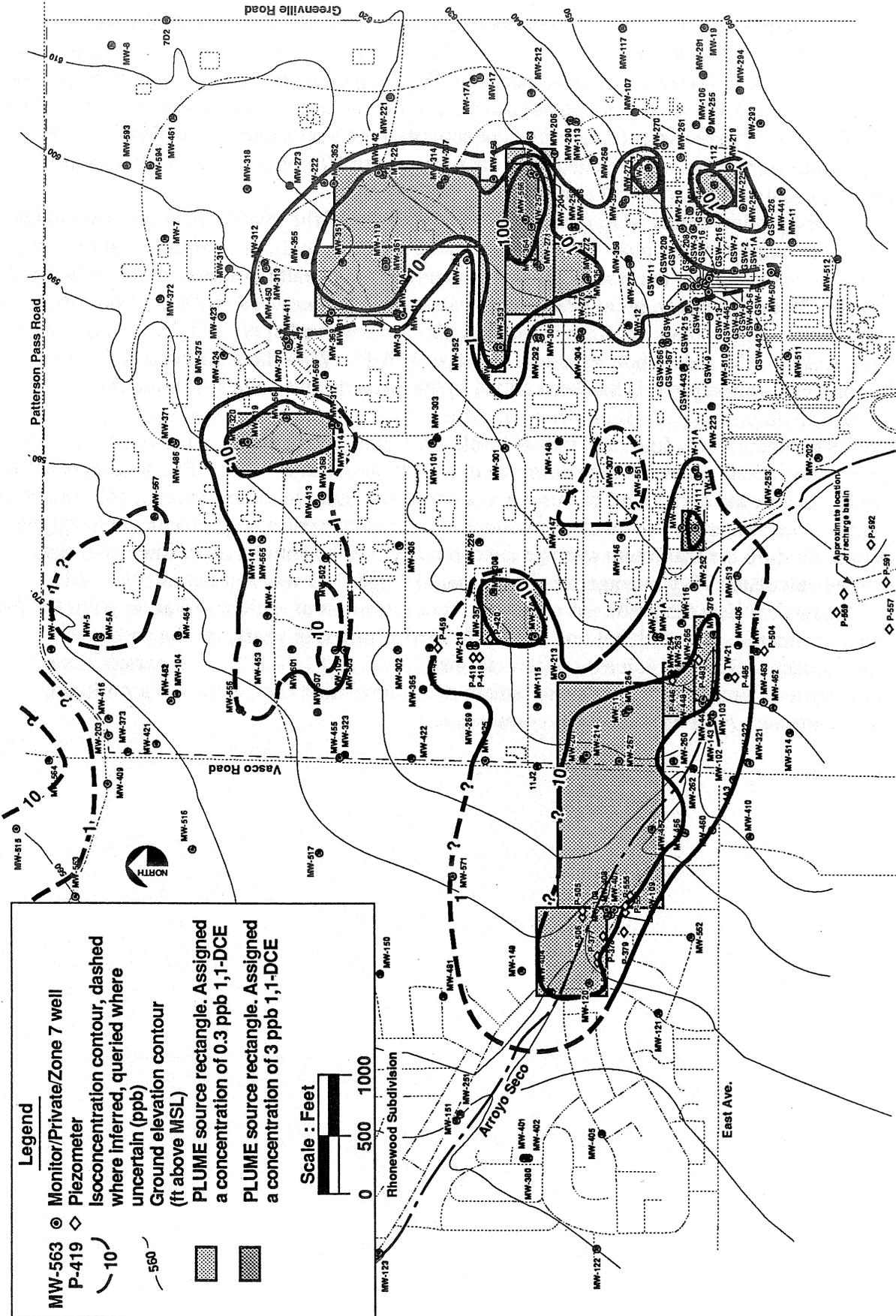


Figure A-5. Isoconcentration contour map of 1,1-DCE in ground water (Spring 1989), showing PLUME source area rectangles.

and carbon tetrachloride = 0.5 ppb. These concentrations may be lower than MCLs. For instance, 1,1-DCE is usually associated with TCE and found at lower concentrations than TCE, beneath the LLNL site. When the concentration of TCE in ground water is reduced to 5 ppb, the concentration of 1,1-DCE is reduced below its MCL of 6 ppb. Source rectangles with more than 100 ppb of 1,1-DCE were assigned an initial concentration of 3 ppb, one-half its MCL. Other 1,1-DCE source rectangles were located over the present-day 10-ppb isoconcentration contours (Figure A-5) and assigned an initial concentration of 0.3 ppb.

The observation points were positioned downgradient of the maximum concentration for each modeled compound within an observation field, i.e., near-, mid-, or far-field (Figure A-6). Tables A-1 and A-2 present the results of the best-estimate and health-conservative simulations, respectively. The observation point labels are consistent with those used in the RI report (e.g., the maximum concentration of chloroform in the near-field is observed at point A-N; the maximum concentrations of TCE and carbon tetrachloride at point B-F). With the addition of 1,1-DCE simulations, observation point D has been added to the analysis and Tables A-1 and A-2.

The simulated compounds are listed in column two, and the modeling results are presented in columns three, four, and five of Tables A-1 and A-2. Column three contains 70-y average concentration values for each compound at each observation point. The maximum 70-y average is listed for the compound of interest at a particular observation point (e.g., chloroform at "A" points). The values for the other compounds at a particular point were calculated using the 70-y period yielding the maximum average concentration for the compound of interest at that point. If the calculated 70-y average was lower than 0.1 ppb, ND was entered into the table.

Column four lists the predicted maximum concentrations at each observation point for the compound of interest. The fifth column shows the arrival times, in years, for the predicted maximum concentrations. Predicted concentrations of PCE and 1,1-DCE are reported in the mid-field because "hot spots" exist downgradient of the near-field (i.e., west of Vasco Road; Figures A-1 through A-5) only for these compounds.

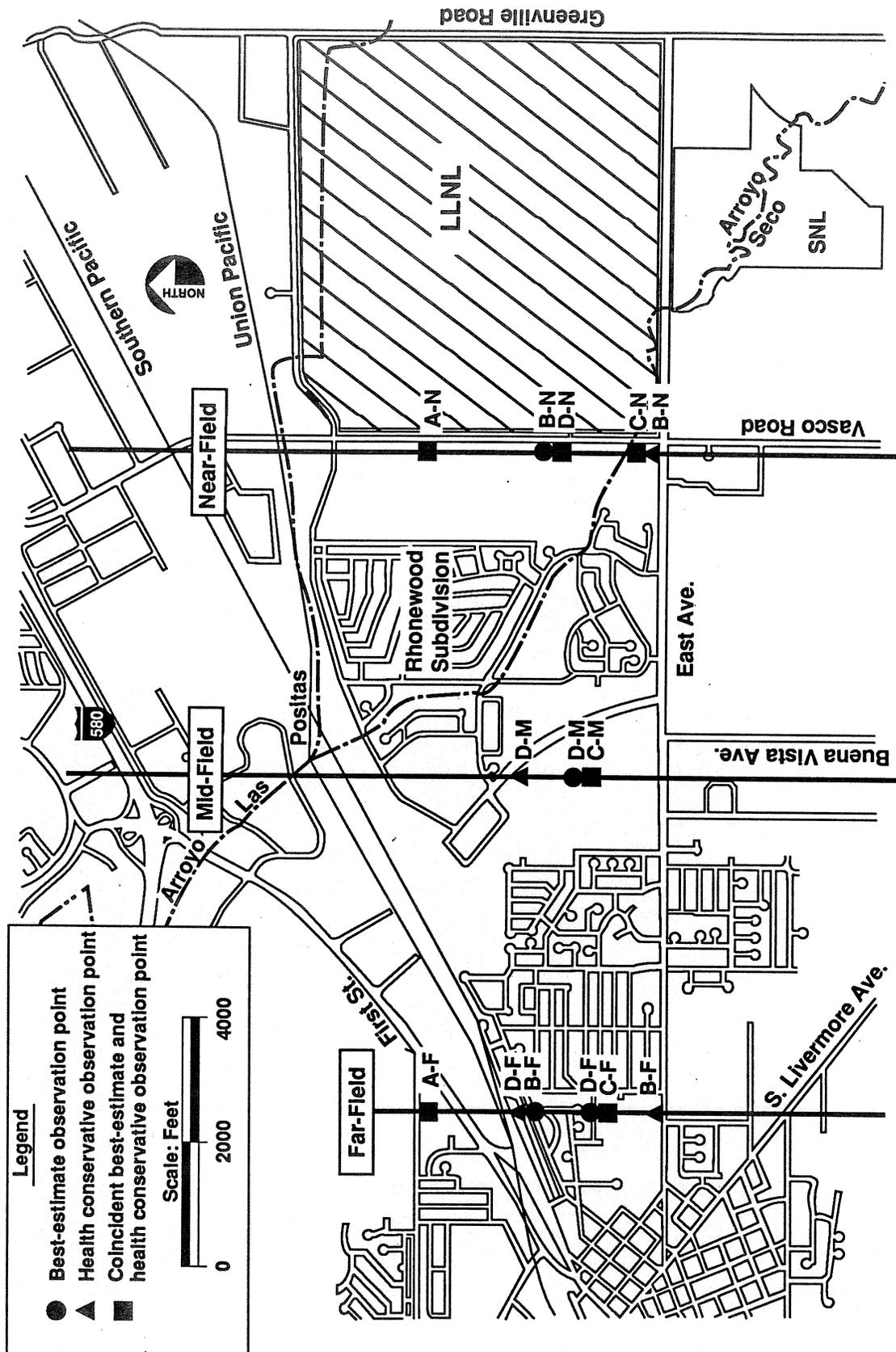


Figure A-6. Observation points for contaminant migration simulations for risk assessment.

**APPENDIX B**  
**ANALYTICAL FLOW MODELING**

## APPENDIX B

# ANALYTICAL FLOW MODELING

### B-1. EXTRACTION WELLS

The two-dimensional analytic flow model CAPTURE was used to estimate the number and placement of extraction wells for the two extraction alternatives considered in Section 3. CAPTURE estimates the flow paths in a water-bearing zone that would result from ground water extraction, and produces graphic output showing horizontal flow lines converging on an extraction well or wells. The model assumes a homogeneous isotropic aquifer of uniform thickness, with a unidirectional, uniform gradient prior to pumping. These simplifying assumptions limit the accuracy of CAPTURE for the heterogeneous alluvial sediments beneath LLNL, but the program is useful for preliminary siting of extraction wells, well field design, and sensitivity analysis. A more detailed description of this model is presented below.

The important input parameters for determining the extent of capture for an extraction well are hydraulic conductivity ( $K$ ), thickness of permeable sediments ( $b$ ), hydraulic gradient ( $i$ ), and pumping rate ( $Q$ ). The values assigned to these parameters in the CAPTURE simulations for Extraction Alternatives Nos. 1 and 2 are presented in Table B-1.

The major uncertainty in predicting capture areas in the alluvial deposits at LLNL is the variability of  $K$ . Preliminary results of pumping tests on existing extraction well EW-415 indicate a local transmissivity ( $T$ ) of about 1 ft<sup>2</sup>/min and a hydraulic conductivity ( $K$ ) of about 0.01 ft/min. In addition, Tompson (1990) applied stochastic theory to pumping test results and obtained an effective conductivity ( $K_{\text{eff}}$ ) of 0.01 ft/min for the LLNL site and vicinity. This was used in both extraction scenarios to site pumping locations for hydraulic control of VOC plumes.

Because the two remedial alternatives encompass different areas, the hydraulic gradient entered into CAPTURE was based on the average hydraulic gradient within each domain. The average hydraulic gradient in the LLNL area is about 0.004 ft/ft, whereas the average hydraulic gradient in the western part of the study area is about 0.0025 ft/ft. These gradient values were assigned a westerly direction in Alternative Nos. 1 and 2, respectively.

The width of the hydraulic capture area ( $w$ ) is directly proportional to the ratio of  $Q/b$  and CAPTURE requires that the simulated aquifer be of uniform thickness. However, the actual values of  $Q$  and  $b$  will vary depending on location and well construction. Preliminary results from EW-415 indicate that it can maintain a pumping rate of 50 gpm without causing excessive drawdowns in the well. EW-415 has a screen length of 100 ft, hence the ratio of  $Q/b$  for EW-415 is about 0.5, which is less than the sitewide average of 1.0 gpm/ft based on hydraulic test results. Assuming the ratio of  $Q/b$  equal to 0.5 is a conservative estimate of well yield over the rest of the LLNL site, we assigned a pumping rate ( $Q$ ) of 20 gpm to all extraction wells and an aquifer thickness ( $b$ ) of 40 ft in both simulations ( $Q/b = 20 \text{ gpm}/40 \text{ ft} = 0.5 \text{ gpm/ft}$ ).

### B-2. DESCRIPTION OF THE ANALYTIC FLOW MODEL CAPTURE

CAPTURE is a proprietary computer program that evaluates the removal or containment of ground water from a water-bearing zone by extraction wells or trenches. It is written in

**Table B-1. Summary of CAPTURE input parameters for Extraction Alternative No. 1 and Alternative No. 2.**

Parameter	Units	Extraction Alternative No. 1 value	Extraction Alternative No. 2 value
Hydraulic conductivity	ft/min	0.01	0.01
Hydraulic gradient	ft/ft	0.004 (west)	0.0025 (west)
Aquifer thickness	ft	40	40
Number of extraction wells	N/A	18	8
Pumping rate of extraction wells	gpm	20	20

FORTTRAN and runs on an MS-DOS microcomputer with a dot matrix printer, plotter, screen graphics, or laser printer. Up to 20 wells and 20 trenches can be modeled simultaneously.

### B-2.1. Theoretical Basis and Assumptions

Ground water flow is modeled according to conservation of mass under transient or steady state conditions (Javandel *et al.*, 1984). Movement of ground water is simulated by injecting particles at each selected well or trench and tracking the particle flow. Plotting the resulting flow lines produces the same pattern as extraction at the same rate and opposite hydraulic gradient. Modeling multiple wells is based on RESSQ (Javandel *et al.*, 1984). Modeling the capture area for a trench is based on a steady state line-sink analytical solution presented by Muskat (1937). The program code was developed independently of RESSQ (Javandel *et al.*, 1984) to run under MS-DOS by Donald G. McEdwards.

The water-bearing zone is assumed to be horizontal, fully saturated, homogeneous, of constant thickness and infinite lateral extent, and confined above and below by impermeable layers. The hydraulic gradient is assumed to be uniform in the absence of pumping. Thus, prior to pumping, undisturbed ground water flow in this idealized water-bearing zone is uniform and horizontal, and ground water "particles" follow parallel paths, or streamlines, in the downgradient direction.

Adding pumping wells and/or trenches alters the background uniform flow pattern. The wells or trenches are assumed to fully penetrate the water-bearing zone. The trenches are assumed to have been pumped at a constant rate for an infinite time, such that the water-bearing zone reaches equilibrium with the trenches. The wells can be either transient or in equilibrium with respect to the water-bearing zone.

### B-2.2. CAPTURE Output and Use

Flow paths of ground water "particles" will be drawn toward the extraction wells or trenches, and some flow will be "captured" and removed from the water-bearing zone. A cone of depression is formed by the concavity of the piezometric surface. This capture is depicted in the CAPTURE plots by flow lines that converge and terminate at pumped wells or trenches. Figure B-1 is a schematic CAPTURE plot that lists some of the model assumptions and describes how the input parameters influence the shape of the resulting flow lines.

The velocity of ground water flow in the capture area is shown graphically on the flow lines by Xs, which represent time intervals of ground water particle flow along each depicted flow path. Water on the upgradient side of a pumped well moves more rapidly toward the well than water on the downgradient side, and the capture area upgradient of the extraction well is larger than the capture area downgradient. The differences between upgradient and downgradient water velocities and capture areas are nonexistent where there is no gradient and increase as the gradient increases. A "stagnation point" exists at the rim of the cone of depression where, under steady state condition, water will not move (Figure B-1).

To achieve efficient capture and removal of contaminated ground water, extraction wells and trenches should be placed so the shape of the capture area closely corresponds to the area of contaminated ground water. The downgradient edge of the capture area should lie at or beyond the downgradient margin of contamination to ensure complete capture or containment.

**Explanation**

— x — x — x — x — x — x —  
Ground water flow line; distance between X's is annual ground water movement

**Assumptions**

- Homogeneous, isotropic hydraulic conductivity (K)
- Constant thickness (b)
- Uniform gradient (i)
- Constant pumping rate (Q)

Capture zone width =  $\frac{Q}{Kbi} = w$

Stagnation point =  $\frac{w}{2\pi}$

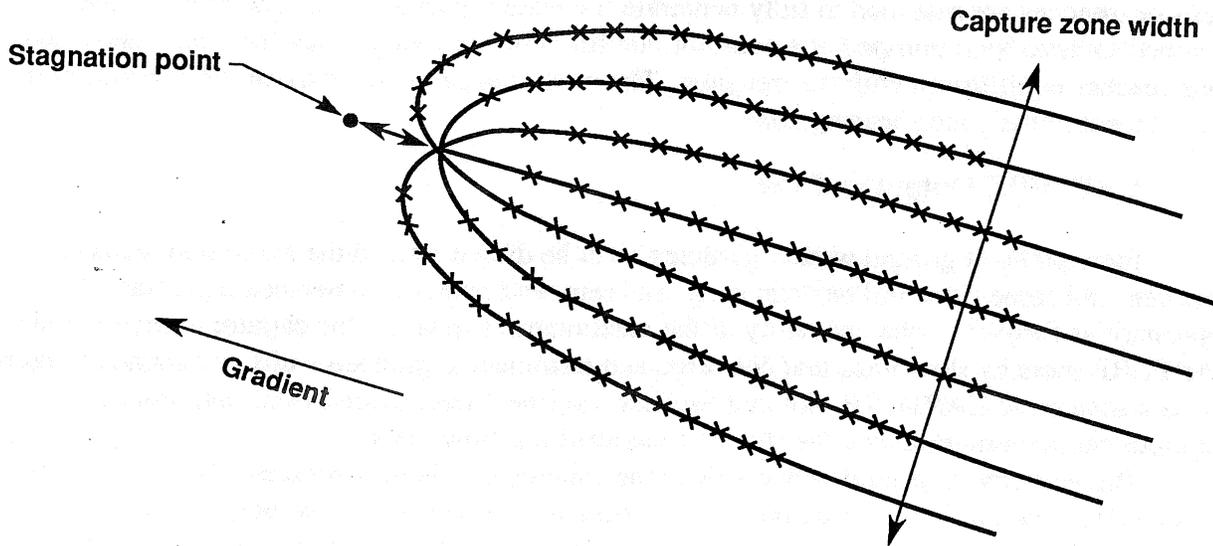


Figure B-1. Schematic CAPTURE plot.

Generally, several iterations are run to represent alternative locations and combinations of wells and trenches, as well as best- and worst-case assumptions for geohydrologic parameters.

In using CAPTURE to optimize the location of extraction wells and trenches, several points should be considered to help assess the accuracy of the predicted capture area:

- The degree to which the water-bearing zone conforms to the idealized conditions assumed by CAPTURE.
- Input pumping rates must not exceed those which can actually be achieved; otherwise, the predicted capture area will be too large.
- Capture area is fairly sensitive to the input parameters of pumping rate, hydraulic conductivity, aquifer thickness, and hydraulic gradient.

### B-2.3. CAPTURE Input

The following data are needed as inputs to the CAPTURE computer program, and are listed in the required order:

TITLE\$ (character string in quotes)

SCALE, GRAD, THETA

- SCALE is a plot scale in feet per inch.
- GRAD is the hydraulic gradient in the water-bearing zone with no pumping. Sign of gradient is taken as positive in the direction of ground water flow.
- THETA is the angle of the downgradient direction in degrees counterclockwise from the positive  $x$  axis.

PERM, STORAGE, HEIGHT, POR

- PERM is the hydraulic conductivity of the water-bearing zone in feet per minute.
- STORAGE is the storativity of the water-bearing zone—dimensionless.
- HEIGHT is the thickness of the water-bearing zone in feet.
- POR is the effective porosity of the water-bearing zone in decimal form.

STP, TEND, LPATH

- STP is the length in feet of the straight line segments used to make each streamline.
- TEND is the time at which the particles reach the pumping wells (= 0 for steady state analysis).
- LPATH is the length of the streamlines to be drawn in feet.

NWSTREAM, NLSTREAM, PLTM1, PLTM2, PLTDT

- NWSTREAM is the number of streamlines converging on each well.
- NLSTREAM is the number of streamline pairs converging on each line sink or source (trench).
- PLTM1 and PLTM2 are the times, in days, of the first and last "X's" plotted along each streamline.
- PLTDT is the time, in days, between each plotted asterisk along the streamlines.

For each trench:

SIGMA(J), XEND1(J), YEND1(J), XEND2(J), YEND2(J), LYN\$(J)

- SIGMA(J) is the flow rate per unit length of the Jth trench in gallons per minute per foot. Pumping is positive and injection is negative.
- XEND1(J) and YEND1(J) are  $x,y$  coordinates of one end of a trench, in feet from the origin of the plot.

- XEND2(J) and YEND2(J) are  $x,y$  coordinates of the other end of the trench, in feet from the origin of the plot.
- LYN\$(J) is "Y" or "N" depending on whether streamlines of the trench are to be plotted.
- SIGMA = 999 signals end of line sink (trench) input.

For each well:

Q(K), XCORD(K), YCORD(K), WYN\$(K)

- Q(K) is the flow rate of the Kth well in gallons per minute. Extraction is positive and injection is negative.
- XCORD(K) and YCORD(K) are the coordinates of the well, in feet from the origin of the plot.
- WYN\$(K) is "Y" or "N" depending on whether or not streamlines of this well are to be plotted.
- Q(K) = 999 signals end of well input.

**APPENDIX C**  
**CLEANUP TIME ESTIMATES**

## APPENDIX C

### CLEANUP TIME ESTIMATES

#### C-1. PUMP-AND-TREAT SCENARIO 1: EXTRACTION OVER ENTIRE VOC PLUME

To estimate the length of time necessary to remediate VOCs in ground water at LLNL, the entire plume can be idealized as a well-mixed "tank" (Figure C-1):

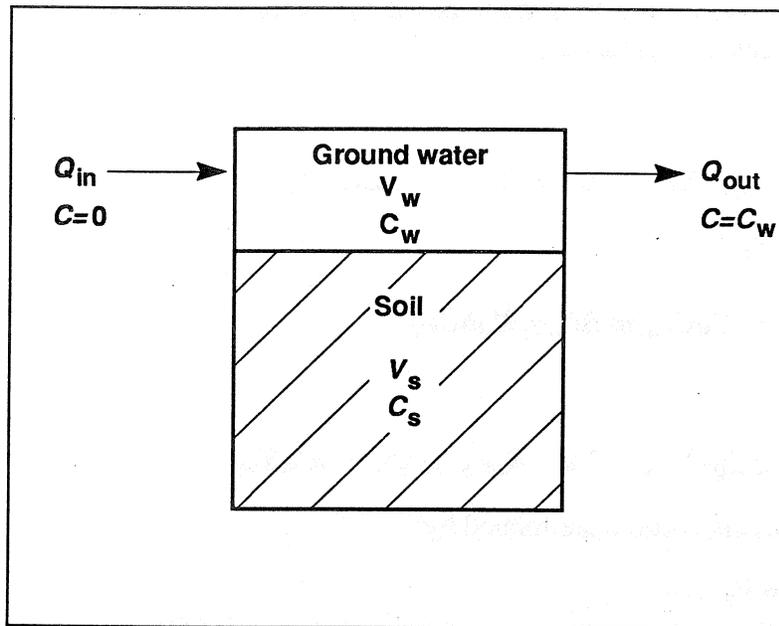


Figure C-1. Idealized VOC plume for cleanup time estimate.

where

- $Q_{in} = Q_{out} = Q_p$  = extraction pumping rate,
- $C_{in}$  = VOC concentration upgradient of plume (assumed = 0),
- $C_{out}$  = VOC concentration in extraction wells (assumed =  $C_w$ ),
- $C_w$  = average VOC concentration in ground water within plume ( $M_w/V_w$ ),
- $V_w$  = volume of ground water within plume,
- $M_w$  = total mass of VOCs in ground water,
- $C_s$  = average VOC concentration sorbed in saturated soil,
- $V_s$  = volume of saturated soil solids within plume, and
- $\rho_s$  = specific gravity of solids.

In this idealization, the plume contains two reservoirs of VOC mass: VOCs in ground water and VOCs sorbed in saturated soil. We assume that all sources of VOCs within the vadose zone have been (or will be) removed so that no more leaching of contaminants from the vadose zone to the saturated zone will occur. As ground water is extracted from the plume, clean ground

water flows inward from the plume margins. This clean ground water comes into contact with soil containing sorbed VOCs and a new concentration equilibrium is established. This process is assumed to be governed by an equilibrium soil-water distribution coefficient ( $K_d$ ), which is defined as (concentration sorbed)/(concentration in solution). Thus, VOC mass is transferred from sorbed soil to ground water and exits the system via the extraction wells. In addition, VOCs in ground water may degrade into nonhazardous compounds. This process is assumed to be first-order with a rate constant ( $\lambda$ ) that results in an equivalent half-life of 50 y (Thorpe *et al.*, 1990). A balance of mass equation can be written as

$$\Delta \text{mass}_{\text{tot}} = \Delta \text{mass}_s + \Delta \text{mass}_w.$$

The change in total mass consists of the removal by pumping ( $-C_w Q_p$ ) and loss due to transformation processes ( $-\lambda C_w V_w$ ),

expanding:

$$(-C_w Q_p - \lambda C_w V_w) \Delta t = \Delta C_s V_s \rho_s + \Delta C_w V_w;$$

invoking the definition of  $K_d$ :

$$K_d = C_s / C_w, \text{ so } \Delta C_s = K_d \Delta C_w;$$

substituting:

$$(-C_w Q_p - \lambda C_w V_w) \Delta t = K_d \Delta C_w V_s \rho_s + \Delta C_w V_w;$$

void volume and solids volume are related by:

$$V_s = V_w (1-n)/n;$$

substituting:

$$(-C_w Q_p - \lambda C_w V_w) \Delta t = K_d \Delta C_w V_w \rho_s (1-n)/n + \Delta C_w V_w;$$

rearranging:

$$\left( \frac{-Q_p}{V_w} - \lambda \right) C_w \Delta t = \Delta C_w [K_d \rho_s (1-n)/n + 1].$$

The quantity in brackets is recognized as the retardation factor,  $R$  (Bear and Verruijt, 1987). Substituting and rearranging:

$$\Delta C_w / C_w = -(Q_p / V_w R + \lambda / R) \Delta t;$$

and reexpressing as a differential:

$$dC_w/C_w = -(Q_p/V_w R + \lambda/R) dt;$$

integrating:

$$\int_{C_{w0}}^{C_w} \frac{dC_w}{C_w} = -\left(\frac{Q_p}{V_w R} + \frac{\lambda}{R}\right) \int_0^t dt;$$

then

$$\ln(C_w) \Big|_{C_{w0}}^{C_w} = -\left(\frac{Q_p}{V_w R} + \frac{\lambda}{R}\right) t;$$

evaluating and reexpressing:

$$C_w(t) = C_{w0} \exp\left[-\left(\frac{Q_p}{V_w R} + \frac{\lambda}{R}\right) t\right].$$

This is recognized as an exponentially declining function in time, with an exponential constant of  $k = Q_p/V_w R + \lambda/R$ . The half-life of this function is  $t_{1/2} = \ln 2/k$ .

- The estimated extraction flow rate ( $Q_{out}$ ) of the 18 proposed extraction wells is about 350 gpm ( $7 \times 10^8$  L/y), based on pilot study experience and capture zone modeling.
- The volume of ground water containing VOCs ( $V_w$ ) is estimated to be  $2.9 \times 10^9$  gal ( $1.1 \times 10^{10}$  L), based on summation of the volumes of the plume where VOC concentrations exceed MCLs or action levels for one or more compounds.
- The mass of VOCs in ground water ( $M_w$ ) within this region is estimated to be 1934 lb (879 kg), based on integration of the concentrations over the volume of the plume exceeding MCLs or action levels.
- The total mass of VOCs in ground water and soil is equal to the mass of VOCs in ground water times the retardation factor ( $R$ ). Assuming a representative retardation factor of 1.5 (Thorpe *et al.*, 1990; Tompson, 1990), the total mass of VOCs in the plume is  $879 \times 1.5 = 1319$  kg.
- The average initial concentration of VOCs in ground water ( $C_{w0}$ ) is  $M_w/V_w = 81$   $\mu$ g/L (ppb).

A plot of the removal rate, based on these estimated parameters, is shown in Section 3 as Figure 3-8. Using these parameters, the half-life of this removal function is 13.3 y. Based on the estimated total extraction pumping rate, one pore volume of ground water is exchanged every 13 y ( $=V_w/Q_w$ ). As shown in Figure 3-8, the length of time necessary to lower the average concentration of the plume to less than 5 ppb (a hypothetical cleanup standard) is about 53 y.

Several of the assumptions and parameter values affect the duration of this cleanup time. Conditions that may decrease cleanup time are:

- The preceding discussion assumes that ground water is extracted uniformly from the entire plume. In practice, we will selectively locate the extraction wells within regions of highest

VOC concentration. This will result in greater rates of VOC removal in the early stages of pumping, and will decrease cleanup time.

- If a greater total extraction pumping rate can be maintained without significant dewatering of the saturated sediments, cleanup time will decrease.
- If less sorbed mass is present (smaller  $R$  and  $K_d$ ), cleanup time will diminish.
- If the degradation half-life is less than 50 y, cleanup time will diminish.

Conditions that may increase cleanup time are:

- If a smaller total extraction pumping rate is achieved, which may result if significant dewatering of saturated sediments occurs, cleanup time may increase.
- If more sorbed mass is present (larger  $R$  and  $K_d$ ), cleanup time may increase.
- If equilibrium concentrations between soil and ground water are not established during pumping (rate-limited desorption), cleanup time may increase.
- If the degradation half-life is greater than 50 y, cleanup time may increase.

## C-2. PUMP-AND-TREAT SCENARIO 2: EXTRACTION AT DOWNGRAIDENT MARGIN OF VOC PLUME

In this scenario, eight extraction wells are located near the western margin of the VOC plumes. These wells will arrest further offsite migration of VOCs by intercepting all ground water that flows beneath the LLNL site. However, these wells will not be located at the regions of highest concentration of VOCs on site, and therefore cleanup times will be longer. The preceding analysis is also applied to this scenario, only the flow rate is reduced.

- The estimated extraction flow rate ( $Q_{out}$ ) of the eight proposed extraction wells is about 200 gpm ( $3.7 \times 10^8$  L/y), based on pilot study experience and capture zone modeling.
- The volume of ground water containing VOCs ( $V_w$ ) remains the same at  $2.9 \times 10^9$  gal ( $1.1 \times 10^{10}$  L), based on summation of the volumes of the plume where VOC concentrations exceed MCLs or action levels for one or more compounds.
- The mass of VOCs in ground water remains the same at 879 kg.
- The total mass of VOCs in the plume ( $M_{tot}$ ) within this region remains the same at 2900 lb (1319 kg).
- The average initial concentration of VOCs in ground water ( $C_{w0}$ ) is also 81  $\mu$ g/L (ppb).

A plot of the removal rate, based on the lower total flow rate and the other estimated parameters, is shown as Figure 3-8. Using these parameters, the half-life of this removal function is 22 y. Based on the estimated total extraction pumping rate, one pore volume of ground water is exchanged every 28 y ( $=V_w/Q_w$ ). As shown in Figure 3-8, the length of time necessary to lower the average concentration of the plume to less than 5 ppb (a hypothetical cleanup standard) is about 87 y.

## C-3. ACHIEVING REMEDIAL ACTION OBJECTIVES WITHOUT ACTIVE REMEDIATION

If active ground water remediation were not implemented, the VOC plume would slowly disperse and degrade by natural processes. The transport model PLUME was used (In-Situ, Inc., 1986) to estimate the time necessary for the concentration of each VOC to fall below its MCL. The model and the "best-estimate" parameters used for the simulations are discussed in the Remedial Investigation (Thorpe *et al.*, 1989). The compounds simulated included PCE, TCE,

chloroform, and "other VOCs," which represent compounds such as carbon tetrachloride and 1,1-DCE. The simulations indicated that, of these VOCs, the concentration of TCE takes the longest time to diminish to its MCL of 5 ppb. This is predicted to occur after about 360 y. These best-estimate simulations predict that all concentrations of VOCs within the plume fall below MCLs before the plume has migrated more than about 6500 ft west of LLNL.

**APPENDIX D**  
**CONCEPTUAL DESIGNS AND**  
**COST ESTIMATES FOR GROUND WATER**  
**TREATMENT TECHNOLOGIES**

# APPENDIX D

## CONCEPTUAL DESIGNS AND COST ESTIMATES FOR GROUND WATER TREATMENT TECHNOLOGIES

### D-1. DESCRIPTION OF GROUND WATER TREATMENT TECHNOLOGIES

The alternative technologies for treatment of extracted ground water are described in this Appendix. General process descriptions are provided together with process flow diagrams for each technology. Factors influencing the design of each treatment system are discussed, as are the operational concerns for each technology.

The cost data presented here for each situation at LLNL provide the basis for assembling the technologies into the treatment alternatives shown in Section 4. All treatment facilities are costed using a 30-y life, as suggested in EPA guidance. However, to compare the extraction alternatives, which differ significantly in the lifetime of operation, a supplemental analysis was performed for the treatment facilities included in Extraction Alternative No. 2. This analysis was based on the estimated time to reach MCLs, as presented in Section 3.4.1.3, of 87 y. Albeit not a well-constrained time of operation, the analysis illustrates the approximate effect of the longer operational lifetime. Although not presented, we also calculated the additional cost of Extraction Alternative No. 1 for operation for 53 y (as estimated in Section 3.4.1.3), rather than the standardized 30 y. This increased the present worth of the alternative by less than 10% because of the effect of discounting future expenditures.

#### D-1.1. Water Treatment with Granular-Activated Carbon (GAC)

This alternative is suitable for the removal of most organic chemicals from the ground water and, hence, is effective for treatment of VOCs and FHCs. GAC treatment of the liquid phase is also somewhat effective for the removal of low concentrations of many heavy metals. Treatment is achieved when the water contacts a fixed bed of GAC. The contaminants in the water are adsorbed onto the surface of the GAC. When the capacity of the GAC to adsorb the chemicals is exhausted, the GAC is removed and replaced with fresh material. The spent GAC can be regenerated onsite or at a commercial facility, either with thermal oxidation of the chemicals or collection for recycling.

A process flow diagram for the system using GAC treatment of the liquid phase is given in Figure D-1. The extracted ground water is pumped from the well through the GAC. The pump design criteria specify a discharge pressure sufficient to pump the water through two adsorber units.

The GAC adsorber for liquid-phase treatment consists of a fixed bed of GAC. The diameter and height of the adsorber is determined by the flow rate of water to be treated and by the anticipated rate of saturation of the GAC. The rate of saturation is determined by the flow rate of water and by the concentrations of the chemicals in the water. The breakthrough front (the distance over which the concentrations change from zero to inlet values) can approach

one-half the height of GAC adsorbers. Therefore, to achieve near full use of the GAC, it is normal practice to use two adsorber vessels in series.

When the capacity of the GAC to adsorb the chemicals from the water has been exhausted, indicated by detection of elevated concentrations of the chemicals in the water exiting the first GAC unit in series, the flow is stopped and the GAC in this unit is removed and replaced with fresh material. When the system is restarted, the order of flow through the two GAC adsorbers is reversed. In this way, the adsorber containing the least contaminated GAC will always be in the final polishing position. The spent GAC can be regenerated onsite or transported to a commercial facility where the adsorbed chemicals are oxidized in a furnace.

#### **D-1.2. Air Stripping with GAC Treatment of the Vapor Effluent**

This alternative is suited to the removal of chemicals of moderate to high volatility from the ground water and, hence, is effective for treatment of VOCs and FHCs. Treatment is achieved by contacting the water with a flow of air in a vertical tower containing high surface area packing media, which provide good contact between the water and air. The volatile chemicals are transferred (stripped) from the water to the air as the water flows down over the packing material countercurrent to the air that is blown upward through the packing material. The chemicals that have been transferred to the air are removed from the air before discharge to the atmosphere by adsorption onto GAC in the vapor stream. When the capacity of the GAC to adsorb the chemicals is exhausted, the GAC must be removed and replaced with fresh material. The spent GAC can be regenerated onsite or at a commercial facility, with either thermal destruction of the chemicals or collection for recycling.

The advantage of first air stripping the chemicals before adsorption onto GAC from the vapor phase over direct adsorption onto GAC from the liquid phase is that the capacity of GAC treatment of the vapor phase (expressed as pounds of chemical adsorbed per pound of GAC) is generally significantly greater than that for GAC treatment of the liquid phase. This results in less frequent replacement of the GAC and, hence, lower operating costs for GAC replacement. This must be balanced against the more complex operation and higher installation cost expected for the air stripping system with vapor-phase treatment with GAC over a liquid-phase treatment with GAC system.

A process flow diagram for air stripping with vapor-phase treatment with GAC is given in Figure D-2. The extracted ground water is pumped to the top of the packing media in the air stripping tower. The pump criteria are designed to produce a discharge pressure sufficient to pump the water to the top of the tower.

The air stripper design is based on flow rate of water to be treated, the incoming chemical concentrations, and concentration limits for the treated water discharge. Selection of the tower diameter is governed by the flow rate of water to be treated. Selection of the blower capacity and, hence, quantity of air flow to the tower is based on chemicals present in the water and water flow rate. The height of packing media in the tower (and, therefore, height of the tower) is based on required reduction in concentrations expressed as the ratio of inlet to outlet values for each chemical requiring treatment.

The GAC adsorber for vapor-phase treatment consists of a fixed bed of GAC. Diameter and height of the adsorber are determined by the flow rate of air to be treated and also by the anticipated rate of saturation of the GAC. Rate of saturation is determined by flow rate of air and concentrations of the chemicals in the air. Break-through front (distance over which the

concentrations change from zero to inlet values) is generally very short for GAC treatment of the vapor-phase adsorbers. Therefore, near full use of the GAC can be achieved with use of a single adsorber vessel. When the capacity of the GAC to adsorb chemicals from the air has been exhausted, indicated by detection of trace concentrations of the chemicals in the air exiting the GAC unit, the GAC will be removed and replaced with fresh material. The spent GAC can be regenerated onsite or transported to a commercial facility where the adsorbed chemicals are oxidized in a furnace.

The higher adsorption capacity which can be achieved using GAC treatment of the vapor phase is significantly reduced if the air entering the adsorber is saturated with water vapor (100% relative humidity). This loss of capacity can be prevented if the air relative humidity is reduced to less than 50%. The air exhaust of the stripping tower will be saturated with water and, hence, an air heater is included between the stripper tower and the GAC unit. Heating the air by approximately 20°F will reduce the relative humidity to less than 50%. A blower is also provided to overcome the pressure loss in the air heater and the vapor treatment GAC unit.

### D-1.3. UV/Oxidation Plus Air Stripping with GAC Treatment of the Vapor Effluent

This alternative uses ultraviolet light and either hydrogen peroxide (UV/H<sub>2</sub>O<sub>2</sub>) or ozone (O<sub>3</sub>) to provide the primary water treatment, and an aeration/carbon adsorption system for secondary treatment or polishing. Because of LLNL's experience with the system described in Section 2, we will confine our discussion to hydrogen peroxide. This alternative is well-suited for treatment of VOCs in ground water and is applicable to sites A, B, C, D, E, and G. The effectiveness of this system on FHCs in ground water has not yet been completely evaluated, but bench scale tests with LLNL ground water have reported satisfactory results. A possible future variation on the UV/oxidation method uses solar collectors to provide the UV energy, rather than electrically powered lamps.

The process flow diagram for this system is shown in Figure D-3. The ground water from the wellhead is pumped through a 5-μ filter to remove any suspended fines and particulates prior to entering the UV/H<sub>2</sub>O<sub>2</sub> treatment unit. Immediately upstream of the UV chamber, hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) is injected into the influent at concentrations of 30 to 50 ppm. The water then enters the bottom of the UV chamber and flows upward past the UV lamps that disassociate H<sub>2</sub>O<sub>2</sub> to create highly reactive hydroxyl radicals (OH). The UV light and hydroxyl radicals then act on the organic compounds to break them down to carbon dioxide, water, and chloride ions. This process is particularly effective on haloalkenes because the alkenes are photoreactive and highly susceptible to oxidation by the hydroxyl radical in the photoexcited state. Other organic molecules are similarly oxidized, but at variable reaction rates.

Besides the UV intensity and injected H<sub>2</sub>O<sub>2</sub>, the amount of VOC destruction that occurs depends upon the residence time of the water in the UV chamber. This can be controlled by varying the flow rate until an optimum destruction efficiency is obtained. The residence time for the unit at Pilot Treatment Facility A is about 90 sec, for an operating flow rate of 50 gpm.

The UV/H<sub>2</sub>O<sub>2</sub> system is effective at destroying haloalkenes such as PCE and TCE with double carbon bonds. However, the UV/H<sub>2</sub>O<sub>2</sub> is not as effective at destroying haloalkanes such as 1,1,1-TCA and 1,1-DCA with single carbon bonds. Rather than greatly increase the power consumption or residence time (decreasing flow rate), we chose to further treat the effluent from the UV/H<sub>2</sub>O<sub>2</sub> system that contains residual haloalkanes, with an aeration/carbon adsorption system.

The design of the polishing system consists of a baffled, 1400-gal tank that receives effluent directly from the UV/H<sub>2</sub>O<sub>2</sub> unit. The water is subjected to intense aeration using a centrifugal blower unit that injects air at a rate of 150 ft<sup>3</sup>/min (cfm). Another centrifugal blower unit extracts VOCs, volatilized during the aeration process at an extraction rate of 250 cfm, that pass through a GAC filter prior to atmospheric discharge. The aeration process reduces the residual haloalkanes to levels much less than 5 ppb such that the treated water can be safely discharged to LLNL's recharge basin, which allows the treated water to percolate back to the water table. The carbon filter adsorbs all volatilized VOCs such that no detectable VOCs are discharged to the air.

#### **D-1.4. Air Stripping with GAC treatment of Both Liquid and Vapor Effluents**

This alternative combines air stripping as the primary treatment with a secondary treatment using GAC on the liquid phase. This alternative is suitable where it is not practical to achieve the required cleanup goals by air stripping alone because of very high inlet concentrations or where contaminants are present which cannot be treated by air stripping, such as metals. This alternative may be applicable to Treatment Facility F in this study, for which high concentrations of benzene, other FHCs, and, possibly, low concentrations of lead are anticipated in the extracted ground water.

A process flow diagram for this system is shown in Figure D-4. The design and operation considerations are the same as described in Sections D-1.1 and D-1.2.

#### **D-1.5. UV/Oxidation Plus GAC Treatment of the Liquid Effluent**

This alternative combines UV/oxidation as the primary treatment with secondary treatment of the liquid phase using GAC. This alternative is suitable where it is not practical to achieve the required effluent concentrations by UV/oxidation alone because of very high inlet concentrations or where contaminants are present that cannot be treated by UV/oxidation alone, such as metals. This alternative may be applicable to Treatment Facility F, at which high concentrations of benzene, other FHCs, and, possibly, low concentrations of lead may be present in the extracted ground water.

A process flow diagram for this system is shown in Figure D-5. The design and operation considerations for this alternative are the same as described in Sections D-1.3 and D-1.1.

#### **D-1.6. Liquid-Phase Treatment with GAC Plus Ion Exchange**

This alternative combines GAC as the primary treatment with a secondary treatment using ion exchange. This alternative is suitable where the ground water needs to be treated for removal of both VOCs and chromium. This alternative would be applicable to Treatment Facility D where concentrations of VOCs and possible chromium exceeding the required cleanup standards are anticipated in the extracted ground water.

A process flow diagram for this system is given in Figure D-6. The design and operation considerations are the same as described in Section D-1.1 for the primary treatment.

The chromium in the +6 valence state in the extracted ground water is expected to be in the form of chromate anions. Therefore, the ion-exchange technology will use an anion-type ion exchange resin. The water discharged from the primary treatment of GAC will be collected in a holding tank and then pumped through a fixed bed of ion-exchange resin. Two ion-exchange

beds are provided so that while one is online treating ground water, the other is being regenerated or is on standby. The diameter of the ion-exchange bed is selected based on the ground water flow rate, and the depth of ion-exchange resin in the bed is selected on the basis of flow rate and concentration of chromium. The ion-exchange bed is sized to require regeneration approximately once per day of operation.

During regeneration, the flow of ground water through the system is switched to the bed which has been on standby, and the bed previously in use is regenerated. The resin is regenerated by flowing a solution of sodium hydroxide through the ion-exchange bed. The waste regeneration solution containing the chromium (sodium chromate) removed from the resin in concentrated form is generally disposed of as a hazardous waste.

#### **D-1.7. Air Stripping with GAC Treatment of the Vapor Effluent and Ion-Exchange Treatment of the Liquid Effluent**

This alternative combines air stripping as the primary treatment with a secondary treatment using ion exchange. As before, GAC is used to treat the vapor effluent from the air stripper. This alternative is suitable where the ground water needs to be treated for removal of both VOCs and chromium. This alternative may be applicable to Treatment Facility D where concentrations of VOCs and possibly chromium exceeding the required cleanup standards are anticipated in the extracted ground water.

A process flow diagram for this system is given in Figure D-7. The design and operation considerations are the same as described in Sections D-1.2 and D-1.6.

#### **D-1.8. UV/Oxidation with Air Stripping and Ion Exchange of the Liquid Effluent and GAC Treatment of the Vapor Effluent**

This alternative combines UV/oxidation as the primary treatment with additional treatment using air stripping and ion exchange. As before, GAC is used to treat the vapor effluent from the air stripper. The UV/oxidation and air stripper treatments are suitable where the ground water is to be treated for removal of VOCs. The ion exchange is added for chromium removal where necessary. This alternative may be applicable to Treatment Facility D where concentrations of VOCs and, possibly, chromium exceeding the required cleanup standards are anticipated in the extracted ground water.

A process flow diagram for this system is given in Figure D-8. The design and operation considerations are the same as described in Sections D-1.3 and D-1.6.

## **D-2. BASIS FOR CONCEPTUAL DESIGNS AND COST ESTIMATES OF TECHNOLOGIES**

The basis for development of the conceptual designs and the cost estimates prepared from these designs are described in this section. These include: (1) the engineering design basis, (2) the basis for development of capital cost estimates, (3) the basis for estimation of operating costs over the project life.

### D-2.1. Engineering Design Basis

The engineering designs that apply to the development of the conceptual treatment technologies at all treatment sites are:

1. Tables D-3, D-4, D-5, D-6, D-7, D-8, D-9, and D-10 provide the design bases for each treatment site. These tables include the maximum and average ground water flow rates to be treated, the maximum and average concentrations of contaminants present in the ground water, and the concentrations to which the contaminants are to be reduced by the treatment system.
2. The conceptual designs and cost estimates include the above-ground water treatment alternatives. Items such as the ground water extraction systems and the treated water discharge systems are common to all treatment alternatives. The capital and operating costs associated with these items would be the same for all treatment alternatives and, therefore, are not included in the analysis of alternatives evaluated in detail. However, costs presented in Section 4 include the cost of extraction and disposal.
3. The conceptual design for each alternative is based on achieving the stated concentrations for treated outlet water at the maximum flow and contaminant concentrations for the extracted ground water. The equipment sizing and selection for the cost estimation is based on this conceptual design. Under average flow and contaminant concentration, the treatment should generally reduce VOC or FHC concentration to levels at or below detection limits.
4. The estimates for operating cost are based on treating the average flow rate of extracted water containing the average concentrations of contaminants.
5. The cost estimates are developed assuming that the treatment alternatives will be operated for 30 y. A 5% discount rate is used for development of present worth calculations. Present worth factors for future costs are calculated using the procedures described in U.S. EPA (1987).
6. The delayed treatment at the point of distribution alternative in central Livermore requires two discounting calculations. The 30 y of operation and maintenance costs are discounted at 5% in accordance with EPA procedures. Because this remediation alternative, if required, would not be installed for an estimated 200 y, the capital and discounted operating costs are discounted at 2% for 200 y. A low real discount rate is used because inflation is ignored in costs.
7. The concentrations of contaminants in the extracted water will decline over the period that the extraction and treatment systems are operated. For estimating operation costs, this decline is assumed to occur in step fashion over 5-y intervals with the concentrations in each interval set equal to one-half the concentrations present during the previous 5 y of operation. That is, the concentrations during years 6 through 10 will be one-half the initial concentrations; the concentrations during years 11 through 15 will be one-half the concentrations during years 6 through 10, and so forth.
8. The estimates for operating costs reflect the decline in concentrations of the contaminants in the extracted ground water. Operating cost items that are adjusted include the costs for replacement of GAC and the electric power used for the UV/oxidation system.
9. The reduction in contaminant concentrations in the extracted ground water described above will result in a reduced rate of use of GAC for the alternatives that use this technology. The rate of GAC use during the first 5 y of operation is based on the average flow rate and average inlet concentrations listed in the design basis table for the system to which the

alternative applies. Estimates obtained from vendors of GAC are used. The rate of use of GAC will decline as a result of the decreased concentrations in the inlet water.

The theoretical capacity of GAC to adsorb organic chemicals is commonly expressed in the form of a Freundlich isotherm equation:

$$q = kC^n$$

where

$q$  = quantity adsorbed onto GAC, mg compound/g GAC;

$C$  = concentration in water, mg/l;

$k$  = Freundlich adsorption constant;

$n$  = Freundlich adsorption exponent.

The values of  $k$  and  $n$  for the compounds of interest in this study were obtained from U.S. EPA (1980). Based on this review, a typical value of 0.6 for the adsorption exponent  $n$  is assumed to apply to all compounds, and the rate of GAC use is adjusted according to the following equation:

$$R_m = R(0.5)^{0.6m}$$

where

$R_m$  = rate of GAC use during the  $m$ th 5-y period following the initial 5 y  
(6 to 10 y,  $m = 1$ ; 11 to 15 y,  $m = 2$ ; etc.),

$R$  = rate of GAC use during the initial 5-y period.

A similar analysis was conducted for estimation of the rate of GAC use for treatment of air stripper exhaust. A similar equation was applied, differing only in the exponent used, 0.5  $m$  instead of 0.6  $m$ .

10. We allow for the decline in electricity use for UV/oxidation. UV/oxidation systems generally use a number of UV lamps, not all of which need be energized, depending on concentration. These consume the majority of electrical power and as concentrations decrease, some lamps may be switched off. UV/oxidation technology continues to undergo development. Recently, one supplier of such treatment systems made modifications that may improve conditions that promote oxidation reactions while at the same time reduce the cost of power required. We have not experimented with the new system in the field. To account for this, we have assumed that power requirements are constant for the first 15 y, after which they are reduced by 50% for the remainder of the assumed period of remediation.

## D-2.2. Capital Cost Estimation

The following assumptions apply to the estimation of capital costs for all treatment alternatives:

1. Vendor quotes or vendor catalog prices are used to develop the costs for major purchased equipment items.
2. A factored estimate for total installed capital cost, accurate to +50%/-30%, is used based on the cost for major purchased equipment. Installation cost factors are based on experience for installation of chemical process equipment.
3. Indirect costs include engineering design and permitting. An estimate of \$50,000 for engineering design is included for all alternatives. Permitting costs are estimated at \$10,000 for alternatives that do not require an air discharge permit and \$20,000 for alternatives requiring an air permit.
4. A contingency factor of 20% is applied to all capital cost estimates.

The costs to install the treatment process equipment for each alternative were estimated by applying factors to the purchase costs for the major items of equipment included in the treatment process. This is a technique commonly used in industry to develop conceptual level cost estimates for analysis of alternatives. The procedure consists of adding a percentage of the major purchased equipment cost to the equipment costs to develop estimated direct costs for construction. These percent factors account for the labor and materials for such items as site preparation, foundation and support structures construction, piping installation, instrumentation, and electrical service. A description of the method and estimated factors can be found in Guthrie (1974). This source and experience with the construction of treatment facilities, similar to those analyzed here, were used to develop the factors applied in the cost estimation for this report. Because the procedure applied was the same for all alternatives considered and because these costs are used only for comparison of alternatives, we feel these factored cost estimates are adequate.

### D-2.3. Operating Cost Estimation

The following assumptions were used to develop operating cost estimates for all alternatives:

1. An operating factor of 90% is assumed for all treatment alternatives.
2. The following annual labor hours and hourly rates, including indirect labor costs, will apply to all alternatives:

Supervision labor	200 h at \$75/h
Operating labor	500 h at \$40/h
3. The cost for electricity will be estimated at the rate of \$0.07 per kW-h plus an annual connection fee of \$36 per kW.
4. The cost for replacement of spent GAC treatment of the liquid phase and GAC treatment of the vapor phase is based on vendor quotes applicable to servicing of the specific GAC treatment units utilized in the conceptual design. This cost includes removal of spent GAC, thermal regeneration of spent GAC, and replacement with fresh GAC, as well as all freight and labor costs.
5. The costs for analysis of air and water samples only include those samples necessary for monitoring the performance of aboveground treatment alternatives. Sample collection and analysis costs associated with monitoring of extraction system performance and ground water quality are common to all alternatives and are not included in the operating cost estimates. We assume that each alternative will be monitored biweekly. The following costs per sample analysis apply:

*Water samples:*

VOC analysis	\$100/sample
FHCs analysis	\$100/sample
Metals (chromium or lead)	\$50/sample

*Air samples:*

VOC analysis	\$100/sample
FHCs analysis	\$100/sample

6. The sample collection and analysis schedule for each alternative would be as follows:
- GAC treatment of the liquid phase alternative will require the collection of samples of the inlet water, the water between the series of two GAC units, and the outlet water. When provision is included for field blanks and duplicates, a total of 110 samples would be collected annually. When the alternative is to treat VOCs only (Facilities A, B, C, E, and G), the samples would be analyzed for VOCs only. When the alternative is to treat VOCs, FHCs, and lead (Facility F), samples would be analyzed for all three parameters.
  - Air stripping with GAC treatment of the vapor phase would require collection and analysis of samples of the inlet water and the outlet water. When provision is included for field blanks and duplicates, a total of 80 water samples would be collected annually. This alternative applies to systems requiring treatment for VOCs only (Facilities A, B, C, E, and G). Therefore, samples would be analyzed only for VOCs. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples would be collected annually and analyzed for VOCs.
  - UV/oxidation plus air stripping with GAC treatment of the vapor phase would require collection and analysis of samples of the inlet water, the water exiting the UV/oxidation unit, and the outlet water. When provision is included for field blanks and duplicates, a total of 110 water samples would be collected annually. This alternative applies to systems used to treat VOCs only (Facilities A, B, C, E, and G). Therefore, these samples are be analyzed for VOCs. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples would be collected and analyzed for VOCs annually.
  - Air stripping with GAC treatment of both the vapor and liquid phases would require collection and analysis of samples of the inlet water, the water exiting the air stripper, the water between the two GAC units, and the outlet water. When provision is included for field blanks and duplicates, a total of 130 water samples would be collected annually. This alternative applies to systems requiring treatment for VOCs, FHCs, and lead (Facility F). Therefore, these samples would be analyzed for all these parameters. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples would be collected annually and analyzed for VOCs and fuel hydrocarbons.
  - UV/oxidation plus GAC treatment of the liquid phase would require collection and analysis of samples of the inlet water, the water exiting the UV/oxidation unit, the water between the two GAC units, and the outlet water. When provision is included for field blanks and duplicates, a total of 130 water samples would be collected annually. This alternative only applies to systems used to treat VOCs, FHCs, and lead (Facility F) only. Therefore, these samples would be analyzed for all these parameters.
  - GAC treatment of the liquid phase plus ion exchange, which applies to systems requiring treatment for VOCs and chromium (Facility D), would require collection of samples of the inlet water, the water between the two GAC units, and the outlet water for VOCs analysis. When provision is included for field blanks and duplicates, a total of

110 samples would be collected annually and analyzed for VOCs. In addition, samples of the inlet water to the ion exchange unit and the outlet water would be collected and analyzed for chromium. When provision is included for field blanks and duplicates, a total of 80 samples would be collected annually and analyzed for chromium.

- Air stripping with GAC treatment of the vapor phase plus ion exchange, which applies to systems requiring treatment for VOCs and chromium (Facility D), would require collection of samples of the inlet water and the outlet water for VOC analysis. When provision is included for field blanks and duplicates, a total of 80 water samples would be collected annually and analyzed for VOCs. Samples of the inlet water to the ion-exchange unit and the outlet water would be collected and analyzed for chromium. When provision is made for field blanks and duplicates, a total of 80 samples would be collected annually and analyzed for chromium. In addition, samples of the air exiting the GAC treatment of the vapor phase unit would be collected. A total of 30 air samples are collected annually and analyzed for VOCs.
  - UV/oxidation plus air stripping with GAC treatment of the vapor phase plus ion exchange, which applies to systems requiring treatment for VOCs and chromium (Facility D), would require collection and analysis of samples of the inlet water, the water exiting the UV/oxidation unit, and the outlet water for VOC analysis. When provision is included for field blanks and duplicates, a total of 110 water samples would be collected annually and analyzed for VOCs. Samples of the inlet water to the ion-exchange unit and the outlet water would be collected and analyzed for chromium. When provision is made for field blanks and duplicates, a total of 80 samples would be collected annually and analyzed for chromium. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples are collected and analyzed for VOCs annually.
7. An annual cost of 2% of the total capital requirement is included in the operating cost for all alternatives.
  8. A contingency of 20% is applied to the operating cost estimate.
  9. Operating cost estimates take into account the decline in GAC or electric use resulting from the decline in inlet water concentrations with time, as previously described.
  10. The operating cost estimates are discounted to 1990 for developing the present worth estimates, with a discount rate of 5%.
  11. The annual UV/oxidation maintenance fee is established by contract with the current vendor to be 10% of the cost of the UV/oxidation chamber itself. This maintenance contract includes periodic cleaning of the quartz UV source bulbs, replacing the quartz bulbs as necessary, rebuilding or replacing the hydrogen peroxide feed pumps as necessary, maintaining the hydrogen peroxide supply reservoir with adequate hydrogen peroxide (LLNL pays \$0.62/lb for the hydrogen peroxide), and performing any other electrical, electronic, or mechanical maintenance or repair required by the UV/oxidation chamber and hydrogen peroxide supply system.
  12. The rate of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) use, a variable operating and maintenance cost item, is estimated as follows:  
The desired concentration of H<sub>2</sub>O<sub>2</sub> in the water stream that is being treated is 50 ppm (50 mg/L); LLNL buys H<sub>2</sub>O<sub>2</sub> at \$0.62/lb of 50% solution.

$$\text{H}_2\text{O}_2 \frac{\text{lb}}{\text{y}} = F \cdot 8.33 \cdot 2,$$

where

F = the annual flow rate processed by the treatment system in gallons per year;

8.33 = the weight of water per gallon, taken as the weight of H<sub>2</sub>O<sub>2</sub>; no correction is made for the density of 50% solution of H<sub>2</sub>O<sub>2</sub> (1.2);

2 = correction factor for the 50% solution (2 lb of 50% solution/1 lb 100% H<sub>2</sub>O<sub>2</sub>)

The cost is estimated by multiplying the pounds of 50% H<sub>2</sub>O<sub>2</sub> solution by \$0.62. During operating years 1 to 16, the above estimate is used; in years 16 to 30, the use rate is assumed to be half that of the earlier period use, consistent with the assumption that the number of UV-quartz bulbs used in years 16 to 30 will also be half the first 15 y.

13. We assume that, for operating years 1 through 15, all four quartz UV lamps will be used, and in years 16 through 30, two will be used. This affects electricity use.

### D-3. TREATMENT FACILITY A

The design basis for the alternatives evaluated for Treatment Facility A is given in Table D-3. The only chemicals of concern anticipated in the ground water at Treatment Facility A are VOCs. The alternatives considered for Treatment Facility A are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is discussed further below.

#### D-3.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-3.1-1. The capital requirement for this alternative is estimated to be \$731,000, as developed in Table D-3.1-2. The present worth of the operating cost is estimated to be \$5,057,000, as developed in Table D-3.1-3. The present worth of the alternative is estimated to be \$5,788,000.

#### D-3.2. Air Stripping With GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-3.2-1. The capital requirement for this alternative is estimated to be \$211,000, as developed in Table D-3.2-2. The present worth of the operating cost is estimated to be \$1,391,000, as developed in Table D-3.2-3. The present worth of the alternative is estimated to be \$1,602,000.

#### D-3.3. UV/Oxidation Plus Air Stripping With GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-3.3-1. The capital requirement for this alternative is estimated to be \$494,074, as developed in Table D-3.3-2. The present worth of the operating cost is estimated to be \$3,031,800, as developed in Table D-3.3-3. The present worth of the alternative is estimated to be \$3,525,900.

## **D-4. TREATMENT FACILITY B**

The design basis for the alternatives evaluated for Treatment Facility B is given in Table D-4. The only chemicals of concern anticipated in the ground water at Treatment Facility B are VOCs. The alternatives considered for Treatment Facility B are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is summarized below.

### **D-4.1. GAC Treatment**

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-4.1-1. The capital requirement for this alternative is estimated to be \$448,000, as developed in Table D-4.1-2. The present worth of the operating cost is estimated to be \$3,051,000, as developed in Table D-4.1-3. The present worth of the alternative is estimated to be \$3,449,000.

### **D-4.2. Air Stripping With GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-4.2-1. The capital requirement for this alternative is estimated to be \$184,000, as developed in Table D-4.2-2. The present worth of the operating cost is estimated to be \$1,362,000, as developed in Table D-4.2-3. The present worth of the alternative is estimated to be \$1,546,000.

### **D-4.3. UV/Oxidation Plus Air Stripping With GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-4.3-1. The capital requirement for this alternative is estimated to be \$367,400, as developed in Table D-4.3-2. The present worth of the operating cost is estimated to be \$1,957,650, as developed in Table D-4.3-3. The present worth of the alternative is estimated to be \$2,325,000.

## **D-5. TREATMENT FACILITY C**

The design basis for the alternatives evaluated for Treatment Facility C is given in Table D-5. The only chemicals of concern anticipated in the ground water at Treatment Facility C are VOCs. The alternatives considered for Treatment Facility C are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is summarized below.

### **D-5.1. GAC Treatment**

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-5.1-1. The capital requirement for this alternative is estimated to be \$448,000, as developed in Table D-5.1-2. The present worth of

the operating cost is estimated to be \$1,800,000, as developed in Table D-5.1-3. The present worth of the alternative is estimated to be \$2,248,000.

#### **D-5.2. Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-5.2-1. The capital requirement for this alternative is estimated to be \$137,000, as developed in Table D-5.2-2. The present worth of the operating cost is estimated to be \$952,000, as developed in Table D-5.2-3. The present worth of the alternative is estimated to be \$1,089,000.

#### **D-5.3. UV/Oxidation Plus Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-5.3-1. The capital requirement for this alternative is estimated to be \$363,336, as developed in Table D-5.3-2. The present worth of the operating cost is estimated to be \$1,799,300, as developed in Table D-5.3-3. The present worth of the alternative is estimated to be \$2,162,600.

### **D-6. TREATMENT FACILITY D**

The design basis for the alternatives evaluated for Treatment Facility D is given in Table D-6. The chemicals of concern anticipated in the ground water at Treatment Facility D are VOCs and chromium. The alternatives considered for Treatment Facility D are GAC treatment of the liquid phase plus ion exchange, air stripping with GAC treatment of the vapor phase plus ion exchange, and UV/oxidation plus air stripping and ion exchange with GAC treatment of the vapor phase. Each is discussed below.

#### **D-6.1. GAC Treatment Plus Ion Exchange**

The process flow diagram for this alternative is shown in Figure D-6. The description and costs for the major equipment items are given in Table D-6.1-1. The capital requirement for this alternative is estimated to be \$559,000, as developed in Table D-6.1-2. The present worth of the operating cost is estimated to be \$2,968,000, as developed in Table D-6.1-3. The present worth of the alternative is estimated to be \$3,527,000.

#### **D-6.2. Air Stripping Plus Ion Exchange With GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-7. The description and costs for the major equipment items are given in Table D-6.2-1. The capital requirement for this alternative is estimated to be \$262,000, as developed in Table D-6.2-2. The present worth of the operating cost is estimated to be \$1,592,000, as developed in Table D-6.2-3. The present worth of the alternative is estimated to be \$1,854,000.

### **D-6.3. UV/oxidation Plus Air Stripping and Ion Exchange With GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-8. The description and costs for the major equipment items are given in Table D-6.3-1. The capital requirement for this alternative is estimated to be \$364,550, as developed in Table D-6.3-2. The present worth of the operating cost is estimated to be \$2,180,000 as developed in Table D-6.3-3. The present worth of the alternative is estimated to be \$2,544,000.

## **D-7. TREATMENT FACILITY E**

The design basis for the alternatives evaluated for Treatment Facility E is given in Table D-7. The only chemicals of concern anticipated in the ground water at Treatment Facility E are VOCs. The alternatives considered for Treatment Facility E are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is discussed below.

### **D-7.1. GAC Treatment**

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-7.1-1. The capital requirement for this alternative is estimated to be \$448,000, as developed in Table D-7.1-2. The present worth of the operating cost is estimated to be \$2,692,000, as developed in Table D-7.1-3. The present worth of the alternative is estimated to be \$3,140,000.

### **D-7.2. Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-7.2-1. The capital requirement for this alternative is estimated to be \$182,000, as developed in Table D-7.2-2. The present worth of the operating cost is estimated to be \$1,359,000, as developed in Table D-7.2-3. The present worth of the alternative is estimated to be \$1,541,000.

### **D-7.3. UV/oxidation plus Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-7.3-1. The capital requirement for this alternative is estimated to be \$364,550 as developed in Table D-7.3-2. The present worth of the operating cost is estimated to be \$1,844,150, as developed in Table D-7.3-3. The present worth of the alternative is estimated to be \$2,208,700.

## **D-8. TREATMENT FACILITY F**

The design basis for the alternatives evaluated for Treatment Facility F is given in Table D-8. The chemicals of concern anticipated in the ground water at Treatment Facility F are

VOCs, FHCs, and lead. The alternatives considered for Treatment Facility E are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase plus GAC treatment of the liquid phase, and UV/oxidation plus GAC treatment of the liquid phase. Each is discussed below.

The design criteria presented do not take into account any progress resulting from ongoing work as part of the Gasoline Spill Pilot Study. Therefore, before actual design begins, LLNL will establish new design criteria to reflect the results of the pilot study. Current plans within the scope of the pilot study are to test remediation of the FHCs in ground water during 1991, using vapor extraction techniques on a de-watered section of the aquifer, and using an innovative steam stripping technology. If these tests are successful, the resulting fuel hydrocarbon concentrations will be much lower than those presented in Table D-8.

### D-8.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-8.1-1. The capital requirement for this alternative is estimated to be \$731,000, as developed in Table D-8.1-2. The present worth of the operating cost is estimated to be \$6,964,000, as developed in Table D-8.1-3. The present worth of the alternative is estimated to be \$7,695,000.

### D-8.2. Air Stripping plus GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-4. The description and costs for the major equipment items are given in Table D-8.2-1. The capital requirement for this alternative is estimated to be \$355,000, as developed in Table D-8.2-2. The present worth of the operating cost is estimated to be \$4,390,000, as developed in Table D-8.2-3. The present worth of the alternative is estimated to be \$4,745,000.

### D-8.3. UV/Oxidation plus GAC Treatment of the Liquid Phase

The process flow diagram for this alternative is shown in Figure D-5. The description and costs for the major equipment items are given in Table D-8.3-1. The capital requirement for this alternative is estimated to be \$642,100, as developed in Table D-8.3-2. The present worth of the operating cost is estimated to be \$2,947,900, as developed in Table D-8.3-3. The present worth of the alternative is estimated to be \$3,590,000.

Although *in situ* bioremediation has reportedly been successful in some highly publicized cases, we find no documentation of success in distributing the required microbes and nutrients at a site as deep as the ground water at the LLNL gas spill. There are also concerns regarding potential interference by inorganic ions, especially iron, which may be present in sufficient natural concentrations to inhibit microbial growth. Consequently, we do not feel as confident of the long-term applicability of *in situ* bioremediation as for the other technologies discussed.

Because *in situ* bioremediation is only applicable to FHCs, it would have to be applied in addition to separate treatment of the VOCs and possibly lead. If, however, the FHCs were remediated separately with bioremediation, the VOC treatment system could be scaled back to treat an influent somewhat equivalent to that shown for TFD. Because the pilot study remediation is likely to have reduced FHC concentrations substantially by the time of the

approved Record of Decision, the practicality of separate bioremediation will have to be reexamined at that time.

Rather than present a table of costs, we have discussed the LLNL situation with two firms who design and install bioremediation systems; both for aboveground bioreactors and for *in situ* operations. Bioremediation is planned as one of the approved approaches at the EPA superfund site in Montana that may be comparable to the LLNL gasoline spill. According to the consultant who designed the bioremediation system, a pilot study involving two injection wells and two monitor wells cost about \$200,000 for a year of operation. Full-scale remediation to be implemented as a result of the ROD is estimated to cost about \$4 million over a 10-y period of operation. This order of expense, added to the costs of setting up a separate facility for treatment of the VOCs and possibly lead, make this alternative unattractive for LLNL at this time.

## **D-9. TREATMENT FACILITY G**

The design basis for the alternatives evaluated for Treatment Facility G is given in Table D-9. The only chemicals of concern anticipated in the ground water at Treatment Facility G are VOCs. The alternatives considered for Treatment Facility G are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is discussed below.

### **D-9.1. GAC Treatment**

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-9.1-1. The capital requirement for this alternative is estimated to be \$245,000, as developed in Table D-9.1-2. The present worth of the operating cost is estimated to be \$1,338,000, as developed in Table D-9.1-3. The present worth of the alternative is estimated to be \$1,583,000.

### **D-9.2. Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-9.2-1. The capital requirement for this alternative is estimated to be \$149,000, as developed in Table D-9.2-2. The present worth of the operating cost is estimated to be \$1,069,000, as developed in Table D-9.2-3. The present worth of the alternative is estimated to be \$1,218,000.

### **D-9.3. UV/oxidation plus Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-9.3-1. The capital requirement for this alternative is estimated to be \$366,000, as developed in Table D-9.3-2. The present worth of the operating cost is estimated to be \$1,754,000, as developed in Table D-9.3-3. The present worth of the alternative is estimated to be \$2,120,000.

## D-10. TREATMENT AT THE POINT OF DISTRIBUTION IN CENTRAL LIVERMORE (TREATMENT FACILITY "L")

The design basis for the alternatives evaluated for delayed remediation in central Livermore at the point of distribution is given in Table D-10. The chemicals of concern would be very low concentrations of VOCs; the transit time of the VOCs to central Livermore is estimated to be at least 200 y. The alternatives for Treatment Facility L are GAC, air stripping, and UV/oxidation. Each is discussed below. The inflow concentrations that were used to design the treatment systems are those predicted in the RI (Thorpe *et al.*, 1990) for the health-conservative case with a 10 to 1 dilution assumed to occur during extraction.

### D-10.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-9. The description and costs for the major equipment items are given in Table D-10.1-1. The capital requirement for this alternative is estimated to be \$772,000 (see Table D-10.1-2) in year 2190 dollars (no inflation considered). The present worth equivalent (1990 dollars, factor = 0.019) is \$14,700. The present worth of 30-y operating costs, discounted over 30 y at 5%, is estimated to be \$13,905,200, as shown in Table D-10.1-3 (present worth is \$264,200). The present worth of the alternative, in 1990 dollars, is estimated to be \$278,900.

### D-10.2 Air Stripping

The process flow diagram for this alternative is shown in Figure D-10. The description and costs for the major equipment items are given in Table D-10.2-1. The capital requirement for this alternative is estimated to be \$322,000, as developed in Table D-10.2-2 in year 2190 dollars (no inflation considered). The present worth equivalent (1990 dollars, factor = 0.019) is \$6,200. The present worth of 30-y operating costs, discounted at 5%, is estimated to be \$1,170,900 as shown in Table D-10.2-3 (present worth is \$22,250). The present worth of the alternative, in 1990 dollars, is estimated to be \$28,365.

### D-10.3 UV/Oxidation

The process flow diagram for this alternative is shown in Figure D-11. The description and costs for the major equipment items are given in Table D-10.3-1. The capital requirement for this alternative is estimated to be \$1,146,272 in year 2190 dollars, as developed in Table D-10.3-2 (no inflation considered). The present worth equivalent (1990 dollars, factor = 0.019) is \$21,800. The present worth of 30-y operating costs, discounted over 30 y at 5%, is estimated to be \$8,365,929 as shown in Table D-10.3-3 (present worth is \$159,000). The present worth of the alternative, in 1990 dollars, is estimated to be \$180,750.

Table D-3. Design criteria for Treatment System A.

Chemical species	Inlet concentrations (average flow rate = 150 gpm) (ppb) <sup>a</sup>	
	Maximum	Average
PCE	350	280
TCE	9	7
1,1-DCE	15	12
1,2-DCE	5	4
1,1,1-TCA	6	5
1,1-DCA	6	5
Chloroform	13	10
Freon 113	6	5
<b>Total VOCs</b>	<b>410</b>	<b>328</b>

<sup>a</sup> From Table 3-8.

Table D-3.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility A.

