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Final Feasibility Study for the Building 834 Operable Unit Lawrence Livermore National Laboratory Site 300

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Executive Summary

This Feasibility Study (FS) was prepared by Lawrence Livermore National Laboratory (LLNL) for the Building 834 operable unit of the LLNL Site 300 test facility near Tracy, California. It is prepared in accordance with the terms outlined in the Site 300 Federal Facility Agreement (FFA) negotiated between the Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), California Department of Toxic Substances Control (DTSC), and California Regional Water Quality Control Board (RWQCB). This FS is prepared in compliance 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). Negotiations to redefine several operable units, including the Building 834 operable unit, were conducted in November and December 1993 between LLNL, DOE, EPA, DTSC, and RWQCB. The results of these recent negotiations have been incorporated in this report. Together with the recently completed Site-Wide Remedial Investigation (SWRI) report (Webster-Scholten, 1994), which characterizes the site, the FS forms the basis for evaluating and selecting technologies for remediation of hazardous substances in the subsurface beneath the Building 834 Complex.

Historical information and analytical data presented in the SWRI indicate that contaminants were released to the environment at ten release sites at the core of the Building 834 Complex between the early 1960s and mid-1980s. Employee interviews indicate that approximately 550 gallons of trichloroethylene (TCE) was released in the vicinity of the Building 834 Complex due to leakage from pipes, pumps, and valves, and from surface spills between 1962 and 1978 (Olsen, 1982). TCE was also released to the septic system leach field via building floor drains, which were plumbed into the septic tank prior to 1978. TCE has been identified as the primary chemical of potential concern.

Data presented in the SWRI report indicate that volatile organic compounds (VOCs), including TCE, perchloroethylene (PCE), Freon 11, benzene, ethylbenzene, toluene, and xylene, are present in subsurface soil at the Building 834 Complex. The highest VOC concentrations detected in soil were reported in samples collected in the vicinity of the TCE pump stations 834C and D, where free-product TCE is known to have spilled or leaked from the Building 834 TCE heat-transfer system. Other confirmed release sites include Buildings 834B, E, F, G, H, and J, the septic system, and a diesel fuel tank fill spout.

Building 834D is the location of the highest concentrations of VOCs (primarily TCE) in ground water in the perched water-bearing zone. The light nonaqueous phase liquids (LNAPLs) tetra 2-ethybutylorthosilicate (T-BOS, a silicon-based lubricant used in the TCE heat transfer system) and diesel fuel have also been detected at the water table surface in the core area of the Building 834 Complex. As a result of the past releases, a TCE ground water plume, originating from the core area and extending nearly 1,500 feet downgradient (i.e., south), has been detected in the shallow perched water-bearing zone beneath the Building 834 Complex area. Other compounds detected in the perched water-bearing zone include PCE, cis-1,2-dichloroethylene, 1,1,1-trichloroethane, acetone, benzene, chloroform, 1,1-DCE, ethylbenzene, Freon 113, methylene chloride, toluene, xylenes (total isomers), and total petroleum hydrocarbons. Analytical data indicate that VOCs, although they are present in the perched water-bearing zone,

have not impacted the regional aquifer, which is nearly 280 feet below the perched zone. Ground water fate and transport modeling supports this conclusion.

A risk analysis was performed as part of the SWRI to evaluate the potential risk and hazard to adults and animals that may be exposed to contaminants in soil and ground water. The risk analysis identified VOCs in subsurface soil (0.5–12.0 ft) beneath the Building 834 core area that would present an unacceptable risk of cancer (i.e., greater than 1×10^{-4}) and noncancer health effects (i.e., hazard index >1) to humans if they inhaled vapors volatilizing from subsurface soils into nearby facility buildings. Specifically, the overly conservative risk analysis yielded a hazard index of 35.9 and an excess cancer risk of 1×10^{-3} for adult TCE vapor inhalation exposure inside storage Building 834D. Sampling of ambient air inside Building 834D, located in the core area of the complex, was completed in October 1993. Analytical results indicated that TCE was present at 1.34 to 1.79 mg/m^3. Although these values are quite close to the TCE concentration predicted in air inside Building 834D (1.31 mg/m^3) as presented in the SWRI, the TCE vapors are believed to be from several possible sources, including volatilization from TCE pumps and equipment, residual TCE in the concrete floor from past spills, and possibly soil vapor. Additional ambient air samples may be collected inside 834D after the equipment is completely removed.

As part of the FS process, we identified the federal, state, and local chemical-, location-, and action-specific and legal Applicable or Relevant and Appropriate Requirements (ARARs), as well as other requirements to be considered (TBCs). The identification of ARARs and TBCs guided development of the remedial action goals, general response actions, and remedial alternatives. Based on the chemicals of concern, exposure routes, potential receptors, and the findings of the baseline risk assessment, the remedial action objectives (RAOs) for the Building 834 operable unit are to prevent human exposure to:

- VOCs that may volatilize from subsurface soil into ambient and indoor air above the 10^{-4} to 10^{-6} risk level or hazard index level >1, whichever is more conservative.
- Chemicals in ground water above the maximum contaminant levels (MCLs).

The potential inhalation exposure risk can be reduced to protect human health and thereby achieve the RAOs through site risk management, which may include institutional controls and/or active remediation. Institutional controls may reduce human exposure and manage risk by restricting access to the site, placing restrictions on property deeds, limiting worker hours, fencing, and creating well drilling prohibitions. Active remediation may reduce human exposure and manage risk by contaminant mass reduction through soil vapor extraction and/or ground water extraction, as well as by innovative remedial technologies. The RAOs can be met by preventing or reducing exposure or by cleaning the subsurface soil vapor VOC concentrations in the vicinity of the Building 834 Complex to less than 1×10^{-4} total cancer risk and less than 1.0 hazard index, which corresponds to a TCE soil vapor concentration of 250 $ppm_{v/v}$.

The 3×10^{-5} total excess cancer risk corresponds to a proposed soil vapor remediation level (PSRVL) of 250 $ppm_{v/v}$, and is between the minimally acceptable 1×10^{-4} cancer risk and the 1×10^{-6} cancer risk point of departure defined in the National Contingency Plan (U.S. EPA, 1993) and in EPA guidance (U.S. EPA, 1988a). The baseline risk assessment modeling of the Building 834 Complex, presented in Webster-Scholten (1994) and summarized in Chapter 1 and Appendix C of this document, was conducted using several extremely conservative default

assumptions. One of these default assumptions was that an adult would work on site in the vicinity of Building 834D over the course of his/her career at Site 300 (8 hours/day, 250 days/year for 25 years). Although slightly above the 1×10^{-6} cancer risk point of departure, the calculated 3×10^{-5} excess cancer risk remediation goal is more appropriate and realistic for the Building 834 Complex for the following reasons:

- To reach the 1×10^{-6} excess cancer risk level (assuming an 8 hours/day, 250 days/year, 25-year exposure scenario), soil and soil vapor TCE concentrations would have to be reduced to 0.0745 mg/kg and 8.5 $ppm_{v/v}$, respectively, which would likely require costly large-scale soil vapor extraction and possibly soil excavation of the Building 834 Complex core area. Excavation is not feasible for this site (Berry and Landgraf, 1994).
- Building 834D is a former equipment and TCE pump building, designed for industrial purposes, and is not intended to be used for offices or residential purposes.
- Building 834D has been converted to a storage facility, similar to Buildings 834B and 834C.
- Occupancy rate of the Building 834 Complex has declined substantially since the mid 1980s (Smith, 1994), making the baseline risk assessment occupancy assumptions overly conservative.
- The 3×10^{-5} cancer remediation goal is based on achieving a hazard index of 1.0, which is justifiable because the cancer potency factor (CPF) for TCE is currently under review as a consequence of differing scientific opinions as to the association between carinogenicity and TCE. It is our opinion, and that of others in the scientific community, that human epidemiological studies for determining CPS values are considered inadequate. EPA Region IX provided the CPF value of 1×10^{-2}. This CPF value is more conservative than the value recommended by the U.S. EPA Environmental Criteria Assessment Office (ECAO), 6×10^{-3}, and thus yields a higher apparent risk.
- DOE intends to occupy and maintain institutional control of Site 300 for the foreseeable future, thus making the residential occupancy of the Building 834 operable unit very unlikely.

Presently, LLNL/DOE is pursuing an amendment to exclude the Building 834 operable unit shallow perched water-bearing zone from the CVRWQCB Basin Plan. The six remedial alternatives presented in this report assume that the Basin Plan amendment will be granted.

A set of general response actions was developed using the ARARs, TBCs, and information presented in the SWRI report. General response actions are conceptual remedial measures, specific to a given environmental medium, that can be implemented to achieve the remedial action objectives. The general response actions are also used to categorize specific remedial action technologies that may be pertinent to remediation of the released chemicals. Environmental media that may require treatment at the Building 834 Complex are soil, rock, and ground water. We screened the remedial action technologies to identify those that: (1) can be reasonably expected to achieve the remedial action goals, (2) can be readily implemented at the site, and (3) are less costly than measures of comparable effectiveness. General response actions and remedial action technologies considered appropriate for remediation of released chemicals at the Building 834 Complex and related off-site areas are listed in Table EX-1. Although other

innovative remedial technologies may prove to be more effective than those considered as current Best Available Technologies (BAT) and presented in Table EX-1, many are still in development stages and will be given consideration.

The general response actions and associated remedial action technologies considered appropriate for the Building 834 Complex were used to develop five remedial alternatives. The key features of the alternatives and present-worth cost estimates are summarized in Table EX-2. These alternatives principally are based on engineering upgrades, extensive soil vapor extraction, and ground water plume control. Each alternative builds on the prior alternative. Alternative 1 is the no-action alternative, as specified under U.S. EPA (1988), and involves only ground water and soil vapor monitoring. Alternative 2 involves engineering upgrades including drainage control, building venting, and LNAPL recovery. Alternative 3 includes soil vapor extraction at the core source area. The fourth alternative adds ground water extraction at the core source area, and the fifth alternative adds ground water extraction for plume control at two locations downgradient of the core source area. A version of Alternative 4 has been operated successfully in the past, and proof-of-system (POS) testing was successfully conducted in March 1994. Alternatives 3, 4, and 5 also integrate testing of innovative treatment technologies with proposed best available technology treatment systems for potential application in the near future. Under Alternatives 3, 4, and 5, should any of these innovative technologies prove to be more efficient and cost effective, we would propose that the innovative technology supplement or replace the previously selected BAT.

A sixth remedial alternative was conceptualized during the May 25 and June 23, 1994, Site 300 Remedial Project Manager's (RPM) meetings. During these two meetings, an agreement was made among LLNL/DOE, RWQCB, DTSC, and EPA to present an interim innovative technology alternative. This sixth alternative allows for the performance assessment of several innovative remedial technologies while providing BAT risk management/reduction through Alternative 3 soil vapor extraction, enhanced by ground water extraction (as needed). Should one or more of the innovative technologies prove effective, then it (they) will be implemented as the primary remedial technology. Regulatory acceptance of Alternative 6 will result in an interim Record of Decision (ROD).

After identifying and screening the applicable remedial action technologies and developing appropriate remedial alternatives, we conducted a detailed analysis and comparison of the remedial alternatives to select the most appropriate, effective, and least costly remedial alternative. To select the best remediation strategy for released chemicals at the Building 834 Complex, each remedial action alternative was evaluated against the first seven of the nine evaluation criteria presented in EPA CERCLA guidance (U.S. EPA, 1988). These criteria include the remedial action objectives and several additional criteria to meet the objectives of the regulatory agencies. The criteria are:

1. Overall protection of human health and environment.
2. Compliance with ARARs.
3. Short-term effectiveness.
4. Long-term effectiveness and permanence.
5. Reduction of toxicity, mobility, or volume.

6. Implementability.
7. Cost.
8. State acceptance.
9. Community acceptance.

The evaluation of state and community acceptance will be completed after the state and local representatives review and respond to this document.

As part of DOE NEPA-CERCLA integration requirements, we also evaluated the potential impacts on the existing on-site and off-site environment due to implementation of the remedial alternatives. No significant adverse impacts due to implementation of the alternatives were identified.

Table EX-1. General response actions and remedial action technologies for the Building 834 Complex.

General response action	Remedial action technologies
No action	Perched water-bearing zone dewatering
Extraction	LNAPL recovery
Treatment	Building venting
Disposal	Treatment of extracted ground water by air stripping and air sparging. Treatment of VOCs in evolved vapor by granular activated carbon (GAC) adsorption. Discharge of treated ground water by misting.
Institutional/administrative control	
Containment	Soil vapor extraction
	Treatment of extracted soil vapor by GAC adsorption

Table EX-2. Building 834 Complex remedial alternatives.

	Alternative 1 No action	Alternative 2 Engineering upgrades	Alternative 3 Source mass removal to 3×10^{-5} risk by SVE[a,b]	Alternative 4 Source mass removal to 3×10^{-5} risk by SVE and dewatering[b]	Alternative 5 Source mass removal by SVE and dewatering and ground water plume control[b]	Alternative 6 Interim source mass removal by innovative technologies and SVE[b]
Key features	No remedial action	Ground water monitoring	All elements of Alternatives 1 and 2	All elements of Alternatives 1, 2, and 3	All elements of Alternatives 1, 2, 3, and 4	Elements of Alternatives 1, 2, and 3 with ground water extraction to enhance SVE
	Ground water monitoring only	Institutional controls Drainage control Building ventilation LNAPL recovery	Vadose zone soil vapor remediation to 3×10^{-5} risk level at core source area GAC treatment of vapor phase VOCs Innovative technolgy testing and application	Vadose zone soil vapor remediation to 3×10^{-5} risk level at core source area and perched zone dewatering Air stripping with GAC treatment of vapor phase VOCs GAC treatment of vapor phase VOCs Innovative technolgy testing and application	Vadose zone soil vapor remediation to 3×10^{-5} risk level at core source area and downgradient plume control Air stripping with GAC treatment of vapor phase VOCs GAC treatment of vapor phase VOCs Innovative technolgy testing and application	Source mass removal through the testing and application of innovative technologies to reduce vadose zone soil vapor to 3×10^{-5} risk level at core source area, and SVE BAT remediation system using Alternative 3 technology to reduce risk. Selection of final system contingent on the performance evaluation and the CVRWQCB Basin Plan amendment to exclude the perched water-bearing zone.
Project life	30 years	30 years monitoring 2 years of LNAPL recovery	5 years remediation 30 years monitoring	5 years remediation/ dewatering 30 years monitoring	30 years remediation/ dewatering 30 years monitoring	Same as (or less than) Alternative 3 or 4, based on success of Basin Plan amendment
Present-worth cost	$ 4.12M	$ 5.69M	$ 8.72M	$10.38M	$16.45M	TBD[c]

[a] SVE = Soil vapor extraction.

[b] Present-worth cost of innovative technology testing and application not included.

[c] TBD = To be determined. Costs could be similar to or less than Alternative 3 or 4, depending on success of innovative technologies.

1. Introduction

This Feasibility Study (FS) was prepared by Lawrence Livermore National Laboratory (LLNL) for the Building 834 operable unit of the LLNL Site 300 test facility near Tracy, California. It is prepared in accordance with the terms outlined in the Site 300 Federal Facility Agreement (FFA). The FFA was negotiated between the Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), California Department of Toxic Substances Control (DTSC), and California Regional Water Quality Control Board (RWQCB). The FFA provides the framework for the conduct of the site cleanup and preparation of necessary regulatory documents. This FS is prepared in compliance 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). Negotiations to redefine several operable units, including the Building 834 operable unit, were conducted in November and December 1993 between LLNL, DOE, EPA, DTSC, and RWQCB. The results of these negotiations have been incorporated in this report. The FS, along with the previously conducted Site-Wide Remedial Investigation (SWRI) (Webster-Scholten, 1994), forms the basis for evaluating and selecting alternative technologies for remediation of hazardous materials in the Building 834 operable unit subsurface. The FS process involves:

- Identifying remedial action objectives based on Applicable or Relevant and Appropriate Requirements (ARARs).
- Identifying general response actions.
- Identifying potential treatment and containment technologies and the associated process options.
- Screening various technologies and process options based on their effectiveness, implementability, and cost.
- Assembling the selected technologies into alternatives for remediation of the contaminated media at the Building 834 operable unit.

1.1. Purpose

The purpose of this FS is to develop and evaluate alternatives for remedial action at the Building 834 operable unit in accordance with CERCLA/SARA and the National Environmental Policy Act (NEPA). The FS process will also result in the selection and subsequent implementation of cost-effective remedial alternatives to provide adequate protection of human health and the environment.

The FS is based on the information in the SWRI report. This chapter provides a summary of the information presented in the SWRI report. Chapters 2 through 5 present the determination of ARARs, evaluation of technologies, description of alternatives, analysis of alternatives, and recommended alternatives, as described above. Chapter 6 presents environmental considerations based on implementation of the alternatives.

1.2. Background

LLNL Site 300 is a Department of Energy (DOE) test facility operated by the University of California. Site 300 is primarily a high explosives (HE) test facility that supports the LLNL Weapons Program in research, development, and testing associated with weapon components. This work includes explosives processing; preparation of new explosives; and pressing, machining, and assembly of explosives components. Site 300 activities also include hydrodynamic testing for experimental verification of computer codes, obtaining equation-of-state data for weapons materials, evaluating material behavior at assembly joints and welds, evaluating the quality and uniformity of implosion, and performance evaluation of post weapons-test design modifications (LLNL, 1991b). Occasionally, experiments performed at Site 300 involve compounds other than HE. These experiments may require more space or isolation, or may have other requirements that cannot be met at the Livermore Main Site (U.S. DOE, 1982). Access to Site 300 is restricted.

Prior to August 1990, investigations of potential chemical contamination at Site 300 were conducted under the oversight of the Central Valley RWQCB Region. In August 1990, Site 300 was placed on the National Priorities List (NPL). Since then, all investigations, including the preparation of the SWRI report, have been conducted in accordance with CERCLA under the oversight of the three supervising regulatory agencies, the EPA, the RWQCB, and the DTSC.

The Building 834 study area that was described in the SWRI report encompasses an area of about 0.51 mi^2 (326 acres) in the southeastern part of Site 300 (Fig. 1-1). The area is characterized by steep-sided ridges and ravines. Data presented in the SWRI report indicate that within the Building 834 study area significant contaminant releases occurred only at the Building 834 Complex. The Building 834 Complex facilities are used to expose materials and test devices to controlled temperatures and temperature cycles. Up until 1994, trichloroethylene (TCE) served as a heat transfer fluid for these operations. VOCs, primarily TCE, diesel fuel, and a silicon-based oil, were released to soil and ground water in the vicinity of the Building 834 Complex as a result of past operations at this facility. The suspected sources include: leakage from pipes, pumps, and valves; accidental surface releases; and the former septic system leach field, which was connected to building floor drains (Lindeken et al., 1986).

As a result of the findings presented in the SWRI report and the recent November and December 1993 negotiations with LLNL, DOE, EPA, DTSC, and RWQCB, the Building 834 Complex and downgradient ground water VOC plume have been defined as the Building 834 Complex operable unit. Specifically, the Building 834 operable unit includes Buildings 834A, B, C, D, E, F, G, H, J, K, L, M, and O; the downgradient ground water VOC plume; and immediately adjacent land (Fig. 1-1).

1.2.1. Description of Site 300

Site 300 is located in the southeastern Altamont Hills of the Diablo Range, which is located about 30 mi east of San Francisco Bay. Site 300 is situated about 17 mi east-southeast of Livermore and 8.5 mi southwest of Tracy, California, and covers 10.4 mi^2, most of which is in San Joaquin County (Fig. 1-2). The western one-sixth of the site is located in Alameda County.

The topography of Site 300 consists of a series of steep hills and canyons generally oriented northwest to southeast. Elevation ranges from about 500 ft in the southeast corner to about

1,750 ft in the northwestern area. Grassland cover grows seasonally. The climate of Site 300 is semiarid and windy. The average annual rainfall for the 27-y period from 1965 through 1991 was 10.03 in. The wind is predominantly from the west-southwest; the temperature extremes in 1991 ranged from 102 degrees in July to 27 degrees in December. The estimated potential evaporation (defined by the U.S. Department of Agriculture [USDA]) at Site 300 is about 30.6 in. (USDA, 1966).

The seven major plant habitats occurring at Site 300, four upland habitats and three less extensive wetland habitats, consist of 14 plant communities containing 343 plant taxa. The upland habitats include introduced grassland, native grassland, coastal sage scrub, and oak woodland. The rare wetland habitats consist of northern riparian woodland, vernal pool, and the most frequently-encountered, herbaceous wetlands. Fauna observed at Site 300 include 20 species of reptiles and amphibians, 70 species of birds, and 25 species of mammals. Mammals include mice, hares, squirrels, skunks, foxes, and black-tailed deer. Detailed ecological information, including assessment of endangered species at Site 300, is included in the SWRI report.

Site 300 has been divided into several operable units based on the nature and extent of contamination at the site. The Building 834 operable unit is in the southeastern portion of the site (Fig. 1-3).

Off-site land use in close proximity to the Site 300 boundary (Fig. 1-4) includes:

- The Gallo ranch to the south, and the Connolly ranch to the south and east—primarily used for cattle grazing.
- California Department of Fish and Game ecological preserve to the east.
- Carnegie State Vehicular Recreation Area (SVRA) to the southwest—an outdoor recreational facility for private and commercial off-road motorcycle riding, testing, and racing.
- Physics International, Inc. to the northeast—a privately owned HE testing facility.

1.2.2. Site 300 History

LLNL, operated by the University of California for the DOE, began weapons research operations at the Livermore Main Site in 1952. At that time, LLNL was a separate part of what was then the University of California Radiation Laboratory (UCRL). Prior to acquisition by UCRL, land use in the area of Site 300 was limited to sheep and cattle grazing. In July 1953, UCRL proposed the location for an HE test site along Corral Hollow between Livermore and Tracy. In 1955, experiments with HE began at the site. The size of the original site was approximately 3 mi^2. In 1957, the site was enlarged to 10.4 mi^2 (U.S. DOE, 1982). In 1971, UCRL became LLNL.

In 1977, the Navy transferred ownership of a 7.44-acre parcel on the eastern edge of Site 300 to LLNL to be used as a pistol range subsequent to its use by the U.S. Navy as a fire-fighting experimentation area. Currently, this parcel is unused (Graham, 1990). In February 1991, LLNL acquired 11.6 acres of the adjoining Connolly Ranch at the southeastern edge of Site 300. The parcel had been in the Connolly family since the 1890s and had been used for seasonal cattle

grazing. LLNL plans to use the property to facilitate remediation of the eastern GSA (Graham, 1991).

1.2.3. Corrective Actions and Facility Upgrades

Concurrent with the remedial investigation of Site 300, we have conducted several corrective actions and facility upgrades. The locations of these activities are shown in Figure 1-5. Each project is briefly described below.

1.2.3.1. HE Rinsewater Lagoon Closures

In 1985, we removed nine HE rinsewater lagoons from service and replaced them with two double-lined surface impoundments. Soils beneath the lagoons were investigated, and the lagoons were capped under RWQCB guidance in 1989 (Carpenter et al., 1988).

1.2.3.2. Well Sealing and Abandonment

From 1988 to 1991, we sealed and abandoned eight inactive water-supply wells at Site 300. Four of these wells were located in the EFA/WFA study area, two in the HE Process Area, and two in the GSA. The wells were sealed to prevent contaminants from migrating into other aquifers beneath the site. This topic is described in Lamarre et al. (1988), Taffet et al. (1989), Crow and Toney (1991), McIlvride et al. (1990), and Webster-Scholten (1994).

1.2.3.3. Removal/Replacement of Firing Table Gravels

In 1988, we removed gravel containing low activities of tritium and low concentrations of metals and ^{238}U beneath six HE firing tables in the EFA/WFA study area. At the three active firing tables, the gravels were replaced by fresh materials. This topic is described in Lamarre and Taffet (1989), Taffet et al. (1990), and Webster-Scholten (1994).

1.2.3.4. EFA/WFA Tritium Evaporator

We have pilot tested a treatment system involving a 20-ft high atomizing tower that was shown to evaporate tritium-bearing ground water from well 8 spring at a maximum rate of 40 gph (Taffet and Oberdorfer, 1991). The evaporator was permitted for operation; however, treatment was discontinued to avoid transferring tritium to the air.

1.2.3.5. Enhanced Soil Bioremediation (ESB)

We are using ESB to reduce concentrations of diesel fuel in soil excavated during underground storage tank (UST) closure activities in the GSA. During the summer of 1990, we conducted an ESB pilot study with about 1 yd^3 of soil that was contaminated with diesel fuel. During the summer and fall of 1991, we used the findings of the 1990 ESB pilot study to design and operate a full-scale ESB for 100 yd^3 of soil with average concentrations of 83 mg/kg total-extractable-petroleum-hydrocarbons (TEPH) diesel. The contaminated soil was spread out on a gravel pad, tilled, watered, and fertilized on a regular schedule. After four months, the average TEPH-diesel concentrations had declined to 40 mg/kg. The full-scale ESB is still in operation.

1.2.3.6. Underground Fuel Storage Tank Removal

Three underground tanks located near Buildings 801 and 850 in the EFA/WFA study area and Building 874 in the GSA were determined to have caused releases of diesel and/or kerosene to the surrounding soil. The contaminated soil was excavated, treated using enhanced soil bioremediation (ESB), and the sites were closed in accordance with environmental regulations.

1.2.3.7. Building 834 Complex Remediation

We have remediated some of the VOCs in the subsurface beneath Building 834 by soil excavation and aeration, soil venting, and ground water extraction and treatment (section 10-4, Webster-Scholten, 1994). In addition, this facility has been used as a test-bed for several innovative technology treatability projects, including an EPA Superfund Innovative Technology Evaluation (SITE) test of a PURUS pulsed ultraviolet soil-vapor treatment system, an electrical soil-heating pilot test, and a demonstration of an electron accelerator to treat soil vapor (Matthews et al., 1992). Appendix D contains several papers that describe these treatability tests and the effectiveness of the various technologies applied.

1.2.3.8. Central GSA CERCLA Removal Action

We are currently operating a ground water and soil vapor extraction and treatment system to remove VOCs released from two dry wells (sumps) near Building 875 in the Central GSA. Ground water is being extracted from seven extraction wells and treated by air sparging and processing through granular activated carbon (GAC) canisters prior to being discharged on site. Soil vapor is being extracted and treated using GAC canisters. An EPA SITE test of a Peroxidation Systems, Inc., UV/H_2O_2 ground water treatment system was performed in 1992.

1.2.3.9. Eastern GSA CERCLA Removal Action

In June 1991, we installed a CERCLA Removal Action ground water treatment system (GWTS) to remediate VOCs, primarily PCE and TCE, emanating from one or more debris burial trenches in the eastern GSA. Ground water is extracted from one to three extraction wells, treated with an air sparger and processed through GAC canisters, and discharged to the Corral Hollow creekbed. As of June 30, 1993, a total of 17,938,788 gallons of ground water have been treated (Rueth, 1993).

1.2.3.10. RCRA Capping of Landfill Pits 1 and 7

We installed 10-ft-thick RCRA caps consisting of several engineered layers of natural earth materials, including a 3-ft-thick layer of low-permeability clay, on these two inactive landfills in the EFA/WFA study area. The RCRA caps are designed to prevent release of landfill contents to the ground water. We are currently monitoring the effectiveness of these landfill caps.

1.2.3.11. Endangered Species Reintroduction

In 1992, we reintroduced a rare endangered plant species, the large-flowered fiddleneck, *Amsinckia grandiflora*, into the Site 300 ecosystem. Site 300 contains two of the three known natural extant populations of this plant. We hope to create a third sustainable population of *Amsinckia grandiflora* at Site 300.

1.2.4. Site 300 Geology

This section contains general descriptions of the principal geologic features of Site 300. Geologic maps and stratigraphic columns based on studies prior to 1981 have been modified by recent investigations conducted during the preparation of RI/FS documents. Detailed geologic logs have been prepared for most boreholes and monitor wells at Site 300. A more detailed discussion of Site 300 geology is presented in Chapter 3 of the SWRI report.

1.2.4.1. Stratigraphy

Bedrock strata exposed within Site 300 have been correlated with five mappable geologic units (Webster-Scholten, 1994). These units are the late Cretaceous Great Valley sequence (Kgv), the late Paleocene to mid-Eocene Tesla Formation (Tts), the mid-Miocene Cierbo Formation (Tmss), the late Miocene Neroly Formation (Tn), and the Pliocene nonmarine unit (Tps) of Dibblee (1980). These bedrock units are locally overlain by mid- to late Pleistocene terrace deposits and late Pleistocene to Holocene floodplain, ravine fill, landslide, and colluvial deposits (Carpenter et al., 1991; Dibblee, 1980) (Table 1-1). A schematic stratigraphic column for Site 300 is presented in Figure 1-6. Summary lithologic and hydrogeologic descriptions of these figures are provided in Table 1-1. Distributions of the various units are shown on the Site 300 geologic map (Fig. 1-7). Detailed descriptions of each are presented in Chapter 3 of the SWRI report.

1.2.4.2. Structure

Site 300 is located in an area of historical seismicity and Quaternary folding (Eaton, 1986; Namson and Davis, 1988; Wentworth and Zoback, 1989). Structural features within Site 300 are shown in Figures 1-7 and 1-8.

1.2.4.2.1. Folds. The bedrock sequence within Site 300 has been slightly deformed into several gentle, low amplitude folds (Fig. 1-8). These folds include:

- Patterson Anticline—controls bedding attitudes throughout much of Site 300; the southern limb of the structure strikes nearly east-west and dips toward the south at 5 to 25 degrees; the northern limb strikes toward the northwest and dips northeast, typically at 5 to 15 degrees.
- East Firing Area (EFA) Syncline—informally named the EFA syncline, is a very broad, open, gently northeast-plunging fold with a wide, nearly flat axial trough (Taffet et al., 1990).
- HE Process Area Syncline—a southeast-plunging syncline, underlies the HE Process Area in the southerly portion of Site 300 (Fig. 1-8).

1.2.4.2.2. Faults. Three general types of faults have been identified within Site 300:

- West-northwest trending, high-angle, presumably strike-slip faults.
- Discontinuous, north-northeast trending, normal faults mapped chiefly in the east-central portion of Site 300 (Webster-Scholten, 1994).
- West-northwest trending, high-angle reverse and thrust faults that are mainly present on the south flank of the Patterson Anticline (Carpenter et al., 1991).

Locations of principal faults within Site 300 are listed below and shown in Figure 1-8.

- Corral Hollow–Carnegie Fault Zone—interpreted as a right lateral strike-slip fault that crosses the southwestern portion of Site 300 and extends southeast and west beyond the limits of the site (Raymond, 1973; Dibblee, 1980); fault system is regarded as active and is judged capable of generating an earthquake in the range of M_S = 6.3 to 7.1 (Carpenter et al., 1991).
- Elk Ravine Fault—a complex structure composed of pre-Holocene strike-slip faults, reverse faults, normal faults, and local folds; two branches of the Elk Ravine Fault mapped as extending across Site 300 from northwest to southeast (Dibblee, 1980) (Fig. 1-8).
- Possible Midway Fault Extension (Dibblee, 1980)—a possible southeasterly extension of the Midway Fault mapped north of Site 300 across the northeastern corner of Site 300 (Fig. 1-8); fault classified as potentially active based on geomorphic criteria and possible associated microseismicity (CDWR, 1979).
- Terrace Fault (informal name)—a pre-Holocene high-angle reverse fault or fault zone within the southern portion of Site 300 (Fig. 1-8); farther east, the projection of the Terrace Fault enters the HE Process Area.
- Unnamed Fault (informal name)—a well-defined, north-south trending fault; approximately 50 ft of pre-Holocene normal offset occurs along this near vertical fault.

1.2.4.2.3. Joint and Fracture Systems. Joint sets are observed most often in the well-indurated rocks within Site 300. These rocks include the Great Valley sequence, Tesla Formation, and Neroly Formation. Joint sets are observed locally in more indurated portions of the Tps unit, but well-defined joints are uncommon in these sediments and in the poorly indurated Cierbo Formation strata.

Rock outcrops at Site 300 are pervasively fractured. Frequently, thin-bedded claystones are intensely fractured. At various locations throughout Site 300, persistent zones of high-angle (often vertical), closely-spaced, healed, and well-cemented fractures form resistant outcrops. These cemented fracture zones are generally 1 to 4 ft wide, cut across regional bedding, strike dominantly north to northeast with a vertical or near vertical dip, and may extend for over 1 mi in length.

As presented in Chapter 3 of the SWRI report (Webster-Scholten, 1994), cores from monitor wells and exploratory boreholes often contain fractures. Fracture intensity has been characterized using the RQD designation system of Deere et al. (1969) locally supplemented by down-hole video studies. In drill cores, iron and manganese oxide and other weathering products are visible on some fracture and bedding plane surfaces to average depths of about 100 ft. The presence of these minerals suggests circulation of oxygen-bearing ground water to these depths through the fracture network. Fractures below 100 ft may also be filled with carbonates, sulfides, opaline silica, and clay minerals (Webster-Scholten, 1994).

1.2.4.3. Seismic Setting

Site 300 is located near the eastern margin of the seismically active San Francisco Bay region and is also within about 4 mi (6 km) of the seismically active Coast Ranges—Central Valley

boundary (Eaton, 1986; Namson and Davis, 1988). Seismic monitoring by LLNL (Hauk, 1990) confirms microseismic activity within the Altamont Hills in the region surrounding Site 300. Table 1-2 lists principal active and potentially active faults in the San Francisco Bay region, and in the Altamont Hills and Central Valley margin areas.

Facilities at Site 300 may experience earthquake shaking from three seismic sources. These sources are:

- A major earthquake on a principal Bay Region fault.
- A strong earthquake generated by a local fault within the Altamont Hills.
- A major earthquake on a regional fault along the Coast Ranges—Central Valley boundary or possibly beneath the western portion of the San Joaquin Valley.

1.2.5. Site 300 Hydrogeology

This section describes the general framework of the hydrogeologic model of Site 300, including the occurrence of surface water and ground water, and natural ground water chemistry. Details specific to the Building 834 operable unit are presented in section 1.3.4.

1.2.5.1 Surface Water

There are no perennial streams at Site 300. Surface water at the site consists of intermittent runoff, springs, and natural and man-made ponds. Surface water drainage basins are shown in Figure 1-9. Surface water sometimes occurs locally as a result of discharge from cooling towers.

1.2.5.1.1. Springs. Of the 25 springs at Site 300 (Fig. 1-10), 19 are perennial, four are intermittent, one (WB) is a zone of shallow saturation (not a true spring), and one (spring 20) has no available information.

Most of the springs have very low flow rates and are recognizable only by small marshy areas, pools of water, or vegetation surrounding them. Vegetation surrounding the springs includes cattails, nettles, willows, and grass. Only three of the springs have flow rates greater than 1 gal./min.

1.2.5.1.2. Other Surface Water. There is a vernal pool in the northwest corner of Site 300, within the EFA/WFA study area. It is a perennial pool created by ponding of water in a natural depression.

Site 300 contains three man-made surface water bodies. A sewage treatment pond is located in the southeast corner of the site in the GSA, and two lined HE rinse-water impoundments are located to the west in the HE Process Area study area. The Carnegie SVRA Residence Pond is located off site just east of pit 6 at the mouth of Middle Canyon. In addition, there are four small off-site stock watering ponds in the area north of Site 300. As mentioned above, other surface water at Site 300 results from blowdown water from cooling towers.

1.2.5.1.3 Drainage. The major drainages at Site 300 are Elk Ravine in the EFA/WFA study area; Draney Canyon, Davis Canyon, Drop Tower Canyon, Firing Range Canyon, Middle Canyon, and Paper Canyon in the Pit 6 study area; Long Canyon in the HE Process Area study area; and 832 Canyon, which extends along the western edges of the Building 834 and Building 833 study areas to the central GSA (Fig. 1-9). Water flows in these drainages only after

heavy storms. The occasional runoff from these drainages eventually flows into Corral Hollow Creek. This creek is an intermittent stream that flows eastward along the southern boundary of Site 300 toward the San Joaquin Valley.