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels, 10-ft diam, 12 ft height, and 20,000 lb GAC per vessel	210,000
<b>Total Major Purchased Equipment Cost</b>		<b>210,000</b>

**Table D-3.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility A.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	210,000
Piping, concrete, steel (46% of MPEC)	96,600
Electrical, instrumentation (12% of MPEC)	25,200
Installation labor (58% of MPEC)	121,800
Major Equipment Installed Cost (MEIC)	453,600
Site preparation (10% of MEIC)	45,400
Total Field Cost (TFC)	499,000
Contractors' overhead and profit (10% of TFC)	49,900
Engineering design	50,000
Permitting	10,000
Subtotal	608,900
Contingency (20% of subtotal)	121,800
Total (TCR)	731,000

**Table D-3.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility A.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			14,620	
Subtotal			<u>60,620</u>	
Present worth (factor, 30 y @ 5% = 15.54)				<u><u>942,000</u></u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	32,000/unit	11.6 units	<u>371,200</u>	
Present worth (factor, @5% = 4.33)				1,607,300
Annual costs, years 6 through 10				
Replacement of GAC	32,000/unit	7.7 units	<u>246,400</u>	
Present worth (factor, @5% = 3.39)				835,300
Annual costs, years 11 through 15				
Replacement of GAC	32,000/unit	5.1 units	<u>163,200</u>	
Present worth (factor, @5% = 2.66)				434,100
Annual costs, years 16 through 20				
Replacement of GAC	32,000/unit	3.3 units	<u>105,600</u>	
Present worth (factor, @5% = 2.08)				219,600
Annual costs, years 21 through 25				
Replacement of GAC	32,000/unit	2.2 units	<u>70,400</u>	
Present worth (factor, @5% = 1.63)				114,800
Annual costs, years 26 through 30				
Replacement of GAC	32,000/unit	1.5 units	<u>48,000</u>	
Present worth (factor, @5% = 1.28)				<u>61,400</u>

Table D-3.1-3 (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Present worth of variable operating costs				3,272,500
Subtotal of present worth of fixed and variable operating and maintenance costs				4,214,500
Contingency (20% of subtotal)				842,900
Present worth of total 30-y operating cost				5,057,000
Total Capital Requirement (TCR)				731,000
Present worth of alternative (30-y operation)				5,788,000
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				731,000
Present worth of O & M, years 1 through 30			5,057,000	
Fixed annual O & M costs, years 31 through 87	60,620			
Present worth (factor, @ 5% = 4.34)		263,100		
Variable annual O & M costs, years 31 through 87	48,000			
Present worth (factor, @ 5% = 4.34)		208,300		
Subtotal of O & M costs, years 31 through 87		471,400		
Contingency (20% of subtotal)		94,300		
Present worth of O & M costs, years 31 through 87			565,700	
Present worth of fixed and variable annual O & M costs, years 1 through 87				5,622,700
Present worth of GAC at Treatment Facility A under Extraction Alternative No. 2				6,353,700

**Table D-3.2-1. Major Purchased Equipment Cost for air stripper with GAC vapor treatment for Treatment Facility A.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 40-in. diam; depth of 24 ft of 2-in. Jaeger Tri-Pak packing	25,300
Air supply feed blower	Centrifugal fan, 500 cfm at 4-in. water pressure with 1-hp motor	1,500
Treated liquid discharge pump	End-suction centrifugal pump, 145 gpm at 50 ft TDH with 5-hp motor	1,200
Air-stripper vapor exhaust blower	Centrifugal fan, 500 cfm at 4-in. water pressure with 1-hp motor	1,500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel, 48-in. diam by 86 in., contains 1800 lb of GAC	10,500
<b>Total Major Purchased Equipment Cost</b>		<b>40,500</b>

**Table D-3.2-2. Total Capital Requirement (TCR) for an air stripper with GAC vapor treatment for Treatment Facility A.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	40,500
Piping, concrete, steel (46% of MPEC)	18,600
Electrical, instrumentation (12% of MPEC)	4,900
Installation labor (58% of MPEC)	23,500
Major Equipment Installed Cost (MEIC)	87,500
Site preparation (10% of MEIC)	8,800
Total Field Cost (TFC)	96,300
Contractors' overhead and profit (10% of TFC)	9,600
Engineering design	50,000
Permitting	20,000
Subtotal	175,900
Contingency (20% of subtotal)	35,200
<b>Total (TCR)</b>	<b>211,100</b>

**Table D-3.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper with GAC vapor treatment for Treatment Facility A.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	58,894 kW-h	4,160	
Electrical capacity charge	36/kW	7.5 kW	270	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			4,220	
Subtotal			54,650	
Present worth (factor, 30 y @ 5% = 15.54)				849,300
<i>Variable operating costs</i>				
<i>Annual costs, years 1 through 5</i>				
Replacement of GAC	4,200/unit	7.8 units	32,760	
Present worth (factor, @ 5% =4.33)				141,900
<i>Annual costs, years 6 through 10</i>				
Replacement of GAC	4,200/unit	5.5 units	32,760	
Present worth (factor, @ 5% =3.39)				141,900
<i>Annual costs, years 11 through 15</i>				
Replacement of GAC	4,200/unit	3.9 units	23,100	
Present worth (factor, @ 5% =2.66)				78,300
<i>Annual costs, years 16 through 20</i>				
Replacement of GAC	4,200/unit	2.8 units	11,760	
Present worth (factor, @ 5% =2.08)				24,500
<i>Annual costs, years 21 through 25</i>				
Replacement of GAC	4,200/unit	2 units	8,400	
Present worth (factor, @ 5% =1.63)				13,700

Table D-3.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.4 units	5,880	
Present worth (factor, @ 5% =1.28)				7,500
Present worth of variable operating costs				309,500
Subtotal of present worth of fixed and variable operating and maintenance costs				1,158,800
Contingency (20% of subtotal)				231,800
Present worth of total 30-y operating and maintenance cost				1,391,000
Total Capital Requirement (TCR)				211,000
Present worth of alternative (30-y operation)				1,602,000
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				211,000
Present worth of O & M, years 1 through 30			1,391,000	
Fixed annual O & M costs, years 31 through 87	54,650			
Present worth (factor, @ 5% = 4.34)		237,200		
Variable annual O & M costs, years 31 through 87	5,880			
Present worth (factor, @ 5% = 4.34)		25,500		
Subtotal of O & M costs, years 31 through 87		262,700		
Contingency (20% of subtotal)		52,500		
Present worth of O & M costs, years 31 through 87			315,200	
Present worth of fixed and variable annual O & M costs, years 1 through 87				1,706,200
Present worth of AS at Treatment Facility A, Extraction Alternative No. 2				1,917,200

**Table D-3.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripper system with GAC vapor treatment for Treatment Facility A.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	1,250
UV/oxidation chamber	Single-chambered, baffled, 316-L stainless steel, 240-gal, skid-mounted, 4 ft $\times$ 8 ft $\times$ 8 ft, high-intensity-UV/oxidation chamber	120,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 550-gal, double-walled, cross-linked, polyethylene, 4 ft-4-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripper) vessel	Closed-top, cylindrical, 5,600-gal, cross-linked polyethylene, 11-ft 10-in. diam $\times$ 7-ft tall, four-chambered, baffled aeration vessel fitted with perforated PVC air-supply pipe	5,100
Volatilization system vapor feed blower	Centrifugal fan, 220 cfm at 4-in. water pressure; 1/2-hp motor	800
Carbon system vapor feed blower	Centrifugal fan, 220 cfm at 4-in. water pressure; 1/2-hp motor	800
Treated liquid discharge pump	End-suction centrifugal pump, 145 gpm at 50 ft TDH; 5-hp motor	1,200
Carbon system vapor heater	2000 W, inline duct heater	500
Fixed-bed GAC chamber		600
<b>Total Major Purchased Equipment Cost</b>		<b>130,750</b>

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-3.3-2. Total Capital Requirement (TCR) for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility A.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	130,750
Piping, concrete, steel (46% of MPEC)	60,145
Electrical, instrumentation (12% of MPEC)	15,690
Installation labor (58% of MPEC)	75,835
Major Equipment Installed Cost (MEIC)	282,420
Site preparation (10% of MEIC)	28,242
Total Field Cost (TFC)	310,662
Contractors' overhead and profit (10% of TFC)	31,066
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	411,728
Contingency (20% of subtotal)	82,346
<b>Total (TCR)</b>	<b>494,074</b>

**Table D-3.3-3. Operating and maintenance cost estimate and present worth analysis of a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility A.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	75 filters	3,800	
UV/oxidation maintenance	10% of UV/Ox unit	120,000	12,000	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			9,900	
Subtotal			71,700	
Present worth (factor @ 5% = 15.54)				1,114,200
<i>Variable Operating Costs</i>				
Annual costs, years 1 through 5				
Electricity	0.07/kW-h	984,712 kW-h	68,900	
Electrical use fee	36/W	125 W	4,500	
Hydrogen peroxide	0.62/lb	57,136 lb	35,400	
Replacement GAC unit	600/change	1.5/y	900	
Subtotal			109,700	
Present worth (factor @ 5% = 4.33)				475,000
Annual costs, years 6 through 10				
Electricity	0.07/kW-h	984,712 kW-h	68,900	
Electrical use fee	36/W	125 W	4,500	
Hydrogen peroxide	0.62/lb	57,136 lb	35,400	
Replacement GAC unit	600/change	1.5/y	900	
Subtotal			109,700	
Present worth (factor @ 5% = 3.39)				371,900

Table D-3.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 11 through 15</b>				
Electricity	0.07/kW-h	984,712 kW-h	68,900	
Electrical use fee	36/W	125 W	4,500	
Hydrogen peroxide	0.62/lb	57,136 lb	35,400	
Replacement GAC unit	600/change	1.5/y	900	
Subtotal			109,700	
Present worth (factor @ 5% = 2.66)				291,800
<b>Annual costs, years 16 through 20</b>				
Electricity	0.07/kW-h	492,356 kW-h	34,500	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	28,568 lb	17,700	
Replacement GAC unit	600/change	0.75/y	500	
Subtotal			54,900	
Present worth (factor @ 5% = 2.08)				114,200
<b>Annual costs, years 21 through 25</b>				
Electricity	0.07/kW-h	492,356 kW-h	34,500	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	28,568 lb	17,700	
Replacement GAC unit	600/change	0.75/y	500	
Subtotal			54,900	
Present worth (factor @ 5% = 1.63)				89,500
<b>Annual costs, years 26 through 30</b>				
Electricity	0.07/kW-h	492,356 kW-h	34,500	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	28,568 lb	17,700	
Replacement GAC unit	600/change	0.75/y	500	
Subtotal			54,900	
Present worth (factor @ 5% = 1.28)				70,300
Present worth of variable operating costs				1,412,700

Table D-3.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,526,900
Contingency (20% of subtotal)				505,400
Present worth of total 30-y operating and maintenance costs				3,032,300
Total Capital Requirement (TCR)				494,100
Present worth of alternative (30-y operation)				3,526,400
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				494,100
Present worth of O & M, years 1 through 30			3,032,300	
Fixed annual O & M costs, years 31 through 87	71,700			
Present worth (factor, @ 5% = 4.34)		311,200		
Variable annual O & M costs, years 31 through 87	54,900			
Present worth (factor, @ 5% = 4.34)		238,300		
Subtotal of O & M costs, years 31 through 87		549,500		
Contingency (20% of subtotal)		109,900		
Present worth of O & M costs, years 31 through 87			659,400	
Present worth of fixed and variable annual O & M costs, years 31 through 87				3,691,700
Present worth of UV/Ox at Treatment Facility A under Extraction Alternative No. 2				4,185,800

Table D-4. Design criteria for Treatment System B.

Chemical species	Inlet concentrations (average flow rate = 50 gpm) (ppb) <sup>a</sup>	
	Maximum	Average
PCE	50	40
TCE	375	300
1,1-DCE	13	10
1,2-DCE	4	3
1,1,1-TCA	1	1
1,1-DCA	6	5
1,2-DCA	1	1
Carbon tetrachloride	3	2
Chloroform	13	10
Freon 113	13	10
<b>Total VOCs</b>	<b>479</b>	<b>382</b>

<sup>a</sup> From Table 3-8.

Table D-4.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility B.

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels, 7.5-ft diam, 10 ft height, and 10,000 lb GAC per vessel	201,000
<b>Total Major Purchased Equipment Cost</b>		<b>201,000</b>

**Table D-4.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility B.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	210,000
Piping, concrete, steel (46% of MPEC)	55,200
Electrical, instrumentation (12% of MPEC)	14,400
Installation labor (58% of MPEC)	69,600
Major Equipment Installed Cost (MEIC)	<u>259,200</u>
Site preparation (10% of MEIC)	25,900
Total Field Cost (TFC)	<u>285,100</u>
Contractors' overhead and profit (10% of TFC)	28,500
Engineering design	50,000
Permitting	10,000
Subtotal	<u>373,600</u>
Contingency (20% of subtotal)	74,700
Total (TCR)	<u><u>448,000</u></u>

**Table D-4.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility B.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			8,960	
Subtotal			<u>54,960</u>	
Present worth (factor, 30 y @ 5% = 15.54)				<u>854,100</u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	16,000/unit	12 units	<u>192,000</u>	
Present worth (factor, @5% = 4.33)				831,400
Annual costs, years 6 through 10				
Replacement of GAC	16,000/unit	7.9 units	<u>126,400</u>	
Present worth (factor, @5% = 3.39)				428,500
Annual costs, years 11 through 15				
Replacement of GAC	16,000/unit	5.2 units	<u>83,200</u>	
Present worth (factor, @5% = 2.66)				221,300
Annual costs, years 16 through 20				
Replacement of GAC	16,000/unit	3.5 units	<u>56,000</u>	
Present worth (factor, @5% = 2.08)				116,500
Annual costs, years 21 through 25				
Replacement of GAC	16,000/unit	2.3 units	<u>36,800</u>	
Present worth (factor, @5% = 1.63)				60,000
Annual costs, years 26 through 30				
Replacement of GAC	16,000/unit	1.5 units	<u>24,000</u>	
Present worth (factor, @5% = 1.28)				30,700
Present worth of variable operating costs				<u>1,688,400</u>

Table D-4.1-3 (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,542,500
Contingency (20% of subtotal)				508,500
Present worth of total 30-y operating cost				3,051,000
<b>Total Capital Requirement (TCR)</b>				<b>448,000</b>
Present worth of alternative				3,499,000
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Total Capital Requirement (TCR)</b>				<b>448,000</b>
Present worth of O & M, years 1 through 30			3,051,000	
Fixed annual O & M costs, years 31 through 87	54,960			
Present worth (factor, @ 5% = 4.34)		238,500		
Variable annual O & M costs, years 31 through 87	24,000			
Present worth (factor, @ 5% = 4.34)		104,200		
Subtotal of O & M costs, years 31 through 87		342,700		
Contingency (20% of subtotal)		68,500		
Present worth of O & M costs, years 31 through 87			411,200	
Present worth of fixed and variable annual O & M costs, years 1 through 87				3,462,200
<b>Present worth of GAC at Treatment Facility B under Extraction Alternative No. 2</b>				<b>3,910,200</b>

**Table D-4.2-1. Major Purchased Equipment Cost for air stripper with GAC vapor treatment for Treatment Facility B.**

Equipment	Description	Equipment cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 24-in. diam, depth of 21 ft of 2-in. Jaeger Tri-Pak packing	17,400
Air supply feed blower	Centrifugal fan, 600 cfm at 4-in. water pressure with 1-hp motor	1,600
Treated liquid discharge pump	End-suction centrifugal pump, 55 gpm at 50 ft TDH with 1-hp motor	500
Air-stripper vapor exhaust blower	Centrifugal fan, 600 cfm at 4-in. water pressure with 1-hp motor	1,500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48-in. diam by 86 in., contains 1800 lb of GAC	10,500
<b>Total Major Purchased Equipment Cost</b>		<b>32,000</b>

**Table D-4.2-2. Total Capital Requirement (TCR) for air stripper with GAC vapor treatment for Treatment Facility B.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	32,000
Piping, concrete, steel (46% of MPEC)	14,700
Electrical, instrumentation (12% of MPEC)	3,800
Installation labor (58% of MPEC)	18,600
Major Equipment Installed Cost (MEIC)	69,100
Site preparation (10% of MEIC)	6,900
Total Field Cost (TFC)	76,000
Contractor's overhead and profit (10% of TFC)	7,600
Engineering design	50,000
Permitting	20,000
Subtotal	153,600
Contingency (20% of subtotal)	30,700
<b>Total (TCR)</b>	<b>184,000</b>

**Table D-4.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper with GAC vapor treatment for Treatment Facility B.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	57,520 kW-h	4,030	
Electrical capacity charge	36/kW	7.3 kW	260	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			3,680	
Subtotal			53,970	
Present worth (factor, 30 y @ 5% = 15.54)				838,700
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	7.5 units	31,500	
Present worth (factor, @ 5% =4.33)				136,400
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	5.3 units	22,260	
Present worth (factor, @ 5% =3.39)				75,500
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	3.7 units	15,540	
Present worth (factor, @ 5% =2.66)				41,300
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.6 units	10,920	
Present worth (factor, @ 5% =2.08)				22,700
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	1.9 units	7,980	
Present worth (factor, @ 5% =1.63)				13,000

Table D-4.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.3 units	5,460	
Present worth (factor, @ 5% = 1.28)				7,000
Present worth of variable operating costs				295,900
Subtotal of present worth of fixed and variable operating and maintenance costs				1,134,600
Contingency (20% of subtotal)				226,900
Present worth of total 30-y operating and maintenance cost				1,362,000
Total Capital Requirement (TCR)				184,000
Present worth of alternative				1,546,000
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				184,000
Present worth of O & M, years 1 through 30			1,362,000	
Fixed annual O & M costs, years 31 through 87	53,970			
Present worth (factor, @ 5% = 4.34)		234,200		
Variable annual O & M costs, years 31 through 87	5,460			
Present worth (factor, @ 5% = 4.34)		23,700		
Subtotal of O & M costs, years 31 through 87		257,900		
Contingency (20% of subtotal)		51,600		
Present worth of O & M costs, years 31 through 87			309,500	
Present worth of fixed and variable annual O & M costs, years 1 through 87				1,671,500
Present worth of AS at Treatment Facility B, Extraction Alternative No. 2				1,855,500

**Table D-4.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility B.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter.	455
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80 gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 200-gal, double-walled, cross-linked, polyethylene, 2-ft 6-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump.	500
Volatilization (air stripper) vessel	Closed-top cylindrical, 2,000 gal, cross-linked polyethylene, 7-ft 6-in. diam $\times$ 7-ft tall, four-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,800
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 55 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	800 W, inline duct heater	500
Fixed-bed GAC chamber		600
<b>Total Major Purchased Equipment Cost</b>		<b>90,355</b>

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-4.3-2. Total Capital Requirement (TCR) for UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility B.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	90,355
Piping, concrete, steel (46% of MPEC)	41,563
Electrical, instrumentation (12% of MPEC)	10,843
Installation labor (58% of MPEC)	52,406
Major Equipment Installed Cost (MEIC)	195,167
Site preparation (10% of MEIC)	19,517
Total Field Cost (TFC)	214,683
Contractors' overhead and profit (10% of TFC)	21,468
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	306,152
Contingency (20% of subtotal)	61,230
<b>Total (TCR)</b>	<b>367,382</b>

**Table D-4.3-3. Operating and maintenance cost estimate and present worth analysis for an UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility B.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
<i>Annual costs:</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	29 filters	1,400	
UV/oxidation maintenance	10% of UV/Ox unit	85,000	8,500	
<i>Sample analysis:</i>				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
Subtotal			63,200	
Present worth (factor @ 5% = 15.54)				<u>982,100</u>
<i>Variable Operating costs</i>				
<i>Annual cost, years 1 through 5</i>				
Electricity	0.07/kW-h	490,385 kW-h	34,300	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	21,672 lb	13,400	
Replacement GAC unit	600/change	0.55/y	300	
Subtotal			50,200	
Present worth (factor @ 5% = 4.33)				217,400
<i>Annual cost, years 6 through 10</i>				
Electricity	0.07/kW-h	490,385 kW-h	34,300	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	21,672 lb	13,400	
Replacement GAC unit	600/change	0.55/y	300	
Subtotal			50,200	
Present worth (factor @ 5% = 3.39)				170,200

Table D-4.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	490,385 kW-h	34,300	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	21,672 lb	13,400	
Replacement GAC unit	600/change	0.55/y	300	
Subtotal			<u>50,200</u>	
Present worth (factor @ 5% = 2.66)				133,500
<b>Annual costs, years 16 through 20</b>				
Electricity	0.07/kW-h	245,193kW-h	17,200	
Electrical use fee	36/W	31 W	1,120	
Hydrogen peroxide	0.62/lb	10,836 lb	6,700	
Replacement GAC unit	600/change	0.275/y	200	
Subtotal			<u>25,200</u>	
Present worth (factor @ 5% = 2.08)				52,400
<b>Annual costs, years 21 through 25</b>				
Electricity	0.07/kW-h	245,193kW-h	17,200	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	10,836 lb	6,700	
Replacement GAC unit	600/change	0.275/y	200	
Subtotal			<u>25,200</u>	
Present worth (factor @ 5% = 1.63)				41,100
<b>Annual costs, years 26 through 30</b>				
Electricity	0.07/kW-h	245,193kW-h	17,200	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	10,836 lb	6,700	
Replacement GAC unit	600/change	0.275/y	200	
Subtotal			<u>25,200</u>	
Present worth (factor @ 5% = 1.28)				32,300
Present worth of variable operating costs				<u><u>646,900</u></u>

Table D-4.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,629,000
Contingency (20% of subtotal)				325,800
Present worth of total 30-y operating and maintenance costs				1,954,800
Total Capital Requirement (TCR)				367,400
Present worth of alternative (30-y operation)				2,322,200
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				367,400
Present worth of O & M, years 1 through 30			1,954,800	
Fixed annual O & M costs, years 31 through 87	63,200			
Present worth (factor, @ 5% = 4.34)		274,300		
Variable annual O & M costs, years 31 through 87	25,200			
Present worth (factor, @ 5% = 4.34)		109,400		
Subtotal of O & M costs, years 31 through 87		383,700		
Contingency (20% of subtotal)		76,700		
Present worth of O & M costs, years 31 through 87			460,400	
Present worth of fixed and variable annual O & M costs, years 31 through 87				2,415,200
Present worth of UV/Ox at Treatment Facility B under Extraction Alternative No.2				2,782,600

**Table D-5. Parameter values used to design remediation alternatives for Treatment Facility C.**

Chemical species	Inlet concentrations (average flow rate = 20 gpm) (ppb)	
	Maximum	Average
PCE	6	5
TCE	25	20
1,1-DCE	3	2
Chloroform	4	3
Freon 113	125	100
<b>Total VOCs</b>	<b>163</b>	<b>130</b>

**Table D-5.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility C.**

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels, 7.5-ft diam, 12 ft height, and 10,000 lb GAC per vessel	210,000
<b>Total Major Purchased Equipment Cost</b>		<b>210,000</b>

**Table D-5.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility C.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	120,000
Piping, concrete, steel (46% of MPEC)	55,200
Electrical, instrumentation (12% of MPEC)	14,400
Installation labor (58% of MPEC)	69,600
<b>Major Equipment Installed Cost (MEIC)</b>	<b>259,200</b>
Site preparation (10% of MEIC)	25,900
<b>Total Field Cost (TFC)</b>	<b>285,100</b>
Contractors' overhead and profit (10% of TFC)	28,500
Engineering design	50,000
Permitting	10,000
<b>Subtotal</b>	<b>373,600</b>
Contingency (20% of subtotal)	74,700
<b>Total (TCR)</b>	<b>448,000</b>

**Table D-5.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility C.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			8,960	
Fixed annual operating and maintenance cost			<u>54,960</u>	
Present worth (factor, 30 y @ 5% = 15.54)				<u><u>854,100</u></u>
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Replacement of GAC	16,000/unit	4.6 units	<u>73,600</u>	
Present worth (factor, @5% = 4.33)				318,700
Annual cost, years 6 through 10				
Replacement of GAC	16,000/unit	3 units	<u>48,000</u>	
Present worth (factor, @5% = 3.39)				162,700
Annual cost, years 11 through 15				
Replacement of GAC	16,000/unit	2 units	<u>32,000</u>	
Present worth (factor, @5% = 2.66)				85,100
Annual cost, years 16 through 20				
Replacement of GAC	16,000/unit	1.3 units	<u>20,800</u>	
Present worth (factor, @5% = 2.08)				43,300
Annual cost, years 21 through 25				
Replacement of GAC	16,000/unit	0.9 units	<u>14,400</u>	
Present worth (factor, @5% = 1.63)				23,500
Annual cost, years 26 through 30				
Replacement of GAC	16,000/unit	0.6 units	<u>9,600</u>	
Present worth (factor, @5% = 1.28)				<u>12,300</u>
Present worth of variable operating costs				<u><u>645,600</u></u>

Table D-5.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				1,499,700
Contingency (20% of subtotal)				299,900
Present worth of total 30-y operating cost				1,800,000
Total Capital Requirement (TCR)				448,000
Present worth of alternative (30-y operation)				2,248,000
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				448,000
Present worth of O & M, years 1 through 30			1,800,000	
Fixed annual O & M costs, years 31 through 87	54,960			
Present worth (factor, @ 5% = 4.34)		238,500		
Variable annual O & M costs, years 31 through 87	9,600			
Present worth (factor, @ 5% = 4.34)		41,700		
Subtotal of O & M costs, years 31 through 87		280,200		
Contingency (20% of subtotal)		56,000		
Present worth of O & M costs, years 31 through 87			336,200	
Present worth of fixed and variable annual O & M costs, years 1 through 87				2,136,200
Present worth of GAC at Treatment Facility C under Extraction Alternative No. 2				2,584,200

**Table D-5.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility C.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 12-in. diam, depth of 25 ft of 1-in. Jaeger Tri-Pak packing	8,500
Air supply feed blower	Centrifugal fan, 70 cfm at 4-in. water pressure with 1/4-hp motor.	500
Treated liquid discharge pump	End-suction centrifugal pump, 20 gpm at 50 ft TDH with 3/4-hp motor	400
Air-stripper vapor exhaust blower	Centrifugal fan, 70 cfm at 4-in. water pressure with 1/4-hp motor	500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48-in. diam by 63 in., contains 1,000 lb of GAC	6,600
<b>Total Major Purchased Equipment Cost</b>		<b>17,000</b>

**Table D-5.2-2. Total Capital Requirement (TCR) for air stripper with GAC vapor treatment for Treatment Facility C.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	17,000
Piping, concrete, steel (46% of MPEC)	7,800
Electrical, instrumentation (12% of MPEC)	2,000
Installation labor (58% of MPEC)	9,900
Major Equipment Installed Cost (MEIC)	36,700
Site preparation (10% of MEIC)	3,700
Total Field Cost (TFC)	40,400
Contractors' overhead and profit (10% of TFC)	4,000
Engineering design	50,000
Permitting	20,000
Subtotal	114,400
Contingency (20% of subtotal)	22,900
Total (TCR)	137,000

**Table D-5.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility C.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	8212 kW-h	570	
Electrical capacity charge	36/kW	1.0 kW	40	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			2,740	
Subtotal			49,350	
Present worth (factor, 30 y @ 5% = 15.54)				766,900
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	2,500/unit	1.1 units	2,750	
Present worth (factor, @ 5% =4.33)				11,900
Annual costs, years 6 through 10				
Replacement of GAC	2,500/unit	0.8 units	2,000	
Present worth (factor, @ 5% =3.39)				6,800
Annual costs, years 11 through 15				
Replacement of GAC	2,500/unit	0.6 units	1,500	
Present worth (factor, @ 5% =2.66)				4,000
Annual costs, years 16 through 20				
Replacement of GAC	2,500/unit	0.4 units	1,000	
Present worth (factor, @ 5% =2.08)				2,100
Annual costs, years 21 through 25				
Replacement of GAC	2,500/unit	0.3 units	750	
Present worth (factor, @ 5% =1.63)				1,200

Table D-5.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	2,500/unit	0.2 units	500	
Present worth (factor, @ 5% = 1.28)				600
Present worth of variable operating costs				26,600
Subtotal of present worth of fixed and variable operating and maintenance costs				793,500
Contingency (20% of subtotal)				158,700
Present worth of total 30-y operating cost				952,000
Total Capital Requirement (TCR)				137,000
Present worth of alternative (30-y operation)				1,089,000
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				137,000
Present worth of O & M, years 1 through 30			952,000	
Fixed annual O & M costs, years 31 through 87	49,350			
Present worth (factor, @ 5% = 4.34)		214,200		
Variable annual O & M costs, years 31 through 87	500			
Present worth (factor, @ 5% = 4.34)		2,200		
Subtotal of O & M costs, years 31 through 87		216,400		
Contingency (20% of subtotal)		43,300		
Present worth of O & M costs, years 31 through 87			259,700	
Present worth of fixed and variable annual O & M costs, years 1 through 87				1,211,700
Present worth of AS at Treatment Facility C, Extraction Alternative No. 2				1,348,700

**Table D-5.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripping system, with GAC vapor treatment, for Treatment Facility C.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	165
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80-gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 100-gal, double-walled, cross-linked, polyethylene, 2-ft diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump.	500
Volatilization (air stripper) vessel	Closed-top cylindrical, 750-gal, cross-linked polyethylene, 6-ft 8-in. diam $\times$ 3-ft 6-in. tall, four-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	900
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 25 gpm at 50 ft TDH; 3/4-hp motor	400
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
<b>Total Major Purchased Equipment Cost</b>		<b>89,065</b>

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-5.3-2. Total Capital Requirement (TCR) for a UV/oxidation and air stripping system, with GAC vapor treatment, for Treatment Facility C.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	89,065
Piping, concrete, steel (46% of MPEC)	40,970
Electrical, instrumentation (12% of MPEC)	10,688
Installation labor (58% of MPEC)	51,658
Major Equipment Installed Cost (MEIC)	192,380
Site preparation (10% of MEIC)	19,238
Total Field Cost (TFC)	211,618
Contractors' overhead and profit (10% of TFC)	21,162
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	302,780
Contingency (20% of subtotal)	60,556
<b>Total (TCR)</b>	<b>363,336</b>

**Table D-5.3-3. Operating and maintenance cost estimate and present worth analysis for a UV/oxidation and air stripping system, with GAC vapor treatment, for Treatment Facility C.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	10 filters	500	
UV/oxidation maintenance	10% of UV/Ox unit	85,000	8,500	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
Subtotal			62,300	
Present worth (30 y, factor @ 5% = 15.54)				968,100
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Electricity	0.07/kW-h	486,443 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	7,881 lb	4,900	
Replacement GAC unit	600/change	0.2/y	100	
Subtotal			41,300	
Present worth (factor @ 5% = 4.33)				178,800
Annual cost, years 6 through 10				
Electricity	0.07/kW-h	486,443 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	7,881 lb	4,900	
Replacement GAC unit	600/change	0.2/y	100	
Subtotal			41,300	
Present worth (factor @ 5% = 3.39)				140,000

Table D-5.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	486,443 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	7,881 lb	4,900	
Replacement GAC unit	600/change	0.2/y	100	
Subtotal			<u>41,300</u>	
Present worth (factor @ 5% = 2.66)				109,900
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	243,222 kW-h	17,000	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	3,941 lb	2,400	
Replacement GAC unit	600/change	0.1/y	100	
Subtotal			<u>20,600</u>	
Present worth (factor @ 5% = 2.08)				42,800
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	243,222 kW-h	17,000	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	3,941 lb	2,400	
Replacement GAC unit	600/change	0.1/y	100	
Subtotal			<u>20,600</u>	
Present worth (factor @ 5% = 1.63)				33,600
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	243,222 kW-h	17,000	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	3,941 lb	2,400	
Replacement GAC unit	600/change	0.1/y	100	
Subtotal			<u>20,600</u>	
Present worth (factor @ 5% = 1.28)				26,400
Present worth of variable operating costs				<u><u>531,500</u></u>

Table D-5.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,499,600
Contingency (20% of subtotal)				299,900
Present worth of total 30-y operating and maintenance costs				1,799,500
Total Capital Requirement (TCR)				363,300
Present worth of alternative (30-y operation)				2,162,800
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				363,300
Present worth of O & M, years 1 through 30			1,799,500	
Fixed annual O & M costs, years 31 through 87	62,300			
Present worth (factor, @ 5% = 4.34)		270,400		
Variable annual O & M costs, years 31 through 87	20,600			
Present worth (factor, @ 5% = 4.34)		89,400		
Subtotal of O & M costs, years 31 through 87		359,800		
Contingency (20% of subtotal)		72,000		
Present worth of O & M costs, years 31 through 87			431,800	
Present worth of fixed and variable annual O & M costs, years 31 through 87				2,231,300
Present worth of UV/Ox at Treatment Facility C under Extraction Alternative No. 2				2,594,600

Table D-6. Design criteria for Treatment System D.

Chemical species	Inlet concentrations (average flow rate = 30 gpm) (ppb)	
	Maximum	Average
PCE	13	10
TCE	1,250	1,000
1,1-DCE	21	17
1,2-DCE	5	4
1,1,1-TCA	4	3
1,1-DCA	4	3
1,2-DCA	26	21
Carbon tetrachloride	38	30
Chloroform	162	130
Chromium	63	50
Freon 113	4	3
<b>Total VOCs</b>	<b>1,527</b>	<b>1,221</b>

Table D-6.1-1. Major Purchased Equipment Cost for a GAC and ion-exchange system for Treatment Facility D.

Equipment	Description	Cost (\$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system; two vessels 7.5-ft diam and 10 ft height; 10,000 lb GAC per vessel	120,000
Holding tank	Closed top, cylindrical tank, 600-gal capacity, cross-linked polyethylene, 4-ft diam × 7 ft 8 in.	1,700
Ion-exchange system feed pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH, 1-hp motor	500
Ion-exchange system	Skid-mounted, dual-column system, 30-in. diam × 96-in. columns each with 20-ft <sup>3</sup> anion resin. Includes caustic tank, regeneration pump, and waste chromium regeneration solution tank	33,000
<b>Total Major Purchased Equipment Cost</b>		<b>155,200</b>

**Table D-6.1-2. Total Capital Requirement (TCR) for a GAC and ion-exchange system for Treatment Facility D.**

<b>Equipment</b>	<b>Cost (1990 \$)</b>
<b>Major Purchased Equipment Cost (MPEC)</b>	<b>155,200</b>
Piping, concrete, steel (46% of MPEC)	71,400
Electrical, instrumentation (12% of MPEC)	18,600
Installation labor (58% of MPEC)	90,000
<b>Major Equipment Installed Cost (MEIC)</b>	<b>335,200</b>
Site preparation (10% of MEIC)	33,500
<b>Total Field Cost (TFC)</b>	<b>368,700</b>
Contractors' overhead and profit (10% of TFC)	36,900
Engineering design	50,000
Permitting	10,000
<b>Subtotal</b>	<b>465,600</b>
Contingency (20% of subtotal)	93,100
<b>Total (TCR)</b>	<b>558,700</b>

**Table D-6.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC and ion-exchange system for Treatment Facility D.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	3182 kW-h	220	
Electrical capacity charge	36/kW	0.4 kW	10	
Supervision Labor	75/h	200 h	15,000	
Operating Labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Water sample chromium analysis	50/sample	80 samples	4,000	
Caustic for ion-exchange regeneration	100/drum	35 drums	3,500	
Disposal of ion-exchange regeneration waste	100/drum	70 drums	7,000	
Maintenance (2% of TCR)			11,180	
Subtotal			71,910	
Present worth (factor, 30 y @ 5% = 15.54)				<u>1,117,500</u>
<i>Variable operating costs</i>				
Annual cost years 1 through 5				
Replacement of GAC	16,000/unit	9.6 units	153,600	
Present worth (factor, @5% = 4.33)				665,100
Annual cost years 6 through 10				
Replacement of GAC	16,000/unit	6.4 units	102,400	
Present worth (factor, @5% = 3.39)				347,100
Annual cost years 11 through 15				
Replacement of GAC	16,000/unit	4.2 units	67,200	
Present worth (factor, @5% = 2.66)				178,800
Annual cost years 16 through 20				
Replacement of GAC	16,000/unit	2.8 units	44,800	
Present worth (factor, @5% = 2.08)				93,200
Annual cost years 21 through 25				
Replacement of GAC	16,000/unit	1.8 units	28,800	
Present worth (factor, @5% = 1.63)				46,900

Table D-6.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost years 26 through 30</b>				
Replacement of GAC	16,000/unit	1.2 units	19,200	
Present worth (factor, @5% = 1.28)				24,600
Present worth of variable operating costs				1,355,700
Subtotal of present worth of fixed and variable operating and maintenance costs				2,473,200
Contingency (20% of subtotal)				494,600
Present worth of total 30-y operating cost				2,968,000
Total (TCR)				559,000
Present worth of alternative (30-y operation)				3,527,000

Table D-6.2-1. Major Purchased Equipment Cost for an air stripper, ion-exchange, and GAC vapor treatment for Treatment Facility D.

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 18-in. diam, depth of 22 ft of 1-in. Jaeger Tri-Pak packing	10,300
Air supply feed blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Air-stripper vapor exhaust blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 86 in., contains 1800 lb of GAC	10,500
Ion-exchange system feed pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH with 1-hp motor	500
Ion-exchange system	Skid-mounted, dual-column system, 30 in. diam × 96-in. columns each with 20-ft <sup>3</sup> anion resin; system includes caustic tank, regeneration pump, and waste chromium regeneration solution tank	33,000
<b>Total Major Purchased Equipment Cost</b>		<b>56,800</b>

**Table D-6.2-2. Total Capital Requirement (TCR) for an air stripper, ion-exchange, and GAC vapor treatment for Treatment Facility D.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	56,800
Piping, concrete, steel (46% of MPEC)	26,100
Electrical, instrumentation (12% of MPEC)	6,800
Installation labor (58% of MPEC)	32,900
Major Equipment Installed Cost (MEIC)	122,600
Site preparation (10% of MEIC)	12,300
Total Field Cost (TFC)	134,900
Contractor's overhead and profit (10% of TFC)	13,500
Engineering design	50,000
Permitting	20,000
Subtotal	218,400
Contingency (20% of subtotal)	43,700
Total (TCR)	262,000

**Table D-6.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper, ion exchange system with GAC vapor treatment for Treatment Facility D.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	31,032 kW-h	2,170	
Electrical capacity charge	36/kW	3.9 kW	140	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Water sample chromium analysis	50/sample	80 samples	4,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Caustic for ion exchange regeneration	100/drum	35/drums	3,500	
Disposal of ion-exchange regeneration waste	100/drum	70/drums	7,000	
Maintenance (2% of TCR)			5,240	
Subtotal			68,050	
Present worth (factor, 30 y @ 5% = 15.54)				1,057,500
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	6.8 units	28,560	
Present worth (factor, @ 5% = 4.33)				123,700
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	4.8 units	20,160	
Present worth (factor, @ 5% = 3.39)				68,300
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	3.4 units	14,280	
Present worth (factor, @ 5% = 2.66)				38,000
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.4 units	10,080	
Present worth (factor, @ 5% = 2.08)				21,000
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	1.7 units	7,140	
Present worth (factor, @ 5% = 1.63)				11,600

Table D-6.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Annual costs, years 26 through 30				
Replacement of GAC	4,200/unit	1.2 units	5,040	
Present worth (factor, @ 5% = 1.28)				6,500
Present worth of variable operating costs				269,100
Subtotal of present worth of fixed and variable operating and maintenance costs				1,326,600
Contingency (20% of subtotal)				265,300
Present worth of total 30-y operating cost				1,592,000
Total Capital Requirement (TCR)				262,000
Present worth of alternative (30-y operation)				1,854,000

Table D-6.3-1. Major Purchased Equipment Costs for aUV/oxidation, air stripping, ion-exchange system with GAC vapor treatment for Treatment Facility D.

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	250
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 800 gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top cylindrical, 150-gal, double-walled, cross-linked, polyethylene, 2-ft 3-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripper) vessel	Closed-top, cylindrical, 1,100-gal, cross-linked polyethylene, 5-ft 4-in. diam $\times$ 7-ft 1-in. tall, four-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,100
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4 in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4 in. water pressure; 1/4-hp motor	500
Liquid transfer pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
Ion-exchange system	Skid-mounted, dual-column system, 30 in. diam $\times$ 96-in. columns each with 20 ft <sup>3</sup> anion resin; includes caustic tank, regeneration pump, and waste chromium tank	33,000
Total major purchased equipment costs		122,450

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-6.3-2. Total Capital Requirement (TCR) for a UV/oxidation, air stripping, and ion-exchange system with GAC vapor treatment for Treatment Facility D.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	122,450
Piping, concrete, steel (46% of MPEC)	56,327
Electrical, instrumentation (12% of MPEC)	14,694
Installation labor (58% of MPEC)	71,021
Major Equipment Installed Cost (MEIC)	264,492
Site preparation (10% of MEIC)	26,449
Total Field Cost (TFC)	290,941
Contractor's overhead and profit (10% of TFC)	29,094
Engineering design	50,000
Permitting	20,000
Subtotal	390,035
Contingency (20% of subtotal)	78,007
<b>Total (TCR)</b>	<b>468,042</b>

**Table D-6.3-3. Operating and maintenance cost estimate and present worth analysis for a UV/oxidation, air stripping, ion-exchange system with GAC vapor treatment for Treatment Facility D.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
<b>Annual costs:</b>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	16 filters	800	
UV/oxidation maintenance contract	10% of UV/ox unit	120,000	12,000	
<b>Sample analysis:</b>				
VOC/FHC water samples	100/sample	80 samples	8,000	
Chromium water samples	50/sample	80 samples	4,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Caustic for ion-exchange regeneration	100/drum	35 drums	3,500	
Disposal of ion-exchange regeneration waste	100/drum	70 drums	7,000	
Maintenance (2% of TCR)			9,400	
Subtotal			<u>82,700</u>	
Present worth (factor @ 5% = 15.54)				<u><u>1,285,200</u></u>
<i>Variable operating costs</i>				
<b>Annual cost, years 1 through 5</b>				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			<u>43,800</u>	
Present worth (factor @ 5% = 4.33)				189,700
<b>Annual cost, years 6 through 10</b>				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			<u>43,800</u>	

Table D-6.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Present worth (factor @ 5% = 3.39)				148,500
Annual cost, years 11 through 15				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 2.66)				116,500
Annual cost, years 16 through 20				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 2.08)				45,800
Annual cost, years 21 through 25				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 1.63)				35,900
Annual cost, years 26 through 30				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 1.28)				28,200
Present worth of variable operating costs				564,600

Table D-6.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				1,848,800
Contingency (20% of subtotal)				370,000
Present worth of total 30-y operating and maintenance costs				2,129,800
Total Capital Requirement (TCR)				468,000
Present worth of alternative (30-y operation)				2,687,800

**Table D-7. Design criteria for Treatment System E.**

Chemical species	Inlet concentrations (average flow rate = 30 gpm) (ppb)	
	Maximum	Average
PCE	313	250
TCE	3,500	2,800
1,1-DCE	44	35
1,1,1-TCA	34	27
1,2-DCA	13	10
Carbon tetrachloride	13	10
Chloroform	125	100
Freon 113	13	10
<b>Total VOCs</b>	<b>4,055</b>	<b>3,242</b>

**Table D-7.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility E.**

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system; two vessels 7.5-ft diam, 10 ft height, 10,000 lb GAC per vessel	120,000
<b>Total Major Purchased Equipment Cost</b>		<b>120,000</b>

**Table D-7.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility E.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	120,000
Piping, concrete, steel (46% of MPEC)	55,200
Electrical, instrumentation (12% of MPEC)	14,400
Installation labor (58% of MPEC)	69,600
Major Equipment Installed Cost (MEIC)	259,200
Site preparation (10% of MEIC)	25,900
Total Field Cost (TFC)	285,100
Contractor's overhead and profit (10% of TFC)	28,500
Engineering design	50,000
Permitting	10,000
Subtotal	373,600
Contingency (20% of subtotal)	74,700
Total (TCR)	448,000

**Table D-7.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility E.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			8,960	
Subtotal			<u>54,960</u>	
Present worth (factor, 30 y @ 5% = 15.54)				<u><u>854,100</u></u>
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Replacement of GAC	16,000/unit	9.9 units	<u>158,400</u>	
Present worth (factor, @5% = 4.33)				685,900
Annual cost, years 6 through 10				
Replacement of GAC	16,000/unit	6.5 units	<u>104,000</u>	
Present worth (factor, @5% = 3.39)				352,600
Annual cost, years 11 through 15				
Replacement of GAC	16,000/unit	4.3 units	<u>68,800</u>	
Present worth (factor, @5% = 2.66)				183,000
Annual cost, years 16 through 20				
Replacement of GAC	16,000/unit	2.8 units	<u>44,800</u>	
Present worth (factor, @5% = 2.08)				93,200
Annual cost, years 21 through 25				
Replacement of GAC	16,000/unit	1.9 units	<u>30,400</u>	
Present worth (factor, @5% = 1.63)				49,600
Annual cost, years 26 through 30				
Replacement of GAC	16,000/unit	1.2 units	<u>19,200</u>	
Present worth (factor, @5% = 1.28)				24,600
Present worth of variable operating costs				<u><u>1,388,900</u></u>

Table D-7.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,243,000
Contingency (20% of subtotal)				448,600
Present worth of total 30-y operating cost				2,692,000
Total Capital Requirement (TCR)				448,000
Present worth of alternative (30-y operation)				3,140,000

Table D-7.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility E.

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 18-in. diam, depth of 24 ft of 1-in. Jaeger Tri-Pak packing	17,800
Air supply feed blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Treated liquid discharge pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH with 1-hp motor	500
Air-stripper vapor exhaust blower	Centrifugal fan, 320 cfm at 4 -in. water pressure with 1/2-hp motor	1,000
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 86 in. contains 1,800 lb of GAC	10,500
Total Major Purchased Equipment Cost		31,300

**Table D-7.2-2. Total Capital Requirement for an air stripper with GAC vapor treatment for Treatment Facility E.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	31,300
Piping, concrete, steel (46% of MPEC)	14,400
Electrical, instrumentation (12% of MPEC)	3,800
Installation labor (58% of MPEC)	18,200
Major Equipment Installed Cost (MEIC)	67,700
Site preparation (10% of MEIC)	6,800
Total Field Cost (TFC)	74,500
Contractor's overhead and profit (10% of TFC)	7,500
Engineering design	50,000
Permitting	20,000
Subtotal	152,000
Contingency (20% of subtotal)	30,400
Total (TCR)	182,000

**Table D-7.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility E.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	31,032 kW-h	2,170	
Electrical capacity charge	36/kW	3.9 kW	140	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			3,640	
Subtotal			51,950	
Present worth (factor, 30 y @ 5% = 15.54)				807,300
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	8.2 units	34,440	
Present worth (factor, @ 5% =4.33)				149,100
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	5.8 units	24,360	
Present worth (factor, @ 5% =3.39)				82,600
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	4.1 units	17,220	
Present worth (factor, @ 5% =2.66)				45,800
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.9 units	12,180	
Present worth (factor, @ 5% =2.08)				25,300
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	2.1 units	8,820	
Present worth (factor, @ 5% =1.63)				14,400

Table D-7.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.5 units	6,300	
Present worth (factor, @ 5% =1.28)				8,100
Present worth of variable operating costs				325,300
Subtotal of present worth of fixed and variable operating and maintenance costs				1,132,600
Contingency (20% of subtotal)				226,500
Present worth of total 30-y operating cost				1,359,000
Total Capital Requirement (TCR)				182,000
Present worth of alternative (30-y operation)				1,541,000

Table D-7.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility E.

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	250
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80-gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 150-gal, double-walled, cross-linked, polyethylene, 2-ft-3-in.-diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripper) vessel	Closed-top, cylindrical, 1100-gal, cross-linked polyethylene, 5-ft 4-in. diam $\times$ 7-ft 1-in. tall, 4-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,100
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4 in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
Total Major Purchased Equipment Cost		89,450

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-7.3-2. Total Capital Requirement (TCR) for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility E.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	89,450
Piping, concrete, steel (46% of MPEC)	41,147
Electrical, instrumentation (12% of MPEC)	10,734
Installation labor (58% of MPEC)	51,881
Major Equipment Installed Cost (MEIC)	193,212
Site preparation (10% of MEIC)	19,321
Total Field Cost (TFC)	212,533
Contractor's overhead and profit (10% of TFC)	21,253
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	303,787
Contingency (20% of subtotal)	60,757
<b>Total (TCR)</b>	<b>364,544</b>

**Table D-7.3-3. Operating and maintenance cost estimate and present worth analysis of UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility E.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	16 filters	800	
UV/oxidation maintenance	10% of UV/Ox unit	85,000	8,500	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
Subtotal			62,600	
Present worth (factor @ 5% = 15.54)				972,800
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 4.33)				189,700
Annual cost, years 6 through 10				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 3.3)				148,500

Table D-7.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 2.66)				116,500
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 2.08)				45,800
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 1.63)				35,900
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 1.28)				28,200
Present worth of variable operating costs				564,600

Table D-7.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,537,400
Contingency (20% of subtotal)				307,500
Present worth of total 30-y operating and maintenance costs				1,844,900
Total Capital Requirement (TCR)				364,500
Present worth of alternative (30-y operation)				2,209,400

Table D-8. Design criteria for Treatment System F.

Chemical species	Inlet concentrations (average flow rate = 30 gpm) (ppb)	
	Maximum	Average
PCE	13	10
TCE	250	200
1,1-DCE	13	10
1,1,1-TCA	4	3
1,2-DCA	163	130
Carbon tetrachloride	13	10
Chloroform	25	20
Freon 113	13	10
Benzene	25,000	20,000
Toluene	38,000	30,000
Xylene	19,000	15,000
Ethylene dibromide	313	250
Total VOCs	82,807	65,643
Lead	38	30

Table D-8.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility F.

Equipment	Description	Cost (\$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels 10 ft diam and 12 ft height and 20,000 lb GAC per vessel.	210,000
<b>Total Major Purchased Equipment Cost</b>		<b>210,000</b>

**Table D-8.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility F.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	210,000
Piping, concrete, steel (46% of MPEC)	96,600
Electrical, instrumentation (12% of MPEC)	25,200
Installation labor (58% of MPEC)	121,800
Major Equipment Installed Cost (MEIC)	453,600
Site preparation (10% of MEIC)	45,400
Total Field Cost (TFC)	499,000
Contractor's overhead and profit (10% of TFC)	49,900
Engineering design	50,000
Permitting	10,000
Subtotal	608,900
Contingency (20% of subtotal)	121,800
Total (TCR)	731,000

**Table D-8.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility F.**

<b>Analysis of Extraction Alternative No. 1: facility operated for 30 y</b>				
<b>Item</b>	<b>Rate (1990 \$)</b>	<b>Usage</b>	<b>Subtotal present worth (1990 \$)</b>	<b>Total present worth (1990 \$)</b>
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Water sample fuel hydrocarbon analysis	100/sample	110 samples	11,000	
Water sample lead analysis	50/sample	110 samples	5,500	
Maintenance (2% of TCR)			14,620	
Subtotal			<u>77,120</u>	
Present worth (factor, 30 y @5% = 15.54)				<u>1,198,400</u>
<i>Variable operating costs</i>				
Annual cost years 1 through 5				
Replacement of GAC	32,000/unit	16.4 units	<u>524,800</u>	
Present worth (factor, @5% = 4.33)				2,272,400
Annual cost years 6 through 10				
Replacement of GAC	32,000/unit	10.8 units	<u>345,600</u>	
Present worth (factor, @5% = 3.39)				1,171,600
Annual cost years 11 through 15				
Replacement of GAC	32,000/unit	7.1 units	<u>227,200</u>	
Present worth (factor, @5% = 2.66)				604,400
Annual cost years 16 through 20				
Replacement of GAC	32,000/unit	4.7 units	<u>150,400</u>	
Present worth (factor, @5% = 2.08)				312,800
Annual cost years 21 through 25				
Replacement of GAC	32,000/unit	3.1 units	<u>99,200</u>	
Present worth (factor, @5% = 1.63)				156,500
Annual cost years 26 through 30				
Replacement of GAC	32,000/unit	2 units	<u>64,000</u>	
Present worth (factor, @5% = 1.28)				81,900
Present worth of variable operating costs				<u>4,604,800</u>

Table D-8.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				5,803,200
Contingency (20% of subtotal)				1,160,600
Present worth of total 30-y operating cost				6,964,000
Total Capital Requirement (TCR)				731,000
Present worth of alternative (30-y operation)				7,695,000
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				731,000
Present worth of O & M, years 1 through 30			6,964,000	
Fixed annual O & M costs, years 31 through 87	77,120			
Present worth (factor, @ 5% = 4.34)		334,700		
Variable annual O & M costs, years 31 through 87	64,000			
Present worth (factor, @ 5% = 4.34)		277,800		
Subtotal of O & M costs, years 31 through 87		612,500		
Contingency (20% of subtotal)		122,500		
Present worth of O & M costs, years 31 through 87			735,000	
Present worth of fixed and variable annual O & M costs, years 1 through 87				7,699,000
Present worth of GAC at Treatment Facility F under Extraction Alternative No. 2				8,430,000

**Table D-8.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility F.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 18-in. diam, depth of 24 ft of 1-in. Jaeger Tri-Pak packing	17,800
Air supply feed blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Treatment system transfer pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH with 1-hp motor	500
Fixed-bed GAC (liquid) units	Skid mounted dual-adsorber vessel system with two vessels 4 ft diam and 8 ft height each containing 2,000 lb GAC	55,000
Air-stripper vapor exhaust blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 86 in. contains 1,800 lb of GAC	10,500
<b>Total Major Purchased Equipment Cost</b>		<b>86,300</b>

**Table D-8.2-2. Total Capital Requirement (TCR) for an air stripper with GAC vapor treatment for Treatment Facility F.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	86,300
Piping, concrete, steel (46% of MPEC)	39,700
Electrical, instrumentation (12% of MPEC)	10,400
Installation labor (58% of MPEC)	50,100
Major Equipment Installed Cost (MEIC)	186,500
Site preparation (10% of MEIC)	18,700
Total Field Cost (TFC)	205,200
Contractor's overhead and profit (10% of TFC)	20,500
Engineering design	50,000
Permitting	20,000
Subtotal	295,700
Contingency (20% of subtotal)	59,100
<b>Total (TCR)</b>	<b>355,000</b>

**Table D-8.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility F.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kw-h	44,477 kw-h	3,110	
Electrical capacity charge	36/kw	5.6 kw	200	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	130 samples	13,000	
Water sample fuel hydrocarbon analysis	100/sample	130 samples	13,000	
Water sample lead analysis	50/sample	130 samples	6,500	
Air sample VOC analysis	100/sample	30 samples	3,000	
Air sample fuel hydrocarbon analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,100	
Subtotal			83,910	
Present worth (factor, 30 y @ 5% = 15.54)				<u>1,304,000</u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC (vapor)	4,200/unit	52.6 units	220,920	
Replacement of GAC (liquid)	3,000/unit	10.3 units	30,900	
Subtotal			251,820	
Present worth (factor, @ 5% =4.33)				1,090,400
Annual costs, years 6 through 10				
Replacement of GAC (vapor)	4,200/unit	37.2 units	156,240	
Replacement of GAC (liquid)	3,000/unit	6.8 units	20,400	
Subtotal			176,640	
Present worth (factor, @ 5% =3.39)				598,800
Annual costs, years 11 through 15				
Replacement of GAC (vapor)	4,200/unit	26.3 units	110,460	
Replacement of GAC (liquid)	3,000/unit	4.5 units	13,500	
Subtotal			123,960	
Present worth (factor, @ 5% =2.66)				329,700

Table D-8.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 16 through 20</b>				
Replacement of GAC (vapor)	4,200/unit	18.6 units	78,120	
Replacement of GAC (liquid)	3,000/unit	3 units	9,000	
Subtotal			87,120	
Present worth (factor, @ 5% =2.08)				181,200
<b>Annual costs, years 21 through 25</b>				
Replacement of GAC (vapor)	4,200/unit	13.1 units	55,020	
Replacement of GAC (liquid)	3,000/unit	2 units	6,000	
Subtotal			61,020	
Present worth (factor, @ 5% =1.63)				99,500
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC (vapor)	4,200/unit	9.3 units	39,060	
Replacement of GAC (liquid)	3,000/unit	1.3 units	3,900	
Subtotal			42,960	
Present worth (factor, @ 5% =1.28)				55,000
Present worth of variable operating costs				2,354,600
Subtotal of present worth of fixed and variable operating and maintenance costs				3,658,600
Contingency (20% of subtotal)				731,700
Present worth of total 30-y operating cost				4,390,000
Total Capital Requirement (TCR)				355,000
Present worth of alternative (30-y operation)				4,745,000

Table D-8.2-3. (Continued)

Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				355,000
Present worth of O & M, years 1 through 30			4,390,000	
Fixed annual O & M costs, years 31 through 87	83,910			
Present worth (factor, @ 5% = 4.34)		364,200		
Variable annual O & M costs, years 31 through 87	42,960			
Present worth (factor, @ 5% = 4.34)		186,400		
Subtotal of O & M costs, years 31 through 87		550,600		
Contingency (20% of subtotal)		110,100		
Present worth of O & M costs, years 31 through 87			660,700	
Present worth of fixed and variable annual O & M costs, years 1 through 87				5,050,700
Present worth of AS at Treatment Facility F, Extraction Alternative No. 2				5,405,700

**Table D-8.3-1. Major Purchased Equipment Cost for a UV/oxidation and GAC system for Treatment Facility F.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ , inline, synthetic resin cartridge filter	250
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 240-gal, skid-mounted, 4 ft $\times$ 8 ft $\times$ 8 ft, high-intensity-UV/oxidation chamber	120,000
Hydrogen peroxide supply reservoir	Closed-top cylindrical, 150 gal, double-walled, cross-linked, polyethylene, 2-ft-3-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Holding tank	Closed-top, cylindrical, 600-gal, cross-linked polyethylene, 4-ft diam $\times$ 7-ft 8-in. vessel	1700
Liquid transfer pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH; 1-hp motor	500
GAC unit	Skid-mounted, dual-adsorber vessel system; each vessel is 4 ft diam $\times$ 8 ft tall and contains 2,000 lb carbon per vessel	55,000
<b>Total Major Purchased Equipment Cost</b>		<b>177,950</b>

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-8.3-2. Total Capital Requirement for a UV/oxidation and GAC system for Treatment Facility F.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	177,950
Piping, concrete, steel (46% of MPEC)	81,857
Electrical, instrumentation (12% of MPEC)	21,354
Installation labor (58% of MPEC)	103,211
Major Equipment Installed Cost (MEIC)	384,372
Site preparation (10% of MEIC)	38,437
Total Field Cost (TFC)	422,809
Contractor's overhead and profit (10% of TFC)	42,281
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	535,090
Contingency (20% of subtotal)	107,018
Total (TCR)	642,108

**Table D-8.3-3. Operating and maintenance cost estimate and present worth analysis of UV/oxidation and GAC system for Treatment Facility F.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	16 filters	800	
UV/oxidation maintenance	10% of UV/Ox unit	120,000	12,000	
Sample analysis:				
VOC/FHC water samples	100/sample	260 samples	26,000	
Lead water samples	50/sample	130 samples	6,500	
Maintenance (2% of TCR)			12,800	
Subtotal			93,100	
Present worth (factor @ 5% = 15.54)				1,446,800
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Electricity	0.07/kW-h	953,176 kW-h	66,700	
Electrical use fee	36/W	121 W	4,400	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Carbon regeneration/replacement	3,000/unit	10 units	30,000	
Subtotal			108,400	
Present worth (factor @ 5% = 4.33)				469,400
Annual cost, years 6 through 10				
Electricity	0.07/kW-h	953,176 kW-h	66,700	
Electrical use fee	36/W	121 W	4,400	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Carbon regeneration/replacement	3,000/unit	7 units	21,000	
Subtotal			99,400	
Present worth (factor @ 5% = 3.39)				337,000

Table D-8.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	953,176 kW-h	66,700	
Electrical use fee	36/W	121 W	4,400	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Carbon regeneration/replacement	3,000/unit	5 units	15,000	
Subtotal			<u>93,400</u>	
				248,400
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	476,588 kW-h	33,400	
Electrical use fee	36/W	60 W	2,200	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Carbon regeneration/replacement	3,000/unit	3 units	9,000	
Subtotal			<u>48,300</u>	
Present worth (factor @ 5% = 2.08)				100,500
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	476,588 kW-h	33,400	
Electrical use fee	36/W	60 W	2,200	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Carbon regeneration/replacement	3,000/unit	2 units	6,000	
Subtotal			<u>45,300</u>	
Present worth (factor @ 5% = 1.63)				73,800
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	476,588 kW-h	33,400	
Electrical use fee	36/W	60 W	2,200	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Carbon regeneration/replacement	3,000/unit	1 unit	3,000	
Subtotal			<u>42,300</u>	
Present worth (factor @ 5% = 1.28)				54,100
Present worth of variable operating costs				<u><u>1,283,200</u></u>

Table D-8.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,730,000
Contingency (20% of subtotal)				546,000
Present worth of total 30-y operating and maintenance costs				3,276,000
Total Capital Requirement (TCR)				642,100
Present worth of alternative (30-y operation)				3,918,100
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total capital requirement (TCR)				642,100
Present worth of O & M, years 1 through 30			3,276,000	
Fixed annual O & M costs, years 31 through 87	93,100			
Present worth (factor, @ 5% = 4.34)		404,100		
Variable annual O & M costs, years 31 through 87	42,300			
Present worth (factor, @ 5% = 4.34)		183,600		
Subtotal of O & M costs, years 31 through 87		587,700		
Contingency (20% of subtotal)		117,500		
Present worth of O & M costs, years 31 through 87			705,200	
Present worth of fixed and variable annual O & M costs, years 31 through 87				3,981,200
Present worth of UV/Ox at Treatment Facility F under Extraction Alternative No. 2				4,623,300

**Table D-9. Design criteria for Treatment System G.**

Chemical species	Inlet concentrations (average flow rate = 50 gpm) (ppb)	
	Maximum	Average
PCE	13	10
TCE	125	100
1,1-DCE	13	10
1,2-DCE	1	0.5
1,1,1-TCA	25	20
Carbon tetrachloride	6	5
Chloroform	25	20
Freon 113	13	10
<b>Total VOCs</b>	<b>221</b>	<b>175.5</b>

**Table D-9.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility G.**

Equipment	Description	Equipment cost (1990 \$)
Fixed-bed GAC units	Skid-mounted, dual-adsorber vessel system with two vessels, 4-ft diam, 8 ft-height, and 2,000 lb GAC per vessel	55,000
<b>Total Major Purchased Equipment Cost</b>		<b>55,000</b>

**Table D-9.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility G.**

<b>Equipment</b>	<b>Cost (1990 \$)</b>
<b>Major Purchased Equipment Cost (MPEC)</b>	<b>55,000</b>
<b>Piping, concrete, steel (46% of MPEC)</b>	<b>25,300</b>
<b>Electrical, instrumentation (12% of MPEC)</b>	<b>6,600</b>
<b>Installation labor (58% of MPEC)</b>	<b>31,900</b>
<b>Major Equipment Installed Cost (MEIC)</b>	<b>188,800</b>
<b>Site preparation (10% of MEIC)</b>	<b>11,900</b>
<b>Total Field Cost (TFC)</b>	<b>130,700</b>
<b>Contractor's overhead and profit (10% of TFC)</b>	<b>13,100</b>
<b>Engineering design</b>	<b>50,000</b>
<b>Permitting</b>	<b>10,000</b>
<b>Subtotal</b>	<b>203,800</b>
<b>Contingency (20% of subtotal)</b>	<b>40,800</b>
<b>Total (TCR)</b>	<b>245,000</b>

**Table D-9.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility G.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			4,900	
Subtotal			<u>50,900</u>	
Present worth (factor, 30 y @5% = 15.54)				<u>791,000</u>
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Replacement of GAC	3,000/unit	12.3 units	<u>36,900</u>	
Present worth (factor, @5% = 4.33)				159,800
Annual cost, years 6 through 10				
Replacement of GAC	3,000/unit	8.1 units	<u>24,300</u>	
Present worth (factor, @5% = 3.39)				82,400
Annual cost, years 11 through 15				
Replacement of GAC	3,000/unit	5.4 units	<u>16,200</u>	
Present worth (factor, @5% = 2.66)				43,100
Annual cost, years 16 through 20				
Replacement of GAC	3,000/unit	3.5 units	<u>10,500</u>	
Present worth (factor, @5% = 2.08)				21,800
Annual cost, years 21 through 25				
Replacement of GAC	3,000/unit	2.3 units	<u>6,900</u>	
Present worth (factor, @5% = 1.63)				11,200
Annual cost, years 26 through 30				
Replacement of GAC	3,000/unit	1.5 units	<u>4,500</u>	
Present worth (factor, @5% = 1.28)				5,800
Present worth of variable operating costs				<u>324,100</u>

Table D-9.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				1,115,100
Contingency (20% of subtotal)				223,000
Present worth of total 30-y operating cost				1,338,000
Total Capital Requirement (TCR)				245,000
Present worth of alternative (30-y operation)				1,583,000

**Table D-9.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility G.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 22-in. diam, depth of 21 ft of 2 in. Jaeger Tri-Pak packing	12,100
Air supply feed blower	Centrifugal fan, 154 cfm at 4-in. water pressure with 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 45 gpm at 50 ft TDH with 1-hp motor	500
Air-stripper vapor exhaust blower	Centrifugal fan, 154 cfm at 4-in. water pressure with 1/4-hp motor	500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 63 in. contains 1,000 lb of GAC	6,600
<b>Total Major Purchased Equipment Cost (MPEC)</b>		<b>20,700</b>

**Table D-9.2-2. Total Capital Requirement for an air stripper with GAC vapor treatment for Treatment Facility G.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	20,700
Piping, concrete, steel (46% of MPEC)	9,500
Electrical, instrumentation (12% of MPEC)	2,500
Installation labor (58% of MPEC)	12,000
Major Equipment Installed Cost (MEIC)	44,700
Site preparation (10% of MEIC)	4,500
Total Field Cost (TFC)	49,200
Contractors' overhead and profit (10% of TFC)	4,900
Engineering design	50,000
Permitting	20,000
Subtotal	124,400
Contingency (20% of subtotal)	24,800
Total (TCR)	149,000

**Table D-9.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility G.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	18,173 kW-h	1,270	
Electrical capacity charge	36/kW	2.3 kW	80	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			2,980	
<b>Fixed annual operating and maintenance costs</b>			<b>50,330</b>	
Present worth (factor, 30 y @ 5% = 15.54)				<b>782,100</b>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	2,500/unit	4.6 units	11,500	
Present worth (factor, @ 5% = 4.33)				49,800
Annual costs, years 6 through 10				
Replacement of GAC	2,500/unit	3.3 units	8,250	
Present worth (factor, @ 5% = 3.39)				28,000
Annual costs, years 11 through 15				
Replacement of GAC	2,500/unit	2.3 units	5,750	
Present worth (factor, @ 5% = 2.66)				15,300
Annual costs, years 16 through 20				
Replacement of GAC	2,500/unit	1.6 units	4,000	
Present worth (factor, @ 5% = 2.08)				8,300
Annual costs, years 21 through 25				
Replacement of GAC	2,500/unit	1.1 units	2,750	
Present worth (factor, @ 5% = 1.63)				4,500

Table D-9.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	2,500/unit	0.8 units	2,000	
Present worth (factor, @ 5% =1.28)				2,600
Present worth of variable operating costs				108,500
Subtotal of present worth of fixed and variable operating and maintenance costs				890,600
Contingency (20% of subtotal)				178,100
Present worth of total 30-y operating cost				1,069,000
Total Capital Requirement (TCR)				149,000
Present worth of alternative (30-y operation)				1,218,000

Table D-9.3-1. Major Purchased Equipment Cost for a UV/oxidation and air-stripping system with GAC vapor treatment for Treatment Facility G.

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	375
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80 gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 200-gal, double-walled, cross-linked, polyethylene, 2 ft-7 in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripping) vessel	Closed-top, cylindrical, 1,650 gal, cross-linked polyethylene, 7-ft 2 in. diam $\times$ 6-ft 4-in. tall, 4-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,400
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 45 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
Total Major Purchased Equipment Cost		89,875

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-9.3-2. Total Capital Requirement (TCR) cost estimate for UV/oxidation and air stripper system with GAC vapor treatment for Treatment Facility G.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	89,875
Piping, concrete, steel (46% of MPEC)	41,343
Electrical, instrumentation (12% of MPEC)	10,785
Installation labor (58% of MPEC)	52,128
Major Equipment Installed Cost (MEIC)	<u>194,130</u>
Site preparation (10% of MEIC)	19,413
Total Field Cost (TFC)	<u>213,543</u>
Contractor's overhead and profit (10% of TFC)	21,354
Engineering design	50,000
Permitting	20,000
Subtotal	<u>304,897</u>
Contingency (20% of subtotal)	60,979
Total (TCR)	<u><u>365,877</u></u>

**Table D-9.3-3. Operating and maintenance cost estimate and present worth analysis for UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility G.**

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	23 filters	1,200	
UV/oxidation maintenance,	10% of UV/Ox	85,000	8,500	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
Subtotal			63,000	
Present worth (factor @ 5% = 15.54)				979,000
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Electricity	0.07/kW-h	488,808 kW-h	34,200	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	17,732 lb	11,000	
Replacement GAC unit	600/change	0.45/y	300	
Subtotal			47,700	
Present worth (factor @ 5% = 4.33)				206,500
Annual cost, years 6 through 10				
Electricity	0.07/kW-h	488,808 kW-h	34,200	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	17,732 lb	11,000	
Replacement GAC unit	600/change	0.45/y	300	
Subtotal			47,700	
Present worth (factor @ 5% = 3.39)				161,700

Table D-9.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	488,808 kW-h	34,200	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	17,732 lb	11,000	
Replacement GAC unit	600/change	0.45/y	300	
Subtotal			47,700	
Present worth (factor @ 5% = 2.66)				126,900
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	244,404 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	8,866 lb	5,500	
Replacement GAC unit	600/change	0.225/y	100	
Subtotal			23,800	
Present worth (factor @ 5% = 2.08)				49,500
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	244,404 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	8,866 lb	5,500	
Replacement GAC unit	600/change	0.225/y	100	
Subtotal			23,800	
Present worth (factor @ 5% = 1.63)				38,800
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	244,404 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	8,866 lb	5,500	
Replacement GAC unit	600/change	0.225/y	100	
Subtotal			23,800	
Present worth (factor @ 5% = 1.28)				30,500
Present worth of variable operating costs				613,900

Table D-9.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,592,900
Contingency (20% of subtotal)				318,600
Present worth of total 30-y operating and maintenance costs				1,911,500
Total Capital Requirement (TCR)				365,900
Present worth of alternative (30-y operation)				2,277,400

**Table D-10. Design criteria for Treatment System L (point of distribution, downtown Livermore).**

Chemical species	Inlet concentrations (average flow rate = 470 gpm) (ppb)	
	Maximum (worst case)	Average (best estimate)
PCE	46	0.02
TCE	90	0.1
1,1-DCE	7.6	0.02
1,2-DCE	7.6	0.02
1,1,1-TCA	7.6	0.02
1,1-DCA	7.6	0.02
1,2-DCA	7.6	0.02
Carbon tetrachloride	7.6	0.02
Chloroform	12	0.2
Freon 113	7.6	0.02

**Table D-10.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC units	Skid-mounted, dual-adsorber vessel system with two vessels 10-ft diam, 12 ft height, and 20,000 lb GAC per vessel	210,000
Treated water storage tank	Closed top cylindrical tank, 11,000-gal capacity, cross-linked polyethylene, 12 ft diam × 14 ft	11,500
Treated water discharge pump	End-suction centrifugal pump, 470 gpm at 30 ft TDH, with 7-1/2-hp motor	1700
<b>Total Major Purchased Equipment Cost</b>		<b>223,200</b>

**Table D-10.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	223,200
Piping, concrete, steel (46% of MPEC)	102,700
Electrical, instrumentation (12% of MPEC)	26,800
Installation labor (58% of MPEC)	129,500
Major Equipment Installed Cost (MEIC)	482,200
Site preparation (10% of MEIC)	48,200
Total Field Cost (TFC)	530,400
Contractor's overhead and profit (10% of TFC)	53,000
Engineering design	50,000
Permitting	10,000
Subtotal	643,400
Contingency (20% of subtotal)	128,700
Total (TCR)	772,000

**Table D-10.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility L (point of distribution, downtown Livermore).**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07 /kW-h	29,903 kW-h	2,090	
Electrical capacity charge	36 /kW	3.8 kW	140	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	210 samples	21,000	
Replacement of GAC	32,000 /units	21 units	672,000	
Maintenance (2% of TCR)			15,440	
Subtotal			745,670	
Contingency (20%)			149,130	
Subtotal			894,800	
Discounted value (factor, 30 y @5% = 15.54)				13,905,200
Total Capital Requirement (TCR)				772,000
Subtotal of future costs				14,677,200
Present worth of alternative (discount factor, 200 y @ 2% =0.019)				278,900

**Table D-10.2-1. Major Purchased Equipment Cost for an air stripper for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Description	Cost (1990 \$)
Air-stripper tower	Fiberglass-reinforced plastic tower 5-ft diam, depth of 25 ft of 3.5-in. Jaeger Tri-Pak packing	59,000
Air-supply feed blower	Centrifugal fan, 1,600 cfm at 4-in. water pressure with 3-hp motor	2,000
Treated liquid transfer pump	End-suction centrifugal pump, 470 gpm at 30 ft TDH with 7-1/2-hp motor	1,700
Treated liquid storage tank	Closed top cylindrical tank, 11,000-gal capacity, cross-linked polyethylene construction, 12 ft diam × 14 ft height	11,500
Treated liquid discharge pump	End suction centrifugal pump, 470 gpm at 30 ft TDH with 7-1/2-hp motor	1,700
<b>Total Major Purchased Equipment Cost</b>		<b>75,900</b>

**Table D-10.2-2. Total Capital Requirement (TCR) for an air stripper for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	75,900
Piping, concrete, steel (46% of MPEC)	34,900
Electrical, instrumentation (12% of MPEC)	9,100
Installation labor (58% of MPEC)	44,000
<b>Major Equipment Installed Cost (MEIC)</b>	<b>163,900</b>
Site preparation (10% of MEIC)	16,400
<b>Total Field Cost (TFC)</b>	<b>180,300</b>
Contractor's overhead and profit (10% of TFC)	18,000
Engineering design	50,000
Permitting	20,000
<b>Subtotal</b>	<b>268,300</b>
Contingency (20% of subtotal)	53,700
<b>Total (TCR)</b>	<b>322,000</b>

**Table D-10.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper for Treatment Facility L (point of distribution, downtown Livermore).**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	199,108 kW-h	5,020	
Electrical capacity change	36/kW	25.3 kW	330	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	160 samples	16,000	
Maintenance (2% of TCR)			6,440	
Subtotal			62,790	
Contingency (20%)			12,560	
Subtotal			75,560	
Discounted value (factor, 30 y @ 5% = 15.54)				1,170,900
Total Capital Requirement (TCR)				322,000
Subtotal of future costs				1,492,900
Present value of alternative (discount factor, 200 y @ 2% = 0.019)				28,365

**Table D-10.3-1. Major Purchased Equipment Cost for UV/oxidation system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	4,000
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80-gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	320,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 1,800-gal, double-walled, cross-linked, polyethylene, 7-ft-10-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	1,500
Treated water storage tank	Closed-top, cylindrical, 11,000 gal, cross-linked polyethylene, 12 ft diam $\times$ 14 ft tank	11,500
Treated liquid discharge pump	End-suction centrifugal pump, 470 gpm at 30 ft TDH; 7-1/2-hp motor	1,700
Total Major Purchased Equipment Cost		338,700

<sup>a</sup> Cost included with UV/oxidation unit.

**Table D-10.3-2. Total Capital Requirement (TCR) for an UV/oxidation system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	338,700
Piping, concrete, steel (46% of MPEC)	155,802
Electrical, instrumentation (12% of MPEC)	40,644
Installation labor (58% of MPEC)	196,446
Major Equipment Installed Cost (MEIC)	<u>731,592</u>
Site preparation (10% of MEIC)	73,159
Total Field Cost (TFC)	<u>804,751</u>
Contractor's overhead and profit (10% of TFC)	80,475
Engineering design	50,000
Permitting	20,000
Subtotal	<u>955,226</u>
Contingency (20% of subtotal)	191,045
Total (TCR)	<u><u>1,146,272</u></u>

**Table D-10.3-3. Operating and maintenance cost estimate and present worth analysis for UV/oxidation system for Treatment Facility L (point of distribution, downtown Livermore).**

<b>Analysis of Extraction Alternative No. 1: facility operated for 30 y</b>				
<b>Item</b>	<b>Rate (1990 \$)</b>	<b>Usage</b>	<b>Subtotal present worth (1990 \$)</b>	<b>Total present worth (1990 \$)</b>
<i>Fixed annual operating and maintenance costs</i>				
Electricity	2,892,114 kW-h	0.07	202,448	
Electrical use fee	367/kW	36	13,206	
Hydrogen peroxide	0.62/lb	185,200	114,824	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	244 filters	12,220	
UV/oxidation maintenance	10% of UV/Ox unit	320,000	32,000	
VOC/FHC water samples	100/sample	160 samples	16,000	
Maintenance (2% of TCR)			22,925	
Subtotal annual fixed operating and maintenance costs			448,623	
Contingency (20% of subtotal)			89,725	
<b>Total annual operating and maintenance costs</b>			<b>538,348</b>	
Present worth (discount 30-y factor @ 5% = 15.54)				8,365,929
<b>Total Capital Requirement (TCR)</b>				<b>1,146,272</b>
Subtotal				<b>9,512,201</b>
Present worth of alternative (discount factor, 200 y @ 2% = 0.019)				<b>180,732</b>

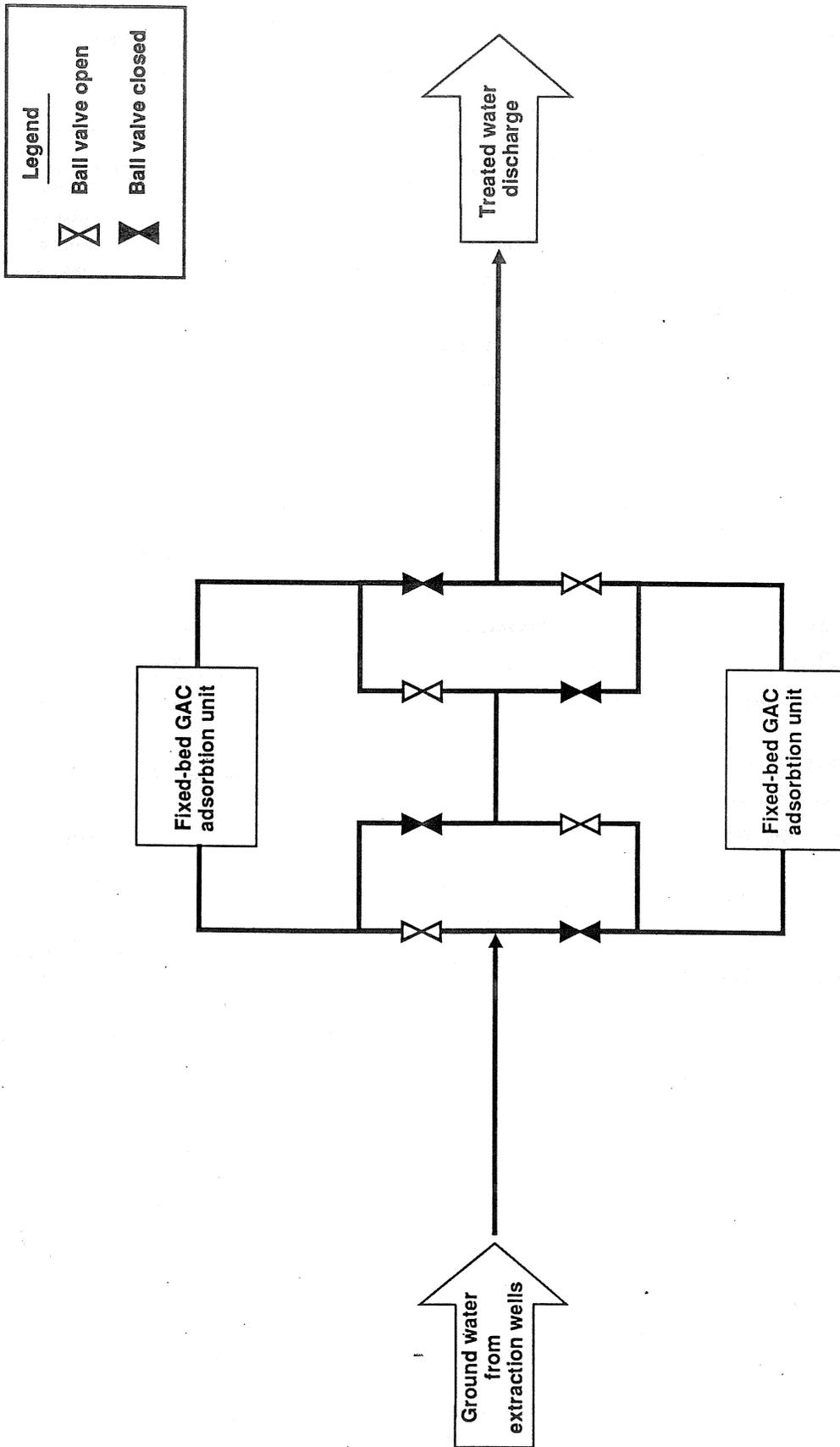


Figure D-1. A GAC system for removing VOCs and metals from ground water at Treatment Facilities A, B, C, E, F, and G.