1.2.5.2. Ground Water

Site 300 is a large and hydrogeologically diverse site. Due to topographic relief, stratigraphic heterogeneity, and structural complexity, the stratigraphic units described in section 1.2.4 and Table 1-1 are discontinuous across the site. Consequently, unique hydrogeologic conditions govern the occurrence and flow of ground water and the fate and transport of contaminants beneath each operable unit. We have defined individual hydrologic units consisting of one or more stratigraphic intervals that comprise a single hydraulic system within each study area. These hydrologic units and their stratigraphic components are shown in Figure 1-11 and are described in detail in Webster-Scholten (1994). Site-wide stratigraphic relationships are depicted in cross-sections A-A' and B-B' (Fig. 1-12). The hydraulic relationships between the northwest and southeast portions of the site, however, have not been well established due to sparse well control in the center of the site. Separate potentiometric surface contour maps for the six major hydrologic units at Site 300 are shown in Figure 1-13.

In the northeast part of Site 300, ground water occurs under unconfined to confined conditions primarily within the $Tnbs_1$ and Tmss stratigraphic units, which are part of the Qal-Tmss hydrologic unit. As shown by the potentiometric surface contours, the general ground water flow direction in the EFA/WFA study area is to the east (Fig. 1-13). This ground water flow direction is controlled primarily by the dip of the bedding planes. Perched water-bearing zones also occur within Quaternary alluvial sands and gravels, and fractured siltstones and claystones of the $Tnbs_1$ and Tmss stratigraphic units. These perched zones are highly discontinuous and variable.

Throughout most of the southeastern part of Site 300, the $Tnbs_1$ hydrologic unit is a continuous, regional water-bearing zone (Figs. 1-13 and 1-14). Ground water in the $Tnbs_1$ hydrologic unit occurs within sandstones of the $Tnbs_1$ stratigraphic unit under confined to flowing artesian conditions. As shown by the potentiometric surface contours, ground water generally flows to the south and southeast (i.e., in the direction of dip) in the southeastern part of Site 300 (Fig. 1-14). In the eastern GSA, the $Tnbs_1$ stratigraphic unit occurs as a subcrop beneath Corral Hollow alluvium as part of the Qal-Tmss hydrologic unit, and ground water occurs under semiconfined to unconfined conditions. The ground water flow direction in this unit is controlled primarily by the orientation of the permeable alluvial sands within the Corral Hollow stream channel.

Other water-bearing zones that exist in the southeastern part of the site include the $Tnbs_2$ and Tps hydrologic units. Ground water occurs under unconfined to artesian conditions in the $Tnbs_2$ hydrologic unit beneath the HE Process Area study area. The ground water flow direction in this hydrologic unit is also dip-controlled and sub-parallels the flow direction in the underlying $Tnbs_1$ hydrologic unit. Perched ground water occurs primarily in gravel channels within the Tps hydrologic unit beneath the Building 834 and the HE Process Area study area (Fig. 1-11). The ground water flow direction within these shallow, perched zones is controlled by the orientation of sand and gravel channels and the dip direction.

Ground water-supply wells within Site 300 and within 0.5 mi of the site are shown in Figure 1-15. Site 300 ground water levels of total dissolved solids (TDS) generally range from 300 to 2,000 mg/L; specific conductivity ranges from 770 to 2,400 μhos/cm. The ground water in this area contains naturally-occurring selenium and arsenic above the MCLs for drinking water.

1.3. Building 834 Operable Unit Background

As part of the site-wide remedial investigation of Site 300, six remedial investigation study areas were defined, one being the Building 834 study area. The Building 834 study area includes Buildings 831, 832, 838, and the Building 834 Complex (Fig. 1-1). As a result of the nature and extent of contamination identified at the Building 834 Complex, the Complex and downgradient plume were designated as the Building 834 operable unit for the purpose of this feasibility study.

The Building 834 operable unit is located on a north-south trending ridge in the southeastern part of Site 300 (Fig. 1-1). As discussed in the SWRI, the buildings were constructed to conduct the Weapons Test Area (WTA) activities. Prior to the purchase of Site 300 land for development as a DOE HE test facility, the land was used for cattle ranching and livestock grazing.

1.3.1. Description of the Building 834 Operable Unit

The Building 834 operable unit contains Buildings 834A, B, C, D, E, F, G, H, J, K, L, M and O and perched ground water plume downgradient of the facility. Northwest of the operable unit, the dominant topographic feature is an east-west-trending ridge. To the southeast of that ridge is a valley that contains Building 831, the Building 832 Complex, and Building 838. Farther to the east is a north-south-trending, nearly flat-topped ridge; the Building 834 Complex is located at the northern end of this ridge. A valley and a northwest-southeast-trending ridge extend from the Building 834 Complex to the eastern boundary of the operable unit (Fig. 1-1).

1.3.2. History of the Building 834 Operable Unit

By the early 1960s, construction was completed for the majority of the Building 834 facilities, consisting of Buildings 834A, B, C, D, E, F, G, H, J, and K. Two additional test cells, Buildings 834L and M, were constructed in about 1969 and 1979, respectively. Since their construction, the Building 834 facilities have been used to expose test specimens to thermal shock, thermal cycling, and long-term elevated or reduced temperatures. This facility is only minimally active today. TCE, also called "brine," served as a heat transfer fluid for these operations until 1994 when the TCE system was dismantled. Via controls in Building 834A, TCE was sent through aboveground pipes from each of the pumping station Buildings 834B, C, and D to the associated test cells, Buildings 834E, F, G, H, and J, which are located around the control building and pump station buildings. Buildings 834B and C were previously deactivated; Building 834D was deactivated in 1994. The testing schedule is significantly reduced today compared to the 1960s, when the facility operated 24 hours a day, seven days a week. Figure 1-16 identifies the original functions of each of the buildings. This figure also delineates the "Building 834 Complex core area," which is the focus of proposed remedial actions discussed in subsequent chapters of this feasibility study. In 1990, a portable trailer was moved

to the Building 834 Complex to provide overflow office space. Recently, the portable trailer was identified by the facility coordinator as Building 834O.

As mentioned in section 1.2.3.7, the Building 834 Complex has been used to test several innovation technologies. These technologies are described in Chapter 3 and Appendix D.

1.3.3. Building 834 Operable Unit Geology

The Building 834 operable unit geology is summarized below and is shown in Figures 1-7 and 1-17. Hydrogeologic cross sections are presented in section 1.3.4. Building 834 operable unit hydrogeology is discussed in section 1.3.4.

1.3.3.1. Stratigraphy

The age of the stratigraphic units in the operable unit ranges from Holocene to Late Miocene. At the top of the section is an uplifted and eroded, unconsolidated terrace deposit (Qt) with abundant Franciscan clasts unconformably overlying an older, unindurated channel and channel margin assemblage of silty gravels, clays with partly lithified silty sandstone, and mudstone beds (Tps).

The Qt deposits are limited to relatively minor exposures at or near topographic highs. The more extensively exposed Tps unit consists dominantly of lacustrine clays with sand and gravel channels, including the perched water-bearing zone that is contained in a basal Tps gravel (Tpsg) channel. Both the Qt and Tps units are characterized by lateral and vertical heterogeneity.

The Tps unit overlies a moderately- to well-indurated, blue-weathering, fluvial-lacustrine sequence that is rich in volcanically-derived source material. This bedrock sequence, the Late Miocene Neroly Formation, has been divided into several informal stratigraphic units, four of which are penetrated by boreholes in the operable unit. Table 1-3 contains detailed descriptions of these stratigraphic units. As shown in hydrogeologic cross-sections A-A' through D-D', the Neroly Formation hydrostratigraphic units extend laterally throughout the operable unit (Figs. 1-18 through 1-21). The $Tnsc_2$ unit at the top of the Neroly Formation grades upward into the overlying Tps unit, and the contact between these two units is difficult to determine. The regional ground water aquifer consists of sandstones and conglomerates contained within the lower blue ($Tnbs_1$) sandstone unit near the base of the Neroly Formation.

1.3.3.2. Structure

The dominant structural feature in the operable unit is low-angle homoclinal dip in a southerly direction, depicted in hydrogeologic cross-section A-A' (Fig. 1-18). The Neroly Formation appears to dip about 5 degrees more steeply than the Pliocene nonmarine unit, which dips up to about 4 degrees. There is local variability in attitude. A second cross section extends in a more westerly direction from the core of the Building 834 Complex to one of the operable unit wells completed in the regional aquifer ($Tnbs_1$) (Fig. 1-19). Depths of stratigraphic contacts used to construct these cross sections are presented in Tables 1-4 and 1-5. The locations of these cross sections are shown in Figure 1-17.

Figure 1-22 is a contour map of the base of the Tpsg. This horizon is significant because it influences ground water flow in the perched water-bearing zone. The density of the well spacing is sufficient to indicate that this is an erosional surface that dips 4 to 5 degrees south to southwest

and thereby controls the flow of the perched ground water. Figure 1-23 illustrates the vertical and lateral heterogeneity characteristic of a fluvial depositional system. This illustration is based on boreholes located near Building 834D (Fig. 1-24).

Structurally induced (as distinct from drilling-induced) fractures were observed in core from operable unit boreholes and in test pits excavated on the western slope of the Building 834 Complex site. Some of the fracture zones are intensely fractured. The dominant pattern of occurrence in lithologic logs for wells W-834-D9A, -T1, -T3, and W-831-01 (west of the operable unit) is that fracture zones, ranging from a few tenths of a foot to a few feet in thickness, are separated by several feet of unfractured rock. Both sandstones and claystones of the Neroly Formation contained fractures in the core. Sandstones contained high-angle (60-plus degree) fractures while siltstones and claystones contained low-angle fractures (0 to 15 degrees) and shear planes.

Fracture surfaces are variable in direction. Slickensides are present on some fracture surfaces in cores and in test pit grab samples; however, they were not frequently noted. (Gouge was even less common.) More common on the fracture surfaces is the presence of mineralization, suspected to be manganese and/or iron oxide, and silica cement. Some fractures are filled with minerals, and others are only stained. No pattern of occurrence with respect to mineral type, degree of filling, or depth was discerned.

No faults are known to occur within the boundaries of the operable unit. Existing data were reviewed to examine the possibility of a normal fault, located about 500 to 1,000 ft (152 to 305 m) from the eastern boundary of the operable unit, with an orientation parallel to the Callahan Fault (which appears to project beneath Corral Hollow east of the operable unit). Data are insufficient to verify the existence of this fault.

1.3.4. Building 834 Operable Unit Hydrogeology

This section describes the general hydrogeology of the Building 834 operable unit, including the occurrence of surface water and ground water, and natural ground water chemistry. At the Building 834 Complex, perched ground water contains TCE and other chemicals of concern. Data indicate that the perched ground water is confined below by the low-permeability siltstones and claystones of the associated perching horizon, which serves as a lower confining layer to prevent vertical migration through deeper unsaturated sediments to the regional aquifer.

1.3.4.1. Surface Water

Surface water occurrences near the operable unit are limited to two intermittent springs (springs 4 and 19). Spring 19, located at the southeast corner, shows only dead mesophytic vegetation as evidence of the spring's former existence. In 1987 and early 1988, spring 19 supported live vegetation (Gregory, 1992). Spring 4, located about 900 ft south of Building 838 and outside the Building 834 operable unit, currently supports cattails (*Typha sp.*) and thistles. In the 1982 to 1983 rainy season, the amount of rainfall was unusually high, resulting in higher infiltration and discharge. At that time, the ground at spring 4 was soggy; however, the quantity of moisture was insufficient to collect a sample (Carpenter, 1992).

Figure 1-25 depicts the springs near the operable unit and the three drainage basins. Two of these basins empty into Corral Hollow Creek to the south; the third empties into the Elk Ravine drainage, which joins the Corral Hollow Creek drainage to the northeast.

Spring 4 is reported to discharge from a coarse-grained lens in the Pliocene nonmarine stratigraphic unit (Carpenter, 1992). Spring 4 is believed to receive its recharge from one of the saturated water bodies under the easternmost ridge of the HE Process Area study area. Spring 19 may be receiving its recharge from intermittent surface infiltration to the ridge immediately north of the spring.

In an average year, precipitation at Site 300 is limited to about 10 or 11 in. (25.4 to 27.9 cm). Because the climate is semiarid, and expansive clay-rich soils are present, the ground is commonly desiccated during late spring to early fall, resulting in a large potential for infiltration until the clay-rich soil expands. During typical winter storms, surface runoff in the natural drainages is rarely observed, and commonly infiltrates before reaching the Site 300 boundary. In the developed area adjacent to Buildings 834B and D, precipitation has been observed collecting in two small, shallow depressions during heavy storms.

The general direction of surface water flow for these buildings is to the southwest, due to the topography of the canyon where they are located. Prior to February 1989, infiltration from cooling tower blowdown was a source of recharge to the perched water-bearing zone (Qt-Tpsg) at the Building 834 Complex site. At that time, the effluent was rerouted into a buried pipe that discharges to the surface to the northwest of the complex, away from the TCE plume in the perched water-bearing zone (Fig. 1-26).

1.3.4.2. Ground Water

Since studies began at the Building 834 Complex in 1982, 13 exploratory boreholes have been drilled, and 48 ground water monitor wells have been installed. Borehole and well locations are shown on Figures 1-27 and 1-28, respectively. Well construction data for monitor wells are described in detail in Appendix E of the SWRI report; techniques used for monitor well installation and completion are described in detail in SWRI Appendix A.

Hydraulic tests have been performed on wells in the Building 834 Complex to determine the hydraulic characteristics of the hydrologic units and to define hydrostratigraphic relationships. The results of these tests are summarized in Table 1-6. Well completion data are provided in Tables 1-7 and 1-8 and shown in Figure 1-29. Hydrogeologic cross sections of the Building 834 Complex are presented in Figures 1-18 through 1-21.

Four primary hydrologic units have been identified in the operable unit, based on their hydraulic, physical, and geochemical characteristics: a shallow, more coarse-grained saturated zone (Qt-Tpsg hydrologic unit) underlain by a unit of lower permeability ($Tps\text{-}Tnsc_2$ hydrologic unit), a predominately unsaturated zone underlain by a second unit of lower permeability ($Tnbs_2\text{-}Tnsc_1$ hydrologic unit), and a thick sequence of mudstones and sandstones that contains a semiconfined aquifer at depth ($Tnbs_1$ hydrologic unit) (Fig. 1-30). The separation between the shallower saturated zone and deeper, regional aquifer is about 280 ft (85 m). The hydraulic characteristics of the water-bearing zones are summarized in Table 1-9. Ranges of values of common hydrochemical characteristics for the ground water occurring in these hydrologic units are listed in Table 1-10.

Three terms are used in this report to refer to the shallow water-bearing soil and rock at the Building 834 Complex site: perched zone, perched water-bearing zone, and perching horizon. Perched zone is the most general of the three; it includes the vadose zone and the unsaturated materials at the perimeter of the saturated zone. This term is also used to refer to data collected from wells that are completed across the Qt-Tpsg (perched water-bearing zone) hydrologic unit and the Tps-$Tnsc_2$ (perching horizon) hydrologic unit. We refer to these wells as being completed in the Qt-Tpsg/Tps-$Tnsc_2$ hydrologic unit.

As presented in Appendix F, we estimate the volume of ground water in the core area to be 140,000 ft^3 (1,100,000 gal.) and 700,000 ft^3 (5,200,000 gal.) in the entire perched water-bearing zone. Based on these volumes and the hydraulic parameters presented in Table 1-6, we estimate that it will take two years to dewater the core area, and seven years to dewater the entire perched water-bearing zone.

1.3.4.2.1. Quaternary Terrace Deposits-Member Pliocene Nonmarine Sequence (Qt-Tpsg) Hydrologic Unit. The Qt-Tpsg hydrologic unit is composed of stratigraphic units Qt and Tpsg and underlies the Building 834 Complex. Figure 1-31 shows the potentiometric surface elevations of the perched water-bearing zone within the Qt-Tpsg hydrologic unit for December 1991. The ground water from this unit flows south to southwestward, generally following the dip of the perching horizon (Fig. 1-22).

The vertical and lateral heterogeneity within the Qt-Tpsg hydrologic unit is pronounced. Permeability is low as a result of cementation within the coarser gravel units; porosity is predominately primary, with secondary porosity in the form of fractures playing a lesser role, if any, in ground water flow. The observed well yields are low, producing less than 120 gpd. Wells often "dry out" (i.e., temporarily cease yielding water to the well after 1 to 2 casing volumes are removed) during quarterly sampling.

The hydrochemical values for the Qt-Tpsg hydrologic unit (perched water-bearing zone) are generally comparable to the values for the Tps-$Tnsc_2$ (perching horizon). TDS values in the Qt-Tpsg hydrologic unit range from 760 to 910 mg/L (ppm), and specific conductivity ranges from 1,020 to 1,400 µmhos/cm. The pH values range from 7.4 to 8.2. Arsenic and selenium concentrations in all ground water samples were below the MCLs of 0.05 and 0.01 mg/L, respectively, for these naturally occurring metalloids.

The distinction between the hydrochemical signatures of the perched water-bearing zone (Qt-Tpsg) and silty sandstone lenses in the perching horizon (Tps-$Tnsc_2$) is the dominance of the carbonate and bicarbonate anions in the perched water-bearing zone, and the dominance of the chloride anion in the perching horizon silty sandstone lenses. This hydrochemical data shows distinct hydrochemical signatures, suggesting poor mixing of the water between the Qt-Tpsg and Tps-$Tnsc_2$ units. The ground water of both perched water-bearing zone and perching horizon sandstones is rich in sodium and potassium cations. Regional aquifer ($Tnbs_1$) ground water, in contrast, has calcium cations mixed with the sodium/potassium cations.

The boundary between the Qt-Tpsg and the Tps-$Tnsc_2$ units is leaky, as evidenced by the presence of TCE in perching horizon (Tps-$Tnsc_2$) ground water. However, the concentration of TCE at the W-834-S1 and -S9 well cluster is much higher in the perched water-bearing zone (Qt-Tpsg) than in the perching horizon (Tps-$Tnsc_2$) (Table 1-11). Furthermore, the hydrochemical signatures for the Qt-Tpsg and Tps-$Tnsc_2$ units at the Building 834 Complex site

discussed above and lower TCE concentration in the Tps-Tnsc$_2$ indicate poor mixing of the water.

1.3.4.2.2. Pliocene Nonmarine Sequence-Miocene Neroly Upper Siltstone/Claystone (Tps-Tnsc$_2$) Hydrologic Unit. The Tps-Tnsc$_2$ hydrologic unit consists of siltstones and claystones with minor silty sandstone lenses. An infiltration packer test on a fractured perching horizon (Tps-Tnsc$_2$) interval showed a low initial flow rate and a correspondingly low hydraulic conductivity value. Wells completed solely in the Tps-Tnsc$_2$ would probably have production or yield rates lower than wells that have screen or sandpack open to the Qt-Tpsg unit.

The TDS values in the Tps-Tnsc$_2$ hydrologic unit range from 680 to 1,400 mg/L. The pH values range from 7.9 to 9.5. The specific conductivity values range from 1,000 to 2,430 µmhos/cm. The Tps-Tnsc$_2$ unit has a broader range of values for TDS and higher pH and specific conductivity values than the Qt-Tpsg unit.

Though the presence of TCE in the perching horizon ground water does indicate some hydraulic communication between the Qt-Tpsg and the Tps-Tnsc$_2$, the natural hydrochemical data for the two hydrologic units plot as distinct populations, suggesting poor mixing of the water.

1.3.4.2.3. Miocene Neroly Upper Sandstone-Miocene Neroly Middle Siltstone/Claystone (Tnbs$_2$-Tnsc$_1$) Hydrologic Unit. No samples were collected from within the Tnbs$_2$-Tnsc$_1$ hydrologic unit for ground water chemistry analysis because the wells completed in these units contained no water.

Based on limited evidence, the Tnbs$_2$-Tnsc$_1$ hydrologic unit in the vicinity of the Building 834 Complex is not saturated. No springs are associated with outcrops of the Tnbs$_2$ sandstone that extend along the slopes of hills in this operable unit.

A barrier to downward migration of ground water exists at the interface of the Tps-Tnsc$_2$ and Tnbs$_2$ units. This barrier results from the lack of matrix suction between a hydrated, fine-grained clay or claystone above, and an unsaturated coarser-grained sandstone below. Also, several laterally extensive, low permeability claystones, including the Neroly aquitard (Tnsc$_1$) (Figs. 1-18 through 1-21), are present within the Tnbs$_2$-Tnsc$_1$ hydrologic unit; these claystones provide a further barrier to vertical ground water migration to the regional aquifer (Tnbs$_1$).

1.3.4.2.4. Miocene Neroly Lower Sandstone (Tnbs$_1$) Hydrologic Unit. The deeper, Neroly Formation aquifer (within the Tnbs$_1$ unit) is believed to be continuous throughout the operable unit, lying at a greater depth than the deepest canyon. Figure 1-14 is a potentiometric map of the regional aquifer in southeastern Site 300. Direction of flow beneath the Building 834 operable unit is to the south-southeast at a gradient of about 0.04 ft/ft.

Recharge to the Neroly Formation lower sandstone occurs from subsurface inflow at the upgradient boundaries of the operable unit. Ground water in the Tnbs$_1$ regional aquifer discharges as subsurface outflow at the downgradient boundaries.

The hydraulic conductivity values calculated from pump test data from regional aquifer wells W-834-T1 and -T3, and from slug test data from regional aquifer well W-831-01 (west of Building 834) (Weiss Associates, 1988) suggest that secondary porosity in the form of fractures may have contributed slightly to the yields. These wells are completed in sandstone (W-831-01 and W-834-T1) and conglomerate (W-834-T3) (Table 1-7), and the hydraulic conductivity values

are slightly above the upper value expected for sandstone. Evidence, however, suggests that within the operable unit, fractures increase permeability only slightly in the regional aquifer.

The TDS values in the $Tnbs_1$ hydrologic unit range from 440 to 470 mg/L (ppm). The specific conductivity range of 640 to 710 µmhos/cm is relatively low compared to the Qt-Tpsg and Tps-$Tnsc_2$ values. The pH values range from 7.7 to 7.9. The $Tnbs_1$ (regional aquifer) water samples have pH values within the range of values for the Qt-Tpsg, and the specific conductivity and TDS values range from lower to much lower in the $Tnbs_1$ than those for the Qt-Tpsg hydrologic unit. Concentrations of arsenic in ground water ranged from 0.023 to 0.058 mg/L, which exceeds the 0.05 mg/L MCL. The occurrence of arsenic within the $Tnbs_1$ probably results from natural leaching of *in situ* constituents (Raber and Carpenter, 1983). Selenium concentrations were well below MCL levels.

1.3.4.3. Recharge and Discharge

The Qt-Tpsg hydrologic unit is recharged by infiltration of precipitation at the core of the Building 834 Complex. Prior to 1989, cooling tower blowdown and the septic system leach field associated with the Building 834 Complex also discharged to the perched zone. These two sources of man-made recharge were rerouted away from the perched zone in 1989. The saturated water body at the Building 834 Complex site is inferred to discharge by evapotranspiration along portions of the perimeter that "daylight" on the hillsides. The Qt-Tpsg aquifer at the Building 834 Complex site is unconfined.

The local saturated lenses within the Tps-$Tnsc_2$ hydrologic unit are recharged by the Building 834 Complex site perched water-bearing zone where it is overlain by perched ground water. Perched ground water may also discharge by evapotranspiration along nearby hillslopes.

Based on limited evidence, the $Tnbs_2$-$Tnsc_1$ hydrologic unit does not appear to be saturated within the operable unit. No springs are associated with outcrops of the $Tnbs_2$ sandstone that extend along the slopes of hills. The regional aquifer in the $Tnbs_1$ unit is inferred to recharge primarily by subsurface inflow at the upgradient operable unit boundary in Elk Ravine, based on the lack of seasonal response exhibited in the wells screened in the aquifer (Fig. 1-32). Discharge is inferred to occur by downgradient subsurface outflow. Water budget calculations are presented in sections 5.3.1.4 and 5.3.1.5 of Bryn et al. (1990).

1.3.5. Beneficial Uses of Ground Water

Any future beneficial uses of the perched water-bearing zone (Qt-Tpsg) have been contravened by San Joaquin County Health Ordinance 1862 that requires any well in the County to be grouted to a depth of at least 100 ft (30.5 m). (Exceptions are made for monitor wells.) Historically, there is no evidence that water from the perched water-bearing zone has ever been used for any purpose. Compliance with these statutes would also prevent use of water from the perching horizon (Tps-$Tnsc_2$) sandstones. In addition the limited yield of <110 gpd makes the perched zone incapable of supplying drinking water under State Water Resources Control Board (SWRCB) Resolution 88-63. SWRCB Resolution 88-63 specifies that "...all surface and ground waters of the state are considered suitable, or potentially suitable, for municipal or domestic water supply and should be so designated by the Regional Board with the exception of surface and ground waters where: the water source does not provide sufficient water to supply a single well capable of producing an average sustained yield of 200 gallons per day." As a result, LLNL

is in the process of applying for an amendment to the Central Valley RWQCB (CVRWQCB) Basin Plan to exclude the Building 834 Complex shallow perched water-bearing zone.

Within the operable unit, there are no current or past uses of the regional aquifer ($Tnbs_1$) ground water except for monitoring. Outside of the operable unit, wells completed in the $Tnbs_1$ regional aquifer have been used to supply drinking water at Site 300 and off site. Other uses include domestic supply, irrigation, process makeup water, fire fighting, and livestock watering.

1.3.5.1. Description of Water-Supply Wells

There are no water-supply wells in the Building 834 operable unit. Water-supply wells outside the operable unit within Site 300 and within 0.5 mi of the site are shown in Figure 1-15.

1.3.5.2. Inorganic Water Quality

We evaluated the inorganic quality of ground water in the Building 834 operable unit relative to potential beneficial domestic, agricultural, and industrial use. Two ground water types are present in the area:

- A perched water-bearing zone (Qt-Tpsg) along a ridgetop near the core of the Building 834 Complex and extending to the south for about 1,800 ft (Fig. 1-33). This perched water is at a typical depth of about 10 to 70 ft beneath the ground surface, depending on topography (Fig. 1-34).
- The regional aquifer is located in the lower Neroly Formation ($Tnbs_1$) at a depth of about 280 ft beneath the ground surface. This range of depth is due to topographic relief.

Monitor wells completed in the perched water-bearing zone have low yields, from 1 to 25 gpd (Table 1-9). These yields are less than the sustained yield of 200 gpd from a single well that is specified by SWRCB Resolution No. 88-63 to qualify as a suitable or potentially suitable source of municipal or domestic supply. It should also be noted that the perched water-bearing zone is 4 ft thick, or less in many places, and the zone is too near the surface to be easily protected from typical domestic septic systems. The TDS for ground water samples in the perched water-bearing zone ranged from 520 to 1,500 mg/L, and chloride ranged from 20 to 500 mg/L (Appendix H in the SWRI). The agricultural water quality goal for TDS is 450 mg/L, and for chloride 106 mg/L. The secondary MCLs (SMCLs) for humans are 500 mg/L TDS and 250 mg/L (22 CCR 64473). Arsenic in the two water samples analyzed averaged 0.017 mg/L, which is less than the MCL of 0.050 mg/L. The average major ions in ground water from this hydrologic unit indicated a system rich in carbonate and bicarbonate anions, and sodium and potassium cations (Fig. 1-35). The relatively small volume and small flow rate of water available for use from the perched water-bearing zone, combined with some analyses exceeding the TDS and chloride SMCLs and agricultural goals, make the water unsuitable for domestic, agricultural, or industrial use and further substantiate the appropriateness of the Basin Plan Amendment to exclude the perched water-bearing zone.

Ground water from the regional aquifer had TDS that ranged from 430 to 470 mg/L. Chloride ranged from 47 to 56 mg/L. Of the two water samples analyzed for arsenic, one had 0.023 mg/L and the other had 0.058 mg/L, which is above the MCL. This is likely a natural occurrence of arsenic. Major ions in ground water from this hydrologic unit showed a dominance of mixed calcium and sodium plus potassium cations, along with moderately

balanced anions. Other than the arsenic concern, the regional aquifer would likely provide beneficial use for domestic and limited volume agricultural and industrial purposes.

1.3.6. Chemical Use

As part of the SWRI report, 22 locations in the Building 834 study area were identified as sites where chemicals were used, stored, or disposed. Table 1-12 summarizes the identification and screening of the locations at the Building 834 operable unit where chemicals were used, stored, or disposed. Since the early 1960s, the Building 834 facilities have been used to expose test specimens to thermal shock, thermal cycling, and long-term elevated or reduced temperatures. TCE, also called "brine," serves as a heat transfer fluid for these operations until 1994 when the TCE system was dismantled. A silicon-based oil, tetra 2-ethyl butyl ortho-silicate (T-BOS), was used as an additive to the brine during the 1970s. Via controls in Building 834A, TCE was sent through aboveground pipes from each of the pumping station Buildings 834B, C, and D to the associated test cells, Buildings 834E, F, G, H, and J, which are located around the control building and pump station buildings. Buildings 834B and C have been deactivated; only Building 834D contains operable pumping station equipment. The testing schedule is reduced today compared to the 1960s, when the facility operated 24 hours, seven days a week.

1.3.7. Chemical Releases

Historical information and analytical data presented in Chapter 10 of the SWRI report confirm that VOCs, primarily TCE, were released at ten release sites at the Building 834 Complex between the early 1960s and mid-1980s (Table 1-13). Based on employee interviews, we estimate that an aggregate of about 550 gallons of TCE were released in the vicinity of the Building 834 Complex between 1962 and 1978 (Olsen, 1982) due to leakage from pipes, pumps, and valves, and from surface releases. The estimated total quantity of 550 gallons spilled/released at the Building 834 Complex is an order-of-magnitude estimate and is consistent with the 297 gallons (270 gal. in soil and 27 in ground water) of TCE estimated based on field data (Appendix A). The decommissioned septic system leach field is also considered to be a potential release location for TCE and other VOCs in soil and ground water because, prior to 1978, the floor drains in pump station Buildings 834B, C, and D were connected to the old septic system. Sometime after that date, the drains were filled with cement (Lindeken et al., 1986). Diesel fuel, attributed to accidental overfilling of an underground tank located near Building 834B, has been detected in ground water; however, tank testing has proven tank integrity. T-BOS, a silica-based lubricant used in the TCE system, has been identified in ground water samples collected adjacent to Building 834D, indicating that it was released along with the TCE.

The TCE pumping system was upgraded in 1985. The system consists of closed delivery and return loops; an alarm sounds if a leak occurs.

Confirmed releases in the Building 834 operable unit occurred only at the core of Building 834 Complex site and the facility septic system (Fig. 1-16). The quantity of TCE released there greatly exceeded that of other VOCs, which had either minor use in facility operations (Bryn et al., 1990; Webster-Scholten, 1994) or were present as impurities in the TCE supply (Vonder Haar et al., 1992). TCE was released to the ground surface at the core of the complex as surface spills, leakage from valves and pump seals, discharge from drains behind the

pump station buildings, and discharge to floor drains in the pump station buildings that once emptied to the septic system leach field. Soil and rock, soil vapor, and shallow, perched zone (Qt-$Tpsg$/Tps-$Tnsc_2$) ground water were affected. Although low VOC concentrations have been reported in selected regional aquifer ground water samples, long-term monitoring of the regional aquifer ($Tnbs_1$) does not suggest that there is hydraulic communication between the aquifer and the TCE-bearing, shallow perched zone.

1.4. Nature and Extent of Contamination

This section of the FS summarizes the nature and extent of contamination (primarily TCE) in soil and ground water in the Building 834 Complex. The remainder of this FS will focus on the containment, removal, and treatment of this contamination. Tables 1-14 through 1-16 summarize the chemicals of potential concern in the Building 834 Complex and their maximum concentrations.

1.4.1. VOCs at Building 834

1.4.1.1. VOCs in Soil

As mentioned in section 1.3.7, TCE was released to the ground surface by surface spills, and leakage from pipes, pumps, and valves behind the TCE pump stations and test cells. Maximum TCE concentrations in borehole soil samples are shown in Figures 1-36 and 1-37. Maximum PCE concentrations in borehole soil samples are shown in Figure 1-38. As shown in Figure 1-37, TCE in vadose-zone soil is mainly confined within the core of the Building 834 Complex, comprising Buildings 834B, C, and D. Appendix G of the SWRI report contains all analytical results for soil from the SWRI database.

Within the core area, the maximum concentrations of TCE in soil and rock are adjacent to pump station Buildings 834C and D, and test cell Building J (Fig. 1-39), and occur mostly within 5 ft above or below the contact between the perched zone (Qt-$Tpsg$) and perching horizon (Tps-$Tnsc_2$) (Fig. 1-40). The maximum TCE concentration (12,000 mg/kg) in soil was detected in a soil sample collected in 1982 from a depth of 3.2 ft from the vicinity of a former TCE overflow drain behind Building 834C (Fig. 1-39). Soil in this location was excavated, aerated and replaced with clean soil between June and July 1982, prior to drilling borehole 834-C1. Subsequent soil sampling of boreholes 834-C1 and 834-C2 confirmed soil cleanup. The next highest TCE concentration (970 mg/kg) was found in the vicinity of Building 834D at a depth of 29.2 ft. This was well below the 0–12.0 ft soil depth considered for the baseline risk assessment presented in the SWRI report and Appendix C of this report. Of the test cells, test cell 834J had the highest TCE concentration in soil (52 mg/kg) (Fig. 1-37). A lower concentration of TCE (2.8 mg/kg) was found in a sample from borehole W-834-S1, about 20 ft southeast of the leach field. South of the former septic tank leach field area, 6 of 12 sample locations contained less than 0.019 mg/kg of TCE, and the remaining 6 samples (all between 0.5 and 12.0 ft depth) were below detection limits. Except for samples from the borehole of W-834-T8, TCE was not detected in soil and rock along the eastern and southern perimeter of the Building 834 Complex site. Table 1-17 lists the concentrations of TCE detected at the greatest depths within boreholes drilled at the Building 834 Complex.

Low concentrations of VOCs reported in subsurface soil (0.5–12.0 ft) include PCE, Freon 11, benzene, ethylbenzene, toluene, and xylene (Table 1-18). These VOCs are detected in concentrations ranging from 0.0002 to 14 mg/kg, the highest being a detection of PCE in a shallow (<5 ft) soil sample collected from behind Building 834D (Fig. 1-38). Toluene, benzene, ethylbenzene, and xylenes (total isomers) have primarily been detected in soil samples collected by Building 834D and the T2 wells to the south. Freon 11 detection in soil samples is mostly limited to the Building 834D area and the former leach field. TCE is the only chemical that has been detected in soil and rock samples south of well W-834-T4. PCE is common in soil and rock samples from wells adjacent to Building 834D and in the borehole for well W-834-J1; it has not been detected in samples collected south of well W-834-S5. South of the former leach field, outside the area of confirmed chemical releases to the surface, TCE and PCE concentrations are low. The pronounced vertical and lateral variability of TCE concentrations in the core area is attributed to multiple releases, release amounts, and release occurrences, as well as lithologic heterogeneity.

A concentration of 100 mg/kg total petroleum hydrocarbons (TPH) was detected in a sample from the borehole of W-834-D8 at a depth of 20 ft (Table 1-18). This sample was the only one analyzed for TPH from the W-834-D8 borehole. This well is located near an underground diesel fuel tank (Fig. 1-41). Since tests on the tank and associated lines have indicated no apparent leaks, the TPH release is probably an artifact of surface spills and/or overfilling of the tank.