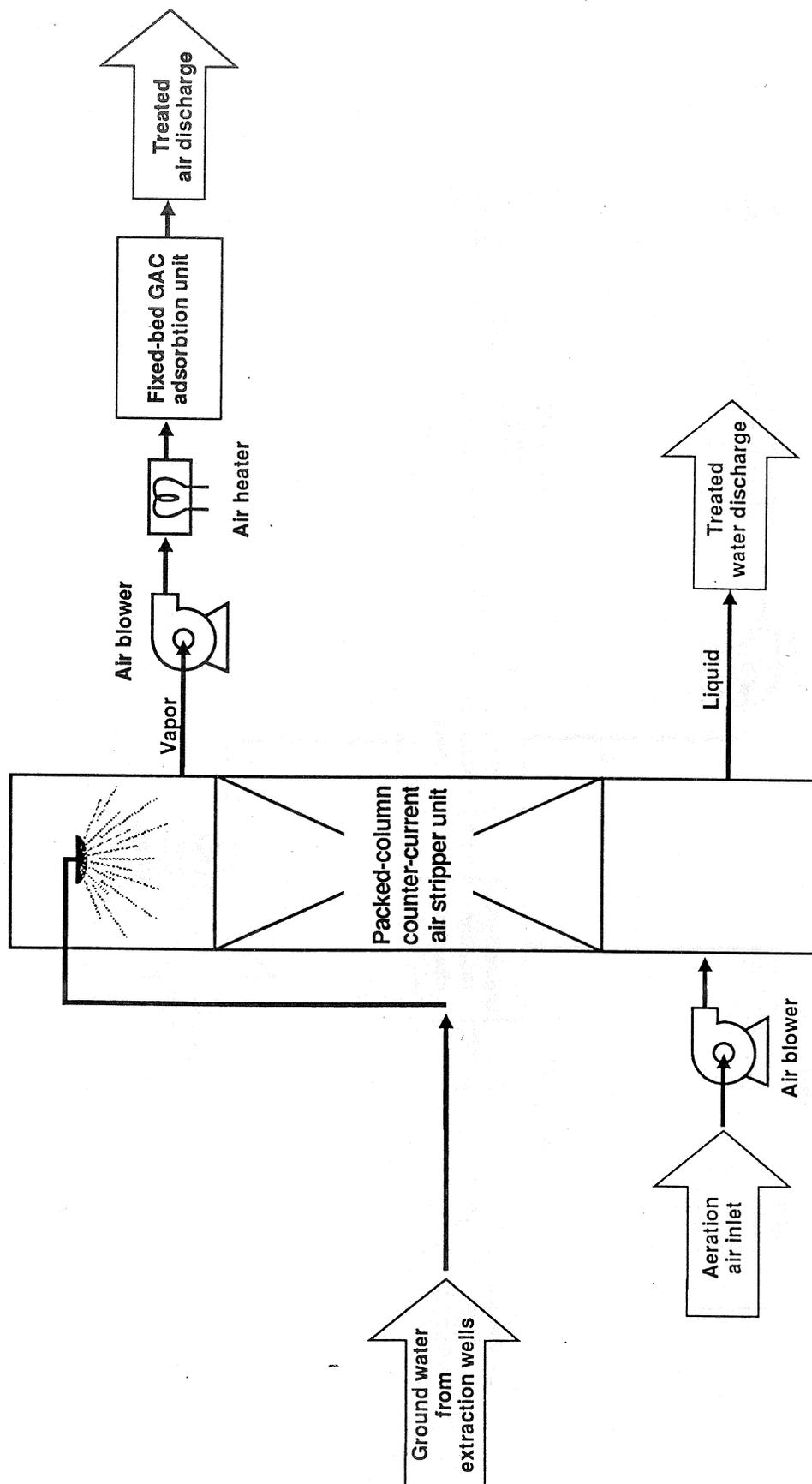


Figure D-2. An air stripper and GAC vapor system for removing VOCs and FHCs from ground water at Treatment Facilities A, B, C, E, and G.

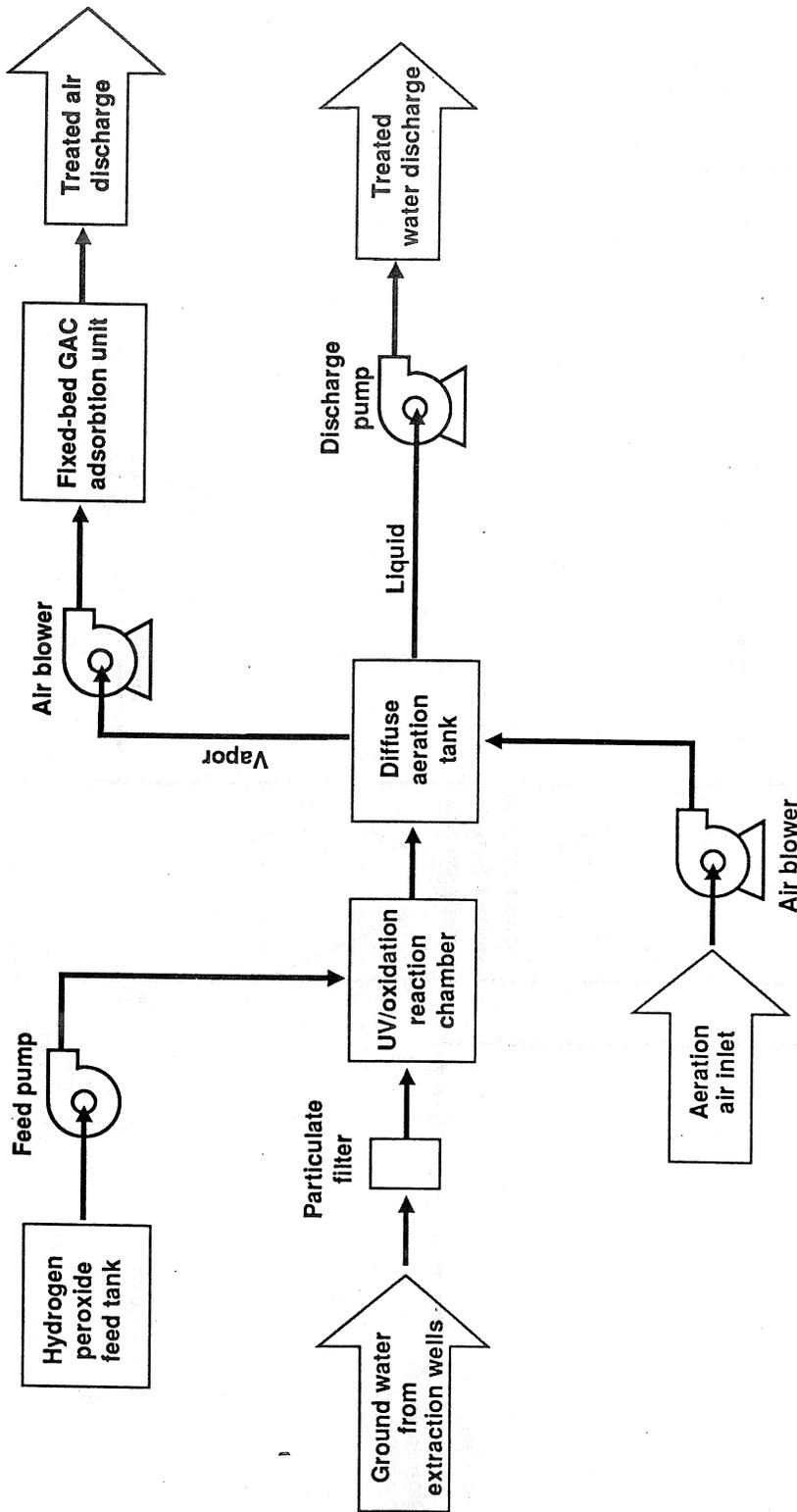


Figure D-3. A UV/oxidation and air stripping system, with GAC vapor treatment for oxidizing and removing VOCs from ground water at Treatment Facilities A, B, C, E, and G.

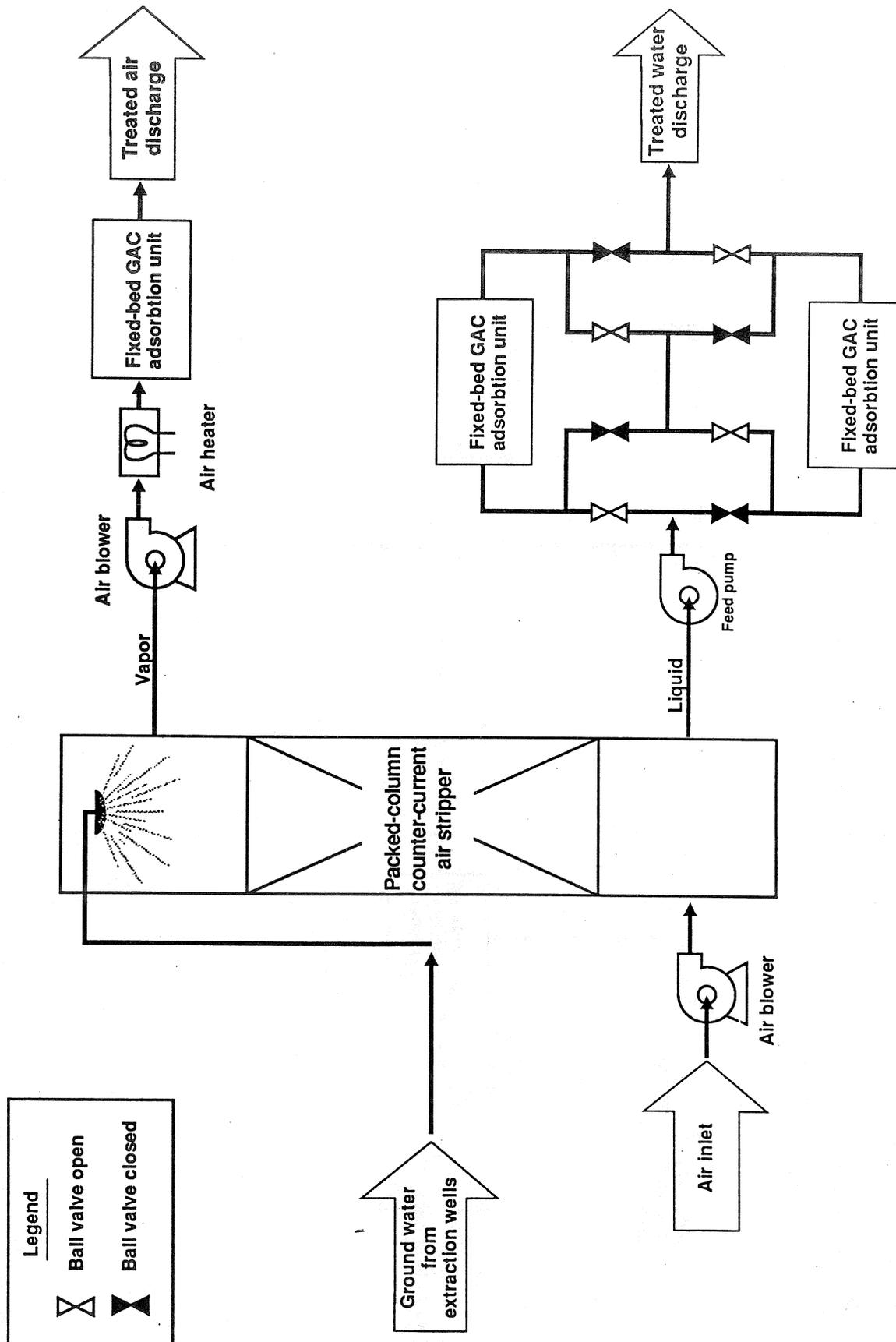


Figure D-4. Air stripper and GAC system with GAC vapor treatment for removing VOCs, FHCs, and lead from ground water at Treatment Facility F.

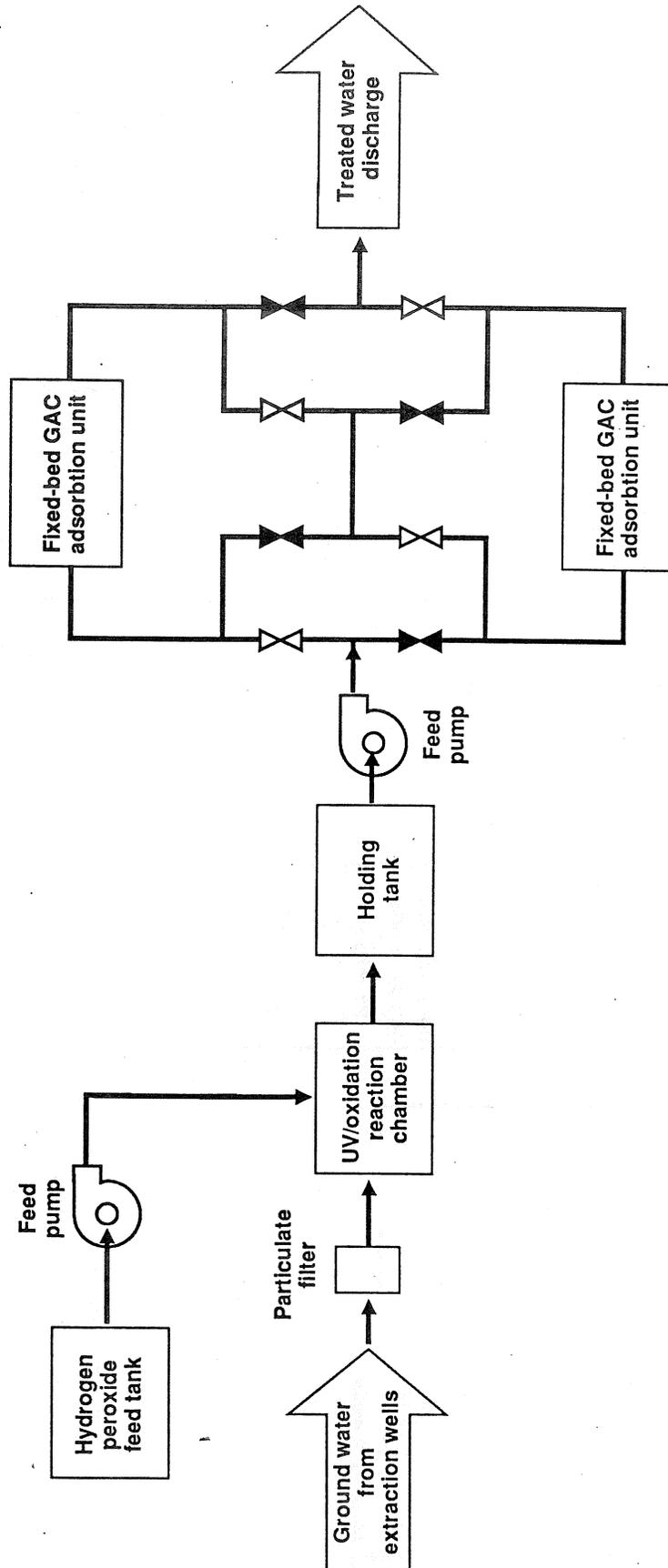
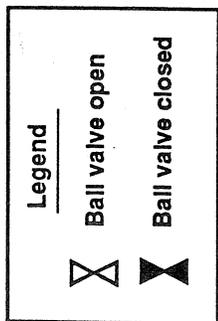


Figure D-5. UV/oxidation and GAC system for oxidizing and removing VOCs, FHCs, and lead from ground water (Treatment Facility F).

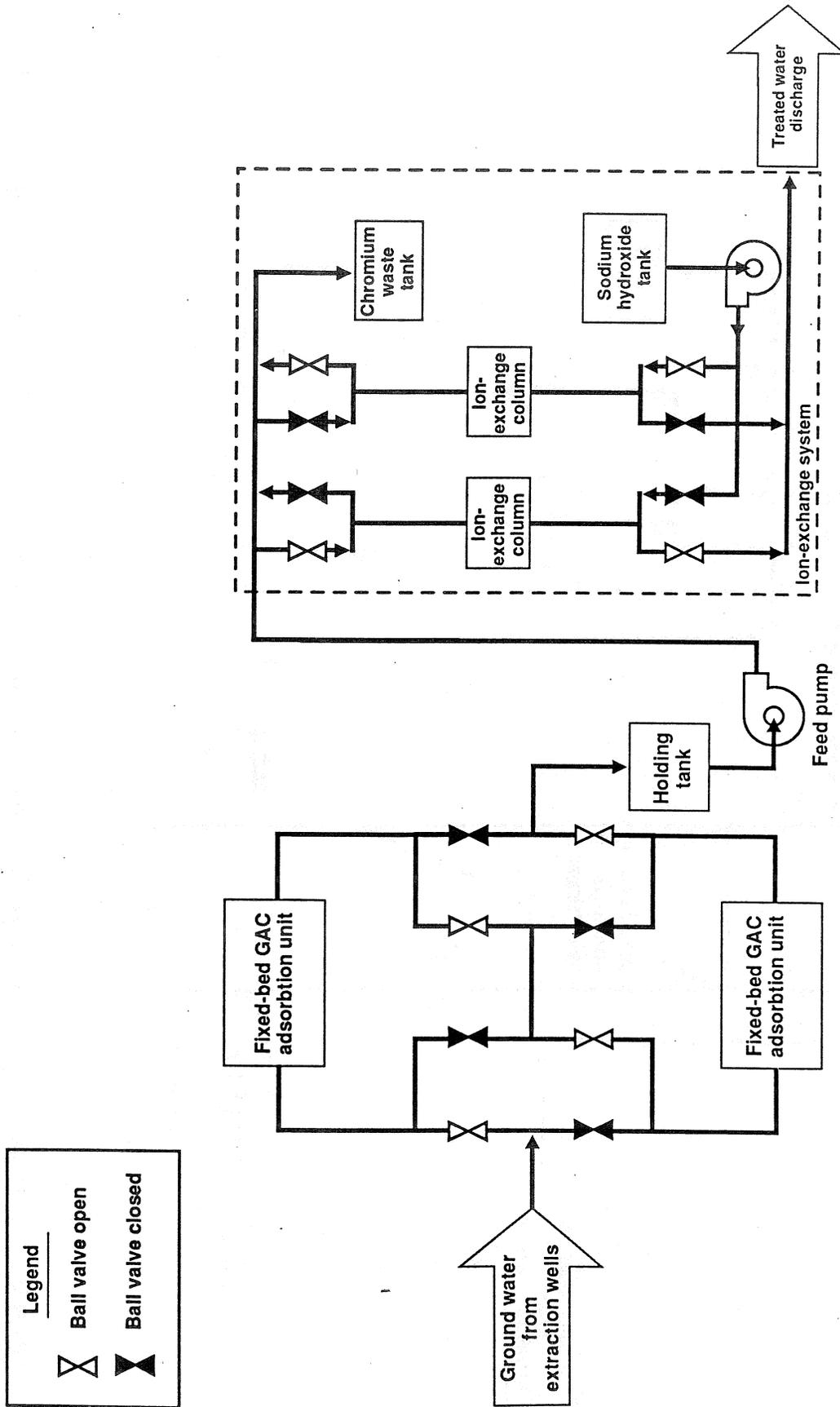


Figure D-6. A GAC and ion-exchange system for removing VOCs and chromium from ground water at Treatment Facility D.

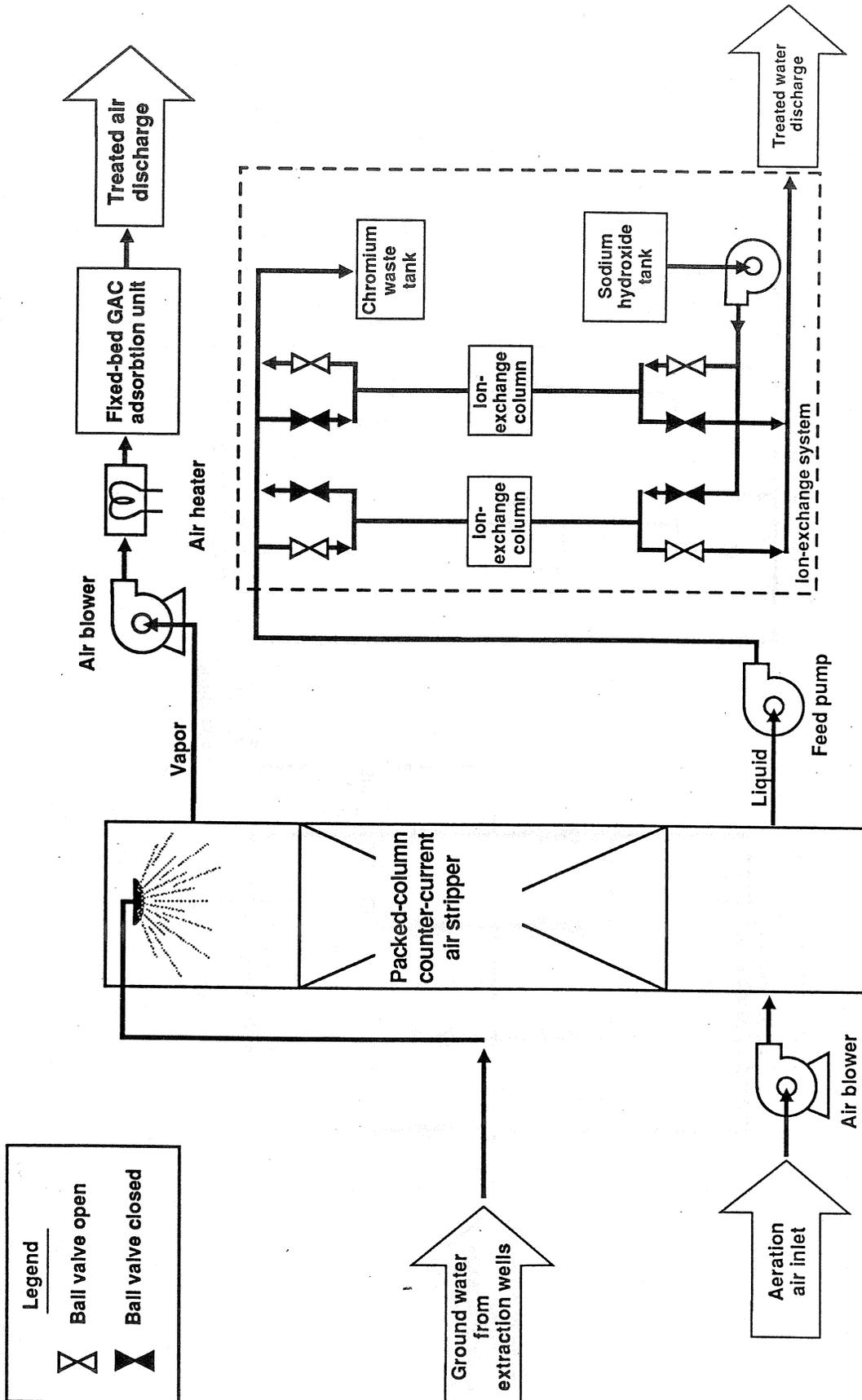


Figure D-7. An air stripper and ion-exchange system with GAC vapor treatment for removing VOCs, FHCs, and chromium from ground water at Treatment Facility D.

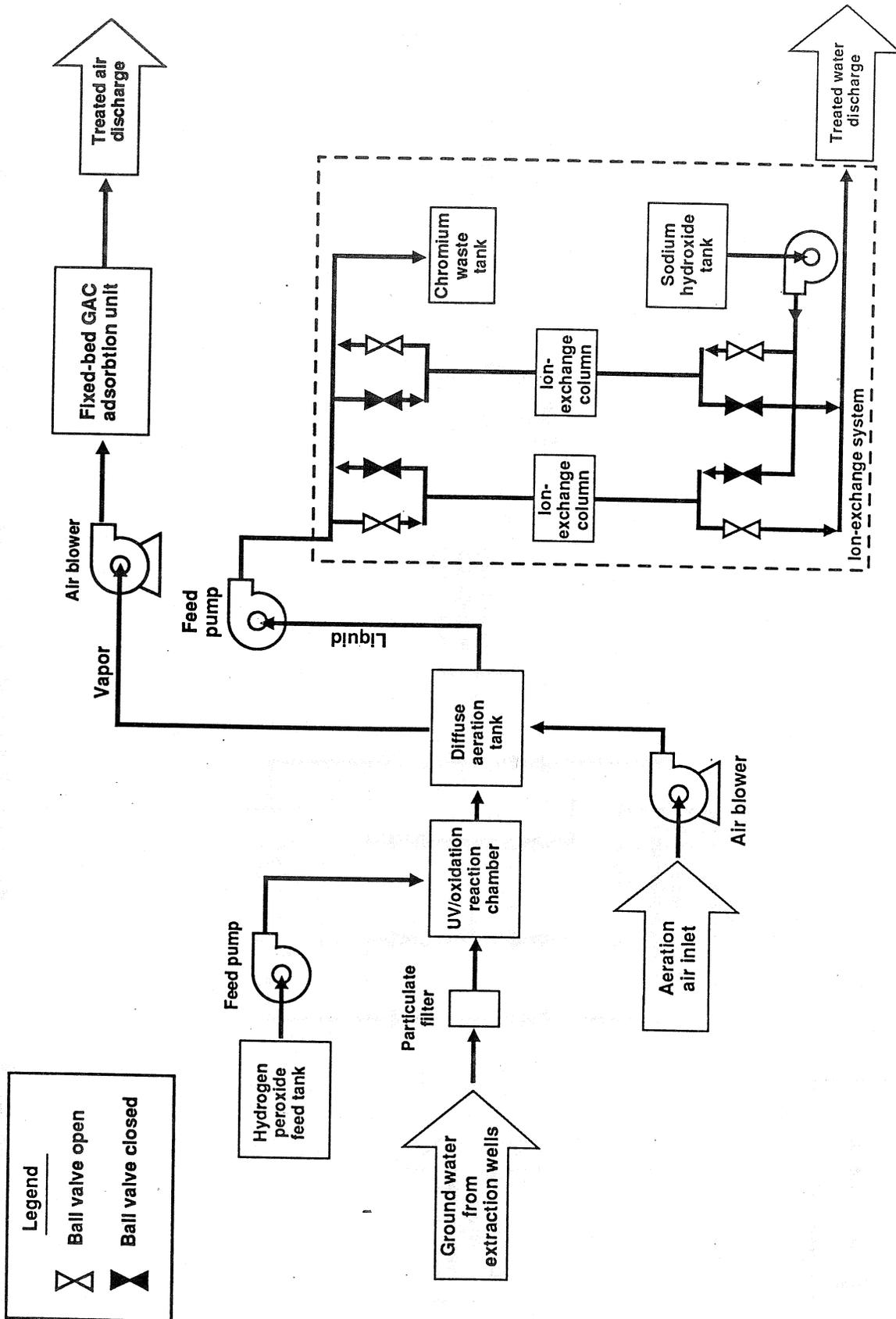


Figure D-8. A UV/oxidation, air stripping, and ion-exchange system with GAC vapor treatment for removing VOCs and chromium from ground water at Treatment Facility D.

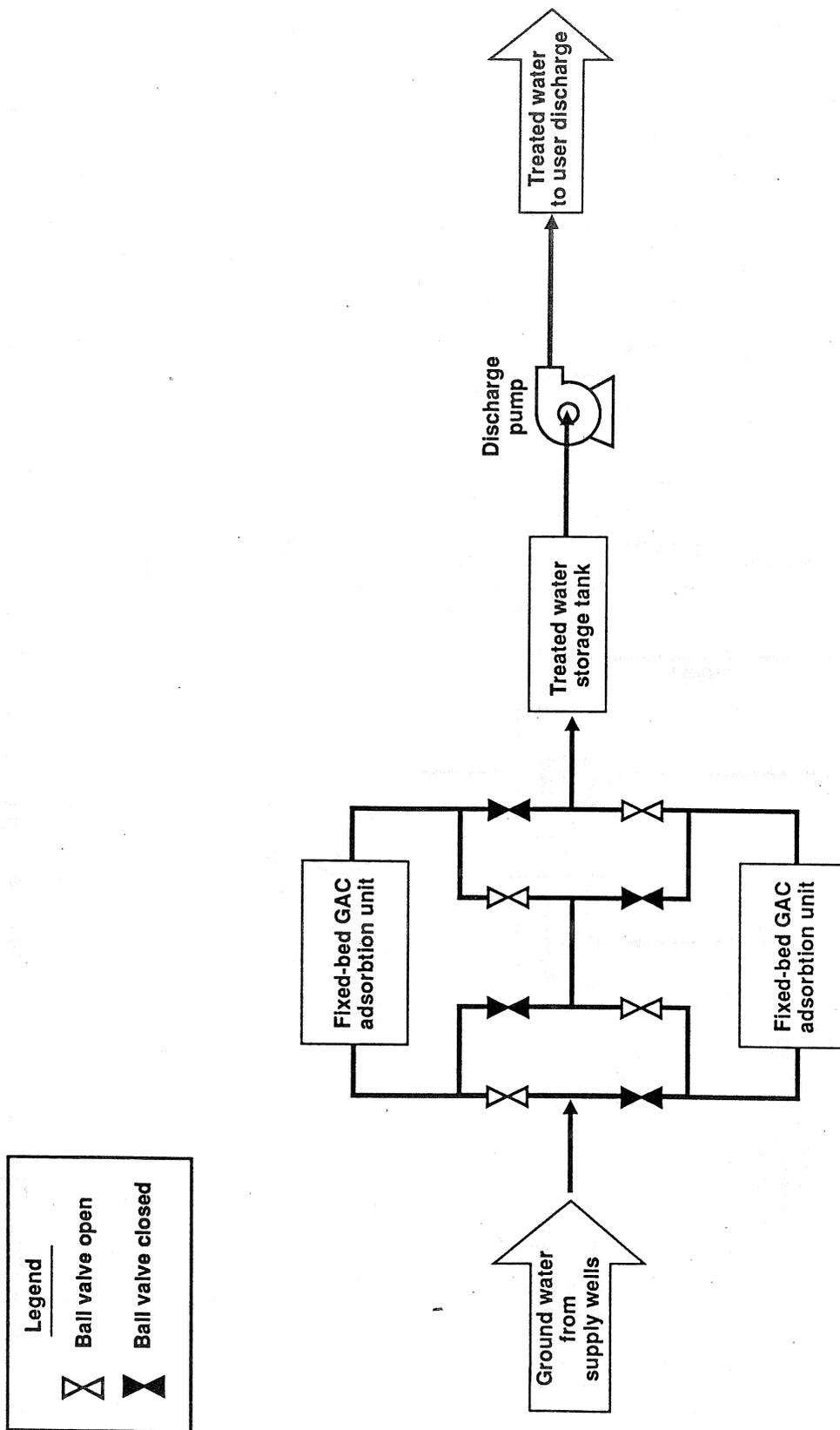


Figure D-9. GAC system for removing VOCs from ground water at the point of distribution in Livermore.

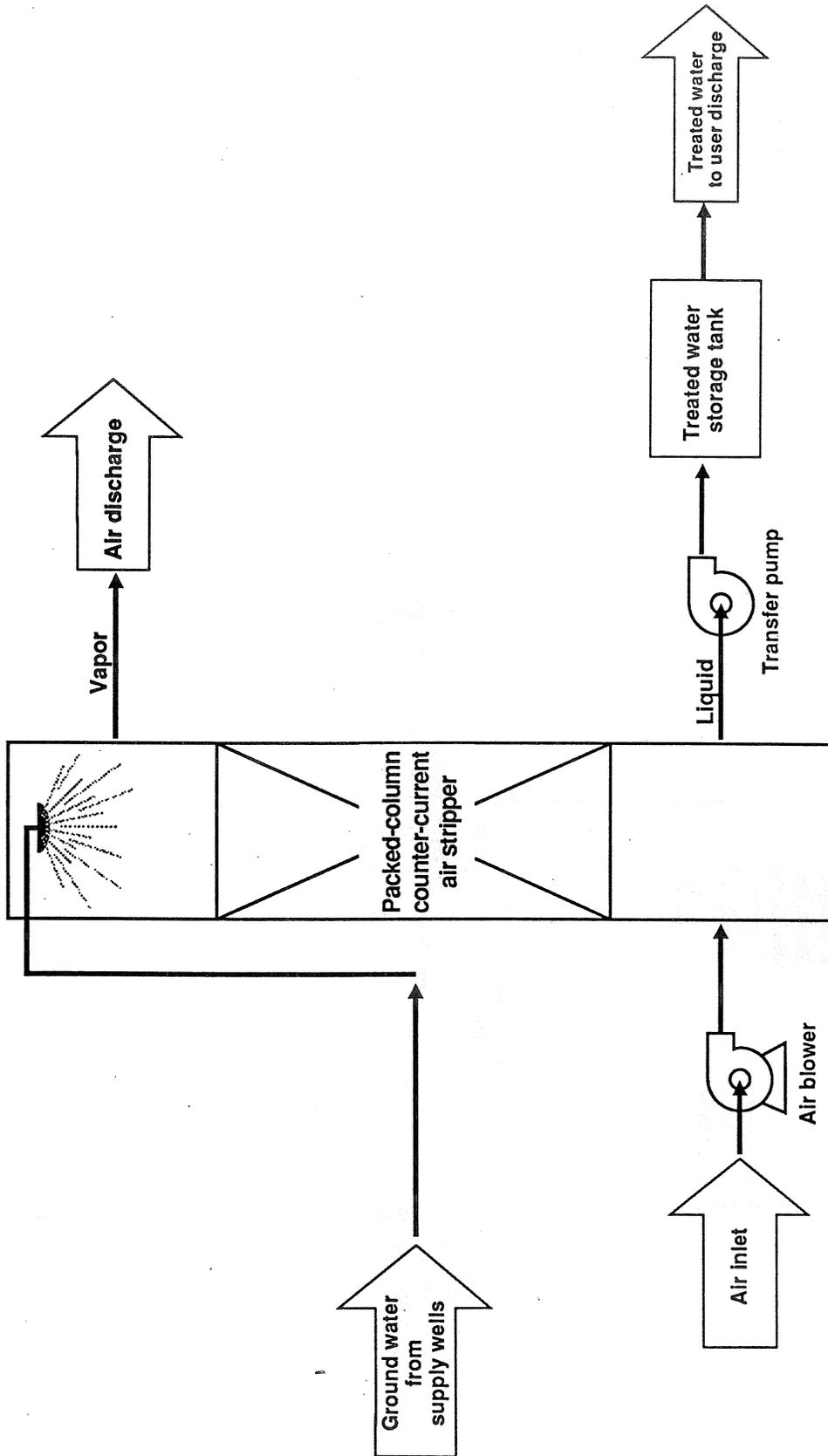


Figure D-10. Air stripper for removing VOCs from ground water at the point of distribution in Livermore.

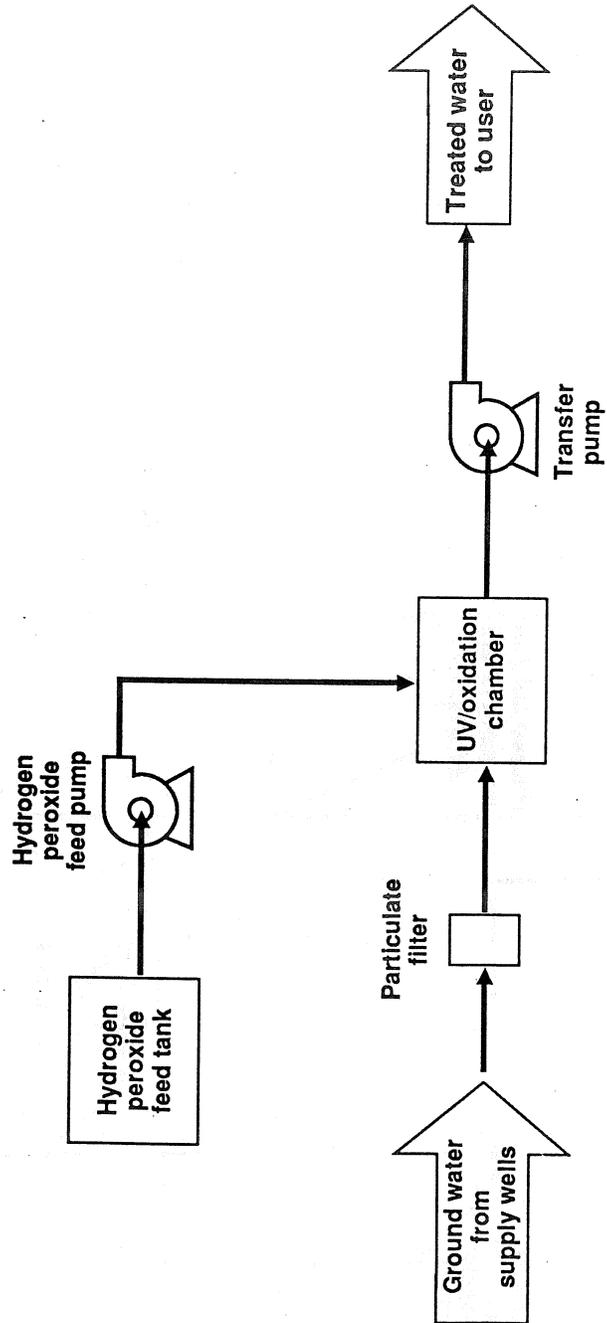


Figure D-11. UV/oxidation for treatment at the point of distribution in downtown Livermore.

**APPENDIX E**  
**CONCEPTUAL DESIGNS AND COST ESTIMATES FOR**  
**VADOSE ZONE TREATMENT TECHNOLOGIES**

# APPENDIX E

## CONCEPTUAL DESIGNS AND COST ESTIMATES FOR VADOSE ZONE TREATMENT TECHNOLOGIES

### E-1. BASIS FOR CONCEPTUAL DESIGNS AND COST ESTIMATES

The basis for development of the conceptual designs for vadose zone treatment alternatives, with the cost estimates prepared from these designs, are provided in this section. First, the engineering design basis is described; then, the basis for development of capital cost estimates is given; and, finally, the basis for estimation of operating costs over the project life is developed.

#### E-1.1. Engineering Design Basis

The following assumptions apply to the development of the conceptual treatment alternatives at all sites:

1. The vacuum-induced venting system at the site of FHC contamination of the vadose zone is assumed to be operated at a total soil gas extraction rate of 300 cfm. The system is assumed to operate for 10 y. The concentration of FHCs in the soil gas is assumed to change with time, as follows: first 6 months, the TPH concentration in the gas will be 4000 ppm by volume; second 6 months, 1000 ppm; second year, 300 ppm; years 3 through 10, 20 ppm. This rate of decline in concentrations is estimated from data on operation of the existing pilot vacuum-induced venting system. The estimates of usage of GAC and propane for oxidation systems reflect this decline in concentrations. For example, according to vendor supplied design data, the propane consumption rate will be 5.8 gal/h during the first 6 months of operation, 7.6 gal/h during the next 6 months, and 8 gal/h thereafter. Estimates of GAC use and disposal were similarly based on information supplied by vendors and were adjusted to reflect the decline in contaminant concentrations.
2. The vacuum-induced venting system at the site of VOC contamination of the vadose zone is assumed to be operated at a total soil gas extraction rate of 100 cfm. The system is assumed to operate for 5 y. The concentration of VOCs in the soil gas is assumed to change with time, as follows: during the first 6 months, the vapor concentrations will be 500 ppm. This concentration is based on the highest measured soil concentrations onsite and soil/vapor partitioning factors. The concentration was assumed to decline with time at the same rate as for the FHCs, for the following total VOC concentrations: second 6 months, 125 ppm; second year, 33 ppm; years 3 through 5, 2 ppm. The estimates of usage of GAC and propane for oxidation systems reflect this decline in concentration.
3. The conceptual designs and cost estimates include only the aboveground gas treatment alternatives. Items such as the soil gas extraction wells and piping connecting the wells to the treatment units are common to all treatment alternatives. The capital and operating costs associated with these items are the same for all treatment alternatives and so are not included in the analysis of alternatives. However, the costs shown in Section 4 include the costs of vapor extraction wells.

4. The conceptual design for each alternative is based on the shared soil gas flow rates and concentrations. The equipment sizing and selection for the capital cost estimation are based on this conceptual design basis, as is the estimation of operating costs.
5. A 5% discount rate is assumed for development of present worth calculations. Present worth factors for future costs are calculated using the procedures described in the Remedial Action Costing Procedures Manual, October 1987 (EPA/600/8-87/049).
6. The estimates for operating costs reflect the decline in concentrations of the contaminants in the extracted soil gas. Operating cost items that may be adjusted include the costs for replacement of GAC and the propane fuel used for oxidation systems.
7. The reduction in contaminant concentrations in the extracted soil gas described above results in a reduced rate of use of GAC for the alternatives that use this technology. The rate of GAC use during the first 6 months of operation is based on the initial soil gas concentrations given above. Information obtained from vendors of vapor-phase GAC is used to estimate the initial rate of use. The rate of use of GAC during subsequent periods is less as a result of the decreased concentrations in the soil gas.

The theoretical capacity of GAC to adsorb organic chemicals from vapor is commonly expressed in the form of a Freundlich isotherm equation:

$$q = kC^n$$

where:

- $q$  = quantity adsorbed onto GAC, mg compound/g GAC;
- $C$  = concentration in air, ppm;
- $k$  = Freundlich adsorption constant; and
- $n$  = Freundlich adsorption exponent.

The values of  $k$  and  $n$  for the compounds of interest in this study were obtained from GAC vendors and reviewed to obtain a typical value of 0.5 for the adsorption exponent  $n$ . This value is assumed to apply to all compounds and the rate of GAC use is adjusted according to the following equation:

$$R_m = R(C_m/C_0)^{0.5}$$

where:

- $R_m$  = rate of GAC use during the  $m$ th period following the initial 6 months;
- $R$  = rate of GAC use during the initial 6-month period;
- $C_m$  = total concentration of VOCs or FHCs in the extracted soil gas during the  $m$ th period.
- $C_0$  = total concentration of VOCs or FHCs in the extracted soil gas during the initial 6 months.

8. The estimate of rate of use of propane fuel for the thermal and catalytic oxidation systems has been obtained from vendors. These estimates include the effect of the decline in heat value of the vapor to be treated resulting from the decline in VOC or FHC concentrations.

### E-1.2. Capital Cost Estimation

The following assumptions apply to the estimation of capital costs for all treatment alternatives:

1. Vendor quotes or vendor catalog prices are used to develop the costs for major purchased equipment items.
2. A factored estimate for total installed capital cost, accurate to +50%/-30%, has been prepared based on the cost for major purchased equipment. Installation cost factors are based on experience for installation of chemical process equipment.
3. Indirect costs included in the estimation of the total capital requirement are engineering design and permitting. An estimate of \$20,000 for engineering design is included for all alternatives. Permitting costs are estimated at \$10,000 for all alternatives.
4. A contingency factor of 20% is applied to all capital cost estimates.

### E-1.3. Operating Cost Estimation

The following assumptions apply to the development of operating cost estimates for all alternatives:

1. An operating factor of 90% is assumed for all treatment alternatives.
2. The following annual labor hours and hourly rates, including indirect labor costs, apply to all alternatives:
 

Supervision labor	200 h at \$75/h
Operating labor	500 h at \$40/h
3. The cost for electricity is estimated to be \$0.07 per kW/h plus an annual connection fee of \$36 per kW.
4. The cost for replacement of spent vapor-phase GAC is based on vendor quotes applicable to servicing of the specific GAC units utilized in the conceptual design. This cost includes removal of spent GAC, thermal regeneration of spent GAC and replacement with fresh GAC, as well as all freight and labor costs.
5. The costs for analysis of air samples include only those samples necessary for monitoring the performance of the aboveground treatment facilities. For each system, a sample of the gas entering the treatment unit and a sample of the gas exiting the treatment unit is collected. It is assumed that each alternative is monitored biweekly. When provision is made for collection of blank and duplicate samples, 60 samples are analyzed each year for each alternative. The following costs per sample analysis apply:
 

Air sample:	
VOC analysis	\$100/sample
TPH analysis	\$100/sample
6. An annual cost of 2% of the total capital requirement is included in the operating cost for all alternatives.
7. A contingency of 20% is applied to the operating cost estimate.
8. Operating cost estimates take into account the decline in GAC use or propane use, resulting from the decline in inlet gas concentrations with time, as described previously.
9. The operating cost estimates are discounted to 1990 for developing the present worth estimates assuming a discount rate of 5%.

**Table E-1. Major Purchased Equipment Cost for soil gas extraction with GAC for treatment of FHCs.**

Equipment	Description	Equipment cost (1990 \$)
Water separation/collection tank	Lined steel 55-gal capacity	450
Rotary vacuum blower	End-suction centrifugal pump, 145 gpm at 50 ft TDH with 5-hp motor	3,700
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48-in. diam by 86 in. contains 1800 lb GAC	10,500
<b>Major Purchased Equipment Cost</b>		<b>14,650</b>

**Table E-2. Total Capital Requirement (TCR) for soil gas extraction with GAC for treatment of FHCs.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	14,650
Piping, concrete, steel (46% of MPEC)	6,700
Electrical, instrumentation (12% of MPEC)	1,800
Installation labor (58% of MPEC)	8,500
Major Equipment Installed Cost (MEIC)	31,650
Site preparation (10% of MEIC)	3,200
Total Field Cost (TFC)	34,850
Contractors' overhead and profit (10% of TFC)	3,500
Engineering design	20,000
Permitting	10,000
Subtotal	68,350
Contingency (20% of subtotal)	13,700
Total (TCR)	82,000

Table E-3. Operating cost estimate and present worth analysis for soil gas extraction with GAC for treatment of FHCs.

Item	Rate (1990 \$)	Quantity	Cost (1990 \$)	Present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	30,000 kW-h	2,100	
Electric capacity charge	36/kW	3.8 kW	140	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	60 samples	6,000	
Maintenance (2% of TCR)			1,640	
Subtotal			44,880	
Present worth (factor, 30 y @ 5% = 7.72)				346,500
<i>Variable operating costs</i>				
Annual costs, year 1				
Replacement of GAC	4,200/unit	178.3 units	748,860	
Present worth (factor, @5% = 4.33)				712,910
Annual costs, year 2				
Replacement of GAC	4,200/unit	65.2 units	273,840	
Present worth (factor, @5% = 0.907)				248,370
Annual costs, years 3 through 10				
Replacement of GAC	4,200/unit	16.8 units	70,560	
Present worth (factor, @5% = 5.862)				413,600
Present worth of variable operating costs (10 y)				1,374,880
Subtotal of present worth of fixed and variable operating and maintenance costs				1,721,380
Contingency (20% of subtotal)				344,300
Present worth of total 10-y operating and maintenance cost				2,065,680
Total Capital Requirement (TCR)				82,000
Total present worth of alternative				2,147,680

**Table E-4. Major Purchased Equipment Cost for soil gas extraction with thermal oxidation of FHCs.**

Equipment	Description	Equipment cost (1990 \$)
Water separation/collection tank	Lined steel 55-gal capacity	450
Rotary vacuum blower	300-cfm capacity, 5-hp motor	3,700
Thermal oxidation unit	Propane fueled, 300-cfm capacity	62,000
Propane storage tank	Cylindrical steel pressure vessel, 1000-gal capacity	2,000
<b>Major Purchased Equipment Cost</b>		<b>68,150</b>

**Table E-5. Total Capital Requirement (TCR) for soil gas extraction with thermal oxidation of FHCs.**

Item	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	68,150
Piping, concrete, steel (46% of MPEC)	31,300
Electrical, instrumentation (12% of MPEC)	8,200
Installation labor (58% of MPEC)	39,500
Subtotal Major Equipment Installed Cost (MEIC)	147,150
Site preparation (10% of MEIC)	14,700
Total Field Cost (TFC)	161,850
Contractors' overhead and profit (10% of TFC)	16,200
Engineering design	20,000
Permitting	10,000
Subtotal	208,050
Contingency (20% of subtotal)	41,600
Total (TCR)	250,000

Table E-6. Operating cost estimate and present worth analysis for soil gas extraction with thermal oxidation of FHCs.

Item	Rate (1990 \$)	Quantity	Cost (1990 \$)	Present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	40,000 kW-h	2,800	
Electric capacity charge	36/kW	5.1 kW	180	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	60 samples	6,000	
Maintenance (2% of TCR)			5,000	
Subtotal			48,980	
Present worth (factor, 10 y @ 5% = 7.72)				378,100
<i>Variable operating costs</i>				
Annual costs, year 1				
Propane fuel	0.50/gal	52,823 gal	26,410	
Present worth (factor, @5% = 0.952)				25,140
Annual costs, year 2				
Propane fuel	0.50/gal	63,072 gal	31,540	
Present worth (factor, @5% = 0.907)				28,610
Annual costs, years 3 through 10				
Propane fuel	0.50/gal	63,072 gal	31,540	
Present worth (factor, @5% = 5.862)				184,900
Present worth of variable operating costs				238,650
Subtotal of present worth of fixed and variable operating and maintenance costs				616,750
Contingency (20% of subtotal)				123,400
Present worth of total 10-y operating and maintenance cost				740,150
Total Capital Requirement (TCR)				250,000
Total present worth of alternative				990,150

**Table E-7. Major Purchased Equipment Cost for soil gas extraction with catalytic oxidation of FHCs.**

Equipment	Description	Equipment cost (1990 \$)
Water separation/collection tank	Lined steel 55-gal capacity	450
Rotary vacuum blower	300-cfm capacity, 5-hp motor	3,700
Catalytic oxidation unit	Propane fueled, 300-cfm capacity	65,000
Propane storage tank	Cylindrical steel pressure vessel, 1000-gal capacity	2,000
<b>Major Purchased Equipment Cost</b>		<b>71,150</b>

**Table E-8. Total Capital Requirement (TCR) for soil gas extraction with catalytic oxidation of FHCs.**

Item	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	71,150
Piping, concrete, steel (46% of MPEC)	32,700
Electrical, instrumentation (12% of MPEC)	8,500
Installation labor (58% of MPEC)	41,300
<b>Total Major Equipment Installed Cost (MEIC)</b>	<b>153,650</b>
Site preparation (10% of MEIC)	15,400
<b>Total Field Cost (TFC)</b>	<b>169,050</b>
Contractor's overhead and profit (10% of TFC)	16,900
Engineering design	20,000
Permitting	10,000
<b>Subtotal</b>	<b>215,950</b>
Contingency (20% of subtotal)	43,200
<b>Total (TCR)</b>	<b>259,000</b>

**Table E-9. Operating cost estimate and present worth analysis for soil gas extraction with catalytic oxidation of FHCs.**

Item	Rate (1990 \$)	Quantity	Cost (1990 \$)	Present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	40,000 kW-h	2,800	
Electric capacity charge	36/kW	5.1 kW	180	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Air sample VOC analysis	100/sample	60 samples	6,000	
Maintenance (2% of TCR)			5,180	
Subtotal			49,160	
Present worth (factor, 10 y @ 5% = 7.72)				379,500
<i>Variable operating costs</i>				
Annual costs, year 1				
Propane fuel	0.50/gal	5322 gal	2,660	
Present worth (discount factor, @5% = 0.952)				2,530
Annual costs, year 2				
Propane fuel	0.50/gal	11,045 gal	5,520	
Present worth (discount factor, @5% = 0.907)				5,010
Annual costs, years 3 through 10				
Propane fuel	0.50/gal	11,774 gal	5,890	
Present worth (factor, @5% = 5.862)				34,500
Present worth of variable operating costs (10 y)				42,040
Subtotal of present worth of fixed and variable operating and maintenance costs				421,540
Contingency (20% of subtotal)				84,300
Present worth of total 10-y operating and maintenance cost				505,840
Total Capital Requirement (TCR)				259,000
Total present worth of alternative				764,840

**Table E-10. Major Purchased Equipment Cost for soil gas extraction with GAC for treatment of VOCs.**

Equipment	Description	Equipment cost (1990 \$)
Water separation/collection tank	Lined steel 55-gal capacity	450
Rotary vacuum blower	100-cfm capacity, 2-hp motor	2,000
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. in diam by 63 in. contains 1000 lb of GAC	6,600
<b>Major Purchased Equipment Cost</b>		<b>9,050</b>

**Table E-11. Total Capital Requirement (TCR) for soil gas extraction with GAC for treatment of VOCs.**

Item	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	9,050
Piping, concrete, steel (46% of MPEC)	4,200
Electrical, instrumentation (12% of MPEC)	1,100
Installation labor (58% of MPEC)	5,200
<b>Total Major Equipment Installed Cost (MEIC)</b>	<b>19,550</b>
Site preparation (10% of MEIC)	2,000
<b>Total Field Cost (TFC)</b>	<b>21,550</b>
Contractors' overhead and profit (10% of TFC)	2,200
Engineering design	20,000
Permitting	10,000
<b>Subtotal</b>	<b>53,750</b>
Contingency (20% of subtotal)	10,800
<b>Total (TCR)</b>	<b>65,000</b>

**Table E-12. Operating cost estimate and present worth analysis for soil gas extraction with GAC for treatment of VOCs.**

Item	Rate (1990 \$)	Quantity	Cost (1990 \$)	Present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	12,000 kW-h	840	
Electric capacity charge	36/kW	1.5 kW	50	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Air sample VOC analysis	100/sample	60 samples	6,000	
Maintenance (2% of TCR)			1,300	
Subtotal			<u>43,190</u>	
Present worth (factor, 5 y @ 5% = 4.32)				186,600
<i>Variable operating costs</i>				
Annual costs, year 1				
Replacement of GAC	2,500/unit	21.9 units	<u>54,750</u>	
Present worth (discount factor, @5% = 0.952)				52,120
Annual costs, year 2				
Replacement of GAC	2,500/unit	6.1 units	<u>15,250</u>	
Present worth (discount factor, @5% = 0.907)				13,830
Annual costs, years 3 through 5				
Replacement of GAC	2,500/unit	1.2 units	<u>3,000</u>	
Present worth (factor, @5% = 2.470)				<u>7,400</u>
Present worth of variable operating costs				<u>73,350</u>
Subtotal of present worth of fixed and variable operating and maintenance costs				<u>259,950</u>
Contingency (20% of subtotal)				<u>52,000</u>
Present worth of total 5-y operating and maintenance cost				<u>311,950</u>
Total Capital Requirement (TCR)				<u><u>65,000</u></u>
Total present worth of alternative				<u><u>376,950</u></u>

**Table E-13. Major Purchased Equipment Cost for soil gas extraction with thermal oxidation of VOCs.**

Equipment	Description	Equipment cost (1990 \$)
Water separation/collection tank	Lined steel 55-gal capacity	450
Rotary vacuum blower	100-cfm capacity, 2-hp motor	2,000
Thermal oxidation unit	Propane fueled, 100-cfm capacity	62,000
Propane storage tank	Cylindrical steel pressure vessel, 1000-gal capacity	2,000
<b>Major Purchased Equipment Cost</b>		<b>66,450</b>

**Table E-14. Total Capital Requirement (TCR) estimate for soil gas extraction with thermal oxidation of VOCs.**

Item	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	66,450
Piping, concrete, steel (46% of MPEC)	30,600
Electrical, instrumentation (12% of MPEC)	8,000
Installation labor (58% of MPEC)	38,500
<b>Total Major Equipment Installed Cost (MEIC)</b>	<b>143,550</b>
Site preparation (10% of MEIC)	14,400
<b>Total Field Cost (TFC)</b>	<b>157,950</b>
Contractors' overhead and profit (10% of TFC)	15,800
Engineering design	20,000
Permitting	10,000
<b>Subtotal</b>	<b>203,750</b>
Contingency (20% of subtotal)	40,800
<b>Total (TCR)</b>	<b>245,000</b>

**Table E-15. Operating cost estimate and present worth analysis for soil gas extraction with thermal oxidation of VOCs.**

Item	Rate (1990 \$)	Quantity	Cost (1990 \$)	Present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	24,000 kW-h	1,680	
Electric capacity charge	36/kW	3.0 kW	110	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Air sample VOC analysis	100/sample	60 samples	6,000	
Maintenance (2% of TCR)			4,900	
Subtotal			<u>47,690</u>	
Present worth (factor, 5 y @ 5% = 4.323)				206,200
<i>Variable operating costs</i>				
Annual costs, year 1				
Propane fuel	0.50/gal	21,100 gal	<u>10,550</u>	
Present worth (discount factor, @5% = 0.952)				10,040
Annual costs, year 2				
Propane fuel	0.50/gal	22,100 gal	<u>11,050</u>	
Present worth (discount factor, @5% = 0.907)				10,020
Annual costs, years 3 through 10				
Propane fuel	0.50/gal	22,100gal	<u>11,050</u>	
Present worth (factor, @5% = 2.470)				<u>27,300</u>
Present worth of variable operating costs				<u>47,360</u>
Subtotal of present worth of fixed and variable operating and maintenance costs				<u>253,560</u>
Contingency (20% of subtotal)				<u>50,700</u>
Present worth of total 5-y operating and maintenance cost				<u>304,260</u>
Total Capital Requirement (TCR)				<u><u>245,000</u></u>
Total present worth of alternative				<u>549,260</u>

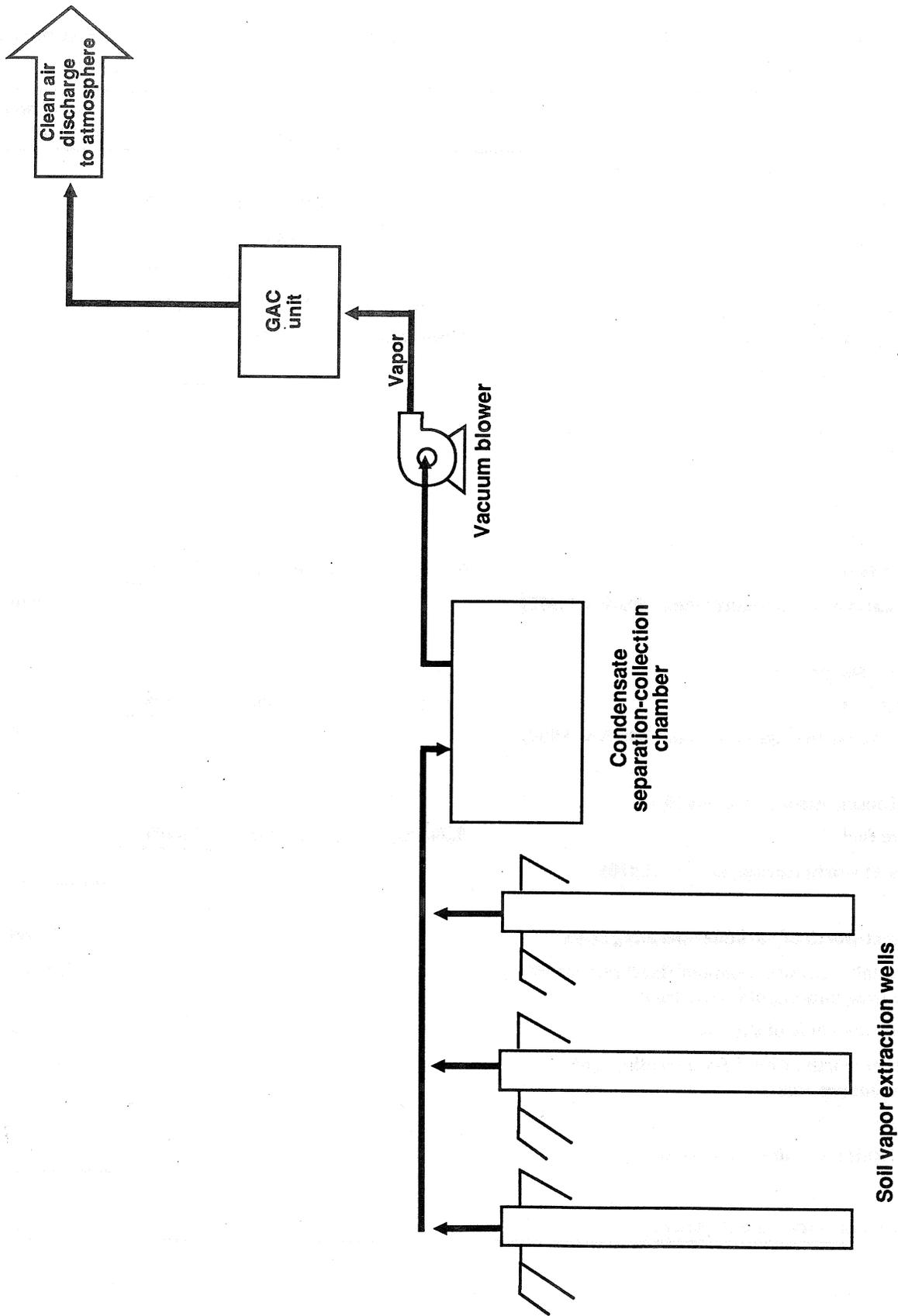


Figure E-1. A vapor-phase treatment with GAC for removing VOCs or FHCs from vapor extracted by vacuum-induced venting of the vadose zone.

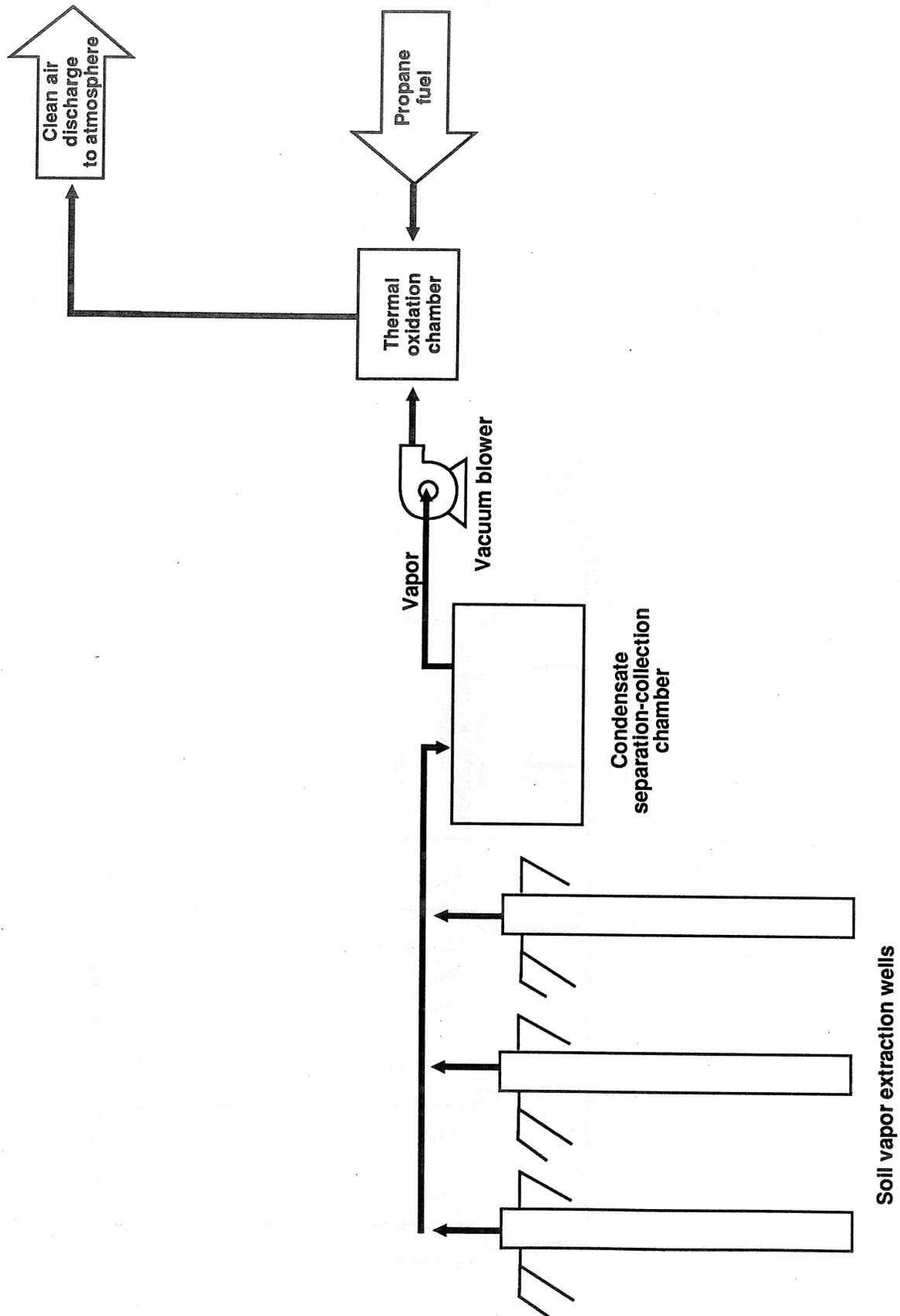


Figure E-2. A thermal oxidation system for removing VOCs or FHCs from vapor extracted by vacuum-induced venting of the vadose zone.

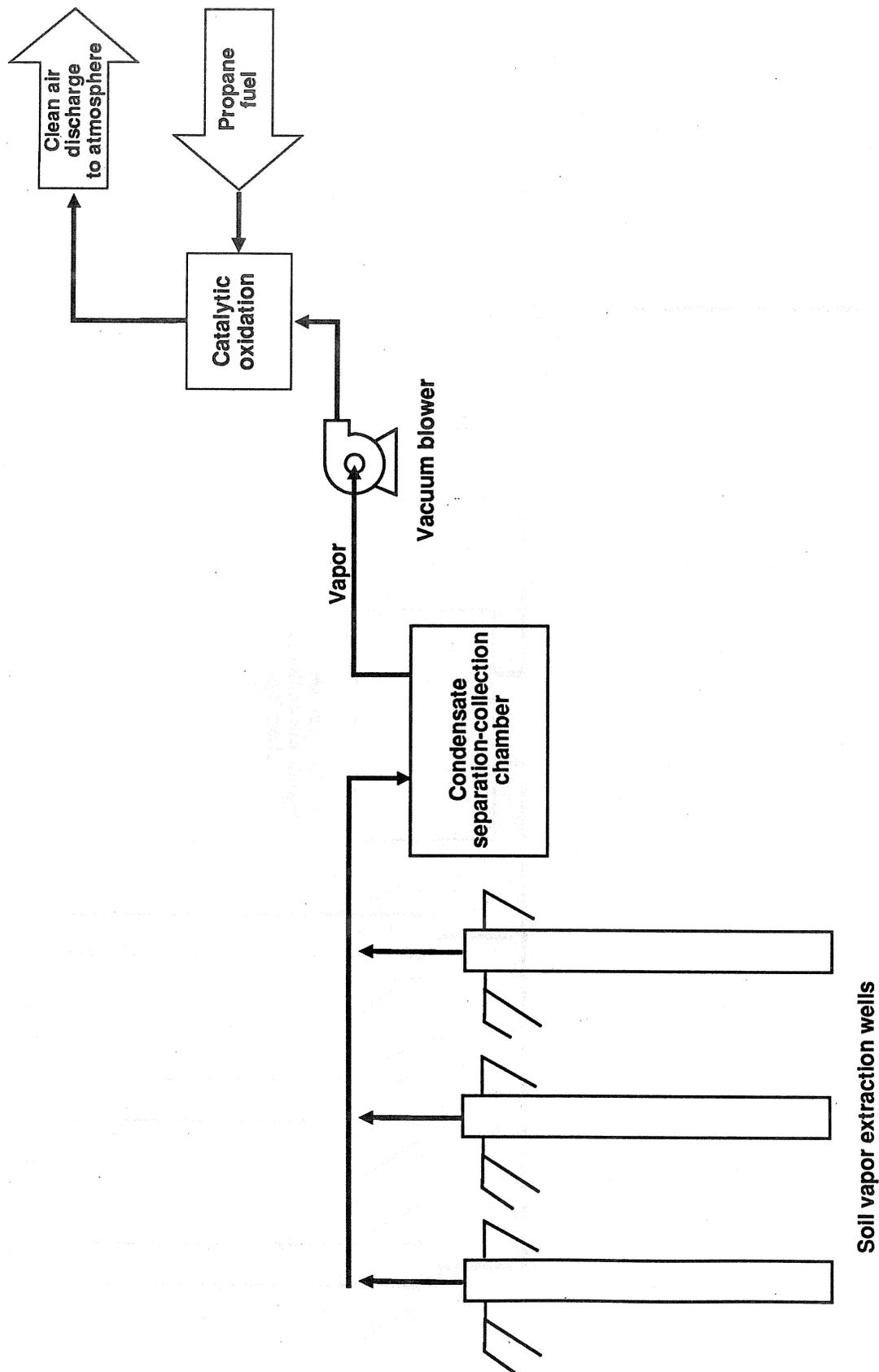


Figure E-3. A catalytic oxidation system for removing FHCs from vapor extracted by vacuum-induced venting of the vadose zone.

**APPENDIX F**  
**CONCEPTUAL DESIGN AND COST ESTIMATES FOR**  
**PIPING AND DISPOSAL**

## APPENDIX F

# CONCEPTUAL DESIGN AND COST ESTIMATES FOR PIPING AND DISPOSAL

### F-1. ENGINEERING DESIGN BASIS

Each treatment facility is served by a number of extraction wells, some of which are existing monitor wells. Piping is required to convey the extracted water from the wells to the treatment facility and from the facility to the point of discharge to one of several disposal alternatives. Proposed treatment facility locations and piping routes are shown in Figure 3-7. Four disposition alternatives are available, depending on proximity and cost of piping the treated water:

1. A recharge basin located south of East Avenue.
2. The arroyo system via lined and unlined drainage ditches.
3. A retention basin located in the center of the LLNL site.
4. Recharge wells.

The first three disposal alternatives and facilities to access them have already been installed. These existing facilities are considered sunk costs for purposes of cost estimation. The estimated costs of the recharge wells are included for Treatment Facilities F and G, where they might be most protected.

The conceptual design for the extraction and disposal system for each treatment facility includes the necessary lengths of the specified type and size of piping, leak monitoring system for buried lines carrying untreated ground water, development of required extraction wells, and installation of pumps. The specific location of the piping determines the type of pipe. Some pipe is single-walled iron or schedule 40 polyvinylchloride (PVC) pipe. In other locations, double-contained pipe with leak monitoring tape is specified.

### F-2. CAPITAL COST ESTIMATION

The following assumptions apply to the estimation of capital costs for all extraction and disposal alternatives:

1. Vendor quotes, vendor catalog prices, or LLNL cost experience are used to develop the cost estimates for the major purchased equipment items.
2. A factored estimate for total installed capital cost, accurate to +50%/-30%, is used based on the cost for major purchased equipment. Installation cost factors are based on experience for installation of chemical process equipment.
3. Indirect costs include engineering design and permitting. An estimate of \$15,000 (300 h at \$50/h) is included for engineering design, \$12,000 (160 h at \$75/h) for supervision, and \$10,000 for permits.
4. A contingency factor of 20% is applied to all capital cost estimates.
5. The cost of underground, double-contained transmission pipe with a leak monitoring system (UGDC+LM) includes (per foot):

Design, supervision, and management	10
Installation (trenching, sand/gravel, backfill, tamping, resurfacing, cutting and assembly of pipe and fittings, installing leak monitoring tape, electrical and electronic hookups, inspection)	40
Pipe (straight sections, connectors, T and elbow fittings, valves, seals, adhesive, leak monitoring tape) for two pipe systems	50
Total	100
6. The cost of aboveground pipe (AGP) includes (per foot):	
Design, supervision, and management	10
Installation (pipe station foundations, cutting and assembly of pipe and fittings, installation of pipe on stations, inspection)	10
Pipe (straight sections, connectors, T and elbow fittings, valves, seals, sealant, stations, support brackets)	20
Total	40
7. The cost of underground, single-walled pipe (UGSW) includes (per foot):	
Design, supervision, and management	10
Installation (trenching, sand/gravel, backfill, tamping, resurfacing, cutting and assembly of pipe and fittings, inspection)	30
Pipe (straight sections, connectors, T and elbow fittings, valves, seals, and sealant)	20
Total	60
8. The cost for extraction wells is developed using the following assumptions:	
Average depth: 130 ft	
Components included:	
• Drilling	
• Well development	
• Casing and screening	
• Grout	
• Well design	
• Sieve analyses	
• Concrete pad	
• Well-head protection (Christie box or stone pipe style)	
• Pump	
• Formation stabilizer	
• Pump discharge pipe	
• Three protective bollards	

We assume that half the wells will have to be substantially redeveloped or a new bore drilled during the life of the project.

### F-3. OPERATING COST ESTIMATION

The following assumptions apply to the estimation of operating costs for all extraction and disposal alternatives:

1. A factored operating cost of 2% per year, based on the total capital cost requirement, is assumed for operating, maintenance, repair, and upkeep of the extraction, piping, and disposal systems.
2. A cost of \$7000 per well is assumed for well closure at the completion of remediation.
3. A contingency of 20% is applied to all operating cost estimates.
4. The operating cost estimates are discounted to 1990 for developing the present worth estimates using a discount rate of 5%.

Table F-1. Major installed components, capital, operating, and maintenance costs for extraction wells, and disposal pipelines for Treatment Facility A (TFA).

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>							
<i>Extraction system and transport pipe (a)</i>							
Extraction location 1	Existing	1,000 ft	AGP	Existing	0		
Extraction location 2	Existing	100 ft	AGP	40 /ft	4,000		
Extraction location 3	Existing	1,600 ft	UGDC+LM	100 /ft	160,000		
Extraction system subtotal	0					164,000	
Leak monitoring system					25,000		
Jack boring under Vasco Road					60,000		
Pipeline subtotal						85,000	
<i>Disposal of treated effluent</i>							
Pipeline from TFA to the RB (c)		2,500 ft	AGP/UGSW	Existing	0		
Subtotal disposition pipeline						0	
Total major installed components						249,000	
<i>Project management</i>							
Engineering design		300 h		50 /h	15,000		
Installation/supervision labor		160 h		75 /h	12,000		
Permits					10,000		
Subtotal project management						37,000	
Subtotal capital requirement costs							286,000
Contingency (20% of subtotal)							57,200
Total Capital Requirement (TCR) costs							343,200
<b>Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 y)</b>							
<b>Total Capital Requirement (TCR) costs</b>							
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)							
Present worth of 30-y operation and maintenance costs (factor = 15.54)				6,900 /y		107,200	
Well closure/reclamation							
Present worth of closure cost at 30-y completion (factor = 0.23)		6 wells		7,000 ea	42,000		
Subtotal present worth of operating, maintenance, and reclamation costs						9,700	
Contingency (20% of subtotal)							116,900
Present worth of 30-y operating, maintenance, and reclamation costs							23,400
Present worth of extraction system and pipeline for TFA (EPA guidance analysis 30-y operation)							140,300
							483,500

Table F-1. (Continued)

Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Supplemental analysis of Extraction Alternative No. 2 (treatment facility operated for 87 y)						
<b>Total Capital Requirement (TCR) Costs</b>						
<i>Operation and Maintenance costs</i>						
<b>Operation and Maintenance (O&amp;M) costs (2% of TCR)</b>						
Present worth of 87-y operation and maintenance costs (factor = 19.71)			6,900 /y		136,000	
Well closure/reclamation wells	6 wells		7,000 ea	42,000		
Present worth of closure cost at 87-y completion (factor = 0.014)					600	
Subtotal of present worth of O&M and reclamation					136,600	
Contingency (20% of subtotal)					27,300	
Present worth of O&M and reclamation subtotal						163,900
Present worth of extraction system and transmission pipeline for TFA						507,100

- a Extraction locations are shown on Figure 3-9.
- b UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe).  
 AGP = aboveground pipe.  
 LM = leak monitoring system.
- c UGSW = underground single-walled 3-in. ID schedule-40 PVC pipe.  
 RB = recharge basin south of East Avenue.

Table F-2 Major installed components, capital, operating, and maintenance pipelines costs for extraction wells, and disposal for Treatment Facility B (TFB).

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>							
<i>Extraction system and transport pipe (a)</i>							
Extraction location 4	53,500	1,100 ft	UGDC+LM	100 /ft	110,000		
Extraction location 5	Existing	1,000 ft	AGP	Existing	0		
Extraction location 6	53,500	100 ft	AGP	40 /ft	4,000		
Extraction location 7	53,500	800 ft	UGDC+LM	100 /ft	80,000		
	160,500				194,000		
<i>Extraction system and transport pipe subtotal</i>							
Leak monitoring system						354,500	
Total extraction system and pipeline						25,000	
						379,500	
<i>Disposal of treated effluent</i>							
Pipeline from TFB to Arroyo Las Positas		1,200 ft	Ditch	Existing	0		
Subtotal disposal pipeline						0	
<i>Total major installed components</i>							
<i>Project management</i>							
Engineering design		300 h		50 /h	15,000		
Installation/supervision labor		160 h		75 /h	12,000		
Permits					10,000		
Subtotal project management						37,000	
<i>Subtotal capital requirement costs</i>							
Subtotal capital requirement costs						416,500	
Contingency (20% of subtotal)						83,300	
Total Capital Requirement (TCR) costs						499,800	
<i>Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 years)</i>							
<i>Total Capital Requirement (TCR) costs</i>							
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)						10,000	
Present worth of 30-y operation and maintenance costs (factor = 15.54)							155,400
<i>Well closure/reclamation</i>							
Present worth of closure cost at 30-y completion (factor = 0.23)							42,000
Subtotal present worth of operating, maintenance, and reclamation costs							9,700
Contingency (20% of subtotal)							165,100
Present worth of 30-y operating, maintenance, and reclamation cost							33,000
Present worth of extraction and pipeline for TFB (EPA guidance analysis 30-y operation)							198,100
							697,900

Table F-2. (Continued)

Supplemental analysis of Extraction Alternative No. 2 (treatment facility operated for 87 y)						
	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Total present worth (1990 \$)
<b>Total Capital Requirement (TCR) costs</b>						499,800
<i>Operation and maintenance costs</i>						
Operation and maintenance (2% of TCR)						
Present worth of 87-y operation and maintenance costs (factor = 19.71)				10,000		
Well closure/reclamation		6 wells		7,000	42,000	197,100
Present worth of closure cost at 87-y completion (factor = 0.014)						600
Subtotal present worth of operating, maintenance, and reclamation costs						197,700
Contingency (20% of subtotal)						39,500
Present worth of 30-y operating, maintenance, and reclamation cost						237,200
Present worth of extraction and pipeline for TFB (EPA guidance analysis 87-y operation)						737,000

a Extraction locations are identified on Figure 3-9.

b UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe).

AGP = aboveground pipe.

LM = leak monitoring system.

Table F-3. Major installed components, capital, operating, and maintenance costs for extraction wells, and disposal pipelines for Treatment Facility C (TFC).

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>							
<i>Extraction system and transport pipe (a)</i>							
Extraction location 8	53,500	400 ft	UGDC+LM	100 /ft	40,000		
Extraction location 9	53,500	600 ft	UGDC+LM	100 /ft	60,000		
					100,000		
Extraction system subtotal						207,000	
Leak monitoring system						25,000	
Total extraction system and pipeline						232,000	
<i>Disposal of treated effluent</i>							
Pipeline from TFC to Arroyo Las Postas		900 ft	AGP	40 /ft	36,000		
Subtotal disposal pipeline						36,000	
Total major installed components						268,000	
<i>Project management</i>							
Engineering design		300 h		50 /h	15,000		
Installation/supervision labor		160 h		75 /h	12,000		
Permits					10,000		
Subtotal project management						37,000	
Subtotal capital requirement costs						305,000	
Contingency (20% of subtotal)						61,000	
<b>Total Capital Requirement (TCR) costs</b>						<b>366,000</b>	
<b>Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 y)</b>							
<b>Total Capital Requirement (TCR) costs</b>							
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)						7,300	
Well closure/reclamation		6 wells		7,000 ea	42,000	113,400	
Present worth of closure cost at 30-y completion (factor = 0.23)						9,700	
Subtotal present worth of operating and maintenance costs						123,100	
Contingency (20% of subtotal)						24,600	
Present worth of 30-y operating, maintenance, and reclamation costs						147,700	
Present worth of extraction and pipeline for TFC B (EPA guidance analysis 30-y operation)						513,700	

Table F-3. (Continued)

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Supplemental analysis of Extraction Alternative No. 2 (Treatment facility operated for 87 y)							
Total Capital Requirement (TCR) costs							366,000
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)				7,300		143,900	
Present worth of 87-y operation and maintenance costs (factor = 19.71)							
Well closure/reclamation		6 wells		7,000 ea	42,000		
Present worth of closure cost at 87-y completion (factor = 0.014)						600	
Subtotal present worth of operating and maintenance costs						144,500	
Contingency (20% of subtotal)						28,900	
Present worth of extraction and pipeline for TFC B (EPA guidance analysis 87-y operation)							173,400
Extraction locations are identified on Figure 3-9.							539,400
a UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe). b AGP = aboveground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe). LM = leak monitoring system.							

Table F-4. Major installed components, capital, operating, and maintenance costs for extraction wells, and pipelines for Treatment Facility D (TFD).

	Cost per extraction location (1990 \$)		Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>								
<i>Extraction system and transport pipe (a)</i>								
Extraction location 10	53,500	2,200 ft	UGDC+LM	100 /ft	220,000			
Extraction location 11	53,500	100 ft	UGDC+LM	100 /ft	10,000			
Extraction location 12	53,500	800 ft	UGDC+LM	100 /ft	80,000			
	160,500				310,000			
Extraction system subtotal							470,500	
Leak monitoring system								25,000
Total extraction system and pipeline								495,500
<i>Disposition of treated effluent</i>								
Pipeline from TFD to DRB (b)		200 ft	UGSW	60 /ft	12,000			
Subtotal disposition pipeline								12,000
Total major installed components								507,500
<i>Project management</i>								
Engineering design		300 h		50 /h	15,000			
Installation/supervision		160 h		75 /h	12,000			
Permits					10,000			
Subtotal project management								37,000
Subtotal capital requirement costs								544,500
Contingency (20% of subtotal)								108,900
Total Capital Requirement (TCR) costs								653,400
Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 y)								
Total Capital Requirement (TCR) costs								653,400
<i>Operation and maintenance costs</i>								
Operation and maintenance (2% of TCR)								
Present worth of 30-y operation and maintenance costs (factor = 15.54)								
Well closure/reclamation								
Present worth of closure cost at 30-y completion (factor = 0.23)								
Subtotal present worth of operating and maintenance costs								
Contingency (20% of subtotal)								
Present worth of 30-y operating and maintenance cost								
Present worth of extraction and pipeline for TFD								
								256,000
								909,400

Table F-4. (Continued)

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Supplemental analysis of Extraction Alternative No. 2 (treatment facility operated for 87 y)

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Treatment Facility D not required in Extraction Alternative No. 2

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a Extraction locations are identified on Figure 3-9.

b UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe).

LM = leak monitoring system.

UGSW = underground single-walled 3-in. ID schedule-40 PVC pipe.

DRB = drainage retention basin in the center of the LLNL site.

Table F-5. Major installed components, capital, operating, and maintenance costs for extraction wells and pipelines for Treatment Facility E (TFE).

Extraction location (a)	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>							
<i>Extraction system and transport pipe</i>							
Extraction location 13	53,500	800 ft	UGDC+LM	100 /ft	80,000		
Extraction location 14	53,500	600 ft	UGDC+LM	100 /ft	60,000		
	107,000				140,000		
Extraction system subtotal						247,000	
Leak monitoring system						25,000	
Total extraction system and pipeline						272,000	
<i>Disposal of treated effluent</i>							
Pipeline from TFE to DRB (b)							
		900 ft	UGSW	60 /ft	54,000		
Subtotal disposal pipeline						54,000	
Total major installed components						326,000	
<i>Project management</i>							
Engineering design							
		300 h		50 /h	15,000		
Installation/supervision labor							
		160 h		75 /h	12,000		
Permits							
					10,000		
Subtotal project management						37,000	
Subtotal capital requirement costs							363,000
Contingency (20% of subtotal)							72,600
Total Capital Requirement (TCR) costs							435,600
<b>Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 y)</b>							
Total Capital Requirement (TCR) costs							435,600
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)						8,700	
Present worth of 30-y operation and maintenance costs (factor = 15.54)							135,200
Well closure/reclamation (6 wells at \$7,000 per well)							
		6 wells		7,000 ea	42,000		
Present worth of closure cost at 30-y completion (factor = 0.23)							9,700
Subtotal present worth of operating and maintenance costs							144,900
Contingency (20% of subtotal)							29,000
Present worth of 30-y operating and maintenance cost							173,900
Present worth of extraction and pipeline for TFE							609,500

Table F-5. (Continued)

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Supplemental analysis of Extraction Alternative No. 2 (treatment facility operated for 87 y)

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Treatment Facility F not required in Extraction Alternative No. 2

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a Extraction locations are identified on Figure 3-9.

b UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe).

LM = leak monitoring system.

UGSW = underground single-walled 3-in. ID schedule-40 PVC pipe.

DRB = drainage retention basin in the center of the LLNL site.

Table F-6. Major installed components, capital, operating, and maintenance costs for extraction wells and pipelines for Treatment Facility F (TFF).

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>							
<i>Extraction system and transport pipe (a)</i>							
Extraction location 17	53,500	200 ft	UGDC+LM	100 /ft	20,000		
Extraction location 18	53,500	900 ft	UGDC+LM	100 /ft	90,000		
Subtotal extraction system and transport pipe	107,000				110,000		
Total extraction system and transport pipe						217,000	
Leak monitoring system							25,000
Total leak monitoring system, extraction system, and pipeline							242,000
<i>Disposal of treated effluent (three alternatives)</i>							
1. Recharge, Well S of TFF	64,400	100 ft	UGSW	60 /ft	6,000		
Alternative 1 subtotal					70,400		
2. Recharge Well NE of TFF	64,400	800 ft	UGSW	60 /ft	48,000		
Alternative 2 subtotal					112,400		
3. Pipe to DRB (b)	0	2,900 ft	UGSW	60 /ft	174,000		
Alternative 3 subtotal					174,000		
Subtotal disposal pipeline (minimum cost alternative)						70,400	
Total major installed components							312,400
<i>Project management</i>							
Engineering design		300 h		50 /h	15,000		
Installation/supervision		160 h		75 /h	12,000		
Permits					10,000		
Subtotal project management							37,000
Subtotal capital requirement costs							349,400
Contingency (20% of subtotal)							69,900
Total Capital Requirement (TCR) costs							419,300

Table F-6. (Continued)

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 y)							
Total Capital Requirement (TCR) costs							419,300
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)				8,400 /y		130,500	
Present worth of 30-y operation and maintenance costs (factor = 15.54)					42,000		
Well closure/reclamation		6 wells		7,000 ea		9,700	
Present worth of closure cost at 30-y completion (factor = 0.23)						140,200	
Subtotal present worth of operating, maintenance, and reclamation costs						28,000	
Contingency (20% of subtotal)							168,200
Present worth of 30-y operating and maintenance cost							587,500
Present worth of extraction and pipeline for TFF							
Analysis of Extraction Alternative No. 2 (treatment facility operated for 87 y)							
Total Capital Requirement (TCR) costs							419,300
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)				8,400 /y		165,600	
Present worth of 30-y operation and maintenance costs (factor = 19.71)					42,000		
Well closure/reclamation		6 wells		7,000 ea		600	
Present worth of closure cost at 30-y completion (factor = 0.014)						166,200	
Subtotal present worth of operating and maintenance costs						33,200	
Contingency (20% of subtotal)							199,400
Present worth of 30-y operating and maintenance cost							618,700
Present worth of extraction and pipeline for TFF							

a Extraction locations are identified on Figure 3-9.

b UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe).  
 LM = leak monitoring system.

UGSW = underground single-walled 3-in ID schedule-40 PVC pipe.  
 DRB = drainage retention basin in the center of the LLNL site.

Table F-7. Major installed components, capital, operating, and maintenance costs for extraction wells, and pipelines for Treatment Facility G (TFG).

	Cost per extraction location (1990 \$)	Quantity	Pipe type (b)	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>							
<i>Extraction system and transport pipe (a)</i>							
Extraction location 15	53,500	900 ft	UGDC+LM	100 /ft	90,000		
Extraction location 16	53,500	200 ft	UGDC+LM	100 /ft	20,000		
	107,000				110,000		
Extraction system and transport pipe subtotal						217,000	
Leak monitoring system						25,000	
Total extraction system and pipeline						242,000	
<i>Disposal of treated effluent (two alternatives)</i>							
Pipe from TFG Alt to DRB (b)		1,300 ft	UGSW	60 /ft	78,000		
Subtotal disposal pipeline (minimum cost alternative)						78,000	
Total major installed components						320,000	
<i>Project management</i>							
Engineering design		300 hr		50 /hr	15,000		
Installation/supervision		160 hr		75 /hr	12,000		
Permits					10,000		
Subtotal project management						37,000	
Subtotal capital requirement costs						357,000	
Contingency (20% of subtotal)						71,400	
<b>Total Capital Requirement (TCR) costs</b>						<b>428,400</b>	
<b>Analysis of Extraction Alternative No. 1 (treatment facility operated for 30 y)</b>							
<b>Total Capital Requirement (TCR) costs</b>							
<i>Operation and maintenance costs</i>							
Operation and maintenance (2% of TCR)					8,600		
Present worth of 30-y operation and maintenance costs (factor = 15.54)						133,600	
Well closure/reclamation		6 wells		7,000 ea	42,000		
Present worth of closure cost at 30-y completion (factor = 0.23)						9,700	
Subtotal present worth of operating and maintenance costs						143,300	
Contingency (20% of subtotal)						28,700	
Present worth of 30-y operating and maintenance cost						172,000	
Present worth of extraction and pipeline for TFG—Alternate location						600,400	

Table F-7. (Continued)

Supplemental analysis of Extraction Alternative No. 2 (treatment facility operated for 87 y)	
Treatment Facility G not required in Extraction Alternative No. 2	
a	Extraction locations are identified on Figure 3-9.
b	UGDC = underground double-contained pipe (3-in. ID polypropylene inner pipe in 6-in. ID polypropylene outer pipe). LM = leak monitoring system. UGSW = underground single-walled 3-in ID schedule-40 PVC pipe. DRB = drainage retention basin in the center of the LLNL site.

**Table F-8. Major installed components, capital, operating, and maintenance costs for extraction wells, and pipelines for extracting vapors from the vadose zone in the Gasoline Spill Area.**

	Cost per soil vent/vapor extraction well (1990 \$)	Quantity	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>						
<i>Extraction system and transport pipe</i>						
Venting well	Existing well	1	Existing	0		
Additional venting wells (3 at \$22,000 ea)	66,000	300	20	6,000		
	66,000			6,000		
Extraction system and transport pipe subtotal						72,000
<i>Project management</i>						
Engineering design		300 hr	50 /hr	15,000		
Installation/supervision labor		160 hr	75 /hr	12,000		
Permits				10,000		
Subtotal project management						37,000
Subtotal capital requirement costs						109,000
Contingency (20% of subtotal)						21,800
<b>Total Capital Requirement (TCR) costs</b>						<b>130,800</b>
<i>Operation and maintenance costs</i>						
Operation and maintenance (2% of TCR)				2,600		
Present worth of 30-y operation and maintenance costs (factor = 15.54)						
Well closure/reclamation (4 wells at \$7,000 per well)		4 wells	7,000 ea	28,000		
Present worth of closure cost at 30-y completion (factor = 0.23)						
Subtotal present worth of operating, maintenance, and reclamation						6,400
Contingency (20% of subtotal)						46,800
Present worth of 30-y operating, maintenance, and reclamation costs						9,400
Present worth of vapor extraction system for the vadose zone						56,200
						<b>187,000</b>

Table F-9. Major installed components, capital, operating, and maintenance costs for extraction wells, and pipelines for extracting VOC vapors from the vadose zone, hypothetical site in Building 518 Area.

	Cost per soil vent/vapor extraction well (1990 \$)	Quantity	Unit cost (\$)	Subtotal cost (\$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>CAPITAL COSTS</b>						
<i>Extraction system and transport pipe</i>						
B 518 Area (2 at \$22,000 ea)	44,000	200	20	4,000		
	44,000			4,000	48,000	
<i>Extraction system and transport pipe subtotal</i>						
<i>Project management</i>						
Engineering design		300 hr	50 /hr	15,000		
Installation/supervision labor		160 hr	75 /hr	12,000		
Permits				10,000		
					37,000	
<i>Subtotal project management</i>						
						85,000
<i>Subtotal capital requirement costs</i>						
Contingency (20% of subtotal)						17,000
<i>Total Capital Requirement (TCR) costs</i>						
<i>Operation and maintenance costs</i>						
<i>Operation and maintenance (2% of TCR)</i>						
Present worth of 30-y operation and maintenance costs (factor = 15.54)				2,000		
Well closure/reclamation (4 wells at \$7,000 per well)		4 wells	7,000 ea	28,000		
Present worth of closure cost at 30-y completion (factor = 0.23)					31,100	
						6,400
<i>Subtotal present worth of operating, maintenance, and reclamation</i>						
Contingency (20% of subtotal)						37,500
<i>Present worth of 30-y operating, maintenance, and reclamation costs</i>						
Present worth of vapor extraction system for the vadose zone						7,500
						45,000
						147,000

**APPENDIX G**

**MODELING OF VOC MIGRATION FROM THE  
VADOSE ZONE TO GROUND WATER IN THE  
BUILDING 518 AND 511 AREAS**

# APPENDIX G

## MODELING OF VOC MIGRATION FROM THE VADOSE ZONE TO GROUND WATER IN THE BUILDING 518 AND 511 AREAS

### G-1. INTRODUCTION

In 1989, LLNL continued its source investigation of the LLNL superfund site by systematically evaluating 14 high priority potential source areas (Thorpe *et al.*, 1990). VOCs in the vadose zone were found in three areas at concentrations of 500 to greater than 5000 ppb. To determine whether these maximum detected levels will significantly increase VOC concentrations in the underlying ground water, we have performed a quantitative evaluation of vadose zone VOC migration processes.

The highest concentrations of total VOCs in the LLNL vadose zone reported by Thorpe *et al.* (1990) were immediately south of Building 518 and near the southeast corner of Building 511 (Figure G-1). The Building 518 Area is the only place where VOC concentrations exceeded 1 ppm. At Building 511, the highest concentrations (almost 1 ppm) were found in a single borehole at a depth of 3 m. This Appendix presents our initial efforts to evaluate VOC migration in these two areas by the gas diffusion transport process, which dominates transport from the vadose zone to the ground water in areas at LLNL where water infiltration is low. Quantitative arguments are presented to demonstrate the relative unimportance of other transport processes.

We begin our discussion with a brief overview of the conceptual and mathematical model governing the various processes in the vadose zone. We then discuss the dominant transport process, gaseous diffusion, and the dependence of the peak concentration at the water table on hydrological vadose zone parameters. A semi-analytical mathematical solution to the three-dimensional gaseous diffusion problem is given, and the solution is applied to the trichloroethylene (TCE) distribution at Building 518 and the 1,2-dichloroethylene (1,2-DCE) distribution in the Building 511 Area. A parameter sensitivity study is presented for the TCE distribution which is applicable to the 1,2-DCE investigation. We have also simulated the resulting transport in the ground water of TCE from the vadose zone.

### G-2. VADOSE ZONE VOC TRANSPORT PROCESSES

#### G-2.1. CONCEPTUAL MODEL

We first define the terms used in this Appendix. The *saturated zone* is the region where the pores are saturated, or filled, with water. *Ground water* is the term used for

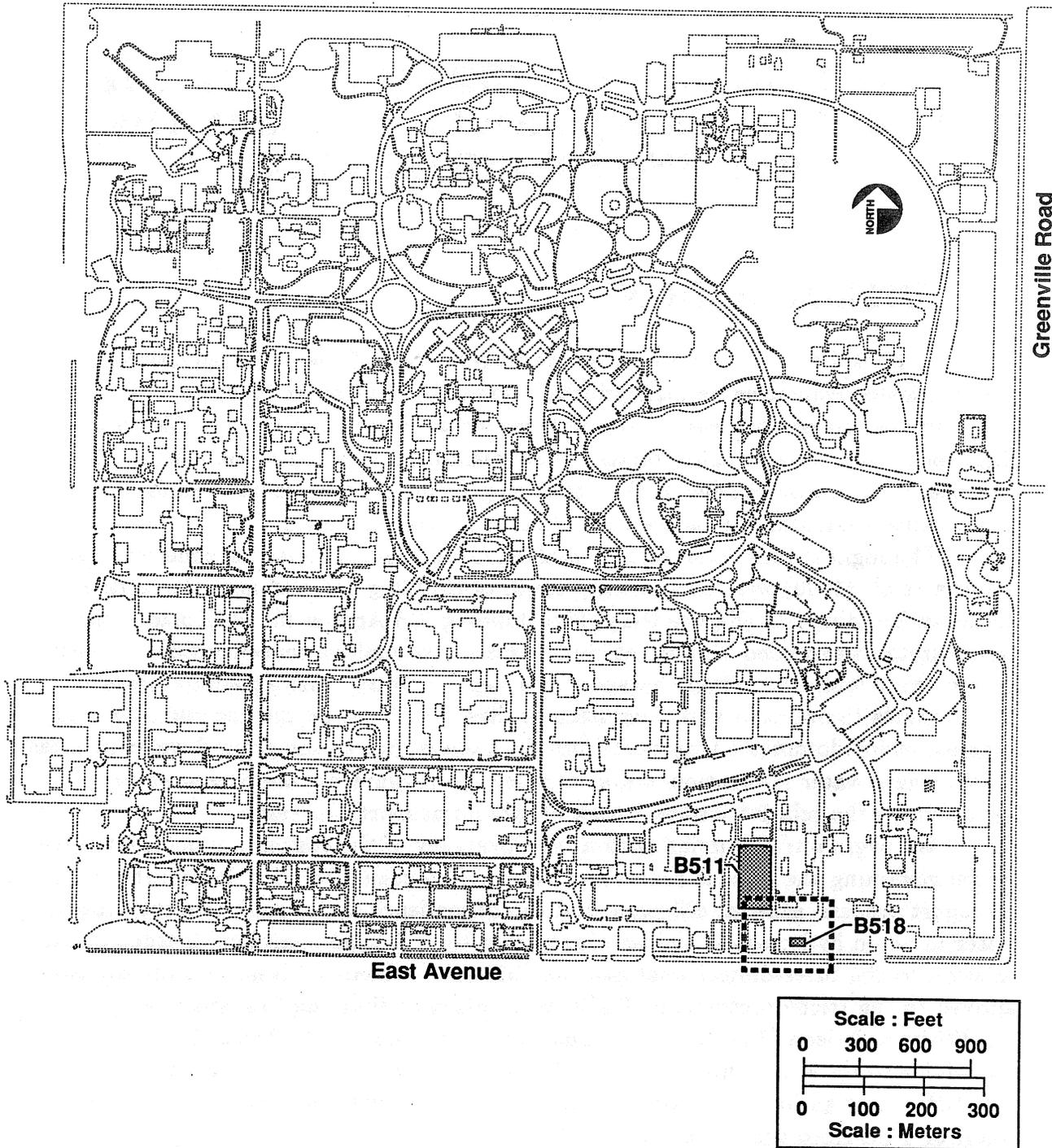


Figure G-1. Location map for the Building 518 and 511 Areas.

pore water in this region. The *water table* is the upper boundary of the saturated zone. As we move upward above the saturated zone, the amount of water in the pores changes from being fully saturated to a relatively constant, but grain-size-dependent, saturation distribution over most of the vadose zone. We will term this region the *transition zone*, and its thickness is typically on the order of one meter depending on the pore-size distribution of the soil. (The transition zone is frequently called the capillary fringe (Bear 1988), but we have avoided this term because it can have another meaning; see, for example, Freeze and Cherry (1979).) The zone above the transition zone is called the *vadose zone*.

Many compounds including VOCs, migrate through the vadose zone in response to five possible primary mechanisms:

- Free-phase advection.
- Aqueous advection.
- Gaseous advection.
- Aqueous diffusion.
- Gaseous diffusion.

Prediction of VOC transport in the vadose zone is complicated by

1. The possible presence of three different phases: a free VOC phase, an aqueous phase, and a VOC vapor phase.
2. Mass transfer between all three phases.
3. VOC retardation by solid sorption and by water-gas partitioning.
4. *In situ* biological and chemical degradation that reduces VOC concentration in the vadose zone according to transformations that are chemical and site-specific.

During the early stages of a free-phase VOC product release to the subsurface, free-phase advection will occur. As the free product migrates downward, most of it volatilizes, while the remaining portion partitions into the aqueous and gaseous phases and onto soil particles. Vapor pressure gradients will move VOC vapor away from the areas of volatilization. Free-phase advection will proceed to increasing depths until all the material has volatilized and partitioned into the different phases. Sorption onto the solid phase occurs primarily via the water phase. Vapor-solid sorption is minimal because the soil particles are generally surrounded by a thin film of water, except near the ground surface where the water film is highly reduced or virtually nonexistent.

After complete volatilization of the free phase, downward migration of VOCs can continue by gaseous advection by gravity-driven density gradients if the vapor density is heavier than air. If the VOC is lighter than air, it will migrate upwards. This process is highly dependent on the concentration of the vapor as well as its density.

Gaseous diffusion occurs by moving VOC vapor from areas of high concentration to areas of low concentration. This process involves the movement of vapor by intermolecular collisions. Gaseous diffusion and gaseous advection are significantly

reduced by high soil moisture content. Aqueous diffusion is similar to gaseous diffusion but very slow and can be assumed to be negligible compared to gaseous diffusion.

Aqueous advection is the passive transport of a VOC dissolved in the aqueous phase. Aqueous fluxes may typically occur from rainfall infiltration into the vadose zone. This transport mechanism may dominate if the fluxes are high. VOCs migrate through the vadose zone by one or more of the transport processes described above, until the transition zone is encountered. VOCs are mobilized to the ground water from the transition zone by infiltration, aqueous and gas phase diffusion, or fluctuations of the water table.

## G-2.2. MATHEMATICAL MODEL

The balance equation for transport of a single VOC in the vadose zone is

$$\begin{aligned} \frac{\partial}{\partial t} (\phi S_l C_l + \phi S_g C_g + C_s) = & -\nabla \cdot [C_g q_g] - \nabla \cdot [C_l q_l] \\ & + \nabla \cdot [\rho_g \phi S_g \tau_g D_g \nabla (C_g / \rho_g)] + \nabla \cdot [\rho_l \phi S_l \tau_l D_l \nabla (C_l / \rho_l)] \\ & - \lambda_l \phi S_l C_l - \lambda_g \phi S_g C_g - \lambda_s \phi \rho_B K_d C_l \\ & + q_{src} \end{aligned} \quad (G-1)$$

The abbreviations for the variables are

$t$	= time,
$C$	= VOC concentration (mass/volume),
$\phi$	= effective porosity,
$S$	= saturation
$p$	= phase pressure,
$l$	= subscript for aqueous phase,
$g$	= subscript for gas phase,
$s$	= subscript for sorption onto solid phase,
$src$	= subscript for source term,
$x$	= mass fraction in the aqueous phase,
$y$	= mass fraction in the gas phase,
$a$	= subscript for air component in the aqueous or gas phase,
$w$	= subscript for water component in the aqueous or gas phase,
$voc$	= subscript for VOC component in the aqueous or gas phase,
$\tau$	= tortuosity factor,
$\rho_B$	= bulk density,
$D$	= diffusion coefficient of the VOC,
$\lambda$	= decay constant for VOC degradation,
$q$	= mass flux,
$\rho$	= density,
$k$	= saturated permeability,
$k(S)$	= relative permeability function,
$p_c(S)$	= capillary pressure function,

- $g$  = gravitational acceleration,  
 $z$  = vertical coordinate (positive up),  
 $\nabla \cdot$  = divergence operator,  
 $\nabla$  = gradient operator,  
 $\mu$  = dynamic viscosity of the aqueous or gas phase.

The three terms in the parentheses on the left-hand side of Eq. G-1 are the changes in accumulated mass of VOC in the aqueous, gas, and solid phases, respectively. The first two terms in the square brackets on the right-hand side are the advective fluxes in the gas and aqueous phases. The next two terms in the square brackets are the diffusive fluxes in the gas and aqueous phases. The next three terms are the chemical or biological degradation in the three phases, and the last term is the source term. Hydrodynamic dispersion in multiphase flow can be an important factor in transport but has been ignored in our equation because its practical treatment is an active area of current research. The advective phase fluxes  $q_g$  and  $q_l$  computed from the conservation equations for air and water are, respectively,

$$\frac{\partial}{\partial t} (\phi S_l \rho_l x_a + \phi S_g \rho_g y_a) + \nabla \cdot (x_a q_l + y_a q_g) = q_{src_a}, \quad (G-2)$$

$$\frac{\partial}{\partial t} (\phi S_l \rho_l x_w + \phi S_g \rho_g y_w) + \nabla \cdot (x_w q_l + y_w q_g) = q_{src_w}. \quad (G-3)$$

The mass fractions in the aqueous and gas phases obey

$$x_a + x_w + x_{voc} = 1, \quad y_a + y_w + y_{voc} = 1, \quad (G-4)$$

where the mass fraction of VOC is defined in terms of the concentrations by

$$x_{voc} = C_l / \rho_l, \quad y_{voc} = C_g / \rho_g. \quad (G-5)$$

The saturations obey

$$S_l + S_g = 1. \quad (G-6)$$

The phase mass fluxes are given by Darcy's law:

$$q_\alpha = -\rho_\alpha \frac{k k_\alpha(S_\alpha)}{\mu_\alpha} (\nabla p + \rho_\alpha g \nabla z), \quad (G-7)$$

where  $\alpha = g, l$ . The phase pressure are related to each other by the capillary pressure function

$$p_g - p_l = p_c(S_l). \quad (G-8)$$

Equilibrium partitioning between the solid and aqueous phases is described by a linear isotherm

$$C_s = \rho_B K_d C_l, \quad (G-9)$$

where  $K_d$  is a partitioning coefficient between the aqueous phase and the solid phase in units of volume/mass. Henry's law is used to partition the VOC between the gas and the aqueous phase;

$$C_g = H C_l, \quad (G-10)$$

where  $H$  is Henry's law constant for the individual VOC. The relative humidity is assumed to be sufficiently high that vapor-to-solid sorption is not present. Then Eq. G-1 can be rewritten as

$$\frac{\partial}{\partial t} \phi R C_l = \text{flux terms}, \quad (\text{G-11})$$

where we define the unsaturated retardation factor

$$R = S_l + S_g H + \frac{\rho_B K_d}{\phi}. \quad (\text{G-12})$$

### G-2.3. BOUNDARY CONDITIONS

To assess the movement of VOCs through the vadose zone, boundary conditions must be established at the ground-air interface and at the transition zone interface. In this section, we present a qualitative discussion of these interface fluxes.

The boundary at the ground surface acts as a sink to gaseous diffusion, because the VOC concentration at this surface is approximately zero as a result of dispersion into the atmosphere by wind currents. An exception occurs when sufficient vegetative cover creates a stagnant boundary layer resulting in a buffer zone between the air in motion above the surface and the upper boundary of the vadose zone. Transport across this zone is primarily by diffusion. In the areas considered by this study, there is no vegetative cover. If the surface is paved, an additional buffer zone exists that has a diffusion coefficient specific to the paving material. Of course, if the paving material were completely impervious, a no-flow boundary would apply instead. Laboratory studies indicate that soils with less than 90% relative humidity will have a very high sorptive capacity due to the direct sorption of the vapor onto the solid phase (Chiou and Shoup, 1985). Under these conditions, the upper layers of the soil may retard vapor flux diffusing to the surface. Because LLNL field data do not indicate the presence of a surface layer with high VOC concentrations, we consider this phenomenon unimportant for the purposes of this study.

At the transition zone, any infiltration fluxes will transport VOCs by aqueous advection. The effect of a rising or oscillating water table will also move VOCs from the vadose zone to the ground water. VOCs sorbed onto the solid will desorb into the water each time the water table rises and will be replenished through gaseous diffusion or aqueous advection from the overlying vadose zone. If infiltration fluxes are low and water table movement is small, the dominant transfer mechanism across the transition zone is diffusion. Diffusion occurs primarily in the gas phase over most of the upper part of the transition zone, while in the lower portion, VOCs are primarily transported by aqueous diffusion because gaseous diffusion through the gas pore space is restricted by high liquid saturation.

## G-3. A SIMPLIFIED VADOSE ZONE TRANSPORT MODEL

### G-3.1. SIMPLIFYING ASSUMPTIONS

In the preceding sections, we described the general VOC transport processes both in a qualitative and quantitative manner. The following discussion will describe simplifying assumptions that were made in evaluating vadose zone VOC transport at LLNL.

#### G-3.1.1. Aqueous Advection

Movement of water through the vadose zone transports VOCs in the aqueous phase downward to the ground water. In arid climates such as LLNL's, much of the infiltration flux from rainfall is lost to the surface by evapotranspiration. When water percolates downward, VOCs bound to the solid by sorption and VOCs in the gas phase will partition into the aqueous phase and be carried to deeper depths. The net infiltration flux at LLNL is small based on tritium tracer and soil moisture studies by Stone *et al.* (1982). The source of the tritium was an LLNL facility that had been active for 30 y at the time of the study. No tritium above background levels was found at depths greater than 6.1 m, except (1) near arroyos and the LLNL drainage retention basin, and (2) at wells located near relatively long-term tritiated water releases. These data suggest that the infiltration fluid velocities are generally less than 6 m/30 y. This velocity is converted to flux by dividing by the average effective porosity of 0.3 and liquid saturation of 0.50 to get an infiltration flux of less than 3 cm/y. Because this is only an upper limit, the infiltration flux could, in reality, be much less. The inferred low infiltration rate at LLNL is supported by chemical data from boreholes, which have generally shown peak VOC concentrations localized between depths of 6 to 9 m.

We now compare the relative significance of aqueous advection and gaseous diffusion. For a volumetric flux  $u_l$  of water infiltrating through the vadose zone, the advected mass flux of VOC is given by  $C_g u_l / HR$ . The apparent diffusion coefficient for the diffusion of VOC in gas is  $S_g \phi \tau D_g / R$ . The Peclet number  $Pe$  provides a quantitative estimate of the relative importance of aqueous advection compared to gaseous diffusion as the dominant mode of transport, and is given by

$$Pe = \frac{L u_l}{S_g \phi \tau D_g H} \quad (G-13)$$

The characteristic distance  $L$  is the distance traveled by the aqueous front during a rainfall event, and is equal to

$$L = u_l \delta T / \phi R. \quad (G-14)$$

If the maximum flux, not including evapotranspiration losses, during a time period of  $\delta T = 1$  day is less than  $u_l = 5.0$  cm/day, and using parameters for TCE (the major constituent of the VOCs in the Building 518 Area), we obtain  $Pe \leq 0.12$ . In most

advective-diffusive problems, the Peclet number must be greater than 10 for advection to become important (Bejan, 1984). The parameters used in this calculation are given in Table G-1. The tortuosity factor  $\tau$  is computed using the Millington (1959) formula

$$\tau = S^{7/3} \phi^{1/3}, \quad (\text{G-15})$$

where  $S$  is the saturation of the diffusing phase (here, it is the gas saturation  $S_g$ ).

The above computation assumed a short infiltration event. However, it is more likely that temporal variations in flux are highly attenuated by the time infiltrating water reaches the depth where most of the VOCs are located in the vadose zone, and an almost constant flux exists down to the water table. The characteristic length becomes the distance from the center of the VOC distribution to the water table,  $L = 27$  m (at Building 518 discussed below). The mean annual rainfall at LLNL is approximately 37 cm (Stone *et al.*, 1982). Evapotranspiration significantly reduces the amount available for subsurface infiltration (Marshall and Holmes, 1979). From Stone *et al.* (1982), we concluded that the average net infiltration flux at LLNL is, in general, less than 3.1 cm/y. The resulting value for the Peclet number in Eq. G-13 is 0.4, which is still much less than 10. Another way to compare the two modes of transport is to note that the movement of the aqueous front during one year is  $10 \text{ cm}/\phi R = 6$  cm. On the other hand, the distance traveled by the diffusive front is on the order of

$$\sqrt{(S_g \tau D_g H) \times 1 \text{ year}/R} = 114 \text{ cm}, \quad (\text{G-16})$$

which is 19 times greater.

In summary, it appears, that on the basis of both field studies and theoretical considerations, aqueous advection is not the most significant transport mechanism in our study area.

### G-3.1.2. Gaseous Advection

If a VOC vapor is denser than air, it will sink towards the ground water in the gas phase; otherwise, it will rise to the ground surface. Consider a VOC denser than air. The density gradients in the gas phase driving the VOC to the ground water are significant during the early and intermediate stages of the VOC release because of elevated concentrations. However, in time, concentrations in the vadose zone become diluted by gaseous diffusion, and transport by gravity-driven density gradients become unimportant compared to gaseous diffusion (Falta *et al.*, 1989). Gaseous advection due to vapor pressure gradients also become unimportant as concentration gradients are reduced by diffusion. We now show theoretically that gravity-driven density gradients are not likely to be important in the Building 518 and 511 Areas. A similar argument can be made for advection driven by vapor pressure gradients.

Falta *et al.* (1989) derived an approximate expression for the maximum nonretarded Darcy flux under vapor density gradients;

$$u_g = K_g \frac{M_{voc} - M_a}{M_{voc}} \left( \frac{C_{voc}}{\rho_g} \right), \quad (\text{G-17})$$

where

Table G-1. Parameters used in computing the Peclet number.

Parameter	Symbol	Value
Porosity	$\phi$	0.3
Liquid saturation	$S_l$	0.5
Soil sorption parameter	$\rho_B K_d / \phi$	5.0
Henry's constant for TCE	$H$	0.39
Free gas diffusion coefficient	$D_g$	0.7 m <sup>2</sup> /day

$K_g$	= pneumatic conductivity,
$M_{voc}$	= molecular weight of VOC,
$M_a$	= molecular weight of air,
$C_{voc}$	= vapor concentration (mass/volume) of VOC.

This simple expression for the maximum velocity is accurate to within 20% (Falta *et al.*, 1989). We again consider the Peclet number, which gives the relative importance of gaseous advection through density gradients compared to gaseous diffusion,

$$Pe = \frac{Lu_g}{S_g \phi \tau D_g} \quad (G-18)$$

The maximum Peclet number occurs at the maximum VOC concentration. Using the parameter values in Table G-2 for TCE and the maximum total TCE soil concentration at Building 518 of 6.1 ppm (equivalent to gas concentration of 3430 ppm assuming parameters in Table G-2), the Peclet number is 2.6. Most of the total soil TCE concentrations at Building 518 are less than 1 ppm, and the Peclet number is less than unity in those areas.

The mathematical equations for natural convection in heat transfer are identical to the diffusive and density-driven transport of VOC (Bejan, 1984). The Rayleigh number used in natural thermal convection problems corresponds to the Peclet number, and a value less than 1 to 10 has been found to indicate that density gradients are unimportant compared to diffusion (Bejan, 1984). Moreover, by estimating  $u_g$ , it was found that the portions of the VOC mass exceeding a Peclet number of unity travel a few meters at most, in which time the concentrations decrease to a Peclet number less than unity ( $u_g$  is divided by the retardation factor in this calculation). A similar argument about the lack of importance of density gradients can be made for 1,2-DCE, since it is slightly less dense than TCE.

### G-3.1.3. Gaseous Diffusion

Diffusion of a component in a fluid phase arises from random molecular movement. The resulting net flux of the component is proportional to the negative of the concentration gradient as given by Fick's law:

$$q = -D \nabla C, \quad (G-19)$$

where the constant of proportionality  $D$  is the diffusion coefficient. In a porous medium filled with a single phase it is customary to write this equation in the form,

$$q = -\phi \tau D_f \nabla C, \quad (G-20)$$

where  $D_f$  is the free diffusion coefficient and  $\tau$  is the tortuosity factor, which accounts for the constrictions and turns in the pore pathways. For diffusion in partially saturated media, the flux becomes

$$q = -S \phi \tau D_f \nabla C, \quad (G-21)$$

Table G-2. Parameters used in comparing gaseous diffusion to density gradients.

Parameter	Symbol	Value
Porosity	$\phi$	0.3
Liquid saturation	$S_l$	0.5
Pneumatic conductivity	$K_g$	$\leq 0.5$ m/day
Tortuosity factor	$\tau$	0.13 (Millington, 1959)
Molecular weight of air	$M_a$	0.0289 kg/mole
Molecular weight of TCE	$M_{voc}$	0.1314 kg/mole
Molecular weight of 1,2-DCE	$M_{voc}$	0.09695 kg/mole
Free gas diffusion coefficient	$D_g$	0.7 m <sup>2</sup> /day
Vadose zone thickness	$L$	27 m
Soil sorption parameter	$\rho_B K_d / \phi$	5.0

where  $S$  is one minus the saturation of the respective phase. The Millington (1959) formula given in Eq. G-15 is often used to compute  $\tau$ . Because the free diffusion coefficient in gas is several orders of magnitude larger than diffusion in liquid, gas phase diffusion dominates over aqueous phase diffusion unless the pores are nearly saturated; hence, we neglect aqueous diffusion in the vadose zone.

In the absence of other transport processes, the aqueous and solid phases act as storage components, with sorbed VOCs on the solid phase partitioning with the water and aqueous phase VOCs partitioning with the gas phase. This reversible process retards the diffusion gas flux and can be expressed as

$$q_g = -\frac{S\phi\tau D_f H}{R} \nabla C, \quad (\text{G-22})$$

where  $R$  is the unsaturated aqueous phase retardation factor given by Eq. G-12. Because this quantity is usually greater than unity, the diffusion flux is decreased. By conservation of mass, the gas phase concentration is found from the following diffusion equation:

$$\frac{\partial C}{\partial t} = \frac{S\tau D_f H}{R} \nabla^2 C. \quad (\text{G-23})$$

## G-3.2. GASEOUS DIFFUSION PARAMETER DEPENDENCE

The transport of VOCs by gaseous diffusion will result in an aqueous VOC concentration at the water table. Site-generic conclusions are made on the dependence of this concentration distribution on vadose zone  $K_d$ , liquid saturation, and porosity, and the VOC degradation half-life. The importance of the boundary condition between the vadose zone and the ground water is also quantitatively discussed.

### G-3.2.1. No VOC Degradation

In the case of a uniform, isotropic soil where there is no biological or chemical degradation, the soil concentration from Eq. G-23 satisfies

$$\frac{\partial C_{soil}}{\partial t} = D_{app} \nabla^2 C_{soil}, \quad (\text{G-24})$$

where  $D_{app}$  is the apparent diffusivity for gaseous diffusion given by

$$D_{app} = S_g \tau D_g H / R. \quad (\text{G-25})$$

The initial concentration is some distribution in space given by

$$C_{soil}(t = 0, x, y, z) = f(x, y, z). \quad (\text{G-26})$$

We nondimensionalize space and time by

$$x' = x/L, \quad y' = y/L, \quad z' = z, \quad t' = tD_{app}/L^2, \quad (\text{G-27})$$

where  $L$  is the vadose zone thickness. The diffusion equation then becomes dimensionless,

$$\frac{\partial C'_{soil}}{\partial t'} = \nabla_{x'}^2 C'_{soil}, \quad (G-28)$$

where the VOC distribution  $C_{soil}$  is related to the solution  $C'_{soil}$  of this equation by

$$C_{soil}(t, x, y, z) = C'_{soil}(tD_{app}/L^2, x/L, y/L, z/L). \quad (G-29)$$

Because the governing equation, Eq. G-28, is independent of any site-specific parameters, the solution  $C'_{soil}$  is also independent of them, except for the initial distribution. The effect of these system-specific parameters is to influence the time and length scales of the VOC distribution as implied by the time and distance scales in Eq. G-27, but they do not affect the maximum magnitude of the concentration field.

The soil concentration field  $C_{soil}$ , which is a function of time and space, determines the maximum concentration history at the top of the transition zone. The transfer of VOCs from this boundary to the water table will be discussed in more detail in Section G-3.2.4. Mass transfer calculations across the transition zone are given in Section G-6.2. They show that under the base case ground water velocity of 1 m/y, there is only a 10% reduction in concentration from the top of the transition zone to the saturated zone. This calculation does not take into account water table fluctuations which will further decrease any differences in concentration between these two regions. Hence, we can assume that the total soil VOC concentration at the bottom of the vadose zone remains virtually unchanged as it moves to the water table. Converting from total soil to aqueous concentration at the saturated zone, we have

$$(C_i)_{sat-zone} = F(C_{soil})_{vadose}, \quad (G-30)$$

where the conversion factor is given by

$$F = \frac{\rho_l + \rho_B/\phi}{\rho_l R_{sat}}, \quad (G-31)$$

and the saturated retardation factor by

$$R_{sat} = 1 + \rho_B K_d/\phi. \quad (G-32)$$

Because we have shown that the peak vadose zone VOC soil concentration  $(C_{soil})_{vadose}$  is independent of site-specific parameters (except for the dependence on initial VOC distribution), the dependence of the peak aqueous concentration at the water table is given entirely by  $F$ . In particular, the peak aqueous concentration depends on  $\phi$ ,  $\rho_B$ , and  $R_{sat}$ . The dependence on vadose zone thickness and initial soil concentration is found by solving Eq. G-28 together with the appropriate boundary conditions. Notice that the peak concentration is independent of liquid saturation, although the arrival time of the peak is significantly affected.

From Eqs. G-27 and G-25, the time  $t_{max}$  at which the peak concentration arrives at the water table has the parameter dependence

$$t_{max} \sim 1/D_{app}, \quad (G-33)$$

which is given approximately by

$$1/D_{app} \approx \frac{(\rho_B K_d / \phi)}{S_g \tau D_g}, \quad (G-34)$$

where we assumed that  $R \approx \rho_B K_d / \phi H$ . Hence,  $t_{max}$  is proportional to the sorption parameter group  $\rho_B K_d / \phi$ . The Millington (1959) formula for  $\tau$ ,

$$\tau = S_g^{7/3} \phi^{1/3}, \quad (G-35)$$

shows that peak breakthrough time  $t_{max}$  is inversely proportional to  $S_g^{10/3}$  and, therefore, depends strongly on the amount of moisture  $S_i$  in the pores, especially at high values.

### G-3.2.2. Effect of Degradation

For the case of spatially uniform properties and only gaseous diffusion, Eq. G-1 becomes

$$\frac{\partial C_{soil}}{\partial t} = \frac{S_g \tau D_g H}{R} \nabla^2 C_{soil} - \lambda(1 - S_g/R) C_{soil}, \quad (G-36)$$

where we have assumed first-order decay; that is, the decay rate is proportional to the VOC concentration. The last term can be approximated by  $\lambda C_{soil}$ . The decay constant  $\lambda$  is related to the half-life  $T$  by

$$\lambda = \ln(2)/T. \quad (G-37)$$

Equation G-36 can be nondimensionalized as described in the previous subsection. The resulting solution can be obtained by multiplying the solution to the no-degradation equation (Eq. G-28) by the factor  $2^{(-t'L^2/TD_{app})}$ . Hence, the peak concentration at the water table is proportional to this degradation factor, in addition to the dependence described in the previous subsection. In particular, the peak concentration is strongly dependent on the apparent diffusivity  $D_{app}$ , which is strongly dependent on liquid saturation and  $K_d$ . Physically speaking, a high liquid saturation or a high  $K_d$  value will result in later peak arrival times which, in turn, increase the net amount of degradation taking place and lower the peak concentration. The degradation factor will also change the peak arrival time by making it occur earlier.

### G-3.2.3. Relationship between $K_d$ and Total Soil Concentration

The total VOC mass in a soil sample of unit volume is given by

$$m_T = \phi R C_l, \quad (G-38)$$

where

$$R = S_l + S_g H + \frac{\rho_B K_d}{\phi}. \quad (G-39)$$

The mass fractions in the aqueous gas, and solid phases are

$$m_l = S_l/R, \quad m_g = HS_g/R, \quad m_s = \rho_B K_d/\phi R. \quad (G-40)$$

Using typical values for a fine grained material at LLNL:  $S_l = 0.5$ ,  $\phi = 0.3$ , and  $\rho_B K_d / \phi = 5.0$ , we obtain

$$m_l = 0.09, \quad m_g = 0.03, \quad m_s = 0.88. \quad (\text{G-41})$$

For a material with 50% gravel:  $S_l = 0.2$ ,  $\phi = 0.3$ , and  $\rho_B K_d / \phi = 2.6$ , we have

$$m_l = 0.06, \quad m_g = 0.10, \quad m_s = 0.84. \quad (\text{G-42})$$

Hence, most of the VOCs exist as a sorbed phase on the solid. Note that the amount sorbed is relatively insensitive to the amount of liquid present. The contribution of the first two terms of  $R$  varies only from  $H$  (which for the VOCs evaluated in this study is 0.39 for TCE and 0.384 for 1,2-DCE), to a maximum of unity, while the third term  $\rho_B K_d / \phi$  is at least 2.6 for the site and dominates over the variance of the other two terms. Hence, the total soil concentration, to the first-order approximation, is given by the  $K_d$  parameter group. Therefore, the total soil concentration (mass/vol) is given approximately by

$$C_{soil} = C_l \phi (1 + \rho_B K_d / \phi). \quad (\text{G-43})$$

Note that the expression in the parentheses is the saturated retardation factor.

If two different layers of materials as described above are adjacent to each other, and the gas phase VOC concentrations are equal through gaseous diffusion, the total resulting ratio of the total soil concentration of the fine-grained material to the gravelly material is given approximately by the ratio of the respective saturated retardation factors, which is equal to 1.7. Hence, the soil concentration can vary only as much as a factor of two due to variations in retardation factors.

#### G-3.2.4. Boundary Conditions

In Section G-2.3, we described the various boundary conditions at the top of the vadose zone and at the transition zone. Because there is no significant vegetative cover at the Building 518 and 511 Areas, we assume that the stagnant boundary layer can be neglected. As long as the boundary layer is much thinner than the distance of the VOC mass to the surface, the effect of the boundary layer is not important. Under these circumstances, the boundary layer will not have any more resistance to diffusion than an equivalent thickness soil, and adding this additional thickness will clearly have no impact on the movement of the VOC mass. Thus, we assume a zero concentration at the ground surface,

$$C_v = 0. \quad (\text{G-44})$$

The boundary between the vadose zone and the ground water is important because our main goal is to estimate VOC migration across the transition zone and into the ground water. If we assume a steady state flux relationship of the form

$$q = -D(S_l) \frac{\partial C}{\partial z}, \quad (\text{G-45})$$

where  $D(S_i)$  is a diffusion coefficient, which is the sum of the apparent diffusion coefficients in the gas and aqueous phases, then

$$D(S_i) = D_g^{app}(S_i) + D_l^{app}(S_i). \quad (G-46)$$

The dependence of the coefficients on  $S_i$  arises from the Millington (1959) formula given by Eq. G-15 for the tortuosity factor. Integrating over the transition zone,

$$q \int_0^L \frac{dz}{D(S_i)} = -(C_{vadose} - C_{sat}), \quad (G-47)$$

which gives

$$q = -D_{mean} \frac{(C_{vadose} - C_{sat})}{L}, \quad (G-48)$$

where the mean diffusion coefficient is defined by

$$D_{mean} = \frac{L}{\int_0^L \frac{dz}{D(S_i)}}. \quad (G-49)$$

Hence, we obtain the boundary condition

$$-D_{vadose} \frac{\partial C}{\partial z} = D_{mean} \frac{(C_{vadose} - C_{sat})}{L}. \quad (G-50)$$

The variation of  $S_i$  with respect to depth  $z$  depends on the characteristic curves and the infiltration flux.

Using a no-flow boundary condition instead of Eq. G-50 will yield a lower concentration at the transition zone. But, if the magnitude of  $D_{mean}$  is much smaller than the vadose zone diffusion coefficient, the no-flow condition is a good approximation. We quantify this statement by presenting a bound on the error arising from a no-flow condition. Let  $C_{no-flow}$  denote the solution to the diffusion equation with no-flow condition at the transition zone and a zero concentration at the ground surface. At the transition zone, the solution  $C_{no-flow}$  will be greater than the solution  $C_{vadose}$  satisfying the boundary condition Eq. G-50, because the latter has positive flux leaving the vadose zone. Hence, an upper bound to the flux in Eq. G-48 is

$$q = D_{mean} \frac{C_{no-flow}}{L}. \quad (G-51)$$

A further upper bound is obtained by replacing  $C_{no-flow}$  by its maximum value

$$q_{upper} = D_{mean} \frac{C_{no-flow}^{max}}{L}, \quad (G-52)$$

which is a constant in time and space along the boundary.

We now consider the solution  $C_m$  to the diffusion equation with zero concentration at the surface, but with flux  $q_{upper}$  at the transition zone. Its solution is

$$C_m = C_{no-flow} - \frac{q_{upper}}{D_{vadose}} z. \quad (G-53)$$

Using Eq. G-52 and letting  $z$  equal the depth to the top of the transition zone  $L_{vadose}$ ,

$$C_m = C_{no-flow} - \frac{L_{vadose} D_{mean}}{LD_{vadose}} C_{no-flow}^{max} \quad (G-54)$$

Because the flux at the transition zone for this solution is greater than for the solution using Eq. G-50, the former solution will be a lower bound. An upper bound to the relative error in the peak concentration is, therefore,

$$\left| \frac{C_m - C_{no-flow}^{max}}{C_{no-flow}^{max}} \right| = \frac{L_{vadose} D_{mean}}{LD_{vadose}} \quad (G-55)$$

This expression indicates that the error will be small if the vadose zone liquid saturation is low, because  $D_{vadose}$  will then be much greater than  $D_{mean}$ . On the other hand, the error could be large if the saturation is high.

In applying the error bound to the base case calculation that is described later, our calculations show that the relative error is at most 8% using van Genuchten (1980) characteristic curve parameters typical for a silty soil such as that at Buildings 518 and 511. For this calculation, the integral in Eq. G-49 was evaluated numerically. The conclusion, that the mass transfer across the water table will not significantly affect the vadose zone VOC distribution, is consistent with numerical calculations performed by Mendoza and McAlary (1990). We, therefore, have used a no-flow bottom boundary condition to calculate the vadose zone diffusive movement. A separate model is used to compute the transfer across the transition zone and transport in the ground water.

### G-3.3. MATHEMATICAL SOLUTION

To estimate VOC migration in the vadose zone under vapor diffusion, we used a semi-analytical solution of the diffusion equation with the initial mass distribution approximated by a three-dimensional, radially symmetric Gaussian function. The steps followed were to (1) solve the diffusion equation to obtain the soil concentration in the vadose zone as a function of time, (2) obtain the soil concentration just above the transition zone, and (3) convert the soil concentration to aqueous concentration in the ground water including the reduction in concentration across the transition zone.

If there is no degradation, the VOC soil concentrations  $C$  satisfy the diffusion equation given by Eq. G-24. We assume radial symmetry so that the concentration distribution is a function in cylindrical coordinates,  $r$  and  $z$ , as well as a function of  $t$ . The initial VOC distribution is approximately equal to the product of Gaussian functions in the vertical  $z$  and horizontal  $r$  directions

$$C(r, z, t = 0) = C_0 e^{-(z-a)^2/2h^2} e^{-r^2/2w^2} \quad (G-56)$$

Here,  $h$  is the standard deviation half-width of the initial release in the vertical direction,  $w$  is the width in the horizontal direction, and  $a$  is the distance from the center of the VOC mass from the ground surface (Figure G-2). The constant  $C_0$  represents peak concentration at the center of the VOC distribution.

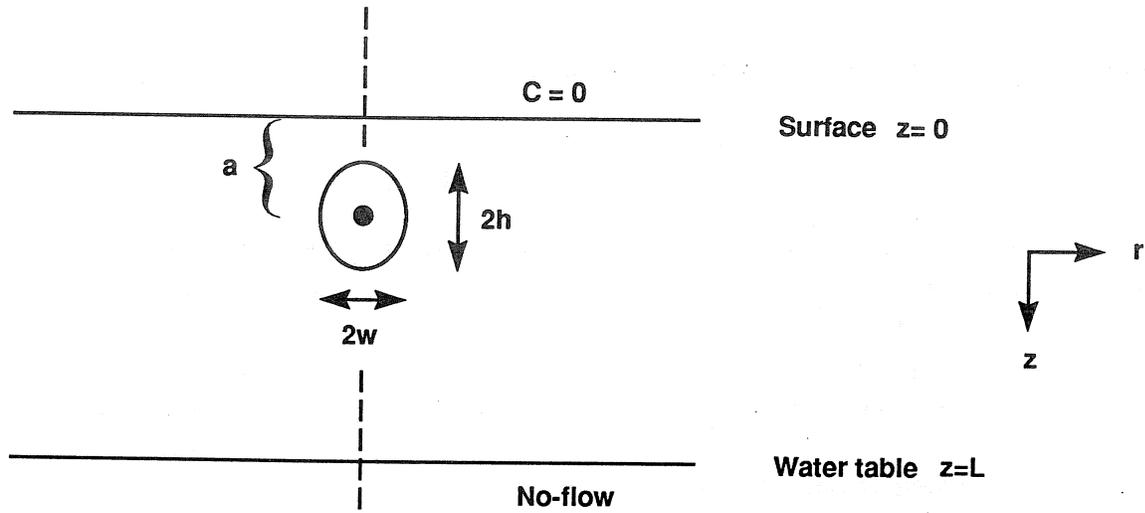


Figure G-2. Parameters for describing initial VOC distribution.

The boundary condition at the ground surface is set at zero concentration. The top of the ground water, as discussed in Section G-3.2.4, can be approximated as a no-flow boundary. Therefore,

$$C(r, z = 0, t) = 0, \quad \frac{\partial C(r, z = L, t)}{\partial z} = 0 \quad (\text{G-57})$$

are applied to the top  $z = 0$  and bottom  $z = L$  of the vadose zone, respectively. By making the variable substitution  $z \rightarrow z/L$ ,  $r \rightarrow r/L$ , and  $t \rightarrow t/\sqrt{L^2/D_{app}}$ , the diffusion equation, Eq. G-24, becomes

$$\frac{\partial C}{\partial t} = \nabla^2 C. \quad (\text{G-58})$$

Substituting  $C(r, z, t) = R(r, t)Z(z, t)$  we obtain

$$\frac{\partial R}{\partial t} = \frac{1}{r} \frac{\partial R}{\partial r} + \frac{\partial^2 R}{\partial r^2} \quad (\text{G-59})$$

and

$$\frac{\partial Z}{\partial t} = \frac{\partial^2 Z}{\partial z^2}. \quad (\text{G-60})$$

Solutions that are Gaussian at time zero are given by

$$R(r, t) = \frac{1}{t + w^2/2} e^{-r^2/4(t+w^2/2)} \quad (\text{G-61})$$

and

$$Z(z, t) = \frac{1}{\sqrt{t + h^2/2}} e^{-z^2/4(t+h^2/2)}. \quad (\text{G-62})$$

To satisfy the boundary conditions, we superimpose solutions from periodic images to obtain the final solution

$$C(r, z, t) = R(r, t) \sum_{n=-\infty}^{\infty} \left[ (-1)^n Z(z - (2n + a), t) + (-1)^{n+1} Z(z - (2n - a), t) \right]. \quad (\text{G-63})$$

This solution is adjusted to give the correct peak concentration at the center of the release by using a multiplication factor. Because of this superposition, the parameters  $a$ ,  $h$ , and  $w$  do not exactly correspond to their definitions given above, but must be readjusted to match the shape of the initial distribution.

The above solution is applicable when there is no degradation. As described in Section G-3.2.2, multiplying this solution by the appropriate exponential time-decay factor provides the solution for first-order VOC decay.

## G-4. MODEL RESULTS BASED ON OBSERVED VOC MASS AND DISTRIBUTION

Building 518 was constructed in 1958 and has been used continuously as a gas-cylinder, solvent-drum, and oil-drum storage dock facility. A total of five possible

sites of hazardous material release were identified in this area and are discussed in Thorpe *et al.* (1990). The most significant of these is in the southern portion of the Building 518 Area (Figure G-3), where anecdotal information indicates that leaking drums may have been allowed to drain onto the unpaved ground. A maximum total VOC concentration of about 6 ppm has been detected in the unsaturated sediments at this site at about a depth of 6 m.

At the southeast corner of Building 511, two boreholes, SIB-518-008 and SIB-514-001 (Figure G-4), were drilled to evaluate relatively high soil vapor measurements (SIB denotes source investigation borehole). The first borehole, SIB-518-008, was drilled in a major soil vapor anomaly as defined in Thorpe *et al.* (1990). However, it was in the second borehole, SIB-514-001, that about 1 ppm total VOC concentration was measured in shallow soil.

## G-4.1. BUILDING 518 AREA

### G-4.1.1. Physical Setting

The subsurface near Building 518 was initially investigated in 1984 with eight boreholes drilled to a depth of approximately 18 m (Carpenter, 1984). These data were used to identify the area for future investigations. Soil vapor surveys to depths of 1.5 to 5 m over an expanded area and nine boreholes drilled to the water table at about 33.5 m were completed in 1988 and 1989 (Dresen *et al.*, 1989; Thorpe *et al.*, 1990). Figure G-4 presents total VOC soil vapor survey concentrations at 1.5 m, the locations of the boreholes, and the location of cross sections referenced in this and the subsequent section.

The maximum total VOC concentration detected in boreholes south of Building 518 is about 6.4 ppm. The dominant constituent is TCE, with a maximum concentration of 6.1 ppm (Figure G-5). The vadose zone is about 33.5 m thick, and consists of a heterogeneous distribution of silt, clay, and sand with minor amounts of clayey gravel and gravelly sand. The approximate center of the VOC mass distribution is near SIB-518-001.

The exact age of this release is not known but has been estimated to be at least 15 y. Also unknown is the total amount of VOC released. Currently, the maximum measured total soil TCE concentration is far below the free-phase concentration. However, when the release occurred, the VOCs may have entered the subsurface as free liquid with a major portion of the free product volatilizing. Free-phase advection was terminated well above the water table, because the highest VOC concentrations are above a 6.1-m depth as described below.

Figure G-5 shows the current vadose zone distribution of TCE along section A - A'. In general, the TCE distribution appears to be irregularly shaped with a peak concentration of about 6 ppm lying about 27.4 m above the water table and 6.1 m below the surface. The irregular distribution of TCE is believed to be caused by lateral spreading as the TCE encountered different soil layers during its progress downward. This irregular distribution is also observed in boreholes, as shown in Figure G-6, which presents the concentrations in SIB-518-001, C-518-2, and C-518-6 located in the center of

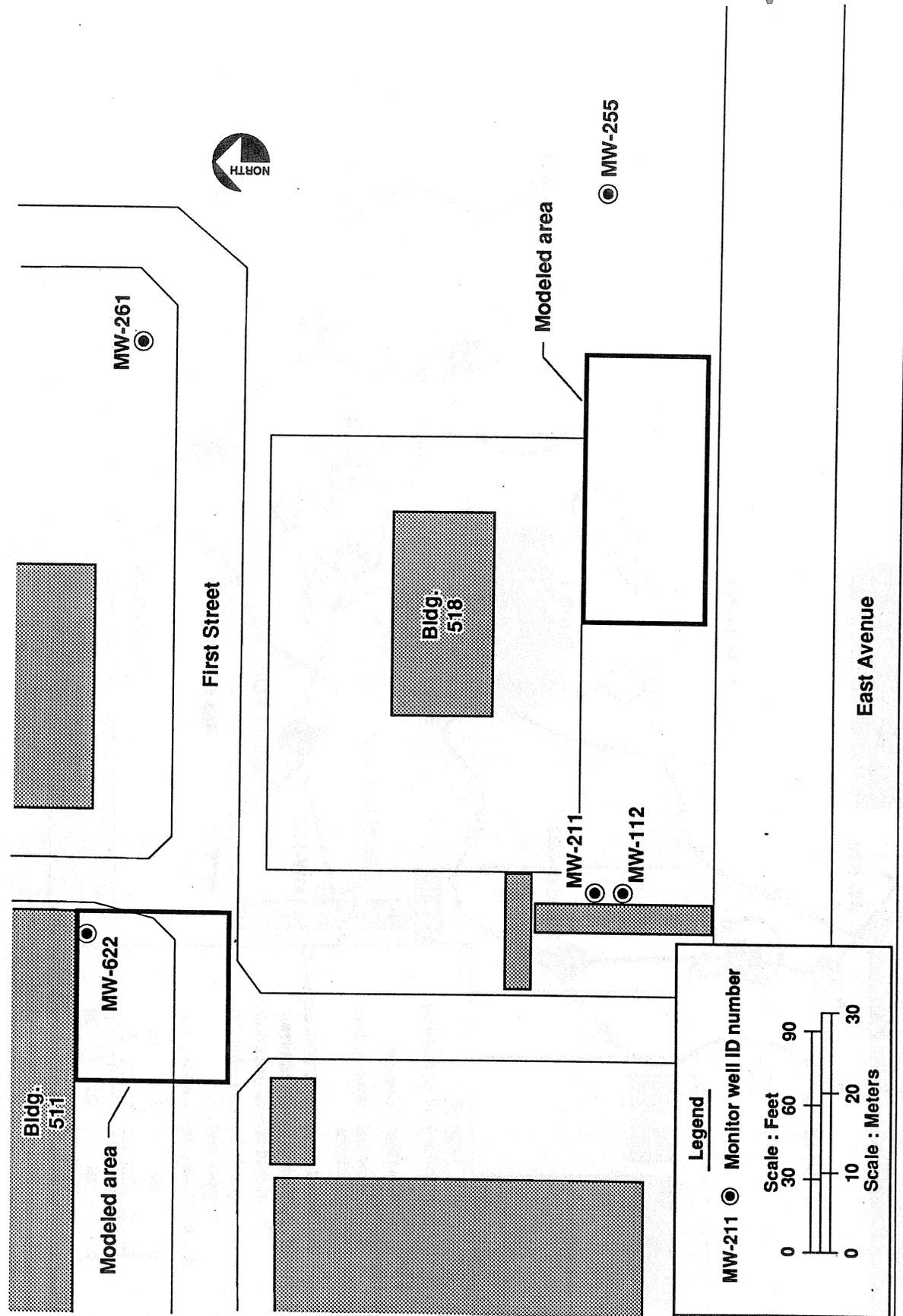


Figure G-3. Areas modeled for vadose zone transport in the Building 518 and 511 Areas.

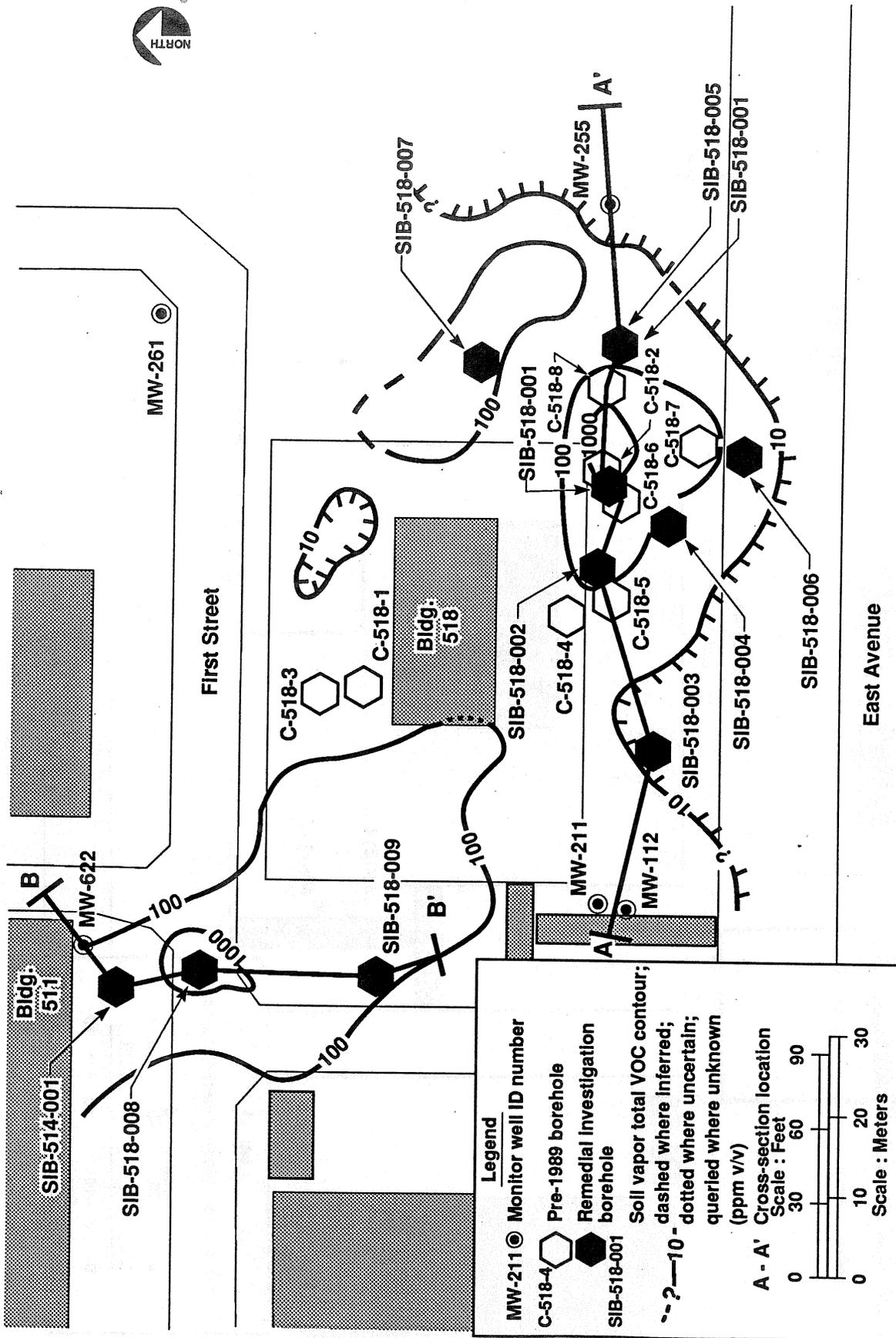


Figure G-4. Borehole locations and total soil vapor at 5-ft depth.



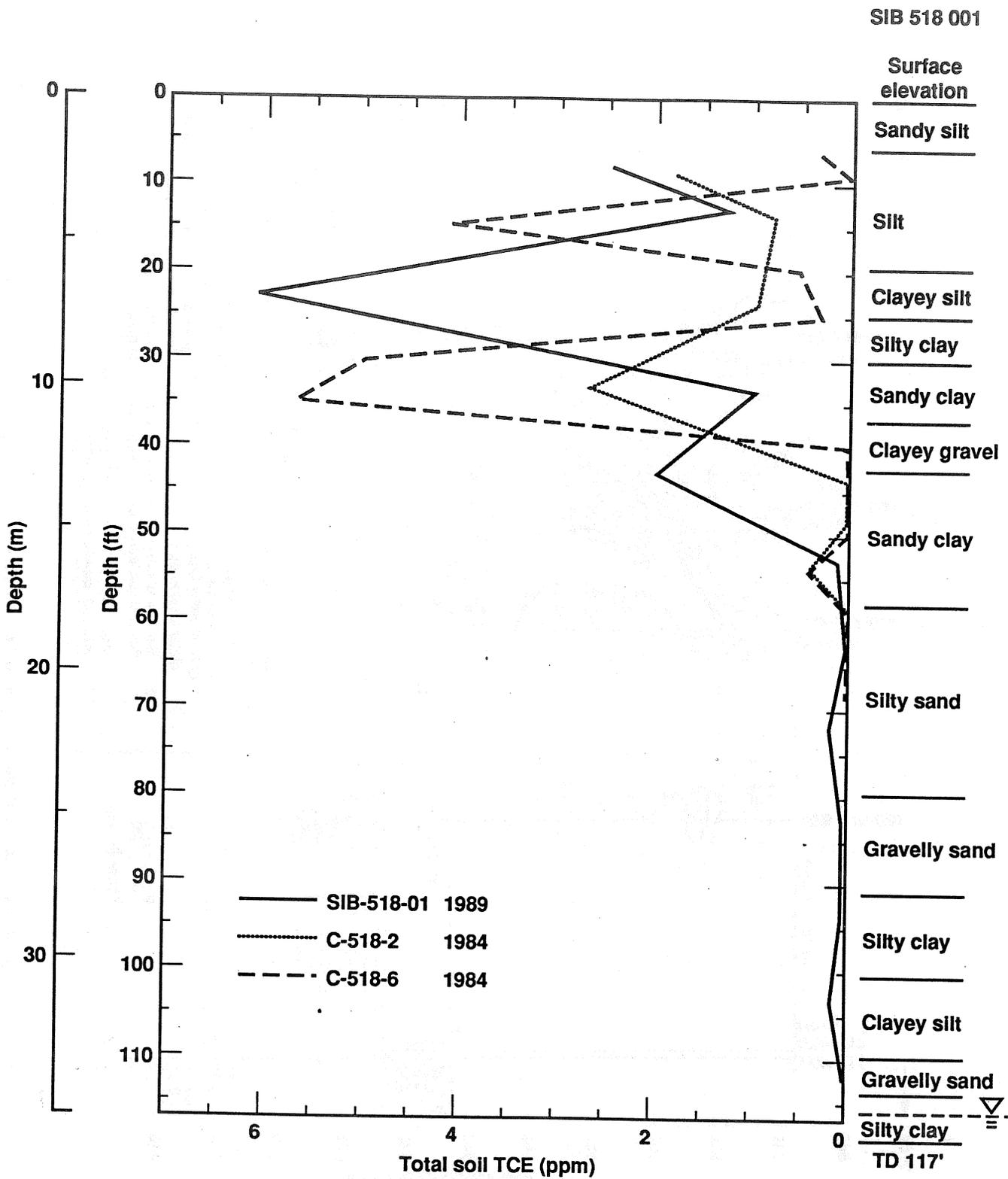


Figure G-6. TCE concentration profiles in boreholes SIB-518-001, C-518-2, and C-518-6. Lithology from SIB-518-001 is also shown.

the VOC distribution. This figure also shows the lithology for SIB-518-001. Concentrations exceeding 100 ppb generally form an irregular ellipsoidal shape that extends from just beneath the ground surface to a maximum depth of 15 m at SIB-518-001, except for two apparent lenses at about 20 and 30 m. These regions reflect areas of higher clay content.

The volume of TCE-bearing sediment in the Building 518 vadose zone exceeding a concentration of 1 ppm is about 2500 m<sup>3</sup>. The mass of TCE within the 1-ppm isocontour is calculated to be 13.2 kg. These estimates were calculated using the interactive volume modeling (IVM) software developed by Dynamic Graphics, Inc. TCE concentration data were processed by the IVM software, producing a grid and 3-dimensional contour model. The resultant contour model was evaluated both statistically and visually. When necessary, additional gridding was performed to refine the model. The volume of the TCE region exceeding 1 ppm was calculated by IVM using the grid. The mass of TCE present within the volume was calculated by assuming a geometric mean concentration of 2.4 mg/kg and a dry bulk density of 1.9 g/cm<sup>3</sup>.