1.4.1.1.1. DNAPLs/LNAPLs. Based on the release of nearly 550 gallons of the TCE heat exchange fluid at several locations within the Building 834 Complex core, it is likely that residual TCE fluid may be present in a portion of the soil/rock pores (U.S. EPA, 1992a, b; 1993a). The locations of these residual dense nonaqueous phase liquids (DNAPLs) can be problematic. It is probable that residual DNAPLs exist, scattered at various depths beneath the source areas and at some distance outward from the sources. However, TCE concentrations in soil and rock at the Building 834 Complex core are not so high as to indicate the presence of massive quantities of residual DNAPLs. Although the highest soil concentrations (10,000 and 12,000 mg/kg TCE) were excavated, recent TCE concentrations of up to 800,000 µg/L (ppb) in ground water strongly suggest this presence of DNAPLs. As presented in Figures 1-36 through 1-39, the highest soil TCE concentrations are localized behind former TCE pump stations 834C and 834D. Anecdotal information suggests that some of the soil excavated behind these buildings 'smelled of TCE' and some liquid may have oozed or dropped from the excavated soil. However, this anecdotal information has not been substantiated nor has the liquid been analyzed or quantified. The term TCE fluid is used alone because the TCE probably contained other DNAPL chemicals, such as PCE, as trace co-contaminants (Vonder Haar et al., 1992). In addition, T-BOS and perhaps related compounds were added to the TCE fluid. T-BOS is a light nonaqueous phase liquid (LNAPL) that floats on the perched ground water in the vicinity of Building 834D, but could become trapped in vadose-zone soil pores. No lenses or pools of TCE DNAPLs or LNAPLs have been identified in soil/rock in this area.

1.4.1.2. VOCs in Ground Water

TCE is the most prevalent VOC in ground water within the perched water-bearing zone and perching horizon at the Building 834 Complex site. Table 1-19 is a summary of TCE occurrence in operable unit wells. Other compounds that have been detected include: PCE, cis-1,2-DCE,

1,1,1-TCA, acetone, benzene, chloroform, 1,1-DCE, ethylbenzene, Freon 113, methylene chloride, toluene, xylenes (total isomers), T-BOS, and TPH. As presented in Appendix A, we estimate the entire volume of contaminated ground water to be 320,000 ft^3 (2,400,000 gal.).

1.4.1.2.1. Perched Zone. Figure 1-42 shows TCE distribution in perched ground water beneath the Building 834 Complex. The width of the plume varies from about 200 ft at the southern end to about 550 ft in the area of the former septic system leach field. The wider dimension in the northern portion of the plume is attributed to past recharge resulting from infiltration of cooling tower effluent at the former discharge location. The eastern and western extent of TCE in ground water is limited by the extent of saturation in the perched zone. The hydrogeology of the perched zone is discussed in section 1.3.4. The plume extends from the core area southward for about 1,500 ft. The area of maximum concentration within the plume generally corresponds with the area of maximum saturated thickness of the perched water-bearing zone, which is 4 to 5 ft thick adjacent to the core area and 4 ft or less in the remainder of the plume (Fig. 1-33).

Historically, the core area and former leach field area have shown the highest concentrations of TCE in perched ground water. In September 1991, the highest concentrations of dissolved TCE in the plume were adjacent to Building 834D—220,000 µg/L in well W-834-D3, and 350,000 µg/L in well W-834-D4. Well W-834-S1, about 20 ft southeast and downgradient from the former leach field release site, contained 76,000 µg/L TCE. As noted in Table 1-19, the historical (through December 31, 1991) maximum TCE concentration for the plume is 510,000 µg/L, sampled in June 1988 at well W-834-D3 (a concentration of 800,000 µg/L TCE was reported from a February 9, 1993 sample from well W-834-D3). These concentrations suggest that DNAPL phase TCE is present.

Other chemical compounds commonly detected in the perched ground water in the Building 834 Complex include PCE, 1,2-DCE, 1,1,1-TCE, T-BOS, and diesel fuel. TCE concentrations in perched zone ground water generally exceed those for PCE, 1,2-DCE, and 1,1,1-TCA, occasionally by up to three orders of magnitude (Table 1-20).

Based on interviews with site personnel, T-BOS was added to the TCE heat transfer fluid to improve the performance of seals and gaskets. The amber colored T-BOS has been observed floating in samples collected from well W-834-D3. It was also observed in the tank used to collect ground water during previous pilot testing of the remediation system at pump station Building 834D.

As a result of sampling well W-834-D8, diesel fuel detected in ground water at the core of the Building 834 Complex is attributed to accidental overfilling of the underground tank located adjacent to the well (Fig. 1-41). EPA Method 8015, "Total Fuel Hydrocarbons," detected a concentration of 25,000 µg/L. The "Hydrocarbons by IR" method yielded a concentration of 73,000 µg/L. As noted earlier, the tank and associated lines have been tested for leaks; there are no apparent leaks from this equipment.

One important question for this FS is whether or not, or to what degree, DNAPLs and LNAPLs are present in the perched water. No DNAPL lenses have been detected to date beneath the perched water. However, given the nature and magnitude of the TCE fluid releases, and the concentrations observed, it is possible that such lenses exist (U.S. EPA, 1992a, b; 1993a), but the extent and location of the DNAPLs/LNAPLs remain open to investigation. Given the relatively

high concentration (800,000 µg/L TCE in ground water) and recent product thickness measurement (1–3.5 in.) (Gregory, 1993) as well as proof-of-system (POS) test results (Landgraf, 1994), we believe that some residual DNAPL, and LNAPLs T-BOS and diesel are present and in the soil and rock pores in the perched zone water and in the capillary fringe above the perched zone.

1.4.1.2.2. Perching Horizon. Four wells at the Building 834 Complex site are screened exclusively in the perching horizon (Tps-Tnsc$_2$). They are: W-834-D10, W-834-S2A, W-834-S8, and W-834-S9. The first well, W-834-D10, located in the core area, has never produced water. The remaining wells are located in the former septic tank leach field area.

Table 1-20 shows a comparison between the concentration of TCE in September 1991, the total number of detections of TCE, and the maximum concentration of PCE, 1,2-DCE, and 1,1,1-TCA throughout the period of record for perching horizon wells. It is apparent that the concentration of TCE greatly exceeds those of the other most prevalent VOCs. The total number of detections of PCE (13) exceeds that of 1,2-DCE (11).

Not all intervals in the perching horizon will produce TCE-bearing ground water. This is demonstrated by nonproducing well W-834-D10, which underlies the area of maximum saturated thickness and maximum TCE concentration in the perched water-bearing zone. Wells W-834-S1 and W-834-S9 comprise a cluster in the perched water-bearing zone (Qt-Tpsg) and perching horizon (Tps-Tnsc$_2$), respectively, adjacent to the former septic system release site. In September 1991, the concentrations of TCE in ground water were 56,000 µg/L in W-834-S1, and 1,200 µg/L in W-834-S9. In quarterly monitoring results from September 1988 to December 1991, the smallest spread between the concentration of TCE in the perched water-bearing zone well compared to that in the perching horizon well is a factor of about 6 or 7. In some quarters, the difference is much greater. Based on the hydraulic relationship between the Qt-Tpsg and Tps-Tnsc$_2$, it is expected that concentrations of TCE (if any) in the perching horizon would be less than in the perched water-bearing zone in any perched water-bearing zone/perching horizon cluster drilled throughout the Building 834 Complex site (with proper well completion).

1.4.1.2.3. Tnbs$_1$ Regional Aquifer. Four wells penetrate the Neroly lower sandstone (Tnbs$_1$) in the vicinity of the Building 834 operable unit: W-831-01, W-834-D2, W-834-T1, and W-834-T3. The total depth of W-834-D2 was insufficient to penetrate the Tnbs$_1$ regional aquifer and it has been dry since completion. It is inferred that the Tnbs$_1$ regional aquifer underlies the entire operable unit. Detections of any VOCs within the regional aquifer have been infrequent, sporadic, and at low concentrations, ranging from 0.5 to 15 µg/L. Quarterly sampling began in December 1986 for well W-834-T1, and in March 1987 for wells W-831-01 and W-834-T3. Sampling extended through June 1994 for all three wells. As shown in Table 1-21, the majority of VOC detections occurred near the beginning of the sampling record for each well and are believed to be the result of inadvertent cross-contamination through the wellbore during installation (Buddemeier et al., 1987; Ruggieri et al., 1987). The absence of detected TCE since March 1987 supports this assessment. Although Freon 113 and chloromethane were reported once each between 1987 and 1991, the analytical history of this well leads us to conclude that these two reported detections are due to laboratory or sampling error. All ground water samples taken from these three wells since December 1991 have been below detection limits (0.5 µg/L) for all VOCs analyzed.

The dissolved TCE plume in the perched zone at the Building 834 Complex site is separated from the regional aquifer below by a distance of about 280 ft. The sporadic detections, low concentrations, and specific chemical species detected in the regional aquifer indicate that the perched zone plume has not affected the regional aquifer.

Arsenic has been detected in well W-834-T1 at 0.058 mg/L and in well W-834-T3 at 0.023 mg/L. It is inferred that the arsenic originated in naturally occurring arsenopyrite within the Neroly lower sandstone. The occurrence of the arsenopyrite in the Neroly lower sandstone at Site 300 was documented by x-ray fluorescence analysis (Raber and Carpenter, 1983).

1.4.1.3. VOCs in Soil Vapor

Active vacuum induced (AVI) soil vapor surveys (SVSs) were conducted between February and March 1989 at the core area to identify sources and the extent of TCE contamination and other VOCs, and to monitor the progress of vacuum extraction pilot studies. Chapter 2 of the SWRI report contains descriptions of SVS methods. Figure 1-43 is a map of the SVS points and the dedicated soil vapor monitoring points at the Building 834 Complex. Figure 1-44 shows the vertical distribution of TCE in soil vapor at the Building 834 Complex core. Table 1-22 summarizes maximum concentrations of TCE encountered at various SVS locations. Analytical data for soil vapor samples are included in Appendix I of the SWRI report.

High concentrations of TCE in soil vapor do not appear to correlate directly with high concentrations of TCE in soil and rock (Figs. 1-39 and 1-44). However, the SVS sample results do corroborate the soil and rock analytical data that indicate the maximum releases of TCE occurred adjacent to pump station Buildings 834B, C, and D. In addition, TCE soil vapor concentrations collected close to the surface of the perched water-bearing zone suggest TCE may be volatilizing in the vicinity of the capillary fringe.

1.5. Contaminant Fate and Transport

We developed conceptual models to identify the probable migration processes of the chemicals of concern from release sites and source media in the Building 834 operable unit to selected exposure points. The conceptual models provided the basis for selection of the quantitative models used to generate estimates of release rates and exposure-point concentrations. The exposure-point concentrations were used to estimate the magnitude of exposure to contaminants in the baseline public health evaluation presented in Chapter 6 of the SWRI report. The release areas, migration processes and exposure points identified in the Building 834 operable unit are given in Table 1-23. In addition, this table presents the mathematical models used to estimate release rates and the exposure-point concentrations for the chemicals of concern in each environmental media.

We applied mathematical models to estimate the rate of VOC flux from subsurface soil (0.5–12.0 ft) to the atmosphere in the vicinity of pump station Building 834D and to estimate the concentrations of contaminants that diffuse through the concrete slab into the indoor air of the building. A worst-case exposure scenario is assumed to occur in the outdoor atmosphere and the indoor air in the vicinity of the building because it is the location where the highest contaminant concentrations detected in subsurface soil have been reported.

In addition, we estimated the concentrations of contaminants in surface soil (defined here as the uppermost 6 in.) bound to resuspended particles throughout the Building 834 operable unit. The exposure-point concentrations for direct dermal contact and incidental ingestion of contaminants in surface soil are the same as the 95% UCLs (mg/kg) of the mean concentration of the chemicals and are presented in Table 1-23.

As discussed above, the Building 834 operable unit contains a perched water-bearing zone located near the ground surface on a ridgetop, and a regional aquifer that underlies the entire area at depth. The confirmed release sites are located at the Building 834 Complex, which is above the perched water-bearing zone. To determine the potential for contamination of the $Tnbs_1$ regional aquifer, we modeled the fate and transport of TCE from the base of the perched water-bearing zone through 178 ft of unsaturated Neroly Formation to the regional water table using the one-dimensional numerical model VLEACH (U.S. EPA, 1990a). This model was used to simulate downward contaminant transport by infiltrating water via liquid advection, gaseous diffusion, and linear partitioning. The model assumes that the water has an initial TCE concentration of 1,100,000 µg/L (the limit of solubility for TCE in water) that migrates through a homogeneous unsaturated sandstone column of constant moisture content. This approach was conservative for several reasons. First, it neglects the natural impediment to hydraulic transport provided by siltstone and claystone intervals in the unsaturated units between the perched zone and regional aquifer. Second, open borehole straddle packer tests across fractured intervals in W-834-D9A show the $Tnsc_2$ siltstone/claystone to have a low hydraulic conductivity, on the order of 10^{-7} cm/s. Third, neutron logging tests show a sharp decrease in moisture beneath the $Tnsc_2$ siltstone/claystone unit, indicating that the $Tnsc_2$ siltstone/claystone acts as a barrier to fluid transport between the Tps perched water-bearing zone and the unsaturated $Tnbs_2$ unit below. Thus the $Tnsc_2$ unit is a competent confining layer (Madrid, 1992). Fourth, monitor wells W-834-T1 and W-834-T3 (completed across the regional aquifer) do not have historic trends of TCE contamination, further indicating the integrity of the $Tnsc_2$ confining layer (i.e., perching horizon). Fifth, the 1,100,000 µg/L (the limit of solubility for TCE in water) TCE concentration used in the VLEACH model is significantly higher than the one-time highest reported TCE concentration of 800,000 µg/L. Sixth, the model neglects upward gaseous diffusion of VOCs, making more TCE available for downward advection. Finally, the model assumes a continuous source, whereas the contamination present in the Building 834 Complex is finite (i.e., there is no new TCE being introduced into the ground). Based on this simulation, the predicted maximum average 70-y TCE concentration reaching the regional aquifer ($Tnbs_1$) beneath the Building 834 Complex from the perched zone is 10^{-4} µg/L (ppb), significantly below the federal MCL for TCE of 5 µg/L (ppb).

For completeness, we also modeled the fate and transport of trace VOCs (including TCE) detected sporadically in samples from wells W-834-T1, W-834-T3, and W-831-01, which are completed in the $Tnbs_1$ regional aquifer. These sporadic VOC detections were individually modeled as point sources migrating from the well location downgradient to off-site water-supply well CDF-1, using the two-dimensional model PLUME (In-Situ, Inc., 1986). Although detections of a given chemical occurred on different dates, we made the conservative assumption that the source releases for the aggregate mass of a given chemical occurred on the same date. As presented in the SWRI, the PLUME model was used to simulate advection, longitudinal and lateral dispersion, linear partitioning, and natural degradation of each contaminant during 4,100 ft of ground water transport from the point source to the well CDF-1 exposure point. The

predicted exposure-point concentrations were summed to estimate the cumulative impact at well CDF-1. The maximum 70-y average TCE concentration at CDF-1 from each point source is predicted to be 10^{-12} µg/L (ppb), significantly below the federal MCL of 5 µg/L (ppb) for TCE. Table 1-23 presents the exposure-point concentrations of VOCs in ground water in the Building 834 operable unit that are predicted to reach water-supply well CDF-1. More detailed information concerning the fate and transport modeling of contaminants in the Building 834 operable unit is presented in section 10-5 of the SWRI.

1.6. Baseline Risk Assessment

The Committee on Institutional Means for Assessment of Risks to Public Health, formed within the National Research Council, defines risk analysis as "the use of the factual base to define the health effects of exposure of individuals or populations to hazardous materials and situations. ...We use risk assessment to mean the characterization of the potential adverse health effects of human exposure to environmental hazards. Risk assessments include several elements: description of the potential adverse health effects based on an evaluation of results of the epidemiologic, clinical, toxicologic, and environmental research; extrapolation from those results to predict the type and estimate the extent of health effects in humans under given conditions of exposure; judgments as to the number and characteristics of persons exposed and various intensities and durations; and summary judgments on the existence and overall magnitude of the public-health problem. Risk assessment also includes characterization of the uncertainties inherent in the process of inferring risk" (National Research Council, 1983).

In the SWRI report and Appendix C of this report, we used the Hwang et al. (1986) volatilization flux rate model, the McKone (1992) vapor flux through concrete model, and the highly conservative Turner (1982) air dispersion inhalation exposure model to estimate the potential exposure of adults on site who may work in or around Building 834D, or outdoors throughout the operable unit, 8 hours per day for 25 years (a highly unlikely, and thus overly conservative, occupancy rate). Because field-measured parameters were not available for the risk assessment, several conservative default parameters were used for the modeling. Results of the modeling were used to calculate the cancer risk and noncancer hazard associated with this exposure.

Building 834D is directly adjacent to a region of VOC-contaminated subsurface soil (0.5–12.0 ft), and we evaluated exposure to this contamination by calculating the risk and hazard associated with inhalation of VOCs that volatilize from subsurface soil (1) to the atmosphere or (2) to the air inside Building 834D. For the operable unit as a whole, we evaluated exposure associated with contaminated surface soil (<0.5 ft) by examining the inhalation of resuspended particulates, and incidental ingestion and dermal absorption of contaminants following direct contact with contaminated soil.

Both extremely health-conservative exposure scenarios for Building 834D resulted in estimates of individual excess lifetime cancer risk (6×10^{-4} and 1×10^{-3}) and noncancer HIs (22 and 36) that exceed acceptable limits (40 CFR 300). Our calculations of risk and hazard for exposures resulting from surface soil (<0.5 ft) contamination yielded estimates of individual excess lifetime cancer risk of 4×10^{-7} (inhalation of resuspended particulates) and 4×10^{-10} (ingestion and dermal absorption). The corresponding HIs are 7.2×10^{-5} and 1.1×10^{-2}, respectively.

Adults who work outdoors in the vicinity of Building 834D could be exposed simultaneously to VOCs that volatilize from subsurface soil (0.5–12.0 ft) into the atmosphere and contaminants in surface soil. For an adult who works at the Building 834 Complex 8 hours per day for 25 years, the total individual excess lifetime cancer risk associated with this scenario is 6×10^{-4}, and the HI is 22. Both values are dominated by contaminants in subsurface soil (0.5–12.0 ft) near Building 834D and are not substantially affected by contributions to risk or hazard from surface soil (<0.5 ft) contaminants. The estimates of risk and hazard indices for potential adult on-site exposures are summarized in Tables 1-24 through 1-27.

We also calculated the risk and hazard associated with potential residential use of contaminated ground water that was modeled from the Building 834 Complex to off-site water-supply well CDF-1. These calculations yielded an estimate of individual excess lifetime cancer risk of 7×10^{-11} and an HI of 2.7×10^{-6} (Table 1-28).

We calculated ecological HIs associated with the potential exposure of three ecological measurement endpoints (individual California ground squirrels, black-tailed deer, and San Joaquin kit fox) to VOCs and cadmium (Tables 1-29 through 1-31). The HI values were then related to individual assessment endpoints for the kit fox and overall Site 300 population endpoints for ground squirrel and deer. The HIs exceed 100 for the VOC TCE for ground squirrel and kit fox. Because no California ground squirrel burrows were found in the primary area of VOC soil contamination (Building 834D), it is possible that VOCs at 834D may have a local impact on the ground squirrels. However, other habitat modification in the area or simple stochastic variation may also be responsible. The HI for exposure to cadmium by black-tail deer is also greater than 1, suggesting that individual black-tail deer may be at risk from cadmium in surface soil. Currently there are insufficient data to assess the impact of cadmium on the deer population. Although there is no evidence of kit fox in the operable unit, data suggest that they could be at risk from exposure to VOCs and cadmium should they den in the vicinity of Building 834D.

The baseline risk assessment summarized above and presented in Appendix C and the SWRI report identified subsurface soil (0.5–12.0 ft) as the only environmental medium in the Building 834 operable unit associated with an unacceptable level of risk and/or hazard. To address this potential risk, five remedial alternatives are developed, analyzed, and compared in Chapters 4 through 6.

1.7. Ongoing Innovative Technology Development

Due to the unique hydrogeologic and contaminant characteristics of the operable unit, remote location, and well defined extent of contamination, the Building 834 Complex has been an ideal location for developing and testing experimental innovative treatment technologies. To date, several remedial actions and treatability studies have been taken in the Building 834 Complex to remove TCE from the subsurface by the use of both common and experimental innovative treatment technologies. The innovative technologies tested at the site include an electron accelerator, Joule heating, and an ultraviolet flashlamp system. The remedial actions completed and the innovative technologies tested to date at the site are summarized in Table 1-32. As discussed in Chapters 3 through 6, the development of innovative technologies is consistent with the history of the Building 834 Complex and LLNL's mission to benefit DOE and the public. As

a result, we will integrate the development of innovative treatment technologies with the alternatives presented in Chapters 4 through 6.

2. Remedial Action Objectives

Remedial action objectives are specific goals for protecting human health and the environment. The development of these goals involves the integration of all legally Applicable or Relevant and Appropriate Requirements (ARARs) and the results of the remedial investigation, including the human and ecological risk assessments. ARARs and other potential requirements are discussed below, followed by a discussion of cleanup goals and remedial action objectives.

Because of the changing and evolving nature of public policy, risk assessment, environmental law, and remediation technology, the proper development of remedial action objectives is an ongoing and iterative process. As such, actual final cleanup goals and objectives might not be established until the Record of Decision.

2.1. Identification of Applicable or Relevant and Appropriate Requirements

CERCLA section 121 (d)(2)(A) requires that remedial actions meet any federal standards, requirements, criteria, or limitations that are determined to be legally applicable or relevant and appropriate requirements. CERCLA section 121 (d)(2)(A)(ii) requires state ARARs to be met if they are more stringent than federal requirements. This involves an analysis of state standards or regulations to determine whether they impose additional or exclusive requirements. California received authority to carry out the federal RCRA program in July 1992. The California hazardous waste regulations are not identical to RCRA. To the extent these regulations are "broader in scope" and address additional substances or activities, the regulations may be "more stringent" than the federal RCRA program, and may be state ARARs. State regulations that are "more stringent" but not "broader in scope" will exist as federal standards. In addition, the National Contingency Plan (NCP), published in 40 CFR 300, requires local ordinances, nonpromulgated criteria, advisories, or guidance that do not meet the definition of ARARs but may assist in the development of remedial objectives be listed as "to be considered" (TBC).

Based on CERCLA guidance, LLNL has divided ARARs into three areas:

1. Chemical-specific requirements that define acceptable exposure concentrations or water quality standards;
2. Location-specific requirements that may restrict remediation activities at sensitive or hazard-prone locations such as wildlife habitat and floodplains; and
3. Action-specific requirements that may control activities and/or technology.

Table 2-1 lists current ARARs developed by the signatories to the Site 300 FFA for the Building 834 operable unit. These ARARs are pending approval by the signatories. Additional TBCs are also included to assist in determining what is necessary to protect human health and the environment. Table 2-2 shows whether the proposed remedial alternatives comply with the ARARs and TBCs.

2.2. Chemical-Specific ARARs

2.2.1. Risk-Based Requirements

The SWRI (Webster-Scholten, 1994) identified subsurface soil (0.5 to 12 feet in depth) as the only contaminated environmental medium at the Building 834 Complex in the Building 834 operable unit associated with an unacceptable level of risk and/or hazard. The NCP indicates that excess cancer risks greater than one in ten thousand (10^{-4}) are unacceptable, while excess cancer risks less than or equal to one in one million (10^{-6}) point of departure are generally acceptable; U.S. EPA (1989) indicates that a hazard index (HI) greater than 1.0 may be associated with noncarcinogenic adverse health effects. Calculations presented in the SWRI report indicated that individuals who may work either outdoors in the immediate vicinity of the Building 834D storage facility or inside of the building 8 hours per day for 25 years may be exposed to potentially hazardous concentrations of VOCs that volatilize from subsurface soil. In addition, VOCs present in subsurface soil pose an ecological risk for the ground squirrel and, if present, the kit fox. Hazard indices (HIs) exceed 1.0 for these mammals from exposure to TCE, and to a lesser extent PCE, present in subsurface soil (section 1.6). The contaminants of potential concern in subsurface soil near Building 834D were identified as benzene, PCE, TCE, ethylbenzene, toluene, trichlorofluoromethane (Freon 11), and xylenes (total isomers). Of these substances, benzene, PCE, and TCE are classified as known or probable human carcinogens; however, all of the contaminants are associated with noncarcinogenic adverse health effects. Appendix C and Tables C-11, C-16, C-17, C-22, and C-23 present a comparison of 10^{-4} and 10^{-6} cancer risk health-based restoration concentrations for subsurface TCE.

Exposure calculations for individuals who may work in or near the Building 834D storage facility were based on a single set of VOC concentration data obtained from boreholes in the vicinity of the building and assume an adult occupancy factor of 8 hours per day for 25 years. Data from the vicinity of the Building 834D storage facility were selected because VOC distribution and concentrations in subsurface soil near this building are well characterized, and subsurface soil near this building has the highest VOC concentrations currently identified in the operable unit. Using the same data set, we also calculated potential risk and hazard associated with subsurface soil beneath two additional structures in the same vicinity, a trailer designated as Building 834O and the Building 834D rain shed. These buildings were not evaluated in the SWRI because they were initially considered to be temporary structures (Appendix C). Other areas in the operable unit also exhibit subsurface soil contamination; however, concentrations are much lower.

As previously discussed, no unacceptable risks or hazards were associated with surface soil contaminants, with the exception of possible wildlife exposure to cadmium, which is present at some locations (section 1.6). We are uncertain about the source of this cadmium. Available data, however, indicate that wildlife exposure is not likely since the above-mentioned metal is either limited to nonhabitat areas or has been detected only sporadically. If future ecological or analytical data indicate that habitat of rare, threatened, or endangered species is affected, remediation may be required.

2.2.2. Federal and State ARARs

No state or federal ARARs exist as potential cleanup levels for vadose zone soils. Therefore, we will apply health-based concentrations (HBCs) as soil vapor restoration levels (SVRLs) in lieu of ARARs.

State and federal MCLs for public drinking water systems apply directly to public drinking water systems with 15 or more service connections. Regional ground water within Site 300 is considered a potential public drinking water source under federal or California law. As discussed previously (section 1.4), the regional aquifer has not been adversely affected by activities at the Building 834 operable unit. MCL requirements may become relevant and appropriate if VOCs are detected in the regional aquifer in the future.

San Joaquin County Ordinance No. 1862 specifies that all ground water wells used for drinking, domestic use, or industrial use require a permit and a 100-ft annular surface seal, preventing use of shallow ground water. This indicates that the shallow perched water-bearing zone in the Building 834 operable unit does not contain potential drinking water since it is less than 100 ft deep.

State Water Board Resolution No. 68-16 reflects the state's policies for "maintaining high quality of waters in California." Commonly referred to as the "nondegradation policy," it applies to the discharge of water that might affect the existing high quality of the receiving water and thus affect its beneficial use. The policy advocates the "best practicable treatment" coupled with "technical and economic feasibility." This policy is an ARAR for the discharge of treated perched ground water to the surface, if the water creates a potential impact on the regional aquifer.

SWRCB Resolution No. 88-63 specifies that municipal or domestic water supply must be able to produce a sustained yield of 200 gpd from a single well. Sustainable well yields (<100 gpd) on existing monitoring and extraction wells screened in the perched water-bearing unit indicate that water in this unit is not considered suitable or potentially suitable as drinking water (section 1.3.5).

The perched water-bearing zone beneath the Building 834 operable unit is not a suitable water source because it fails to meet San Joaquin Count Ordinance No. 1862 and SWRCB Resolution No. 88-63, and it does not contain potable water. Therefore, LLNL is requesting an amendment to exclude the zone from the Central Valley Regional Water Quality Control Board Water Quality Control Plan (Basin Plan). This request is justifiable for the above stated reasons and because water from this zone has no beneficial uses.

2.2.3. Soil Restoration Levels

Soil vapor restoration levels (SVRLs) applicable for subsurface soil in the core area of the Building 834 Complex are presented in Table 2-3. SVRLs were estimated by using HBCs of TCE in subsurface soil. The concentrations are based on calculations of potential human health risk or noncancer health effects, and were derived based on the methodology, pathway exposure factors, and toxicity values for an adult on-site exposure scenario presented in the SWRI report. Additional details of the methods used to calculate the HBCs and SVRLs are presented in Appendix C. These calculations were developed in accordance with U.S. EPA (1989). That document stipulates that additivity of risk or noncancer hazard from simultaneous exposure to

multiple contaminants at an exposure location be accounted for by summing the risk or noncancer hazard from all contaminants present at an exposure location.

Accordingly, for the contaminant concentrations presented in Table 2-3, the percentage contribution of risk and hazard quotients were used to obtain the estimated chemical-specific concentration for each carcinogen and noncarcinogen. Since TCE contributes 98%, 88%, and 95% of the human hazard, human risk, and ecological hazard, respectively, we chose TCE as the indicator chemical for subsurface soil and soil vapor at this operable unit. Because the other chemicals of concern are also VOCs, we assume that remedial actions implemented to reduce TCE concentrations in subsurface soil and soil vapor will also effectively reduce concentrations of the other chemicals of concern. The ecological hazards are excluded as a basis for calculating SVRLs, because the overall ground squirrel population at Site 300 appears to be healthy, and the kit fox currently do not reside in the operable unit (Webster-Scholten, 1994). Consequently, SVRLs are based on human risk and hazard. Under the risk/scenario of exposure to air inside Building 834D (8 hours per day for 25 years), the hazard-based soil concentration for TCE is 1.3 mg/kg, which is associated with a hazard index of 1.0 and corresponds to a cancer risk of 3×10^{-5}. For potential exposure to TCE in outdoor air in the vicinity of Building 834D, the hazard-based soil concentration is 2.2 mg/kg. This concentration is associated with a hazard index of 1.0 and corresponds to a cancer risk of 3×10^{-5}. When converted to SVRLs, the hazard-based soil concentrations of 2.2 mg/kg and 1.3 mg/kg correspond to SVRLs and 250 $ppm_{v/v}$ and 150 $ppm_{v/v}$, respectively. The methods used to derive the SVRLs from HBCs are presented in Appendix C.

As discussed in Chapter 4, ventilation inside buildings at the Building 834 Complex, including Building 834D, can be designed to reduce TCE concentrations in indoor air to (at a minimum) estimated ambient levels (Appendix C). With the addition of filtration, concentrations can be reduced to acceptable target levels. Therefore, we selected the hazard-based level (outdoor air exposure) of 250 $ppm_{v/v}$ TCE as the SVRL, which was calculated from the hazard-based soil concentration of 2.2 mg/kg.

Because the SVRL was calculated based on data from the region of the operable unit with the highest current concentrations of VOCs in subsurface soil, implementation of this SVRL throughout the remainder of the core area should ensure that potential human health risks and hazards remain within acceptable levels.

2.3. Location-Specific ARARs

2.3.1. Faults

California seismic regulation 22 CCR section 66264.18(a) prohibits location of portions of new treatment, storage, or disposal facilities or substantial modification of existing facilities, within 200 feet of a Holocene fault. There is no evidence of active faults within 200 feet of any portion of the Building 834 operable unit. Therefore, we excluded this regulation as an ARAR.

2.3.2. Wilderness Areas, Wildlife Refuges, and Scenic Rivers

No area within or near Site 300 is designated as a Federal Wilderness area, Wildlife Refuge, or Scenic River. The California Department of Fish and Game maintains an ecological preserve

adjacent to the eastern Site 300 boundary. No remedial action activities related to the Building 834 operable unit will occur within this preserve.

2.3.3. Floodplains and Wetlands

There are no floodplains within the operable unit. Two small wetland areas (approximately 1,000 ft^2 each) are located near Building 832 (U.S. DOE, 1992). These wetlands are located over 2,000 feet away from the core of the Building 834 Complex; no future activity is proposed for this location. In addition, although these areas are consistent with the state and federal definition of wetlands, they are not currently regulated as wetlands by the U.S. Army Corps of Engineers (Coe, 1991). Any future treatment-related activities will be carried out in accordance with DOE regulations (10 CFR 1022) to satisfy environmental review requirements.

2.3.4. Historical Sites and Archaeological Findings

A detailed summary of archaeological investigations at Site 300 and descriptions of potential historic sites near the Building 834 operable unit is presented in Chapter 6, Environmental Considerations.

In 1981, sample areas of Site 300 were surveyed for cultural resources resulting in the location of 24 archaeological sites: 3 prehistoric, 20 historic, and 1 multicomponent site. Because it is unclear whether the Building 834 operable unit was surveyed during the 1981 investigation, an archaeological field survey was conducted on August 19, 1993, to determine whether eligible historic properties exist within this operable unit. No cultural resources were located during this survey. Additionally, a background literature search indicates that none of the previously recorded sites are located within the vicinity. Project construction personnel will be advised of the possibility of buried cultural deposits and be alerted to likely indicators prior to any construction activities.

2.3.5. Rare, Threatened, or Endangered Species

The SWRI report and Site 300 EIR/EIS (U.S. DOE, 1992) indicate that portions of Site 300 are habitat for several threatened or endangered species as designated by the federal and/or state regulations. Federally-designated threatened or endangered animal species for which habitat have been identified but which have not been observed on site are the San Joaquin kit fox (endangered) and the Valley elderberry longhorned beetle (threatened). In addition, the flora species commonly known as the large-flowered fiddleneck (endangered) grows on site, but has not been observed at the operable unit; a portion of Site 300 (outside the Building 834 operable unit) has been set aside as critical habitat. Potential habitat for the San Joaquin kit fox has been identified in the operable unit, although not in the core area. No kit fox have been observed of Site 300.

LLNL is committed to protecting all potential habitat for these species. Mandatory 60-d advance notification of all ground-breaking initiates an ecological survey by a biologist to identify the presence of sensitive species and/or habitat, and to mitigate any adverse impacts by the project.

2.4. Action-Specific ARARs

Most action-specific ARARs address treatment, transportation, and disposal of hazardous waste. Table 2-1 includes descriptions of action-specific ARARs that may be associated with possible remedial actions. A detailed discussion of specific technologies and cleanup activities and their compliance with these ARARs is included in Chapter 5.

2.5. Remedial Action Objectives

In accordance with the NCP and other EPA guidance, LLNL conducted a comprehensive assessment of human and ecological risk (Webster-Scholten, 1994) and the potential risks associated with various cleanup scenarios for the Building 834 Complex (Appendix C). Exposure to subsurface soils (0.5–12 ft) containing TCE, PCE, Freon 11, benzene, ethyl benzene, toluene, and xylenes presents the only unacceptable risk or hazard. There are no chemical specific ARARs for these chemicals in soil. Although current analytical data and ground water fate and transport modeling indicate that the regional aquifer will not be affected by any contaminants at the operable unit, LLNL continues to monitor ground water in the perched water-bearing zone and regional aquifer. Should any data indicate that contaminants could affect water quality or human health, steps will be taken to contain the plume and mitigate any further migration.

Remedial action objectives (RAOs) are aimed at protecting potential human receptors (identified in the baseline risk assessment [SWRI Chapter 6, Appendix C of this report]) from exposure to contaminants in all affected media. Because the RAOs are not specifically related to cleanup goals, they are not included as a part of the EPA nine-point alternative evaluation process, outlined in U.S. EPA (1988b). As summarized in section 1.6, the primary risk associated with contamination at the Building 834 Complex is related to human inhalation exposure from TCE volatilizing from contaminated subsurface soil (0.5–12.0 ft) beneath the core of the complex. Based on the chemicals of concern, exposure routes, potential receptors, and the findings of the baseline risk assessment, the RAOs for the Building 834 operable unit are to prevent human exposure to:

- VOCs that may volatilize from subsurface soil into ambient and indoor air above the 10^{-4} to 10^{-6} risk level or hazard index level >1, whichever is more conservative.
- Chemicals in ground water above the maximum contaminant levels (MCLs).

The RAOs for all affected media in the Building 834 operable unit are summarized in Table 2-4, along with the proposed cleanup goals and general response actions (GRAs). All six proposed remedial action alternatives (presented in Chapter 4), at a minimum, meet these RAOs. The alternatives are later evaluated against the nine evaluation criteria (U.S. EPA, 1988b), including compliance with ARARs, long- and short-term effectiveness, and cost in Chapter 5.

3. Evaluation and Screening of General Response Actions and Remedial Action Technologies

3.1. Overview and Evaluation of Screening Process

In this chapter, we explore the use of a variety of response actions and remedial technologies to address the contaminants present in the vicinity of the Building 834 Complex. These measures are designed to manage risk and to control and/or remove the contaminants from the site. We also evaluate the potential of the response actions and technologies to achieve the remedial objectives discussed in Chapter 2. We screen these technologies based on applicability, effectiveness, implementability, and cost. In the last section of this chapter, we present technologies retained through this screening process. The retained technologies will be used to build the remedial alternatives presented in Chapter 4.

3.2. General Response Actions

General Response Actions are those which can achieve the remedial objectives established in Chapter 2. These actions are intended to control the migration of, and/or remove the chemicals of potential concern identified in the SWRI report (Webster-Scholten, 1994). The no action response required for CERCLA Feasibility Studies (U.S. EPA, 1988b) and the seven General Response Actions identified for the Building 834 Complex are listed below:

- No action.
- Containment.
- Enhanced airflow.
- Extraction/excavation.
- Aboveground treatment.
- *In situ* treatment.
- Disposal.
- Institutional/administrative controls.

Table 3-1 summarizes the eight applicable response actions for the Building 834 operable unit. For our discussion below, we have combined extraction/excavation, treatment, and disposal since, in practice, they are integrated.

3.2.1. No Action

In CERCLA feasibility studies, the no action alternative is used as a basis for comparison to other actions. All activities except ongoing ground water monitoring and additional soil vapor monitoring would cease under this response. Natural degradation, dispersion, and adsorption are the only processes that would take place, and they will occur regardless of our intervention.

3.2.2. Containment

As a General Response Action, containment is used to control the migration or mobilization of contaminants. It can be directed at containing a ground water or soil vapor contaminant plume, or at preventing recharge water from creating or spreading a plume. At the Building 834 Complex, containment could be implemented to prevent VOCs from dispersing to air, to provide drainage control and retard infiltration, or to control downgradient plume migration.

Common physical barriers employed for the purposes of containment are an asphalt surface cover and lined ditches. These barriers are used to reroute recharge water or leachate and restrict the flow of ground water and contaminants. Surface covers can also control soil vapor migration to the atmosphere and retard leaching of contaminants from the soil to ground water. Physical barriers alone, while they may be protective of human health and the environment, would result in relatively slow VOC removal by natural degradation compared to more active response actions. Physical barriers are commonly used in combination with extraction techniques, such as ground water pumping or *in situ* treatment.

3.2.3. Enhanced Air Flow

Engineered ventilation of selected Building 834 Complex buildings can disperse VOCs. If the VOCs are dispersed adequately, long-term inhalation risks related to elevated VOC concentrations can be lowered to an acceptable level.

3.2.4. Extraction/Excavation with Treatment and Disposal

Surface treatment of soil, soil vapor, and ground water involves extraction, usually by pumping wells or excavation; conveyance to a treatment system, such as air stripping or air sparging; and discharge of the treated air emissions, water, or soil. This combination of response actions is intended to remove contaminants from the site permanently. There are, however, other considerations such as decommissioning the Building 834 facilities, removal of buildings and underground utilities, and disposal and/or destruction of excavated contaminated soil/rock. These considerations can make excavation costly. Extraction/excavation, treatment, and disposal technologies are discussed in more detail in section 3.3. Screening and evaluation are addressed in Table 3-2.

3.2.5. *In Situ* Treatment

In situ treatment involves the destruction of VOCs or conversion of VOCs in soil/rock and/or ground water to less toxic compounds. Possible *in situ* strategies include air sparging, biological, and thermal treatments for soil, and air sparging for ground water.

In situ air sparging is an applicable treatment for nonaqueous-phase liquids (NAPLs), and in particular for light nonaqueous-phase liquids (LNAPLs). This technology requires a thorough knowledge of the subsurface hydrogeology and surface conditions to control vapor diffusion in the subsurface and surface. Air sparging is less effective on dense nonaqueous phase liquids (DNAPLs), which tend to sink to the bottom of an aquifer; additionally, the extent of DNAPL contamination is difficult to characterize. Therefore, the extraction of DNAPLs from saturated zones is dependent on their diffusion rate into the ground water and solubility in water, as well as Henry's Law constant for diffusion from water to air.

3.2.6. Institutional/Administrative Controls

One multifaceted General Response Action is the use of institutional and administrative controls as a means of risk management to mitigate some or all access to, and thereby exposure to, hazards in a contaminated area. These controls can involve a range of measures, from simply posting signs and installing fences, to restricting new construction in contaminated areas. At the Building 834 Complex, institutional/administrative measures can limit human activities or restrict access to a contaminated area so that risk from inhalation or use of contaminated ground water is minimized or eliminated. For risks that result only from long-term exposure, such as in the Building 834 operable unit, several institutional and administrative controls could be implemented effectively as a stand-alone alternative or in conjunction with other remedial technologies.

3.3. Evaluation and Screening of General Response Actions and Remedial Technologies

Table 3-2 summarizes the screening and evaluation of the General Response Actions, technology types, technologies, and treatment options available for the remedial alternatives. The remedial action objectives presented in Chapter 2 apply to all treatment options and remedial alternatives (Table 3-2).. At the Building 834 Complex, the primary objectives are to remove contaminants from the vadose zone to control inhalation risks, and to preclude migration of contaminants to the regional ground water aquifer.

The General Response Actions are listed in the first column of Table 3-2. Listed with each General Response Action are the one or more technologies that are considered potentially or even remotely feasible. The table documents our reasons for retaining a technology or deleting it from further consideration, based on applicability, effectiveness, implementability, and cost. The last column indicates if the technology was retained for development of our remedial alternatives.

Only the retained remedial actions/technologies that protect public health and environment and/or lead to positive, permanent removal of the constituents of interest from the vadose zone and ground water are discussed in this section.

3.3.1. No Action

The no action alternative does not include any remedial measures, and thus allows contaminants to remain in the vadose zone. This alternative also allows continued water quality degradation and migration of the compounds in the ground water. It is very likely that the compounds of interest will be reduced in concentration through the processes of natural sorption and degradation.

3.3.2. Containment

Although it may be protective of human health and the environment, containment by itself does not quickly restore the vadose zone to concentrations specified in the remedial action objectives. Constructing low-permeability surface covers to retard leaching from soil and minimize recharge would most reasonably be used in conjunction with more active measures to

remediate VOCs. Asphalt surface covers would help contain soil vapors as well as minimize short circuiting of air flow during vapor extraction. Lined ditches could also be constructed to minimize recharge and leaching of VOCs into the perched water-bearing zone.

3.3.3. Extraction/Excavation

Soil vapor extraction (SVE) is the technology 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 beneath the Building 834 Complex. Partial dewatering of the perched water-bearing zone is also considered for the purposes of enhancing the soil vapor extraction program. To address LNAPL floating product removal, in particular diesel and T-BOS, skimming is reviewed. This technology removes contaminants that are already naturally separated by density contrasts with water.

3.3.4. Treatment

3.3.4.1 Vadose Zone

3.3.4.1.1. GAC Vapor Adsorption. The use of GAC treatment for soil vapors is a well-established technology for the removal of VOCs from air streams. With few exceptions, most VOCs can be effectively removed from the vapor exhaust of a soil-vapor extraction system using a fixed-bed GAC method. The GAC is effective over a broad range of constituent concentrations in the air stream. The spent GAC may be regenerated on site or at a commercial facility in a furnace in which the VOCs are desorbed from the GAC and then completely oxidized. GAC treatment of the vapor phase is an applicable, effective, and implementable method to physically remove VOCs from vapors. Treatment costs associated with GAC are usually quite high initially, and generally decreases over time as VOC concentrations in the soil vapor effluent decrease.

3.3.4.2. Ground Water

3.3.4.2.1. GAC Adsorption. GAC adsorption is a well-established technology for ground water treatment that is generally effective for removing high molecular weight compounds and chlorinated solvents. Activated carbon removes contaminants from water by adsorbing them onto its surface. GAC units are made from a variety of carbonaceous materials. A GAC adsorption system consists of a packed column with a system to distribute the water evenly over the carbon bed. Organic compounds adsorb onto the surface of the GAC as the water flows through the fixed bed. The spent GAC may be thermally regenerated by heating the carbon in a natural gas-fired furnace. GAC is an applicable, effective, and implementable method to remove VOCs from an aqueous medium. The cost is dependent upon flow rates and VOC concentrations. Generally, GAC is cost-effective for low flow and low concentration applications (LLNL, 1991a).

3.3.4.2.2. Air Stripping. Air stripping is a process by which VOCs are removed from water by bringing water into contact with forced air. Air stripping is most commonly achieved with air stripping towers or trays. In conventional air strippers, ground water is sprayed into the top of an air stripping tower. As water cascades down through the tower and through packing material within the tower, a high-powered blower forces an upward air stream through the water,

transferring the VOCs from water to air. Because air stripping towers are tall and inflexible, manufacturers have designed modified equipment that is more flexible under expansion (or reduction) forces, and more compact. Tray aeration is achieved by spraying extracted ground water into an inlet chamber. The water flows along baffled aeration trays and air is blown up through small diameter holes in the trays. A froth forms, creating a large mass-transfer surface. The high air-to-water ratio causes the organic contaminants to volatilize (evaporate) into air, leaving substantially reduced concentrations of VOCs in the water.

Air stripper design and operation and maintenance must be tailored to the general water quality at the site. High calcium and magnesium hardness, which exists at Site 300, can clog the packed towers, reduce efficiency, and increase operating costs. To eliminate VOC discharge to the atmosphere, this technology would be used in conjunction with vapor-phase GAC. Packed-column or tray aeration using counter-flow air stripping is an applicable, effective, and implementable method to remove VOCs by physical means from aqueous streams. This technology would be used in conjunction with vapor-phase GAC (LLNL, 1991a). The cost is dependent upon flow rates and VOC concentrations. Generally, air stripping is cost-effective for high flow rates and high VOC concentrations unless mineral content causes operating problems.

3.3.4.2.3. Air Sparging. Air sparging employs the same physical process as air stripping in creating a large air-to-water ratio to provide mass transfer to air. Air sparging consists of forcing air through coarse air bubble diffusers into large tanks filled with contaminated water. The agitation of the water along with contact with forced air promotes the volatilization of VOCs. This technology would be used in conjunction with vapor-phase GAC (LLNL, 1991a). High calcium and magnesium hardness, which exists at Site 300, can clog the packed towers, reduce efficiency, and increase operating costs. Generally, air sparging has higher energy requirements than air stripping.

3.3.4.2.4. UV/Oxidation. UV/oxidation is a remedial technology that involves the use of an oxidizing agent, such as hydrogen peroxide or ozone, and ultraviolet (UV) light as an agent to augment the dissociation of the oxidizing agent to a hydroxyl radical. UV/oxidation minimizes waste that otherwise would require further treatment or disposal (LLNL, 1991a).

A type of UV/oxidation technology is Perox-Pure™. The Perox-Pure™ chemical oxidation technology was demonstrated under the Superfund Innovative Technology Evaluation (SITE) program at the GSA operable unit. Over a 3-week period in September 1992, about 40,000 gallons of VOC-contaminated ground water was treated in the Perox-Pure™ system. For the SITE demonstration, the Perox-Pure™ system achieved TCE and PCE removal efficiencies of about 99.7 and 97.1%, respectively. In general, the Perox-Pure™ system produced an effluent that contained (1) TCE, PCE, and 1,1-DCA below detection limits, and (2) chloroform and 1,1,1-TCA slightly above detection limits. The system also achieved chloroform, DCA, and TCA removal efficiencies of 93.1, 98.3, and 81.8%, respectively. The treatment system effluent met California drinking water action levels and federal drinking water MCLs for TCE, PCE, chloroform, DCA, and TCA at the 95% confidence level (U.S. EPA, 1993b).

3.3.5. *In Situ* Treatment

3.3.5.1. Air Sparging

Air sparging can also be conducted *in situ*. This requires either trenching to lay a shallow network of air injection and extraction piping and subsequent backfilling, or vertical and/or horizontal drilling to construct a deep subsurface network of piping. The difficulty in using this method is plume control. The air may diffuse away from collection points and mobilize the contaminants in an undesirable direction. This method also has an inherent expense when horizontal drilling is used, due to the specialized nature of horizontal drilling.

3.3.6. Disposal

After treatment, disposal of air emissions, ground water, and LNAPLs will be required. The following is a discussion of the five disposal options presently available to us.

3.3.6.1. Treated Air Emissions

3.3.6.1.1. Permitted Discharge to Air. Treated vapor-emissions can be disposed of by permitted discharge to air. We presently possess a permit to discharge treated vapor on site by the San Joaquin Valley Air Pollution Control District. These emissions would be a by-product of ground water treatment. The treatment consists of the following steps: (1) an air stripping system enhances the volatilization of organic compounds from extracted ground water to air stream; (2) the VOC-enhanced air is fed into two sets of two GAC treatment canisters, in series; and (3) the treated air is then released into the atmosphere. We sample and test emissions from the canisters for TCE on a daily basis for the first month of operation and weekly thereafter. The permit limits TCE emissions to 2 $ppm_{v/v}$.

We have also obtained an "Operating Under Authority to Construct" permit from the San Joaquin County Air Pollution Control District, allowing air emissions from a TCE vapor extraction system while the system is constructed and tested. This system treats soil vapors extracted by venting at the Building 834 operable unit. The vapors are fed through two GAC canisters in series before being released to the atmosphere. We are required by the permit to test emissions for TCE vapors on a daily basis for the first month, and weekly thereafter. We replace or regenerate GAC canisters if TCE vapor breakthrough exceeds 3 $ppm_{v/v}$ in a sample.

3.3.6.2. Treated Ground Water

3.3.6.2.1. On-site Surface Discharge. We are presently discharging treated ground water from the central GSA on site, to the surface, as part of an interim central GSA CERCLA Removal Action. The treated water is collected in a Baker tank, and then it is sprayed into a remote canyon, where the recharge rapidly infiltrates. However, infiltration rates in the vicinity of the Building 834 Complex are very low and the slopes are steeper, creating a potential for unacceptable surface runoff.

3.3.6.2.2. Air Misting. Air misting is the atomization of treated ground water by forcing it through spray heads that separates the water into fine droplets as it is expelled into the air. This process allows maximum areal dispersion of discharge. When an air misting system is operated during appropriate meteorologic conditions, these droplets will evaporate before reaching the

ground. This discharge process eliminates problems associated with surface discharge. Presently, all purge water containing VOCs is treated and then discharged through misting at Building 833. A similar system has been installed for use at the Building 834 Complex.

3.3.6.2.3. Reinjection. Reinjection wells can function as a means to discharge treated ground water and/or as a means to hydraulically control plume movement. The reinjection of treated ground water can be an efficient, cost-saving measure. However, the quality of this water is important because of potential for recontamination and potential scaling from precipitates such as carbonate. Scaling can damage and significantly reduce the efficiency of the injection well.

3.3.6.3. LNAPLs

The primary LNAPLs at the Building 834 Complex are diesel and T-BOS floating product. Since TCE preferentially dissolves in T-BOS over water, the extracted T-BOS will presumably contain TCE when removed. These products will be transported off site to a certified incineration facility.

3.3.7. Institutional/Administrative Controls

In the Building 834 Complex, several applicable institutional and administrative controls are retained as a means of risk management to reduce or eliminate exposure to contaminants in the vadose zone, in particular those controls that affect long-term exposure. Fencing and warning signs can be installed to warn people of areas where inhalation could cause contaminant exposure. These measures would be particularly effective when combined with the use of security guards and patrols. Signs and fencing are inexpensive, whereas ground patrol several times a day can be expensive over 30 years or more. Other effective controls are limiting Site 300 worker access to the buildings most affected in the Building 834 operable unit, and restricting construction or soil disturbance in the areas of elevated risk. Institutional/administrative controls are feasible since DOE intends to occupy and maintain institutional control of Site 300 for the foreseeable future, and thus maintain control of the facility. As a result, such controls can serve as a stand-alone alternative or serve in conjunction with other remedial alternatives.

3.4. Innovative Technologies

Several innovative technologies are being considered for performance testing at the Building 834 Complex. These technologies include electron accelerator, adsorption-regeneration resin *in situ* air sparging, surfactants (food grade and alcohol), and biological enhancement, as shown in Table 3-2. Because the Building 834 operable unit is hydraulically isolated and relatively remote, it is an ideal location for testing innovative technologies. The performance testing of innovative technologies can be implemented through a contingent source mass removal alternative as presented in Chapter 4. A description of these technologies is presented in Appendix E.

3.5. Summary of Retained Technologies

Through the development and screening of General Response Actions and remedial technologies, we have retained several actions and technologies. These actions and technologies are the basis for the remedial alternatives developed and discussed in Chapter 4. Table 3-3 summarizes the retained technologies.

4. Description of Remedial Action Alternatives

In this chapter, we present six alternatives for remediation of VOCs in the vadose zone in the Building 834 Complex of the Building 834 operable unit to address inhalation risks and to accelerate source mass removal of subsurface VOCs. Although the perched water-bearing zone contains VOCs (primarily TCE), it is not a potable water-supply source under SWRCB Policy 88-63. LLNL/DOE is therefore pursuing an amendment to exclude the shallow perched water-bearing zone from the CVRWQCB Basin Plan. Perched water-bearing zone fate and transport modeling and risk analysis presented in SWRI Chapter 10 indicates that the contaminated perched ground water does not pose a significant threat to the regional $Tnbs_1$ aquifer. For these reasons, ground water in the shallow perched water-bearing zone will not be remediated to achieve perched water chemical-specific cleanup goals. However, any ground water extracted and treated as part of the subsurface soil and soil vapor (0.5–12.0 ft) cleanup alternatives will subsequently reduce the mass of contaminants in the perched zone, further reducing potential exposure risk and subsequent mass migration. Because contaminated soil vapor in the upper 12 feet of the vadose zone beneath the core of the complex may pose a threat to human health, its management, institutional controls, and remediation will be the focus of this feasibility study. Each of the remedial action alternatives is developed uniquely from retained remedial technologies described in Chapter 3 and designed to meet the RAOs discussed in Chapter 2. These six remedial action alternatives are described in Table 4-1.

As described in Chapter 1, the concentration of TCE is higher than that of any other VOC detected in soil, soil vapor, and ground water beneath the Building 834 Complex and contributes the majority of estimated exposure risk. Other chemicals of concern, such as PCE and 1,2-DCE, have been detected, but their historic concentrations relative to TCE have been much lower. We assume that this VOC-to-TCE ratio is relatively constant and, therefore, use TCE as an indicator chemical for 3×10^{-5} cancer risk (hazard index [HI] = 1.0) proposed soil and soil vapor restoration levels (PSRL and PSVRL, respectively). The acceptable 3×10^{-5} cancer risk and 1.0 HI concentration that was calculated for TCE in the upper 12 feet of vadose-zone soil vapor is 250 $ppm_{v/v}$, as presented in Appendix C. As we remediate TCE to this health-based level, we expect the concentrations of other chemicals of concern will also decrease to their respective health-based concentrations. We also expect that the total HI of the chemicals of concern in soil vapor will be no greater than 1.0, which corresponds to a conservative cancer risk of 3×10^{-5}. Since baseline human cancer and noncancer risks associated with using ground water from the regional aquifer are 7×10^{-11} and 2.8×10^{-6}, respectively, no aquifer restoration goals were defined in Chapter 2. The derivation of risk-based concentrations is discussed in Appendix C. Because the shallow perched water-bearing zone fails to meet the criteria discussed in Chapter 2 for a potable water source, no concentration-based cleanup criteria have been established for this zone, and LLNL is requesting an amendment to exclude it from the CVRWQCB Basin Plan for the same reason. All alternatives presented here, except Alternative 1, are contingent on this amendment.

The differences between the proposed alternatives are highlighted with respect to the aggressiveness in achieving cleanup goals. For example, in Alternative 3 we have incorporated

soil vapor extraction and treatment to remediate the VOCs in the vadose zone. In Alternative 4 we include perched zone dewatering, which will aid in reducing the cleanup time for vadose zone remediation by exposing more soil to vapor extraction as well as mitigate TCE in ground water in the vicinity of the release sites. The vadose zone restoration goals are discussed in detail in Chapter 2, and the area and volume estimate calculations for these goals are presented in Appendix A, which also contains a sensitivity analysis of these calculations.

In 1992, the EPA approved the Building 834 Complex as an area to test innovative VOC extraction and treatment technologies under the EPA/SITE Emerging Technologies Program. Section 4.7 describes the EPA/Site testing as well as other innovative technologies that may be considered for future testing and implementation at the Building 834 Complex such as proposed under Alternative 6. The proposed Best Available Technology (BAT) air emission control devices and ground water treatment equipment would ensure that regulatory cleanup standards are met during pilot testing. Because the Building 834 Complex is isolated, a secondary objective of Alternatives 3, 4, and 5 is to provide the capability for continued testing of innovative technology treatment in conjunction with ongoing source mass removal. If testing shows that an innovative technology is efficient and cost effective in reaching our cleanup goals, LLNL would propose amending the remedial plan.

Because of the site-specific geologic and hydrogeologic characteristics of the site, including the fact that there is a perched water-bearing zone, the Building 834 Complex is an ideal place to develop innovative technologies for remediation of vadose zone soils and possible DNAPLs in the perched water-bearing zone. Potential innovative technologies are evaluated as separate activities; however, these innovative technologies can be amended to Alternative 3, 4, or 5 if they prove to be more efficient and cost effective. Alternative 6 provides for innovative remediation technology treatability testing first in conjunction with soil vapor extraction (Alternative 3). Should the innovative technology prove implementable and cost effective, it would become the primary remedial technology.

The duration for each component of the remedial alternatives was based on the estimated time necessary for meeting cleanup goals. Specifically for Alternatives 3, 4, and 5, the duration of the LNAPL recovery component is estimated to be 2 years (based on limited data), and the five-year duration of the core area SVE and associated perched zone dewatering components is based on modeling results presented in Appendix F. The duration of downgradient plume control, which does not have a chemical-specific cleanup goal, was costed for 5, 10, 20, and 30 years in Alternative 5, to be consistent with the proposed length of monitoring in the other alternatives.

The actual duration of any implemented remedial action and subsequent monitoring will be reevaluated at least every 5 years in accordance with U.S. EPA guidelines (1988). To facilitate comparison of costs for the alternatives, we have summarized cumulative present-worth costs for each alternative in 5-year intervals in Figure G-5 (Appendix G). Since costs for innovative technology testing are not included in Alternative 3, 4, or 5, the present-worth cost for Alternative 6 is likely to be similar to or less than Alternative 3, 4, or 5.

Soil vapor sampling, ground water sampling, and elevation monitoring would be conducted to assure that changes in hydrogeologic conditions do not result in the redistribution or migration of VOCs such that the conditions specified in the baseline risk assessment are no longer valid. Should such conditions change, remediation objectives and/or risk would be reevaluated among

DOE/LLNL, DTSC, RWQCB, and EPA. Ground water monitoring would also provide continuing data on the water quality in the perched zone and the $Tnbs_1$ regional aquifer. Following EPA guidance, the monitoring program for these alternatives has a 30-year project life.

Soil vapor and ground water sample collection will be conducted as specified in *The Quality Assurance Project Plan LLNL Site 300 Environmental Restoration Project (QAPP)* (Carlsen et al., 1992). Ten percent of all ground water samples will be collected in duplicate and submitted for the same analyses, as outlined in SOP S4.9, *Final LLNL Site 300 Environmental Restoration Project Standard Operating Procedures (SOPs)* (Carlsen et al., 1993). Analyses of other QA/QC samples, including trip blanks, method blanks, matrix spikes, and matrix spike duplicates, will be conducted as specified in SOP S4.6 (Carlsen et al., 1992 and 1993).

As part of each alternative, water levels would be measured at least quarterly in 50 wells for Alternatives 1 and 2, and in 52 wells for Alternatives 3, 4, 5, and 6 (Fig. 4-1). All ground water samples would be analyzed for VOCs by EPA Method 601, and samples from at least three monitor wells also would be analyzed for diesel.

Comparative cost estimates are presented in this report for the purpose of analyzing and selecting the preferred remedial action alternative. These costs may be subject to:

- Variations in specific assumptions such as alternative implementation, construction, effectiveness, and system life;
- Changes in dollar value at the time of construction;
- Changes in available equipment and technology at the time of construction;
- Changes in assumed discount rate used in present-worth calculations;
- Uncertainties associated with the hydrogeologic characteristics, subsurface heterogeneities, estimated contaminant mass and volume, and estimated cleanup time; and
- Estimated cost accuracy of −30% to +50%.

Although the alternative cost estimates are believed to be accurate and in accordance with U.S. EPA cost estimate guidelines (U.S. EPA, 1987 and 1988b), they are subject to change and therefore should not be used for budgetary purposes. A more detailed cost analysis of the selected remedial action alternative will be presented in the Remedial Design (RD) report, following the Record of Decision (ROD) report.

An additional cost/benefits comparison between Alternative 3, which proposes a reduction in cancer risk to 3×10^{-5} (HI = 1.0) using soil vapor extraction, and the additional expense required to further reduce the cancer risk to 1×10^{-6} is presented in Berry and Landgraf (1994). The additional costs required represent a 64 to 88% increase above the base present-worth cost of Alternative 3, and thus are deemed not justifiable.

4.1. Alternative 1—No Action

Alternative 1 is defined as no action. A no-action alternative is generally required in studies of remedial alternatives as a basis from which to develop and evaluate the other remedial

alternatives and is the postulated basis of the baseline risk assessment. Under a no-action response, all remedial activities in the Building 834 Complex would cease. Sampling and analysis of soil vapor and ground water from monitor wells in the area would continue in order to monitor TCE and other VOCs in the subsurface.

As shown in Figure 4-1, downgradient wells W-834-S2A and -S3 would be destroyed because each is screened over two separate intervals. Proposed new well W-834-S10 would be installed in the Tps-Tnsc$_2$ hydrologic unit to replace the upper screened interval of well W-834-S2A. The lower screened interval of well W-834-S2A does not produce water and would not be replaced. Proposed new well W-834-S11 would be installed in the Qt-Tpsg hydrologic unit to replace the upper screened interval of well W-834-S3. Proposed new well W-834-S12 would be installed in the Tps-Tnsc$_2$ hydrologic unit to replace the lower screened interval of well W-834-S3.

Ten shallow dedicated soil vapor points would be installed adjacent to core area buildings as shown in Figure 4-2. These points would be screened at uniform depths less than 12 feet deep to monitor the shallow portion of the vadose zone where elevated health risk exists. Although several dedicated soil vapor points already exist (Fig. 1-43), these are installed at various depths and as such are not as viable for compliance monitoring. Should soil flux monitoring methods prove to be reliable, cost-effective, and repeatable, we may modify the compliance sampling plan to replace the 0- to 12-ft depth soil vapor sampling with surface soil flux monitoring, pending regulatory approval.

We developed cost estimates for Alternative 1 based on the soil vapor and ground water monitoring and sampling program described below. Cost estimates are presented in Appendix G. These costs include: water level measurements, soil vapor and ground water sample collection and analysis, project management, database management, and project report preparation that would be required at the end of each quarter. The present-worth cost of Alternative 1 is $4.19 million. This includes 30 years of soil vapor and ground water monitoring.

4.1.1. Monitoring for Alternative 1

The soil vapor and ground water monitoring program includes biannual soil vapor sampling of the 10 shallow soil vapor points for 5 years, followed by annual sampling of the same points for 25 years. For the first 5 years, ground water samples would be collected and analyzed quarterly in 8 wells, biannually in 11 wells, and annually in 30 wells. Sampling would include wells at the Building 834 Complex core area and downgradient wells located between the septic system release area and the W-834-T2 and -T4 well cluster areas. Annual ground water sampling and analysis of 49 wells would continue for an additional 25 years. This well sampling schedule is based on an analysis of the historical VOC data and the well completion interval for each well. New wells, contaminated wells at the leading edge of the VOC plume, and selected wells located at the primary VOC release area are scheduled to be sampled biannually for the first 5 years. Generally, guard wells (wells that monitor downgradient or vertical plume migration) are sampled quarterly.

The ground water data obtained as part of the Alternative 1 monitoring programs will be reviewed at least every five years, as suggested in CERCLA guidance documents (U.S. EPA, 1988b). If the data indicate that contaminant concentrations or ground water flow direction and velocity have changed, the well monitoring program would be reevaluated. Because such

changes cannot be predicted, we have conservatively assumed that the monitoring program described in this alternative will be implemented for a full 30-year period. This approach also helps to simplify the cost analysis of this alternative.

4.2. Alternative 2—Exposure Control

Alternative 2 includes:

- Modification of building ventilation in selected buildings to provide increased circulation.
- Institutional controls to reduce the health risk represented by exposure to VOCs within potential risk areas, as defined by the SWRI risk assessment (Webster-Scholten, 1994) and summarized in section 1.6.

Additional drainage controls, such as asphalt paving, would also be constructed along the perimeter of the Building 834 Complex core area.

Passive LNAPL recovery will also be included as a component of this alternative.

This alternative includes installation of the 10 dedicated shallow soil vapor points and installation and destruction of downgradient monitor wells as described in Alternative 1.

The present-worth cost of Alternative 2 is $5.69 million. This includes 2 years of LNAPL recovery and 30 years of soil vapor and ground water monitoring. Assumptions and cost tables are provided in Appendix G.

4.2.1. Building Ventilation

Improvements to the ventilation systems of selected buildings in the Building 834 Complex would be designed and installed to reduce VOC concentrations inside buildings to acceptable levels. As presented in Appendix C, the acceptable indoor air concentration for TCE is 0.036 mg/m^3. We have identified Buildings 834A, D, O, and J for possible ventilation system retrofitting because workers periodically use the facilities, and the buildings are close to the identified VOC releases and/or surrounding vadose-zone soil vapor concentrations exceeding the proposed 3×10^{-5} cancer risk (HI = 1.0) soil vapor remediation level (250 $ppm_{v/v}$). An air sampling program currently is being performed to verify model predictions of indoor air concentrations and to further evaluate the need for ventilation. Because these data are not yet available, we have conservatively assumed that ventilation retrofits would be necessary to reduce indoor air concentrations and have included these costs in this alternative.

Elements of the ventilation retrofit in all four buildings would include installation of carbon filters in air intake ducts, increasing air circulation rates, increasing air intake duct height, and modifying ducts and motors. Carbon filters installed in the intake duct would remove VOC vapors present in the outdoor ambient air. Because modeled air concentrations are predicted to decrease with height above the ground surface, increasing the intake height would reduce the concentration of TCE in intake air. Increasing air flow will increase the number of air exchange volumes, reduce VOC vapor buildup, and thus reduce the indoor air concentration.

Cracks in concrete walls would be sealed and concrete floors would be epoxy-coated to further reduce the potential for vapor to enter the buildings.

4.2.2. Institutional Controls

As part of Alternative 2, institutional controls would be implemented in the Building 834 Complex core area to restrict or limit exposure to VOCs, which may volatilize from subsurface soil to the atmosphere and thereby reduce potential inhalation risk. Institutional controls may consist of:

- Fences and warning signs.
- Restricted access.
- Security patrols.
- Restrictions and procedures for construction in the Building 834 Complex.

These institutional controls already exist but may need to be modified to increase their effectiveness in limiting exposure to VOCs at the Building 834 Complex.

4.2.3. Drainage Control

Currently, drainage control in the core area consists of unlined ditches along the base of the berms. Sediment washed downhill from previous rainstorms has partially filled these ditches. During rainstorms, surface water also flows along the paved areas between Buildings 834A and B and between Buildings 834A and D. The majority of runoff flows southwest out of the core area. Some runoff infiltrates into vadose zone soils in the area immediately southeast of Building 834D and southwest of Building 834B.

The installation of diversion channels along the side of the road between Buildings 834A and D, and extending downhill to the lower part of the Building 834 Complex core area, would intercept runoff and transfer it southwest of the core area.

Most of the core area is covered by buildings or asphalt pavement; however, the surface area immediately southeast of Building 834D and southwest of Building 834B is not paved and is covered by coarse gravels. To reduce vadose zone recharge, we propose that this area be paved with asphalt and a sealant applied to the total paved area in the Building 834 Complex core area.

4.2.4. LNAPL Removal

Although the LNAPLs (primarily diesel and T-BOS) detected in monitor wells W-834-D3, 4, 5, and 8 have not been determined to have a quantifiable health risk at the complex, passive LNAPL recovery is an easily implementable, relatively inexpensive means of source mass removal. As a result of the low removal cost and ease of implementation, the LNAPLs will be extracted at the four wells by a downhole recovery system that uses a passive skimmer in each well. A passive skimmer consists of a screened skimmer assembly that is lowered into the well to the zone of floating product. A hydrophobic filter automatically separates floating product from the ground water surface, and recovered product is stored in a collection chamber, which would be emptied manually each month. Recovered LNAPLs (diesel and T-BOS) would be transported off site for recycling or destruction.

LNAPL recovery would continue until LNAPL thickness is reduced to a sheen and LNAPLs are no longer effectively removable. Based on the available data, it appears that the lateral extent

of LNAPLs is limited. We conservatively estimate that LNAPL recovery will continue for two years.

4.2.5. Monitoring for Alternative 2

Monitoring protocol would be similar to that described in section 4.1. Soil vapor samples would be collected and analyzed biannually in the 10 soil vapor monitor points for 5 years, followed by annual sampling for 25 years. For the first 5 years, ground water samples would be collected and analyzed quarterly in 12 wells, biannually in 8 wells, and annually in 29 wells. This sample schedule differs from Alternative 1 in that wells that have LNAPL skimmers are sampled quarterly for VOCs. Sampling would include wells at the Building 834 Complex core area and downgradient wells located between the septic system release area and the W-834-T2 and -T4 well cluster areas. Annual ground water sampling and analysis of 49 wells would continue for an additional 25 years.

4.3. Alternative 3—Source Mass Removal

The objective of Alternative 3 is to reduce soil vapor VOC concentrations in the upper 12 feet of the vadose zone to acceptable health-risk-based concentrations associated with a total HI of 1.0, which corresponds to a cancer risk of 3×10^{-5}, as discussed in Chapter 2. Alternative 3 consists of:

- The exposure controls described in Alternatives 1 and 2, including additional ventilation, as necessary to reduce exposure risks due to inhalation of VOC vapors, plus thirty years of soil vapor monitoring.
- Source mass removal to reach soil vapor restoration goals, through soil vapor extraction and treatment.
- LNAPL skimming and disposal, as described in Alternative 2.
- Installation of 10 shallow soil vapor monitor compliance points, as described in Alternative 1.
- Installation of three extraction wells in the core area (in addition to three downgradient wells installed and two destroyed, as described in Alternative 1).

The following sites are included for remediation to the cancer risk of 3×10^{-5} and HI of 1, on the basis that TCE concentrations in soil vapor less than 12 feet deep exceed the PSVRL of 250 $ppm_{v/v}$ and/or Site 300 staff work in close proximity to the release sites:

- Former pump station Building 834D
- Former pump station Building 834C
- Former pump station Building 834B
- Trailer 834O.

Remediation in the vicinity of test cell 834J is also included because, as presented in Table 1-12, "substantial" TCE soil stains were documented near the northern corner of 834J.

The present-worth cost of Alternative 3 is $8.72 million. This includes 2 years of LNAPL recovery, 5 years of SVE, and 30 years of soil vapor and ground water monitoring. Assumptions and cost tables are provided in Appendix G.

An additional cost/benefits comparison between Alternative 3, which proposes a reduction in cancer risk to 3×10^{-5} (HI = 1.0) using soil vapor extraction, and the additional expense required to further reduce the cancer risk to 1×10^{-6} is presented in Berry and Landgraf (1994). The additional costs required represented a 64 to 88% increase above the base present-worth cost of Alternative 3, and thus are deemed not justifiable.

For Alternative 3, soil vapor treatment technology may be augmented by an innovative technology in the near future. Innovative technologies applicable to the Building 834 Complex are described in section 4.7 and Appendix E. These include a resin adsorption and regeneration system, UV photo-oxidation, electron accelerator, and surfactant injection. Innovative technology treatability tests at the Building 834 Complex would lead to development of more cost-effective and efficient methods of treatment, destruction, and disposal of VOCs in soil vapor. To ensure worker safety and regulatory compliance, any innovative technology testing at the Building 834 Complex would be conducted in conjunction with the approved remedial treatment system (i.e., BAT) under this alternative. The innovative technology treatment system would be installed in series between the SVE system and the approved and permitted air emissions control device to ensure that air discharge to the atmosphere meets regulatory permit standards. If treatability testing indicates that an innovative technology, such as a resin adsorption-regeneration system, is more cost effective than the BAT system, we would propose that the innovative technology either supplement or replace the previously selected BAT system.