#### G-4.1.2. Base Case Description

Vadose zone hydrological parameters are not available for the Building 518 Area. However, data are available from other boreholes and wells at LLNL (Bishop *et al.*, 1990), and average values are given in Table G-3. Note that there is relatively little variation in the values for porosity and bulk density. Base case parameter values are described below. A sensitivity analysis of these parameters is presented in Section G-5.

Moisture measurements of the vadose zone in the Building 518 are also not available, but, recently, measurements were made for borehole SIB-TOM-102 in the LLNL recharge basin south of LLNL. Infiltration in this area is high and not typical of the Building 518 Area, where infiltration is much lower. The saturation measurements taken from the borehole are also probably higher than is typical for the Building 518 Area. Liquid saturations for the nongravelly material increased roughly linearly with depth and ranged from 52 to 100%. The liquid saturation for gravelly sediments, as expected, were lower and ranged from 14 to 62%. The principal effect of increasing liquid saturation is to reduce the apparent diffusivity, and hence, the speed of the VOC movement (Section G-3.2). Therefore, we chose the lowest liquid saturation value that matched the lack of movement of the TCE between the 1984 and 1989 data sets from the boreholes shown in Figure G-6. Saturations below 0.5 gave excessively fast predictions, whereas saturations greater than 0.5 were consistent with the data. Therefore, the value we chose for the base case was 0.5. This matching relied on the Millington formula in Eq. G-15 for the gas phase tortuosity factor, which may overpredict the tortuosity factor by a factor of four (Peterson *et al.*, 1988). If this factor of four is used, a saturation of 0.3 would be the lowest value consistent with the data.

Based on several published measurements, we use a Henry's law constant  $H$  of 0.39 for TCE. The sensitivity of this parameter is discussed in Section G-5.1.6. The base case bulk density 1.8 g/cm<sup>3</sup> is from Bishop *et al.* (1989) and is consistent with the range

Table G-3. Average LLNL sediment property values (from Bishop *et al.*, 1990).

Sediment type	Bulk dry density g/cm <sup>3</sup>	Porosity	Hydraulic conductivity x 10 <sup>-9</sup> m/s	TCE K <sub>d</sub>	Sorption parameter ρ <sub>B</sub> K <sub>d</sub> /φ
Gravelly sand	1.91	0.25	250.	0.52	4.0
Sandy gravel	1.92	0.26	2000.	0.11	0.8
Gravelly silt	1.91	—	2.3	—	—
Silty gravel	1.98	0.27	11.	0.60	4.4
Sandy silt	1.83	0.31	3.0	0.74	4.4
Silty sand	1.88	0.31	25.	0.80	4.9
Silt	1.77	0.30	0.2	0.66	3.9
Clayey silt	1.85	0.30	4.1	0.71	4.4

of values in Table G-3. The effect of differences in bulk density were found to be insignificant over the range of values in the table.

A literature study by Mallon (1989) indicates that the half-life for biological degradation of TCE under anaerobic or methanogenic conditions is on the order of 30 to 200 y. Few data are available for biological degradation under aerobic conditions and for chemical degradation. In our study, we used a half-life of 50 y for the base case, which is the same as the half-life for VOC transport modeling used in Thorpe *et al.* (1990) for the saturated zone.

Initial sensitivity studies were performed for an isotropic, homogeneous material. Because the site lithology is predominantly fine grained with little gravel (Figure G-6), we chose the base case parameters for our sensitivity analysis, accordingly, as shown in Table G-4. The parameters are consistent with those for silty sand given in Table G-3 from LLNL sediments measured by Bishop *et al.* (1990). The table shows that the parameters do not depend very much on lithology, except for permeability, which does not play a role in vapor diffusion.

#### G-4.1.3. Base Case Calculations

We calculated the movement of TCE in the vadose zone using the solution described in Section G-3.3. The base case parameter values used in the calculations are shown in Table G-4. Figure G-5 shows the contours of the initial soil TCE distribution from field measurements. The model uses distributions that are a product of Gaussian functions in the vertical  $z$  and horizontal  $r$  coordinates. This limitation can be overcome by implementing several Gaussian sources and choosing their peak concentrations so that the least square deviation from the initial measured VOC concentrations is minimized. The center of the Gaussian source is set at  $a = 6.10$  m below the surface. The half-width of the Gaussian distribution in the horizontal direction is  $w = 6.31$  m and in the vertical direction is  $h = 4.11$  m (Figure G-2). These values were obtained as follows:

1. The parameter  $a$  was chosen so that the peak of the Gaussian distribution, which is actually a sum of Gaussian distributions chosen to satisfy the boundary conditions, matched the peak concentration of the measured current distribution.
2. The parameter  $h$  was adjusted in the model until the depth of the 1 ppm concentration closest to the water table matched the field data.
3. The parameter  $w$  was adjusted to match the volume of region estimated to exceed 1 ppm in concentration.

The values were determined through manual iterations, but only a few iterations were required, because localized sources are known to eventually approach a single Gaussian distribution under diffusive transport (Oran and Boris, 1987).

Figures G-7 through G-9 show the soil concentration of TCE at present and its migration into the future at 50 and 100 y, respectively. Diffusive fluxes are proportional to the concentration and the steepest gradients are always near the surface, indicating that the highest fluxes are moving toward the zero concentration boundary at the

Table G-4. Base case parameter values, Building 518 Area (TCE).

Property	Value
Bulk dry density $\rho_B$	1.8 g/cm <sup>3</sup>
Effective porosity $\phi$	0.30
Solid sorption ( $\rho_B K_d / \phi$ )	5.0
Henry's constant for TCE $H$	0.39
Liquid saturation $S_l$	0.50
Degradation half-life	50 y

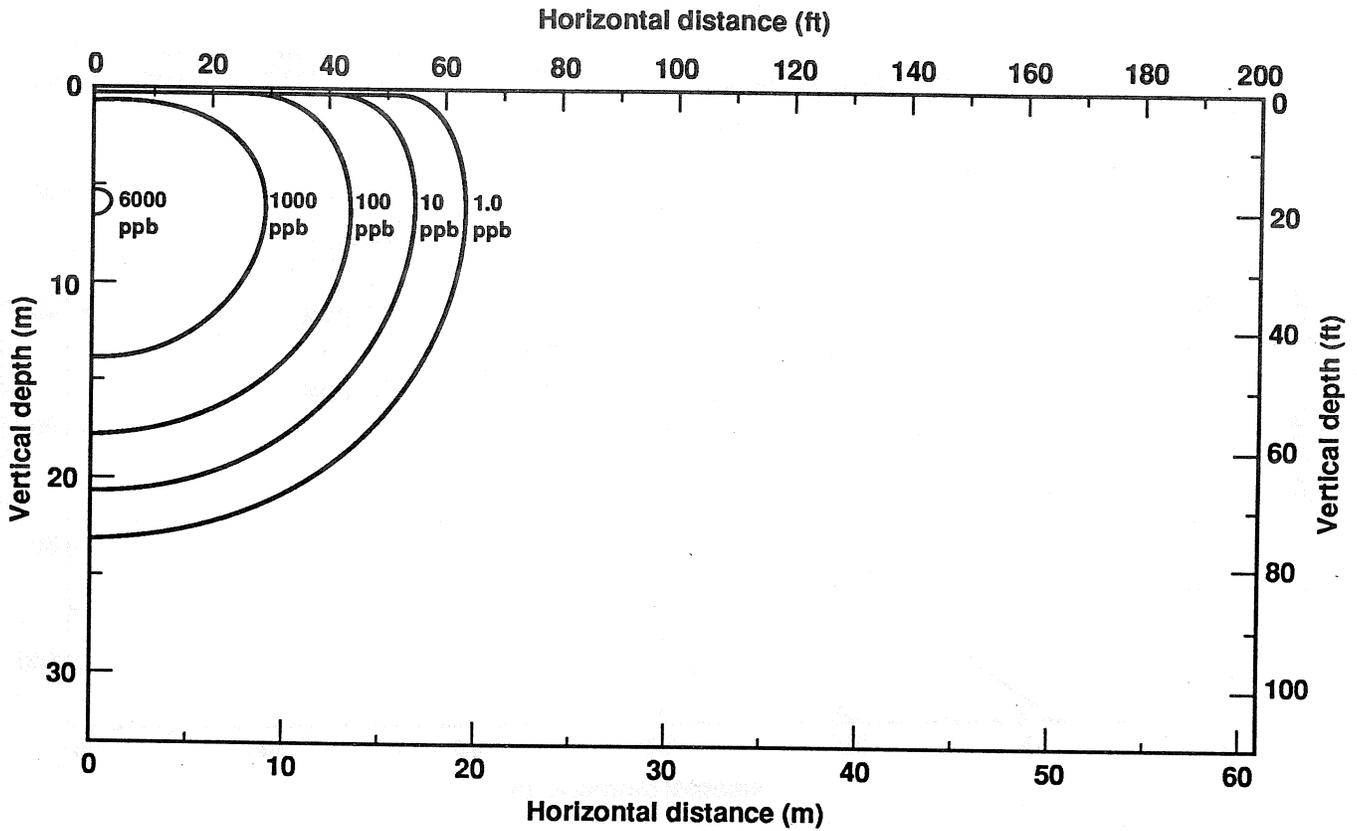


Figure G-7. Cross section showing initial TCE soil concentration used by model for Building 518 Area.

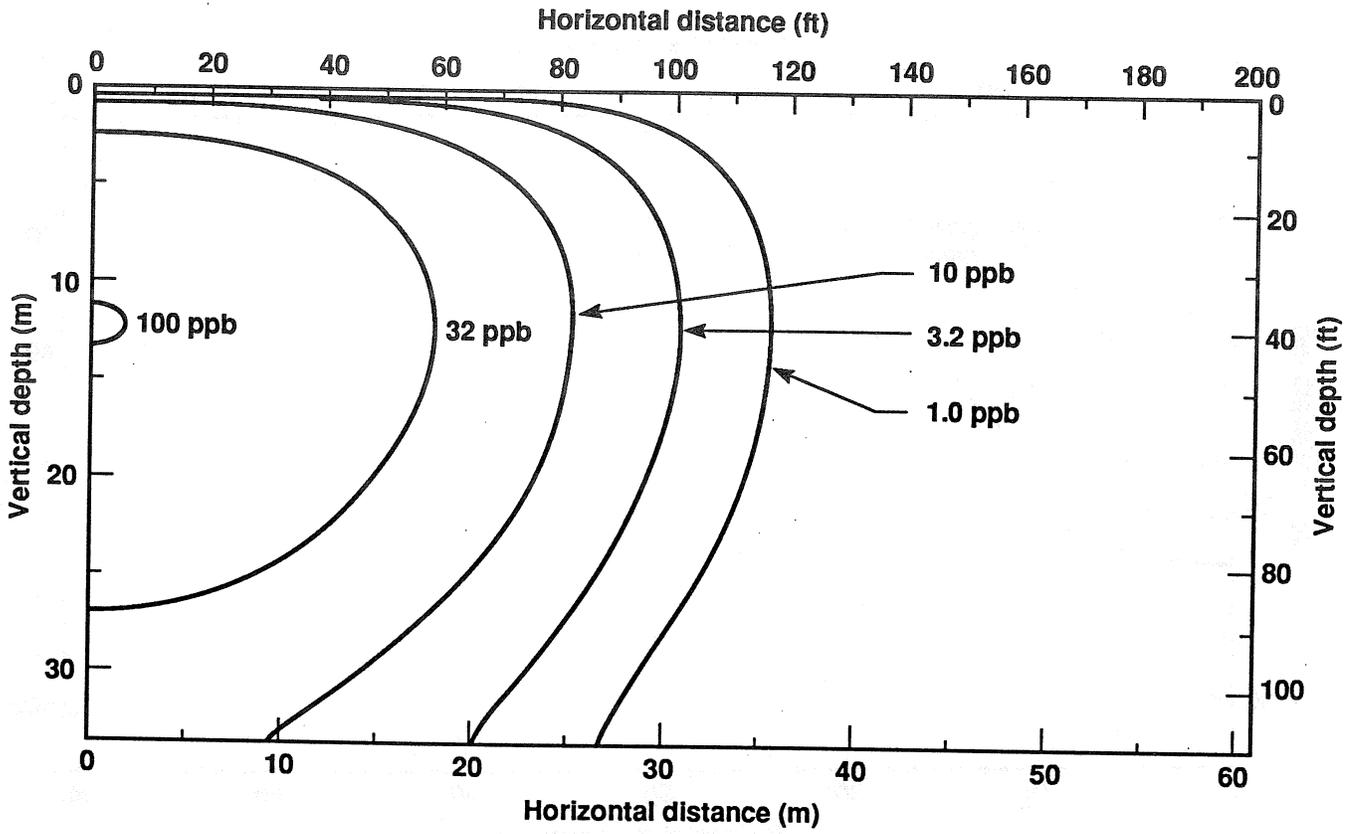


Figure G-8. Cross section of predicted TCE soil concentration at 50 y for the Building 518 Area.

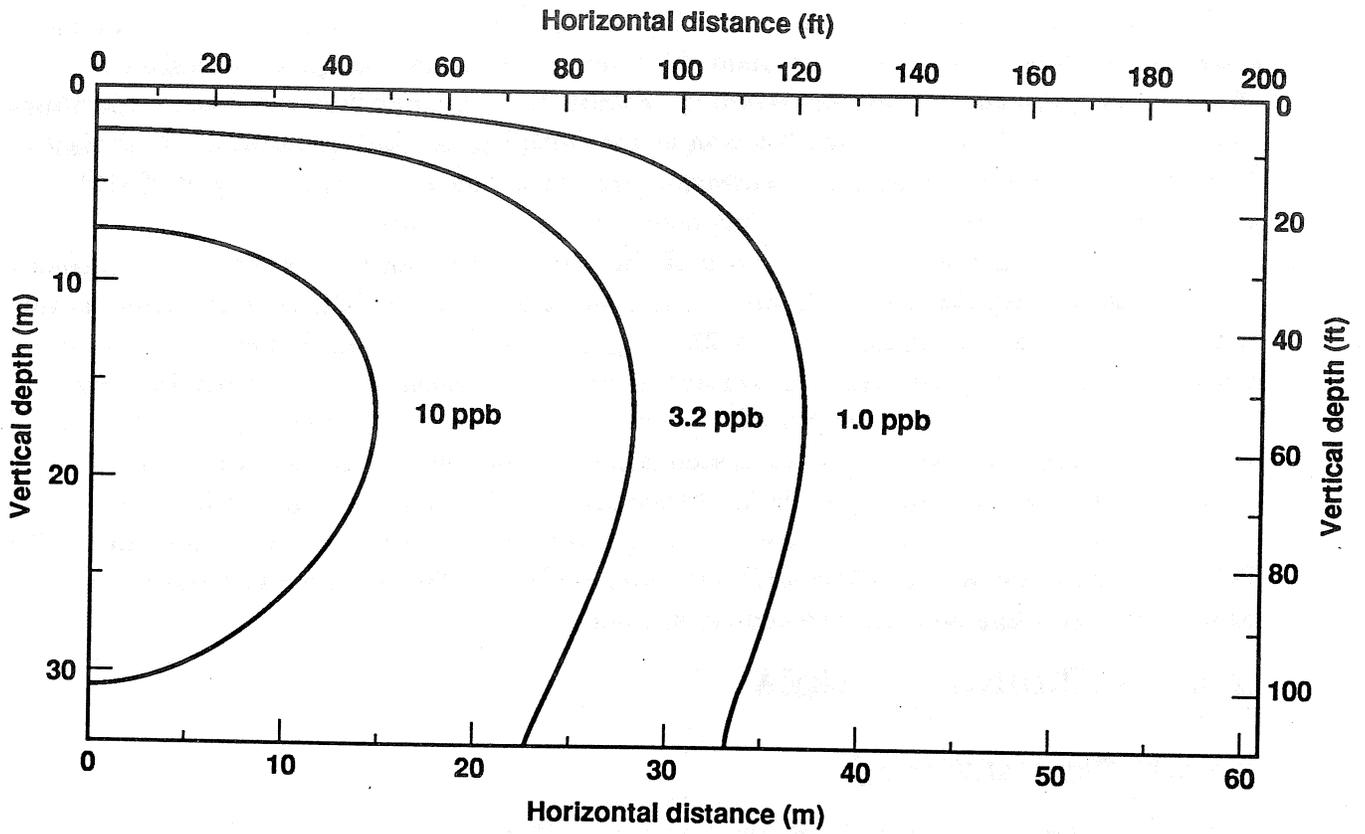


Figure G-9. Cross section of predicted TCE soil concentration at 100 y for the Building 518 Area.

surface. Figure G-10 is a vertical profile of the soil concentration through the center of the TCE mass. Note the rapid decline in the first 50 y caused by diffusion of TCE to the surface. In the second 50 y, the decline is slower because most of the TCE near the surface has already escaped. The remaining concentrations are those that were diffusing towards the water table when the main TCE body was large enough to obscure the effects of the zero concentration boundary. Figure G-11 further illustrates the importance of this boundary by showing the fraction of the initial mass that escapes to the surface. In about 55 y, when the peak concentration arrives at the water table (Figure G-12), about 60% of the initial TCE mass has been lost to the surface.

The soil concentration at the top of the water table can be converted to aqueous concentration using Eq. G-30. Figure G-12 shows the aqueous TCE concentration at top of the water table just under SIB-518-001 (Figure G-5), the center of the vadose zone concentrations. The peak aqueous concentration at the water table is approximately 17 ppb at 55 y. This value assumes that there is no reduction in concentration from the top of the transition zone to the saturated zone. In Section G-6.2, we show that the reduction in concentration is negligible based on expected ground water velocities. Figure G-13 is the horizontal profile of the aqueous concentration at the water table. The TCE concentration is above the MCL of 5 ppb (CDHS, 1989; U.S. EPA, 1988c) out to 20 m from the point beneath the center of mass.

## G-4.2. BUILDING 511 AREA

### G-4.2.1. Physical Setting

This area was chosen for study because (1) it was the second largest mass of VOCs identified in the vadose zone, and (2) it may illustrate a useful upper bound for sites that do not require remediation. Although the data are sparser than for the Building 518 Area, the proximity of two boreholes with low concentrations provides adequate control for illustration purposes. Additionally, data from the borehole of a subsequently drilled monitor well, MW-622, are also available to define the source.

Borehole SIB-514-001 was drilled near the southeast corner of Building 511 to investigate relatively high soil vapor measurements (Figure G-4). The maximum concentration of total VOCs detected in this borehole was 982 ppb at 3 m. The dominant VOC was 1,2-DCE at 590 ppb. Similar to the VOC release near Building 518, the exact time of the VOC release at this location is not known, but it may have been more than 15 y ago. The subsurface distribution of 1,2-DCE along cross section B-B' (Figure G-4) is presented in Figure G-14. Lithology of the area is comparable to that described for the Building 518 Area.

The estimated volume and mass of 1,2-DCE in the vadose zone exceeding 0.100 ppm was calculated to be 230 m<sup>3</sup> and 0.12 kg, respectively.

### G-4.2.2. Base Case Description

The base case parameters for the Building 511 Area investigation are essentially the same as for the Building 518 Area described in section G-4.1.2, except that we

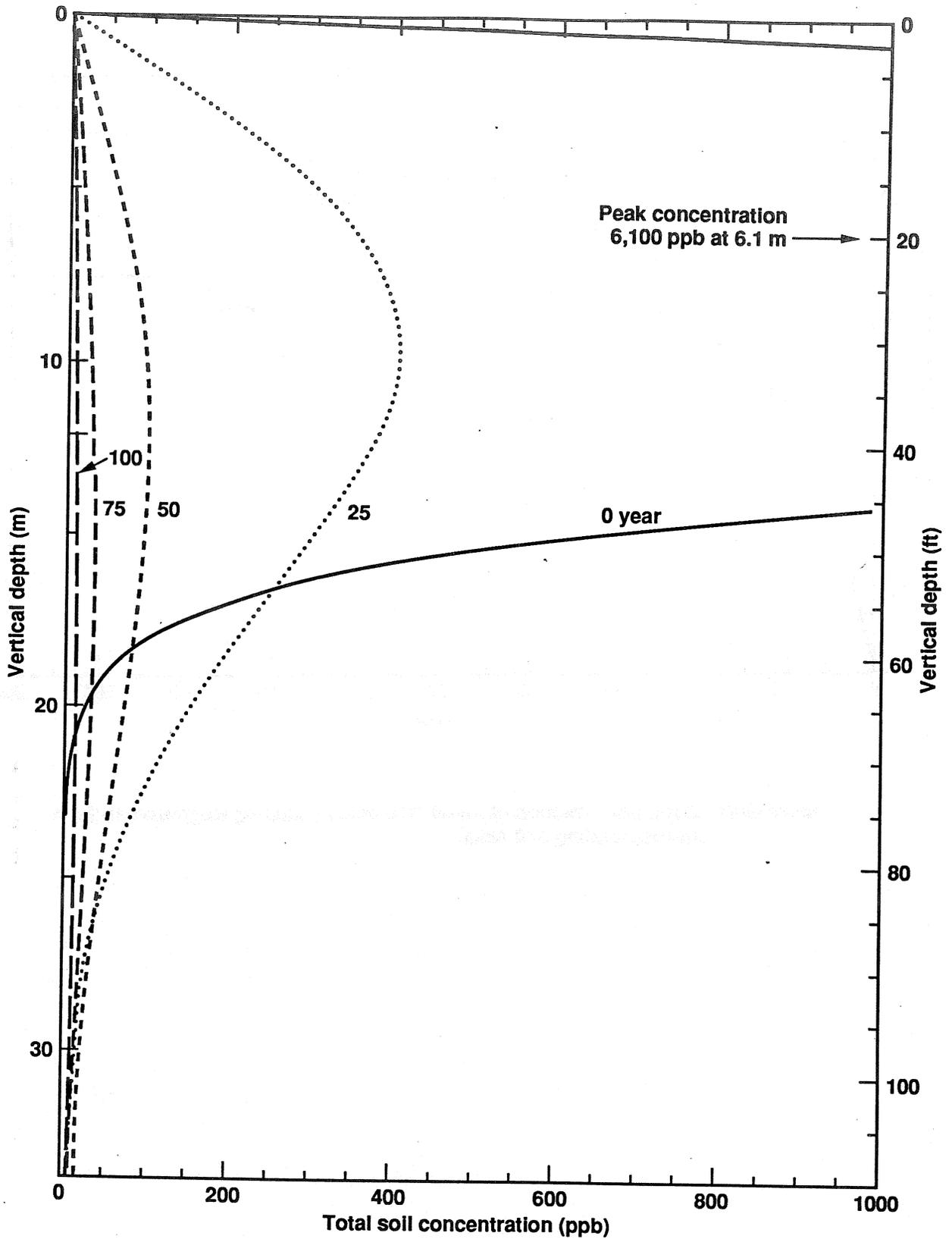


Figure G-10. Vertical profile of TCE soil concentration through center of VOC mass for the Building 518 Area.

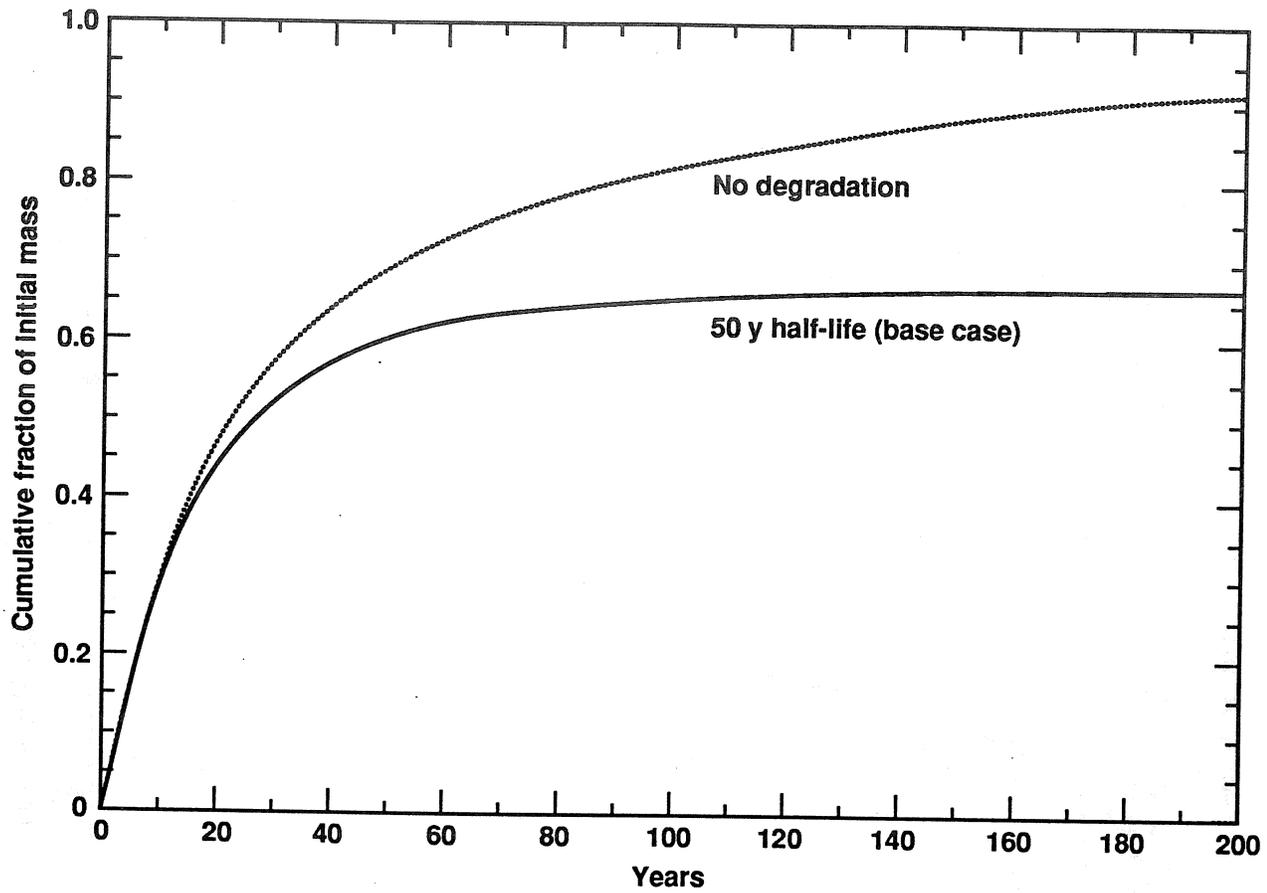


Figure G-11. Cumulative fraction of initial TCE mass escaping to ground surface for the Building 518 Area.

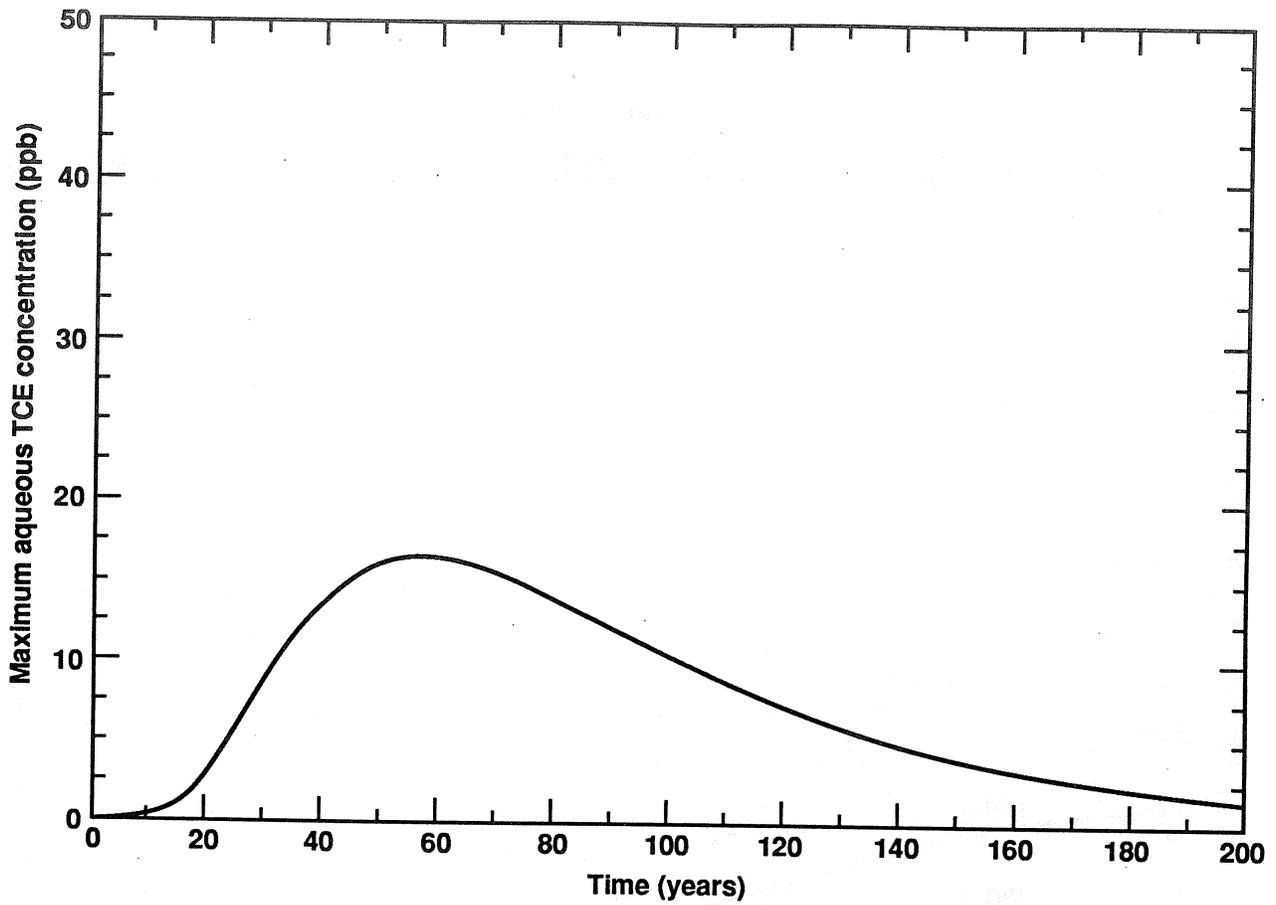


Figure G-12. Peak aqueous TCE concentration at water table as a function of time for the Building 518 Area.

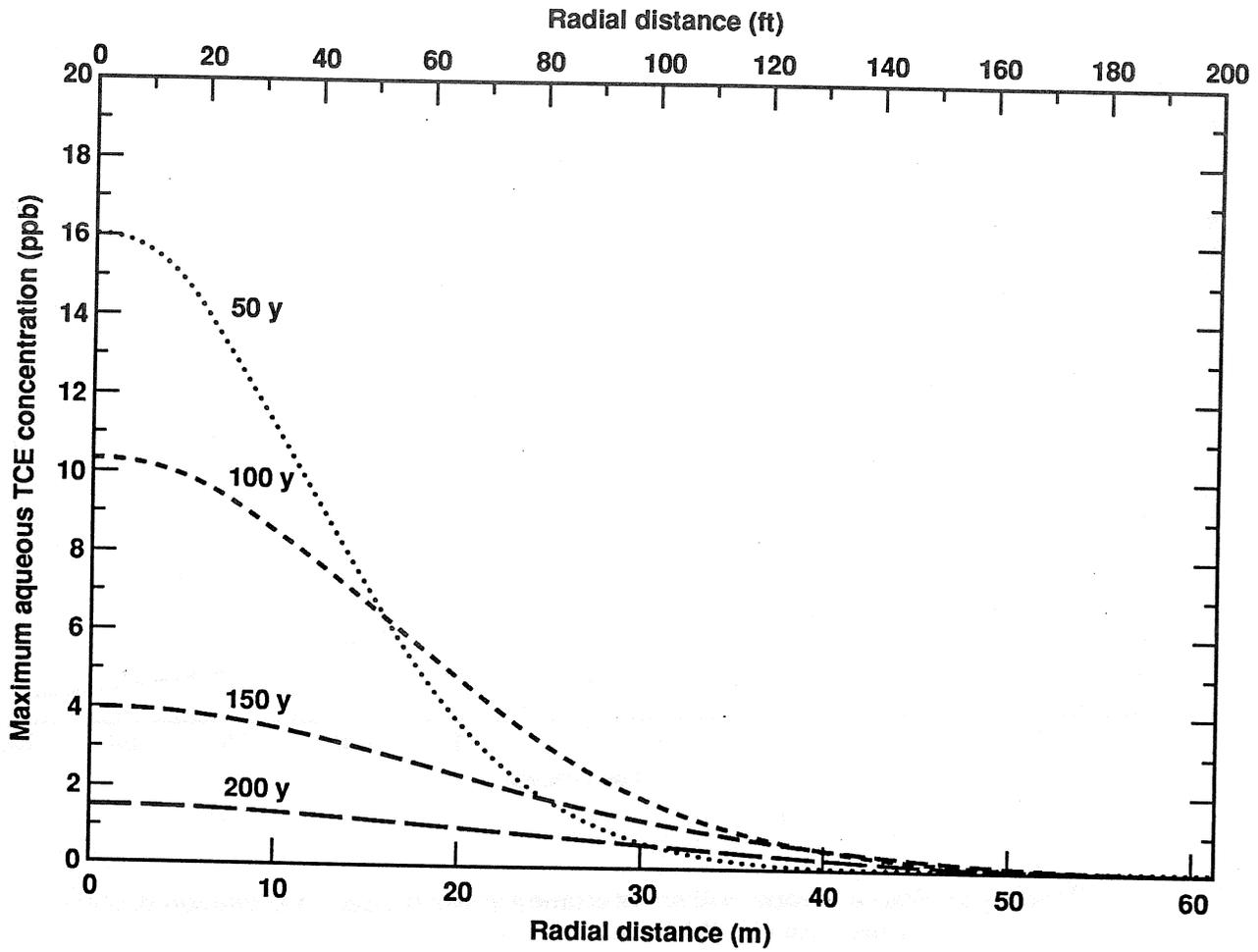


Figure G-13. Predicted horizontal profiles of aqueous TCE concentration at the water table at different times for the Building 518 Area.



consider 1,2-DCE instead of TCE. The only differences between the two compounds are the Henry's law constant and the  $K_d$ , as shown in Table G-5.

In the southeast corner area of Building 511, significant concentrations of 1,2-DCE were detected in only SIB-514-001 (Figure G-14). The 1,2-DCE soil concentrations are extremely localized and consist of 590, 130, and 26 ppb at depths of 0.9, 2.0, and 2.9 m, respectively. The concentrations in MW-622 do not exceed 4 ppb. The vertical width of the initial Gaussian distribution used by our model was chosen to closely match these values. The horizontal width of the Gaussian distribution was chosen to yield a spherically shaped 1,2-DCE mass distribution as shown in Figure G-15.

The  $K_d$  for 1,2-DCE is not available for LLNL sediments. The  $K_d$  value was calculated for this study using the empirical expression (McCarty *et al.*, 1981)

$$K_d = \frac{A_s}{K_{ow}^{0.16}}, \quad (\text{G-64})$$

where  $A_s$  is the surface area per unit mass of soil material and  $K_{ow}$  is the octanol-water partitioning coefficient. This expression is valid for low-organic sediments such as those at LLNL, where sorption is principally due to the mineral surfaces. The value of  $A_s$  was back-calculated using laboratory measurements of  $K_d$  for TCE. The value of  $K_{ow}$  used for 1,2-DCE was 30 and for TCE was 263 (Banerjee *et al.*, 1980). The  $K_d$  for 1,2-DCE calculated from the formula was a factor of 1.4 times that for TCE. Laboratory values for TCE in Bishop *et al.* (1989) were used to compute the  $K_d$  for 1,2-DCE. The values for this and other parameters are shown in Table G-5 for the base case calculations for 1,2-DCE.

#### G-4.2.3. Base Case Calculations

Figure G-16 shows the time history of the maximum 1,2-DCE aqueous concentration at the water table for various degradation half-lives. The base case half-life is 50 y, yielding a peak concentration of 0.04 ppb. The no-degradation case has a maximum of 0.14 ppb. In the following section, we present an extensive sensitivity analysis on the Building 518 TCE, showing that the upper range of variability in the peak concentration is much less than an order of magnitude. Because TCE and 1,2-DCE have similar physicochemical properties, we conclude that the maximum 1,2-DCE concentration will not exceed the 6 ppb MCL (CDHS, 1989; U.S. EPA, 1988c) for any reasonable parameter values under gaseous diffusion transport.

## G-5. PARAMETER SENSITIVITY ANALYSIS FOR BUILDING 518 AREA

A sensitivity analysis was performed on the base case calculation that was reported for the vadose zone TCE at Building 518 in Section G-4.1.3. A sensitivity study

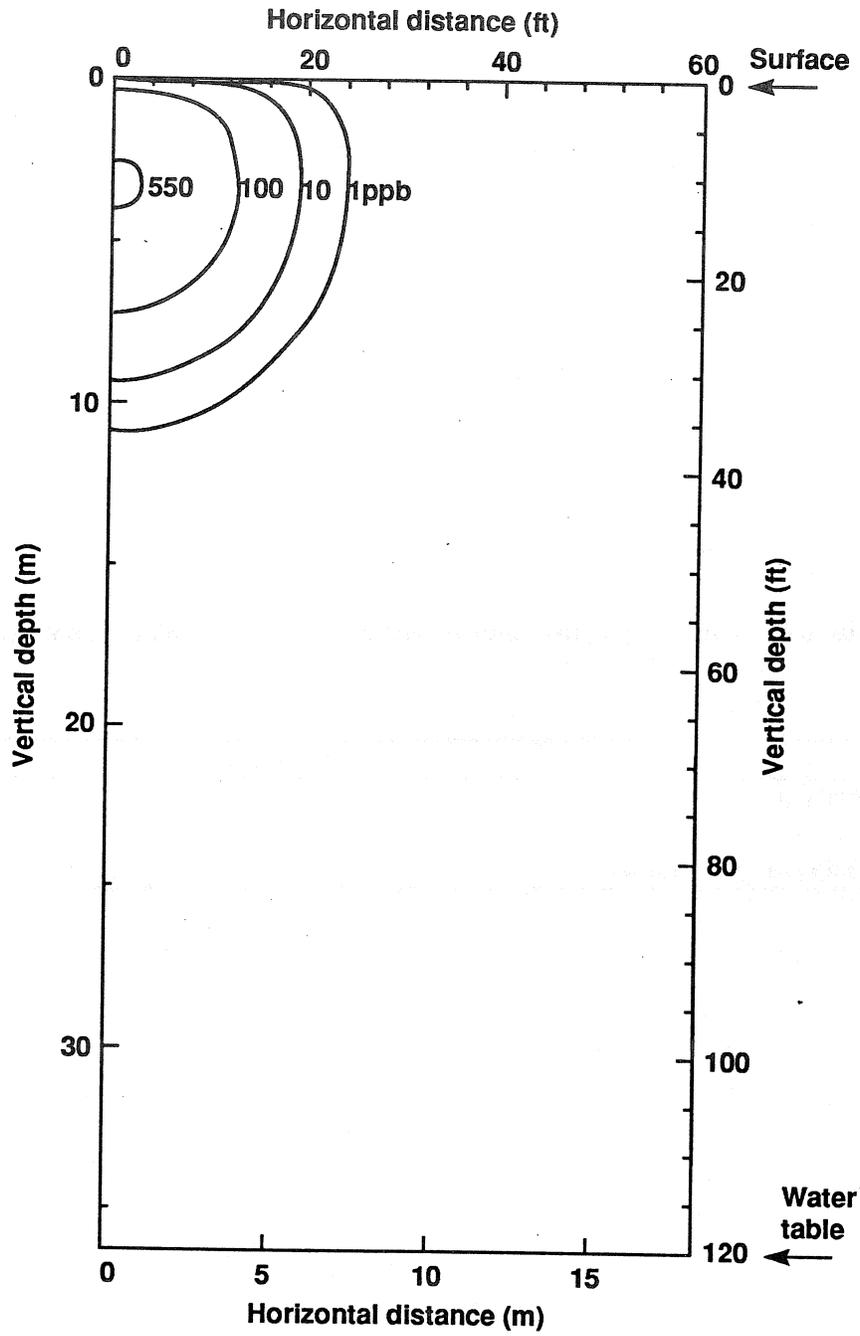


Figure G-15. Cross section showing initial 1,2-DCE soil concentrations used by the model for Building 511 Area.

**Table G-5. Base case parameter values, Building 511 Area (1,2-DCE).**

<b>Parameter</b>	<b>Symbol</b>	<b>Value</b>
Henry's constant	$H$	0.723
Soil sorption parameter	$\rho_B K_d / \phi$	7.0
Free gas diffusion coefficient	$D_g$	0.8 m <sup>2</sup> /day

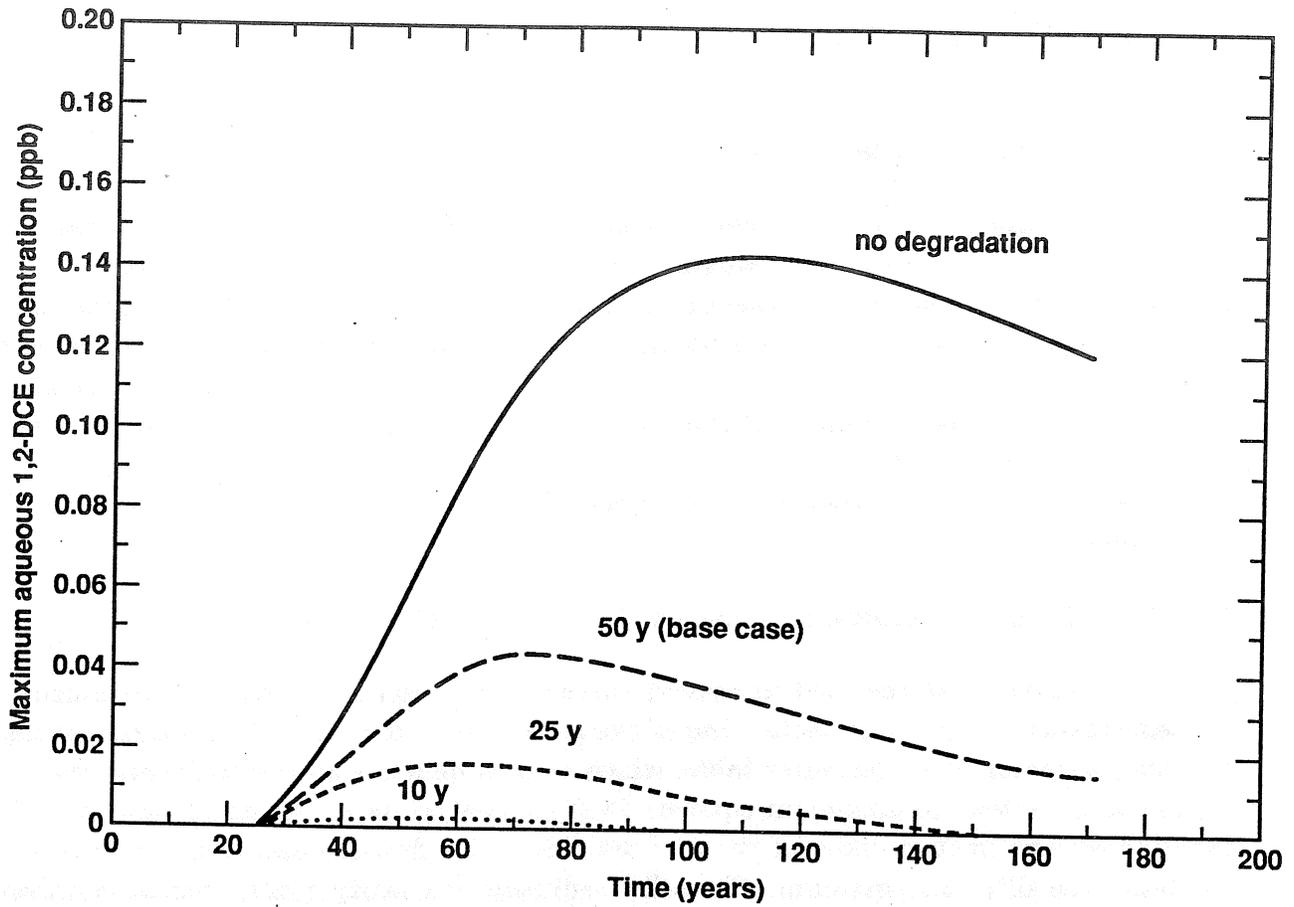


Figure G-16. Peak aqueous 1,2-DCE concentration at the water table as a function of time for the Building 511 Area.

for the 1,2 DCE at the southeast corner of Building 511 was not done because the results of the TCE sensitivity study are applicable to the 1,2-DCE study as well.

## G-5.1. ISOTROPIC MEDIUM

### G-5.1.1. Effect of Initial Mass

The single 6.1 ppm TCE peak concentration in SIB-518-001 accounts for much of the initial mass. Therefore, we evaluated the effect of lowering the peak concentration to 2.5 ppm, which is close to the concentrations at the neighboring data points in the same borehole (Figure G-6). The vertical width of the Gaussian distribution was readjusted to match the 1 ppm contour, and the resulting initial mass was about one-half of the base case mass. Figure G-17 shows that the maximum TCE concentration at the top of the water table is about 60% of the base case. The time when the concentration starts to decrease occurs slightly earlier at 50 y, instead of the 55 y for the base case, because of the smaller initial mass.

### G-5.1.2. Effect of Sediment Type at the Water Table

Equation G-30 was used to convert values of total soil concentrations to aqueous concentrations at the water table. One of the parameters affecting the conversion is the retardation factor  $R$  at the water table, which in turn depends on the sediment type. Figure G-18 shows the maximum aqueous TCE concentration at the water table as a function of time for two different types of sediment. The first sediment corresponds to the base case silty sand material. The other sediment is a sandy gravel with 50% gravel clasts and varies from the base case in that the solid sorption parameter group,  $\rho_B K_d / \phi$ , is 2.5 instead of 5.0 (Bishop *et al.*, 1989). Note that only the sediment type at the water table is changed; the sediment type at the vadose zone remains base case silty sand.

In Figure G-18, peak TCE concentration for the sandy gravel is about 28 ppb compared to 17 ppb for the base case silty sand. The smaller sorption for the sandy gravel material effectively increases the aqueous concentration, explaining the higher aqueous concentration in the figure. Data indicates that the water table sediments in the Building 518 Area are silty clay (Figure G-6) so that the lower concentration of 17 ppb is more likely.

### G-5.1.3. Effect of Liquid Saturation

Figure G-19 shows the effect of varying only the liquid saturation. As previously mentioned, increasing the saturation delays the peak aqueous concentration and allows more time for degradation, resulting in a decrease in the peak concentration. As described in Section G-4.1.2, a saturation of at least 0.5 is needed to match the relative lack of movement of the TCE between measurements taken in 1984 and 1989.

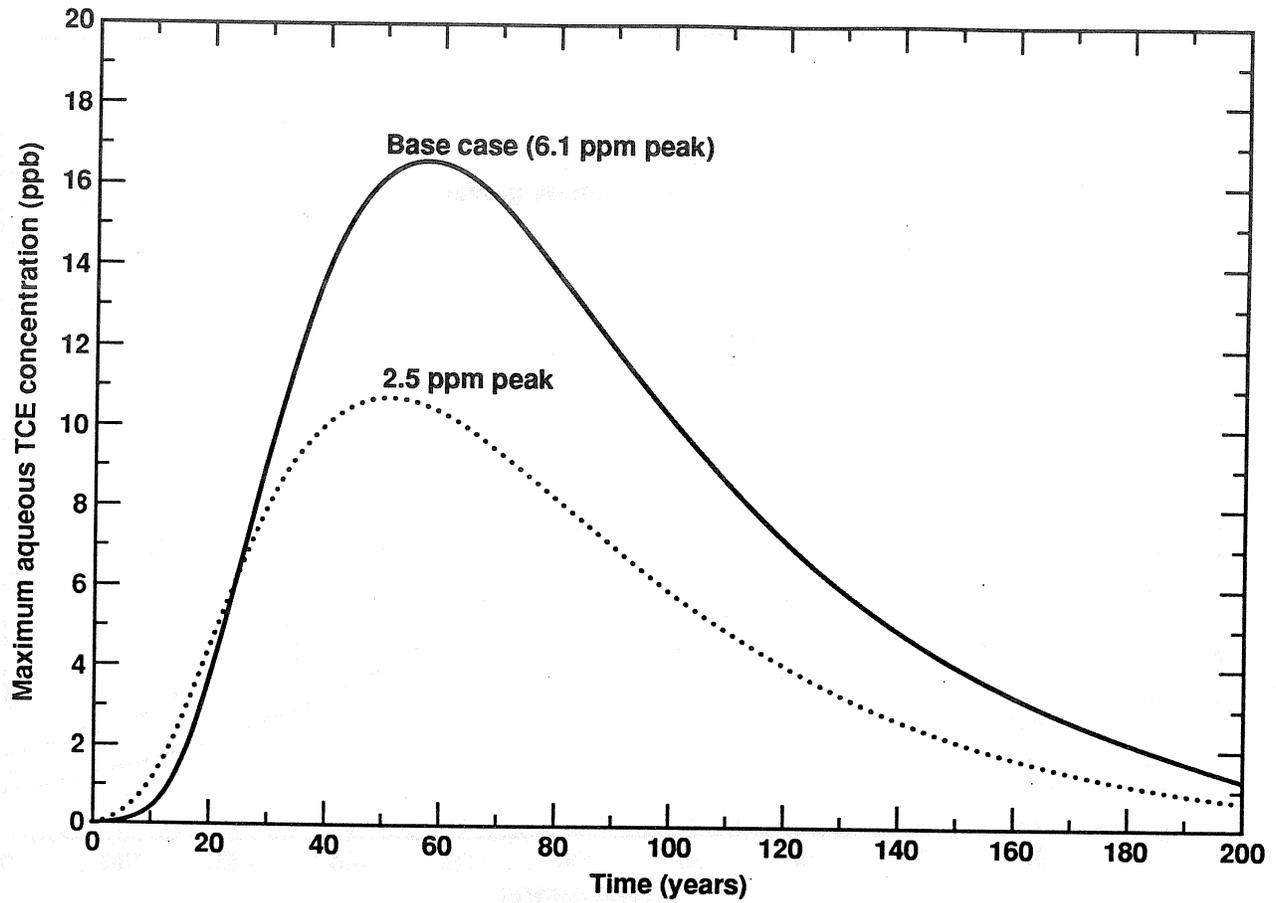


Figure G-17. Peak aqueous TCE concentration as a function of time showing the effect of reducing maximum concentration of initial TCE mass from 6.1 to 2.5 ppm for the Building 518 Area.

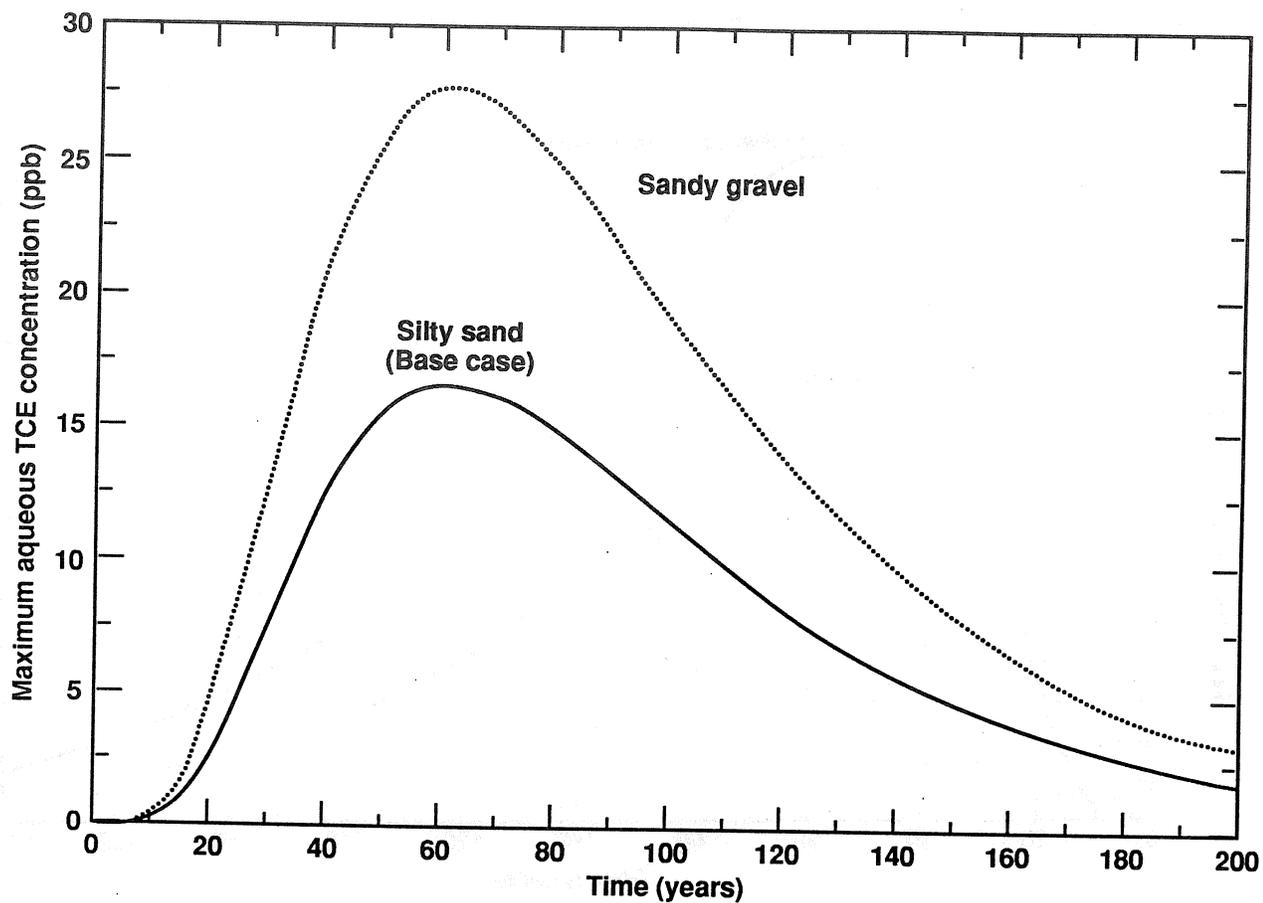


Figure G-18. Peak aqueous TCE concentration as a function of time showing the effect of differences in sediment type at water table for the Building 518 Area.

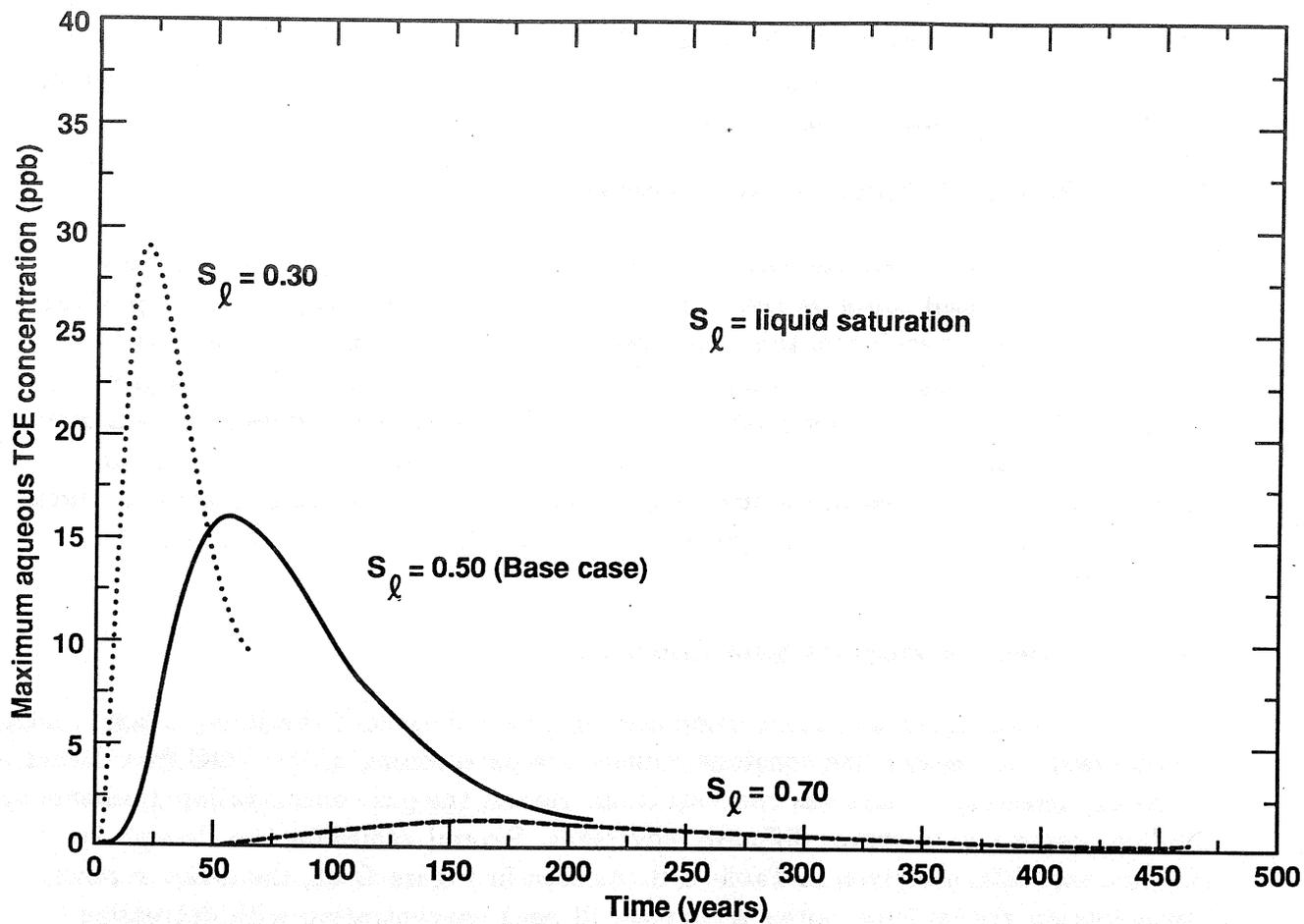


Figure G-19. Peak aqueous TCE concentration as a function of time showing the effect of varying liquid saturation for the Building 518 Area.

#### G-5.1.4. Effect of Porosity

Figure G-20 shows the sensitivity of the maximum TCE aqueous ground water concentration for porosities of 25, 30, and 35%. As shown in Table G-3, porosity for LLNL sediments ranges from 25 to 31%. The variation in peak concentration over this range is relatively small, from 15 to 18 ppb.

#### G-5.1.5. Effect of Distribution Coefficient

Figure G-21 shows the effect of varying the distribution coefficient in both the vadose and saturated zones on the maximum aqueous concentration at the top of the water table. For convenience, this was done by varying the equivalent saturated retardation factor,  $R_{sat} = 1 + \rho_B K_d / \phi$  at values of 5.0, 6.0, and 7.0. The range of  $R_{sat}$  (Table G-3) is from 4.9 to 5.9, except for the sandy gravel, which does not occur at the Building 518 site (Figure G-6). As explained earlier, increasing the solid sorption (increasing  $K_d$ ) decreases the aqueous concentration. It also increases the retardation factor, causing the peak arrival time to be later, which further reduces the peak concentration.

#### G-5.1.6. Effect of Henry's Law Constant

The peak aqueous concentration arrival time is delayed if the Henry's law constant is decreased. Decreasing the constant reduces the partitioning of the VOC from liquid to gas and, therefore, reduces gas concentration. Hence, the gas concentration gradients are smaller, giving rise to slower diffusive movement. Several values for the Henry's law constant for TCE are given in Table G-6. As seen in Figure G-22, the delay in peak concentration arrival time causes a decrease in peak concentration with decreasing Henry's law constant. We have used a value of 0.39 for TCE in the base case, averaging the values after eliminating the low value of 0.236.

In Figure G-23 we have replaced the Henry's law constant for TCE with that of the VOCs listed in Table G-7 to compare the different transport properties of various VOCs through gaseous diffusion. All the other parameters, including  $K_d$ , were kept at the base case values; no attempt was made to vary  $K_d$  based on the different sorptive properties of the VOC. All of the VOCs except for PCE have peak concentrations lower than that for TCE because their lower Henry's constant implies less partitioning into the vapor phase and, consequently, slower vapor diffusion.

#### G-5.1.7. Effect of Degradation

The effect of biological or chemical degradation characterized by an exponential decay was discussed in Section G-3.2.2. Estimates of the decay can be obtained by multiplying the no-degradation solution by a factor  $2^{(-t/T)}$  where  $T$  is the VOC degradation half-life. Figure G-24 shows predicted TCE concentrations with time using degradation half-lives of 5, 10, 25, and 50 y. A no-degradation case is also included for

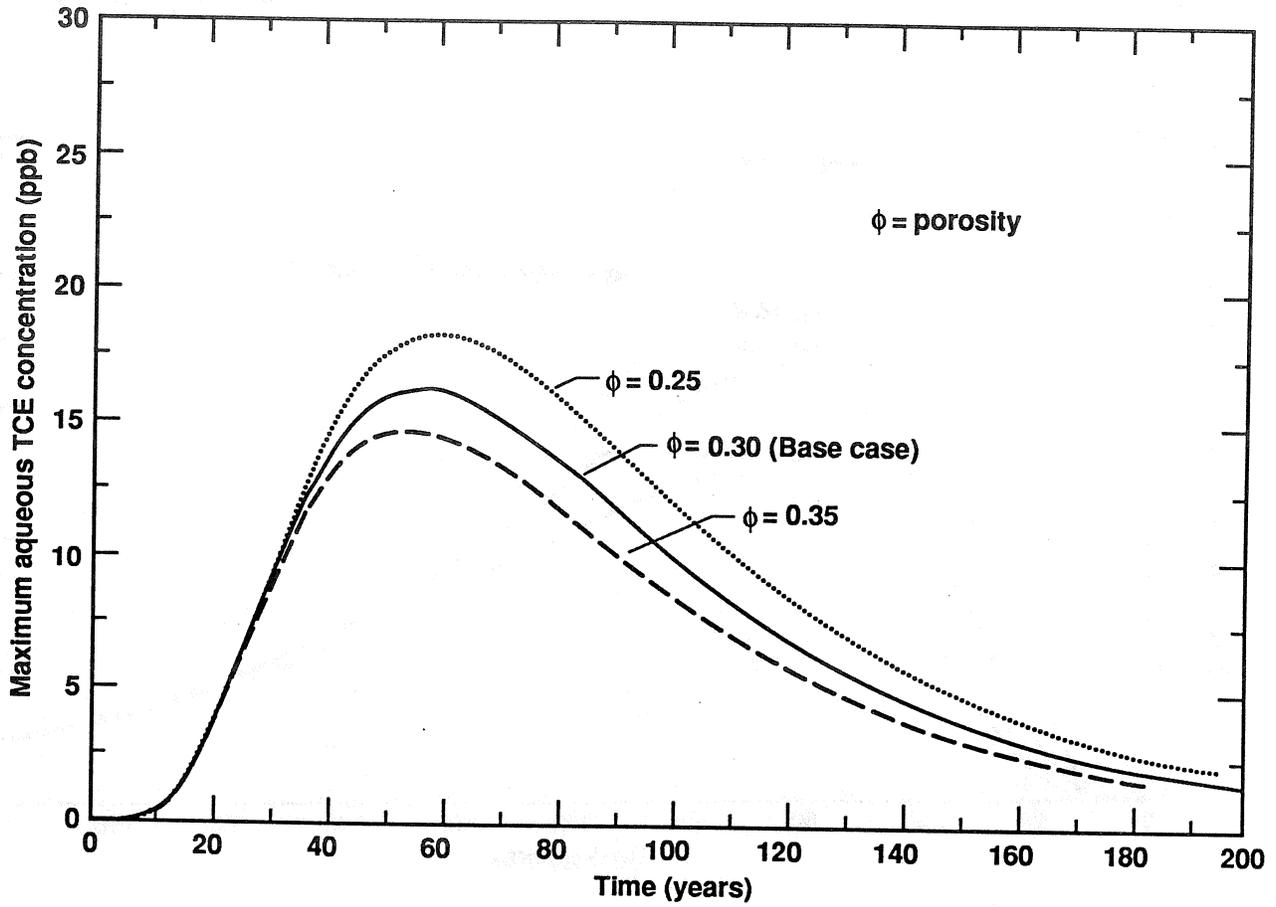


Figure G-20. Peak aqueous TCE concentration as a function of time showing the effect of varying porosity for the Building 518 Area.

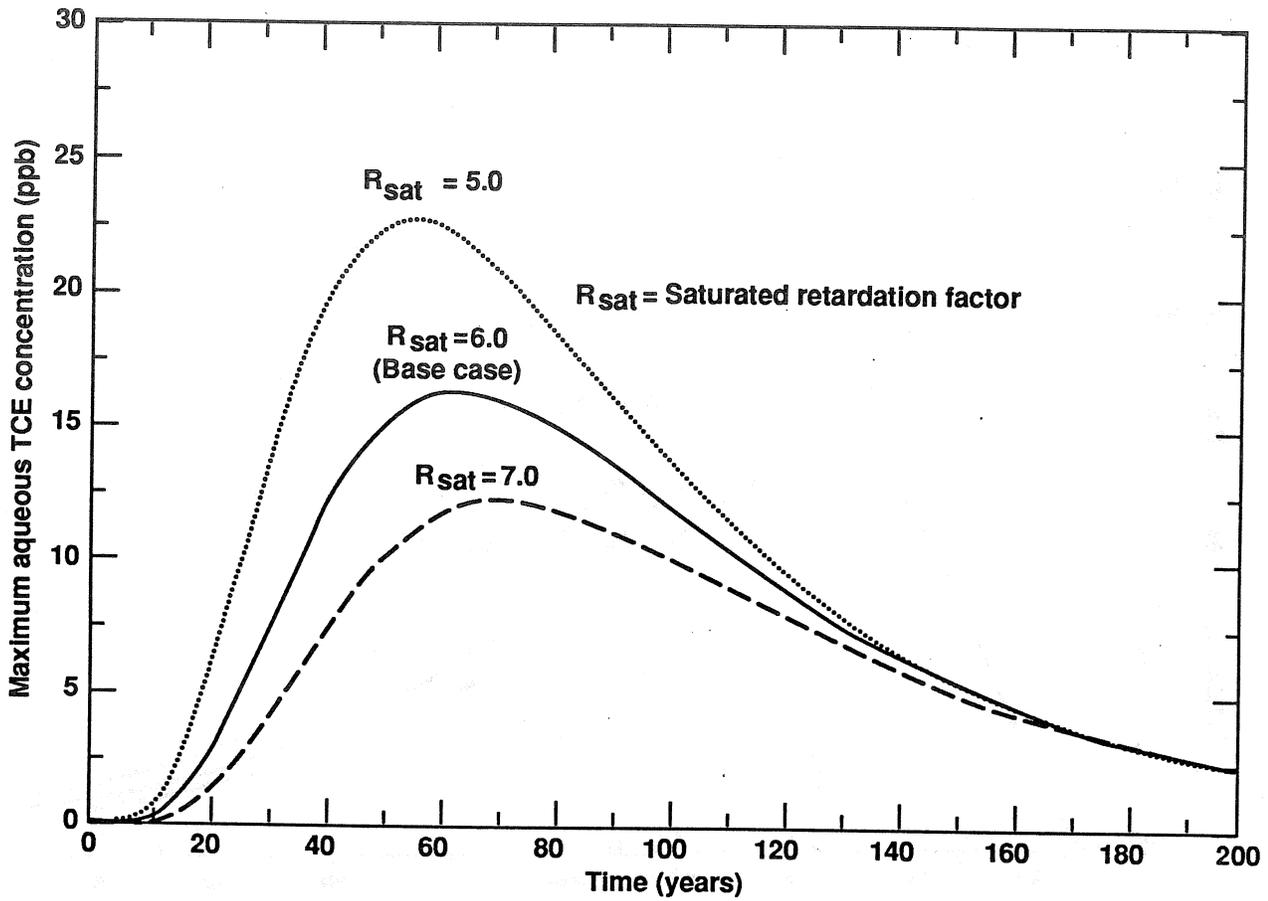


Figure G-21. Peak aqueous TCE concentration as a function of time showing the effect of varying retardation factor for the Building 518 Area.

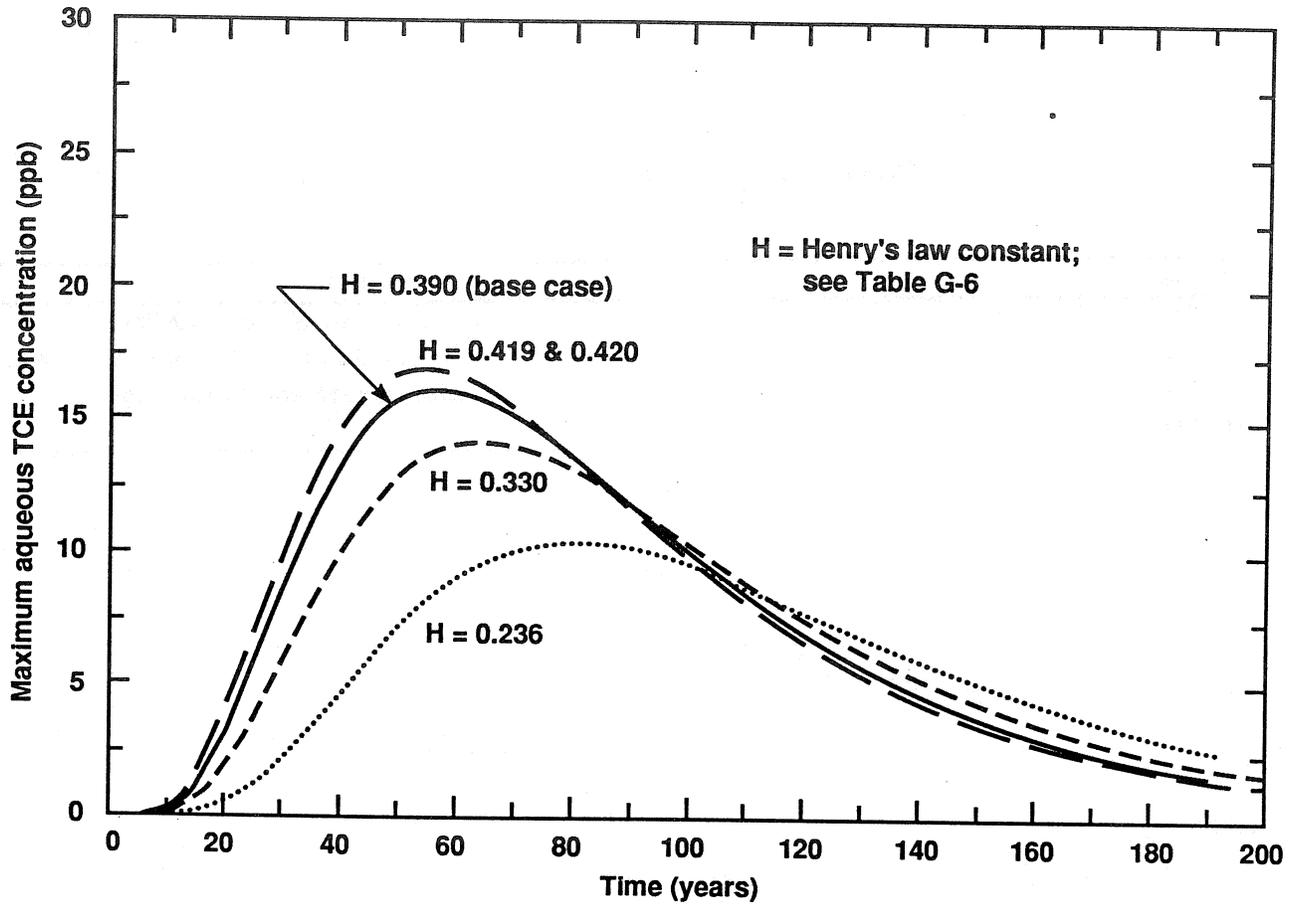


Figure G-22. Peak aqueous TCE concentration as a function of time showing the effect of varying Henry's law constant for the Building 518 Area.

Table G-6. Henry's law constant for TCE.

Value	Reference
0.236	Sleep and Sykes (1989)
0.330	Lappalla and Thompson (1984)
0.419	Garbarini and Lion (1985)
0.420	Thomas (1982)

Table G-7. Henry's law constant for various VOCs (Bishop *et al.*, 1989.)

VOC	Value
Tetrachloroethylene (PCE)	0.72
Trichloroethylene (TCE)	0.39
1,2-dichloroethylene (1,2-DCE)	0.38
1,2-dichloroethane (1,2-DCA)	0.23
Chloroform (CHCl <sub>3</sub> )	0.15

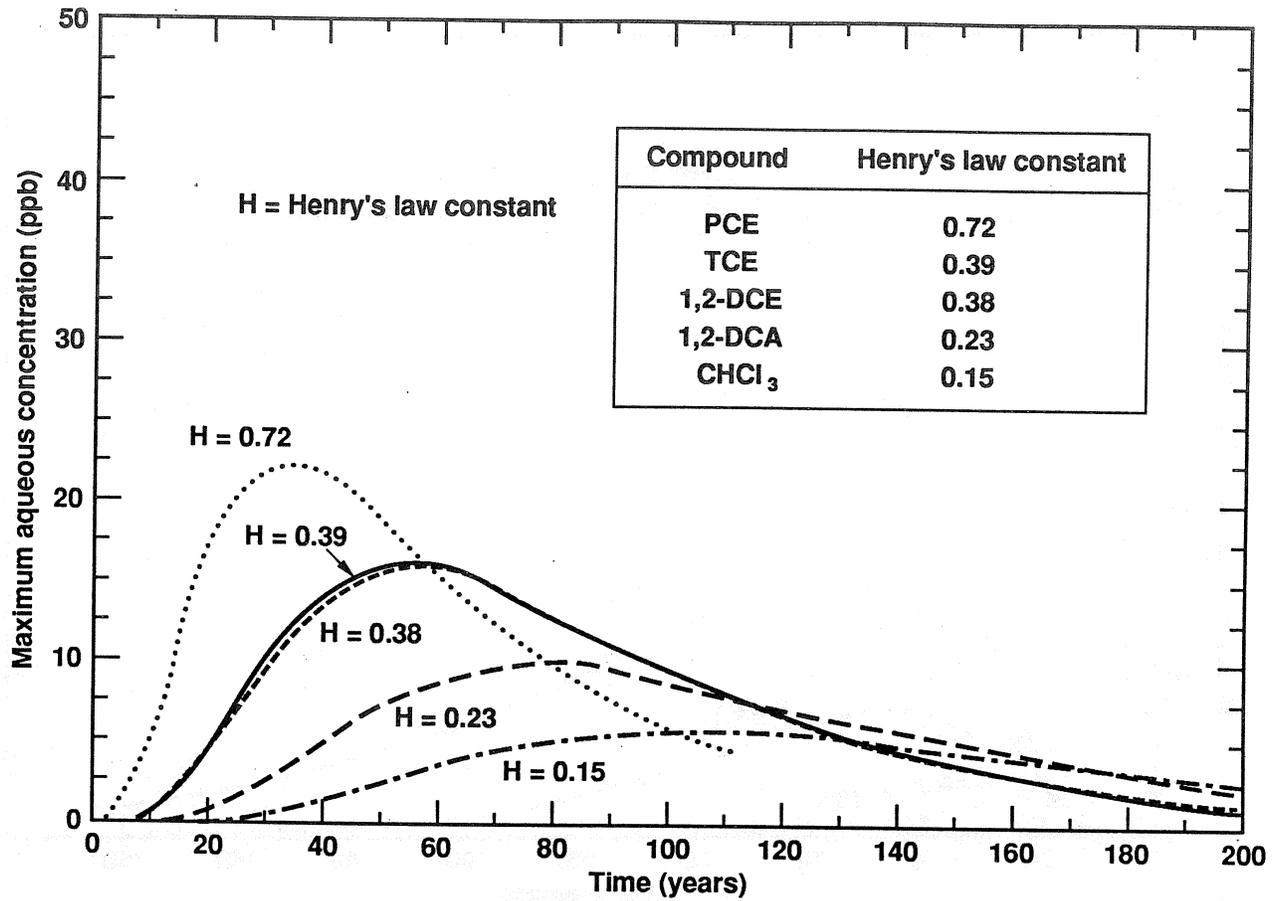


Figure G-23. Peak aqueous concentration as a function of time showing the effect of varying Henry's law constant for different VOCs.