4.3.1. Soil Vapor Extraction

For this alternative, the VOC source mass removal mechanism would be by SVE. Soil vapor would be extracted from 16 existing monitoring wells in the vicinity of pumping station Buildings 834B, C, D, at test cell 834J, and from three new vapor extraction wells, W-834-B4, W-834-C3, and W-834-J3 (Fig. 4-2).

As presented in SWRI Chapter 10, soil samples were collected and analyzed for VOCs during well installation at the core area. These data report that maximum VOC concentration (970 mg/kg TCE) was detected at 29 feet. Concentrations of VOCs up to 12,000 mg/kg TCE were detected in shallow soil behind Building 834C, but these soils were excavated in 1982 (Carpenter et al., 1983). Currently, 14 soil vapor extraction wells are already manifolded for soil vapor extraction. The screened intervals and sandpacks will permit vapor extraction from depths less than 12 feet to about 33 feet below the surface where the highest soil and soil vapor concentrations have been detected. The existing SVE system uses a vacuum pump to extract soil vapor at a rate up to 250 cfm. Prior to discharge to the atmosphere, the extracted vapor is passed through a knock-out tank to remove water vapor and then through two vapor-phase GAC canisters connected in series. The SVE system startup and testing to document the mass removal rate and area of vacuum influence to ready to begin pending agency concurrence. Table 4-2 lists the construction details for the proposed wells that will be used for SVE.

Although SVE modeling (presented in Appendix F) and previous SVE tests suggest that the proposed extraction system is sufficient, we will optimize the extraction system's efficiency based on the startup test results. The SVE model VENTING predicted a cleanup time of a less

than five years, even with a low venting efficiency factor (Appendix F). We expect the influence of the SVE system to be adequate based on the 1989 SVE vacuum influence treatability test (Bryn et al., 1990 and Appendix D of this report). This test demonstrated a slight vacuum influence 60 to 85 feet away from well W-834-D5 using a blower with a significantly smaller capacity than our current blower. As a result, we expect to observe a greater vacuum extraction efficiency with the current extraction system.

The existing soil vapor treatment system would be used to treat effluent vapor from the SVE wells. This SVE system will be upgraded, if necessary, to operate for five years. The locations of the remediation system, monitor wells, and proposed extraction wells are shown in Figure 4-2. A program would be developed and implemented to evaluate SVE performance and assess when the remedial action goals have been achieved. Elements of this program would include soil vapor monitoring, as well as criteria for determining when to cease vapor extraction and initiate confirmatory soil sampling.

The SVE system will be operated until soil vapor concentrations in the shallow soil vapor monitoring points are below the 3×10^{-5} cancer risk and HI of 1.0 (PSVRL of 250 $ppm_{v/v}$). Although SVE modeling results discussed in Appendix F indicate that the PSVRL of 250 $ppm_{v/v}$ would be reached between 46 and 445 days, we have conservatively estimated operating costs for the SVE system for 5 years to account for the volatilization of residual VOCs in the vadose zone and possible vapor transport from the saturated zone.

4.3.2. Extraction Well Installation

Three new extraction wells, shown on Figure 4-1 (W-834-B4, -C3, and -J3), would be installed to provide more complete capture of contaminants in the core area. These wells would be constructed similarly to existing wells with screens extending through the vadose zone down into the saturated zone. The purpose for this type of well completion is two-fold. It provides the capability for ground water extraction, and also provides for a greater zone to apply soil vapor extraction.

4.3.3. Monitoring for Alternative 3

Soil vapor samples would be collected and analyzed quarterly for the first year and biannually for the next four years in 19 soil vapor wells and 10 shallow soil vapor points in the Building 834 Complex core area. After the SVE system is shutdown, soil vapor monitoring would be reduced to annual sampling of these wells and points for an additional 5 years followed by 20 years of annual sampling from the shallow soil vapor points only. For the first year, ground water samples would be collected and analyzed quarterly in 28 wells, biannually in 7 wells, and annually in 17 wells. Because the existing SVE wells are screened in both the vadose zone and perched water-bearing zone, the SVE wells would be sampled quarterly for VOCs in ground water for the first year, then biannually thereafter. Samples would include wells at the Building 834 Complex core area and downgradient wells located between the septic system release area and the W-834-T2 and -T4 well cluster areas. For the next four years, ground water samples would be collected and analyzed quarterly in 8 wells, biannually in 26 wells, and annually in 18 wells, followed by 25 years of post-remediation annual ground water sampling and analysis of up to 52 wells. Soil vapor extraction would continue until the goal of 3×10^{-5} cancer risk and HI = 1.0 (PSVRL of 250 $ppm_{v/v}$) is reached in the shallow soil

vapor monitoring compliance points. In addition, subsurface soil samples may be collected and analyzed to verify that the 2.2 mg/kg (ppm) PSRL health-based concentration (HI = 1.0) goal has been achieved.

4.4. Alternative 4—Source Mass Removal

As with Alternative 3, the objective of Alternative 4 is to reduce VOC concentrations in the vadose zone to acceptable health-risk-based concentrations associated with a total HI of 1.0, which corresponds to a cancer risk of 3×10^{-5}. Alternative 4 would include all of the elements of Alternative 3, plus perched zone dewatering of the Building 834 Complex core area to augment the effectiveness of vadose zone source area SVE and provide plume control and VOC mass removal. This alternative would also use air misting for disposal of treated ground water. Soil vapor extraction wells are the same as for Alternative 3 and are listed in Table 4-2. Alternative 4 may also be augmented by using an innovative technology for soil vapor and/or ground water treatment. If treatability testing indicates that an innovative technology is more cost effective than BAT treatment, we would propose that the innovative technology supplement or replace the previously selected BAT system. The present-worth cost of Alternative 4 is $10.38 million. This includes 5 years of SVE and dewatering (with two years of combined LNAPL recovery), and 30 years of soil vapor and ground water monitoring. Assumptions and cost tables are provided in Appendix G.

4.4.1. Dewatering for SVE

For this alternative, the VOC source mass removal mechanism would be augmented by dewatering of the perched water-bearing zone. Ground water extraction wells would create a 5- to 8-foot drawdown in the Building 834 Complex core area, exposing more soil to cleanup by SVE and removing VOC mass from the perched water-bearing zone. Another added benefit of dewatering is enhanced DNAPL extraction. As ground water is extracted, the DNAPL phase of TCE may be extracted with the highly contaminated ground water. Once the water table has been lowered sufficiently, residual DNAPLs trapped in the pore spaces of the dewatered zone may be removed by soil vapor extraction. Dewatering would be conducted as long as the SVE system was in operation. Based on modeling presented in Appendix F, we have conservatively estimated operating SVE for 5 years to obtain soil vapor cleanup level of 3×10^{-5} cancer risk and HI = 1.0 (250 $ppm_{v/v}$).

4.4.2. Ground Water Treatment System

The proposed ground water extraction wells are listed in Table 4-3, their locations are shown in Figure 4-2, and construction details for existing wells are listed in Table 4-2. Treatment would consist of an oil/water separator to remove LNAPLs, a low-profile tray air stripper, and a GAC vapor emissions control. VOCs would be removed from extracted ground water by using air stripping technology, which has been used in several pilot tests at the Building 834 Complex and is currently being used at the GSA operable unit.

In traditional, packed tower counter-flow air strippers, this transfer is accomplished by contacting a downward directed spray of water with an upward flow of forced air in a vertical tower that contains a high surface-area packing medium. The packing medium facilitates contact

between the water and the air. In low-profile tray air strippers, water flows across a shallow, baffled tray, and air is forced upward through the water, using a system of numerous, small openings, forming a highly agitated froth.

Because air stripping towers are highly visible and have potentially higher operating and maintenance costs due to cleaning hard water deposits, we have chosen a system featuring the low-profile tray design. This low-profile tray system would be installed at the location of the current treatment system and would have a life expectancy that meets or exceeds the life expectancy of the remediation project (approximately five years). To prevent release of VOCs generated by the air stripping process to the ambient air, the vapor effluent will be vented through a GAC filter unit comprised of two carbon canisters in series. Carbon dioxide gas will be injected into the influent water line to control pH and minimize scale buildup in the system.

Treated ground water effluent would be pumped to an effluent storage tank and later discharged on site, through an air misting system, to a sloped, undeveloped grassy area east of the Building 834 Complex. Air misting would be conducted in a manner to maximize evaporation. During the hottest part of the day, treated ground water would be discharged in a fine spray about 20 feet into the air. On most days, most of the water will evaporate before reaching the ground. On cool or rainy days, if all the water sprayed into the air did not evaporate or disperse and instead landed on the ground, the maximum estimated discharge application rate would be about 0.1 inch per square foot of ground surface per day. To control erosion and reduce infiltration, air misting over a large ground surface area is preferred over direct discharge. This low discharge rate is not expected to create any surface flow nor attract any wildlife. The number of misting heads used at any time would be dependent on rate of discharge, wind conditions, and air temperature.

4.4.3. LNAPL and DNAPL Removal

LNAPLs will be removed from the perched water-bearing zone in the vicinity of wells W-834-D3, 4, 5, and 8 as a result of dewatering. The thickness of floating product in these wells ranges from approximately 1 to 3.5 inches. The benefits of active pumping of floating product are to:

- Maximize LNAPL removal.
- Maximize vadose-zone contaminant removal at source areas associated with the former Building 834 pump station and test cell wells.

LNAPLs would be removed by a total fluids pumping system. A pneumatic pump would be used to extract ground water, along with any floating product, from each of the wells. The product would be discharged through a phase separator. The LNAPLs (diesel and T-BOS) removed from these wells would be pumped to a storage tank and periodically disposed of at an off-site hazardous waste disposal or recycling facility. If monitoring confirms the presence of DNAPLs, then we would install a three-phase separator to remove LNAPLs and DNAPLs from the ground water. Otherwise, a previously installed two-phase oil/water separator would be used to remove LNAPLs only. Also, if design-phase pilot testing indicates that the less volatile dissolved diesel and T-BOS are not fully treated by air stripping, liquid phase GAC will be added as a polishing step. The liquid-phase GAC is not considered in the present-worth cost of

Alternative 4. Although we anticipate that LNAPLs will be removed in less than two years, the phase-separator would be left in line for the duration of dewatering.

Innovative DNAPL remediation technologies may also be tested in the vicinity of the primary release sites at the core of the Building 834 Complex. Should treatability studies prove these technologies implementable and effective, they may be considered for full-scale remediation, pending regulatory approval.

4.4.4. Monitoring for Alternative 4

The monitoring program for this alternative includes quarterly sampling, for the first five years, of all wells that are extracting soil vapor or ground water. Soil vapor monitoring would be the same as in Alternative 3. Therefore, for the first five years, ground water samples would be collected and analyzed quarterly in 28 wells, biannually in 7 wells, and annually in 27 wells, including wells at the Building 834 Complex core area and downgradient wells located between the septic system release area and the W-834-T2 and -T4 well cluster areas. Annual ground water sampling and analysis of up to 52 wells would continue for an additional 25 years. Soil vapor and ground water extraction would continue until the 3×10^{-5} cancer risk level (PSVRL of 250 $ppm_{v/v}$) is reached at the shallow soil vapor compliance monitoring points. In addition, subsurface soil samples may be collected and analyzed to verify that the goal of 3×10^{-5} cancer risk level and HI = 1.0 (2.2 mg/kg TCE in soil) has been achieved in soil.

4.5. Alternative 5—Source Mass Removal and Ground Water Plume Control

As with Alternatives 3 and 4, the objective of Alternative 5 is to reduce VOC concentrations in the vadose zone to acceptable health risk-based concentrations. Alternative 5 would include all of the elements for Alternative 4 and use additional dewatering at the Building 834 septic tank release area and the W-834-T2 and -T4 well cluster areas to provide downgradient perched water-bearing zone VOC plume control and additional mass removal. Alternative 5 may also be augmented by an innovative technology for soil vapor, ground water and/or DNAPL treatment. Alternative 5 may also be augmented by innovative technology for soil vapor and/or ground water treatment. If treatability testing indicates that an innovative technology is more cost effective, we would propose that the innovative technology supplement or replace the previously selected BAT system. The present-worth cost of Alternative 5 ranges from $11.80 million to $16.45 million depending on the duration of ground water extraction. This includes 5 years of SVE, between 5 and 30 years of dewatering (with two years of combined LNAPL recovery), 20 years of soil vapor monitoring, and 30 years of ground water monitoring. Assumptions and cost tables are provided in Appendix G.

4.5.1. Downgradient Plume Control and Mass Removal

As mentioned above, this alternative combines the source mass removal of Alternative 4 with downgradient plume control and mass removal by ground water extraction. The wells used in the ground water extraction system for this alternative are listed in Table 4-4. Perched zone ground water would be extracted from well W-834-S1 and a new extraction well W-834-S1 at the septic tank release area, and wells W-834-T2, W-834-T2A, W-834-T2D, W-834-T4, and

W-834-T4C in the W-834-T2 and -T4 well cluster areas, in addition to the extraction wells listed for Alternative 4. Pneumatic ground water extraction pumps would pump ground water from the wells to a centrally located transfer tank. A transfer pump would then pump water from the transfer tank uphill to the treatment facility at the core area.

Treated water effluent from the treatment facility would be discharged to an effluent storage tank and then discharged through an air misting system, with four to five misting ports, located east of the Building 834 Complex core area.

As mentioned earlier, no concentration-based cleanup criteria have been established for the perched ground water and, because it is not considered suitable or potentially suitable as a drinking water source, LLNL is requesting that the CVRWQCB Basin Plan be amended to exclude the shallow perched water-bearing zone. The purpose of downgradient ground water extraction is downgradient plume control and mass removal. As discussed in Appendix F, we estimate that dewatering of the perched water-bearing zone would take approximately 7 years. However, a longer period of time may be required, as well yields decrease with the lowering of the water table. Therefore, we present costs for 5, 10, 20, and 30 years of ground water extraction in Table G-8 (Appendix G). Continuance of plume control would be reevaluated at least every five years, in accordance with U.S. EPA (1988b).

4.5.2. Monitoring for Alternative 5

Soil vapor monitoring would be the same as in Alternative 3. The ground water monitoring program for this alternative is similar to that for Alternative 4, with the exception that downgradient ground water extraction wells, new monitor wells, and all wells in the W-834-T2 and -T4 areas are sampled quarterly. For the first five years, ground water samples would be collected and analyzed quarterly in 40 wells and annually in 12 wells, followed by 25 years of biannual ground water sampling in 38 wells and annual sampling in 14 wells. Soil vapor and ground water extraction would continue until the 3×10^{-5} cancer risk and HI = 1.0 (PSVRL = 250 $ppm_{v/v}$) level is reached in the shallow soil vapor compliance monitoring points. In addition, subsurface soil samples may be collected and analyzed to verify that the goal of 3×10^{-5} cancer risk and HI = 1.0 (2.2 mg/kg TCE in soil) has been achieved in soil.

4.6. Alternative 6—Interim Source Mass Removal

During the June 23, 1994, Site 300 Remedial Project Manager's Meeting, an agreement was made among LLNL/DOE, RWQCB, DTSC, and EPA to present a sixth remedial action alternative for the Building 834 operable unit. The sixth alternative combines the treatability testing of innovative technologies with the BAT soil vapor extraction proposed under Alternative 3, in conjunction with ground water extraction to enhance soil vapor extraction. This would provide system flexibility should the water table need to be lowered, thereby exposing more soil for soil vapor extraction. Alternative 6 would be established under an Interim ROD. This alternative differs from Alternative 3 in that it allows the innovative technologies to be tested and deployed first to determine their feasibility, implementability, and effectiveness. It also provides soil vapor extraction as a means to reduce risk and mass between treatability testing. As indicated in U.S. EPA (1991), the Interim ROD will specify the circumstances/criteria that will be used to evaluate the performance of the innovative

technologies. Should one (or more) innovative technologies prove acceptable, then it (they) will be implemented as the primary remedial technology. Should none of the innovative technologies meet the criteria established in the forthcoming contingent ROD, discussions will be conducted among LLNL/DOE, RWQCB, DTSC, and EPA to either test additional promising innovative technologies or fully implement the Alternative 3 BAT remediation system with ground water extraction to enhance soil vapor extraction. The costs associated with Alternative 6 should be similar to or less than Alternative 3, 4, or 5.

The advantage of Alternative 6 is that it provides for the testing/implementation of innovative technologies that may prove to be more efficient and effective than the currently available BAT. The application of innovative technologies is extremely important especially in addressing subsurface DNAPL contamination, as no BAT DNAPL remediation systems currently exist.

Alternatives 3, 4, and 5 are contingent remedial strategies because the perched water-bearing zone Basin Plan amendment process is not yet complete. LLNL's request for an amendment to exclude the perched water-bearing zone from the CVRWQCB Basin Plan is the first of its kind. No previous Basin Plan amendment requests have been filed with the CVRWQCB. Although the request is technically defensible and justifiable, the process has never been completed. Alternative 3 provides existing best available technology to address risk reduction and source mass removal, should the amendment be granted and none of the innovative technologies tested meet the performance criteria. Should none of the innovative technologies tested meet the performance criteria and should the RWQCB decide that although the perched water-bearing zone fails to meet the criteria of a potable water source, it must be remediated as such, discussions can be conducted among DOE, LLNL, DTSC, RWQCB, and EPA as part of the standard ongoing CERCLA review to determine the final scope of remediation. The RWQCB's decision on the Basin Plan amendment for the perched water-bearing zone will be presented in the Interim ROD associated with Alternative 6.

Because Alternative 6 applies the same BAT described in Alternative 3 and the same innovative technologies described in Alternatives 4 and 5, the evaluation of Alternatives 3, 4, and 5 also applies to Alternative 6. For this reason, and because the presentation of Alternative 6 was not agreed upon until June 23, 1994, Alternative 6 may not be presented in all tables of this document. In this case, the reader should refer to the material presented for Alternatives 3, 4, and 5 instead.

Several innovative technologies have been presented in this chapter and Appendix E that may be applicable for testing at the Building 834 operable unit as part of Alternative 6. These include, but are not limited to: alcohol flooding, surfactants, bioremediation, joule-heating, dual gas partitioning tracers, *in situ* radio frequency, thermal oxidation, resin adsorption and regeneration, electron accelerator, UV/photo-oxidation, and *in situ* air sparging. Three of these innovative technologies (alcohol flooding, surfactants, and dual gas partitioning tracers) are directly applicable to characterizing and/or remediating subsurface DNAPLs, and are currently under consideration for the Building 834 Complex core area. Some of these innovative technologies are discussed in section 4.7.

4.7. Innovative Technology Testing

This section describes several innovative remediation technologies being reviewed for the Building 834 Complex. If any of these and/or other innovative technologies prove to be implementable and cost effective, they can be implemented as the primary remedial technology, thereby supplementing or replacing current BAT remedial systems, pending LLNL/DOE and regulatory approval.

4.7.1. Resin Adsorption-Regeneration System

The resin adsorption-regeneration system is described in Appendix E. Briefly, it is a vapor treatment system that traps VOC vapors on an adsorbent resin bed. The advantage of this system is its on-site regenerative capacity. The system consists of one or more resin beds that are on-line while another bed is being regenerated in a desorption cycle. The resin beds are automatically switched between adsorption and desorption cycles. Desorption is accomplished using a combination of temperature, pressure, and a carrier gas. During the desorption cycle, the VOCs trapped in the adsorbent material are removed, condensed, and transferred, in liquid phase, to a storage tank. This liquid would be recycled or destroyed off site.

The resin system has two advantages over the conventional carbon treatment system. Because the adsorbent material can be regenerated on site, the cost is much lower than carbon adsorption, which typically must be transported off site for disposal or treatment as hazardous waste. Although on-site carbon regeneration is feasible, the carbon has limited reuse capacity before replacement. Carbon regeneration also produces acids when treated for VOCs, thus causing corrosion problems. Literature for the resin system states that the adsorbent resin beds may be recycled in excess of 2,000 times with no measurable loss of adsorption capacity (Appendix E). In addition, activated carbon's capacity to adsorb VOCs is significantly affected by moisture. The resin system's adsorbent beds have a high tolerance to water vapor, thereby allowing treatment of vapor streams in which the relative humidity is greater than 90% with minimal impact on adsorption efficiency. These two factors would lower the operation and maintenance costs of the Building 834 vapor treatment system and make the resin system more cost effective and efficient for long-term treatment. To test the resin system, it could be installed in series with the existing GAC vapor treatment system so it would polish any vapors not captured by the resin beds. If treatability testing indicates that the resin system is more cost effective than GAC, we would propose that the resin system supplement or replace the GAC system.

4.7.2. UV Photo-Oxidation

As described in Chapter 3, UV photo-oxidation is an innovative technology that uses low-wavelength (λ_{max} = 230 nm) emission lamps to break down VOCs in air by photolysis. This technology uses xenon flashlamps, a high intensity ultraviolet light source that operates in a pulsed mode by alternately storing electrical energy in a capacitor and discharging it through a gas filled chamber of UV transmissive quartz (Appendix E).

The advantage of UV photo-oxidation is that it destroys VOCs, thereby reducing waste that requires further treatment or disposal. A disadvantage is that the main degradation product of TCE is dichloroacetyl chloride (DCAC). Further oxidation of DCAC is much slower than TCE,

requiring longer residence time. In addition, one of the intermediate conversion products of DCAC is dichlorocarbonyl (DCC or phosgene). However, with continued photo-oxidation, the decay products are hydrochloric acid and carbon dioxide.

A bench-scale and pilot test of two full-scale vapor emissions control systems from the Building 834 Complex SVE system have been performed previously. Both full-scale reactors demonstrated a greater than 99% reduction in TCE effluent vapor, although toxicity-level goals were not attained because of the accumulation of intermediate toxic products (Johnson et al., 1992). Further examination of this technology is needed to determine the effects of shorter wavelength UV lamps and the effectiveness of scrubbers for removing acidic photo-oxidation products and potential post-treatment products, such as DCAC. Installation of a UV photo-oxidation unit may be implemented easily into Alternative 3, 4, 5, or 6.

4.7.3. Electron Accelerator

Details of electron beam technology for destruction of VOCs in air or water are described in Appendix E. This innovative technology involves radiolysis, a process that uses high energy electrons to break down chemical bonds in the VOC and transform them to stable nonhazardous compounds, such as carbon dioxide.

The advantage of electron beam processing is that it destroys VOCs, thereby reducing waste requiring further treatment or disposal. A comparative analysis indicates that electron beam processing can be more cost effective than GAC treatment at LLNL (Matthews et al., 1992). A treatability test of this technology was performed in 1991 at the Building 834 Complex. An electron accelerator produced ionizing irradiation that radiolytically decomposed TCE and PCE from initial concentrations of 40 and 110 ppm_v to 0.1 and 2 ppm_v, respectively. However, chloromethane, dichloromethane, chloroform, acetone, and triethylbenzene by-products were produced at concentrations up to 400 ppm_v. Further development of this innovative technology and reduction of reaction products is needed to determine its effectiveness. An electron accelerator can be installed in line with the vapor effluent waste stream from the SVE and/or sparge tanks, and can destroy the VOC vapors prior to atmospheric discharge, thereby eliminating or reducing the consumption of GAC. Thus, installation of an electron accelerator may be implemented easily into Alternative 3, 4, 5, or 6.

4.7.4. Surfactant Injection

Surfactant injection is a relatively new, *in-situ* technique for remediation of DNAPLs. The technique is applied by pumping water, with surfactants, into the ground water zone via injection wells. The surfactants cause a significant increase in the solubility of the DNAPLs by forming colloidal clusters (called micelles) in which the DNAPLs are solubilized. The DNAPLs essentially go into solution to concentrations several orders of magnitude greater than their normal water solubility. The resulting water/DNAPL mixture can be pumped to extraction wells, without the DNAPL becoming sorbed by soil particles, and treated with conventional ground water treatment systems (Appendix E).

At the Building 834 area, a laboratory treatability study would be conducted to select the surfactant that will best increase the solubility of the DNAPLs present at the site. A small-scale pilot test could be conducted to verify the model predictions and determine parameters for a full-scale field operation.

This technique may have significant benefit in removing potential DNAPLs in the subsurface at the Building 834 Complex. This would result in more efficient mass removal and a quicker cleanup time, thereby significantly reducing cleanup costs. Ground water could be pumped from the perched zone, treated, and reintroduced, with surfactants, into the perched zone. However, because of the low, discontinuous flow from the perched zone, an additional water supply may be needed for injection. If surfactant technologies prove reliable, we will consider their application to the Building 834 operable unit remediation, pending regulatory approval.

4.7.5. *In Situ* Biological Enhancement

Bioremediation could be used at the Building 834 Complex core area to enhance *in situ* biodegradation processes that appear to already be occurring. The presence of the TCE degradation product, 1,2-DCE in ground water, suggests that an anaerobic environment may exist in parts of the subsurface. Anaerobic bioremediation would only be applicable if SVE is not used as a remediation technology, since SVE would likely enhance aerobic conditions, which counter the *in situ*, anaerobic biomasses that may be present. However, SVE would stimulate aerobic bioremediation, which could degrade TCE.

It is also possible that LNAPLs (T-BOS or diesel) may be creating small anaerobic pockets (or zones) in the perched water-bearing zone by limiting oxygen exchange from the surface. For example, well W-834-D8, in particular, has both significant levels of diesel and relatively low levels of dissolved oxygen in ground water. In this case, the removal of LNAPLs may cause these pockets to become aerobic environments, undermining the natural anaerobic degradation processes and augmenting aerobic degradation processes.

Additional characterization of the degradation environment and processes at the Building 834 Complex is needed before considering the implementation of *in situ* field scale enhanced bioremediation treatability study.

4.7.6. *In Situ* Air Sparging

In situ air sparging has been used with some success at the DOE Savannah River facility. *In situ* air sparging at the Building 834 Complex would require the modification of one or more monitor/extraction wells to inject air into the subsurface. (Such modifications have already been made at six wells at the core of the complex.) This method could be used to enhance the volatilization of VOCs in the immediate vicinity of the well. It also requires air injection wells to be within soil vapor and ground water extraction capture zones to contain contaminant movement.

5. Detailed Evaluation of Remedial Alternatives

5.1. Criteria and Evaluation Process

This chapter presents our detailed analysis and comparison of the remedial alternatives developed for the Building 834 Complex. U.S. EPA (1988b) 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.

Media-specific response actions and technologies are combined into remedial alternatives based on current knowledge of the distribution of the contaminants in the subsurface. The media of interest are the soil and soil vapor in the vadose zone and, to a lesser-extent, the ground water within the perched water-bearing zone. VOCs in the shallow perched water-bearing zone have not impacted the regional aquifer, which is located 280 feet below.

In this chapter, we evaluate the remedial alternatives against the first seven criteria.

State acceptance will be determined by agency review and commentary on this document. Analysis of technical and administrative concerns that these agencies may have regarding each of the alternatives will be addressed in the ROD. Public comments concerning each of the alternatives will also be addressed in the ROD.

5.2. Detailed Analysis of Remedial Alternatives

As summarized in Table 5-1, Alternatives 1 through 6 are compared in relation to the first six evaluation criteria defined in U.S. EPA (1988b). A cost comparison of the six alternatives is presented in Table 5-2. Table 5-3 presents a comparative summary of the six alternatives with respect to the nine criteria evaluated.

5.2.1. Evaluation of Alternative Development

As discussed in Chapter 4, the alternatives build upon one another; with each alternative, more remedial technologies are implemented to achieve restoration goals more effectively and completely. To address potential health risks from exposure to inhalation of vapors, we

developed Alternative 2, which utilizes risk management/control through building ventilation and institutional controls. Ventilation systems in Buildings 834A, D, J, and O at the Building 834 Complex already exist. If necessary, increased ventilation and air purifying controls would be designed and installed in these buildings to ensure that indoor air concentrations of TCE are below the acceptable human health risk levels. Alternative 2 also includes minimal source migration control by controlling localized perched zone recharge and controlling drainage in the core area, as well as mass removal by passive LNAPL skimming from four wells.

To accomplish soil vapor restoration levels through mass removal, we developed Alternatives 3, 4, 5, and 6. These alternatives provide source mass contaminant removal, and are protective of human health and the environment. Soil vapor remediation goals are protective of human health and will provide further protection of the environment through reduction of VOCs. Remediation will reduce VOCs in soil vapor to concentrations corresponding to a noncancer HI of 1.0, which corresponds to a total cancer risk of 3×10^{-5} (Appendix C). For the indicator chemical, TCE, this level of risk is equivalent to the PSVRL of 250 $ppm_{v/v}$.

In Alternative 3, 19 conceptual SVE well locations within the complex were chosen to recover VOCs from the vadose zone, thereby reducing risk associated with volatilized VOCs in air. The treatment facility, located at the core of the complex, would consist of a soil vapor extraction (SVE) system and air emission controls. GAC would be used to adsorb VOCs and prevent their release to the atmosphere. Modified building ventilation, drainage controls, and passive LNAPL recovery elements of Alternative 2 also would be implemented.

Alternative 4 is the same as Alternative 3, except that we would add perched water-bearing zone dewatering and active LNAPL recovery as a part of ground water treatment instead of passive skimming. SVE would still be the primary mechanism for mass removal of VOCs. Dewatering from 19 wells would be conducted to maximize the exposed unsaturated soil column to augment removal of VOC mass by SVE. Dewatering also enhances VOC mass removal by extracting VOCs solubilized in ground water and possibly capturing DNAPLs in the vicinity of the ground water extraction wells. A ground water treatment system, designed for a flow rate of 1.3 gpm, will treat extracted ground water from wells in the Building 834 Complex to the point where concentrations are acceptable for on-site disposal via misting. Major components of the ground water treatment system will be a liquid-phase separator, low-profile air stripper, and vapor-phase GAC. If DNAPL monitoring, which will be conducted in the near future, confirms the presence of DNAPLs, then we would install a three-phase separator to remove LNAPLs and DNAPLs from the pumped ground water. Otherwise, the previously installed two-phase oil/water separator would be used to remove LNAPLs only. Also, should design-phase pilot testing indicate that the less volatile dissolved diesel and T-BOS are not fully treated by air stripping, liquid-phase GAC will be added for effluent polishing.

At such low flows, treated ground water would be discharged by air misting, conducted in a manner to maximize evaporation, in a sloped, undeveloped grassy area east of the Building 834 Complex. During the hottest part of the day, treated ground water would be discharged in a fine spray into the air about 20 feet above the ground surface. On most days, most of the water will evaporate before reaching the ground. On cool or rainy days, if all the water sprayed into the air did not evaporate or disperse and, instead, landed on the ground, the maximum estimated discharge application rate would be 0.1 inch per square foot of ground

surface per day. This low discharge rate is not expected to create surface flow nor attract any wildlife. To prevent erosion and minimize infiltration, air misting over a large ground surface area is preferred over direct discharge.

In Alternative 5, we would extract from seven more ground water wells downgradient of the Building 834 Complex to intercept and hydraulically contain the perched contaminant plume and to provide additional mass removal. Ground water extracted from these downgradient wells would be pumped uphill to the treatment facility at the core and treated with the other extracted ground water.

Alternative 6 is the same as Alternative 3, except that we would test several promising innovative remediation technologies first. A number of these innovative technologies are designed to directly address the remediation of DNAPLs as well as LNAPLs. If any of these innovative technologies prove to be implementable and cost effective, they will be implemented as the primary remedial technology. If the treatability testing of the innovative remediation technologies does not identify an appropriate remediation technology, the BAT system described in Alternative 3 would be implemented as the contingent remediation system.

5.2.2. Criteria Evaluation of Alternative 1

Alternative 1 serves as a baseline scenario to compare to the other alternatives. Because the only action taken is well destruction and replacement, all current and potential future risks to human health and the environment remain the same as presented in the baseline risk assessment. This alternative meets ARARs. LLNL/DOE is currently pursuing a RWQCB amendment to exclude the shallow perched water-bearing zone from the Basin Plan. With respect to risk, this alternative is not effective in either the short or long term. This alternative depends on natural processes to reduce volume, mobility, and toxicity, which do not result in a timely reduction of VOCs in soil vapor, soil or ground water. Fate and transport and risk assessment modeling indicates that while there is no impact to the general public, workers in the vicinity of the Building 834 Complex may be exposed to potentially unacceptable inhalation risks due to volatilization of VOCs from the vadose zone into the air. Because the Building 834 Complex is located in a remote fenced facility with restricted access, worker access is also restricted. DOE/LLNL will retain institutional control over the facility. In addition, this alternative includes no response actions to reduce source contaminant mass and the potential for VOCs to migrate to the regional aquifer, 280 feet below the perched water-bearing zone. However, ground water and soil vapor monitoring would be implemented to alert LLNL of any significant VOC migration requiring a response action. This alternative is readily implementable.

5.2.3. Criteria Evaluation of Alternative 2

Alternative 2 would be protective of human health inside the buildings through the use of institutional controls, by sealing floors and cracks, and by providing building ventilation. Risk to human health and environmental protection outside of the buildings may be reduced, but not eliminated, by institutional controls, drainage diversion/paving, and soil vapor and ground water monitoring. Monitoring for VOCs would alert LLNL of any significant VOC migration requiring a response action. The long-term effectiveness depends on continued operation of the building ventilation systems, which are designed to control worker exposure to VOCs in building air. Ventilation will reduce indoor air concentrations at Buildings 834A, D, J, and O to an EPA-

accepted level (0.0363 mg/m^3) by increasing air circulation and filtering influent air. Except for the removal of LNAPLs from the four wells in the core area, Alternative 2 relies on natural processes to reduce volume, mobility, and toxicity of VOCs in the soil vapor, soil, and ground water. In the short term, there are some exposure risks associated with managing LNAPL recovery and grading the surface for drainage control. LNAPLs would be handled in compliance with ARARs. However, because there are no source mass removal actions other than LNAPL removal, Alternative 2 relies on natural attenuation for long-term effectiveness and permanence. The alternative can be easily implemented, because building ventilation, drainage control, and asphalt paving are common construction tasks.

5.2.4. Criteria Evaluation of Alternative 3

Alternative 3 provides source mass contaminant removal, and is protective of human health and the environment. Soil vapor remediation goals are protective of human health and will provide further protection of the environment through reduction of VOCs. Building ventilation will reduce indoor TCE concentrations in air to EPA-accepted risk levels.

Risk management through inhalation exposure controls (building ventilation and SVE) will provide long-term effectiveness to protect human health. However, VOC solubility limits and diffusion rates might limit the effectiveness of SVE for mass removal and its ability to reach PSVRLs (U.S. EPA, 1992). Reduction of volume, mobility, and toxicity of VOCs will be achieved through SVE and LNAPL recovery. Because dewatering is not part of this alternative, contaminants will still remain in the perched water-bearing zone.

The SVE and treatment system is conceptually designed to meet ARARs (Table 2-1) using best available technology (BAT). LNAPLs will be handled in compliance with ARARs. Alternative 3 does not remediate ground water, and there are no ground water cleanup goals (e.g., MCLs) because the perched water-bearing zone is not a drinking water source (per SWRCB Policy 88-63) and VOCs in the perched water-bearing zone have not migrated to the regional ground water (Webster-Scholten, 1994). LLNL is in the process of requesting an amendment to exclude the perched water-bearing zone from the CVRWQCB Basin Plan.

As presented in Appendix F, we anticipate reaching PSVRLs within 5 years of SVE start-up. Volatilization of VOCs from the saturated zone may impact the rate and/or permanence of vadose-zone cleanup. In the short-term, construction and operation of this alternative will have no adverse impact on the public. Workers will use protective equipment and follow safety procedures to ensure no adverse risk is encountered. Much of the system is already constructed, and it will be operated so that air emissions will meet permit requirements. The remediation system will also be designed to allow for future testing and implementation of promising innovative technologies that could be cost effective and safe, and could reduce remediation time. Alternative 3 provides for long-term effectiveness through building venting and SVE mass removal to protect human health and the environment.

Alternative 3 can be implemented easily. LLNL already has much of the system constructed and operating, and has air permits for emissions from its SVE treatment system. Other services and materials needed to complete the expanded system are readily available. The existing system consists of three soil vapor and ground water extraction wells, SVE blower, two sparging tanks, and vapor phase carbon. The ground water extraction system was tested in March 1994,

and testing of the SVE system is planned for later in 1994, per our agreement with U.S. EPA, DTSC, and the RWQCB.

5.2.5. Criteria Evaluation of Alternative 4

Alternative 4 provides source mass contaminant removal, and is protective of human health and the environment. Soil vapor remediation goals are protective of human health and will provide further protection of the environment through reduction of VOCs. Building ventilation will reduce indoor TCE concentrations in air to EPA-accepted risk levels.

Risk management through inhalation exposure controls (building ventilation and SVE) will provide long-term effectiveness to protect human health. However, VOC solubility limits and diffusion rates might limit the effectiveness of SVE for mass removal and its ability to reach PSVRLs (U.S. EPA, 1992). Dewatering is included to maximize mass VOC removal from vapor as well as reduce the mass of VOCs in the perched water-bearing zone. Reduction of volume, mobility, and toxicity of VOCs will be achieved through SVE, dewatering, and LNAPL recovery. DNAPLs may also be extracted during dewatering.

All treatment and discharge systems are conceptually designed to meet ARARs (Table 2-1) using BAT. LNAPLs will be handled in compliance with ARARs. The purpose of dewatering is to enhance SVE, not to restore ground water quality. However, VOC mass in the core area saturated zone would be reduced as a result of dewatering and SVE. As described for Alternative 3 ground water cleanup goals have not been established. Long-term effectiveness and protection of human health and the environment is provided through VOC mass removal by dewatering, SVE, and building venting.

As presented in Appendix F, we anticipate reaching PSVRLs within 5 years of SVE startup. This conservative estimate should account for SVE removal of contaminants exposed by dewatering. Alternative 4 will result in no adverse impacts on the public. Worker safety will be promoted as described in Alternative 3. As with Alternative 3, promising innovative technologies will be tested and implemented as appropriate.

Alternative 4 can be implemented easily. As described under Alternative 3, LLNL already has portions of the system constructed and is ready to operate pending regulatory approval. Other services and materials needed to complete the system are readily available.

5.2.6. Criteria Evaluation of Alternative 5

Alternative 5 provides source mass contaminant removal and plume containment, and is protective of human health and the environment. Soil vapor remediation goals are protective of human health and will provide further protection of the environment through reduction of VOCs. Building ventilation will reduce indoor TCE concentrations in air to EPA-accepted risk levels.

Risk management through inhalation exposure controls and SVE will provide long-term effectiveness to protect human health. However as described under Alternatives 3 and 4, VOC solubility limits and diffusion rates may also limit SVE effectiveness. Dewatering is included to maximize mass VOC removal in vapor. Reduction of volume, mobility, and toxicity of VOCs will be achieved through SVE, dewatering, and LNAPL recovery, and, to a limited extent, ground water extraction downgradient of the core area.

All treatment and discharge systems are conceptually designed to meet ARARs (Table 2-1) using BAT. LNAPLs will be handled in compliance with ARARs. The purpose of dewatering is to enhance SVE in the core area and reduce VOC mass in ground water, not to restore ground water quality. However, when combined with the downgradient extraction system, perched zone plume containment will occur and VOC mass and concentrations in the ground water will be reduced. Again, ground water cleanup goals have not been established.

As presented in Appendix F, we anticipate reaching SVRLs within 5 years of SVE startup. This conservative estimate allows for SVE removal of contaminants exposed by dewatering. In the short-term, construction and operation of this alternative will have no adverse impact on the public. Workers will use protective equipment and follow safety procedures to ensure no adverse risk is encountered. Much of the treatment facility is already constructed. However, connecting downgradient wells to the system requires additional design and construction. As with Alternatives 3 and 4, this alternative also allows for future testing and implementation of promising innovative technologies. Long-term effectiveness and protection of human health and the environment is provided through VOC mass removal by dewatering, SVE, and building venting.

Alternative 5 can be implemented pending the required system modifications and construction. As stated earlier, LLNL already has portions of the core area system constructed and permitted, and it is ready to operate pending agency approval. Other services and materials needed to expand the extraction system as presented in Chapter 4 are readily available.

5.2.7. Criteria Evaluation of Alternative 6

As mentioned in Chapter 4, Alternative 6 uses the same BAT systems as Alternative 3, except that Alternative 6 provides for treatability testing of innovative technologies. The innovative technologies would be implemented as the primary remediation technologies if they meet the performance criteria established in the forthcoming Interim ROD. If none of the innovative technologies meet these performance criteria, than the contingent BAT system described in Alternative 3 would be implemented, pending agreement among LLNL/DOE, RWQCB, DTSC, and EPA. All alternatives, except Alternative 5 are based on an amendment to exclude the shallow perched water-bearing zone from the CVRWQCB's Basin Plan. If the RWQCB does not accept our proposal to remove the nonpotable perched water-bearing zone from the Basin Plan, and thus requires LLNL/DOE to address it as a water-supply source, the application of the BAT system of Alternative 5 could be considered, pending discussions among DOE/LLNL, DTSC, RWQCB, and EPA.

The evaluation of Alternative 6 would therefore be very similar to that for Alternative 3, 4, or 5. The relative performance of the innovative technology will meet or exceed that of the BAT system of Alternative 3, 4, or 5, based on the nine evaluation criteria.

5.2.8. Remedial Alternative Costs

The estimated present worth of the life-cycle costs of the Building 834 Complex alternatives are shown in Table 5-2. Each alternative is costed on the basis of a design to reduce inhalation risks and provide source mass removal of contaminants of concern, to prevent emissions of VOCs to the air, and to treat wastewater to a concentration of 0.5 μg/L TCE. Comparisons of costs are presented in Figure 5-1.

The cost data summarize the cost analyses presented in Appendix G. Capital, installation, and operation and maintenance costs are itemized in the appendix, but are combined for comparison here. Assumptions upon which cost estimates are based are also discussed in Appendix G.

5.3. Comparative Evaluation of Remedial Alternatives

We have evaluated the characteristics of each alternative with respect to the first seven EPA evaluation criteria and present this evaluation in this section. The most significant distinguishing features among the alternatives are:

- Effectiveness of mass removal by the technology specified in each alternative.
- Extent of plume control and mass reduction achieved by dewatering and downgradient ground water extraction.
- Costs.

These three features have the greatest effect on the following EPA criteria:

- Overall protection of human health and environment.
- Long-term effectiveness and permanence.
- Reduction in mass and volume.
- Implementability.
- Costs.

5.3.1. Overall Protection of Human Health and the Environment

As discussed in Chapter 1 and Appendix C, both elevated health and ecological baseline risks are associated with VOC contamination in vadose-zone soil vapor between 0 and 12 feet beneath the Building 834 Complex. Therefore, the main focus in the development of remedial alternatives is to reduce the risk associated with VOC contamination in shallow soil vapor, thereby protecting human health and the environment. In addition, the alternatives are developed to reduce the potential for migration of VOCs to the regional aquifer. Alternative 1, which does not actively remediate contaminated soil vapor or ground water, is not protective of human health or the environment. Alternative 2 is only protective of human health inside the buildings by providing ventilation. It is not protective of human health or the environment outside of the buildings because it does not actively remove VOCs from the subsurface.

The goals and implementation of all the other alternatives are protective of human health and the environment. In Alternatives 3, 4, 5, and 6, overall protection of human health and the environment is addressed by SVE to remove VOCs from the vadose zone. These alternatives also use emissions control and ground water treatment before discharge. Alternative 3 uses SVE without dewatering to target only the shallow vadose zone. Alternatives 4 and 5 couple SVE with dewatering to expose a larger soil column, which may increase mass removal rates to reach remediation goals faster. Alternative 5 provides plume containment and mass removal by ground water extraction downgradient of the Building 834 Complex core source area. However, the additional mass removal of TCE by ground water extraction in Alternative 5 would provide

no significant, quantifiable health risk benefit as compared to Alternative 4 because the perched water-bearing zone has no beneficial use. Alternative 6 would be at least as protective to human health and the environment as Alternative 3, and may be more protective. The effects of the innovative technologies are difficult to predict; however, the purpose of testing and implementing them is to demonstrate technologies that are more efficient and/or more cost effective than BAT systems.

SVE with dewatering at the Building 834 core area is the one remedial action that will result in the greatest mass removal and, therefore, provide the greatest protection to human health and the environment. In addition, protection of human health will be ensured by institutional controls via ventilation improvements in Buildings 834A, D, J, and O.

5.3.2. Compliance with ARARs

ARARs affecting each remedial alternative are presented in Chapter 2 (Table 2-1). A significant factor affecting the compliance with ARARs criteria is that the perched water-bearing zone at the Building 834 Complex is not a drinking water supply per SWRCB Policy 88-63. LLNL/DOE is currently pursuing a RWQCB amendment to exclude the perched zone from the Basin Plan. Therefore, no chemical-specific ARARs are identified that require ground water remediation or the setting of ground water restoration goals. All of the remedial actions described within each alternative (e.g., LNAPL recovery and disposal, SVE, air emissions, dewatering, and ground water treatment and disposal) can be designed and implemented in compliance with ARARs.

5.3.3. Long-Term Effectiveness and Permanence

As discussed in section 5.3.1, source mass removal in the vadose zone is the primary focus of the remedial actions developed for the Building 834 Complex. The long-term effectiveness and permanence of each alternative is evaluated according to its ability to remediate the area and volumes of concern, meet PSVRLs, and reduce and control risk. For each alternative, the reliability of the processes to perform to specifications is also evaluated.

Alternative 1 (no action) does not provide long-term effectiveness in meeting PSVRLs and acceptable risks, or remediating the area of concern. Alternative 2 removes only LNAPLs from the site and relies on ventilation to reduce the human noncancer risk to acceptable levels. Long-term effectiveness of Alternative 2 relies on maintenance of the ventilation systems, particularly replacement and maintenance of filters, to ensure long-term risk reduction and control of worker exposure inside the buildings. Because this alternative does not reduce VOC mass to meet SVRLs, it is not effective for risk reduction outside of the buildings. Drainage systems to control recharge may provide long-term effectiveness in controlling the migration of VOCs to ground water.

Alternatives 3, 4, 5, and 6 provide long-term effectiveness through mass removal, which will reduce soil vapor concentrations of VOCs to PSVRLs and acceptable risk levels for outdoor exposures. Improved ventilation in Buildings 834A, D, J, and O would reduce indoor VOC concentrations that have volatilized and migrated from the subsurface, as well as their associated risks, to acceptable levels. By controlling recharge, drainage systems would provide long-term effectiveness in controlling the migration of VOCs to ground water.

SVE provides an efficient means to remove VOCs from the subsurface. The dewatering elements of Alternatives 4 and 5 will enhance mass removal from the saturated zone. Results of SVE tests at the Building 834 Complex have demonstrated that SVE can be effective in removing VOCs from the subsurface. Use of vapor-phase GAC is a reliable technology for VOC emissions control. Although regeneration facilities are available, liability issues must be addressed before carbon is sent to a facility for regeneration.

Air stripping to remove VOCs from ground water has proven long-term effectiveness. However, air strippers are less efficient in removing diesel and T-BOS dissolved in water, and therefore the treatment system may require liquid-phase carbon for polishing. The adsorption capacity of T-BOS to carbon is presently unknown and would be determined during the design phase of the project.

Application of innovative technologies for mass removal and treatment can be incorporated into any of these alternatives if, among other factors, long-term effectiveness of remediation can be enhanced. Two remedial actions that have the potential for the application of innovative technologies are DNAPL removal and treatment of vapors containing VOCs. Alternative 6 would provide long-term effectiveness through the application of innovative remediation technologies and/or the BAT remediation system of Alternative 3.

Ground water extraction, as presented in Alternative 5, would provide long-term plume control. However, it is not an effective technology for mass removal of VOCs dissolved in ground water. This is especially true when the presence of DNAPLs is likely, which may be the case in the Building 834 core area.

In summary, Alternatives 4 and 5 provide the greatest BAT long-term effectiveness by combining SVE with dewatering. Long-term containment and plume control is enhanced by downgradient ground water extraction. However, unless source mass removal of DNAPLs is achieved through SVE or application of innovative technologies, it is not likely that PSVRLs would be met in a timely manner. As a result, Alternative 6, which provides for innovative DNAPL remediation in conjunction with the BAT system of Alternative 3 (enhanced with ground water extraction as needed), provides the overall greatest long-term effectiveness.

5.3.4. Reduction of Toxicity, Mobility, and Volume

As discussed in sections 5.3.1 and 5.3.3, Alternatives 1 and 2 do not remove significant quantities of VOCs from the subsurface. Therefore, implementation of these alternatives would not reduce toxicity, mobility, and volume of the VOCs. Alternative 2 reduces the risk of worker exposure to VOCs, but does not significantly reduce the volume of VOCs in the vadose zone. LNAPLs would be skimmed, stored, handled, and disposed off site as hazardous waste, but skimming would not significantly reduce the volume of VOCs. Under Alternatives 2, 3, 4, 5, and 6 drainage control to reduce recharge would reduce the migration of vadose-zone VOCs to ground water.

Under Alternatives 3, 4, and 5, remedial actions involve removing VOCs from the vadose zone and ground water by transferring VOCs to an air stream and adsorbing them to carbon. Toxicity of VOCs will be reduced through treatment. When the carbon adsorption capacity is exhausted, the spent GAC would be regenerated off site. The regeneration process destroys VOCs and restores the adsorption capacity of carbon so that it can be reused; therefore, the

reduction of toxicity occurs during the regeneration process. As with skimming, both DNAPLs and LNAPLs that are recovered in the phase separator would be stored, handled, and disposed off site as hazardous waste.

Contaminant volume and mobility in the vadose zone and ground water will be reduced irreversibly by SVE, dewatering, plume control, and DNAPL and LNAPL recovery. The mobility and volume of TCE in the subsurface would be reduced significantly by SVE in Alternatives 3, 4, and 5 and by innovative technologies and/or SVE in Alternative 6. Under Alternative 4, dewatering in the core area would enhance VOC mass removal in the saturated zone by SVE, as well as control mobility, volume, and mass in ground water. Similarly, remedial actions in Alternative 5 for downgradient plume control would further reduce mobility, volume, and mass of contaminated ground water. Other remedial actions (i.e., innovative technologies) will be considered after the BAT system is installed to increase our ability to remove DNAPLs and thus significantly reduce contaminant mobility and volume. Alternative 6 would reduce the mobility, volume, and mass of VOCs in the vadose zone and saturated zone by first applying innovative technologies and supplementing them with BAT as needed. A number of the innovative technologies to be tested under Alternative 6 are designed to address remediation of DNAPL and LNAPL contamination.

5.3.5. Short-Term Effectiveness

Due to the remoteness of the site and the distance between the perched water-bearing zone and the regional aquifer, remedial actions under each alternative would have minimal impact on the public during construction and the subsequent operation of the remedial systems. A health and safety plan will be developed prior to implementation of the selected remedial action.

The construction phases of the remedial activities, particularly drainage control and the ventilation improvements proposed in all alternatives except for Alternative 1, could disrupt access to and ongoing activities at the Building 834 Complex. Remedial activities would be coordinated with the Building 834 facilities manager to mitigate risk and minimize disruption. In Alternatives 3, 4, 5, and 6, risks to workers associated with drilling new wells would be minimized, since most of the extraction wells either are already installed or would be converted from monitoring wells.

Potential exposure to DNAPLs increases as additional remedial actions are incorporated into each alternative. During implementation of each alternative, workers could be exposed to both DNAPLs and LNAPLs during monitoring. Potential exposure to LNAPLs occurs with the diesel and T-BOS skimming proposed in Alternative 2. Under Alternatives 3, 4, 5, and 6, workers could be exposed to VOCs, DNAPLs, and LNAPLs while wells are being drilled and during operation of the treatment facilities. Workers will follow Site 300 operation procedures, and will use personal protective equipment and clothing to mitigate potential risks.

Discharge of treated ground water by air misting is an effective disposal method in a remote area where annual evaporation rates are higher than rainfall and discharge to surface water or sanitary sewers is not feasible. While the objective of air misting is evaporation of water before it reaches the ground, some misted water may reach the ground surface during some discharges. The air misting system was designed so that misted water would reach the ground at an application rate that would not impact slope stability or recharge ground water. However, in the event that misting is occurring during a rainstorm, some discharge water vapor would commingle

with rain and infiltrate the subsurface. Because the discharge water is treated to discharge permit standards prior to misting, there will be no adverse effects due to this infiltration. In addition, the misting system is located northeast of the core area and outside of the perimeter of the perched water-bearing zone. Misted water reaching the ground surface may provide adequate water to sustain some plant growth, but we believe it would not be enough to create a wetland.

As presented in Appendix F, we estimate that human health and environmental protection will be achieved within 5 years of SVE startup for Alternatives 3, 4, 5, and 6.

5.3.6. Implementability

Each of the alternatives can be implemented. However, implementation becomes more complicated with each additional remedial action. Alternative 1 can be implemented easily with slight modification to the existing ground water monitoring program. Alternative 2 can be implemented using standard design and construction techniques and materials to modify building ventilation and surface drainage. Passive skimmers for LNAPL recovery are readily available, and LLNL has facilities to properly handle recovered LNAPLs as hazardous waste. As in Alternative 1, the existing monitoring program would be modified slightly.

The treatment technologies incorporated into Alternatives 3, 4, and 5 are BAT for VOCs in soil vapor and ground water, and they are readily available. However, implementation becomes more complicated because these alternatives involve construction and long-term operation of remediation facilities, in addition to the drainage control and ventilation projects. Major elements of the remediation system are in place already, and the selected technologies, including SVE, phase separation, air stripping, and vapor-phase GAC, are commercially available BAT.

The full-scale implementation of innovative technologies requires treatability testing to determine the efficiency and cost effectiveness of the technology. As a result of their various stages of development, some innovative technologies may be more easily implemented than others. However, the purpose the Alternative 6 treatability testing of innovative technologies is to identify a better remediation technology, rather than simply apply a BAT system that may not be capable of adequately addressing the source area LNAPL and DNAPL contamination. Treatability testing may show that some innovative technologies can be more easily implemented than current BAT systems.

LLNL has the technical resources and experience to implement each of these alternatives.

5.3.7. Cost

The estimated present worth of the life-cycle costs for the Building 834 alternatives range from $4.19 million to $16.45 million. Costs are summarized and compared in Table 5-2, Figure 5-1, and Figure G-5 (Appendix G). Capital, operation and maintenance, and monitoring costs were developed for each alternative and subtotaled. Present-worth costs for each alternative have been estimated to an accuracy of +50 and –30 percent in accordance with U.S. EPA (1987) guidance.

The costs for each alternative were developed on the basis of engineering designs to reduce inhalation risks and provide source mass removal of VOCs, diesel, and T-BOS. The more complex Alternatives 3, 4, 5, and 6 include remedial actions requiring treatment of extracted air and ground water. Cost estimates do not include implementation, operation, or maintenance of

innovative technologies. Detailed cost and design assumptions regarding labor, equipment, construction, project and construction management, operations and maintenance, and monitoring are presented in Appendix G.

Significant differences in the costs of the alternatives are due to major differences in the alternatives listed below. Compared to the other alternatives:

- Alternative 1 has a low cost because it includes only monitoring and no remedial actions.
- Alternative 2 has a moderate cost because it includes capital construction projects (drainage controls and ventilation retrofits) and ground water monitoring, but no remediation by long-term extraction and treatment.
- Alternatives 3 and 4 have high costs because both alternatives include the capital construction projects, as well as ground water monitoring and remediation treatment with an estimated duration of five years. The dewatering and ground water treatment in Alternative 4 adds cost, so estimated total costs for that alternative are greater than for Alternative 3.
- Alternative 5 estimated total costs are the highest, because we assumed the duration of ground water extraction is 30 years, compared to 5 years for Alternatives 3 and 4. In addition, the alternative includes a second ground water extraction and treatment system.
- Alternative 6 estimated total costs are expected to be similar to the estimated costs associated with Alternatives 3, 4, and/or 5. The costs associated with the treatability testing and implementation of innovative technologies are variable and uncertain. As a result, these costs have not been included in the total present-worth costs of Alternatives 3, 4, 5, and 6.

6. Environmental Considerations

6.1. Introduction

LLNL proposes several alternatives to reduce contaminant levels in soil and ground water in the Building 834 Complex to below concentrations that would pose a risk to human health or the environment. Contaminants that would be removed from soil and ground water consist primarily of TCE and LNAPLs (diesel and T-BOS). The six proposed remedial action alternatives include source mass removal by soil vapor extraction, dewatering the perched water-bearing zone at the Building 834 Complex core area, plume control at the septic system release site and the W-834-T2 and -T4 well clusters, and treatment and discharge of extracted soil vapor and ground water. Treated water would be released to two proposed discharge points located on site within the Building 834 operable unit. The proposed alternatives also include testing a combination of innovative technologies that may result in more efficient, more rapid, or more cost-effective remediation than conventional technologies under the conditions at Site 300.

The Record of Decision, issued on January 21, 1993, for the August 1992 *Final Environmental Impact Statement and Environmental Impact Report for Continued Operation of Lawrence Livermore National Laboratory and Sandia National Laboratories, Livermore* (U.S. DOE, 1992) published DOE's decision to continue operation of LLNL, including near-term (within 5 to 10 years) proposed projects. One of the proposed actions described in the 1992 EIS/EIR is the remediation of soil and ground water contamination at Site 300. In compliance with the requirements of the DOE National Environmental Policy Act (NEPA) Implementing Procedures (10 CFR 1021) and the Council of Environmental Quality (CEQ) Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act (40 CFR 1500–1508, July 1986, as amended), this chapter further evaluates the potential for environmental impacts from each remedial alternative evaluated for the Building 834 Complex.

In response to U.S. DOE Order 5400.4, issued October 6, 1989, this chapter integrates the requirements of NEPA with those of CERCLA. According to the DOE order, integration is to be accomplished by conducting the NEPA and CERCLA environmental planning and review procedures concurrently to avoid duplication, conflicting analysis, and delays in implementing remedial action on procedural grounds.

This chapter does not present all information that would normally be associated with a stand-alone environmental assessment. As stated in the *Federal Register*, Vol. 55, No. 67 (April 1990), where DOE remedial actions under CERCLA trigger the procedures set forth in NEPA, the procedural and documentation requirements of NEPA and CERCLA are to be integrated. The primary instrument for this integration is the RI/FS process, supplemented as needed to meet the requirements of NEPA. Therefore, not all the site descriptions needed to assess the impacts of the proposed action and alternatives are included in this chapter alone. Instead, some of the evaluations in this chapter are based on the descriptions and information presented in other chapters of this FS as well as information presented in the SWRI report. These descriptions are supplemented in this chapter, where necessary, to provide the necessary framework for the

assessment of environmental impacts so that the requirements of the DOE and CEQ regulations implementing NEPA can be met.

6.2. Purpose of and Need for the Proposed Project

The Building 834 operable unit consists of about 55 acres in the southeast portion of Site 300. The Building 834 operable unit encompasses buildings numbered 834 A, B, C, D, E, F, G, H, J, K, L, M, and O. The buildings were constructed primarily in the mid-1950s and early 1960s and have been used mainly for the mechanical and thermal testing of weapons components. Between 1962 and 1978, based on employee interviews, an aggregate of about 550 gallons of TCE was estimated to have been released in the vicinity of the Building 834 Complex from leaking pipes and valves and from other surface releases. Chemical releases have been confirmed at ten sites. Pump station Buildings 834B, C, D, test cell 834J, and the former septic system leach field have been identified as the areas where the greatest aggregate releases occurred. The accidental overfilling of an underground diesel tank in the Building 834 Complex has been identified as the source of diesel fuel detected in ground water. Other contaminants identified in soil and ground water include PCE, T-BOS ethylbenzene, Freon 11, xylene, benzene, and toluene.

Since 1982, LLNL has conducted investigations of potential chemical contamination of soil and ground water at Site 300. In August 1990, Site 300 was placed on the NPL as a result of prior releases of VOCs. Since then, all investigations at Site 300 have been conducted in accordance with the 1980 CERCLA. DOE, the U.S. EPA, DTSC, and the California RWQCB entered into an Federal Facility Agreement on June 29, 1992, to coordinate efforts, standardize requirements, and ensure compliance.

Since 1978, facilities in the Building 834 Complex have been upgraded to minimize the possibility of further chemical releases. These upgrades have included sealing floor drains that lead to the septic tank and leach field, removing or replacing mechanical equipment, installing secondary containment around storage tanks, and relocating cooling tower and septic system leach lines. In September 1993, 2,465 gallons of TCE were removed from the TCE system as part of dismantling the system. The remainder of the TCE system was entirely dismantled in May 1994. Starting in 1983, remedial actions have also been taken to remove VOCs from the subsurface. These activities have included the excavation and aeration of about 100 yd^3 of soil containing VOCs; also, soil vapor and ground water extraction and treatment have been conducted. The effectiveness of electron accelerator and ultraviolet flash lamp innovative technologies to destroy VOCs in extracted soil vapor has also been tested (Appendix D).

The purpose of the proposed remedial action for the Building 834 Complex is to reduce contaminant levels in soil in the Building 834 Complex to below concentrations that would pose a risk to human health. To determine the best way to meet this objective, a range of general response actions and remedial action technologies is evaluated in this FS for applicability to site conditions at the Building 834 Complex.

6.3. Relationship of the Proposed Remedial Alternatives to Other Activities at LLNL

The proposed remedial efforts are part of a larger effort by LLNL to mitigate contamination caused by activities at Site 300. At present, five RI/FS actions are being conducted at Site 300 in addition to those at the Building 834 operable unit. Specifically, these actions concern the Building 833 Area, the East and West Firing Areas, the HE Process Area, the Pit 6 Area, and the General Services Area (GSA) (Fig. 1-3).

6.4. LLNL Site 300 Environmental Setting and Potentially Affected Environment

Descriptions of the geology, hydrology, and other aspects of the natural environment are presented in Chapter 1. The descriptions presented below are those that may be needed to assess impacts as required under NEPA and that have not been presented in other sections of this FS. A more detailed description of the Site 300 environment can be found in the site-wide EIS/EIR (U.S. DOE, 1992), and the Draft SWRI report (Webster-Scholten, 1994).

6.4.1. Location

Site 300 is located approximately 15 miles southeast of the city of Livermore in the Altamont Hills and straddles the border between Alameda and San Joaquin County (Fig. 1-1). The topography at Site 300 consists of southeasterly-trending ridges and canyons of moderate-to-high relief that vary in elevation from slightly more than 152 meters (500 feet) at the entrance to the site on Corral Hollow Creek, to over 518 meters (1,700 feet) at the highest point, in the northwest corner of the site. The on-site drainage pattern is well developed. Occasional runoff collects in several small, normally dry arroyos that lead directly off site to Corral Hollow Creek, located adjacent to the southern boundary of the site, and in Elk Ravine, a larger normally dry on-site canyon that drains into Corral Hollow Creek approximately 0.8 kilometers (0.5 miles) downstream from the Site 300 property line.

The Building 834 Complex is located on a hilltop in the eastern part of Site 300 (Fig. 1-3). Steep hillsides and gullies slope away from the complex to the north, southwest, and southeast. Man-made earth berms form small, steep hills immediately adjacent to the buildings of the complex. Much of the area surrounding the buildings is paved with asphalt.

6.4.2. Land Use and Socioeconomics

The Building 834 operable unit consists of approximately 55 acres located entirely within San Joaquin County along the southeast boundary of Site 300. San Joaquin County is a leading agricultural county, with associated industries for food processing, wholesale trade, and transportation. Important nonagricultural employers include educational institutions, federal defense installations, and related service industries. Major transportation networks and facilities in the county include interstate and local highways, several major rail carriers, the Stockton Metropolitan Airport, and the Port of Stockton. Industrial activities are allowed if they are compatible with the County's applicable criteria for industrial land use.

Most of the area surrounding Site 300 is ranch land, privately held in parcels of section size (640 acres), although land immediately adjacent to Corral Hollow Road in the vicinity of Site 300 is generally held in smaller parcels ranging in size from five to 640 acres. The San Joaquin County General Plan has four designations for land use in the Site 300 area. The portion of Site 300 located in San Joaquin County is designated "Public and Quasi-Public—Other Governmental and Institutional." Areas north and east of Site 300 are designated "Agricultural." Areas south of Site 300 are designated "Recreation" or "Conservation."

LLNL operations at Site 300 are consistent with the San Joaquin County General Plan land use designations (U.S. DOE, 1992). Although there is no prime agricultural land at Site 300 or immediately adjacent to it, surrounding land is used primarily for cattle grazing. Much of the land adjacent to the Site 300 southern boundary is part of the Connolly and Gallo Ranches. Along the eastern site boundary is a 15-acre ecological preserve operated by the California Department of Fish and Game. The preserve was formerly part of Site 300, but, with the exception of seven acres, was declared excess property in 1973 and transferred to the State of California. The California Department of Forestry (CDF) leases a small portion of the Connolly ranch located about 2,500 feet southeast of the main entrance to Site 300. The CDF Castle Rock Fire Station is located on this property. Physics International and SRI International also test high explosives on holdings near the site. The State of California operates the 1,300-acre Carnegie State Vehicular Recreation Area (CSVRA) located along the southwest side of Site 300 on Corral Hollow Road.

A Draft Environmental Impact Report (DEIR) has been prepared for the proposed City of Tracy Urban Management Plan/General Plan. The Tracy Planning Area (TPA) encompassed by the Plan would "build out" to a population of 160,000 by the year 2013. Under the proposed Plan's land use map, Site 300 would be designated as "Federal Reserve/Open Space." Site 300 operations would be consistent with this land use designation, if adopted. Under the Plan's proposed action, the City of Tracy also proposes to designate land adjoining the east portion of the Site 300 north border and the northern portion of the Site 300 east border as "Residential—Very Low (Density)" or "Open Space" and, together with its commercial and industrial elements, would have a projected population of 23,000 by the year 2013. This area, bounded by Site 300 on the southwest side and extending beyond Highway 5 to the northeast, is the location of the proposed Tracy Hills Community Area/Urban Center, which would consist of developed areas with two dwelling units per gross acre or less, and open space. All of the alternatives proposed in the DEIR would allow residential development on land adjacent to the northern and eastern boundaries of Site 300, with the exception of the "Reduced Intensity Alternative." Under this latter alternative, land immediately bordering Site 300 would be designated as "Agricultural," and residential development would be restricted to areas further to the east of Site 300.

An important factor in land use in San Joaquin County is the availability of suitable water supplies. Ground water accounts for 30 percent of all San Joaquin County's water needs (San Joaquin County, 1992). The Tracy area has three major water sources: the Delta-Mendota Canal, the California Aqueduct, and San Joaquin Valley ground water aquifers. The Delta-Mendota Canal and the California Aqueduct are operated by the U.S. Bureau of Reclamation and the State Department of Water Resources, respectively.

The population of San Joaquin County increased by 18.6 percent between 1985 and 1990, to a total population of 480,628. In 1989, San Joaquin had a total employed labor force of 181,000.

The annual workforce at Site 300 averages about 300 people, with temporary increases during construction projects. Most of the Site 300 workforce is based within the GSA, where about 150 employees are currently assigned.

6.4.3. Surface Water and Shallow Ground Water

Drainage at Site 300 remains primarily in its natural state; drainages are mainly located in steep-walled canyons, and they do not have well-developed floodplains or terraces. Erosion results from both natural conditions and those resulting from human use of the site. Several normally dry arroyos may occasionally have flow at Site 300 for brief periods of time during exceptionally wet winter months, with discharge into Corral Hollow Creek at the southern boundary of the Site 300. Flow may be direct runoff, with a contribution from both intermittent or perennial springs or man-made sources. Figure 1-9 is a drainage map of Site 300.

Minor surface water runoff is observed in ditches and gullies at the Building 834 Complex only after heavy rains. Natural surface flow is limited to that which gathers in man-made ditches and flows toward the drainage ditches along Linac Road to normally dry arroyos. Figure 1-25 is a drainage map of the Building 834 Complex. Based on surface runoff sampling of surface drainages, it has been determined that released chemicals at the site have not affected surface water.

Ground water used for operations at Site 300 is pumped from production wells in the HE Process Area study area, west of the GSA. There are no water-supply wells in the Building 834 operable unit.

Hydrogeologic conditions, including low precipitation, limited recharge, active evapotranspiration, and barriers to downward ground water flow, have restricted the vertical and lateral migration of chemicals released at the Building 834 Complex. The TCE ground water plume is contained within a shallow perched water-bearing zone that is 300 to 600 feet wide, and predominantly less than 5 feet thick, and extends only about 1,400 feet south-southwest of the core of the Building 834 Complex. Chemicals released into soil and rock have almost exclusively been contained within 80 feet of the ground surface; most contaminants occur at the core of the complex at depths of 40 feet or less. TCE concentrations within much of the ground water plume range from 10,000 µg/L to a recorded high of 800,000 µg/L (February 9, 1993, well W-834-D3). The highest concentrations of TCE in soil occur within a lateral area of about 0.008 mi^2 at the core of the complex.

The ground water in the perched water-bearing zone and perching horizon at the Building 834 Complex is not considered suitable or potentially suitable as a municipal or domestic water supply under SWRCB Resolution 88-63, because pumping enhanced by vacuum extraction produces only about 100 gpd or less, from a single well. Ground water from the perched water-bearing zone and perching horizon has not been used as a source of drinking water for humans or livestock or for irrigation.

There is one intermittent spring in the Building 834 operable unit, identified as spring 19. Spring 19 is located about 1,200 feet southeast of the center of the Building 834 Complex and may be receiving its recharge from intermittent infiltration to the easternmost ridge in the Building 834 operable unit. Samples from soils at the spring indicate that contamination in the Building 834 area has not migrated to the spring location.

6.4.4. Floodplains and Wetlands

The Building 834 Complex is located on top of a ridge. The locations of the proposed treatment facilities and the release areas are not within an identified floodplain.

Wetlands at Site 300 were mapped during 1991 using the unified federal method (Federal Interagency Committee for Wetland Delineation, 1989), and a total of 6.76 acres of wetlands were identified (U.S. DOE, 1992). These wetlands are small and are in areas associated with natural springs or runoff from four on-site building complexes. Most wetlands (totaling 4.58 acres) occur at springs in the bottom of deeper canyons in the southern half of the site. Other wetlands (totaling 1.88 acres) were formed from building runoff. The only non-spring-fed natural wetland observed on site is a 0.32-acre vernal pool in the northwest section of Site 300. Spring 19 does not produce enough water to result in surface flow or to support riparian vegetation. The only potential wetland area in the operable unit is at the Building 834 cooling tower discharge point, about 900 feet west of the center of the Building 834 Complex.

6.4.5. Vegetation, Wildlife, and Sensitive Species

Four major vegetation types are found at Site 300. They are: (1) introduced grassland, (2) native grassland, (3) coastal sage scrub, and (4) oak woodland (Taylor and Davilla, 1986). Most of the vegetation at Site 300 is grassland dominated by mixtures of introduced annual and native perennial grasses. Ongoing practices at Site 300 are considered to benefit site vegetation. These practices include the exclusion of grazing and other agricultural uses and the annual burning of approximately 2,000 acres in the northern and eastern portions of Site 300. Vegetation at the proposed treatment facilities and discharge points consists primarily of annual grasses, although native perennial grasses may be found in less disturbed areas. One of the proposed discharge points is located in the area at Site 300 that is burned annually.

A detailed, systematic survey for populations of rare and endangered plants was conducted at Site 300 in the spring of 1986 (Taylor and Davilla, 1986); an additional survey was conducted in 1991 in support of the 1992 EIS/EIR (U.S. DOE, 1992). No rare or endangered plants were found in the Building 834 area. The only sensitive plant species known to occur at Site 300 is the large-flowered fiddleneck (*Amsinckia grandiflora*), which is categorized as endangered by the state and federal governments. This species has been identified in two locations at Site 300 neither of which is near the Building 834 Complex. Approximately 160 acres at one location has been designated a critical habitat for the large-flowered fiddleneck. This larger population is protected through fencing, and the area surrounding this enclosure is also protected and is accessible only with prior approval from the Site 300 Resident Manager. The second location is in a remote western area of the site and is extremely difficult to access. Both areas are further protected through implementation of U.S. Fish and Wildlife Service-approved management plans that include limited access, and workforce and visitor orientation programs. Off site, an introduced population of *Amsinckia grandiflora* now occurs in the southern end of the preserve adjacent to the Site 300 boundary (Pavlik, 1992), as well as on the Connolly Ranch.