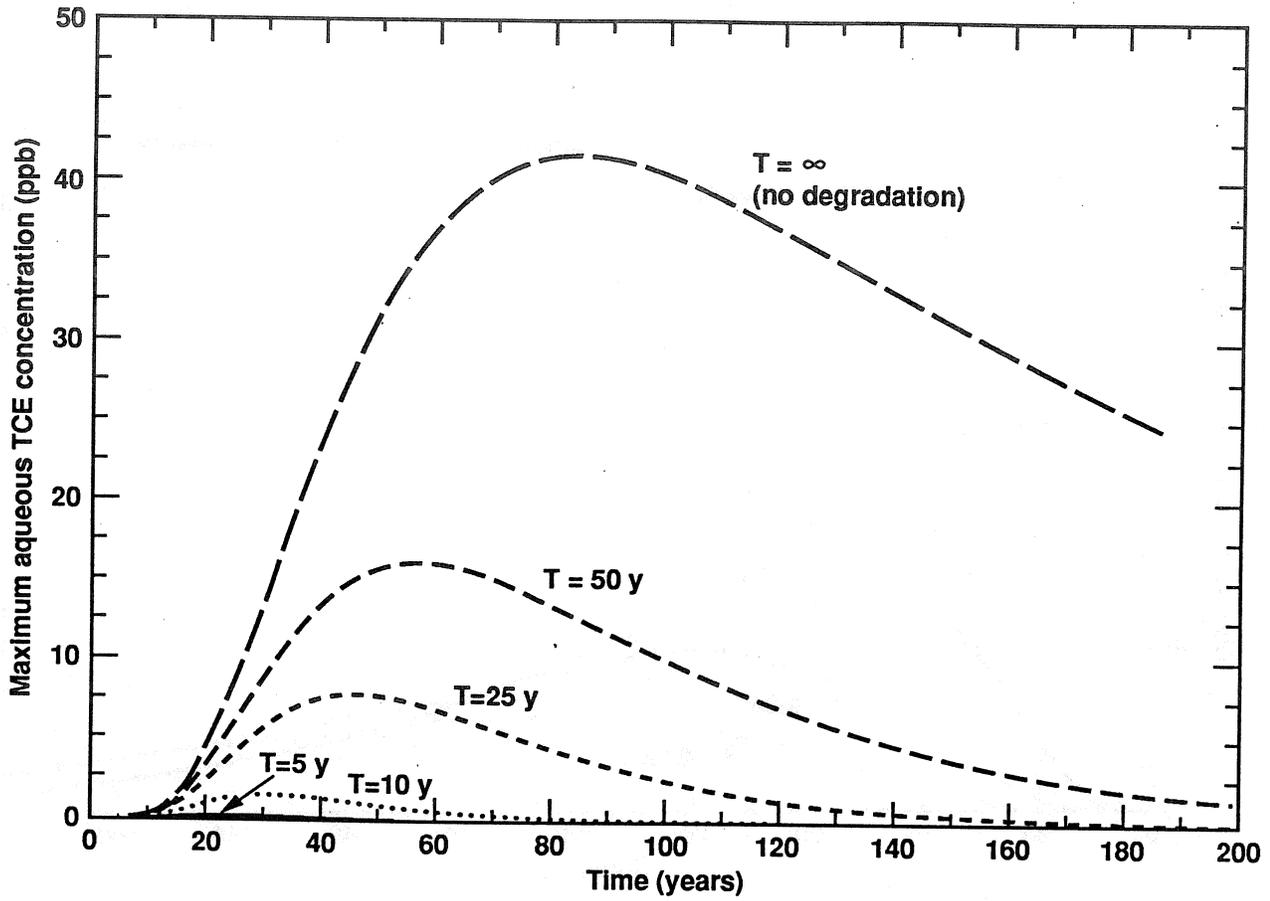


Figure G-24. Peak aqueous TCE concentration as a function of time showing the effect of varying degradation half-life for the Building 518 Area.

reference. This figure shows that a half-life of about 15 y or less will reduce the peak concentration to less than 5 ppb.

## G-5.2. ANISOTROPIC MEDIUM

Until this point, we have assumed isotropic properties and conditions that yield gaseous diffusion coefficients in the diffusion equation that are the same in both the vertical and horizontal directions. Possible causes of anisotropy are horizontal layers of higher or lower diffusivity due to variations in moisture or soil type. In this section, we assess anisotropy when the horizontal and vertical diffusivities  $D_h$  and  $D_v$ ,  $D_h \neq D_v$ , are uniform in space. The anisotropic diffusion equation can be transformed to the isotropic Eq. G-24 by scaling the horizontal coordinate by the factor  $\sqrt{D_h/D_v}$  (see Carslaw and Jaeger, 1959, p. 42). Therefore, we may use the same solution technique for the isotropic case. Rescaling will change the width  $w$  of the initial Gaussian distribution so that it no longer matches the observed width of the VOC distribution. Therefore, we pre-multiply  $w$  by the inverse of the scaling factor so that rescaling will have no net effect on  $w$ . In general, the net effect of increasing the anisotropy ratio  $D_h/D_v$  is to decrease the peak concentration at the water table because of enhanced lateral diffusion.

### G-5.2.1. Fine-Scale Layered Heterogeneity

Figure G-25 illustrates alternating layers of materials No. 1 and No. 2, each with different diffusivities. The ratio of the cumulative thickness of material No. 1 to the total thickness is given by  $\gamma$ . If the scale of the layering is small, we may assume that the gaseous phase concentration is approximately in local equilibrium from one layer to the next. Therefore, the horizontal diffusivity is similar to a "parallel" resistor using arithmetic weighted averaging,

$$D_h = \left[ \gamma(\phi S_g \tau)_1 + (1 - \gamma)(\phi S_g \tau)_2 \right] \frac{H}{R_c \phi_c} D_g, \quad (G-65)$$

and the vertical diffusivity is similar to a "series" resistor using harmonic averaging,

$$D_v = \left[ \frac{1}{\frac{\gamma}{(\phi S_g \tau)_1} + \frac{(1-\gamma)}{(\phi S_g \tau)_2}} \right] \frac{H}{R_c \phi_c} D_g. \quad (G-66)$$

Here,  $R_c$  and  $\phi_c$  are composite values given by

$$R_c = \gamma R_1 + (1 - \gamma) R_2, \quad (G-67)$$

where

$$R_i = (S_l)_i + H(S_g)_i + (\phi_B K_d / \phi)_i \quad (G-68)$$

and

$$\phi_c = \gamma \phi_1 + (1 - \gamma) \phi_2. \quad (G-69)$$

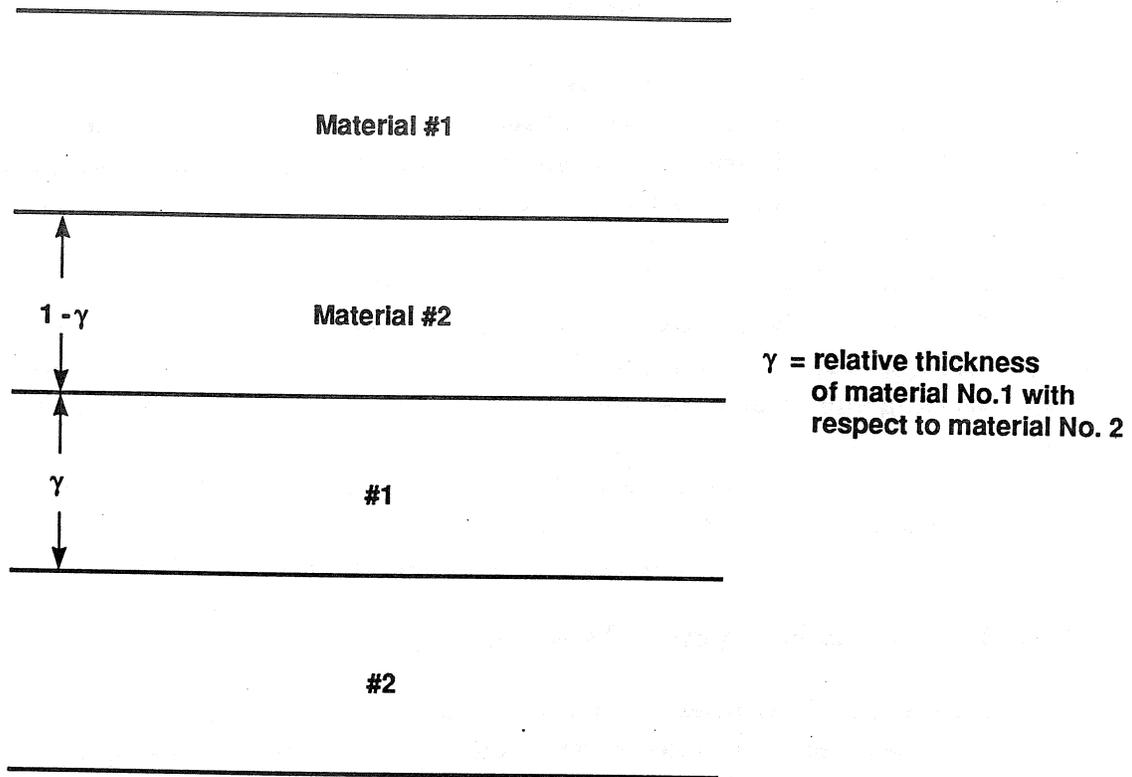


Figure G-25. Cross section of alternating layers which cause anisotropy.

Consider the effect of anisotropy due to alternating layers of base case silty sand (material No. 1) and sandy gravel (material No. 2). The silty sand has a liquid saturation of 0.50 and sorption parameter  $\phi K_d/\phi$  of 5.0. The sandy gravel has a lower liquid saturation of 0.05 and lower sorption parameter  $\phi K_d/\phi$  equal to 3.6. The sandy gravel material will have a higher diffusivity, because its tortuosity factor  $\tau$  is increased by the smaller liquid saturation (larger gas pore space). Table G-8 shows the anisotropy ratio versus the proportion of silty sand material,  $\gamma$ . The anisotropy ratio is the largest when the layers have the same thickness, that is,  $\gamma = 0.5$ .

Figure G-26 shows that the peak concentration is reduced slightly from 17 to 14 ppb as the amount of gravel layers is increased to 50% due to higher lateral diffusive fluxes compared to vertical fluxes. As we increase the relative thickness of the gravel layers to 90%, the peak concentration increases again due to the decreased solid sorption responsible for the partitioning to the aqueous phase at the water table. The number and thickness of the gravel layers at the site is small, and the sensitivity analysis shows that their effect on the peak concentration is not significant when the gravel layers range from about 0 to 50%.

If, instead of coarser and dryer, material No. 2 is a layer of wetter clayey material with liquid saturation of 0.80, vertical diffusive fluxes across these layers will be slowed, and the time necessary to reach the ground water will be increased, providing time for degradation processes to reduce VOC concentrations. Table G-9 shows that the maximum anisotropy is, again, when relative thickness of the base case material is 50%. Figure G-27 shows that in the case where the relative thickness of the base case material is only 10%, the peak concentration is reduced from the base case peak aqueous concentration of 17 ppb to around 4 ppb. An even higher anisotropy can be obtained by alternating layers of relatively dry base case material (e.g., liquid saturation equal to 0.2) and relatively wet material (e.g., liquid saturation equal to 0.80). The peak aqueous concentration is reduced even farther, to concentrations less than 1 ppb. Field data from other areas at LLNL indicate that such contrasts in saturation are not very likely under the low infiltration conditions at LLNL.

### G-5.2.2. Large-Scale Layered Heterogeneities

The previous discussion assumed that the layers were sufficiently small for vapor equilibrium to exist, resulting in a composite retardation factor. However, if the layers are thick, this assumption is not true. The retardation in the gravelly layers under nonequilibrium is less than in the finer grained layers. A possible solution is to use arithmetic and harmonic averaging for the horizontal and vertical diffusivities, respectively. This approach is valid only for steady-state, not transient diffusion, but it will provide a rough idea of the possible effects. The anisotropy ratio is

$$\frac{D_h}{D_v} = \frac{\gamma(S_g\tau/R)_1 + (1-\gamma)(S_g\tau/R)_2}{1 / \left( \frac{\gamma}{(S_g\tau/R)_1} + \frac{(1-\gamma)}{(S_g\tau/R)_2} \right)} \quad (\text{G-70})$$

Note that each layer has its own retardation factor. Again, the maximum anisotropy and therefore the maximum reduction in peak concentration is reached when the relative

Table G-8. Anisotropy resulting from thin gravel layers.

Relative thickness of of gravel layers %	$D_h/D_v$	$D_v/D_{base-case}$
10	1.6	1.2
20	2.1	1.3
40	2.6	1.9
50	2.7	2.3
60	2.6	3.0
80	2.1	5.4
90	1.6	16.

Table G-9. Anisotropy resulting from thin, high-moisture layers.

Relative thickness of gravel layers %	$D_h/D_v$	$D_v/D_{base-case}$
10	2.7	0.3
20	4.1	0.2
40	5.6	0.1
50	5.8	0.09
60	5.6	0.07
80	4.1	0.06
90	2.7	0.05

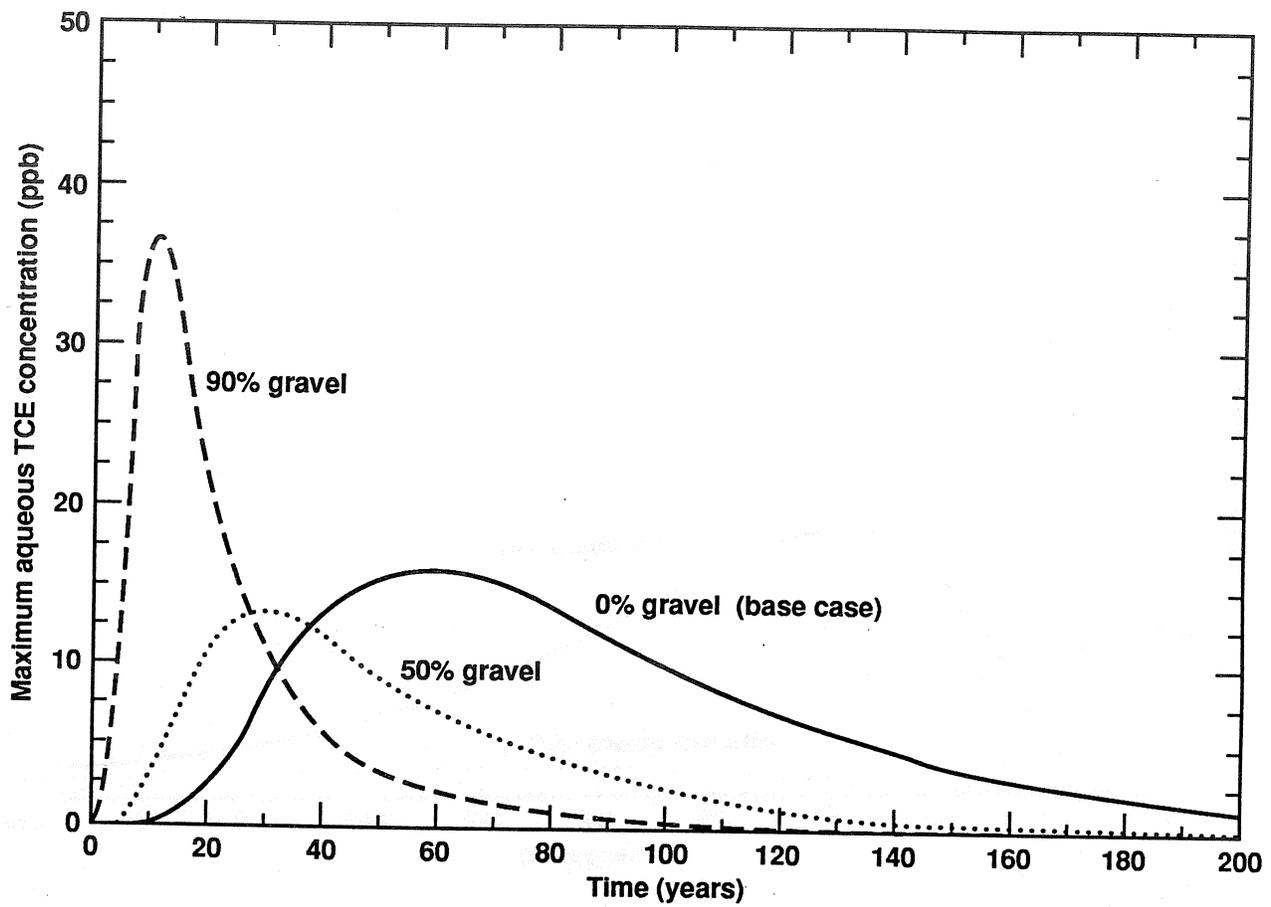


Figure G-26. Peak aqueous TCE concentration as a function of time showing the effect of anisotropy due to thin gravel layers for the Building 518 Area.

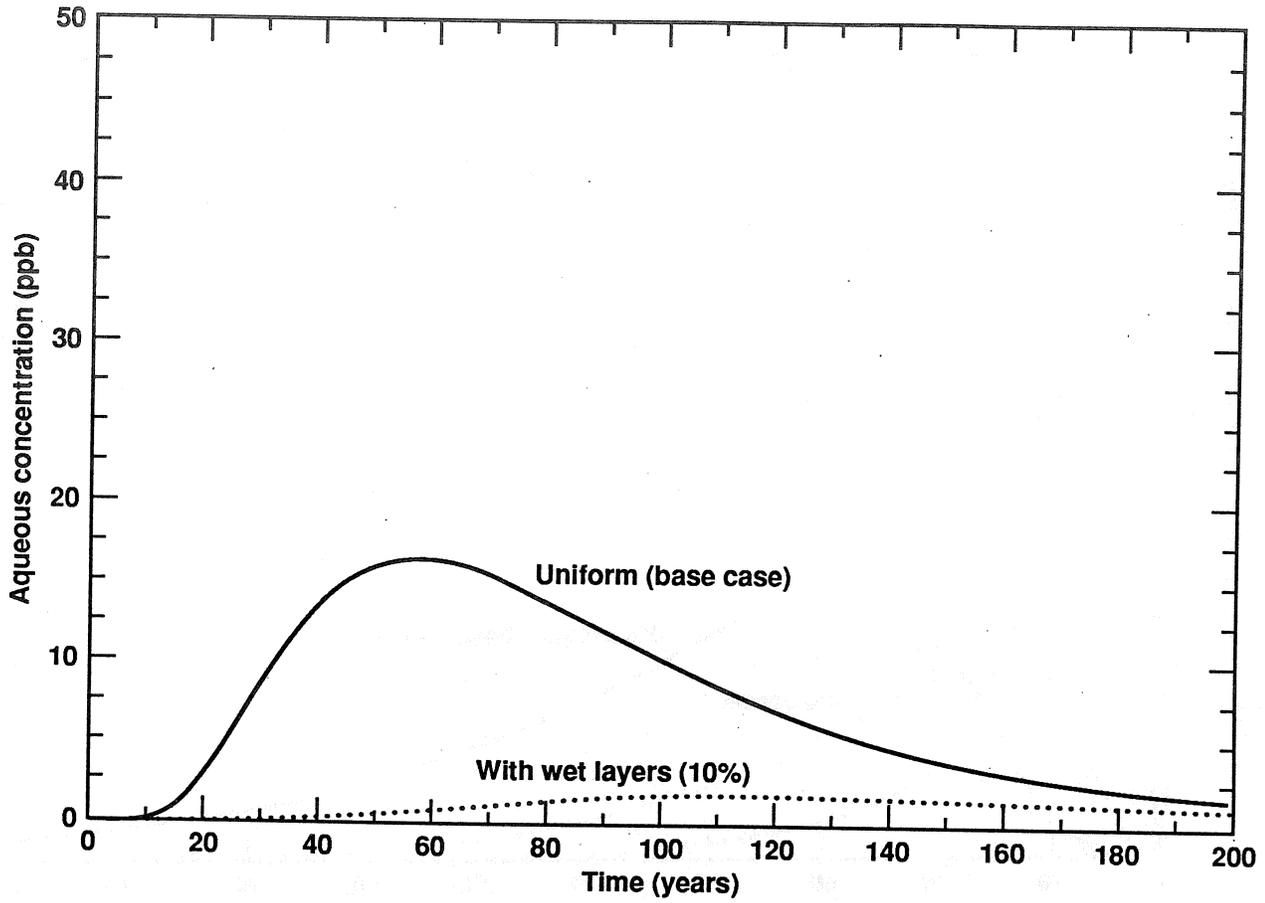


Figure G-27. Peak aqueous TCE concentration as a function of time showing the effect of anisotropy due to drier or wetter layers for the Building 518 Area.

thickness of the base case material compared to the high gravel material is 50%. Figure G-28 shows that the peak TCE concentration for this high-anisotropy case is 7 ppb.

## G-6. GROUND WATER TRANSPORT

As VOC vapor in the transition zone dissolves into the ground water, it is carried downgradient by the ground water and becomes progressively diluted through dispersive mixing. This VOC transport was computed using a steady-state dispersion model that includes first-order decay due to degradation. If the ground water flow is in the positive  $x$  direction, the concentration  $C(x, y, z, t)$  in the ground water is given by the equation

$$K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + K_z \frac{\partial^2 C}{\partial z^2} = v \frac{\partial C}{\partial x} + \lambda C, \quad (\text{G-71})$$

where  $K_x$ ,  $K_y$ , and  $K_z$  are the longitudinal, lateral, and vertical dispersion coefficients, respectively,  $v$  is the pore water velocity, and  $\lambda$  is the decay constant, which is related to the half-life by Eq. G-37. This steady-state model neglects the finite time necessary for the VOC to spread out and attain its ultimate steady concentration field.

The lateral extent of the TCE concentration at the top of the transition zone as predicted by the vadose zone modeling is shown in Figure G-13. The concentrations are fairly uniform up to a distance of about 10 m from the centerline of the release. Moreover, the concentrations change relatively slowly in time. The TCE source was, therefore, idealized as a "disk" of radius 10 m lying above the transition zone with constant concentration equal to 17 ppb. The boundary condition at the source "disk" is modeled by equating the vertical dispersion flux to the sum of flux across the transition zone, diffusive flux, infiltration flux, and flux due to water table fluctuations:

$$-\frac{(D_{liq} + |v_{sat}|A_v)}{R_{sat}} \frac{\partial C_{sat}}{\partial z} = \frac{D_{TZ}}{R_{TZ}L_{TZ}} (C_{vadose} - C_{sat}) + \frac{q_{infil}}{R_{TZ}} C_{vadose} + v_{WT}\phi C_{vadose}, \quad (\text{G-72})$$

where

- $z$  = vertical coordinate,
- $sat$  = subscript referring to saturated zone,
- $vadose$  = subscript referring to vadose zone,
- $TZ$  = subscript referring to a property averaged over the transition zone,
- $C$  = aqueous concentration,
- $D$  = non-retarded apparent diffusion coefficient,
- $D_{liq}$  = apparent aqueous diffusion coefficient in saturated zone,
- $v_{aq}$  = saturated zone flow velocity,
- $A_v$  = saturated zone vertical dispersivity,
- $R$  = retardation factor (for liquid phase concentration),
- $q_{infil}$  = volumetric infiltration flux through transition zone,

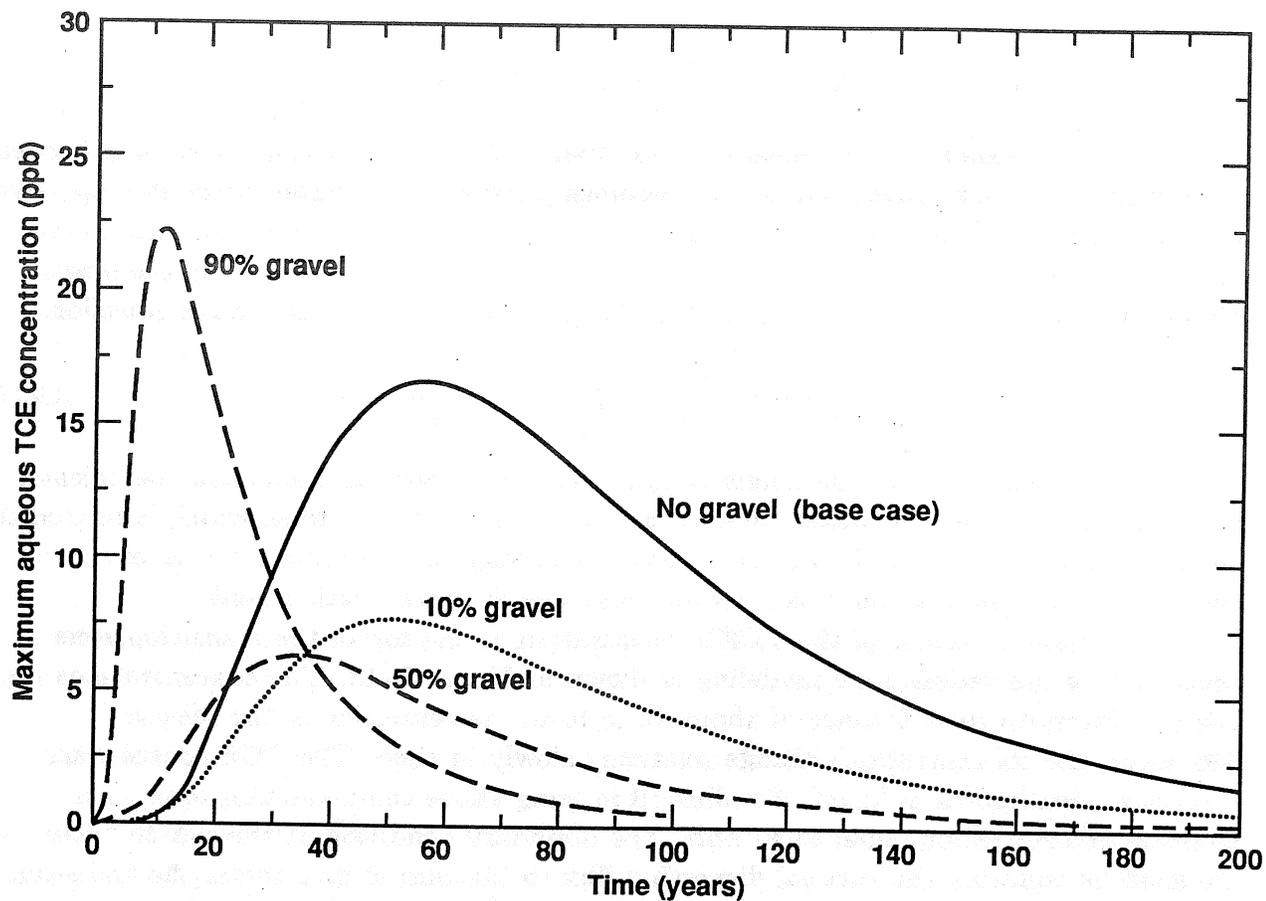


Figure G-28. Peak aqueous TCE concentration as a function of time showing the effect of anisotropy due to thick gravelly layers for the Building 518 Area.

$L_{TZ}$  = thickness of transition zone,  
 $\phi$  = porosity,  
 $v_{WT}$  = velocity of water table fluctuation.

The boundary condition can be written in the form

$$\frac{\partial C_{sat}}{\partial z} = AC_{sat} + BC_{vadose}, \quad (G-73)$$

$$r < r_0, \quad z = 0, \quad (G-74)$$

where  $r_0$  is the radius of the source concentration "disk," and  $A$  and  $B$  are constants. The term for the advective flux due to infiltration was found to have negligible effect, at least for Darcy fluxes up to 4 in./y. Hence, at the low fluxes expected in the study areas discussed above, diffusion across the transition zone dominates over infiltration. The diffusion coefficient  $D_{TZ}$  is computed by using Eq. G-50.

### G-6.1. SOLUTION OF TRANSPORT EQUATIONS

Transport from the lower boundary of the vadose zone and through the transition zone is modeled by the boundary condition described by Eq. G-73. If the ground water flow is in the positive  $x$  direction, the steady-state equation for dispersion in the ground water is given by Eq. G-71. By making the change of variables

$$x \rightarrow x/\sqrt{r_0 K_x/v}, \quad y \rightarrow y/\sqrt{r_0 K_y/v}, \quad z \rightarrow z/\sqrt{r_0 K_z/v}, \quad (G-75)$$

where  $r_0$  is the radius of the source disk we obtain

$$\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} = \alpha \frac{\partial C}{\partial x} + \beta C, \quad (G-76)$$

where  $\alpha = \sqrt{r_0 v/K_x}$  and  $\beta = r_0 \lambda/v$ . Note that when the change of variables is made, the source is transformed from a circular disk to an ellipse. The solution for a point source is, in the new variables,

$$U(x, y, z) = \frac{1}{r} \exp\left(-\frac{\alpha}{2}z\right) \exp\left(-r\sqrt{\frac{\alpha^2}{4} + \beta}\right), \quad (G-77)$$

where  $r$  is defined as  $r^2 = x^2 + y^2 + z^2$ . To solve the problem with an elliptical source several point sources are distributed on the ellipse and superimposed:

$$C(x, y, z) = \sum_n f_n U(x - x_n, y - y_n, z - z_n), \quad (G-78)$$

where the coefficients  $f_n$  are to be determined so as to minimize the least square of the residual to the boundary condition

$$E = \sum_n \left(\frac{\partial C}{\partial z} - AC - BC_v\right)^2 \quad (G-79)$$

at selected points  $(x'_n, y'_n, z'_n)$  on the ellipse. To satisfy the no-flow boundary conditions at the top and bottom of the saturated zone (except at the ellipse, which is a source), additional point source solutions are added that are centered about image points. The coefficients  $f_n$  are found numerically using the QR factorization algorithm (Dahlquist and Bjorck, 1974).

## G-6.2. CALCULATIONS

The analytical method described in the preceding subsection was used to compute relative concentrations for TCE with respect to the source "disk." To distinguish these cases from those in the vadose zone, they are referred to as case SZ-I (the base case), case SZ-II, and case SZ-III (see Table G-10). Table values for the longitudinal and lateral dispersivities are consistent with those estimated by Tompson (1990). Estimates of vertical dispersivity are not available at this time, so we chose to use a value of 5 m, which is on the same order as the lateral dispersivity. A half-life of 50 y is used for degradation in the saturated zone (Thorpe *et al.*, 1990). The ground water velocity for the base case is 1 m/y (Nichols, 1990). The Building 518 and 511 Areas are underlain by low conductivity sediments resulting in relatively low ground water velocities compared to the rest of LLNL. The effect of ground water table fluctuation was neglected in our calculations.

Figure G-29 is a plan view of the contours on the horizontal plane of the water table showing the reduction in TCE concentration relative to the source concentration. Ground water flow is from right to left. The relative concentration decreases downgradient from the source due to hydrodynamic dispersion. Figure G-30 is a cross section of the saturated zone passing through the center of the VOC volume in the direction of flow. Recall that a maximum concentration of 17 ppb was predicted at the water table for the base case. A relative TCE concentration of less than 0.3 would be required to reduce concentrations to less than the 5 ppb MCL. This condition is met roughly 35 m downgradient from the centerline of the vadose zone TCE mass. Therefore, this analysis indicates that concentrations above regulatory limits are restricted to a small area directly beneath the current TCE distribution in the vadose zone.

Figure G-31 shows the change in relative TCE concentrations for case SZ-II in Table G-10 when ground water velocity increased to 10 m/y. The relative concentration 0.3 corresponding to a TCE concentration of 5 ppb is reached at around 10 m from the centerline of the vadose zone TCE mass. Figure G-32, shows the contours for case SZ-III in Table G-10, with all the dispersivities decreased by one-tenth. The 5-ppb TCE contour is reached at around 30 m from the centerline of the vadose zone TCE mass. The relative insensitivity of the 5-ppb contour to ground water velocity and dispersivity is explained by the fact that the 5-ppb contour is sufficiently close to where VOC enters the ground water that hydrodynamic mixing has not had a chance to occur.

## G-7. CONCLUSIONS

A preliminary modeling analysis has been performed to investigate the impact on ground water of VOCs present in the vadose zone south of Building 518 and southeast of

Table G-10. Modeling parameters used in saturated zone cases.

Parameter	Case SZ-I (base case)	Case SZ-II (increase ground water velocity)	Case SZ-III (decrease dispersivity)
Flow velocity	1 m/y	10 m/y	1 m/y
$A_L$ longitudinal dispersivity	80 m	80 m	8.0 m
$A_L$ lateral dispersivity	8 m	8 m	0.8 m
$A_V$ vertical dispersivity	5 m	5 m	0.5 m
$T$ half-life	50 y	50 y	50 y

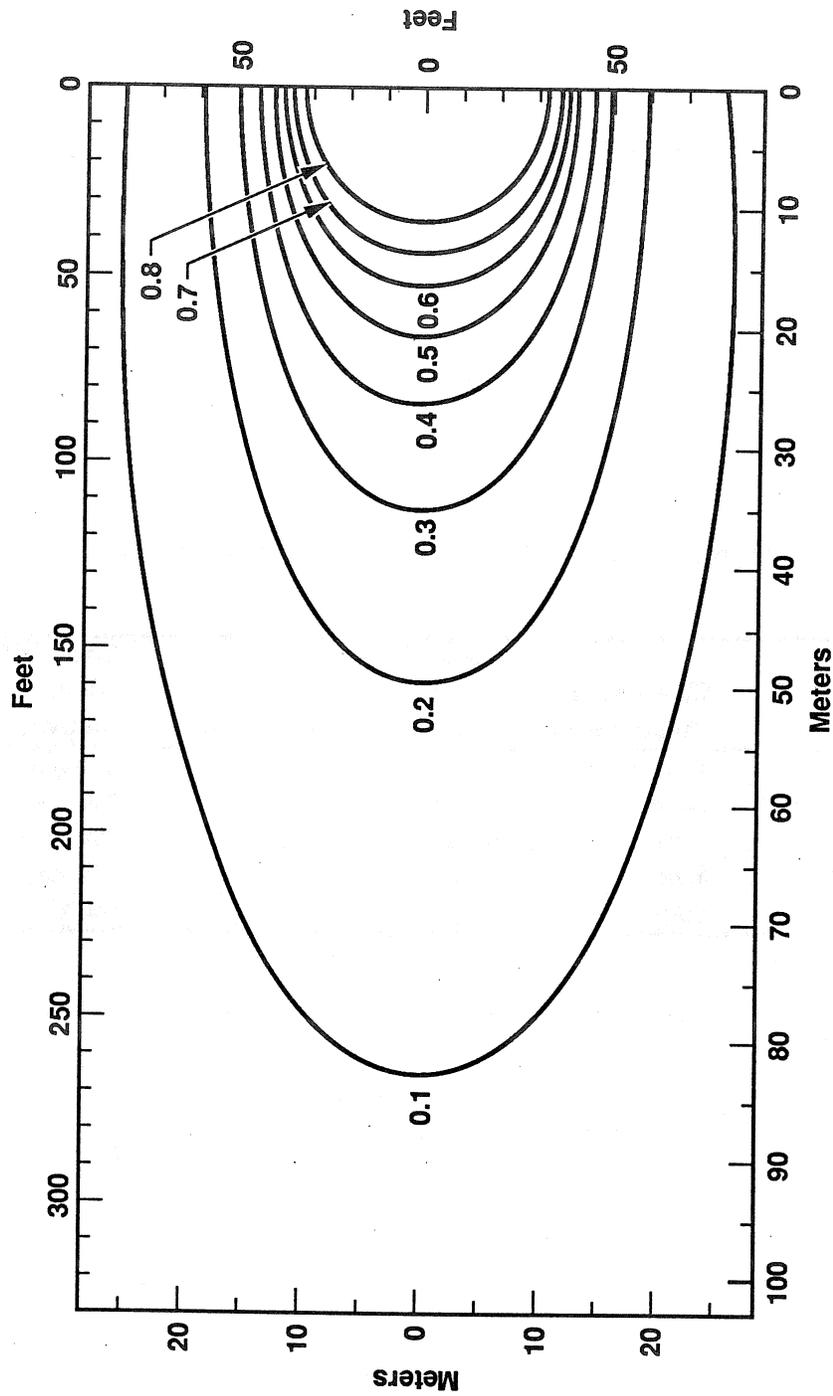


Figure G-29. Planview of relative TCE concentration with respect to source for Building 518 Area, ground water velocity 1m/y (case SZ-1).

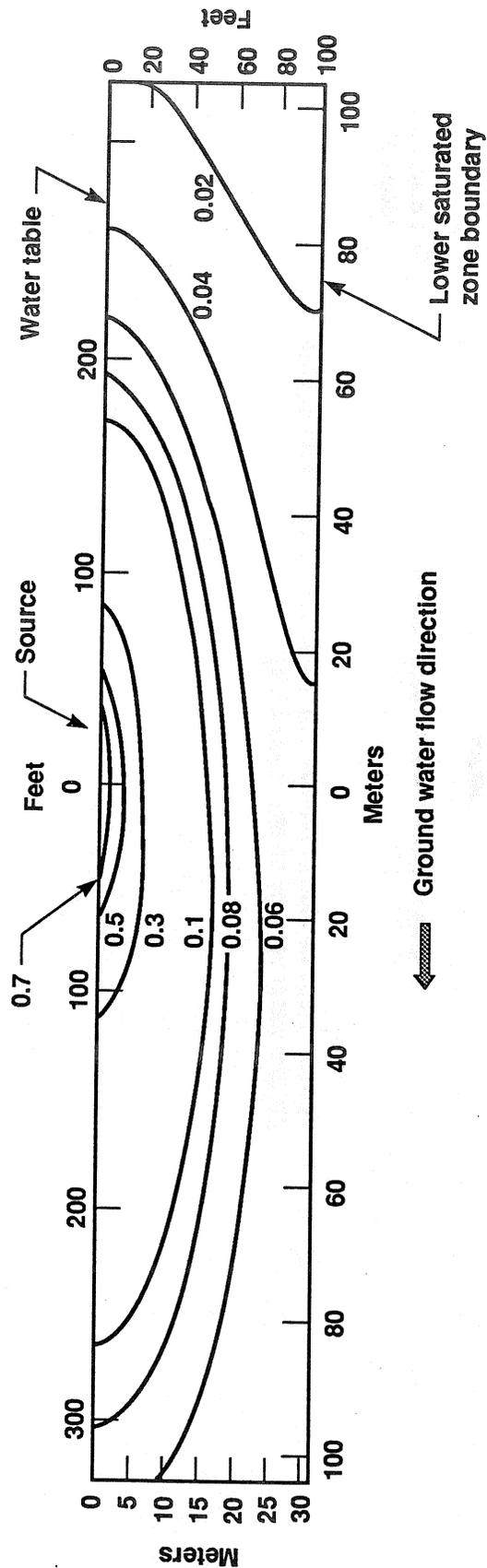


Figure G-30. Vertical cross section of relative TCE concentration for Building 518 Area, ground water velocity 1 m/y (case SZ-1).

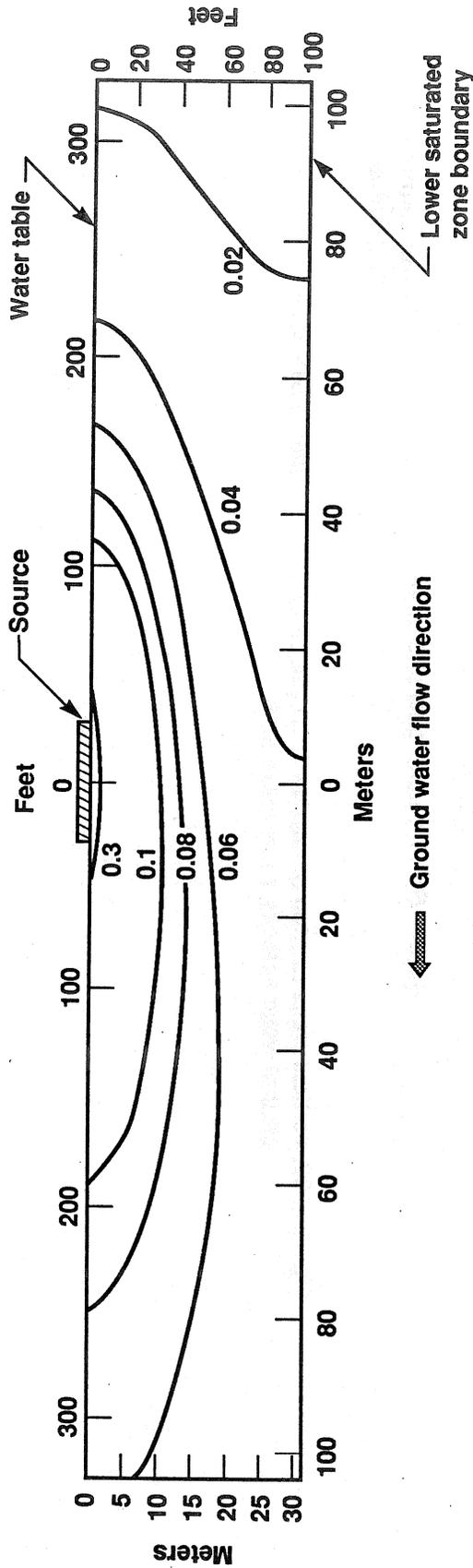


Figure G-31. Vertical cross section of relative TCE concentration for Building 518 Area, ground water velocity 10 m/y (case SZ-II).

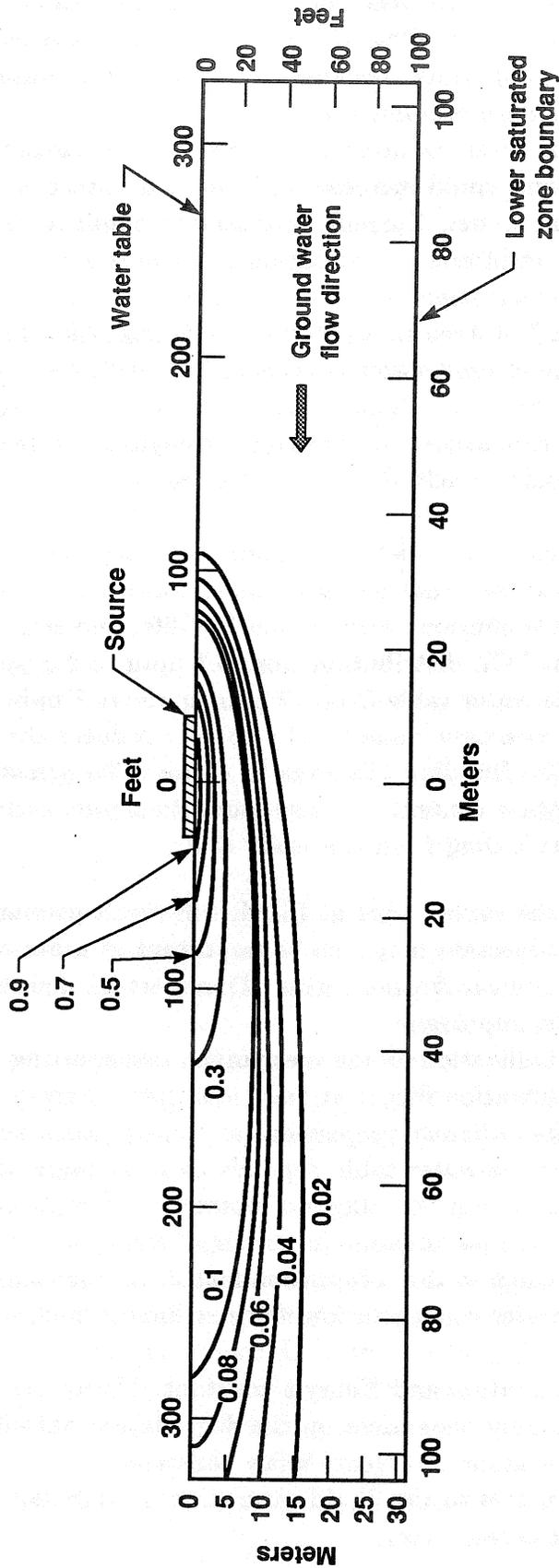


Figure G-32. Vertical cross section of relative TCE concentration for Building 518 Area, ground water velocity 1 m/y, dispersivities decreased from 80, 8, and 5 m to 8, 0.8, and 0.5 m respectively (case SZ-III).

Building 511. For this study, we focused on the observed soil concentrations of TCE in the Building 518 Area and 1,2-DCE in the Building 511 Area. The transport of VOCs in the vadose zone has only recently received study. Because of this, and the limitations of the available field data, our conclusions are preliminary.

We conclude that gaseous diffusion is the dominant transport mechanism for the two sites. Liquid advection, if important, could increase the peak concentration beyond that predicted by the gaseous diffusion model. Current data tend to confirm the relative unimportance of infiltration flux, but additional confirmation is being sought.

Our analysis predicts TCE concentration of 17 ppb at 55 y from now in the ground water underlying the Building 518 Area as a result of TCE migration in the vadose zone. The predicted increase in ground water concentration resulting from the 1,2-DCE distribution in the vadose zone at the Building 511 Area is 0.04 ppb at 75 y from the present. These predictions are sensitive to various hydrological parameters and uncertainties, but can be used as a guide to help determine the need to remediate the vadose zone at these sites.

A sensitivity study was performed on model parameters to identify key parameters and processes in the vadose zone that impact ground water. Critical vadose zone parameters are the VOC mass distribution, degradation half-life, and soil anisotropy. A decrease in peak spatial TCE distribution from 6.1 ppm to 2.5 ppm lowers the peak aqueous concentration at the water table from 17 ppb to about 7 ppb. Reducing the TCE half-life from the base case value of 50 y to 10 y reduces the peak TCE ground water concentration in the Building 518 Area to 4 ppb. The presence of thin sediment layers having high moisture content was also found to significantly reduce peak concentration. Other conclusions arising from the study are

1. The future migration of VOCs in the vadose zone at LLNL will result primarily from gaseous diffusion. Aqueous phase advection may also be important in areas of high recharge, such as beneath arroyos and catchment basins. Transport by density-driven, advective gas phase gradients is not important.
2. Gaseous diffusion dominates over infiltration as the mechanism transporting VOCs across the transition zone if the infiltration flux is at least less than 10 cm/y.
3. If there is no degradation and if the sediment properties are homogeneous and isotropic, the peak concentration at the water table depends most strongly on the initial VOC mass and distribution. Within the ranges of porosity and bulk soil density measured at LLNL, variations in these parameters do not significantly affect the ground water concentrations. A change in the retardation factor, on the other hand, can moderately affect the ground water concentration if the sediment material has a low retardation factor such as a sandy gravel. The peak concentration is relatively insensitive to variation in liquid saturation and Henry's constant. If degradation occurs, the peak concentration is highly dependent on the degradation half-life and becomes sensitive to the liquid saturation and Henry's law constant.
4. The peak arrival time is highly sensitive to the liquid saturation at high saturation. It is moderately sensitive to the retardation factor.

5. Anisotropy due to alternating layers of silty sand and sandy gravel does not significantly lower the peak concentrations as compared to the base case, but the presence of high moisture content layers can significantly reduce peak concentrations.
6. A nonrigorous calculation for alternating thick layers of silty sand and gravel layers reduced the peak TCE concentration by more than half for the Building 518 Area. Although there are no thick gravel layers in the the Building 518 Area, the effect of this type of anisotropy may be important at other sites.
7. Concentrations in the ground water fall rapidly with distance from the source area. For the Building 518 Area base case, TCE concentrations decrease to below 5 ppb at a distance of about 35 m downgradient of the current TCE distribution in the vadose zone.

The following field measurements will help evaluate and validate model results and assumptions.

1. Field monitoring programs to assess future subsurface VOC movement.
2. Field measurements of upward VOC flux at the ground surface to aid in model calibration.
3. Tensiometers and neutron probe measurements, together with numerical modeling studies, to refine the magnitude of infiltration flux at the LLNL site.
4. Tests to evaluate the importance of other processes, such as changes in barometric pressure.

**CERCLA  
Feasibility Study for the  
LLNL Livermore Site**

**Errata**

**October 1991**

**Technical Editors**

**W. F. Isherwood**

**C. H. Hall**

**M. D. Dresen\***

**Contributing Authors**

**A. J. Boegel**

**R. S. Lawson\***

**J. I. Daniels**

**P. F. McKereghan\***

**R. O. Devany\***

**E. M. Nichols\***

**M. D. Dresen\***

**J. J. Nitao**

**L. C. Hall**

**D. W. Rice**

**C. H. Hall**

**J. Scott\*\*\***

**W. F. Isherwood**

**R. K. Thorpe**

**J. L. Iovenitti\***

**B. C. Toler\*\***

**\*Weiss Associates, Inc., Emeryville, California**

**\*\*Science Applications International Corporation**

**\*\*\*Woodward-Clyde Consultants**

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# **CERCLA Feasibility Study for the LLNL Livermore Site: Errata**

The following pages contain information revised since issuance of the *CERCLA Feasibility Study for the Feasibility Study for the LLNL Livermore Site* in December 1990. Please use the information in this Errata in conjunction with the December 1990 Feasibility Study.

Many changes have been made to Tables 4-1 through 4-6 and 4-8 through 4-13 and Figures 4-1 through 4-3 in the text and Appendices D, E, and F, upon which the text tables and figures are based. Due to the number of changes, Appendices D, E, and F have been issued as errata in their entirety. Most of the changes in Tables 4-1 through 4-6 and 4-8 through 4-13 and Appendices D, E, and F were made to (1) correct the discount factor used in some of the analyses; (2) add the cost of well replacement, which often added to the cost of well reclamation; (3) change the cost of piping; and (4) make rounding consistent throughout the analysis.

None of the changes affected the relative cost of any of the technology options at any of the treatment facilities. In the long-term perspective, these changes have little effect on the estimate of the cost of remediating ground water at the LLNL Livermore site.

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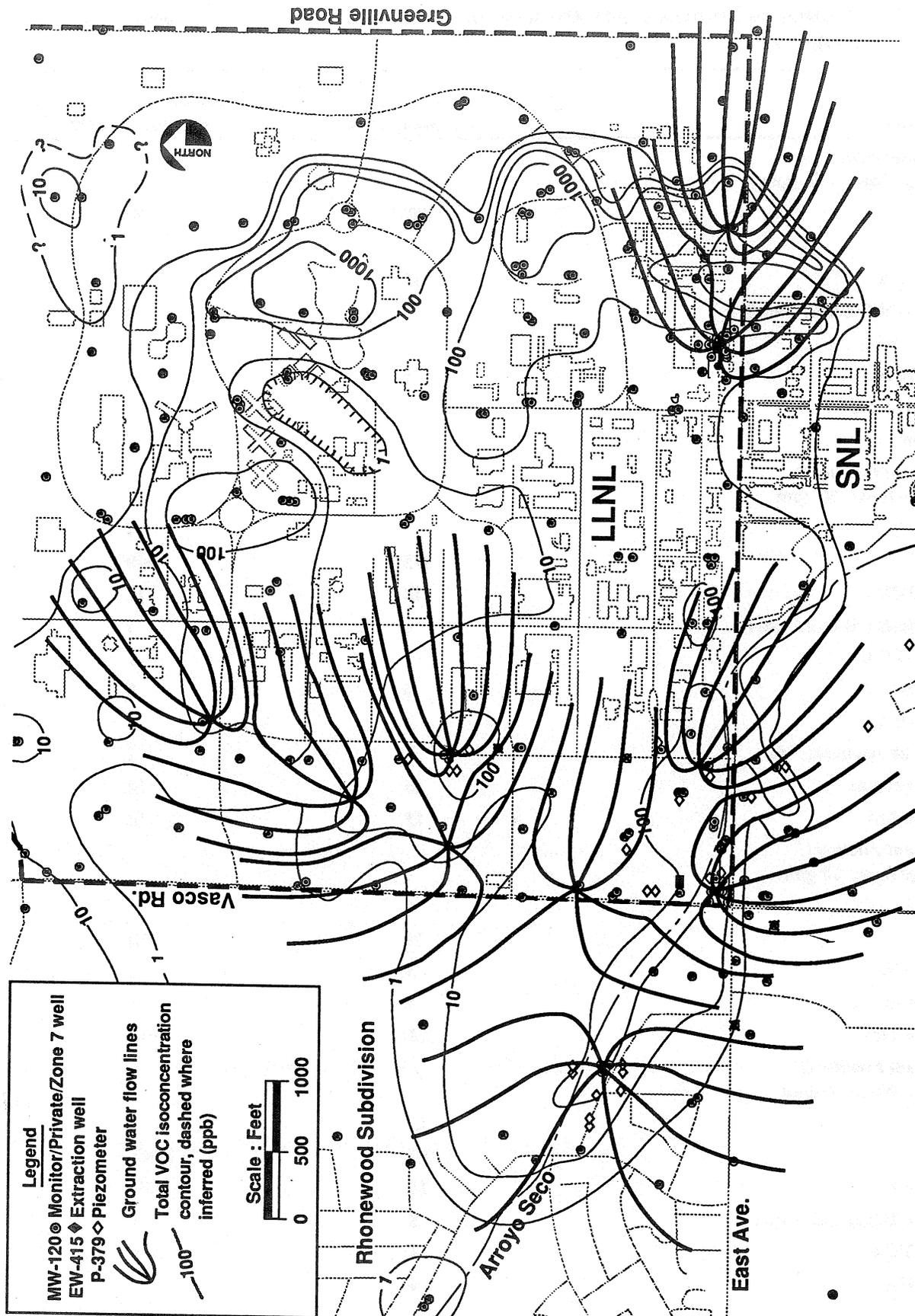


Figure 3-8. Capture plot for Extraction Alternative No. 2—Downgradient Plume Margin Control, with Southeast Corner Extraction.

Table 3-9. Estimated influent concentrations for seven postulated ground water treatment facilities.

Constituents	Concentration (ppb)	
	Maximum influent	Average influent
<i>Treatment Facility A</i>		
Average flow: 150 gpm		
PCE	350	280
TCE	9	7
1,1-DCE	15	12
1,2-DCE (cis and trans)	5	4
1,1,1-TCA	6	5
1,1-DCA	6	5
Chloroform	13	10
Freon 113	6	5
<i>Treatment Facility B</i>		
Average flow: 50 gpm		
PCE	50	40
TCE	375	300
1,1-DCE	13	10
1,2-DCE (cis and trans)	4	3
1,1,1-TCA	1	1
1,1-DCA	6	5
1,2-DCA	1	1
Carbon tetrachloride	3	2
Chloroform	13	10
Freon 113	13	10
<i>Treatment Facility C</i>		
Average flow: 20 gpm		
PCE	6	5
TCE	25	20
1,1-DCE	3	2
Chloroform	4	3
Freon 113	125	100
<i>Treatment Facility D</i>		
Average flow: 30 gpm		
PCE	13	10
TCE	1,250	1,000
1,1-DCE	21	17
1,2-DCE (cis and trans)	5	4
1,1,1-TCA	4	3
1,1-DCA	4	3

Table 3-9. (Continued)

Constituents	Concentration (ppb)	
	Maximum influent	Average influent
<i>Treatment Facility D (continued)</i>		
1,2-DCA	26	21
Carbon tetrachloride	38	30
Chloroform	162	130
Freon 113	4	3
Chromium	63	50
<i>Treatment Facility E</i>		
Average flow: 30 gpm		
PCE	313	250
TCE	3,500	2,800
1,1-DCE	44	35
1,2-DCE (cis and trans)	0	0
1,1,1-TCA	34	27
1,1-DCA	0	0
1,2-DCA	13	10
Carbon tetrachloride	13	10
Chloroform	125	100
Freon 113	13	10
<i>Treatment Facility F</i>		
Average flow: 30 gpm		
PCE	13	10
TCE	250	200
1,1-DCE	13	10
1,1,1-TCA	4	3
1,2-DCA	163	130
Carbon tetrachloride	13	10
Chloroform	25	20
Freon 113	13	10
Benzene	25,000	20,000
Toluene	38,000	30,000
Xylenes	19,000	15,000
Lead	38	30

Table 3-9. (Continued)

Constituents	Concentration (ppb)	
	Maximum influent	Average influent
<i>Treatment Facility G</i>		
Average flow: 50 gpm		
PCE	13	10
TCE	125	100
1,1-DCE	13	10
1,2-DCE (cis and trans)	1	0.5
1,1,1-TCA	25	20
Carbon tetrachloride	6	5
Chloroform	25	20
Freon 113	13	10
Constituents	Health conservative	Best estimate
<i>Downtown Livermore production wells</i>		
<i>point of distribution</i>		
Average flow: 470 gpm		
PCE	460	0.02
TCE	900	0.10
1,1-DCE	42	0.01
1,2-DCE (cis and trans)	4.2	0.001
1,1,1-TCA	4.2	0.001
1,1-DCA	8.4	0.002
1,2-DCA	8.4	0.002
Carbon tetrachloride	8.4	0.002
Chloroform	120	0.20

Table 3-10. Summary of screening process, showing general process options.

General response action	Remediation technology type	Technology (process option)	Screening comments	
<b>GROUND WATER</b>				
<i>No action</i>	No action			
	Natural degradation, dispersion, adsorption	No action	Not acceptable to LLNL, DOE, and the regulatory agencies	
<i>Immediate action</i>				
Containment	Vertical barrier	Slurry wall	Not practical at LLNL	
		Grout curtain	Not practical at LLNL	
		Hydraulic barrier	Applicable in conjunction with treatment	
	Capping	Asphalt cover	Practical in conjunction with extraction	
Extraction	Pump	Electric pump	Applicable	
	Gravity	French drains	Not practical at LLNL	
	Excavation	Physical removal	Limited to shallow depths	
Treatment	<i>In situ</i> treatment	Bioremediation	Enhanced bioremediation Not applicable to VOCs Applicable to FHCs	
		Surface treatment		
		Physical transfer:		
		Volatilization	Air stripping	Applicable
		Sorption	GAC (liquid or vapor)	Applicable
			Ultrafiltration	Applicable to nondissolved compounds as small as 1 $\mu\text{m}$
		Chemical transformation	UV/oxidation	Applicable
			Precipitation	Applicable
			Ion exchange	Applicable
	Disposal	Surface	Recharge basin	Applicable
Retention pond			Applicable	
Surface water ways			Applicable	
Recharge wells			Applicable	
Infiltration galleries			Applicable but complex	
Subsurface				

Table 3-10. (Continued)

Effectiveness	Preliminary evaluation	
	Implementability	Cost <sup>a</sup>
<b>GROUND WATER</b>		
Does not immediately remediate ground water or vadose zone. Is probably protective of human health	Not acceptable to LLNL, DOE, and the regulatory agencies	None
Dropped	Dropped	Dropped
Dropped	Dropped	Dropped
Not evaluated separately	Not evaluated separately	Not evaluated separately
Prevents surface recharge	Implementable	Low
Effective	Implementable	(b)
Dropped	Dropped	Dropped
Effective	Dropped	Dropped
Not effective for VOCs	Dropped for VOCs	Dropped
Possibly effective for FHCs	Implementable for FHCs	Medium to high
Effective technology for VOCs and FHCs	Implementable; transfers compounds to air	Medium
Effective technology for VOCs, FHCs, lead, not for chromium	Implementable; transfers compounds to carbon	Medium to high
Effective for nondissolved compounds over 1 $\mu\text{m}$ in size	Dropped	Dropped
Effective technology for VOCs and FHCs	Implementable in combination with other technologies	Medium to high
Effective for chromium	Dropped	Dropped
Effective for chromium	Implementable; hazardous residue	Medium
Effective	Implementable; permit obtained	Medium
Effective	Implementable; permit obtained	High
Effective	Implementable; permit obtained	Low
Effective	Implementable; permit required	Medium
Dropped	Dropped	Dropped

Table 3-10. (Continued)

General response action	Remediation technology type	Technology (process option)	Screening comments
	Use	Landscape irrigation	Applicable
		Cooling towers, other process water	Applicable
<i>Deferred action</i>			
Monitor and treat if necessary at the point of use	Monitor (treat), administrative/institutional measures	Same as for immediate treatment, if necessary. Restrict well development	Technically feasible; least expensive remediation measure; fully protective of human health
<b>VADOSE ZONE</b>			
<i>No action</i>	No action		
	Natural degradation, dispersal, adsorption	No action	Acceptability dependent upon initial concentrations
<i>Immediate action</i>			
Containment	Horizontal barrier (capping)	Asphalt cover	Applicable
Extraction	Extraction technologies:		
	Excavation	Soil removal	Applicable if compounds not too deep
	Vent	Vacuum-induced vent	Applicable
		Steam-enhanced vent	Heat not required
		RF-enhanced vent	Heat not required
Treatment	Treatment technologies:		
	Extract and treat:		
	Physical transfer	GAC	Applicable
	Chemical transformation	Thermal oxidation	Applicable
		Catalytic oxidation	Applicable
	Biological	Bioreactor	Complex operations
	<i>In situ</i> treatment	Enhanced bioremediation	Difficult distribution of nutrients Experimental for VOCs
<i>Deferred action</i>			
Monitor and treat as necessary	Monitor migration and desorption processes	Treat compounds that desorb and leach to ground water	Technically feasible; compounds would be treated with other ground water contaminants

<sup>a</sup> Cost ranges defined in Tables 4-8 through 4-12; Appendix D provides actual cost breakdowns.

<sup>b</sup> Costs for various treatment options applied to individual treatment facilities provided in Tables 4-8 through 4-12.

Table 3-10. (Continued)

Effectiveness	Preliminary evaluation	
	Implementability	Cost <sup>a</sup>
Effective use of treated water	Implementable	Very low
Effective use of treated water	Implementable	Very low
Effective in protecting human health. Allows continued migration; natural degradation reduces volume and toxicity; does not reduce mobility; does not fully meet ARARs	Requires Zone 7 participation in administrative/institutional control measures. No new supply wells anticipated	Very, very low or none
<b>VADOSE ZONE</b>		
Does not immediately remediate vadose zone. Ground water remediation assures health protection	Implementable	None
Retards leaching from soil. Does not remediate soil. Can supplement other means	Implementable	Low
Effective in limited situations	Situation dependent	Dependent on situation
Effective	Implementable	Low to medium
Dropped	Dropped	Dropped
Dropped	Dropped	Dropped
Effective technology for VOCs and FHCs	Implementable; regeneration an issue	Medium
Effective technology for VOCs and FHCs	Implementable	Low
Effective technology for FHCs	Implementable	Low
Dropped	Dropped	Dropped
Dropped	Dropped	Dropped
Does not result in immediate remediation of vadose zone. Ground water remediation assures health protection	Implementable	Very, very low

**Table 4-1. Detailed evaluation of treatment options for VOCs or FHCs in ground water to concentrations below detection limits (Facilities A, B, C, E, and G).**

Assessment factor	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction with air stripping and GAC treatment (vapor phase)	Ground water extraction with UV/oxidation plus air stripping with GAC treatment (vapor phase)
Overall protection of human health and the environment	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water. No air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water or air emissions.
Compliance with ARARs	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.
Long-term effectiveness and permanence	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until concentrations in ground water meet ARARs. UV/oxidation destroys most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.
Reduction in toxicity, mobility, or volume	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. UV/oxidation destroys most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants.

Table 4-1. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction with air stripping and GAC treatment (vapor phase)	Ground water extraction with UV/oxidation plus air stripping with GAC treatment (vapor phase)
Short-term effectiveness	Minimal impact to community during construction. No impact to community during operation. Possible exposure of workers during construction of extraction wells, piping, and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. Use of GAC for control of air emissions from stripper will prevent impact on community. Possible exposure of workers during construction of extraction wells, piping, and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. Use of GAC for control of air emissions from stripper will prevent impact on community. Possible exposure of workers during construction of extraction wells, piping, and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.
Implementability	GAC is proven for treatment of VOCs and FHCs in ground water. Services and materials for system construction, operation and maintenance, and for disposal or regeneration of GAC are readily available, but may involve shipment offsite. Permit required for discharge of treated water.	Air stripping is proven for treatment of VOCs and FHCs in ground water. Stripping towers may have visual impacts. GAC is proven for control of air emissions. Services and materials for system construction, operation and maintenance, and for disposal or regeneration of GAC are readily available, but may involve shipment offsite. Permits required for discharge of treated water and operation of air stripper.	Onsite pilot testing has shown that combination of UV/oxidation and air stripping will achieve required treatment of ground water. GAC is proven for control of air emissions. Services and materials for system construction, operation, and maintenance. Minimizes waste requiring further treatment or disposal. Permits required for discharge of treated water or any air emissions.
Cost <sup>a</sup>	Ranges from \$2.2 million (medium) for TFG to \$6.3 million (very high) for TFA.	Ranges from \$1.6 million (low) for TFC and \$2.2 million (medium) for TFB.	Ranges from \$2.7 million (medium) for TFC to \$4.0 million (high) for TFA.
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> See Table 4-8 for definition of cost ranges, which include extraction and disposition.

Table 4-2. Detailed evaluation of treatment options for VOCs and chromium in ground water to concentrations below detection limits (Facility D).

Assessment factor	Ground water extraction with GAC treatment (liquid phase) plus ion-exchange treatment	Ground water extraction and air stripping (vapor phase) plus ion-exchange treatment	Ground water extraction with UV/oxidation and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment
Overall protection of human health and the environment	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water. No air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public from system operation and discharged treated water or air emissions.
Complies with ARARs	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.
Long-term effectiveness and permanence	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Ion-exchange residues properly disposed of. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Ion-exchange residues properly disposed of. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until concentrations in ground water meet ARARs. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Ion-exchange residues properly disposed of. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.

Table 4-2. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase) plus ion-exchange treatment	Ground water extraction and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment	Ground water extraction with UV/oxidation and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment
Reduction in toxicity, mobility, or volume	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants. Stabilized sludge containing metals from ion exchange may require disposal at a hazardous waste landfill.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants. Stabilized sludge containing metals from ion exchange may require disposal at a hazardous waste landfill.	Volume and toxicity of contaminants reduced by ground water by extraction and treatment. Mobility reduced by hydraulic control. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Stabilized sludge containing metals from ion exchange may require disposal at a hazardous waste landfill.
Short-term effectiveness	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y estimated to achieve remedial objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y estimated to achieve remedial objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of about 50 y estimated to achieve remedial objectives.
Implementability	GAC is proven technology for removal of VOCs and FHCs, and ion exchange is proven for removal of chromium from ground water. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Air stripping is proven technology for removal of VOCs and FHCs, and ion exchange is a proven technology for removal of chromium from ground water. Stripping towers may have visual impacts. GAC is proven for removal of VOCs and FHCs from air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permits required for discharge of treated water and operation of air stripper.	Onsite pilot testing for over a year has shown UV/oxidation in combination with air stripping with GAC treatment of VOCs as reliable for removal of VOCs from ground water. Ion exchange is proven technology for removal of chromium from ground water. Services, materials, and equipment are readily available. Minimizes waste requiring further treatment or disposal. Permits required for discharge of treated water or any air emissions.

Table 4-2. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase) plus ion-exchange treatment	Ground water extraction and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment	Ground water extraction with UV/oxidation and air stripping with GAC treatment (vapor phase) plus ion-exchange treatment
Cost <sup>a</sup>	\$4.5 million (high).	\$2.5 million (medium).	\$3.6 million (high).
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> See Table 4-9 for definition of cost ranges.

Table 4-3. Detailed evaluation of treatment options for VOCs, FHCs, and lead in ground water to concentrations below detection limits (Facility F).

Assessment factor	Ground water extraction and air stripping with GAC		<i>In situ</i> bioremediation	
	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	
Overall protection of human health and the environment	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative results in negligible risk to employees and the public from system operation and discharged treated water. No air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment from the constituents is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public from system operation and discharged treated water or air emissions.	Risk to human health and the environment is substantially reduced by this alternative. Alternative will result in negligible risk to employees and the public.
Compliance with ARARs	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	Effluent concentrations significantly below ARARs, and ARARs for ambient ground water achieved in minimum time.	No aboveground effluents. ARARs for FHCs in ambient ground water likely achievable, but not suitable for VOCs or lead.
Long-term effectiveness and permanence	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until ambient ground water meets ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Extraction and treatment systems operated until concentrations in ground water meet ARARs. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants. Lead treated with GAC regeneration. Sources of constituents have been removed and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources.	Experience limited on cleanup completeness. Microbes destroy FHCs, but may not be effective for VOCs or lead. Would have to be used in conjunction with other techniques. Bioorganisms are sensitive to the presence of inorganic compounds and other <i>in situ</i> conditions that are difficult to control.

Table 4-3. (Continued)

Assessment factor	Ground water extraction with air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)	Ground water extraction and air stripping with GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	<i>In situ</i> bioremediation
Reduction in toxicity, mobility, or volume	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants, except lead, which volatilizes as lead oxide.	Volume and toxicity of contaminants reduced by ground water extraction and treatment. Mobility reduced by hydraulic control. Thermal regeneration of spent GAC destroys or recycles contaminants, except lead, which volatilizes as lead oxide.	Volume and toxicity of contaminants reduced by ground water by extraction and treatment. Mobility reduced by hydraulic control. UV/oxidation will destroy most contaminants, and thermal regeneration of spent GAC destroys or recycles remaining contaminants, except lead, which volatilizes as lead oxide.	Volume and toxicity of FHCs reduced by biodegradation. Most FHCs would be destroyed, but not effective for VOCs or lead.
Short-term effectiveness	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment mitigates risk. Period of about 50 to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment mitigates risk. Period of about 50 to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment mitigates risk. Period of about 50 to over 90 y estimated to achieve remedial objectives, depending on extraction alternative.	No impact to employees or public during operation. Possible exposure of employees during installation of emplacement wells. Use of protective procedures, clothing, and equipment mitigates risk. Time estimates for remediation of FHCs not available; not feasible for VOCs or lead. No cleanup time estimate possible.

Table 4-3. (Continued)

Assessment factor	Ground water extraction with GAC treatment (liquid phase)	Ground water extraction and air stripping with GAC treatment (vapor phase) plus GAC treatment (liquid phase)	Ground water extraction with UV/oxidation plus GAC treatment (liquid phase)	<i>In situ</i> bioremediation
Implementability	GAC treatment of the liquid phase is proven for removal of VOCs, FHCs, and lead from ground water. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Air stripping is proven for removal of VOCs and FHCs, and GAC treatment of the liquid phase is proven for removal of lead from ground water. Stripping tower may have visual impacts. GAC is proven for removal of these constituents from an air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated water.	Onsite pilot testing for over a year has established UV/oxidation in combination with air stripping with GAC treatment of the vapor as reliable for removal of VOCs from ground water. GAC treatment of the liquid phase is proven for removal of lead from ground water. Services, materials, and equipment are readily available. Minimizes waste requiring further treatment or disposal. Permit required for discharge of treated water.	Implementable for localized FHC problem only. No practical way to disburse microbes and nutrients to entire VOC plume in the area. Services for bioremediation are readily available.
Cost <sup>a</sup>	\$9.1 million (extremely high).	\$5.3 million (high).	\$4.5 million (high).	Not comparable because only FHCs treated; costs for FHCs medium to high; estimated in the range of \$4 million for 10 y of treatment.
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> See Table 4-10 for definition of cost ranges, which include extraction and disposition.

Table 4-4. Detailed evaluation of treatment options for low concentrations of VOCs in ground water at point of distribution in downtown Livermore.

Assessment factor	GAC treatment	Air stripping	UV/oxidation
Overall protection of human health and the environment	Risk to human health and the environment reduced, if necessary, by treatment at point of use. Ground water quality reduced until MCLs met via natural degradation.	Risk to human health and the environment reduced, if necessary, by treatment at point of use. Ground water quality reduced until MCLs met via natural degradation.	Risk to human health and the environment reduced, if necessary, by treatment at point of use. Ground water quality reduced until MCLs met via natural degradation.
Compliance with ARARs	ARARs for ambient ground water met by natural degradation in an estimated 360 y. Nondegradation policy violated.	ARARs for ambient ground water met by natural degradation in an estimated 360 y. Nondegradation policy violated.	ARARs for ambient ground water met by natural degradation in an estimated 360 y. Nondegradation policy violated.
Long-term effectiveness and permanence	Treatment system will be operated until concentrations in supply well water meet or are lower than ARARs.	Treatment system will be operated until concentrations in supply well water meet or are lower than ARARs.	Treatment system will be operated until concentrations in supply well water meet or are lower than ARARs.
Reduction in toxicity, mobility, or volume	Toxicity and volume of compounds area reduced by natural degradation. If monitoring indicates treatment is required, toxicity and volume would be reduced by treatment at the point of withdrawal from the aquifer and the treated water. Thermal regeneration of spent GAC completely destroys or recycles contaminants.	Toxicity and volume of compounds area reduced by natural degradation. If monitoring indicates treatment is required, toxicity and volume would be reduced by treatment at the point of withdrawal from the aquifer and the treated water. Operation of treatment system transfers small volumes of contaminants from ground water to the atmosphere.	Toxicity and volume of compounds area reduced by natural degradation. If monitoring indicates treatment is required, toxicity and volume would be reduced by treatment at the point of withdrawal from the aquifer and the treated water. UV/oxidation results in complete destruction of contaminants.
Short-term effectiveness	This alternative does not result in immediate remediation of the ground water. Administrative/institutional measures have no anticipated adverse impact on the public. Treatment is assumed to require 10 to 50 y from time of commencement, estimated to be over 200 y from now.	This alternative does not result in immediate remediation of the ground water. Administrative/institutional measures have no anticipated adverse impact on the public. Treatment is assumed to require 10 to 50 y from time of commencement, estimated to be over 200 y from now.	This alternative does not result in immediate remediation of the ground water. Administrative/institutional measures have no anticipated adverse impact on the public. Treatment is assumed to require 10 to 50 y from time of commencement, estimated to be over 200 y from now.

Table 4-4. (Continued)

Assessment factor	GAC treatment	Air stripping	UV/oxidation
Implementability	GAC treatment of the liquid phase is proven for treatment of VOCs in ground water. Services, materials, and equipment for construction are readily available, but may involve transshipment of hazardous waste. Alternative may not be acceptable to regulatory agencies because it delays remediation an estimated 200 y.	Air stripping is a well-proven technology for treatment of VOCs in ground water. Stripping towers may have visual impacts. Services, materials, and equipment for construction are readily available. Alternative may not be acceptable to regulatory agencies because it delays remediation an estimated 200 y.	UV/oxidation alone should achieve required treatment of ground water. Services, materials, and equipment for construction are readily available. Alternative may not be acceptable to regulatory agencies because it delays remediation an estimated 200 y.
Cost <sup>a</sup>	\$0.3 million (very low).	\$0.03 million (extremely low).	\$0.18 million (very low).
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> Assumes treatment would take place at municipal water supply wells. See Table 4-11 for definition of cost ranges, which include extraction and disposition.