The wildlife at Site 300 strongly reflects the dominance of grasslands. A total of 116 species of wildlife were observed at Site 300 during field surveys performed in 1991 in support of the 1992 EIS/EIR (U.S. DOE, 1992). The results indicated the presence of 26 species of mammals, 70 species of birds, and 20 species of reptiles and amphibians (U.S. DOE, 1992). Representative

species observed in the undeveloped grassland areas include the fence lizard, black-tailed hare, California ground squirrel, red fox, western meadowlark, and turkey vulture. Nesting birds include the American crow, American robin, house finch, mockingbird, and house sparrow; these species live in the planted trees on site.

The American badger (designated a species of special concern by the state) was the only special-status mammalian species observed at Site 300 in 1991 (U.S. DOE, 1992). The American badger was observed in the more rolling terrain in the northern portions of Site 300. The San Joaquin pocket mouse, observed at Site 300 during both 1986 and 1991 surveys, is no longer considered a federal candidate species.

Site 300 is located in the extreme northern portion of the range of the San Joaquin kit fox (designated as an endangered species by the federal government, and as a threatened species by the state). Detailed surveys for the kit fox were conducted at Site 300 in 1980 (Rhoads et al., 1981), 1986 (Orloff, 1986), 1990 (BioSystems, 1990b), and 1991 (U.S. DOE, 1992). Neither the kit fox nor active dens were observed at Site 300 during any of these surveys; however, three possible kit fox scats and one possible track were observed on site in 1991. At present, the kit fox is not considered a resident species at Site 300, although this area is potential habitat.

The valley elderberry longhorn beetle is the only insect presently designated as threatened by the federal government that could exist at Site 300; however, no elderberry longhorn beetles were observed during the 1991 survey (U.S. DOE, 1992). This species is found almost exclusively on elderberry bushes and, since several groups of elderberry bushes are present on site, Site 300 is considered potential habitat. No elderberry bushes were found near the Building 834 Complex.

Four species of fairy shrimp (federal candidate species) could exist at Site 300 (U.S. DOE, 1992). However, none of these species were observed during sampling of water and soil in the most appropriate areas of Site 300 during 1991. The California tiger salamander and red-legged frog (both federal candidate and state species of special concern) were observed at Site 300 during 1986 surveys (Orloff, 1986). These species were not observed on site during 1991 surveys, except for red-legged frog tadpoles in the Site 300 sewage pond (U.S. DOE, 1992).

The Alameda whipsnake (federal candidate species and designated by the state as threatened) was observed on site in 1986 (Orloff, 1986). This species was not observed at Site 300 in 1991, although the closely related California whipsnake was recorded in two locations in 1991 (U.S. DOE, 1992). Potential habitat for the whipsnake subspecies is most commonly considered to be chaparral brush, broken by grassy patches and rocky gullies, or stream courses with scattered trees and shrubs (Orloff, 1986). The California horned lizard (state species of special concern) was observed during the 1991 field surveys (U.S. DOE, 1992). This species was observed in the more open grasslands with sandy or gravely areas at the northern portion of the site.

The golden eagle and burrowing owl (both state species of special concern) were the only special-status bird species observed during the 1991 surveys (U.S. DOE, 1992). Immature and adult golden eagles were observed frequently at Site 300, soaring and feeding mostly in the rolling terrain in the northern segment of the site. All cliffs and other appropriate areas were searched for golden eagle nests, and none were observed. In 1986, the burrowing owl was a relatively common nesting species at Site 300, especially in the more gently rolling terrain in the

north (Orloff, 1986). Surveys in 1991 confirmed that this species is still nesting at Site 300, but at reduced levels. The tricolored blackbird (federal candidate species) was observed nesting in cattail at two locations at Site 300 in 1986 (Orloff, 1986); this species was not observed at Site 300 in 1991 (U.S. DOE, 1992).

6.4.6. Climate and Air Quality

The climate at Site 300 is characterized by warm, dry summers and mild winters. Precipitation is generally a product of cyclonic storms in the winter and, occasionally, thunderstorms in the summer. The average annual rainfall at Site 300 is about 11 inches. Fog from the San Joaquin Valley occasionally reaches the site during December and January. Summer sea breezes often develop in the afternoons as marine air moves eastward through Corral Hollow. The marine stratus layer that extends inland from the Pacific Ocean during summer and fall does not usually reach Site 300. Winds are predominantly from the west and northwest.

The California Air Resources Board conducts criteria pollutant monitoring in the San Joaquin Valley Air Basin to determine the area's ambient air quality and to determine the area's compliance with federal and state ambient air quality standards. When an area meets compliance standards, it is classified as an "attainment" area under federal law. The entire San Joaquin Valley Air Basin, including Site 300, is designated as an attainment area for all criteria pollutants except ozone (O_3) and particulate matter less than 10 microns in size (PM_{10}). Elevated levels of O_3 and PM_{10} are a result of transport from urban areas, mobile source emissions, and agricultural activities. Ambient air quality at Site 300 is very good because of the region's sparse population and limited industrial and commercial development.

6.4.7. Cultural and Historical Resources

Archaeological evidence indicates that the Central California area has been inhabited since 9,000 B.C. Although little is known about the earliest prehistoric peoples, the Site 300 area is within the ethnohistoric tribal boundaries of two California Native American groups: the Costanoans (Ohlone) and the Northern Valley Yokuts. Current sentiment holds that the area was probably used sporadically by both tribes for marginal hunting and gathering. During the Hispanic and American historic periods (ca. 1750–1930), grazing and coal and clay mining were established in Corral Hollow Canyon. Three company towns were built in the canyon to support the coal and clay mines and factories. Portions of the largest town, Carnegie (population 2,500), were located inside the southern boundary of Site 300 and south of Corral Hollow Road. By 1912, Carnegie was abandoned and, shortly after, completely dismantled. By 1919, only mine tailings, plant foundations, dredging mounds, and miscellaneous depressions marked the industrial past of Corral Hollow Canyon.

Section 106 of the National Historic Preservation Act (NHPA) identifies an area of potential effect (APE) as the area in which planned development may directly or indirectly affect a cultural resource. The APE at Site 300 is identified in the 1992 EIS/EIR (U.S. DOE, 1992) and includes the Building 834 Complex.

In 1981, sample areas of Site 300 were surveyed for cultural resources resulting in the location of 24 archaeological sites: 3 prehistoric, 20 historic, and 1 multicomponent site. A background literature search indicates that none of the previously recorded sites are located

within the vicinity of the Building 834 proposed project area. From the report, however, it is unclear whether this area was surveyed during the 1981 investigation. Consequently, on August 19 and September 22, 1993, archaeological field surveys were conducted to determine whether eligible historic properties exist within the project boundary. No cultural resources were located.

6.4.8. Noise and Traffic

The background noise at Site 300 is primarily from wind and vehicle traffic on Corral Hollow Road. Away from structures, wind noise levels may range from 70 to 80 decibels (dB), with gusts on ridgetops up to 90 dB (U.S. DOE, 1992). Detonations of explosives during experiments at firing tables at Site 300 can cause instantaneous short-term peak impulse noise level increases, occasionally to levels near 126 dB (Kang and Kleiber, 1993). Other noise sources include Interstate 580 (I-580); the Tracy Airport; the explosives testing at Physics International, Inc. and SRI International; traffic on Corral Hollow Road; and offroad vehicles operating in the CSVRA.

Site 300 lies 18 road miles from the LLNL Livermore site and ten road miles from central Tracy. The only access to Site 300 is from Corral Hollow Road, on the southern boundary of the site. I-580 lies to the north and east of the site. Patterson Pass Road is located near the northern edge of Site 300, but provides no access to the site. The primary access routes in the area are Corral Hollow Road from either the Livermore Valley or from I-580 and Tracy. Approximately 32 percent of the Site 300 workers reside in Tracy. Because there are only about 300 employees at Site 300, the various street segments traveled by Site 300 commuters are virtually free of traffic congestion. Traffic counts on Corral Hollow Road indicate that of the 325 average daily trips, approximately two-thirds are to or from Site 300 (LLNL, 1988). Traffic density on Corral Hollow Road will undoubtedly increase if the Tracy Hills Community Area/Urban Center matures to 23,000 population.

6.4.9. Aesthetics

Site 300 is predominantly hilly grassland, with some blue oak trees, coastal sage scrub, and rock outcrops. Paved roads link the widely scattered facilities. The Building 834 Complex is not visible from any public road or from publicly held lands.

Annual controlled burning of grass at Site 300 impacts the aesthetic quality of portions of the site. However, those portions of Site 300 that are burned are only partially visible from Corral Hollow Road, or Site 300's northern and eastern boundaries. Furthermore, many other landowners in the area also conduct controlled burning on their property to prevent wildfires during the summer, when weather conditions create extreme fire hazards. The controlled burns at Site 300 are essential to prevent uncontrollable burns that could result from explosives testing. In addition, the controlled burns are thought to be the primary cause for the occurrence of native perennial bunch grass communities at Site 300; these communities are very rare throughout California (Taylor and Davilla, 1986).

6.5. Potential Environmental Impacts of the Remedial Alternatives

This section describes the potential environmental impacts of the six remedial alternatives presented in Chapter 4. Due to the technical similarities among Alternatives 4, 5, and 6, the impacts and evaluation of Alternatives 4 and 5 are deemed representative of Alternative 6. An independent assessment of Alternative 6 therefore has not been presented separately.

6.5.1. Alternative 1

Under this alternative, no action would be taken to remove contaminants in soil and ground water beneath the Building 834 Complex. Site 300 would continue to be a restricted-access federal facility for the foreseeable future, and public access to the Building 834 area would be prohibited. A detailed description of this alternative is presented in Chapter 4. Consideration of Alternative 1 serves as a basis from which to evaluate proactive remediation alternatives, as well as the postulated basis of the baseline public health evaluation. Consideration of the "no action" alternative is required by CEQ NEPA regulations.

Other than the procedures required for the safe operation and maintenance of the Building 834 Complex equipment, the only physical activity required under Alternative 1 is the destruction of two wells, installation of three wells, installation of ten dedicated soil vapor monitoring points, sampling of the ground water monitoring wells and dedicated soil vapor monitoring points, and the maintenance of wells and pumps. Those areas of the environment that could be impacted by implementing Alternative 1 are discussed below.

6.5.1.1. Human Health

Three sets of calculations of exposure, risk, and hazard related to subsurface soil contamination in this operable unit (described in the SWRI report and in Appendix C of this document) were completed. These calculations pertain to potential adult on-site exposure both inside and outside of Building 834D, and inside of Building 834O. The calculations yielded unacceptable levels of risk and hazard. The cancer risk is the total chemical-specific individual lifetime risk, above background, of developing cancer. The National Contingency Plan (40 CFR 300) indicates that excess cancer risks greater than 10^{-4} are unacceptable, while excess cancer risks less than or equal to 10^{-6} are generally acceptable. The noncancer hazard is estimated by comparing the chronic daily intake of contaminant from all exposure pathways with established reference doses. U.S. EPA (1989) indicates that a hazard index (HI) greater than 1.0 may be associated with noncarcinogenic adverse health effects. The adult on-site exposure scenario is based on the assumption that an adult employee of LLNL will spend their entire career (25 years) working in the building or area of interest on a regular (i.e., daily) basis.

For exposure outside of Building 834D, the incremental excess cancer risk was calculated to be 6×10^{-4}; the HI was 22. Exposure inside Building 834D was associated with a cancer risk of 1×10^{-3} and an HI of 36. For exposure inside Building 834O, a cancer risk of 2×10^{-3} was calculated, with an HI of 62. The three estimates of cancer risk associated with potential adult on-site exposure in this operable unit indicate that if exposure were to occur on a regular basis, each of the three scenarios is associated with an unacceptable risk of cancer. Similarly, each HI is greater than 1.0, thus indicating a potential for the occurrence of adverse, noncancer health

effects. Because no remediation of contaminated subsurface soil is proposed for this alternative, the potential cancer risks and hazards calculated for the baseline case would remain unchanged.

6.5.1.2. Ground Water

Mechanical systems and equipment in the Building 834 Complex have been upgraded and changes have been made in operational procedures to prevent releases of chemicals, and on September 30, 1993, 2,465 gallons of TCE was removed from the TCE-brine system as part of dismantling procedures (Smith, 1993). As of May 31, 1994, the entire TCE transfer system had been dismantled. Under the no action alternative, therefore, additional releases of chemicals in the Building 834 Complex are not anticipated. Sampling activities and water-level measurements would not have the potential to introduce additional contaminants to soils or ground water.

Ground water contamination in the Building 834 Complex is confined to the shallow perched water-bearing zone. The lateral migration of ground water contaminants is limited by topography and the outcropping of the perched water-bearing zone. The potential for downward migration is limited due to a sequence of low conductivity siltstone and claystone layers. The results of modeling calculations presented in the SWRI report show that the maximum 70-year average modeled TCE concentration to reach the regional aquifer is 10^{-4} µg/L, far below the federal MCL for TCE (5 µg/L). The no action alternative would not, therefore, result in the migration of contaminants laterally off site, or downward into the regional aquifer in concentrations above the federal MCL.

Monitoring that would be conducted under this alternative would include the monitoring of contaminant concentrations in the ground water plume, and the direction and rate of ground water flow. It is assumed that contaminant levels in the migrating plume should be reduced over time through dilution and by natural attenuation processes such as biodegradation, dispersion, evapotranspiration, and abiotic degradation. Although, no biodegradation rates have been calculated, concentrations of 1,2-DCE have increased while concentrations of TCE have decreased in several of the highly contaminated wells at the core of the complex. Water samples obtained during monitoring activities under this alternative would be analyzed to assess the reduction in contaminant levels due to natural processes.

6.5.1.3. Soil and Soil Vapor

Under this alternative, the concentrations of contaminants would likely decrease over time due to the natural attenuation process discussed in section 6.5.1.2. As with ground water, soil vapor would be sampled periodically under this alternative to assess the reduction in contaminant levels due to natural processes.

6.5.1.4. Vegetation, Wildlife, and Sensitive Species

Populations of the endangered plant species, *Amsinckia grandiflora*, occur in four locations at or near Site 300: in Draney Canyon, in Droptower Canyon, within the California Department of Fish and Game ecological preserve, and on the Connolly property. None occur near the Building 834 Complex. Kit fox are not considered to be a resident species at Site 300 at this time. American badger have not been identified in the Building 834 Complex (U.S. DOE, 1992).

An evaluation of the environmental risk associated with historic chemical releases in the Building 834 Complex area was presented in the SWRI report. The evaluation describes the transport and fate of the chemicals released in the Building 834 Complex and determines the potential routes of chemical exposure to flora and fauna (including sensitive species) in the Building 834 Complex area. For this evaluation, the abundance of the California ground squirrel and black-tailed deer, and the reproductive potential and life span of individual San Joaquin kit fox were selected as ecological assessment endpoints. To estimate potential hazards from exposure to contaminants of potential concern, HIs and toxicity quotients (TQs) were calculated for the potential exposure of individual members of the ground squirrel, black-tailed deer, and kit fox populations to VOCs and cadmium. An HI of less than 1.0 indicates a low potential hazard.

The HIs for the VOCs PCE and TCE exceed 100 for the adult ground squirrel and the adult kit fox. It is possible that VOCs in soils primarily in the vicinity of Building 834D could have a local impact to ground squirrels. However, other habitat modification in the area, or simple stochastic variation, may also be responsible. In addition, the overall Site 300 ground squirrel population remains robust. Although the kit fox is not presently considered a resident species at Site 300, the area around the Building 834 Complex is potential habitat. The data suggest that, if kit fox den in the vicinity of the Building 834 Complex, they could be at risk from exposure to VOCs. The HI for exposure of black-tailed deer to cadmium in surface soils also exceeded 1.0, suggesting that individual black-tailed deer could be at risk from exposure to cadmium.

Some temporary and minor disturbances to vegetation and wildlife could occur from monitoring and well-installation activities at on-site wells. Impacts would be relatively minor and short-term, and would be minimized by restricting vehicular movement to existing access routes.

6.5.1.5. Air Quality

If Alternative 1 were to be implemented, a slow release of VOCs from soil vapor dispersion and evapotranspiration from surface soils and shallow ground water would likely continue for decades. As discussed in section 6.5.1.1, concentrations of VOCs that may volatilize and disburse in ambient air would result in an individual excess lifetime cancer risk and noncancer HI for workers in or around Building 834D exceeding acceptable levels.

6.5.1.6. Noise and Traffic

Vehicular activity associated with monitoring and sample collection would continue to result in minor periodic incremental increases in ambient noise levels in the Building 834 area. These impacts are anticipated to be insignificant.

6.5.1.7. Land Use and Socioeconomics

Ground water, soil, and soil vapor contamination at the Building 834 Complex is confined to the shallow perched water-bearing zone, and soils and soil vapor above the water-bearing zone closer to the surface near the release sites. The perched water-bearing zone is of limited extent downgradient of the Building 834 Complex and does not extend off site. As discussed in section 6.4.3, the shallow perched water-bearing zone is not considered suitable or potentially suitable as a municipal or domestic water supply, and no future use for human consumption,

livestock water, or irrigation is anticipated. Ground water contamination at Building 834, therefore, should not limit the potential future uses of Site 300. The TCE plume is separated from the regional aquifer by a 250-foot sequence of interbedded, low permeability siltstone, sandstone, and claystone. As discussed in section 6.5.1.2, the maximum 70-year average modeled TCE concentration at the off-site water-supply well CDF-1 resulting from contamination at Building 834 is predicted to be far below the federal MCL. Since contamination is extremely unlikely to move off site, either through horizontal migration of the shallow plume or vertical migration to the regional aquifer, contamination in soil and ground water at the Building 834 Complex would not constrain the range of feasible uses of land surrounding Site 300 or limit its economic value.

VOCs present in surface soils in the Building 834 Complex may volatilize and be released to the atmosphere. As discussed in section 6.5.1.1, both the estimates of individual excess lifetime cancer risk and noncancer HI for the three scenarios at the Building 834 Complex exceed acceptable limits as defined by the U.S. EPA. Since these estimates are above acceptable limits, the potential future uses of the Building 834 Complex area may be limited with a corresponding reduction in economic value. With time, contaminant levels in soils and ground water should decrease through dilution and natural attenuation processes. It is, therefore, possible that the land values would eventually return to values seen for comparable uncontaminated land.

6.5.2. Alternative 2

The implementation of the second alternative would result in all of the potential impacts discussed under Alternative 1, plus measures to limit the potential for human exposure to VOCs in soils, soil vapor, and ground water. Building ventilation systems would be installed to increase circulation in buildings and reduce the potential for TCE that may volatilize from surface soils to collect in building interiors. LNAPL skimming equipment would be installed to recover LNAPLs from ground water at the core of the complex. Surface drainage would be controlled by paving currently unpaved areas and installing concrete-lined ditches to route storm runoff away from areas that would allow recharge to the shallow perched water-bearing zone. Institutional controls would be implemented to limit the potential for human exposure to contaminated soils and ground water. Institutional controls at the Building 834 Complex would include:

- Fences around the Building 834 Complex with warning signs.
- Restricting access to the Building 834 Complex.
- Area patrols by Site 300 security personnel.
- Restrictions on construction activities in the Building 834 area.
- Prohibiting the disturbance or reuse of soils from the area.
- Deed restrictions, primarily prohibiting the installation of drinking water supply wells.

The potential impacts associated with monitor well and soil vapor point installation, monitoring, and maintenance activities would be the same as those resulting from Alternative 1. The potential environmental impacts associated with the installation and operation of building venting systems and drainage controls are discussed below.

6.5.2.1. Human Health

This alternative includes general proposals (applicable to Buildings 834A, D, J, and O in the core of the Building 834 Complex) to install mechanical devices or implement institutional controls in order to reduce the magnitude of human exposure to VOCs. Specific calculations of risk and hazard were completed only for Buildings 834D and 834O (as detailed in the SWRI report and Appendix C of this document), due to their proximity to the area of maximum subsurface soil contamination. These calculations yielded baseline estimates of increased cancer risk of 1×10^{-3}, 6×10^{-4}, and 2×10^{-3}, for exposure inside Building 834D, outside of Building 834D, and inside Building 834O, respectively. The corresponding HIs are 36, 22, and 62.

As described in Chapter 4, a reduction in VOC concentrations in air inside of either Building 834D or 834O would be achieved by the installation of building ventilation systems to provide increased circulation. Institutional controls (e.g., formal limitations on allowable work time outdoors near Building 834D) would be used to minimize exposure (and thus risk and noncancer hazard) associated with volatilization of VOCs to outdoor air in the vicinity of this building. Indoor air in buildings in the core area of the Building 834 operable unit will be monitored to ensure that VOC concentrations remain within acceptable levels. This alternative does not include a specific level of reduction in risk or noncancer HIs as a goal, and, consequently, the extent of human health protection that would be achieved by implementation of this alternative cannot be quantified.

6.5.2.2. Ground Water

The potential impacts associated with Alternative 1 would also occur under Alternative 2. Under normal and expected operations of the Building 834 Complex, there would be no additional adverse impacts to ground water under this alternative. The removal of LNAPLs under this alternative would be slightly beneficial to ground water quality. Institutional controls would reduce the potential for the use of ground water in the shallow aquifer for human consumption.

6.5.2.3. Soil and Soil Vapor

Under normal and expected operations of the Building 834 Complex, there would be no adverse impacts to soils or soil vapor under this alternative. Concentrations of contaminants in soil vapor would likely decline over time as discussed in section 6.5.1.3, as a result of natural processes. Future construction activities would be limited to those that would not result in ground disturbance, and there would be prohibitions against the reuse of soil from the Building 834 area.

Minor construction-related soil disturbance would occur during the construction of the drainage control ditch and paving of previously unpaved areas of the Building 834 Complex. Best management practices (BMPs) appropriate for site conditions would be followed during the construction of the ditch to prevent the transport of disturbed soils or construction materials from the construction sites. One BMP for Alternative 2 might be revegetation with native grasses of any areas that are disturbed during construction, if appropriate, to restore soils in the area to near-original conditions. Construction activities would also be in accordance with the requirements of

the NPDES California General Construction Activity Storm Water Permit. Alternative 2 would not directly impact any natural drainage and, therefore, a California Department of Fish and Game Streambed Alteration Agreement would not be required. Any excess excavated soil, asphalt, or concrete would be analyzed and disposed of in accordance with applicable state and federal regulations, local laws, and DOE orders.

During storms, the drainage control ditch would channel surface runoff northwest from the Building 834 Complex area, releasing the runoff into a canyon leading to Elk Ravine. A pipe would be installed at the outfall of the ditch to carry runoff down the canyon, where it would be released to a low (1 to 5 percent) gradient section. An energy dissipater would be installed at the pipe outfall to prevent soil erosion.

6.5.2.4. Vegetation, Wildlife, and Sensitive Species

The risks to wildlife from soil contamination associated with this alternative would be the same as discussed in section 6.5.1.4, because institutional controls would not restrict wildlife movement. Impacts to vegetation and wildlife that could occur as a result of construction activities would be relatively minor and short-term, and would be minimized by restricting vehicular movement associated with monitoring and construction to existing access routes.

The known locations of elderberry bushes at Site 300 are northwest of the proposed facility locations, and none are within a 300-foot radius of any construction activity that would be part of Alternative 2. Preconstruction surveys for wildlife and vegetative species (listed as federal or state species of special concern) would be conducted within 60 days prior to ground-disturbing activities. The survey area would include a minimum 300-foot buffer zone around the proposed ditch and pipeline location. Depending upon the results of the survey, additional mitigation measures, including the establishment of exclusion zones around any active dens found and the posting of these dens, may be required.

6.5.2.5. Air Quality

The construction of a drainage control ditch may result in (1) temporary air emissions (VOCs) from disturbed soils, and (2) increased dust levels. Because surface soil disturbance would be very minor, any VOCs or dust released to the atmosphere due to construction activities would have insignificant impacts on air quality. Water would be applied as necessary during construction activities to meet regulatory limits for dust suspension. Removed LNAPLs would be collected in a covered container that would prevent the release of VOCs to the atmosphere.

6.5.2.6. Cultural and Historic Resources

In accordance with the federal and state location-specific ARARs (Table 2-1), the APE in the vicinity of Building 834 area was surveyed prior to remedial activity to ensure that no historic properties would be affected by the activity. Although no cultural resources were located, project construction personnel will be advised of the possibility of buried cultural deposits and be alerted to likely indicators. An archaeologist would assess any unearthed resources found at the construction site; the archaeologist has authority to halt disturbance of any cultural resources, conduct testing, and recommend mitigation measures in accordance with DOE and NHPA guidelines. Construction activities to be monitored would include grading and trenching. In

addition, access to any identified cultural resource located near the proposed facility location, but not directly impacted by construction activities, would be restricted by means of stakes and flagging or warning fences.

6.5.2.7. Noise and Traffic

The construction of drainage control and the installation of building venting systems would result in noise increases from standard construction practices. Vehicular activity associated with continued monitoring and sample collection would also result in temporary and minor noise increases. These impacts would be short-term and would not be significant. The operation of the building venting systems may result in minor increases in ambient noise levels; these are not anticipated to be significant.

6.5.2.8. Aesthetics

The Building 834 Complex is not visible from public roads or publicly held lands. Construction activities associated with this alternative would not result in any adverse impact to the aesthetic quality of the area.

6.5.2.9. Land Use

Institutional controls implemented under this alternative would limit the range of feasible uses of the Building 834 area. New construction involving the disturbance or reuse of area soils would not be allowed. The area fencing would be maintained or extended, and warning signs would be installed. Restrictions would be placed in the property deed that would prevent the use of the shallow perched water-bearing zone as a water source. These restrictions on the feasible uses would reduce the economic value of the property.

6.5.3. Alternative 3

The implementation of Alternative 3 (and Alternative 6) would result in all of the potential impacts discussed under Alternatives 1 and 2 plus the potential impacts resulting from soil vapor extraction (SVE) and treatment. Contaminants in soils would be reduced to levels that would not present a health risk to humans.

The innovative technologies that may be investigated under this alternative are described in Chapter 4. The potential environmental impacts of treatability tests of these technologies are discussed in section 6.5.6.

6.5.3.1. Human Health

This alternative targets a 3×10^{-5} cancer risk and HI = 1.0 PSVRL for TCE of 250 $ppm_{v/v}$, which corresponds to a PSRL of 2.2 mg/kg (the current best estimate of the average TCE concentration in subsurface soil in the vicinity of Building 834D is 47.6 mg/kg). The selection of a remediation goal for TCE alone was based on the observation that TCE is the principal subsurface contaminant, and contributed approximately 90 percent of the total baseline risk. The remediation level for TCE was chosen from a range of values presented in Appendix C, and pertains to vapor inhalation exposure outside of Building 834D. Baseline estimates of risk and hazard associated with exposure to TCE outside of Building 834D are 5.6×10^{-4} and 2.13×10^{1},

respectively (Webster-Scholten, 1994). Remediation of TCE in soil vapor to the 3×10^{-5} cancer risk and HI = 1.0 level proposed under this alternative (250 $ppm_{v/v}$) is associated with a chemical-specific risk of 2.6×10^{-5}, and a hazard quotient (chemical-specific) of 9.8×10^{-1}, both of which are within the range of acceptable levels of risk and/or hazard (U.S. EPA, 1989 and 1990b). This alternative does not include a remediation level based on exposure inside Building 834D or 834O because it is assumed that the proposed remediation of TCE in combination with installation of building ventilation systems and implementation of institutional controls would hold exposures inside these buildings to acceptable levels.

An Operational Safety Procedure (OSP) would be developed to include instructions for the safe operation of the treatment facility and for handling concentrated contaminants removed during the treatment process and saturated GAC. Containers used to collect LNAPLs removed by treatment would be provided with secondary containment to prevent a release to ground in the event of an accidental spill. These containers would also be closed to prevent the possible volatilization of VOCs to the atmosphere.

6.5.3.2. Ground Water

The impacts from this alternative on ground water conditions beneath the Building 834 Complex are anticipated to be beneficial. LNAPLs in ground water would be removed by skimming the water surface in existing ground water monitoring wells. The vacuum extraction of soil vapor above the perched water-bearing zone may increase the volatilization of VOCs from ground water to soils (which would then be drawn off), thereby reducing the concentrations of VOCs in ground water. Also, the mass removal of VOCs from vadose zone soils would reduce the potential for downward migration of VOCs from soils to ground water.

New wells would be installed under this alternative to provide additional locations for SVE. The wells would not penetrate the impervious perching horizon below the perched water-bearing zone or create a pathway for contaminants to migrate downward into the regional aquifer.

6.5.3.3. Soil and Soil Vapor

The impacts from this alternative on soil and soil vapor conditions beneath the Building 834 Complex are also anticipated to be beneficial. As a result of SVE and treatment, the concentrations of contaminants in soils and soil vapor would be reduced. The vacuum applied at each extraction point would draw soil vapor toward that point, thereby reducing the movement of contaminants away from the Building 834 Complex core into other areas of the vadose zone. The concentrations of contaminants in soil vapor would be monitored at dedicated soil vapor sampling points.

Construction-related disruption of the soil would occur during installation of the treatment facilities, pipelines, and extraction wells. Potential construction-related impacts to soils are expected to be similar to those discussed under section 6.5.2.3. BMPs appropriate for site conditions would be followed during the construction of Alternative 3 to prevent the transport of disturbed soils or construction materials from the construction sites. Any undisturbed areas that are disturbed during construction would be revegetated with native grasses and/or shrubs to restore the area to near-original conditions. Any excess excavated soil, asphalt, or concrete would be analyzed and disposed of in accordance with applicable state and federal regulations, local laws, and DOE orders.

6.5.3.4. Vegetation, Wildlife, and Sensitive Species

In the Building 834 area, contaminants in soil vapor have been identified as a potential health risk for burrowing animals (such as ground squirrels or kit fox if they use the area for denning). The removal of contaminants from soil vapor would decrease VOC concentrations in soil and soil vapor. The potential health risk to burrowing animals in the Building 834 area should, therefore, be reduced under this alternative.

6.5.3.5. Air Quality

The impact to air quality under this alternative would be beneficial. The skimming system that removes LNAPLs directly from ground water would be a closed system to deliver the removed substances to a closed container. This system would not allow VOCs to volatilize from the skimmed LNAPLs to the atmosphere. SVE and treatment would reduce contaminants in surface soils, thus reducing the potential for VOCs to volatilize into the atmosphere. VOC contamination in extracted soil vapor would be removed by passing the extracted vapor through two vapor-phase GAC canisters in series prior to release to the atmosphere. The treatment facility would be operated in accordance with an air permit from the San Joaquin Valley Unified Air Pollution Control District. The air releases under this alternative would be within permit limitations and, therefore, would not significantly impact ambient air quality at Site 300.

6.5.3.6. Cultural and Historic Resources

The APE in the vicinity of the Building 834 area has been surveyed for cultural resources, and no new sites were found. Mitigation measures described under Alternative 2 would be followed to prevent any adverse impacts to cultural resources discovered during the construction of the proposed facilities.

6.5.3.7. Noise and Traffic

Drilling and installation of extraction wells would result in temporary noise increases from equipment operation. During construction of the treatment facilities, there would be noise generated due to standard construction practices. Vehicular activity associated with continued monitoring and sample collection would also result in temporary and minor noise increases. These impacts would be short-term and are not considered significant.

Up to 85 dB of noise would be generated in the immediate proximity of each facility by the blowers for the treatment units and the vapor extraction system. This noise level is the permissible exposure limit for this type of equipment. Due to the remote nature of the facilities and lack of immediately adjacent sensitive receptors, the noise generated by the blowers would not have a significant impact.

6.5.3.8. Land Use

Implementation of Alternative 3 would have beneficial effects on land use. The treatment operations would remove contaminants from soil and ground water, thereby reducing the potential for restrictions on the range of feasible land uses.

It is anticipated that implementation of this alternative would not require more than three additional permanent workers. However, the number of workers actually at Building 834 and the duration of their residence would be neither constant nor continuous. This increase in workforce would not represent a significant change, and it falls within the range of variability seen for normal operations at Site 300.

6.5.3.9. Aesthetics

None of the new treatment facilities would be exposed to views from public roads or publicly held lands.

6.5.4. Alternative 4

The implementation of Alternative 4 would result in all of the potential impacts discussed under Alternatives 1, 2, and 3. Other potential impacts could result from ground water extraction and treatment and the construction and operation of a new ground water treatment facility.

The innovative technologies that may be investigated under this alternative, as well as Alternatives 5 and 6, are described in Chapter 4. The potential environmental impacts of treatability tests of these technologies are discussed in section 6.5.6.

6.5.4.1. Human Health

This alternative has a goal similar to Alternative 3, which is to reduce VOC concentrations in subsurface soil and soil vapor in the core area of the Building 834 operable unit. Alternative 4 also has the same 3×10^{-5} cancer risk and 1.0 HI PSVRL for TCE (250 $ppm_{v/v}$) as Alternative 3, and again includes proposals to install ventilation systems in buildings and implement institutional controls as originally described in Alternative 2. Alternative 4 would, however, add an additional treatment technique (dewatering of the perched water-bearing zone in the core area) beyond that proposed in Alternative 3, which would augment the rate of cleanup and mass removal.

The soil remediation level for TCE is based on exposure outside of Building 834D, as described with respect to Alternative 3. Baseline estimates of risk and hazard associated with exposure to TCE outside of Building 834D are the same as those under Alternative 3, and are given in section 6.5.3.1. For the same reasons given under Alternative 3, this alternative does not include a soil vapor remediation level based on exposure inside Building 834D or 834O.

Workers operating the facility would follow procedures outlined in an OSP developed specifically for the treatment system. The OSP would include procedures for the safe handling of LNAPLs and VOCs removed from extracted ground water during treatment. Removed contaminants would be collected in containers provided with secondary containment to prevent a release to the environment as a result of an accidental spill. The containers would also be closed to prevent exposure of workers to VOCs or other contaminants.

6.5.4.2. Ground Water

Under this alternative, the perched water-bearing zone beneath the Building 834 core area would be partially dewatered. Extracted ground water would be treated to remove VOCs and LNAPLs and then discharged by misting to an area that would not allow infiltration back into the

perched water-bearing zone. This alternative would improve water quality of extracted ground water by removing VOCs to below 0.5 µg/L. The pumping of ground water from the shallow perched water-bearing zone would create localized cones of depression in the water table, drawing ground water toward the extraction points. This effect would reduce the potential for migration of contaminants away from the Building 834 core area.

6.5.4.3. Surface Water

The air misting system would release up to 1,800 gallons of treated water over a 30,000-square-foot area over a period of about 70 minutes, assuming no wind. Winds common at Site 300 would tend to disperse the released mist over a much greater area. Releases under this alternative would most likely infiltrate or evaporate without any surface runoff.

6.5.4.4. Soil and Soil Vapor

It is anticipated that the continuous pumping of the extraction wells will cause localized drawdown in the perched water-bearing zone in the areas surrounding the wells. This would enlarge the vadose zone, and result in greater mass removal of VOCs by SVE. Construction-related disruption of soils would occur during installation of the treatment facilities, pipeline, and extraction wells. These impacts would be minor and short-term and essentially the same as under Alternative 3. Slightly damp areas may be created in surface soils surrounding the air misting ports, east of the core area, but no soil erosion is expected.

6.5.4.5. Wetlands

The small volumes of treated ground water released to the atmosphere by the air misting system would tend to evaporate or disperse, and would not collect on the ground surface in amounts great enough to sustain riparian vegetation. Releases of treated ground water under this alternative, therefore, would not be expected to create any wetland areas.

6.5.4.6. Vegetation, Wildlife, and Sensitive Species

Releases of treated water through the air misting system may support slightly greater amounts of annual and perennial grasses in the release area. These grasses would, however, be burned during annual controlled burning at Site 300.

LLNL currently operates an air misting system at Building 833, south of the Building 834 operable unit. The Building 833 system releases treated ground water in amounts similar to the planned releases under this alternative. Since the air misting system has been operating at Building 833, we have not observed any significant changes in the number of species or the number of individuals present in the release area. The experience at Building 833 indicates that wildlife would not be attracted to the air misting site(s) under this alternative.