**Table 4-5. Summary costs for treatment options and remedial alternatives for ground water at the LLNL site (millions of 1990 dollars).**

Treatment facility	Remediation alternative	Capital costs	Present worth of 30-y operating and maintenance costs	Total present worth	Present worth of complete remediation system
Treatment Facility A	Extraction and disposal	0.34	0.14	0.48	
	GAC	0.73	5.06	5.79	6.27
	AS(L), GAC(V)	0.21	1.39	1.60	2.09
	UV(L), AS(L), GAC(V)	0.49	3.03	3.53	4.01
Treatment Facility B	Extraction and disposal	0.50	0.20	0.70	
	GAC	0.45	3.05	3.50	4.20
	AS(L), GAC(V)	0.18	1.36	1.55	2.24
	UV(L), AS(L), GAC(V)	0.37	1.96	2.33	3.02
Treatment Facility C	Extraction and disposal	0.39	0.15	0.51	
	GAC	0.45	1.80	2.25	2.76
	AS(L), GAC(V)	0.14	0.95	1.09	1.60
	UV(L), AS(L), GAC(V)	0.36	1.80	2.16	2.68
Treatment Facility D	Extraction and disposal	0.65	0.26	0.91	
	GAC, IX(Cr)	0.56	2.97	3.53	4.44
	AS(L), GAC(V), IX(Cr)	0.26	1.59	1.85	2.76
	UV(L), AS(L), GAC(V), IX(Cr)	0.47	2.22	2.69	3.60
Treatment Facility E	Extraction and disposal	0.44	0.17	0.61	
	GAC	0.45	2.69	3.14	3.75
	AS(L), GAC(V)	0.18	1.36	1.54	2.15
	UV(L), AS(L), GAC(V)	0.36	1.84	2.21	2.82
Treatment Facility F	Extraction and disposal	0.42	0.17	0.59	
	GAC	1.33	7.15	8.48	9.07
	AS(L), GAC(V), GAC(Pb)	0.36	4.39	4.75	5.33
	UV(L), GAC(Pb)	0.64	3.28	3.92	4.51

Table 4-5. (Continued)

Treatment facility	Remediation alternative	Capital costs	Present worth of 30-y operating and maintenance costs	Total present worth	Present worth of complete remediation system
Treatment Facility G	Extraction and disposal	0.43	0.17	0.60	
	GAC	0.25	1.34	1.58	2.18
	AS(L), GAC(V)	0.15	1.07	1.22	1.82
	UV(L), AS(L), GAC(V)	0.37	1.91	2.28	2.88
<i>Summary:</i>					
<i>Immediate action</i>					
Combination of all seven TFs; Extraction Alternative No. 1 <sup>a</sup>	Extraction and disposal	3.15	1.26	4.40	
	Lowest cost	1.77	10.74	12.50	16.90
	Highest cost	4.33	24.63	28.96	33.37
Combination of TFA, TFB, TFC, and TFF; Extraction Alternative No. 2 <sup>b</sup>	Extraction and disposal	1.65	0.77 <sup>b</sup>	2.41 <sup>b</sup>	
	Lowest cost	1.17	8.57 <sup>b</sup>	9.75 <sup>b</sup>	12.14 <sup>b</sup>
	Highest cost	2.87	19.26 <sup>b</sup>	22.13 <sup>b</sup>	24.54 <sup>b</sup>
<i>Summary:</i>					
<i>Deferred action</i>					
Treatment facility at point of distribution <sup>c</sup>	Extraction and disposal	NA	NA	NA	
	GAC(L)	0.01	0.26	0.28	0.28
	AS(L)	0.01	0.02	0.03	0.03
	UV(L)	0.02	0.16	0.18	0.18
<i>No action</i>					
No action	No treatment <sup>c</sup>	0.00	0.00	0.00	0.00

<sup>a</sup> Thirty years of O & M costs are discounted at 5% to the present.

<sup>b</sup> Costs adjusted to reflect operating expense for 87 y and discounted at 5% to the present, to account for the longer time necessary to complete remediation.

<sup>c</sup> Thirty years of operation and maintenance (O & M) costs are discounted at 5% to the beginning of operation, assumed to be 200 y in the future; then, the capital and discounted O & M costs are discounted from 200 y in the future to 1990 at 2%.

L = For treatment of liquid phase.

V = For treatment of vapor phase.

GAC = Granular activated carbon.

AS = Air stripping.

UV = Ultraviolet light, hydrogen peroxide.

IX = Ion exchange.

Cr = Chromium.

Pb = Lead.

NA = Not applicable.

Table 4-6. Detailed evaluation of alternatives for treatment of FHCs and VOCs in the vadose zone.

Assessment factor	Vacuum-induced venting with GAC treatment	Vacuum-induced venting with thermal oxidation	Vacuum-induced venting with catalytic oxidation
Overall protection of human health and the environment	Risk to human health and the environment from these constituents is reduced by this alternative. Results in negligible risk to employees, the public, and the environment from system operation and treated vapor emissions.	Risk to human health and the environment from these constituents is reduced by this alternative. Results in negligible risk to employees, the public, and the environment from system operation and treated vapor emissions.	Risk to human health and the environment from these constituents is reduced by this alternative. Results in negligible risk to employees, the public, and the environment from system operation and treated vapor emissions.
Compliance with ARARs	Reduces concentrations of constituents in vadose zone below ARARs. Thermal regeneration of spent GAC destroys or recycles contaminants.	Reduces concentrations of constituents in vadose zone below ARARs. Air discharge requirements met.	Reduces concentrations of constituents in vadose zone below ARARs. Air discharge requirements met.
Long-term effectiveness and permanence	Extraction and treatment of soil vapors prevent further migration of constituents. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent new sources.	Extraction and treatment of soil vapors prevent further migration of constituents. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent new sources.	Extraction and treatment of soil vapors prevent further migration of constituents. Sources of constituents have been removed, and current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent new sources.
Reduction in toxicity, mobility, or volume	Constituents removed from soil are transformed to nonharmful compounds or collected for reuse in the carbon regeneration process. Placement and design of vent wells prevent migration of the constituents to the ground water.	Constituents removed from soil are transformed to nonharmful compounds in the oxidation process. Placement and design of vent wells prevent migration of the constituents to the ground water.	Constituents removed from soil are transformed to nonharmful compounds in the oxidation process. Placement and design of vent wells prevent migration of the constituents to the ground water.

Table 4-6. (Continued)

Assessment factor	Vacuum-induced venting with GAC treatment	Vacuum-induced venting with thermal oxidation	Vacuum-induced venting with catalytic oxidation
Short-term effectiveness	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of up to 10 y estimated to achieve remedial action objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of up to 10 y estimated to achieve remedial action objectives.	Minimal impact to community during construction. No impact to employees or the public during operation. Possible exposure of employees during installation of extraction wells, piping, and treatment system. Use of protective procedures, clothing, and equipment will mitigate risk. Period of up to 10 y estimated to achieve remedial action objectives.
Implementability	Vacuum-induced venting effectively removes volatile constituents from subsurface. GAC treatment of the vapor phase is proven for removal of FHCs and VOCs from an air stream. Services, materials, and equipment are readily available, but may involve offsite shipment of hazardous waste. Permit required for discharge of treated air.	Vacuum-induced venting effectively removes volatile constituents from subsurface. Thermal oxidation is proven for removal of FHCs and VOCs from an air stream. Services, materials, and equipment are readily available. Permit required for discharge of treated air.	Vacuum-induced venting effectively removes volatile constituents from subsurface. Catalytic oxidation is a proven technology for removal of FHCs from an air stream, but not for VOCs. Services, materials, and equipment are readily available. Permit required for discharge of treated air.
Cost <sup>a</sup>	\$2.8 million (medium).	\$1.8 million (low).	\$0.9 million (FHCs only) (low).
State acceptance	To be addressed following State agency comment.	To be addressed following State agency comment.	To be addressed following State agency comment.
Community acceptance	To be addressed following public comment.	To be addressed following public comment.	To be addressed following public comment.

<sup>a</sup> See Table 4-8 for definition of cost ranges, which include extraction and disposition.

Ground Water	Threshold Factors				Balancing Factors				Modifying Factors			
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance			
GAC	●	●	●	●	●	●	L-VH	TBD	TBD			
AS + GAC(V)	●	●	●	●	●	●	L	TBD	TBD			
UV + AS + GAC(V)	●	●	●	●	●	●	M	TBD	TBD			
Extraction, transport, disposal	●	●	●	●	●	●	H	TBD	TBD			

● = Alternative fully satisfies criterion

○ = Alternative fails to satisfy criterion

TBD = To be determined

Cost ranges (millions of dollars)

Treatment Extraction/disposition

L < 2.0 L < 0.3

2.0 < M < 3.5 0.3 < M < 0.5

H > 3.5 H > 0.5

VH > 5.0

Table 4-8. Comparative evaluation of treatment options for ground water containing VOCs at Treatment Facilities A, B, C, E, and G. (AS= air stripping, V= vapor.)

Ground Water	Threshold Factors		Balancing Factors					Modifying Factors	
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance
GAC + IX	●	●	●	●	●	●	H	TBD	TBD
AS + IX + GAC(V)	●	●	●	●	●	●	L	TBD	TBD
UV/OX + AS + IX + GAC(V)	●	●	●	●	●	●	M	TBD	TBD
Extraction, transport, disposal	●	●	●	●	●	●	H	TBD	TBD

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 L < 2.0 L < 0.3  
 2.0 < M < 3.5 0.3 < M < 0.5  
 H > 3.5 H > 0.5  
 VH > 5.0

Table 4-9. Comparative evaluation of treatment options for ground water containing VOCs and chromium at Treatment Facility D. (IX= ion exchange, AS= air stripping, V= vapor.)

Ground Water	Threshold Factors		Balancing Factors					Modifying Factors	
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Volume	Short-term Effectiveness	Implementability	Cost	State Acceptance	Local Acceptance
GAC	●	●	●	●	●	●	VVH	TBD	TBD
AS + GAC + GAC(V)	●	●	●	●	●	●	VH	TBD	TBD
UV/OX + GAC	●	●	●	●	●	●	H	TBD	TBD
Bioremediation <sup>a</sup>	●	◐	◐	◐	◐	◐	H	TBD	TBD
Extraction, transport, disposal	●	●	●	●	●	●	H	TBD	TBD

<sup>a</sup> Implementable for FHCs, but not for VOCs.

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 L> 2.0 <M <3.5 L> 0.3  
 H> 3.5 <H <5.0 0.3 <M < 0.5  
 VH> 5.0 H> 0.5  
 VVH< 7.0 VVH< 7.0

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Table 4-10. Comparative evaluation of treatment options for ground water containing VOCs, FHCs, and lead at Treatment Facility F. (AS= air stripping, V= vapor.)

Ground Water	Threshold Factors			Balancing Factors					Modifying Factors	
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implement-ability	Cost	State Acceptance	Local Acceptance	
GAC	●	○	●	○	●	○	VVL	TBD	TBD	
AS	●	○	●	○	●	○	VVL	TBD	TBD	
UV/OX	●	○	●	○	●	○	VVL	TBD	TBD	

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 VWL < 0.5 N/A

Table 4-11. Comparative evaluation of treatment options for ground water containing VOCs at the point of distribution in Livermore, Deferred-Action Alternative. (AS= air stripping.)

Ground Water	Threshold Factors		Balancing Factors						Modifying Factors	
	Protect Human Health & the Environment	Comply with ARARs	Long-term Effectiveness	Reduce Toxicity, Mobility, Volume	Short-term Effectiveness	Implement-ability	Cost	State Acceptance	Local Acceptance	
Immediate action:	●	●	●	●	●	●	M-H	TBD	TBD	
Extraction Alternative No.1	●	●	●	●	●	●	M-H	TBD	TBD	
Extraction Alternative No.2	●	●	●	●	●	●	VVL	TBD	TBD	
Delayed action	●	●	●	●	●	●				

● = Alternative fully satisfies criterion  
 ○ = Alternative fails to satisfy criterion  
 TBD = To be determined

Cost ranges (millions of dollars)  
 Treatment Extraction/disposition  
 VVL < 0.5 N/A  
 M > 15.0  
 H > 15.0

Table 4-12. Comparative evaluation of remedial alternatives for the combined remediation of ground water at LLNL.

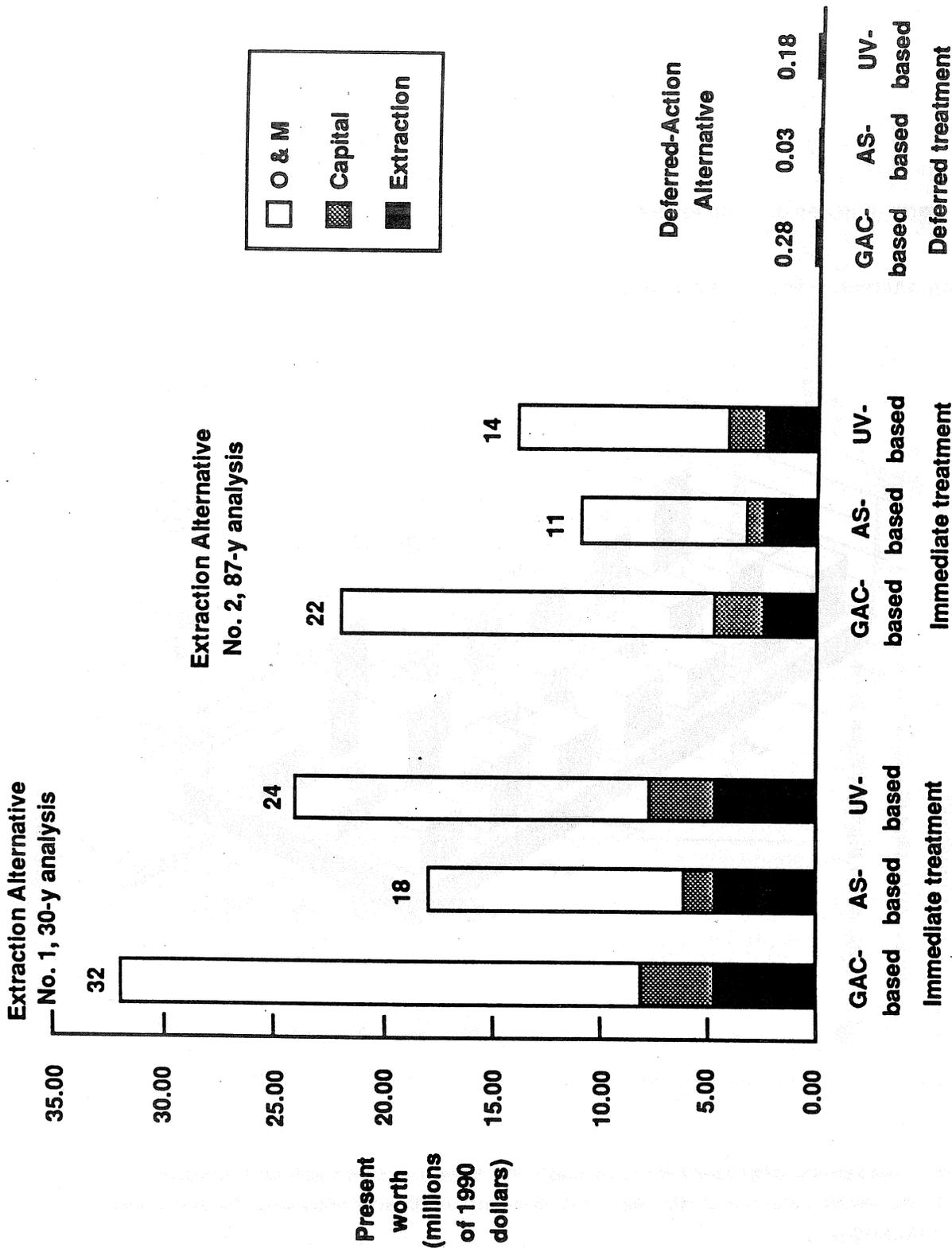


Figure 4-2. A comparison among ground water remedial alternatives for the LLNL Livermore site assuming the same technologies were used for all treatment facilities (technologies will be chosen for each facility separately).

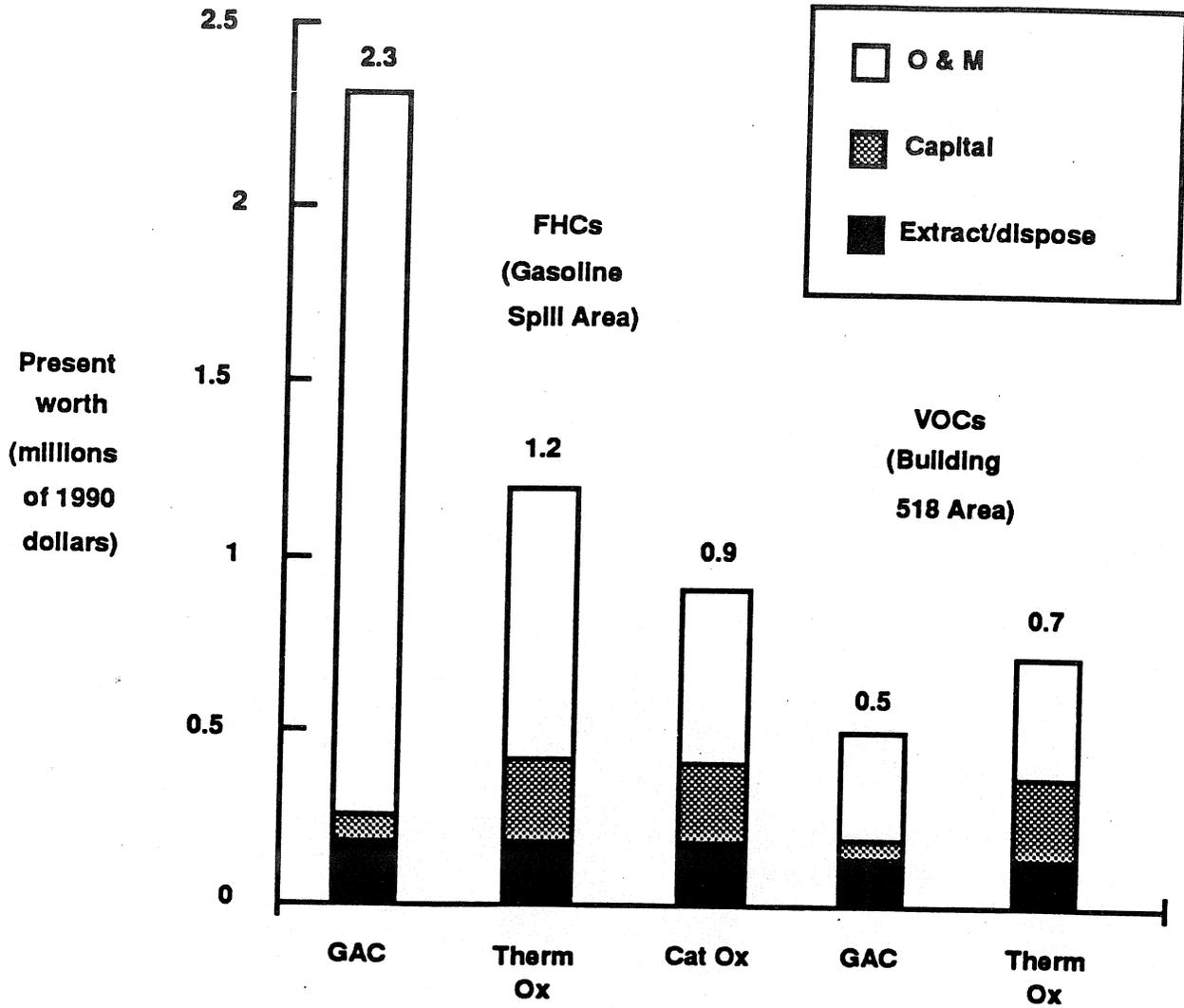


Figure 4-3. Vadose zone treatment options for FHCs and VOCs for the Livermore site.

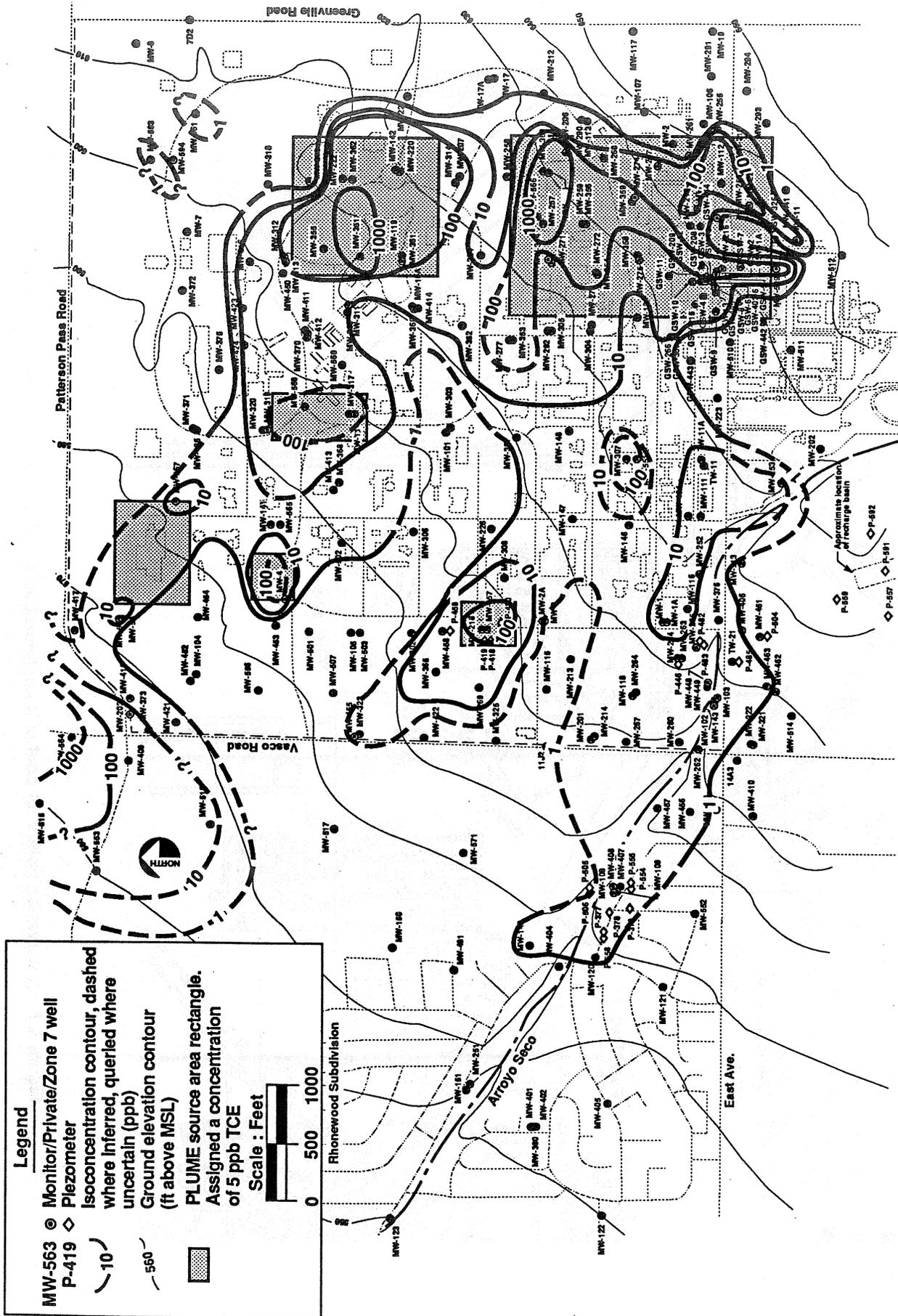


Figure A-2. Isoconcentration contour map of TCE in ground water (Spring 1989), showing location of PLUME source area rectangles.

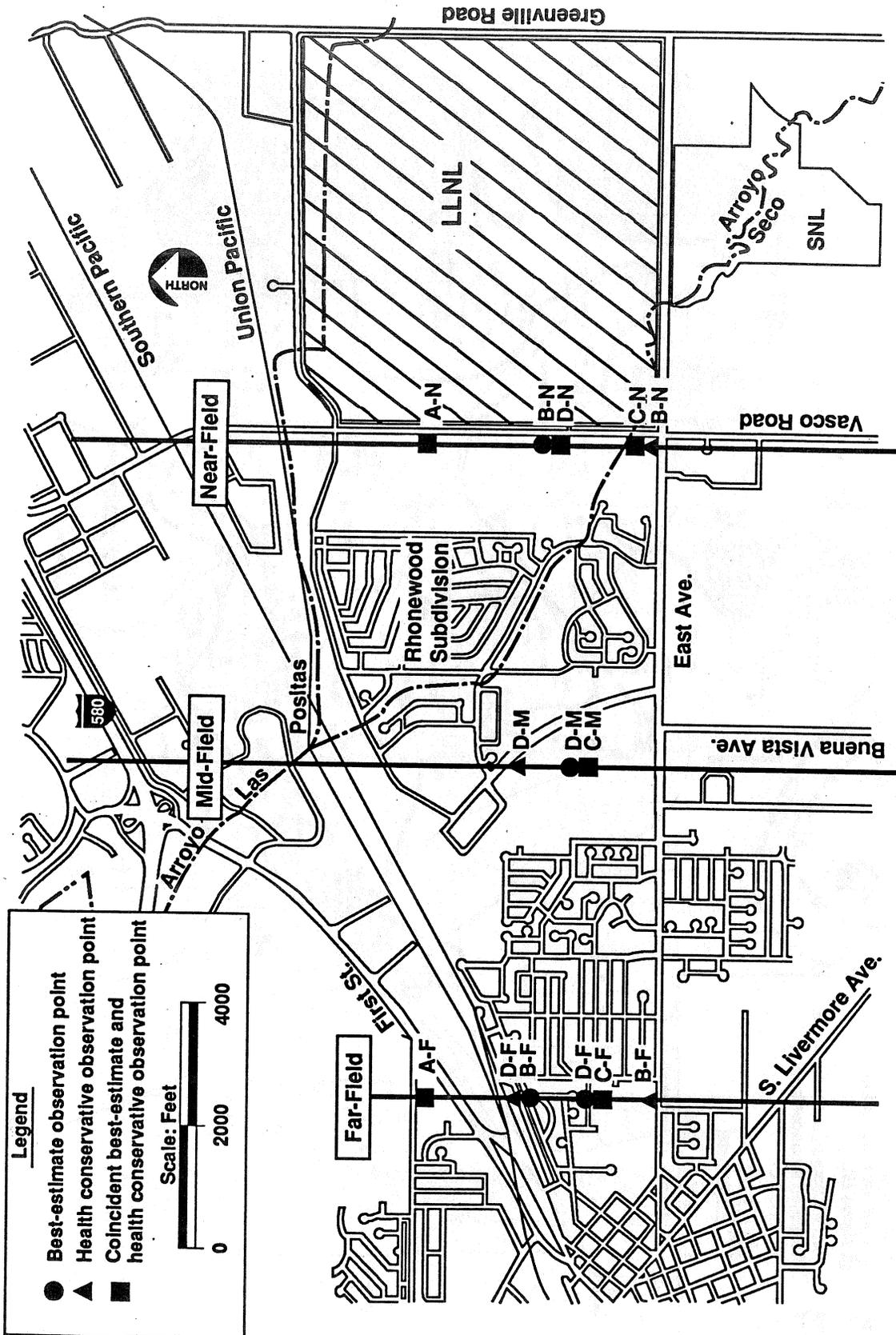


Figure A-6. Observation points for contaminant migration simulations for risk assessment.

FORTRAN and runs on an MS-DOS microcomputer with a dot matrix printer, plotter, screen graphics, or laser printer. Up to 20 wells and 20 trenches can be modeled simultaneously.

### B-2.1. Theoretical Basis and Assumptions

Ground water flow is modeled according to conservation of mass under transient or steady state conditions (Javandel *et al.*, 1984). Movement of ground water is simulated by injecting particles at each selected well or trench and tracking the particle flow. Plotting the resulting flow lines produces the same pattern as extraction at the same rate and opposite hydraulic gradient. Modeling multiple wells is based on RESSQ (Javandel *et al.*, 1984). Modeling the capture area for a trench is based on a steady state line-sink analytical solution presented by Muskat and Wickoff (1937). The program code was developed independently of RESSQ (Javandel *et al.*, 1984) to run under MS-DOS by Donald G. McEdwards.

The water-bearing zone is assumed to be horizontal, fully saturated, homogeneous, of constant thickness and infinite lateral extent, and confined above and below by impermeable layers. The hydraulic gradient is assumed to be uniform in the absence of pumping. Thus, prior to pumping, undisturbed ground water flow in this idealized water-bearing zone is uniform and horizontal, and ground water "particles" follow parallel paths, or streamlines, in the downgradient direction.

Adding pumping wells and/or trenches alters the background uniform flow pattern. The wells or trenches are assumed to fully penetrate the water-bearing zone. The trenches are assumed to have been pumped at a constant rate for an infinite time, such that the water-bearing zone reaches equilibrium with the trenches. The wells can be either transient or in equilibrium with respect to the water-bearing zone.

### B-2.2. CAPTURE Output and Use

Flow paths of ground water "particles" will be drawn toward the extraction wells or trenches, and some flow will be "captured" and removed from the water-bearing zone. A cone of depression is formed by the concavity of the piezometric surface. This capture is depicted in the CAPTURE plots by flow lines that converge and terminate at pumped wells or trenches. Figure B-1 is a schematic CAPTURE plot that lists some of the model assumptions and describes how the input parameters influence the shape of the resulting flow lines.

The velocity of ground water flow in the capture area is shown graphically on the flow lines by Xs, which represent time intervals of ground water particle flow along each depicted flow path. Water on the upgradient side of a pumped well moves more rapidly toward the well than water on the downgradient side, and the capture area upgradient of the extraction well is larger than the capture area downgradient. The differences between upgradient and downgradient water velocities and capture areas are nonexistent where there is no gradient and increase as the gradient increases. A "stagnation point" exists at the rim of the cone of depression where, under steady state condition, water will not move (Figure B-1).

To achieve efficient capture and removal of contaminated ground water, extraction wells and trenches should be placed so the shape of the capture area closely corresponds to the area of contaminated ground water. The downgradient edge of the capture area should lie at or beyond the downgradient margin of contamination to ensure complete capture or containment.

**APPENDIX D**  
**CONCEPTUAL DESIGNS AND**  
**COST ESTIMATES FOR GROUND WATER**  
**TREATMENT TECHNOLOGIES**

## APPENDIX D

# CONCEPTUAL DESIGNS AND COST ESTIMATES FOR GROUND WATER TREATMENT TECHNOLOGIES

### D-1. DESCRIPTION OF GROUND WATER TREATMENT TECHNOLOGIES

The alternative technologies for treatment of extracted ground water are described in this Appendix. General process descriptions are provided together with process flow diagrams for each technology. Factors influencing the design of each treatment system are discussed, as are the operational concerns for each technology.

The cost data presented here for each situation at LLNL provide the basis for assembling the technologies into the treatment alternatives shown in Section 4. All treatment facilities are costed using a 30-y life, as suggested in EPA guidance. However, to compare the extraction alternatives, which differ significantly in the lifetime of operation, a supplemental analysis was performed for the treatment facilities included in Extraction Alternative No. 2. This analysis was based on the estimated time to reach MCLs, as presented in Section 3.4.1.3, of 87 y. Albeit not a well-constrained time of operation, the analysis illustrates the approximate effect of the longer operational lifetime. Although not presented, we also calculated the additional cost of Extraction Alternative No. 1 for operation for 53 y (as estimated in Section 3.4.1.3), rather than the standardized 30 y. This increased the present worth of the alternative by less than 10% because of the effect of discounting future expenditures.

#### D-1.1. Water Treatment with Granular-Activated Carbon (GAC)

This alternative is suitable for the removal of most organic chemicals from the ground water and, hence, is effective for treatment of VOCs and FHCs. GAC treatment of the liquid phase is also somewhat effective for the removal of low concentrations of many heavy metals. Treatment is achieved when the water contacts a fixed bed of GAC. The contaminants in the water are adsorbed onto the surface of the GAC. When the capacity of the GAC to adsorb the chemicals is exhausted, the GAC is removed and replaced with fresh material. The spent GAC can be regenerated onsite or at a commercial facility, either with thermal oxidation of the chemicals or collection for recycling.

A process flow diagram for the system using GAC treatment of the liquid phase is given in Figure D-1. The extracted ground water is pumped from the well through the GAC. The pump design criteria specify a discharge pressure sufficient to pump the water through two adsorber units.

The GAC adsorber for liquid-phase treatment consists of a fixed bed of GAC. The diameter and height of the adsorber is determined by the flow rate of water to be treated and by the anticipated rate of saturation of the GAC. The rate of saturation is determined by the flow rate of water and by the concentrations of the chemicals in the water. The breakthrough front (the distance over which the concentrations change from zero to inlet values) can approach

one-half the height of GAC adsorbers. Therefore, to achieve near full use of the GAC, it is normal practice to use two adsorber vessels in series.

When the capacity of the GAC to adsorb the chemicals from the water has been exhausted, indicated by detection of elevated concentrations of the chemicals in the water exiting the first GAC unit in series, the flow is stopped and the GAC in this unit is removed and replaced with fresh material. When the system is restarted, the order of flow through the two GAC adsorbers is reversed. In this way, the adsorber containing the least contaminated GAC will always be in the final polishing position. The spent GAC can be regenerated onsite or transported to a commercial facility where the adsorbed chemicals are oxidized in a furnace.

#### **D-1.2. Air Stripping with GAC Treatment of the Vapor Effluent**

This alternative is suited to the removal of chemicals of moderate to high volatility from the ground water and, hence, is effective for treatment of VOCs and FHCs. Treatment is achieved by contacting the water with a flow of air in a vertical tower containing high surface area packing media, which provide good contact between the water and air. The volatile chemicals are transferred (stripped) from the water to the air as the water flows down over the packing material countercurrent to the air that is blown upward through the packing material. The chemicals that have been transferred to the air are removed from the air before discharge to the atmosphere by adsorption onto GAC in the vapor stream. When the capacity of the GAC to adsorb the chemicals is exhausted, the GAC must be removed and replaced with fresh material. The spent GAC can be regenerated onsite or at a commercial facility, with either thermal destruction of the chemicals or collection for recycling.

The advantage of first air stripping the chemicals before adsorption onto GAC from the vapor phase over direct adsorption onto GAC from the liquid phase is that the capacity of GAC treatment of the vapor phase (expressed as pounds of chemical adsorbed per pound of GAC) is generally significantly greater than that for GAC treatment of the liquid phase. This results in less frequent replacement of the GAC and, hence, lower operating costs for GAC replacement. This must be balanced against the more complex operation and higher installation cost expected for the air stripping system with vapor-phase treatment with GAC over a liquid-phase treatment with GAC system.

A process flow diagram for air stripping with vapor-phase treatment with GAC is given in Figure D-2. The extracted ground water is pumped to the top of the packing media in the air stripping tower. The pump criteria are designed to produce a discharge pressure sufficient to pump the water to the top of the tower.

The air stripper design is based on flow rate of water to be treated, the incoming chemical concentrations, and concentration limits for the treated water discharge. Selection of the tower diameter is governed by the flow rate of water to be treated. Selection of the blower capacity and, hence, quantity of air flow to the tower is based on chemicals present in the water and water flow rate. The height of packing media in the tower (and, therefore, height of the tower) is based on required reduction in concentrations expressed as the ratio of inlet to outlet values for each chemical requiring treatment.

The GAC adsorber for vapor-phase treatment consists of a fixed bed of GAC. Diameter and height of the adsorber are determined by the flow rate of air to be treated and also by the anticipated rate of saturation of the GAC. Rate of saturation is determined by flow rate of air and concentrations of the chemicals in the air. Break-through front (distance over which the

concentrations change from zero to inlet values) is generally very short for GAC treatment of the vapor-phase adsorbers. Therefore, near full use of the GAC can be achieved with use of a single adsorber vessel. When the capacity of the GAC to adsorb chemicals from the air has been exhausted, indicated by detection of trace concentrations of the chemicals in the air exiting the GAC unit, the GAC will be removed and replaced with fresh material. The spent GAC can be regenerated onsite or transported to a commercial facility where the adsorbed chemicals are oxidized in a furnace.

The higher adsorption capacity, which can be achieved using GAC treatment of the vapor phase, is significantly reduced if the air entering the adsorber is saturated with water vapor (100% relative humidity). This loss of capacity can be prevented if the air relative humidity is reduced to less than 50%. The air exhaust of the stripping tower will be saturated with water and, hence, an air heater is included between the stripper tower and the GAC unit. Heating the air by approximately 20°F will reduce the relative humidity to less than 50%. A blower is also provided to overcome the pressure loss in the air heater and the vapor treatment GAC unit.

### D-1.3. UV/Oxidation Plus Air Stripping with GAC Treatment of the Vapor Effluent

This alternative uses ultraviolet light and either hydrogen peroxide (UV/H<sub>2</sub>O<sub>2</sub>) or ozone (O<sub>3</sub>) to provide the primary water treatment, and an aeration/carbon adsorption system for secondary treatment or polishing. Because of LLNL's experience with the system described in Section 2, we will confine our discussion to hydrogen peroxide. This alternative is well-suited for treatment of VOCs in ground water and is applicable to sites A, B, C, D, E, and G. The effectiveness of this system on FHCs in ground water has not yet been completely evaluated, but bench scale tests with LLNL ground water have reported satisfactory results. A possible future variation on the UV/oxidation method uses solar collectors to provide the UV energy, rather than electrically powered lamps.

The process flow diagram for this system is shown in Figure D-3. The ground water from the wellhead is pumped through a 5- $\mu$  filter to remove any suspended fines and particulates prior to entering the UV/H<sub>2</sub>O<sub>2</sub> treatment unit. Immediately upstream of the UV chamber, hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) is injected into the influent at concentrations of 30 to 50 ppm. The water then enters the bottom of the UV chamber and flows upward past the UV lamps that disassociate H<sub>2</sub>O<sub>2</sub> to create highly reactive hydroxyl radicals (OH). The UV light and hydroxyl radicals then act on the organic compounds to break them down to carbon dioxide, water, and chloride ions. This process is particularly effective on haloalkenes because the alkenes are photoreactive and highly susceptible to oxidation by the hydroxyl radical in the photoexcited state. Other organic molecules are similarly oxidized, but at variable reaction rates.

Besides the UV intensity and injected H<sub>2</sub>O<sub>2</sub>, the amount of VOC destruction that occurs depends upon the residence time of the water in the UV chamber. This can be controlled by varying the flow rate until an optimum destruction efficiency is obtained. The residence time for the unit at Pilot Treatment Facility A is about 90 sec, for an operating flow rate of 50 gpm.

The UV/H<sub>2</sub>O<sub>2</sub> system is effective at destroying haloalkenes such as PCE and TCE with double carbon bonds. However, the UV/H<sub>2</sub>O<sub>2</sub> is not as effective at destroying haloalkanes such as 1,1,1-TCA and 1,1-DCA with single carbon bonds. Rather than greatly increase the power consumption or residence time (decreasing flow rate), we chose to further treat the effluent from the UV/H<sub>2</sub>O<sub>2</sub> system that contains residual haloalkanes, with an aeration/carbon adsorption system.

The design of the polishing system consists of a baffled, 1400-gal tank that receives effluent directly from the UV/H<sub>2</sub>O<sub>2</sub> unit. The water is subjected to intense aeration using a centrifugal blower unit that injects air at a rate of 150 ft<sup>3</sup>/min (cfm). Another centrifugal blower unit extracts VOCs, volatilized during the aeration process at an extraction rate of 250 cfm, that pass through a GAC filter prior to atmospheric discharge. The aeration process reduces the residual haloalkanes to levels much less than 5 ppb such that the treated water can be safely discharged to LLNL's recharge basin, which allows the treated water to percolate back to the water table. The carbon filter adsorbs all volatilized VOCs such that no detectable VOCs are discharged to the air.

#### **D-1.4. Air Stripping with GAC treatment of Both Liquid and Vapor Effluents**

This alternative combines air stripping as the primary treatment with a secondary treatment using GAC on the liquid phase. This alternative is suitable where it is not practical to achieve the required cleanup goals by air stripping alone because of very high inlet concentrations or where contaminants are present which cannot be treated by air stripping, such as metals. This alternative may be applicable to Treatment Facility F in this study, for which high concentrations of benzene, other FHCs, and, possibly, low concentrations of lead are anticipated in the extracted ground water.

A process flow diagram for this system is shown in Figure D-4. The design and operation considerations are the same as described in Sections D-1.1 and D-1.2.

#### **D-1.5. UV/Oxidation Plus GAC Treatment of the Liquid Effluent**

This alternative combines UV/oxidation as the primary treatment with secondary treatment of the liquid phase using GAC. This alternative is suitable where it is not practical to achieve the required effluent concentrations by UV/oxidation alone because of very high inlet concentrations or where contaminants are present that cannot be treated by UV/oxidation alone, such as metals. This alternative may be applicable to Treatment Facility F, at which high concentrations of benzene, other FHCs, and, possibly, low concentrations of lead may be present in the extracted ground water.

A process flow diagram for this system is shown in Figure D-5. The design and operation considerations for this alternative are the same as described in Sections D-1.3 and D-1.1.

#### **D-1.6. Liquid-Phase Treatment with GAC Plus Ion Exchange**

This alternative combines GAC as the primary treatment with a secondary treatment using ion exchange. This alternative is suitable where the ground water needs to be treated for removal of both VOCs and chromium. This alternative would be applicable to Treatment Facility D where concentrations of VOCs and possible chromium exceeding the required cleanup standards are anticipated in the extracted ground water.

A process flow diagram for this system is given in Figure D-6. The design and operation considerations are the same as described in Section D-1.1 for the primary treatment.

The chromium in the +6 valence state in the extracted ground water is expected to be in the form of chromate anions. Therefore, the ion-exchange technology will use an anion-type ion exchange resin. The water discharged from the primary treatment of GAC will be collected in a holding tank and then pumped through a fixed bed of ion-exchange resin. Two ion-exchange

beds are provided so that while one is online treating ground water, the other is being regenerated or is on standby. The diameter of the ion-exchange bed is selected based on the ground water flow rate, and the depth of ion-exchange resin in the bed is selected on the basis of flow rate and concentration of chromium. The ion-exchange bed is sized to require regeneration approximately once per day of operation.

During regeneration, the flow of ground water through the system is switched to the bed which has been on standby, and the bed previously in use is regenerated. The resin is regenerated by flowing a solution of sodium hydroxide through the ion-exchange bed. The waste regeneration solution containing the chromium (sodium chromate) removed from the resin in concentrated form is generally disposed of as a hazardous waste.

#### **D-1.7. Air Stripping with GAC Treatment of the Vapor Effluent and Ion-Exchange Treatment of the Liquid Effluent**

This alternative combines air stripping as the primary treatment with a secondary treatment using ion exchange. As before, GAC is used to treat the vapor effluent from the air stripper. This alternative is suitable where the ground water needs to be treated for removal of both VOCs and chromium. This alternative may be applicable to Treatment Facility D where concentrations of VOCs and possibly chromium exceeding the required cleanup standards are anticipated in the extracted ground water.

A process flow diagram for this system is given in Figure D-7. The design and operation considerations are the same as described in Sections D-1.2 and D-1.6.

#### **D-1.8. UV/Oxidation with Air Stripping and Ion Exchange of the Liquid Effluent and GAC Treatment of the Vapor Effluent**

This alternative combines UV/oxidation as the primary treatment with additional treatment using air stripping and ion exchange. As before, GAC is used to treat the vapor effluent from the air stripper. The UV/oxidation and air stripper treatments are suitable where the ground water is to be treated for removal of VOCs. The ion exchange is added for chromium removal where necessary. This alternative may be applicable to Treatment Facility D where concentrations of VOCs and, possibly, chromium exceeding the required cleanup standards are anticipated in the extracted ground water.

A process flow diagram for this system is given in Figure D-8. The design and operation considerations are the same as described in Sections D-1.3 and D-1.6.

### **D-2. BASIS FOR CONCEPTUAL DESIGNS AND COST ESTIMATES OF TECHNOLOGIES**

The basis for development of the conceptual designs and the cost estimates prepared from these designs are described in this section. These include: (1) the engineering design basis, (2) the basis for development of capital cost estimates, (3) the basis for estimation of operating costs over the project life.

### D-2.1. Engineering Design Basis

The engineering designs that apply to the development of the conceptual treatment technologies at all treatment sites are:

1. Tables D-3, D-4, D-5, D-6, D-7, D-8, D-9, and D-10 provide the design bases for each treatment site. These tables include the maximum and average ground water flow rates to be treated, the maximum and average concentrations of contaminants present in the ground water, and the concentrations to which the contaminants are to be reduced by the treatment system.
2. The conceptual designs and cost estimates include the above-ground water treatment alternatives. Items such as the ground water extraction systems and the treated water discharge systems are common to all treatment alternatives. The capital and operating costs associated with these items would be the same for all treatment alternatives and, therefore, are not included in the analysis of alternatives evaluated in detail. However, costs presented in Section 4 include the cost of extraction and disposal.
3. The conceptual design for each alternative is based on achieving the stated concentrations for treated outlet water at the maximum flow and contaminant concentrations for the extracted ground water. The equipment sizing and selection for the cost estimation is based on this conceptual design. Under average flow and contaminant concentration, the treatment should generally reduce VOC or FHC concentration to levels at or below detection limits.
4. The estimates for operating cost are based on treating the average flow rate of extracted water containing the average concentrations of contaminants.
5. The cost estimates are developed assuming that the treatment alternatives will be operated for 30 y. A 5% discount rate is used for development of present worth calculations. Present worth factors for future costs are calculated using the procedures described in U.S. EPA (1987).
6. The deferred treatment at the point of distribution alternative in central Livermore requires two discounting calculations. The 30 y of operation and maintenance costs are discounted at 5% in accordance with EPA procedures. Because this remediation alternative, if required, would not be installed for an estimated 200 y, the capital and discounted operating costs are discounted at 2% for 200 y. A low real discount rate is used because inflation is ignored in costs.
7. The concentrations of contaminants in the extracted water will decline over the period that the extraction and treatment systems are operated. For estimating operation costs, this decline is assumed to occur in step fashion over 5-y intervals with the concentrations in each interval set equal to one-half the concentrations present during the previous 5 y of operation. That is, the concentrations during years 6 through 10 will be one-half the initial concentrations; the concentrations during years 11 through 15 will be one-half the concentrations during years 6 through 10, and so forth.
8. The estimates for operating costs reflect the decline in concentrations of the contaminants in the extracted ground water. Operating cost items that are adjusted include the costs for replacement of GAC and the electric power used for the UV/oxidation system.
9. The reduction in contaminant concentrations in the extracted ground water described above will result in a reduced rate of use of GAC for the alternatives that use this technology. The rate of GAC use during the first 5 y of operation is based on the average flow rate and average inlet concentrations listed in the design basis table for the system to which the

alternative applies. Estimates obtained from vendors of GAC are used. The rate of use of GAC will decline as a result of the decreased concentrations in the inlet water.

The theoretical capacity of GAC to adsorb organic chemicals is commonly expressed in the form of a Freundlich isotherm equation:

$$q = kC^n$$

where

$q$  = quantity adsorbed onto GAC, mg compound/g GAC;

$C$  = concentration in water, mg/l;

$k$  = Freundlich adsorption constant;

$n$  = Freundlich adsorption exponent.

The values of  $k$  and  $n$  for the compounds of interest in this study were obtained from U.S. EPA (1980). Based on this review, a typical value of 0.6 for the adsorption exponent  $n$  is assumed to apply to all compounds, and the rate of GAC use is adjusted according to the following equation:

$$R_m = R(0.5)^{0.6m}$$

where

$R_m$  = rate of GAC use during the  $m$ th 5-y period following the initial 5 y (6 to 10 y,  $m = 1$ ; 11 to 15 y,  $m = 2$ ; etc.),

$R$  = rate of GAC use during the initial 5-y period.

A similar analysis was conducted for estimation of the rate of GAC use for treatment of air stripper exhaust. A similar equation was applied, differing only in the exponent used, 0.5  $m$  instead of 0.6  $m$ .

10. We allow for the decline in electricity use for UV/oxidation. UV/oxidation systems generally use a number of UV lamps, not all of which need be energized, depending on concentration. These consume the majority of electrical power and as concentrations decrease, some lamps may be switched off. UV/oxidation technology continues to undergo development. Recently, one supplier of such treatment systems made modifications that may improve conditions that promote oxidation reactions while at the same time reduce the cost of power required. We have not experimented with the new system in the field. To account for this, we have assumed that power requirements are constant for the first 15 y, after which they are reduced by 50% for the remainder of the assumed period of remediation.

#### D-2.2. Capital Cost Estimation

The following assumptions apply to the estimation of capital costs for all treatment alternatives:

1. Vendor quotes or vendor catalog prices are used to develop the costs for major purchased equipment items.
2. A factored estimate for total installed capital cost, accurate to +50%/-30%, is used based on the cost for major purchased equipment. Installation cost factors are based on experience for installation of chemical process equipment.
3. Indirect costs include engineering design and permitting. An estimate of \$50,000 for engineering design is included for all alternatives. Permitting costs are estimated at \$10,000 for alternatives that do not require an air discharge permit and \$20,000 for alternatives requiring an air permit.
4. A contingency factor of 20% is applied to all capital cost estimates.

The costs to install the treatment process equipment for each alternative were estimated by applying factors to the purchase costs for the major items of equipment included in the treatment process. This is a technique commonly used in industry to develop conceptual level cost estimates for analysis of alternatives. The procedure consists of adding a percentage of the major purchased equipment cost to the equipment costs to develop estimated direct costs for construction. These percent factors account for the labor and materials for such items as site preparation, foundation and support structures construction, piping installation, instrumentation, and electrical service. A description of the method and estimated factors can be found in Guthrie (1974). This source and experience with the construction of treatment facilities, similar to those analyzed here, were used to develop the factors applied in the cost estimation for this report. Because the procedure applied was the same for all alternatives considered and because these costs are used only for comparison of alternatives, we feel these factored cost estimates are adequate.

### D-2.3. Operating Cost Estimation

The following assumptions were used to develop operating cost estimates for all alternatives:

1. An operating factor of 90% is assumed for all treatment alternatives.
2. The following annual labor hours and hourly rates, including indirect labor costs, will apply to all alternatives:

Supervision labor	200 h at \$75/h
Operating labor	500 h at \$40/h
3. The cost for electricity will be estimated at the rate of \$0.07 per kW-h plus an annual connection fee of \$36 per kW.
4. The cost for replacement of spent GAC treatment of the liquid phase and GAC treatment of the vapor phase is based on vendor quotes applicable to servicing of the specific GAC treatment units utilized in the conceptual design. This cost includes removal of spent GAC, thermal regeneration of spent GAC, and replacement with fresh GAC, as well as all freight and labor costs.
5. The costs for analysis of air and water samples only include those samples necessary for monitoring the performance of aboveground treatment alternatives. Sample collection and analysis costs associated with monitoring of extraction system performance and ground water quality are common to all alternatives and are not included in the operating cost estimates. We assume that each alternative will be monitored biweekly. The following costs per sample analysis apply:

*Water samples:*

VOC analysis	\$100/sample
FHCs analysis	\$100/sample
Metals (chromium or lead)	\$50/sample

*Air samples:*

VOC analysis	\$100/sample
FHCs analysis	\$100/sample

6. The sample collection and analysis schedule for each alternative would be as follows:
- GAC treatment of the liquid phase alternative will require the collection of samples of the inlet water, the water between the series of two GAC units, and the outlet water. When provision is included for field blanks and duplicates, a total of 110 samples would be collected annually. When the alternative is to treat VOCs only (Facilities A, B, C, E, and G), the samples would be analyzed for VOCs only. When the alternative is to treat VOCs, FHCs, and lead (Facility F), samples would be analyzed for all three parameters.
  - Air stripping with GAC treatment of the vapor phase would require collection and analysis of samples of the inlet water and the outlet water. When provision is included for field blanks and duplicates, a total of 80 water samples would be collected annually. This alternative applies to systems requiring treatment for VOCs only (Facilities A, B, C, E, and G). Therefore, samples would be analyzed only for VOCs. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples would be collected annually and analyzed for VOCs.
  - UV/oxidation plus air stripping with GAC treatment of the vapor phase would require collection and analysis of samples of the inlet water, the water exiting the UV/oxidation unit, and the outlet water. When provision is included for field blanks and duplicates, a total of 110 water samples would be collected annually. This alternative applies to systems used to treat VOCs only (Facilities A, B, C, E, and G). Therefore, these samples are be analyzed for VOCs. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples would be collected and analyzed for VOCs annually.
  - Air stripping with GAC treatment of both the vapor and liquid phases would require collection and analysis of samples of the inlet water, the water exiting the air stripper, the water between the two GAC units, and the outlet water. When provision is included for field blanks and duplicates, a total of 130 water samples would be collected annually. This alternative applies to systems requiring treatment for VOCs, FHCs, and lead (Facility F). Therefore, these samples would be analyzed for all these parameters. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples would be collected annually and analyzed for VOCs and fuel hydrocarbons.
  - UV/oxidation plus GAC treatment of the liquid phase would require collection and analysis of samples of the inlet water, the water exiting the UV/oxidation unit, the water between the two GAC units, and the outlet water. When provision is included for field blanks and duplicates, a total of 130 water samples would be collected annually. This alternative only applies to systems used to treat VOCs, FHCs, and lead (Facility F) only. Therefore, these samples would be analyzed for all these parameters.
  - GAC treatment of the liquid phase plus ion exchange, which applies to systems requiring treatment for VOCs and chromium (Facility D), would require collection of samples of the inlet water, the water between the two GAC units, and the outlet water for VOCs analysis. When provision is included for field blanks and duplicates, a total of 110

samples would be collected annually and analyzed for VOCs. In addition, samples of the inlet water to the ion exchange unit and the outlet water would be collected and analyzed for chromium. When provision is included for field blanks and duplicates, a total of 80 samples would be collected annually and analyzed for chromium.

- Air stripping with GAC treatment of the vapor phase plus ion exchange, which applies to systems requiring treatment for VOCs and chromium (Facility D), would require collection of samples of the inlet water and the outlet water for VOC analysis. When provision is included for field blanks and duplicates, a total of 80 water samples would be collected annually and analyzed for VOCs. Samples of the inlet water to the ion-exchange unit and the outlet water would be collected and analyzed for chromium. When provision is made for field blanks and duplicates, a total of 80 samples would be collected annually and analyzed for chromium. In addition, samples of the air exiting the GAC treatment of the vapor phase unit would be collected. A total of 30 air samples are collected annually and analyzed for VOCs.
  - UV/oxidation plus air stripping with GAC treatment of the vapor phase plus ion exchange, which applies to systems requiring treatment for VOCs and chromium (Facility D), would require collection and analysis of samples of the inlet water, the water exiting the UV/oxidation unit, and the outlet water for VOC analysis. When provision is included for field blanks and duplicates, a total of 110 water samples would be collected annually and analyzed for VOCs. Samples of the inlet water to the ion-exchange unit and the outlet water would be collected and analyzed for chromium. When provision is made for field blanks and duplicates, a total of 80 samples would be collected annually and analyzed for chromium. In addition, samples of the air exiting the GAC unit would be collected. A total of 30 air samples are collected and analyzed for VOCs annually.
7. An annual cost of 2% of the total capital requirement is included in the operating cost for all alternatives.
  8. A contingency of 20% is applied to the operating cost estimate.
  9. Operating cost estimates take into account the decline in GAC or electric use resulting from the decline in inlet water concentrations with time, as previously described.
  10. The operating cost estimates are discounted to 1990 for developing the present worth estimates, with a discount rate of 5%.
  11. The annual UV/oxidation maintenance fee is established by contract with the current vendor to be 10% of the cost of the UV/oxidation chamber itself. This maintenance contract includes periodic cleaning of the quartz UV source bulbs, replacing the quartz bulbs as necessary, rebuilding or replacing the hydrogen peroxide feed pumps as necessary, maintaining the hydrogen peroxide supply reservoir with adequate hydrogen peroxide (LLNL pays \$0.62/lb for the hydrogen peroxide), and performing any other electrical, electronic, or mechanical maintenance or repair required by the UV/oxidation chamber and hydrogen peroxide supply system.
  12. The rate of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) use, a variable operating and maintenance cost item, is estimated as follows:  
The desired concentration of H<sub>2</sub>O<sub>2</sub> in the water stream that is being treated is 50 ppm (50 mg/L); LLNL buys H<sub>2</sub>O<sub>2</sub> at \$0.62/lb of 50% solution.

$$\text{H}_2\text{O}_2 \frac{\text{lb}}{\text{y}} = F \cdot 8.33 \cdot 2,$$

where

- F = the annual flow rate processed by the treatment system in gallons per year;
- 8.33 = the weight of water per gallon, taken as the weight of H<sub>2</sub>O<sub>2</sub>; no correction is made for the density of 50% solution of H<sub>2</sub>O<sub>2</sub> (1.2);
- 2 = correction factor for the 50% solution (2 lb of 50% solution/1 lb 100% H<sub>2</sub>O<sub>2</sub>)

The cost is estimated by multiplying the pounds of 50% H<sub>2</sub>O<sub>2</sub> solution by \$0.62. During operating years 1 to 16, the above estimate is used; in years 16 to 30, the use rate is assumed to be half that of the earlier period use, consistent with the assumption that the number of UV-quartz bulbs used in years 16 to 30 will also be half the first 15 y.

13. We assume that, for operating years 1 through 15, all four quartz UV lamps will be used, and in years 16 through 30, two will be used. This affects electricity use.

### D-3. TREATMENT FACILITY A

The design basis for the alternatives evaluated for Treatment Facility A is given in Table D-3. The only chemicals of concern anticipated in the ground water at Treatment Facility A are VOCs. The alternatives considered for Treatment Facility A are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is discussed further below.

#### D-3.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-3.1-1. The capital requirement for this alternative is estimated to be \$731,000, as developed in Table D-3.1-2. The present worth of the operating cost is estimated to be \$5,045,000, as developed in Table D-3.1-3. The present worth of the alternative is estimated to be \$5,776,000.

#### D-3.2. Air Stripping With GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-3.2-1. The capital requirement for this alternative is estimated to be \$211,100, as developed in Table D-3.2-2. The present worth of the operating cost is estimated to be \$1,378,700, as developed in Table D-3.2-3. The present worth of the alternative is estimated to be \$1,589,800.

#### D-3.3. UV/Oxidation Plus Air Stripping With GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-3.3-1. The capital requirement for this alternative is estimated to be \$494,000, as developed in Table D-3.3-2. The present worth of the operating cost is estimated to be \$3,017,600, as developed in Table D-3.3-3. The present worth of the alternative is estimated to be \$3,511,600.

## D-4. TREATMENT FACILITY B

The design basis for the alternatives evaluated for Treatment Facility B is given in Table D-4. The only chemicals of concern anticipated in the ground water at Treatment Facility B are VOCs. The alternatives considered for Treatment Facility B are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is summarized below.

### D-4.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-4.1-1. The capital requirement for this alternative is estimated to be \$448,000, as developed in Table D-4.1-2. The present worth of the operating cost is estimated to be \$3,041,000, as developed in Table D-4.1-3. The present worth of the alternative is estimated to be \$3,489,000.

### D-4.2. Air Stripping With GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-4.2-1. The capital requirement for this alternative is estimated to be \$184,000, as developed in Table D-4.2-2. The present worth of the operating cost is estimated to be \$1,351,000, as developed in Table D-4.2-3. The present worth of the alternative is estimated to be \$1,535,000.

### D-4.3. UV/Oxidation Plus Air Stripping With GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-4.3-1. The capital requirement for this alternative is estimated to be \$367,400, as developed in Table D-4.3-2. The present worth of the operating cost is estimated to be \$1,942,000, as developed in Table D-4.3-3. The present worth of the alternative is estimated to be \$2,309,400.

## D-5. TREATMENT FACILITY C

The design basis for the alternatives evaluated for Treatment Facility C is given in Table D-5. The only chemicals of concern anticipated in the ground water at Treatment Facility C are VOCs. The alternatives considered for Treatment Facility C are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is summarized below.

### D-5.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-5.1-1. The capital requirement for this alternative is estimated to be \$448,000, as developed in Table D-5.1-2. The present worth of

## D-8. TREATMENT FACILITY F

The design basis for the alternatives evaluated for Treatment Facility F is given in Table D-8. The chemicals of concern anticipated in the ground water at Treatment Facility F are VOCs, FHCs, and lead. The alternatives considered for Treatment Facility E are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase plus GAC treatment of the liquid phase, and UV/oxidation plus GAC treatment of the liquid phase. Each is discussed below.

The design criteria presented do not take into account any progress resulting from ongoing work as part of the Gasoline Spill Pilot Study. Therefore, before actual design begins, LLNL will establish new design criteria to reflect the results of the pilot study. Current plans within the scope of the pilot study are to test remediation of the FHCs in ground water during 1991, using vapor extraction techniques on a de-watered section of the aquifer, and using an innovative steam stripping technology. If these tests are successful, the resulting fuel hydrocarbon concentrations will be much lower than those presented in Table D-8.

### D-8.1. GAC Treatment

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-8.1-1. The capital requirement for this alternative is estimated to be \$731,000, as developed in Table D-8.1-2. The present worth of the operating cost is estimated to be \$6,947,800, as developed in Table D-8.1-3. The present worth of the alternative is estimated to be \$7,678,800.

### D-8.2. Air Stripping plus GAC Treatment of the Vapor Effluent

The process flow diagram for this alternative is shown in Figure D-4. The description and costs for the major equipment items are given in Table D-8.2-1. The capital requirement for this alternative is estimated to be \$355,000, as developed in Table D-8.2-2. The present worth of the operating cost is estimated to be \$4,372,700, as developed in Table D-8.2-3. The present worth of the alternative is estimated to be \$4,727,700.

### D-8.3. UV/Oxidation plus GAC Treatment of the Liquid Phase

The process flow diagram for this alternative is shown in Figure D-5. The description and costs for the major equipment items are given in Table D-8.3-1. The capital requirement for this alternative is estimated to be \$642,400, as developed in Table D-8.3-2. The present worth of the operating cost is estimated to be \$3,256,900, as developed in Table D-8.3-3. The present worth of the alternative is estimated to be \$3,899,300.

Although *in situ* bioremediation has reportedly been successful in some highly publicized cases, we find no documentation of success in distributing the required microbes and nutrients at a site as deep as the ground water at the LLNL gas spill. There are also concerns regarding potential interference by inorganic ions, especially iron, which may be present in sufficient natural concentrations to inhibit microbial growth. Consequently, we do not feel as confident of the long-term applicability of *in situ* bioremediation as for the other technologies discussed.

Because *in situ* bioremediation is only applicable to FHCs, it would have to be applied in addition to separate treatment of the VOCs and possibly lead. If, however, the FHCs were remediated separately with bioremediation, the VOC treatment system could be scaled back to treat an influent somewhat equivalent to that shown for TFD. Because the pilot study remediation is likely to have reduced FHC concentrations substantially by the time of the approved Record of Decision, the practicality of separate bioremediation will have to be reexamined at that time.

Rather than present a table of costs, we have discussed the LLNL situation with two firms who design and install bioremediation systems; both for aboveground bioreactors and for *in situ* operations. Bioremediation is planned as one of the approved approaches at the EPA superfund site in Montana that may be comparable to the LLNL gasoline spill. According to the consultant who designed the bioremediation system, a pilot study involving two injection wells and two monitor wells cost about \$200,000 for a year of operation. Full-scale remediation to be implemented as a result of the ROD is estimated to cost about \$4 million over a 10-y period of operation. This order of expense, added to the costs of setting up a separate facility for treatment of the VOCs and possibly lead, make this alternative unattractive for LLNL at this time.

## **D-9. TREATMENT FACILITY G**

The design basis for the alternatives evaluated for Treatment Facility G is given in Table D-9. The only chemicals of concern anticipated in the ground water at Treatment Facility G are VOCs. The alternatives considered for Treatment Facility G are GAC treatment of the liquid phase, air stripping with GAC treatment of the vapor phase, and UV/oxidation plus air stripping with GAC treatment of the vapor phase. Each is discussed below.

### **D-9.1. GAC Treatment**

The process flow diagram for this alternative is shown in Figure D-1. The description and costs for the major equipment items are given in Table D-9.1-1. The capital requirement for this alternative is estimated to be \$245,000, as developed in Table D-9.1-2. The present worth of the operating cost is estimated to be \$1,327,700, as developed in Table D-9.1-3. The present worth of the alternative is estimated to be \$1,572,700.

### **D-9.2. Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-2. The description and costs for the major equipment items are given in Table D-9.2-1. The capital requirement for this alternative is estimated to be \$149,000, as developed in Table D-9.2-2. The present worth of the operating cost is estimated to be \$1,060,100, as developed in Table D-9.2-3. The present worth of the alternative is estimated to be \$1,209,100.

### **D-9.3. UV/oxidation plus Air Stripping with GAC Treatment of the Vapor Effluent**

The process flow diagram for this alternative is shown in Figure D-3. The description and costs for the major equipment items are given in Table D-9.3-1. The capital requirement for this alternative is estimated to be \$366,000, as developed in Table D-9.3-2. The present worth of

the operating cost is estimated to be \$1,898,600, as developed in Table D-9.3-3. The present worth of the alternative is estimated to be \$2,264,600.

## **D-10. TREATMENT AT THE POINT OF DISTRIBUTION IN CENTRAL LIVERMORE (TREATMENT FACILITY "L")**

The design basis for the alternatives evaluated for deferred remediation in central Livermore at the point of distribution is given in Table D-10. The chemicals of concern would be very low concentrations of VOCs; the transit time of the VOCs to central Livermore is estimated to be at least 200 y. The alternatives for Treatment Facility L are GAC, air stripping, and UV/oxidation. Each is discussed below. The inflow concentrations that were used to design the treatment systems are those predicted in the RI (Thorpe *et al.*, 1990) for the health-conservative case with a 10 to 1 dilution assumed to occur during extraction.

### **D-10.1. GAC Treatment**

The process flow diagram for this alternative is shown in Figure D-9. The description and costs for the major equipment items are given in Table D-10.1-1. The capital requirement for this alternative is estimated to be \$772,000 (no inflation considered; see Table D-10.1-2); the present worth equivalent (1990 value) is \$14,700 discounted at 2% (factor = 0.019, which is assumed to be the real cost of money over 200 y net of inflation). Annual operating expenses are estimated at \$894,700 (no inflation considered). If these are treated as the O&M costs for the other treatment facilities are treated, that is, discounted for 30 y (annual costs of \$894,700 from the year 2190 to the year 2220) at 5% (factor = 15.37), the total value of the O&M costs at the beginning of treatment in 200 y (year 2190) would be \$13,751,500. The present worth equivalent (1990 value) of these costs is \$261,300 discounted at 2% (factor = 0.019, which is assumed to be the real cost of money over 200 y net of inflation). The total 1990 value of this alternative is \$276,000 (see Table D-10.1-3), which is comparable to the total present worth of other alternatives for this and other treatment facilities.

### **D-10.2. Air Stripping**

The process flow diagram for this alternative is shown in Figure D-10. The description and costs for the major equipment items are given in Table D-10.2-1. The capital requirement for this alternative is estimated to be \$322,000 (no inflation considered; see Table D-10.2-2). The present worth equivalent (1990 value) is \$6,100 discounted at 2% (factor = 0.019, which is assumed to be the real cost of money over 200 y net of inflation). Annual operating expenses are estimated at \$86,600 (no inflation considered). If these are treated as the O&M costs for the other treatment facilities are treated, that is, discounted for 30 y (annual costs of \$86,600 from the year 2190 to the year 2220) at 5% (factor = 15.37), the total value of the O&M costs at the beginning of treatment in 200 y (year 2190) would be \$1,331,000. The present worth equivalent (1990 value) of these costs is \$25,300 discounted at 2% (factor = 0.019, which is assumed to be the real cost of money over 200 y net of inflation). The total 1990 value of this alternative is \$31,400 (see Table D-10.2-3), which is comparable to the total present worth of other alternatives for this and other treatment facilities.

### D-10.3. UV/Oxidation

The process flow diagram for this alternative is shown in Figure D-11. The description and costs for the major equipment items are given in Table D-10.3-1. The capital requirement for this alternative is estimated to be \$1,146,200 (no inflation considered; see Table D-10.3-2); the present worth equivalent (1990 value) is \$21,800 discounted at 2% (factor = 0.019, which is assumed to be the real cost of money over 200 y net of inflation). Annual operating expenses are estimated at \$538,200 (no inflation considered). If these are treated as the O&M costs for the other treatment facilities are treated, that is, discounted for 30 y (annual costs of \$538,200 from the year 2190 to the year 2220) at 5% (factor = 15.37), the total value of the O&M costs at the beginning of treatment in 200 y (year 2190) would be \$8,272,100. The present worth equivalent (1990 value) of these costs is \$157,200 discounted at 2% (factor = 0.019, which is assumed to be the real cost of money over 200 y net of inflation). The total 1990 value of this alternative is \$179,000 (see Table D-10.2-3), which is comparable to the total present worth of other alternatives for this and other treatment facilities.

Table D-3. Design criteria for Treatment System A.

Chemical species	Inlet concentrations (average flow rate = 150 gpm) (ppb) <sup>a</sup>	
	Maximum	Average
PCE	350	280
TCE	9	7
1,1-DCE	15	12
1,2-DCE	5	4
1,1,1-TCA	6	5
1,1-DCA	6	5
Chloroform	13	10
Freon 113	6	5
<b>Total VOCs</b>	<b>410</b>	<b>328</b>

<sup>a</sup>From Table 3-8.

Table D-3.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility A.

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels, 10-ft diam, 12 ft height, and 20,000 lb GAC per vessel	210,000
<b>Total Major Purchased Equipment Cost</b>		<b>210,000</b>

**Table D-3.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility A.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	210,000
Piping, concrete, steel (46% of MPEC)	96,600
Electrical, instrumentation (12% of MPEC)	25,200
Installation labor (58% of MPEC)	121,800
Major Equipment Installed Cost (MEIC)	453,600
Site preparation (10% of MEIC)	45,400
Total Field Cost (TFC)	499,000
Contractors' overhead and profit (10% of TFC)	49,900
Engineering design	50,000
Permitting	10,000
Subtotal	608,900
Contingency (20% of subtotal)	121,800
<b>Total (TCR)</b>	<b>731,000</b>

**Table D-3.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility A.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			14,600	
Subtotal			<u>60,600</u>	
Present worth (factor, 30 y @ 5% = 15.37)				<u><u>931,400</u></u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	32,000/unit	11.6 units	<u>371,200</u>	
Present worth (factor, @5% = 4.33)				1,607,300
Annual costs, years 6 through 10				
Replacement of GAC	32,000/unit	7.7 units	<u>246,400</u>	
Present worth (factor, @5% = 3.39)				835,300
Annual costs, years 11 through 15				
Replacement of GAC	32,000/unit	5.1 units	<u>163,200</u>	
Present worth (factor, @5% = 2.66)				434,100
Annual costs, years 16 through 20				
Replacement of GAC	32,000/unit	3.3 units	<u>105,600</u>	
Present worth (factor, @5% = 2.08)				219,600
Annual costs, years 21 through 25				
Replacement of GAC	32,000/unit	2.2 units	<u>70,400</u>	
Present worth (factor, @5% = 1.63)				114,800
Annual costs, years 26 through 30				
Replacement of GAC	32,000/unit	1.5 units	<u>48,000</u>	
Present worth (factor, @5% = 1.28)				<u>61,400</u>

Table D-3.1-3 (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Present worth of variable operating costs				3,272,500
Subtotal of present worth of fixed and variable operating and maintenance costs				4,203,900
Contingency (20% of subtotal)				840,800
Present worth of total 30-y operating cost				5,045,000
Total Capital Requirement (TCR)				731,000
Present worth of alternative (30-y operation)				5,776,000
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				731,000
Present worth of O & M, years 1 through 30			5,045,000	
Fixed annual O & M costs, years 31 through 87	60,600			
Present worth (factor, @ 5% = 4.34)		263,000		
Variable annual O & M costs, years 31 through 87	48,000			
Present worth (factor, @ 5% = 4.34)		208,300		
Subtotal of O & M costs, years 31 through 87		471,300		
Contingency (20% of subtotal)		94,300		
Present worth of O & M costs, years 31 through 87			565,600	
Present worth of fixed and variable annual O & M costs, years 1 through 87				5,610,600
Present worth of GAC at Treatment Facility A under Extraction Alternative No. 2				6,341,600

**Table D-3.2-1. Major Purchased Equipment Cost for air stripper with GAC vapor treatment for Treatment Facility A.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 40-in. diam; depth of 24 ft of 2-in. Jaeger Tri-Pak packing	25,300
Air supply feed blower	Centrifugal fan, 500 cfm at 4-in. water pressure with 1-hp motor	1,500
Treated liquid discharge pump	End-suction centrifugal pump, 145 gpm at 50 ft TDH with 5-hp motor	1,200
Air-stripper vapor exhaust blower	Centrifugal fan, 500 cfm at 4-in. water pressure with 1-hp motor	1,500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel, 48-in. diam by 86 in., contains 1,800 lb of GAC	10,500
<b>Total Major Purchased Equipment Cost</b>		<b>40,500</b>

**Table D-3.2-2. Total Capital Requirement (TCR) for an air stripper with GAC vapor treatment for Treatment Facility A.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	40,500
Piping, concrete, steel (46% of MPEC)	18,600
Electrical, instrumentation (12% of MPEC)	4,900
Installation labor (58% of MPEC)	23,500
Major Equipment Installed Cost (MEIC)	87,500
Site preparation (10% of MEIC)	8,800
Total Field Cost (TFC)	96,300
Contractors' overhead and profit (10% of TFC)	9,600
Engineering design	50,000
Permitting	20,000
Subtotal	175,900
Contingency (20% of subtotal)	35,200
Total (TCR)	211,100

**Table D-3.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper with GAC vapor treatment for Treatment Facility A.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	58,894 kW-h	4,100	
Electrical capacity charge	36/kW	7.5 kW	300	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			4,200	
Subtotal			<u>54,600</u>	
Present worth (factor, 30 y @ 5% = 15.37)				<u><u>839,200</u></u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	7.8 units	<u>32,800</u>	
Present worth (factor, @ 5% =4.33)				142,000
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	5.5 units	<u>23,100</u>	
Present worth (factor, @ 5% =3.39)				78,300
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	3.9 units	<u>16,400</u>	
Present worth (factor, @ 5% =2.66)				43,600
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.8 units	<u>11,800</u>	
Present worth (factor, @ 5% =2.08)				24,500
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	2 units	<u>8,400</u>	
Present worth (factor, @ 5% =1.63)				13,700

Table D-3.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.4 units	5,900	
Present worth (factor, @ 5% = 1.28)				7,600
Present worth of variable operating costs				309,700
Subtotal of present worth of fixed and variable operating and maintenance costs				1,148,900
Contingency (20% of subtotal)				229,800
Present worth of total 30-y operating and maintenance cost				1,378,700
Total Capital Requirement (TCR)				211,100
Present worth of alternative (30-y operation)				1,589,800
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				211,100
Present worth of O & M, years 1 through 30			1,378,800	
Fixed annual O & M costs, years 31 through 87	54,600			
Present worth (factor, @ 5% = 4.34)		237,000		
Variable annual O & M costs, years 31 through 87	5,900			
Present worth (factor, @ 5% = 4.34)		25,600		
Subtotal of O & M costs, years 31 through 87			262,600	
Contingency (20% of subtotal)			52,500	
Present worth of O & M costs, years 31 through 87			315,100	
Present worth of fixed and variable annual O & M costs, years 1 through 87				1,693,800
Present worth of AS at Treatment Facility A, Extraction Alternative No. 2				1,904,900

**Table D-3.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripper system with GAC vapor treatment for Treatment Facility A.**

<b>Equipment</b>	<b>Description</b>	<b>Cost (1990 \$)</b>
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	1,250
UV/oxidation chamber	Single-chambered, baffled, 316-L stainless steel, 240-gal, skid-mounted, 4 ft $\times$ 8 ft $\times$ 8 ft, high-intensity-UV/oxidation chamber	120,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 550-gal, double-walled, cross-linked, polyethylene, 4 ft-4-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripper) vessel	Closed-top, cylindrical, 5,600-gal, cross-linked polyethylene, 11-ft 10-in. diam $\times$ 7-ft tall, four-chambered, baffled aeration vessel fitted with perforated PVC air-supply pipe	5,100
Volatilization system vapor feed blower	Centrifugal fan, 220 cfm at 4-in. water pressure; 1/2-hp motor	800
Carbon system vapor feed blower	Centrifugal fan, 220 cfm at 4-in. water pressure; 1/2-hp motor	800
Treated liquid discharge pump	End-suction centrifugal pump, 145 gpm at 50 ft TDH; 5-hp motor	1,200
Carbon system vapor heater	2000 W, inline duct heater	500
Fixed-bed GAC chamber		600
<b>Total Major Purchased Equipment Cost</b>		<b>130,800</b>

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-3.3-2. Total Capital Requirement (TCR) for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility A.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	130,800
Piping, concrete, steel (46% of MPEC)	60,100
Electrical, instrumentation (12% of MPEC)	15,700
Installation labor (58% of MPEC)	75,800
Major Equipment Installed Cost (MEIC)	282,400
Site preparation (10% of MEIC)	28,200
Total Field Cost (TFC)	310,600
Contractors' overhead and profit (10% of TFC)	31,100
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	411,700
Contingency (20% of subtotal)	82,300
Total (TCR)	494,000

**Table D-3.3-3. Operating and maintenance cost estimate and present worth analysis of a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility A.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	75 filters	3,800	
UV/oxidation maintenance	10% of UV/Ox unit	120,000	12,000	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			9,900	
Subtotal			71,700	
Present worth (factor @ 5% = 15.37)				1,102,000
<i>Variable Operating Costs</i>				
Annual costs, years 1 through 5				
Electricity	0.07/kW-h	984,712 kW-h	68,900	
Electrical use fee	36/W	125 W	4,500	
Hydrogen peroxide	0.62/lb	57,136 lb	35,400	
Replacement GAC unit	600/change	1.5/y	900	
Subtotal			109,700	
Present worth (factor @ 5% = 4.33)				475,000
Annual costs, years 6 through 10				
Electricity	0.07/kW-h	984,712 kW-h	68,900	
Electrical use fee	36/W	125 W	4,500	
Hydrogen peroxide	0.62/lb	57,136 lb	35,400	
Replacement GAC unit	600/change	1.5/y	900	
Subtotal			109,700	
Present worth (factor @ 5% = 3.39)				371,900

Table D-3.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 11 through 15</b>				
Electricity	0.07/kW-h	984,712 kW-h	68,900	
Electrical use fee	36/W	125 W	4,500	
Hydrogen peroxide	0.62/lb	57,136 lb	35,400	
Replacement GAC unit	600/change	1.5/y	900	
Subtotal			<u>109,700</u>	
Present worth (factor @ 5% = 2.66)				291,800
<b>Annual costs, years 16 through 20</b>				
Electricity	0.07/kW-h	492,356 kW-h	34,500	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	28,568 lb	17,700	
Replacement GAC unit	600/change	0.75/y	500	
Subtotal			<u>54,900</u>	
Present worth (factor @ 5% = 2.08)				114,200
<b>Annual costs, years 21 through 25</b>				
Electricity	0.07/kW-h	492,356 kW-h	34,500	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	28,568 lb	17,700	
Replacement GAC unit	600/change	0.75/y	500	
Subtotal			<u>54,900</u>	
Present worth (factor @ 5% = 1.63)				89,500
<b>Annual costs, years 26 through 30</b>				
Electricity	0.07/kW-h	492,356 kW-h	34,500	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	28,568 lb	17,700	
Replacement GAC unit	600/change	0.75/y	500	
Subtotal			<u>54,900</u>	
Present worth (factor @ 5% = 1.28)				70,300
Present worth of variable operating costs				<u><u>1,412,700</u></u>

Table D-3.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,514,700
Contingency (20% of subtotal)				502,900
Present worth of total 30-y operating and maintenance costs				3,017,600
Total Capital Requirement (TCR)				494,000
Present worth of alternative (30-y operation)				3,511,600
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				494,000
Present worth of O & M, years 1 through 30			3,017,600	
Fixed annual O & M costs, years 31 through 87	71,700			
Present worth (factor, @ 5% = 4.34)		311,200		
Variable annual O & M costs, years 31 through 87	54,900			
Present worth (factor, @ 5% = 4.34)		238,300		
Subtotal of O & M costs, years 31 through 87		549,500		
Contingency (20% of subtotal)		109,900		
Present worth of O & M costs, years 31 through 87			659,400	
Present worth of fixed and variable annual O & M costs, years 31 through 87				3,677,000
Present worth of UV/Ox at Treatment Facility A under Extraction Alternative No. 2				4,171,000

Table D-4. Design criteria for Treatment System B.

Chemical species	Inlet concentrations (average flow rate = 50 gpm) (ppb) <sup>a</sup>	
	Maximum	Average
PCE	50	40
TCE	375	300
1,1-DCE	13	10
1,2-DCE	4	3
1,1,1-TCA	1	1
1,1-DCA	6	5
1,2-DCA	1	1
Carbon tetrachloride	3	2
Chloroform	13	10
Freon 113	13	10
<b>Total VOCs</b>	<b>479</b>	<b>382</b>

<sup>a</sup>From Table 3-8.

Table D-4.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility B.

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels, 7.5-ft diam, 10 ft height, and 10,000 lb GAC per vessel	120,000
<b>Total Major Purchased Equipment Cost</b>		<b>120,000</b>

**Table D-4.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility B.**

<b>Equipment</b>	<b>Cost (1990 \$)</b>
Major Purchased Equipment Cost (MPEC)	120,000
Piping, concrete, steel (46% of MPEC)	55,200
Electrical, instrumentation (12% of MPEC)	14,400
Installation labor (58% of MPEC)	69,600
Major Equipment Installed Cost (MEIC)	259,200
Site preparation (10% of MEIC)	25,900
Total Field Cost (TFC)	285,100
Contractors' overhead and profit (10% of TFC)	28,500
Engineering design	50,000
Permitting	10,000
Subtotal	373,600
Contingency (20% of subtotal)	74,700
Total (TCR)	448,000

**Table D-4.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility B.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			9,000	
Subtotal			<u>55,000</u>	
Present worth (factor, 30 y @ 5% = 15.37)				<u>854,400</u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	16,000/unit	12 units	<u>192,000</u>	
Present worth (factor, @5% = 4.33)				831,400
Annual costs, years 6 through 10				
Replacement of GAC	16,000/unit	7.9 units	<u>126,400</u>	
Present worth (factor, @5% = 3.39)				428,500
Annual costs, years 11 through 15				
Replacement of GAC	16,000/unit	5.2 units	<u>83,200</u>	
Present worth (factor, @5% = 2.66)				221,300
Annual costs, years 16 through 20				
Replacement of GAC	16,000/unit	3.5 units	<u>56,000</u>	
Present worth (factor, @5% = 2.08)				116,500
Annual costs, years 21 through 25				
Replacement of GAC	16,000/unit	2.3 units	<u>36,800</u>	
Present worth (factor, @5% = 1.63)				60,000
Annual costs, years 26 through 30				
Replacement of GAC	16,000/unit	1.5 units	<u>24,000</u>	
Present worth (factor, @5% = 1.28)				30,700
Present worth of variable operating costs				<u>1,688,400</u>

Table D-4.1-3 (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,533,800
Contingency (20% of subtotal)				506,600
Present worth of total 30-y operating cost				3,041,000
Total Capital Requirement (TCR)				448,000
Present worth of alternative				3,489,000
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				448,000
Present worth of O & M, years 1 through 30			3,041,000	
Fixed annual O & M costs, years 31 through 87	55,000			
Present worth (factor, @ 5% = 4.34)		238,700		
Variable annual O & M costs, years 31 through 87	24,000			
Present worth (factor, @ 5% = 4.34)		104,200		
Subtotal of O & M costs, years 31 through 87		342,900		
Contingency (20% of subtotal)		68,600		
Present worth of O & M costs, years 31 through 87			411,500	
Present worth of fixed and variable annual O & M costs, years 1 through 87				3,452,500
Present worth of GAC at Treatment Facility B under Extraction Alternative No. 2				3,900,500

**Table D-4.2-1. Major Purchased Equipment Cost for air stripper with GAC vapor treatment for Treatment Facility B.**

Equipment	Description	Equipment cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 24-in. diam, depth of 21 ft of 2-in. Jaeger Tri-Pak packing	17,400
Air supply feed blower	Centrifugal fan, 600 cfm at 4-in. water pressure with 1-hp motor	1,600
Treated liquid discharge pump	End-suction centrifugal pump, 55 gpm at 50 ft TDH with 1-hp motor	500
Air-stripper vapor exhaust blower	Centrifugal fan, 600 cfm at 4-in. water pressure with 1-hp motor	1,500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48-in. diam by 86 in., contains 1800 lb of GAC	10,500
<b>Total Major Purchased Equipment Cost</b>		<b>32,000</b>

**Table D-4.2-2. Total Capital Requirement (TCR) for air stripper with GAC vapor treatment for Treatment Facility B.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	32,000
Piping, concrete, steel (46% of MPEC)	14,700
Electrical, instrumentation (12% of MPEC)	3,800
Installation labor (58% of MPEC)	18,600
Major Equipment Installed Cost (MEIC)	69,100
Site preparation (10% of MEIC)	6,900
Total Field Cost (TFC)	76,000
Contractor's overhead and profit (10% of TFC)	7,600
Engineering design	50,000
Permitting	20,000
Subtotal	153,600
Contingency (20% of subtotal)	30,700
<b>Total (TCR)</b>	<b>184,000</b>

**Table D-4.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper with GAC vapor treatment for Treatment Facility B.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	57,520 kW-h	4,000	
Electrical capacity charge	36/kW	7.3 kW	300	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			3,700	
Subtotal			54,000	
Present worth (factor, 30 y @ 5% = 15.37)				830,000
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	7.5 units	31,500	
Present worth (factor, @ 5% =4.33)				136,400
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	5.3 units	22,300	
Present worth (factor, @ 5% =3.39)				75,600
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	3.7 units	15,500	
Present worth (factor, @ 5% =2.66)				41,200
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.6 units	10,900	
Present worth (factor, @ 5% =2.08)				22,700
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	1.9 units	8,000	
Present worth (factor, @ 5% =1.63)				13,000

Table D-4.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.3 units	5,500	
Present worth (factor, @ 5% = 1.28)				7,000
Present worth of variable operating costs				295,900
Subtotal of present worth of fixed and variable operating and maintenance costs				1,125,400
Contingency (20% of subtotal)				225,200
Present worth of total 30-y operating and maintenance cost				1,351,000
Total Capital Requirement (TCR)				184,000
Present worth of alternative				1,535,000
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				184,000
Present worth of O & M, years 1 through 30			1,351,000	
Fixed annual O & M costs, years 31 through 87	53,970			
Present worth (factor, @ 5% = 4.34)		234,200		
Variable annual O & M costs, years 31 through 87	5,460			
Present worth (factor, @ 5% = 4.34)		23,700		
Subtotal of O & M costs, years 31 through 87		257,900		
Contingency (20% of subtotal)		51,600		
Present worth of O & M costs, years 31 through 87			309,500	
Present worth of fixed and variable annual O & M costs, years 1 through 87				1,660,500
Present worth of AS at Treatment Facility B, Extraction Alternative No. 2				1,844,500

**Table D-4.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility B.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter.	500
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80 gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 200-gal, double-walled, cross-linked, polyethylene, 2-ft 6-in. diam $\times$ 5-ft vessel	(a)
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump.	500
Volatilization (air stripper) vessel	Closed-top cylindrical, 2,000 gal, cross-linked polyethylene, 7-ft 6-in. diam $\times$ 7-ft tall, four-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,800
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 55 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	800 W, inline duct heater	500
Fixed-bed GAC chamber		600
<b>Total Major Purchased Equipment Cost</b>		<b>90,400</b>

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-4.3-2. Total Capital Requirement (TCR) for UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility B.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	90,400
Piping, concrete, steel (46% of MPEC)	41,600
Electrical, instrumentation (12% of MPEC)	10,800
Installation labor (58% of MPEC)	52,400
Major Equipment Installed Cost (MEIC)	<u>195,200</u>
Site preparation (10% of MEIC)	19,500
Total Field Cost (TFC)	<u>214,700</u>
Contractors' overhead and profit (10% of TFC)	21,500
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	<u>306,200</u>
Contingency (20% of subtotal)	61,200
Total (TCR)	<u><u>367,400</u></u>

**Table D-4.3-3. Operating and maintenance cost estimate and present worth analysis for an UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility B.**

<b>Analysis of Extraction Alternative No. 1: facility operated for 30 y</b>				
<b>Item</b>	<b>Rate (1990 \$)</b>	<b>Usage</b>	<b>Subtotal present worth (1990 \$)</b>	<b>Total present worth (1990 \$)</b>
<i>Fixed annual operating and maintenance costs</i>				
<b>Annual costs:</b>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	29 filters	1,400	
UV/oxidation maintenance	10% of UV/Ox unit	85,000	8,500	
<b>Sample analysis:</b>				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
<b>Subtotal</b>			<b>63,200</b>	
<b>Present worth (factor @ 5% = 15.37)</b>				<b>971,400</b>
<i>Variable Operating costs</i>				
<b>Annual cost, years 1 through 5</b>				
Electricity	0.07/kW-h	490,385 kW-h	34,300	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	21,672 lb	13,400	
Replacement GAC unit	600/change	0.55/y	300	
<b>Subtotal</b>			<b>50,200</b>	
<b>Present worth (factor @ 5% = 4.33)</b>				<b>217,400</b>
<b>Annual cost, years 6 through 10</b>				
Electricity	0.07/kW-h	490,385 kW-h	34,300	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	21,672 lb	13,400	
Replacement GAC unit	600/change	0.55/y	300	
<b>Subtotal</b>			<b>50,200</b>	
<b>Present worth (factor @ 5% = 3.39)</b>				<b>170,200</b>

Table D-4.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	490,385 kW-h	34,300	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	21,672 lb	13,400	
Replacement GAC unit	600/change	0.55/y	300	
Subtotal			<u>50,200</u>	
Present worth (factor @ 5% = 2.66)				133,500
<b>Annual costs, years 16 through 20</b>				
Electricity	0.07/kW-h	245,193kW-h	17,200	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	10,836 lb	6,700	
Replacement GAC unit	600/change	0.275/y	200	
Subtotal			<u>25,200</u>	
Present worth (factor @ 5% = 2.08)				52,400
<b>Annual costs, years 21 through 25</b>				
Electricity	0.07/kW-h	245,193kW-h	17,200	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	10,836 lb	6,700	
Replacement GAC unit	600/change	0.275/y	200	
Subtotal			<u>25,200</u>	
Present worth (factor @ 5% = 1.63)				41,100
<b>Annual costs, years 26 through 30</b>				
Electricity	0.07/kW-h	245,193kW-h	17,200	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	10,836 lb	6,700	
Replacement GAC unit	600/change	0.275/y	200	
Subtotal			<u>25,200</u>	
Present worth (factor @ 5% = 1.28)				32,300
Present worth of variable operating costs				<u><u>646,900</u></u>

Table D-4.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,618,300
Contingency (20% of subtotal)				323,700
Present worth of total 30-y operating and maintenance costs				1,942,000
Total Capital Requirement (TCR)				367,400
Present worth of alternative (30-y operation)				2,309,400
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				367,400
Present worth of O & M, years 1 through 30			1,942,000	
Fixed annual O & M costs, years 31 through 87	63,200			
Present worth (factor, @ 5% = 4.34)		274,300		
Variable annual O & M costs, years 31 through 87	25,200			
Present worth (factor, @ 5% = 4.34)		109,400		
Subtotal of O & M costs, years 31 through 87		383,700		
Contingency (20% of subtotal)		76,700		
Present worth of O & M costs, years 31 through 87			460,400	
Present worth of fixed and variable annual O & M costs, years 31 through 87				2,402,400
Present worth of UV/Ox at Treatment Facility B under Extraction Alternative No.2				2,769,800

**Table D-5. Parameter values used to design remediation alternatives for Treatment Facility C.**

Chemical species	Inlet concentrations (average flow rate = 20 gpm) (ppb)	
	Maximum	Average
PCE	6	5
TCE	25	20
1,1-DCE	3	2
Chloroform	4	3
Freon 113	125	100
<b>Total VOCs</b>	<b>163</b>	<b>130</b>

**Table D-5.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility C.**

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels, 7.5-ft diam, 12 ft height, and 10,000 lb GAC per vessel	120,000
<b>Total Major Purchased Equipment Cost</b>		<b>120,000</b>

**Table D-5.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility C.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	120,000
Piping, concrete, steel (46% of MPEC)	55,200
Electrical, instrumentation (12% of MPEC)	14,400
Installation labor (58% of MPEC)	69,600
<b>Major Equipment Installed Cost (MEIC)</b>	<b>259,200</b>
Site preparation (10% of MEIC)	25,900
<b>Total Field Cost (TFC)</b>	<b>285,100</b>
Contractors' overhead and profit (10% of TFC)	28,500
Engineering design	50,000
Permitting	10,000
<b>Subtotal</b>	<b>373,600</b>
Contingency (20% of subtotal)	74,700
<b>Total (TCR)</b>	<b>448,000</b>

**Table D-5.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility C.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			9,000	
Fixed annual operating and maintenance cost			55,000	
Present worth (factor, 30 y @ 5% = 15.37)				845,400
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Replacement of GAC	16,000/unit	4.6 units	73,600	
Present worth (factor, @5% = 4.33)				318,700
Annual cost, years 6 through 10				
Replacement of GAC	16,000/unit	3 units	48,000	
Present worth (factor, @5% = 3.39)				162,700
Annual cost, years 11 through 15				
Replacement of GAC	16,000/unit	2 units	32,000	
Present worth (factor, @5% = 2.66)				85,100
Annual cost, years 16 through 20				
Replacement of GAC	16,000/unit	1.3 units	20,800	
Present worth (factor, @5% = 2.08)				43,300
Annual cost, years 21 through 25				
Replacement of GAC	16,000/unit	0.9 units	14,400	
Present worth (factor, @5% = 1.63)				23,500
Annual cost, years 26 through 30				
Replacement of GAC	16,000/unit	0.6 units	9,600	
Present worth (factor, @5% = 1.28)				12,300
Present worth of variable operating costs				645,600

Table D-5.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				1,491,000
Contingency (20% of subtotal)				298,200
Present worth of total 30-y operating cost				1,789,000
Total Capital Requirement (TCR)				448,000
Present worth of alternative (30-y operation)				2,237,000
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				448,000
Present worth of O & M, years 1 through 30			1,789,000	
Fixed annual O & M costs, years 31 through 87	55,000			
Present worth (factor, @ 5% = 4.34)		238,700		
Variable annual O & M costs, years 31 through 87	9,600			
Present worth (factor, @ 5% = 4.34)		41,700		
Subtotal of O & M costs, years 31 through 87		280,400		
Contingency (20% of subtotal)		56,100		
Present worth of O & M costs, years 31 through 87			336,500	
Present worth of fixed and variable annual O & M costs, years 1 through 87				2,125,500
Present worth of GAC at Treatment Facility C under Extraction Alternative No. 2				2,573,500

**Table D-5.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility C.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 12-in. diam, depth of 25 ft of 1-in. Jaeger Tri-Pak packing	8,500
Air supply feed blower	Centrifugal fan, 70 cfm at 4-in. water pressure with 1/4-hp motor.	500
Treated liquid discharge pump	End-suction centrifugal pump, 20 gpm at 50 ft TDH with 3/4-hp motor	400
Air-stripper vapor exhaust blower	Centrifugal fan, 70 cfm at 4-in. water pressure with 1/4-hp motor	500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48-in. diam by 63 in., contains 1,000 lb of GAC	6,600
<b>Total Major Purchased Equipment Cost</b>		<b>17,000</b>

**Table D-5.2-2. Total Capital Requirement (TCR) for air stripper with GAC vapor treatment for Treatment Facility C.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	17,000
Piping, concrete, steel (46% of MPEC)	7,800
Electrical, instrumentation (12% of MPEC)	2,000
Installation labor (58% of MPEC)	9,900
Major Equipment Installed Cost (MEIC)	36,700
Site preparation (10% of MEIC)	3,700
Total Field Cost (TFC)	40,400
Contractors' overhead and profit (10% of TFC)	4,000
Engineering design	50,000
Permitting	20,000
Subtotal	114,400
Contingency (20% of subtotal)	22,900
Total (TCR)	137,000

**Table D-5.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility C.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	8212 kW-h	570	
Electrical capacity charge	36/kW	1.0 kW	40	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			2,700	
Subtotal			49,300	
Present worth (factor, 30 y @ 5% = 15.37)				757,700
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	2,500/unit	1.1 units	2,800	
Present worth (factor, @ 5% = 4.33)				12,100
Annual costs, years 6 through 10				
Replacement of GAC	2,500/unit	0.8 units	2,000	
Present worth (factor, @ 5% = 3.39)				6,800
Annual costs, years 11 through 15				
Replacement of GAC	2,500/unit	0.6 units	1,500	
Present worth (factor, @ 5% = 2.66)				4,000
Annual costs, years 16 through 20				
Replacement of GAC	2,500/unit	0.4 units	1,000	
Present worth (factor, @ 5% = 2.08)				2,100
Annual costs, years 21 through 25				
Replacement of GAC	2,500/unit	0.3 units	800	
Present worth (factor, @ 5% = 1.63)				1,300

Table D-5.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	2,500/unit	0.2 units	500	
Present worth (factor, @ 5% = 1.28)				600
Present worth of variable operating costs				26,900
Subtotal of present worth of fixed and variable operating and maintenance costs				784,600
Contingency (20% of subtotal)				156,900
Present worth of total 30-y operating cost				942,000
<b>Total Capital Requirement (TCR)</b>				<b>137,000</b>
Present worth of alternative (30-y operation)				1,079,000
<b>Analysis of Extraction Alternative No. 2: facility operated for 87 y</b>				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Total Capital Requirement (TCR)</b>				<b>137,000</b>
Present worth of O & M, years 1 through 30			942,000	
Fixed annual O & M costs, years 31 through 87	49,300			
Present worth (factor, @ 5% = 4.34)		214,000		
Variable annual O & M costs, years 31 through 87	500			
Present worth (factor, @ 5% = 4.34)		2,200		
Subtotal of O & M costs, years 31 through 87			216,200	
Contingency (20% of subtotal)			43,200	
Present worth of O & M costs, years 31 through 87			259,400	
Present worth of fixed and variable annual O & M costs, years 1 through 87				1,201,400
Present worth of AS at Treatment Facility C, Extraction Alternative No. 2				1,338,400

**Table D-5.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripping system, with GAC vapor treatment, for Treatment Facility C.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	200
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80-gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 100-gal, double-walled, cross-linked, polyethylene, 2-ft diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump.	500
Volatilization (air stripper) vessel	Closed-top cylindrical, 750-gal, cross-linked polyethylene, 6-ft 8-in. diam $\times$ 3-ft 6-in. tall, four-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	900
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 25 gpm at 50 ft TDH; 3/4-hp motor	400
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
<b>Total Major Purchased Equipment Cost</b>		<b>89,100</b>

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-5.3-2. Total Capital Requirement (TCR) for a UV/oxidation and air stripping system, with GAC vapor treatment, for Treatment Facility C.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	89,100
Piping, concrete, steel (46% of MPEC)	41,000
Electrical, instrumentation (12% of MPEC)	10,700
Installation labor (58% of MPEC)	51,700
Major Equipment Installed Cost (MEIC)	192,500
Site preparation (10% of MEIC)	19,300
Total Field Cost (TFC)	211,800
Contractors' overhead and profit (10% of TFC)	21,200
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	303,000
Contingency (20% of subtotal)	60,600
<b>Total (TCR)</b>	<b>363,600</b>

**Table D-5.3-3. Operating and maintenance cost estimate and present worth analysis for a UV/oxidation and air stripping system, with GAC vapor treatment, for Treatment Facility C.**

<b>Analysis of Extraction Alternative No. 1: facility operated for 30 y</b>				
<b>Item</b>	<b>Rate (1990 \$)</b>	<b>Usage</b>	<b>Subtotal present worth (1990 \$)</b>	<b>Total present worth (1990 \$)</b>
<b>Fixed operating and maintenance costs</b>				
<b>Annual costs:</b>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	10 filters	500	
UV/oxidation maintenance	10% of UV/Ox unit	85,000	8,500	
<b>Sample analysis:</b>				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
<b>Subtotal</b>			<b>62,300</b>	
<b>Present worth (30 y, factor @ 5% = 15.37)</b>				<b>957,600</b>
<b>Variable operating costs</b>				
<b>Annual cost, years 1 through 5</b>				
Electricity	0.07/kW-h	486,443 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	7,881 lb	4,900	
Replacement GAC unit	600/change	0.2/y	100	
<b>Subtotal</b>			<b>41,300</b>	
<b>Present worth (factor @ 5% = 4.33)</b>				<b>178,800</b>
<b>Annual cost, years 6 through 10</b>				
Electricity	0.07/kW-h	486,443 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	7,881 lb	4,900	
Replacement GAC unit	600/change	0.2/y	100	
<b>Subtotal</b>			<b>41,300</b>	
<b>Present worth (factor @ 5% = 3.39)</b>				<b>140,000</b>

Table D-5.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	486,443 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	7,881 lb	4,900	
Replacement GAC unit	600/change	0.2/y	100	
Subtotal			<u>41,300</u>	
Present worth (factor @ 5% = 2.66)				109,900
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	243,222 kW-h	17,000	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	3,941 lb	2,400	
Replacement GAC unit	600/change	0.1/y	100	
Subtotal			<u>20,600</u>	
Present worth (factor @ 5% = 2.08)				42,800
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	243,222 kW-h	17,000	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	3,941 lb	2,400	
Replacement GAC unit	600/change	0.1/y	100	
Subtotal			<u>20,600</u>	
Present worth (factor @ 5% = 1.63)				33,600
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	243,222 kW-h	17,000	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	3,941 lb	2,400	
Replacement GAC unit	600/change	0.1/y	100	
Subtotal			<u>20,600</u>	
Present worth (factor @ 5% = 1.28)				26,400
Present worth of variable operating costs				<u><u>531,500</u></u>

Table D-5.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,489,100
Contingency (20% of subtotal)				297,800
Present worth of total 30-y operating and maintenance costs				1,786,900
Total Capital Requirement (TCR)				363,600
Present worth of alternative (30-y operation)				2,150,500
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				363,600
Present worth of O & M, years 1 through 30			1,786,900	
Fixed annual O & M costs, years 31 through 87	62,300			
Present worth (factor, @ 5% = 4.34)		270,400		
Variable annual O & M costs, years 31 through 87	20,600			
Present worth (factor, @ 5% = 4.34)		89,400		
Subtotal of O & M costs, years 31 through 87		359,800		
Contingency (20% of subtotal)		72,000		
Present worth of O & M costs, years 31 through 87			431,800	
Present worth of fixed and variable annual O & M costs, years 31 through 87				2,218,700
Present worth of UV/Ox at Treatment Facility C under Extraction Alternative No. 2				2,582,300

Table D-6. Design criteria for Treatment System D.

Chemical species	Inlet concentrations (average flow rate = 30 gpm) (ppb)	
	Maximum	Average
PCE	13	10
TCE	1,250	1,000
1,1-DCE	21	17
1,2-DCE	5	4
1,1,1-TCA	4	3
1,1-DCA	4	3
1,2-DCA	26	21
Carbon tetrachloride	38	30
Chloroform	162	130
Chromium	63	50
Freon 113	4	3
<b>Total VOCs</b>	<b>1,527</b>	<b>1,221</b>

Table D-6.1-1. Major Purchased Equipment Cost for a GAC and ion-exchange system for Treatment Facility D.

Equipment	Description	Cost (\$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system; two vessels 7.5-ft diam and 10 ft height; 10,000 lb GAC per vessel	120,000
Holding tank	Closed top, cylindrical tank, 600-gal capacity, cross-linked polyethylene, 4-ft diam × 7 ft 8 in.	1,700
Ion-exchange system feed pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH, 1-hp motor	500
Ion-exchange system	Skid-mounted, dual-column system, 30-in. diam × 96-in. columns each with 20-ft <sup>3</sup> anion resin. Includes caustic tank, regeneration pump, and waste chromium regeneration solution tank	33,000
<b>Total Major Purchased Equipment Cost</b>		<b>155,200</b>

**Table D-6.1-2. Total Capital Requirement (TCR) for a GAC and ion-exchange system for Treatment Facility D.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	155,200
Piping, concrete, steel (46% of MPEC)	71,400
Electrical, instrumentation (12% of MPEC)	18,600
Installation labor (58% of MPEC)	90,000
Major Equipment Installed Cost (MEIC)	<u>335,200</u>
Site preparation (10% of MEIC)	33,500
Total Field Cost (TFC)	<u>368,700</u>
Contractors' overhead and profit (10% of TFC)	36,900
Engineering design	50,000
Permitting	10,000
Subtotal	<u>465,600</u>
Contingency (20% of subtotal)	93,100
Total (TCR)	<u><u>558,700</u></u>

**Table D-6.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC and ion-exchange system for Treatment Facility D.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	3182 kW-h	200	
Electrical capacity charge	36/kW	0.4 kW	10	
Supervision Labor	75/h	200 h	15,000	
Operating Labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Water sample chromium analysis	50/sample	80 samples	4,000	
Caustic for ion-exchange regeneration	100/drum	35 drums	3,500	
Disposal of ion-exchange regeneration waste	100/drum	70 drums	7,000	
Maintenance (2% of TCR)			11,200	
Subtotal			71,900	
Present worth (factor, 30 y @ 5% = 15.37)				<u>1,105,100</u>
<i>Variable operating costs</i>				
Annual cost years 1 through 5				
Replacement of GAC	16,000/unit	9.6 units	153,600	
Present worth (factor, @5% = 4.33)				665,100
Annual cost years 6 through 10				
Replacement of GAC	16,000/unit	6.4 units	102,400	
Present worth (factor, @5% = 3.39)				347,100
Annual cost years 11 through 15				
Replacement of GAC	16,000/unit	4.2 units	67,200	
Present worth (factor, @5% = 2.66)				178,800
Annual cost years 16 through 20				
Replacement of GAC	16,000/unit	2.8 units	44,800	
Present worth (factor, @5% = 2.08)				93,200
Annual cost years 21 through 25				
Replacement of GAC	16,000/unit	1.8 units	28,800	
Present worth (factor, @5% = 1.63)				46,900

Table D-6.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost years 26 through 30</b>				
Replacement of GAC	16,000/unit	1.2 units	19,200	
Present worth (factor, @5% = 1.28)				24,600
Present worth of variable operating costs				1,355,700
Subtotal of present worth of fixed and variable operating and maintenance costs				2,466,800
Contingency (20% of subtotal)				492,200
Present worth of total 30-y operating cost				2,953,000
Total (TCR)				558,700
Present worth of alternative (30-y operation)				3,511,700

Table D-6.2-1. Major Purchased Equipment Cost for an air stripper, ion-exchange, and GAC vapor treatment for Treatment Facility D.

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 18-in. diam, depth of 22 ft of 1-in. Jaeger Tri-Pak packing	10,300
Air supply feed blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Air-stripper vapor exhaust blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 n. diam by 86 in., contains 1800 lb of GAC	10,500
Ion-exchange system feed pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH with 1-hp motor	500
Ion-exchange system	Skid-mounted, dual-column system, 30 in. diam × 96-in. columns each with 20-ft <sup>3</sup> anion resin; system includes caustic tank, regeneration pump, and waste chromium regeneration solution tank	33,000
Total Major Purchased Equipment Cost		56,800

**Table D-6.2-2. Total Capital Requirement (TCR) for an air stripper, ion-exchange, and GAC vapor treatment for Treatment Facility D.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	56,800
Piping, concrete, steel (46% of MPEC)	26,100
Electrical, instrumentation (12% of MPEC)	6,800
Installation labor (58% of MPEC)	32,900
Major Equipment Installed Cost (MEIC)	<u>122,600</u>
Site preparation (10% of MEIC)	12,300
Total Field Cost (TFC)	<u>134,900</u>
Contractor's overhead and profit (10% of TFC)	13,500
Engineering design	50,000
Permitting	20,000
Subtotal	<u>218,400</u>
Contingency (20% of subtotal)	43,700
Total (TCR)	<u><u>262,000</u></u>

**Table D-6.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper, ion exchange system with GAC vapor treatment for Treatment Facility D.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	31,032 kW-h	2,200	
Electrical capacity charge	36/kW	3.9 kW	100	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Water sample chromium analysis	50/sample	80 samples	4,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Caustic for ion exchange regeneration	100/drum	35/drums	3,500	
Disposal of ion-exchange regeneration waste	100/drum	70/drums	7,000	
Maintenance (2% of TCR)			5,200	
Subtotal			68,000	
Present worth (factor, 30 y @ 5% = 15.37)				<u>1,045,200</u>
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	6.8 units	28,600	
Present worth (factor, @ 5% =4.33)				123,800
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	4.8 units	20,200	
Present worth (factor, @ 5% =3.39)				68,500
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	3.4 units	14,300	
Present worth (factor, @ 5% =2.66)				38,000
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.4 units	10,100	
Present worth (factor, @ 5% =2.08)				21,000
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	1.7 units	7,100	
Present worth (factor, @ 5% = 1.63)				11,600

Table D-6.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.2 units	5,000	
Present worth (factor, @ 5% = 1.28)				6,400
Present worth of variable operating costs				269,300
Subtotal of present worth of fixed and variable operating and maintenance costs				1,314,500
Contingency (20% of subtotal)				262,900
Present worth of total 30-y operating cost				1,577,000
Total Capital Requirement (TCR)				262,000
Present worth of alternative (30-y operation)				1,839,000

Table D-6.3-1. Major Purchased Equipment Costs for a UV/oxidation, air stripping, ion-exchange system with GAC vapor treatment for Treatment Facility D.

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	250
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 800 gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top cylindrical, 150-gal, double-walled, cross-linked, polyethylene, 2-ft 3-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripper) vessel	Closed-top, cylindrical, 1,100-gal, cross-linked polyethylene, 5-ft 4-in. diam $\times$ 7-ft 1-in. tall, four-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,100
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4 in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4 in. water pressure; 1/4-hp motor	500
Liquid transfer pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
Ion-exchange system	Skid-mounted, dual-column system, 30 in. diam $\times$ 96-in. columns each with 20 ft <sup>3</sup> anion resin; includes caustic tank, regeneration pump, and waste chromium tank	33,000
Total Major Purchased Equipment Costs		122,500

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-6.3-2. Total Capital Requirement (TCR) for a UV/oxidation, air stripping, and ion-exchange system with GAC vapor treatment for Treatment Facility D.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	122,500
Piping, concrete, steel (46% of MPEC)	56,400
Electrical, instrumentation (12% of MPEC)	14,700
Installation labor (58% of MPEC)	71,100
Major Equipment Installed Cost (MEIC)	<u>264,700</u>
Site preparation (10% of MEIC)	26,500
Total Field Cost (TFC)	<u>291,200</u>
Contractor's overhead and profit (10% of TFC)	29,100
Engineering design	50,000
Permitting	20,000
Subtotal	<u>390,300</u>
Contingency (20% of subtotal)	78,100
Total (TCR)	<u><u>468,400</u></u>

**Table D-6.3-3. Operating and maintenance cost estimate and present worth analysis for a UV/oxidation, air stripping, ion-exchange system with GAC vapor treatment for Treatment Facility D.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
<b>Annual costs:</b>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	16 filters	800	
UV/oxidation maintenance contract	10% of UV/ox unit	120,000	12,000	
<b>Sample analysis:</b>				
VOC/FHC water samples	100/sample	80 samples	8,000	
Chromium water samples	50/sample	80 samples	4,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Caustic for ion-exchange regeneration	100/drum	35 drums	3,500	
Disposal of ion-exchange regeneration waste	100/drum	70 drums	7,000	
Maintenance (2% of TCR)			9,400	
Subtotal			<u>82,700</u>	
Present worth (factor @ 5% = 15.37)				<u><u>1,271,100</u></u>
<i>Variable operating costs</i>				
<b>Annual cost, years 1 through 5</b>				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			<u>43,800</u>	
Present worth (factor @ 5% = 4.33)				189,700
<b>Annual cost, years 6 through 10</b>				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			<u>43,800</u>	

Table D-6.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Present worth (factor @ 5% = 3.39)				148,500
Annual cost, years 11 through 15				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 2.66)				116,500
Annual cost, years 16 through 20				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 2.08)				45,800
Annual cost, years 21 through 25				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 1.63)				35,900
Annual cost, years 26 through 30				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			22,000	
Present worth (factor @ 5% = 1.28)				28,200
Present worth of variable operating costs				564,600

Table D-6.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				1,835,700
Contingency (20% of subtotal)				367,100
Present worth of total 30-y operating and maintenance costs				2,202,800
Total Capital Requirement (TCR)				468,400
Present worth of alternative (30-y operation)				2,671,200

Table D-7. Design criteria for Treatment System E.

Chemical species	Inlet concentrations (average flow rate = 30 gpm) (ppb)	
	Maximum	Average
PCE	313	250
TCE	3,500	2,800
1,1-DCE	44	35
1,1,1-TCA	34	27
1,2-DCA	13	10
Carbon tetrachloride	13	10
Chloroform	125	100
Freon 113	13	10
<b>Total VOCs</b>	<b>4,055</b>	<b>3,242</b>

Table D-7.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility E.

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system; two vessels 7.5-ft diam, 10 ft height, 10,000 lb GAC per vessel	120,000
<b>Total Major Purchased Equipment Cost</b>		<b>120,000</b>

**Table D-7.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility E.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	120,000
Piping, concrete, steel (46% of MPEC)	55,200
Electrical, instrumentation (12% of MPEC)	14,400
Installation labor (58% of MPEC)	69,600
Major Equipment Installed Cost (MEIC)	259,200
Site preparation (10% of MEIC)	25,900
Total Field Cost (TFC)	285,100
Contractor's overhead and profit (10% of TFC)	28,500
Engineering design	50,000
Permitting	10,000
Subtotal	373,600
Contingency (20% of subtotal)	74,700
<b>Total (TCR)</b>	<b>448,000</b>

**Table D-7.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility E.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			8,960	
<b>Subtotal</b>			<b>54,960</b>	
Present worth (factor, 30 y @ 5% = 15.37)				<b>845,400</b>
<i>Variable operating costs</i>				
<b>Annual cost, years 1 through 5</b>				
Replacement of GAC	16,000/unit	9.9 units	158,400	
Present worth (factor, @5% = 4.33)				685,900
<b>Annual cost, years 6 through 10</b>				
Replacement of GAC	16,000/unit	6.5 units	104,000	
Present worth (factor, @5% = 3.39)				352,600
<b>Annual cost, years 11 through 15</b>				
Replacement of GAC	16,000/unit	4.3 units	68,800	
Present worth (factor, @5% = 2.66)				183,000
<b>Annual cost, years 16 through 20</b>				
Replacement of GAC	16,000/unit	2.8 units	44,800	
Present worth (factor, @5% = 2.08)				93,200
<b>Annual cost, years 21 through 25</b>				
Replacement of GAC	16,000/unit	1.9 units	30,400	
Present worth (factor, @5% = 1.63)				49,600
<b>Annual cost, years 26 through 30</b>				
Replacement of GAC	16,000/unit	1.2 units	19,200	
Present worth (factor, @5% = 1.28)				24,600
Present worth of variable operating costs				<b>1,388,900</b>

Table D-7.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,234,300
Contingency (20% of subtotal)				446,900
Present worth of total 30-y operating cost				2,681,000
Total Capital Requirement (TCR)				448,000
Present worth of alternative (30-y operation)				3,129,000

Table D-7.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility E.

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 18-in. diam, depth of 24 ft of 1-in. Jaeger Tri-Pak packing	17,800
Air supply feed blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Treated liquid discharge pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH with 1-hp motor	500
Air-stripper vapor exhaust blower	Centrifugal fan, 320 cfm at 4 -in. water pressure with 1/2-hp motor	1,000
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 86 in. contains 1,800 lb of GAC	10,500
Total Major Purchased Equipment Cost		31,300

**Table D-7.2-2. Total Capital Requirement for an air stripper with GAC vapor treatment for Treatment Facility E.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	31,300
Piping, concrete, steel (46% of MPEC)	14,400
Electrical, instrumentation (12% of MPEC)	3,800
Installation labor (58% of MPEC)	18,200
Major Equipment Installed Cost (MEIC)	<u>67,700</u>
Site preparation (10% of MEIC)	6,800
Total Field Cost (TFC)	<u>74,500</u>
Contractor's overhead and profit (10% of TFC)	7,500
Engineering design	50,000
Permitting	20,000
Subtotal	<u>152,000</u>
Contingency (20% of subtotal)	30,400
Total (TCR)	<u><u>182,000</u></u>

**Table D-7.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility E.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	31,032 kW-h	2,200	
Electrical capacity charge	36/kW	3.9 kW	100	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			3,600	
Subtotal			51,900	
Present worth (factor, 30 y @ 5% = 15.37)				797,700
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	4,200/unit	8.2 units	34,400	
Present worth (factor, @ 5% = 4.33)				149,100
Annual costs, years 6 through 10				
Replacement of GAC	4,200/unit	5.8 units	24,400	
Present worth (factor, @ 5% = 3.39)				82,600
Annual costs, years 11 through 15				
Replacement of GAC	4,200/unit	4.1 units	17,200	
Present worth (factor, @ 5% = 2.66)				45,800
Annual costs, years 16 through 20				
Replacement of GAC	4,200/unit	2.9 units	12,200	
Present worth (factor, @ 5% = 2.08)				25,300
Annual costs, years 21 through 25				
Replacement of GAC	4,200/unit	2.1 units	8,800	
Present worth (factor, @ 5% = 1.63)				14,400

Table D-7.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC	4,200/unit	1.5 units	6,300	
Present worth (factor, @ 5% =1.28)				8,100
Present worth of variable operating costs				325,300
Subtotal of present worth of fixed and variable operating and maintenance costs				1,123,000
Contingency (20% of subtotal)				224,600
Present worth of total 30-y operating cost				1,347,600
Total Capital Requirement (TCR)				182,000
Present worth of alternative (30-y operation)				1,529,600

Table D-7.3-1. Major Purchased Equipment Cost for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility E.

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 µm, inline, synthetic resin cartridge filter	250
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80-gal, skid-mounted, 2 ft × 8 ft × 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 150-gal, double-walled, cross-linked, polyethylene, 2-ft-3-in.-diam × 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripper) vessel	Closed-top, cylindrical, 1100-gal, cross-linked polyethylene, 5-ft 4-in. diam × 7-ft 1-in. tall, 4-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,100
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4 in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
Total Major Purchased Equipment Cost		89,500

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-7.3-2. Total Capital Requirement (TCR) for a UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility E.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	89,500
Piping, concrete, steel (46% of MPEC)	41,200
Electrical, instrumentation (12% of MPEC)	10,700
Installation labor (58% of MPEC)	51,900
Major Equipment Installed Cost (MEIC)	193,300
Site preparation (10% of MEIC)	19,300
Total Field Cost (TFC)	212,600
Contractor's overhead and profit (10% of TFC)	21,300
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	303,900
Contingency (20% of subtotal)	60,800
<b>Total (TCR)</b>	<b>364,700</b>

**Table D-7.3-3. Operating and maintenance cost estimate and present worth analysis of UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility E.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	16 filters	800	
UV/oxidation maintenance	10% of UV/Ox unit	85,000	8,500	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
Subtotal			62,600	
Present worth (factor @ 5% = 15.37)				962,200
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 4.33)				189,700
Annual cost, years 6 through 10				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			43,800	
Present worth (factor @ 5% = 3.3)				148,500

Table D-7.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	487,231 kW-h	34,100	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Replacement GAC unit	600/change	0.3/y	200	
Subtotal			<u>43,800</u>	
Present worth (factor @ 5% = 2.66)				116,500
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			<u>22,000</u>	
Present worth (factor @ 5% = 2.08)				45,800
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			<u>22,000</u>	
Present worth (factor @ 5% = 1.63)				35,900
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	243,616 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Replacement GAC unit	600/change	0.15/y	100	
Subtotal			<u>22,000</u>	
Present worth (factor @ 5% = 1.28)				28,200
Present worth of variable operating costs				<u><u>564,600</u></u>

Table D-7.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,526,800
Contingency (20% of subtotal)				305,400
Present worth of total 30-y operating and maintenance costs				1,832,200
Total Capital Requirement (TCR)				364,700
Present worth of alternative (30-y operation)				2,196,900

Table D-8. Design criteria for Treatment System F.

Chemical species	Inlet concentrations (average flow rate = 30 gpm) (ppb)	
	Maximum	Average
PCE	13	10
TCE	250	200
1,1-DCE	13	10
1,1,1-TCA	4	3
1,2-DCA	163	130
Carbon tetrachloride	13	10
Chloroform	25	20
Freon 113	13	10
Benzene	25,000	20,000
Toluene	38,000	30,000
Xylene	19,000	15,000
Ethylene dibromide	313	250
Total VOCs	82,807	65,643
Lead	38	30

Table D-8.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility F.

Equipment	Description	Cost (\$)
Fixed-bed GAC (liquid) units	Skid-mounted, dual-adsorber vessel system with two vessels 10 ft diam and 12 ft height and 20,000 lb GAC per vessel.	210,000
<b>Total Major Purchased Equipment Cost</b>		<b>210,000</b>

**Table D-8.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility F.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	210,000
Piping, concrete, steel (46% of MPEC)	96,600
Electrical, instrumentation (12% of MPEC)	25,200
Installation labor (58% of MPEC)	121,800
Major Equipment Installed Cost (MEIC)	<u>453,600</u>
Site preparation (10% of MEIC)	45,400
Total Field Cost (TFC)	<u>499,000</u>
Contractor's overhead and profit (10% of TFC)	49,900
Engineering design	50,000
Permitting	<u>10,000</u>
Subtotal	608,900
Contingency (20% of subtotal)	<u>121,800</u>
Total (TCR)	<u><u>731,000</u></u>

**Table D-8.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility F.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Water sample fuel hydrocarbon analysis	100/sample	110 samples	11,000	
Water sample lead analysis	50/sample	110 samples	5,500	
Maintenance (2% of TCR)			14,600	
Subtotal			<u>77,100</u>	
Present worth (factor, 30 y @5% = 15.37)				<u>1,185,000</u>
<i>Variable operating costs</i>				
Annual cost years 1 through 5				
Replacement of GAC	32,000/unit	16.4 units	<u>524,800</u>	
Present worth (factor, @5% = 4.33)				2,272,400
Annual cost years 6 through 10				
Replacement of GAC	32,000/unit	10.8 units	<u>345,600</u>	
Present worth (factor, @5% = 3.39)				1,171,600
Annual cost years 11 through 15				
Replacement of GAC	32,000/unit	7.1 units	<u>227,200</u>	
Present worth (factor, @5% = 2.66)				604,400
Annual cost years 16 through 20				
Replacement of GAC	32,000/unit	4.7 units	<u>150,400</u>	
Present worth (factor, @5% = 2.08)				312,800
Annual cost years 21 through 25				
Replacement of GAC	32,000/unit	3.1 units	<u>99,200</u>	
Present worth (factor, @5% = 1.63)				156,500
Annual cost years 26 through 30				
Replacement of GAC	32,000/unit	2 units	<u>64,000</u>	
Present worth (factor, @5% = 1.28)				81,900
Present worth of variable operating costs				<u>4,604,800</u>

Table D-8.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				5,789,800
Contingency (20% of subtotal)				1,158,000
Present worth of total 30-y operating cost				6,947,800
Total Capital Requirement (TCR)				731,000
Present worth of alternative (30-y operation)				7,678,800
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				731,000
Present worth of O & M, years 1 through 30			6,947,800	
Fixed annual O & M costs, years 31 through 87	77,100			
Present worth (factor, @ 5% = 4.34)		334,600		
Variable annual O & M costs, years 31 through 87	64,000			
Present worth (factor, @ 5% = 4.34)		277,800		
Subtotal of O & M costs, years 31 through 87		612,400		
Contingency (20% of subtotal)		122,500		
Present worth of O & M costs, years 31 through 87			734,900	
Present worth of fixed and variable annual O & M costs, years 1 through 87				7,682,700
Present worth of GAC at Treatment Facility F under Extraction Alternative No. 2				8,413,700

**Table D-8.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility F.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 18-in. diam, depth of 24 ft of 1-in. Jaeger Tri-Pak packing	17,800
Air supply feed blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Treatment system transfer pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH with 1-hp motor	500
Fixed-bed GAC (liquid) units	Skid mounted dual-adsorber vessel system with two vessels 4 ft diam and 8 ft height each containing 2,000 lb GAC	55,000
Air-stripper vapor exhaust blower	Centrifugal fan, 320 cfm at 4-in. water pressure with 1/2-hp motor	1,000
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 86 in. contains 1,800 lb of GAC	10,500
<b>Total Major Purchased Equipment Cost</b>		<b>86,300</b>

**Table D-8.2-2. Total Capital Requirement (TCR) for an air stripper with GAC vapor treatment for Treatment Facility F.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	86,300
Piping, concrete, steel (46% of MPEC)	39,700
Electrical, instrumentation (12% of MPEC)	10,400
Installation labor (58% of MPEC)	50,100
Major Equipment Installed Cost (MEIC)	186,500
Site preparation (10% of MEIC)	18,700
Total Field Cost (TFC)	205,200
Contractor's overhead and profit (10% of TFC)	20,500
Engineering design	50,000
Permitting	20,000
Subtotal	295,700
Contingency (20% of subtotal)	59,100
<b>Total (TCR)</b>	<b>355,000</b>

**Table D-8.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility F.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kw-h	44,477 kw-h	3,100	
Electrical capacity charge	36/kw	5.6 kw	200	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	130 samples	13,000	
Water sample fuel hydrocarbon analysis	100/sample	130 samples	13,000	
Water sample lead analysis	50/sample	130 samples	6,500	
Air sample VOC analysis	100/sample	30 samples	3,000	
Air sample fuel hydrocarbon analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,100	
Subtotal			83,900	
Present worth (factor, 30 y @ 5% = 15.37)				1,289,500
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC (vapor)	4,200/unit	52.6 units	220,900	
Replacement of GAC (liquid)	3,000/unit	10.3 units	30,900	
Subtotal			251,800	
Present worth (factor, @ 5% =4.33)				1,090,300
Annual costs, years 6 through 10				
Replacement of GAC (vapor)	4,200/unit	37.2 units	156,200	
Replacement of GAC (liquid)	3,000/unit	6.8 units	20,400	
Subtotal			176,600	
Present worth (factor, @ 5% =3.39)				598,700
Annual costs, years 11 through 15				
Replacement of GAC (vapor)	4,200/unit	26.3 units	110,500	
Replacement of GAC (liquid)	3,000/unit	4.5 units	13,500	
Subtotal			124,000	
Present worth (factor, @ 5% =2.66)				329,800

Table D-8.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual costs, years 16 through 20</b>				
Replacement of GAC (vapor)	4,200/unit	18.6 units	78,100	
Replacement of GAC (liquid)	3,000/unit	3 units	9,000	
Subtotal			87,100	
Present worth (factor, @ 5% =2.08)				181,200
<b>Annual costs, years 21 through 25</b>				
Replacement of GAC (vapor)	4,200/unit	13.1 units	55,000	
Replacement of GAC (liquid)	3,000/unit	2 units	6,000	
Subtotal			61,000	
Present worth (factor, @ 5% =1.63)				99,400
<b>Annual costs, years 26 through 30</b>				
Replacement of GAC (vapor)	4,200/unit	9.3 units	39,100	
Replacement of GAC (liquid)	3,000/unit	1.3 units	3,900	
Subtotal			43,000	
Present worth (factor, @ 5% =1.28)				55,000
Present worth of variable operating costs				2,354,400
Subtotal of present worth of fixed and variable operating and maintenance costs				3,643,900
Contingency (20% of subtotal)				728,800
Present worth of total 30-y operating cost				4,372,700
Total Capital Requirement (TCR)				355,000
Present worth of alternative (30-y operation)				4,727,700

Table D-8.2-3. (Continued)

Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total Capital Requirement (TCR)				355,000
Present worth of O & M, years 1 through 30			4,372,700	
Fixed annual O & M costs, years 31 through 87	83,900			
Present worth (factor, @ 5% = 4.34)		364,100		
Variable annual O & M costs, years 31 through 87	43,000			
Present worth (factor, @ 5% = 4.34)		186,600		
Subtotal of O & M costs, years 31 through 87		550,700		
Contingency (20% of subtotal)		110,100		
Present worth of O & M costs, years 31 through 87			660,800	
Present worth of fixed and variable annual O & M costs, years 1 through 87				5,033,500
Present worth of AS at Treatment Facility F, Extraction Alternative No. 2				5,388,500

**Table D-8.3-1. Major Purchased Equipment Cost for a UV/oxidation and GAC system for Treatment Facility F.**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ , inline, synthetic resin cartridge filter	300
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 240-gal, skid-mounted, 4 ft $\times$ 8 ft $\times$ 8 ft, high-intensity-UV/oxidation chamber	120,000
Hydrogen peroxide supply reservoir	Closed-top cylindrical, 150 gal, double-walled, cross-linked, polyethylene, 2-ft-3-in. diam $\times$ 5-ft vessel	(a)
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Holding tank	Closed-top, cylindrical, 600-gal, cross-linked polyethylene, 4-ft diam $\times$ 7-ft 8-in. vessel	1,700
Liquid transfer pump	End-suction centrifugal pump, 30 gpm at 50 ft TDH; 1-hp motor	500
GAC unit	Skid-mounted, dual-adsorber vessel system; each vessel is 4 ft diam $\times$ 8 ft tall and contains 2,000 lb carbon per vessel	55,000
<b>Total Major Purchased Equipment Cost</b>		<b>178,000</b>

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-8.3-2. Total Capital Requirement for a UV/oxidation and GAC system for Treatment Facility F.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	178,000
Piping, concrete, steel (46% of MPEC)	81,900
Electrical, instrumentation (12% of MPEC)	21,400
Installation labor (58% of MPEC)	103,200
Major Equipment Installed Cost (MEIC)	384,500
Site preparation (10% of MEIC)	38,500
Total Field Cost (TFC)	423,000
Contractor's overhead and profit (10% of TFC)	42,300
Engineering design	50,000
Permitting	20,000
Subtotal capital equipment cost	535,300
Contingency (20% of subtotal)	107,100
<b>Total (TCR)</b>	<b>642,400</b>

**Table D-8.3-3. Operating and maintenance cost estimate and present worth analysis of UV/oxidation and GAC system for Treatment Facility F.**

<b>Analysis of Extraction Alternative No. 1: facility operated for 30 y</b>				
<b>Item</b>	<b>Rate (1990 \$)</b>	<b>Usage</b>	<b>Subtotal present worth (1990 \$)</b>	<b>Total present worth (1990 \$)</b>
<i>Fixed operating and maintenance costs</i>				
<b>Annual costs:</b>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	16 filters	800	
UV/oxidation maintenance	10% of UV/Ox unit	120,000	12,000	
<b>Sample analysis:</b>				
VOC/FHC water samples	100/sample	260 samples	26,000	
Lead water samples	50/sample	130 samples	6,500	
Maintenance (2% of TCR)			12,800	
<b>Subtotal</b>			<b>93,100</b>	
<b>Present worth (factor @ 5% = 15.37)</b>				<b>1,430,900</b>
<i>Variable operating costs</i>				
<b>Annual cost, years 1 through 5</b>				
Electricity	0.07/kW-h	953,176 kW-h	66,700	
Electrical use fee	36/W	121 W	4,400	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Carbon regeneration/replacement	3,000/unit	10 units	30,000	
<b>Subtotal</b>			<b>108,400</b>	
<b>Present worth (factor @ 5% = 4.33)</b>				<b>469,400</b>
<b>Annual cost, years 6 through 10</b>				
Electricity	0.07/kW-h	953,176 kW-h	66,700	
Electrical use fee	36/W	121 W	4,400	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Carbon regeneration/replacement	3,000/unit	7 units	21,000	
<b>Subtotal</b>			<b>99,400</b>	
<b>Present worth (factor @ 5% = 3.39)</b>				<b>337,000</b>

Table D-8.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	953,176 kW-h	66,700	
Electrical use fee	36/W	121 W	4,400	
Hydrogen peroxide	0.62/lb	11,821 lb	7,300	
Carbon regeneration/replacement	3,000/unit	5 units	15,000	
Subtotal			<u>93,400</u>	
				248,400
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	476,588 kW-h	33,400	
Electrical use fee	36/W	60 W	2,200	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Carbon regeneration/replacement	3,000/unit	3 units	9,000	
Subtotal			<u>48,300</u>	
Present worth (factor @ 5% = 2.08)				100,500
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	476,588 kW-h	33,400	
Electrical use fee	36/W	60 W	2,200	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Carbon regeneration/replacement	3,000/unit	2 units	6,000	
Subtotal			<u>45,300</u>	
Present worth (factor @ 5% = 1.63)				73,800
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	476,588 kW-h	33,400	
Electrical use fee	36/W	60 W	2,200	
Hydrogen peroxide	0.62/lb	5,911 lb	3,700	
Carbon regeneration/replacement	3,000/unit	1 unit	3,000	
Subtotal			<u>42,300</u>	
Present worth (factor @ 5% = 1.28)				54,100
Present worth of variable operating costs				<u><u>1,283,200</u></u>

Table D-8.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				2,714,100
Contingency (20% of subtotal)				542,800
Present worth of total 30-y operating and maintenance costs				3,256,900
Total Capital Requirement (TCR)				642,400
Present worth of alternative (30-y operation)				3,899,300
Analysis of Extraction Alternative No. 2: facility operated for 87 y				
Item	Annual cost (\$)	Increment present worth (1990 \$)	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Total capital requirement (TCR)				642,400
Present worth of O & M, years 1 through 30			3,256,900	
Fixed annual O & M costs, years 31 through 87	93,100			
Present worth (factor, @ 5% = 4.34)		404,100		
Variable annual O & M costs, years 31 through 87	42,300			
Present worth (factor, @ 5% = 4.34)		183,600		
Subtotal of O & M costs, years 31 through 87		587,700		
Contingency (20% of subtotal)		117,500		
Present worth of O & M costs, years 31 through 87			705,200	
Present worth of fixed and variable annual O & M costs, years 31 through 87				3,962,100
Present worth of UV/Ox at Treatment Facility F under Extraction Alternative No. 2				4,604,500

**Table D-9. Design criteria for Treatment System G.**

Chemical species	Inlet concentrations (average flow rate = 50 gpm) (ppb)	
	Maximum	Average
PCE	13	10
TCE	125	100
1,1-DCE	13	10
1,2-DCE	1	0.5
1,1,1-TCA	25	20
Carbon tetrachloride	6	5
Chloroform	25	20
Freon 113	13	10
<b>Total VOCs</b>	<b>221</b>	<b>175.5</b>

**Table D-9.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility G.**

Equipment	Description	Equipment cost (1990 \$)
Fixed-bed GAC units	Skid-mounted, dual-adsorber vessel system with two vessels, 4-ft diam, 8 ft-height, and 2,000 lb GAC per vessel	55,000
<b>Total Major Purchased Equipment Cost</b>		<b>55,000</b>

**Table D-9.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility G.**

<b>Equipment</b>	<b>Cost (1990 \$)</b>
<b>Major Purchased Equipment Cost (MPEC)</b>	<b>55,000</b>
<b>Piping, concrete, steel (46% of MPEC)</b>	<b>25,300</b>
<b>Electrical, instrumentation (12% of MPEC)</b>	<b>6,600</b>
<b>Installation labor (58% of MPEC)</b>	<b>31,900</b>
<b>Major Equipment Installed Cost (MEIC)</b>	<b>188,800</b>
<b>Site preparation (10% of MEIC)</b>	<b>11,900</b>
<b>Total Field Cost (TFC)</b>	<b>130,700</b>
<b>Contractor's overhead and profit (10% of TFC)</b>	<b>13,100</b>
<b>Engineering design</b>	<b>50,000</b>
<b>Permitting</b>	<b>10,000</b>
<b>Subtotal</b>	<b>203,800</b>
<b>Contingency (20% of subtotal)</b>	<b>40,800</b>
<b>Total (TCR)</b>	<b>245,000</b>

**Table D-9.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility G.**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	110 samples	11,000	
Maintenance (2% of TCR)			4,900	
Subtotal			50,900	
Present worth (factor, 30 y @5% = 15.37)				782,300
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Replacement of GAC	3,000/unit	12.3 units	36,900	
Present worth (factor, @5% = 4.33)				159,800
Annual cost, years 6 through 10				
Replacement of GAC	3,000/unit	8.1 units	24,300	
Present worth (factor, @5% = 3.39)				82,400
Annual cost, years 11 through 15				
Replacement of GAC	3,000/unit	5.4 units	16,200	
Present worth (factor, @5% = 2.66)				43,100
Annual cost, years 16 through 20				
Replacement of GAC	3,000/unit	3.5 units	10,500	
Present worth (factor, @5% = 2.08)				21,800
Annual cost, years 21 through 25				
Replacement of GAC	3,000/unit	2.3 units	6,900	
Present worth (factor, @5% = 1.63)				11,200
Annual cost, years 26 through 30				
Replacement of GAC	3,000/unit	1.5 units	4,500	
Present worth (factor, @5% = 1.28)				5,800
Present worth of variable operating costs				324,100

Table D-9.1-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs				1,106,400
Contingency (20% of subtotal)				221,300
Present worth of total 30-y operating cost				1,327,700
Total Capital Requirement (TCR)				245,000
Present worth of alternative (30-y operation)				1,572,700

**Table D-9.2-1. Major Purchased Equipment Cost for an air stripper with GAC vapor treatment for Treatment Facility G.**

Equipment	Description	Cost (1990 \$)
Air stripper tower	Fiberglass-reinforced plastic tower 22-in. diam, depth of 21 ft of 2 in. Jaeger Tri-Pak packing	12,100
Air supply feed blower	Centrifugal fan, 154 cfm at 4-in. water pressure with 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 45 gpm at 50 ft TDH with 1-hp motor	500
Air-stripper vapor exhaust blower	Centrifugal fan, 154 cfm at 4-in. water pressure with 1/4-hp motor	500
Air heater	Inline duct heater, 6 kW	500
Fixed-bed GAC (vapor) unit	Stainless steel vessel 48 in. diam by 63 in. contains 1,000 lb of GAC	6,600
<b>Total Major Purchased Equipment Cost (MPEC)</b>		<b>20,700</b>

**Table D-9.2-2. Total Capital Requirement for an air stripper with GAC vapor treatment for Treatment Facility G.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	20,700
Piping, concrete, steel (46% of MPEC)	9,500
Electrical, instrumentation (12% of MPEC)	2,500
Installation labor (58% of MPEC)	12,000
Major Equipment Installed Cost (MEIC)	44,700
Site preparation (10% of MEIC)	4,500
Total Field Cost (TFC)	49,200
Contractors' overhead and profit (10% of TFC)	4,900
Engineering design	50,000
Permitting	20,000
Subtotal	124,400
Contingency (20% of subtotal)	24,800
Total (TCR)	149,000

Table D-9.2-3. Operating and maintenance cost estimate and present worth analysis for an air stripper with GAC vapor treatment for Treatment Facility G.

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	18,173 kW-h	1,300	
Electrical capacity charge	36/kW	2.3 kW	100	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	80 samples	8,000	
Air sample VOC analysis	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			3,000	
Fixed annual operating and maintenance costs			50,400	
Present worth (factor, 30 y @ 5% = 15.37)				774,600
<i>Variable operating costs</i>				
Annual costs, years 1 through 5				
Replacement of GAC	2,500/unit	4.6 units	11,500	
Present worth (factor, @ 5% =4.33)				49,800
Annual costs, years 6 through 10				
Replacement of GAC	2,500/unit	3.3 units	8,300	
Present worth (factor, @ 5% =3.39)				28,100
Annual costs, years 11 through 15				
Replacement of GAC	2,500/unit	2.3 units	5,800	
Present worth (factor, @ 5% =2.66)				15,400
Annual costs, years 16 through 20				
Replacement of GAC	2,500/unit	1.6 units	4,000	
Present worth (factor, @ 5% =2.08)				8,300
Annual costs, years 21 through 25				
Replacement of GAC	2,500/unit	1.1 units	2,800	
Present worth (factor, @ 5% =1.63)				4,600

Table D-9.2-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Annual costs, years 26 through 30				
Replacement of GAC	2,500/unit	0.8 units	2,000	
Present worth (factor, @ 5% =1.28)				2,600
Present worth of variable operating costs				108,800
Subtotal of present worth of fixed and variable operating and maintenance costs				883,400
Contingency (20% of subtotal)				176,700
Present worth of total 30-y operating cost				1,060,100
Total Capital Requirement (TCR)				149,000
Present worth of alternative (30-y operation)				1,209,100

Table D-9.3-1. Major Purchased Equipment Cost for a UV/oxidation and air-stripping system with GAC vapor treatment for Treatment Facility G.

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 µm, inline, synthetic resin cartridge filter	375
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80 gal, skid-mounted, 2 ft × 8 ft × 7 ft, high-intensity-UV/oxidation chamber	85,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 200-gal, double-walled, cross-linked, polyethylene, 2 ft-7 in. diam × 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	500
Volatilization (air stripping) vessel	Closed-top, cylindrical, 1,650 gal, cross-linked polyethylene, 7-ft 2 in. diam × 6-ft 4-in. tall, 4-chamber, baffled aeration vessel fitted with perforated PVC air-supply pipe	1,400
Volatilization system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Carbon system vapor feed blower	Centrifugal fan, 80 cfm at 4-in. water pressure; 1/4-hp motor	500
Treated liquid discharge pump	End-suction centrifugal pump, 45 gpm at 50 ft TDH; 1-hp motor	500
Carbon system vapor heater	700 W, inline duct heater	500
Fixed-bed GAC chamber		600
Total Major Purchased Equipment Cost		89,900

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-9.3-2. Total Capital Requirement (TCR) cost estimate for UV/oxidation and air stripper system with GAC vapor treatment for Treatment Facility G.**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	89,900
Piping, concrete, steel (46% of MPEC)	41,400
Electrical, instrumentation (12% of MPEC)	10,800
Installation labor (58% of MPEC)	52,100
Major Equipment Installed Cost (MEIC)	<u>194,200</u>
Site preparation (10% of MEIC)	19,400
Total Field Cost (TFC)	<u>213,600</u>
Contractor's overhead and profit (10% of TFC)	21,400
Engineering design	50,000
Permitting	20,000
Subtotal	<u>305,000</u>
Contingency (20% of subtotal)	61,000
Total (TCR)	<u><u>366,000</u></u>

**Table D-9.3-3. Operating and maintenance cost estimate and present worth analysis for UV/oxidation and air stripping system with GAC vapor treatment for Treatment Facility G.**

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed operating and maintenance costs</i>				
Annual costs:				
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	23 filters	1,200	
UV/oxidation maintenance,	10% of UV/Ox	85,000	8,500	
Sample analysis:				
VOC/FHC water samples	100/sample	80 samples	8,000	
VOC/FHC air samples	100/sample	30 samples	3,000	
Maintenance (2% of TCR)			7,300	
Subtotal			<u>63,000</u>	
Present worth (factor @ 5% = 15.37)				<u>968,300</u>
<i>Variable operating costs</i>				
Annual cost, years 1 through 5				
Electricity	0.07/kW-h	488,808 kW-h	34,200	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	17,732 lb	11,000	
Replacement GAC unit	600/change	0.45/y	300	
Subtotal			<u>47,700</u>	
Present worth (factor @ 5% = 4.33)				206,500
Annual cost, years 6 through 10				
Electricity	0.07/kW-h	488,808 kW-h	34,200	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	17,732 lb	11,000	
Replacement GAC unit	600/change	0.45/y	300	
Subtotal			<u>47,700</u>	
Present worth (factor @ 5% = 3.39)				161,700

Table D-9.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<b>Annual cost, years 11 through 15</b>				
Electricity	0.07/kW-h	488,808 kW-h	34,200	
Electrical use fee	36/W	62 W	2,200	
Hydrogen peroxide	0.62/lb	17,732 lb	11,000	
Replacement GAC unit	600/change	0.45/y	300	
Subtotal			47,700	
Present worth (factor @ 5% = 2.66)				126,900
<b>Annual cost, years 16 through 20</b>				
Electricity	0.07/kW-h	244,404 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	8,866 lb	5,500	
Replacement GAC unit	600/change	0.225/y	100	
Subtotal			23,800	
Present worth (factor @ 5% = 2.08)				49,500
<b>Annual cost, years 21 through 25</b>				
Electricity	0.07/kW-h	244,404 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	8,866 lb	5,500	
Replacement GAC unit	600/change	0.225/y	100	
Subtotal			23,800	
Present worth (factor @ 5% = 1.63)				38,800
<b>Annual cost, years 26 through 30</b>				
Electricity	0.07/kW-h	244,404 kW-h	17,100	
Electrical use fee	36/W	31 W	1,100	
Hydrogen peroxide	0.62/lb	8,866 lb	5,500	
Replacement GAC unit	600/change	0.225/y	100	
Subtotal			23,800	
Present worth (factor @ 5% = 1.28)				30,500
Present worth of variable operating costs				613,900

Table D-9.3-3. (Continued)

Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
Subtotal of present worth of fixed and variable operating and maintenance costs.				1,582,200
Contingency (20% of subtotal)				316,400
Present worth of total 30-y operating and maintenance costs				1,898,600
Total Capital Requirement (TCR)				366,000
Present worth of alternative (30-y operation)				2,264,600

**Table D-10. Design criteria for Treatment System L (point of distribution, downtown Livermore).**

Chemical species	Inlet concentrations (average flow rate = 470 gpm) (ppb)	
	Maximum (worst case)	Average (best estimate)
PCE	46	0.02
TCE	90	0.1
1,1-DCE	7.6	0.02
1,2-DCE	7.6	0.02
1,1,1-TCA	7.6	0.02
1,1-DCA	7.6	0.02
1,2-DCA	7.6	0.02
Carbon tetrachloride	7.6	0.02
Chloroform	12	0.2
Freon 113	7.6	0.02

**Table D-10.1-1. Major Purchased Equipment Cost for a GAC system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Description	Cost (1990 \$)
Fixed-bed GAC units	Skid-mounted, dual-adsorber vessel system with two vessels 10-ft diam, 12 ft height, and 20,000 lb GAC per vessel	210,000
Treated water storage tank	Closed top cylindrical tank, 11,000-gal capacity, cross-linked polyethylene, 12 ft diam × 14 ft	11,500
Treated water discharge pump	End-suction centrifugal pump, 470 gpm at 30 ft TDH, with 7-1/2-hp motor	1700
<b>Total Major Purchased Equipment Cost</b>		<b>223,200</b>

**Table D-10.1-2. Total Capital Requirement (TCR) for a GAC system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	223,200
Piping, concrete, steel (46% of MPEC)	102,700
Electrical, instrumentation (12% of MPEC)	26,800
Installation labor (58% of MPEC)	129,500
Major Equipment Installed Cost (MEIC)	482,200
Site preparation (10% of MEIC)	48,200
Total Field Cost (TFC)	530,400
Contractor's overhead and profit (10% of TFC)	53,000
Engineering design	50,000
Permitting	10,000
Subtotal	643,400
Contingency (20% of subtotal)	128,700
Total (TCR)	772,000

**Table D-10.1-3. Operating and maintenance cost estimate and present worth analysis for a GAC system for Treatment Facility L (point of distribution, downtown Livermore).**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07 /kW-h	29,903 kW-h	2,100	
Electrical capacity charge	36 /kW	3.8 kW	100	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	210 samples	21,000	
Replacement of GAC	32,000 /units	21 units	672,000	
Maintenance (2% of TCR)			15,400	
Subtotal			745,600	
Contingency (20%)			149,100	
Subtotal			894,700	
Discounted value (factor, 30 y @5% = 15.37)				13,751,500
Total Capital Requirement (TCR)				772,000
Subtotal of future costs				14,523,500
Present worth of alternative (discount factor, 200 y @ 2% =0.019)				276,000

**Table D-10.2-1. Major Purchased Equipment Cost for an air stripper for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Description	Cost (1990 \$)
Air-stripper tower	Fiberglass-reinforced plastic tower 5-ft diam, depth of 25 ft of 3.5-in. Jaeger Tri-Pak packing	59,000
Air-supply feed blower	Centrifugal fan, 1,600 cfm at 4-in. water pressure with 3-hp motor	2,000
Treated liquid transfer pump	End-suction centrifugal pump, 470 gpm at 30 ft TDH with 7-1/2-hp motor	1,700
Treated liquid storage tank	Closed top cylindrical tank, 11,000-gal capacity, cross-linked polyethylene construction, 12 ft diam × 14 ft height	11,500
Treated liquid discharge pump	End suction centrifugal pump, 470 gpm at 30 ft TDH with 7-1/2-hp motor	1,700
<b>Total Major Purchased Equipment Cost</b>		<b>75,900</b>

**Table D-10.2-2. Total Capital Requirement (TCR) for an air stripper for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	75,900
Piping, concrete, steel (46% of MPEC)	34,900
Electrical, instrumentation (12% of MPEC)	9,100
Installation labor (58% of MPEC)	44,000
<b>Major Equipment Installed Cost (MEIC)</b>	<b>163,900</b>
Site preparation (10% of MEIC)	16,400
<b>Total Field Cost (TFC)</b>	<b>180,300</b>
Contractor's overhead and profit (10% of TFC)	18,000
Engineering design	50,000
Permitting	20,000
<b>Subtotal</b>	<b>268,300</b>
Contingency (20% of subtotal)	53,700
<b>Total (TCR)</b>	<b>322,000</b>

**Table D-10.2-3. Operating and maintenance cost estimate and present worth analysis for air stripper for Treatment Facility L (point of distribution, downtown Livermore).**

Analysis of Extraction Alternative No. 1: facility operated for 30 y				
Item	Rate (1990 \$)	Usage	Subtotal present worth (1990 \$)	Total present worth (1990 \$)
<i>Fixed annual operating and maintenance costs</i>				
Electricity	0.07/kW-h	199,108 kW-h	13,900	
Electrical capacity change	36/kW	25.3 kW	900	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Water sample VOC analysis	100/sample	160 samples	16,000	
Maintenance (2% of TCR)			6,400	
Subtotal			72,200	
Contingency (20%)			14,400	
Subtotal			86,600	
Discounted value (factor, 30 y @ 5% = 15.37)				1,331,000
Total Capital Requirement (TCR)				322,000
Subtotal of future costs				1,667,800
Present value of alternative (discount factor, 200 y @ 2% = 0.019)				31,400

**Table D-10.3-1. Major Purchased Equipment Cost for UV/oxidation system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Description	Cost (1990 \$)
Filter unit and filter	5 $\mu$ m, inline, synthetic resin cartridge filter	4,000
UV/oxidation chamber	Single-chamber, baffled, 316-L stainless steel, 80-gal, skid-mounted, 2 ft $\times$ 8 ft $\times$ 7 ft, high-intensity-UV/oxidation chamber	320,000
Hydrogen peroxide supply reservoir	Closed-top, cylindrical, 1,800-gal, double-walled, cross-linked, polyethylene, 7-ft-10-in. diam $\times$ 5-ft vessel	( <sup>a</sup> )
Hydrogen peroxide feed pump	Diaphragm-type chemical metering pump	1,500
Treated water storage tank	Closed-top, cylindrical, 11,000 gal, cross-linked polyethylene, 12 ft diam $\times$ 14 ft tank	11,500
Treated liquid discharge pump	End-suction centrifugal pump, 470 gpm at 30 ft TDH; 7-1/2-hp motor	1,700
Total Major Purchased Equipment Cost		338,700

<sup>a</sup>Cost included with UV/oxidation unit.

**Table D-10.3-2. Total Capital Requirement (TCR) for an UV/oxidation system for Treatment Facility L (point of distribution, downtown Livermore).**

Equipment	Cost (1990 \$)
Major Purchased Equipment Cost (MPEC)	338,700
Piping, concrete, steel (46% of MPEC)	155,800
Electrical, instrumentation (12% of MPEC)	40,600
Installation labor (58% of MPEC)	196,400
Major Equipment Installed Cost (MEIC)	731,500
Site preparation (10% of MEIC)	73,200
Total Field Cost (TFC)	804,700
Contractor's overhead and profit (10% of TFC)	80,500
Engineering design	50,000
Permitting	20,000
Subtotal	955,200
Contingency (20% of subtotal)	191,000
Total (TCR)	1,146,200

**Table D-10.3-3. Operating and maintenance cost estimate and present worth analysis for UV/oxidation system for Treatment Facility L (point of distribution, downtown Livermore).**

<b>Analysis of Extraction Alternative No. 1: facility operated for 30 y</b>				
<b>Item</b>	<b>Rate (1990 \$)</b>	<b>Usage</b>	<b>Subtotal present worth (1990 \$)</b>	<b>Total present worth (1990 \$)</b>
<i>Fixed annual operating and maintenance costs</i>				
Electricity	2,892,114 kW-h	0.07	202,400	
Electrical use fee	367/kW	36	13,200	
Hydrogen peroxide	0.62/lb	185,200	114,800	
Supervision labor	75/h	200 h	15,000	
Operating labor	40/h	500 h	20,000	
Filter changes	50/filter	244 filters	12,200	
UV/oxidation maintenance	10% of UV/Ox unit	320,000	32,000	
VOC/FHC water samples	100/sample	160 samples	16,000	
Maintenance (2% of TCR)			22,900	
<b>Subtotal annual fixed operating and maintenance costs</b>			<b>448,500</b>	
<b>Contingency (20% of subtotal)</b>			<b>89,700</b>	
<b>Total annual operating and maintenance costs</b>			<b>538,200</b>	
<b>Present worth (discount 30-y factor @ 5% = 15.37)</b>				<b>8,363,600</b>
<b>Total Capital Requirement (TCR)</b>				<b>1,146,200</b>
<b>Subtotal</b>				<b>9,418,300</b>
<b>Present worth of alternative (discount factor, 200 y @ 2% = 0.019)</b>				<b>179,000</b>