In the Building 834 area, contaminants in soil vapor have been identified as a potential health risk for burrowing animals (such as ground squirrels or kit fox if they use the area for denning). The removal of contaminants from soil vapor would be increased under this alternative as a result of dewatering the aquifer and the exposure of more soils to the SVE process. The potential health risk to burrowing animals in the Building 834 area should, therefore, be reduced under this alternative.

6.5.4.7. Cultural and Historic Resources

Mitigation measures necessary to protect cultural or historic resources that may be present in project areas affected by construction activities under this alternative would be the same as those discussed under previous alternatives.

6.5.4.8. Noise and Traffic

The operation of the phase separation and air-stripping treatment system is not expected to significantly increase the amount of noise generated by other equipment at the facility. The potential impacts associated with other noise generated during the construction and operation of treatment facilities would be the same as discussed under previous alternatives.

6.5.4.9. Land Use

The treatment operations under Alternative 4 are intended reduce the concentrations of contaminants in ground water to nondetectable levels, thereby reducing the potential for restrictions on the range of feasible land uses. This alternative, therefore, would have a beneficial effect on land use.

6.5.5. Alternative 5

Alternative 5 includes all of the components of Alternative 4, but would add additional ground water extraction wells and piping. The objectives of Alternative 5 are to: (1) reduce VOC concentrations in subsurface soil in the core area of the Building 834 operable unit to minimize human exposure to VOCs and (2) extract perched ground water in the vicinity of the septic field and the W-834-T2 and -T4 well clusters, thereby controlling the downgradient movement of VOCs within the perched water-bearing zone.

The implementation of Alternative 5 would result in all of the potential impacts discussed under Alternatives 1, 2, 3, and 4 plus the potential impacts resulting from the operation of additional ground water extraction wells at the septic system release site and the W-834-T2 and -T4 well clusters. Electrical utility lines would be extended underground to the wells. A new extraction well would be installed near the septic release site. The technologies used in the ground water treatment system would be the same as discussed in Alternative 4.

This alternative and Alternative 6 also include the testing of innovative technologies for extraction and treatment of contaminated ground water and soil vapor. The technologies that may be investigated under this alternative, as well as Alternatives 3, 4, and 6, are described in Chapter 4. The potential environmental impacts of treatability tests of these technologies are discussed in section 6.5.6.

6.5.5.1 Human Health

Alternative 5 has the same soil vapor remediation level for TCE (250 $ppm_{v/v}$) as Alternatives 3 and 4, and again includes proposals to install ventilation systems in buildings and implement institutional controls as originally described in Alternative 2. The soil vapor remediation level for TCE is also based on exposure outside Building 834D. Baseline estimates of risk and hazard associated with exposure to TCE outside Building 834D are the same as

Alternatives 3, 4, and 6, and are given in section 6.5.3.1. This alternative also does not include a soil vapor remediation level based on exposure inside Building 834D or 834O.

Although one of the goals of this alternative is to control the downgradient movement of VOCs within the perched zone, specific remediation goals for ground water have not been identified. In the SWRI, calculations for residential use of contaminated ground water that originates in the Building 834 operable unit yielded a baseline estimate of risk of 7×10^{-11} and an HI of 7.8×10^{-6}; both values are considerably lower than the acceptable levels of risk and hazard given by the U.S. EPA (1989 and 1990b). Although we cannot quantify the extent of human health protection that would be achieved by the dewatering proposed in this alternative, a reduction in contaminant concentrations would result in levels of risk and hazard lower than those calculated for the baseline case.

6.5.5.2. Ground Water

Under this alternative, ground water from the perched water-bearing zone beneath the septic system release site and the W-834-T2 and -T4 well clusters would be extracted, treated, and released. As under Alternative 4, extracted ground water would be treated to remove VOCs and LNAPLs to below 0.5 µg/L and then discharged by misting to an area northeast of the core area that would not allow infiltration back into the perched water-bearing zone. The pumping of ground water at additional locations under this alternative would reduce the volume and mass of VOCs in the perched zone, and further reduce the potential for migration of the contaminants in ground water.

6.5.5.3. Surface Water

The air misting system for the release of ground water treated at the treatment facility northeast of the core area will discharge the combined treated effluent from the core area and W-834-T2 and -T4 well clusters. As discussed under Alternative 4, releases would be expected to either evaporate or infiltrate (on rare occasions) into soils without creating any surface runoff.

6.5.5.4. Soil and Soil Vapor

Construction-related impacts to soils under this alternative would be essentially the same as under Alternative 4. As under Alternative 4, releases of treated water under this alternative would not be expected to result in surface flows causing soil erosion.

6.5.5.5. Vegetation, Wildlife and Sensitive Species

Under this alternative, greater amounts of contaminants would be removed from ground water than under Alternative 4. The removal of contaminants from ground water would reduce the potential for VOCs to volatilize into vadose zone soil vapor. As a result, the potential health risk to burrowing animals in the Building 834 area would be further reduced under this alternative.

Releases of treated water through the air misting system would also be to an area that is burned during annual burning at Site 300. Released water may slightly increase the amount of annual and perennial grasses in the release locations, but would not be expected to be sufficient to support riparian vegetation or attract wildlife.

6.5.5.6. Noise and Traffic

The construction and operation of the additional extraction wells would result in minor increases in ambient noise levels. These impacts would be short-term and are not considered significant.

6.5.6. Potential Impact of Treatability Tests of Innovative Technologies

Four innovative technologies have been identified for treatability tests under Building 834 operable unit remedial alternatives. These include:

- Resin adsorption-regeneration system.
- UV photo-oxidation.
- Electron accelerator.
- Surfactant injection.

6.5.6.1. Resin Adsorption-Regeneration

The resin adsorption-regeneration system traps VOCs in extracted soil vapor on an adsorbent resin bed. VOCs are removed from the absorbent material in the resin bed by desorption using a combination of temperature, pressure, and a carrier gas (nitrogen). The system has multiple resin beds that can be regenerated on site. VOCs removed during the desorption (i.e., regeneration) cycle would be collected in a closed storage tank that would prevent the release of VOCs to the atmosphere. The storage tank would be provided with secondary containment to prevent the release of VOCs to the ground as the result of an accidental spill or leak; the tank would be closed to prevent release to the atmosphere. The operation of the resin adsorption-regeneration system, the storage of compressed gas, and handling of concentrated contaminants removed during the treatment process would be in accordance with procedures outlined the OSP for the facility.

Unlike the use of a GAC system, the operation of the resin adsorption-regeneration system would not result in the generation of spent carbon that must be handled and shipped off site for regeneration. The resin system, therefore, would have a beneficial impact by reducing the amount of waste generated at Site 300.

6.5.6.2. UV Photo-oxidation

This technology consists of using ultraviolet (UV) light and an oxidizing agent, such as hydrogen peroxide or ozone, to further remove TCE from a treated effluent stream. During a test conducted over a 3-week period in September 1992, about 40,000 gallons of VOC-contaminated ground water extracted from the perched water-bearing zone beneath the Building 834 Complex was treated using this technology. The treatment system achieved TCE and PCE removal efficiencies of about 99.7 and 97.1 percent, respectively, and the treatment system effluent met California drinking water action levels and federal drinking water MCLs for TCE, PCE, chloroform, DCA, and TCA at the 95 percent confidence level (U.S. EPA, 1993).

In the UV oxidation process, hydrogen peroxide would be added to extracted soil vapor containing TCE. The mixture would then be exposed to UV radiation. The treated effluent

vapor would then be returned to the soil vapor treatment system, passed through GAC for final polishing to ensure regulatory compliance, and released to the atmosphere.

There are no adverse environmental impacts or adverse health effects anticipated from the proposed action. The treatment unit would produce no external UV radiation, no hazardous substances, and no air emissions other than the controlled emissions through the carbon filters that are part of the current treatment process. The treatment unit requires no construction and there would be no soil disturbance resulting from the proposed action. The hydrogen peroxide used in the process would be an aqueous solution (50 percent hydrogen peroxide and 50 percent water) that would be stored in a double-lined polyethylene container. The operation of the unit would be in accordance with manufacturer's specifications and procedures outlined in the OSP.

6.5.6.3. Electron Accelerator

This technology consists of the use of an electron accelerator to decompose TCE in extracted soil vapor. A plenum (duct-like device) would be placed underground to provide a chamber where the flowing vapor can interact with an electron beam. The accelerator would be placed at the ground surface and would direct an electron beam downward into the plenum. The treated effluent would then be returned to the soil vapor treatment system. The plenum would be located in a hole lined with corrugated steel pipe. The top of the hole will be covered by steel plate that would support the electron accelerator.

The entire electron beam propagation path, beginning with the accelerator output aperture, would be underground. Only low-level x rays would be produced when the electron beam interacts with metal plating. Due to the downward direction of the electron beam, most of the x rays produced would also be directed downward. The amounts of scattered radiation and bremsstrahlüng radiation are not expected to be significant. The downward direction of the electron beam, the underground placement of the plenum and accelerator aperture, and the limited number of materials exposed to the electron beam would serve to mitigate personnel exposure to x rays. Cement blocks would be stacked around the surface of the hole leading to the plenum to provide additional shielding. Dose rates outside the cement blocks would be no higher than 2 mrem per hour. The area would be roped off at the 1-mrem-per-hour contour, and a flashing warning light would be used when the accelerator is in operation. No personnel would be exposed to dose rates higher than 1 mrem per hour, which is within NRC guidelines for DOE workers. The operation of the unit would be in accordance with manufacturer's specifications and procedures outlined in the OSP.

6.5.6.4. Surfactant Injection

This technology consists of pumping water, with surfactants, into the ground water zone via injection wells. The surfactants cause a significant increase in the recovery rate of DNAPLs during ground water extraction and treatment.

This technology does not pose any significant health or environmental risks. The volume of surfactants introduced into the perched water-bearing zone would be compared to the volume recovered during ground water extraction and treatment. It is anticipated that extraction and treatment would recover almost 100 percent of the surfactants introduced into the water-bearing zone. The handling and injection of surfactants would be in accordance with safety procedures outlined in the OSP.

6.6. Potential Accidents

The CEQ has issued regulations for implementing the procedural provisions of NEPA. The CEQ has determined that NEPA reviews of proposed actions need to consider the potential impacts to the environment resulting from reasonably foreseeable accidents. The NEPA review need not, however, consider potential impacts resulting from incredible accidents that are based on pure conjecture and are not within the rule of reason (CEQ, 1986). To evaluate all foreseeable impacts of the no action alternative and the construction and operation of facilities required under the other remedial alternatives, potential accidents should be examined. For the remedial alternatives considered in the Building 834 Complex, the reasonably forseeable accident that would result in the greatest potential for adverse human health effects is discussed below.

6.6.1. Accidental Pipeline Rupture Scenario

An accidental rupture of the piping connecting all soil vapor extraction points in the Building 834 Complex to the Building 834 Complex treatment facility would represent the reasonably foreseeable accident. This scenario is based on the assumption that the pipe rupture would occur at the startup of the facility (the beginning of the 30-year treatment program) when concentrations of contaminants in soil vapor would be highest, and that the rupture would occur after the end of the workday and would not be discovered until the following morning. This scenario anticipates that untreated soil vapor would be pumped at the maximum rate from the extraction wells unobserved for a period of 12 hours.

6.6.2. Potential Impacts of the Scenario

The primary impact of this release of untreated soil vapor would be the release of TCE to the atmosphere. Under this scenario, the average concentration of TCE in released vapor is estimated to be 2.51 mg/m^3, if contaminants are assumed to be present at their presently-detected average concentrations.

The American Conference of Governmental Industrial Hygienists (ACGIH) has established "Threshold Limit Value–Short-term Exposure Limit" (TLV-STEL) as a 15-minute time-weighted average exposure which should not be exceeded at any time during a workday (ACGIH, 1992–1993). The TLV-STEL for TCE is 269 mg/m^3. Workers can be exposed to concentrations of TCE up to this level without suffering from irritation, chronic or irreversible tissue damage, or narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue, or materially reduce work efficiency. Since the concentration of vapor-phase TCE that the exposed worker would be exposed to (2.51 mg/m^3) would be 100 times less than the TLV-STEL, no adverse health impacts to workers at the facility would result from the reasonably foreseeable accident.

Dispersion of TCE vapor in ambient air would tend to lower concentrations as vapor moved away from the release point. Therefore, the maximally-exposed off-site receptor would be exposed to lower concentrations of TCE than workers on site, and adverse impacts to the health of individuals off site would not be expected as a result of the postulated accident.

6.7. Summary of Environmental Impacts

This section summarizes the areas with the greatest potential for environmental impact as a result the implementation of Alternatives 2 through 6 and provides a general comparison of these impacts with those of the no action alternative. Since the remedial alternatives (Alternatives 3, 4, 5, and 6) are similar, with the exception of the soils exposed to soil vapor extraction and volumes of water treated and released, they will be considered as a group for comparison to the no action alternative.

6.7.1. Impacts on Human Health

The no action alternative would provide no interception or removal of subsurface soil contaminants at the Building 834 Complex. The three estimates of cancer risk associated with potential adult on-site exposure in this operable unit indicate that if exposure were to occur on a regular basis, each of the three scenarios is associated with an unacceptable risk of cancer. Similarly, each of the HIs is greater than 1.0, indicating a potential for the occurrence of adverse, noncancer health effects. These calculations pertain to potential adult on-site exposure both inside and outside of Building 834D, and inside of Building 834O.

A reduction in VOC concentrations in air inside of either Building 834D or 834O would be achieved under Alternatives 2 through 6 by the installation of building ventilation systems to provide increased circulation. Institutional controls, e.g., formal limitations on allowable work time outdoors near Building 834D, would be used to minimize exposure associated with volatilization of VOCs to outdoor air in the vicinity of this building.

The objective of Alternative 3 is to reduce VOC concentrations in subsurface soil in the core area of the operable unit. This alternative proposes a specific soil remediation level for TCE of 250 $ppm_{v/v}$. Remediation of TCE in soil and soil vapor to the level proposed under this alternative is associated with a chemical-specific risk and a hazard quotient within the range of acceptable levels of risk and/or hazard.

Alternative 4 (and Alternative 6) would add dewatering of the perched water-bearing zone. This treatment would augment the rate of cleanup by SVE, and, therefore, would allow the cleanup goals specified under Alternative 3 to be achieved sooner.

Alternative 5 (and Alternative 6) includes all of the components of Alternative 4, but would add additional extraction and treatment systems in two specific locations within the operable unit. The objectives of Alternative 5 are to: (1) reduce VOC concentrations in subsurface soil vapor in the core area of the operable unit to minimize human exposure to VOCs, and (2) extract perched ground water in the vicinity of the septic field and the W-834-T2 and -T4 well clusters, thereby controlling the downgradient movement of VOCs within the perched water-bearing zone. Although we cannot quantify the extent of human health protection that would be achieved by the ground water remediation proposed in this alternative, a reduction in contaminant concentrations would result in levels of risk and hazard lower than those calculated for the baseline case.

6.7.2. Impacts on Soils, Surface Water, and Ground Water

The proposed alternatives include drainage control measures to route surface runoff away from the Building 834 Complex core area and into Elk Ravine northwest of Building 834. The release of runoff from this drainage control system would be in a low gradient section, and an energy dissipater would be installed to prevent soil erosion. The release of treated water through air misting systems would not result in surface flows that could erode soils near the release points.

Under Alternatives 4, 5, and 6, treated ground water would be released to the atmosphere by one and two on-site air misting systems, respectively. This release method would not result in surface runoff that would cause soil erosion or the creation of wetlands or riparian vegetation. The discharge would be to specific areas allowing no infiltration back into the contaminated areas of the perched water-bearing zone.

6.7.3. Impacts on Land Use

The contamination in the perched water-bearing zone appears to be isolated from the regional aquifer. Therefore, the contamination at Building 834 would not result in limitations on the ground water use or limitations that would affect potential land use or land values. Implementation of the remedial alternatives would have a more beneficial effect on the quality of ground water resources than the implementation of the no action alternative, since remediation is expected to capture contaminants at the release points, thus limiting the affected area to no larger than its current size (Alternatives 4, 5, and 6 could reduce the size of affected area).

VOCs that volatilize from surface soils in the Building 834 Complex may present unacceptable cancer risks and noncancer health risks for adults on-site, assuming exposure on a regular basis. If soil contamination is not remediated, the range of potential future uses of the Building 834 area would be limited.

6.7.4. Impacts on Vegetation, Wildlife, and Sensitive Species

Under Alternatives 1 and 2, contaminants would remain in shallow soils and ground water and burrowing animals would be exposed to contaminants at levels that may present a health risk. Implementing Alternative 3, 4, 5, or 6 would reduce the level of contaminants in soils, soil vapor, and ground water, thus reducing the potential for health risks to borrowing animals.

No sensitive species have been identified in the Building 834 area. Surveys for the presence of sensitive species would be conducted prior to ground-disturbing activities, and mitigation measures outlined previously would be implemented if these species were found in the areas affected by any of the proposed alternatives.

6.7.5. Cumulative Impacts

The long-term environmental impacts that may occur in conjunction with, or as a result of, the Building 834 remediation activities could potentially contribute to the cumulative impacts of all remediation projects occurring simultaneously at Site 300 over the next 30 to 70 years (the estimated duration of ground water cleanup in many areas). The environmental areas of potential concern in relation to cumulative impacts of site-wide remediation activities are primarily human

health, land use, air emissions, the generation of hazardous waste (primarily in the form of spent carbon), and the discharge of treated ground water. These are discussed individually below.

6.7.5.1. Cumulative Impacts to Human Health

Existing soil and ground water contamination in the Building 834 operable unit currently contribute to the potential for risks to human health from the past release of hazardous materials at Site 300. Four of the alternatives discussed in this chapter would reduce the potential for human exposure by implementing institutional controls and reducing the concentrations of contaminants. The remedial alternatives for the Building 834 operable unit, therefore, would tend to reduce the potential for human exposure to contamination at Site 300.

6.7.5.2. Cumulative Impacts to Land Use

Since the availability of ground water is a significant constraint to land use, ground water contamination at Site 300, including contamination in the Building 834 operable unit, could have the potential to adversely affect land use in the Site 300 area. The contamination in the operable unit, however, appears to be confined within the perched water-bearing zone, and this water-bearing zone is not suitable as a supply for human use. Ground water contamination resulting from prior chemical releases in the operable unit, therefore, would not tend to contribute to reductions in the range of feasible uses for Site 300 or surrounding property.

The range of feasible uses of Site 300 and surrounding property could be affected by soil contamination at Site 300. If the no action alternative is chosen, VOCs in soils could volatilize and present a health risk to personnel working in the Building 834 Complex. This risk of adverse health effects would contribute to restrictions on the range of feasible uses of Site 300. Since VOCs that volatilize into ambient air would be dispersed by winds, the downwind concentrations would not pose an adverse health risk to persons on adjacent property or limit the range of feasible uses for that property. Therefore, soil and soil vapor contamination in the Building 834 operable unit would contribute to limitations on the feasible uses for Site 300, but would not contribute to potential limitations on the feasible uses of surrounding properties.

6.7.5.3. Cumulative Impacts to Air Quality

Under the no action alternative, minor amounts of VOCs in soils could volatilize into ambient air. Also, as discussed in section 6.6, an accident involving the rupture of an SVE pipe could result in the release of untreated soil vapor to the atmosphere. In these two cases, contamination and remedial activities could contribute to adverse impacts to air quality at Site 300.

Soil vapor treatment would reduce the amount of contaminants that may volatilize into ambient air at Site 300. The remedial alternatives for the operable unit would, therefore, tend to reduce the potential contribution to adverse impacts to air quality from contamination at Site 300.

6.7.5.4. Cumulative Impacts Resulting from Hazardous Waste Generation

Spent carbon generated at the treatment facilities would increase the amount of waste generated at Site 300. This type of waste is routinely regenerated at a permitted off-site facility

that currently has capacity to regenerate the spent carbon. The proposed action, therefore, would not contribute to the need to site and operate new facilities for the regeneration of used carbon.

6.7.5.5. Cumulative Impacts to Surface Water

The volume of ground water that would be treated at the Building 834 treatment facility is estimated to be at most 3,600 gpd. The discharge would be to the atmosphere using an air misting system, and no surface flow would be created that could reach Corral Hollow Creek or any other proposed treated water discharge point at Site 300. Therefore, the Building 834 remedial action would not contribute to the potential for impacts resulting from the release of treated ground water from other treatment facilities at Site 300.

6.7.5.6. Cumulative Impacts to Wildlife

As a result of soil and soil vapor contamination at Site 300, including contamination in the Building 834 operable unit, burrowing animals could be exposed to adverse health risks. The removal of contaminants from soils in the Building 834 operable unit would tend to reduce the risk of exposure.

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Figures

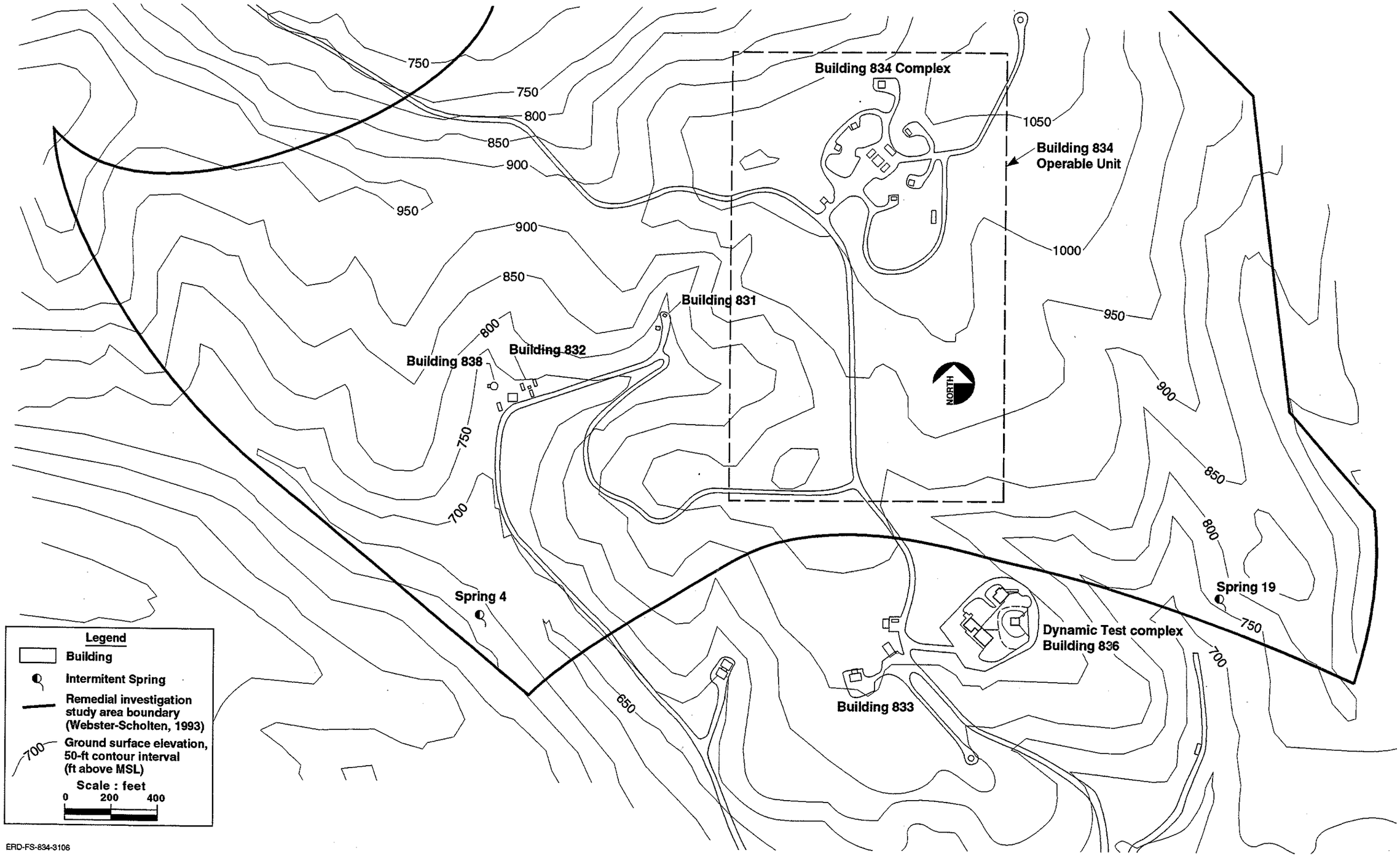


Figure 1-1. Topographic map of Building 834 operable unit.

Figure 1-1

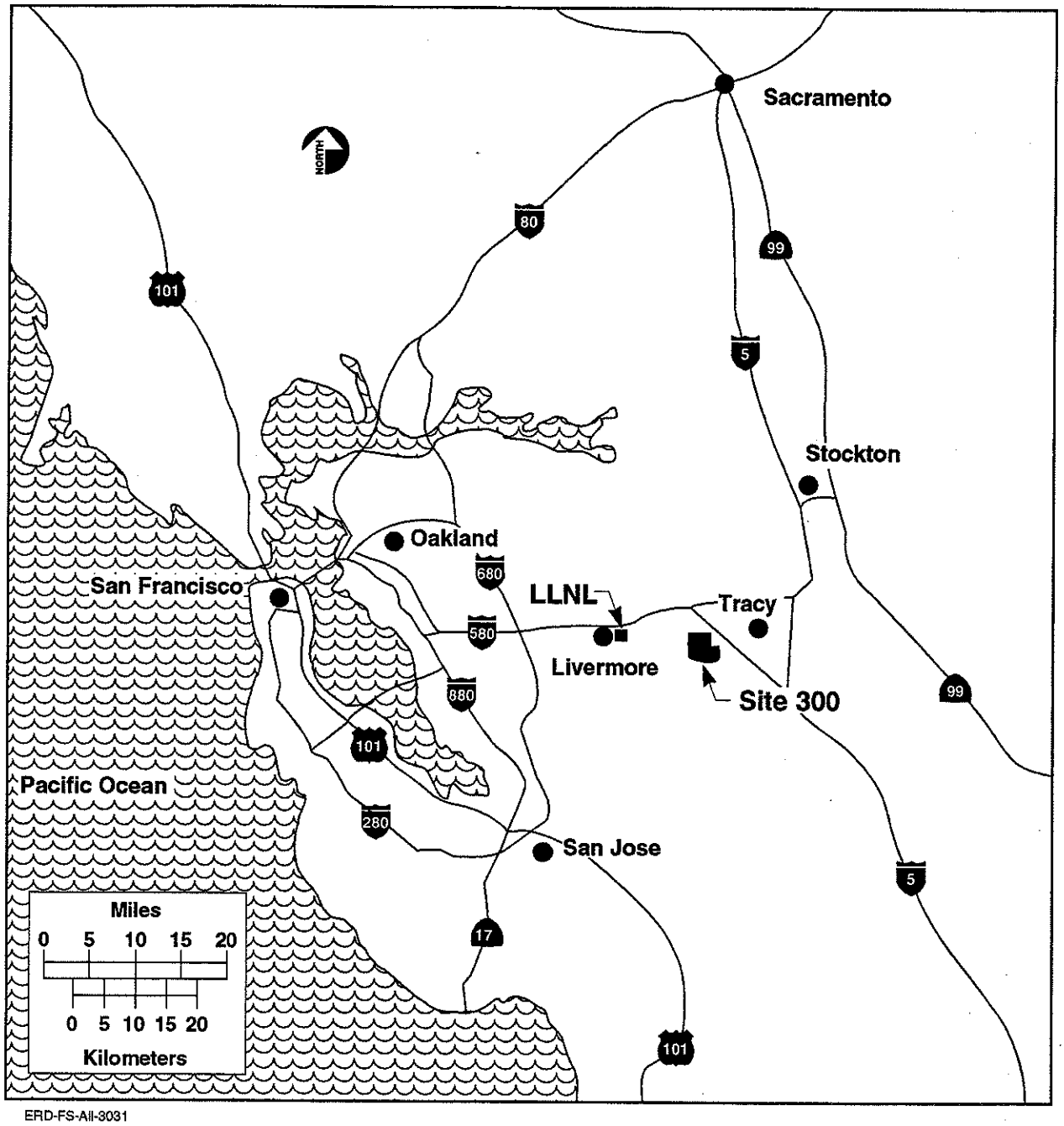


Figure 1-2. Locations of LLNL Main Site and Site 300.

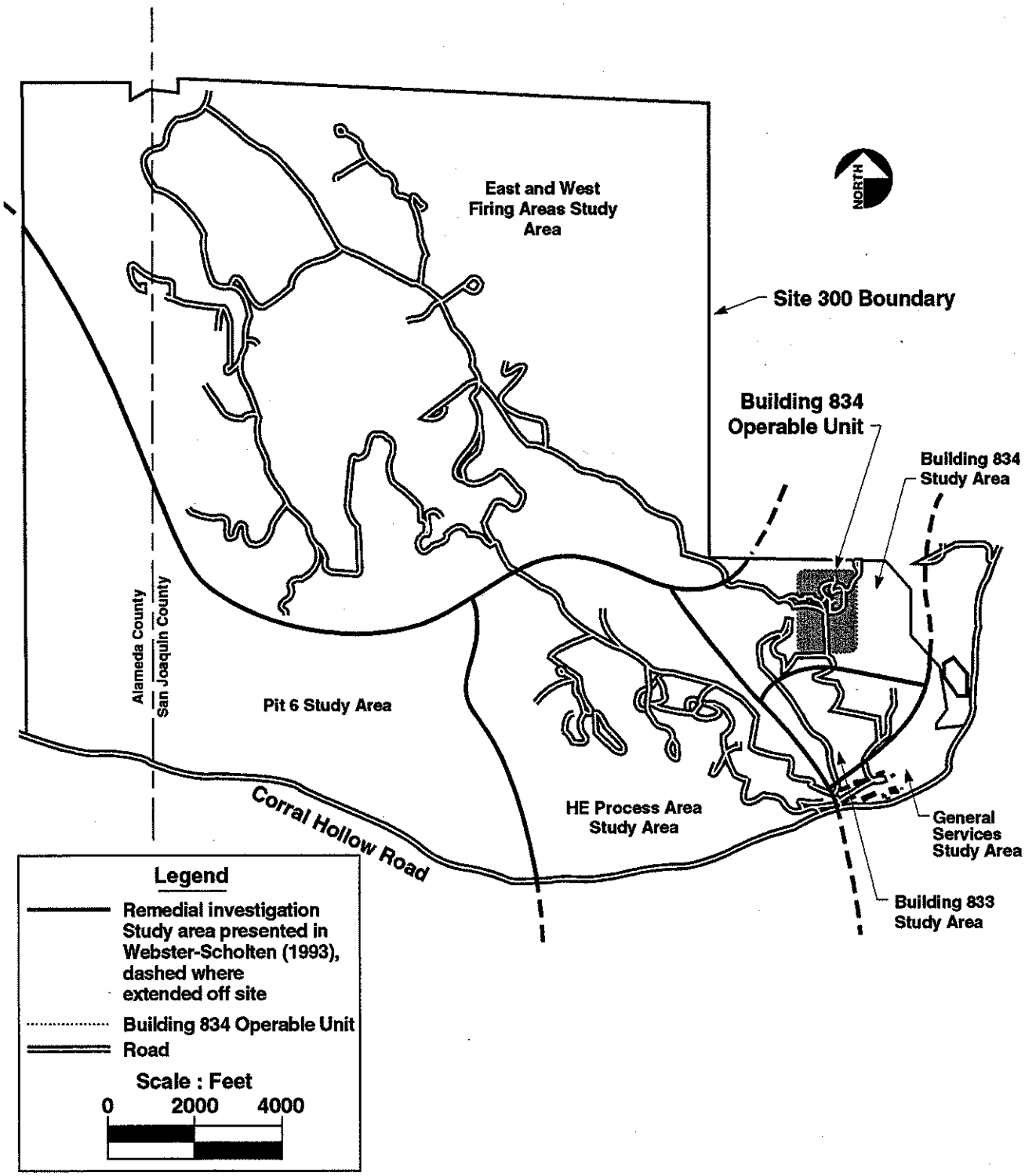
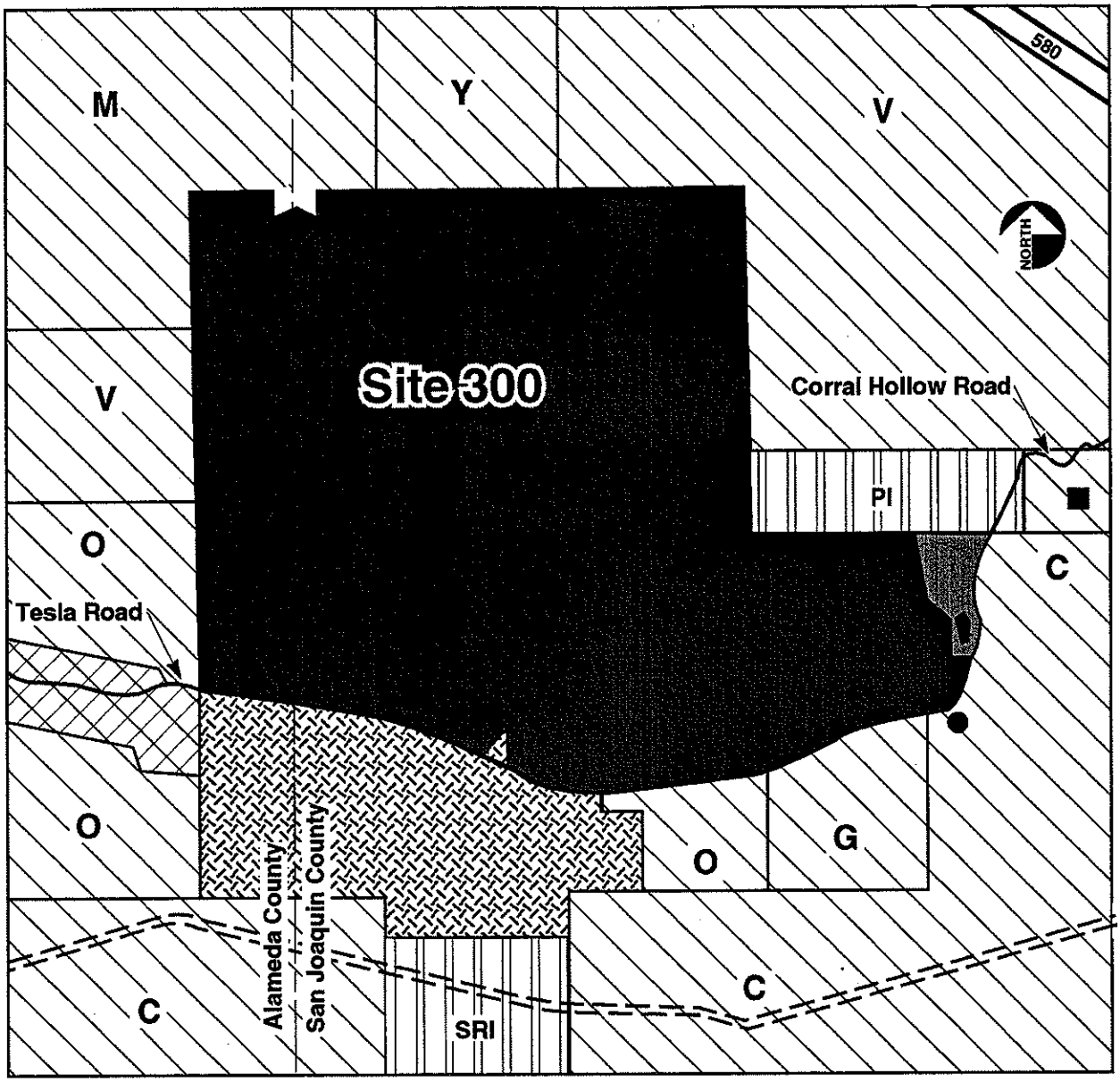


Figure 1-3. Locations of operable units at LLNL Site 300.



Legend

- Federal materials testing and research
- Private materials testing and research
- Private range land
- Residential land
- Carnegie State Vehicular Recreation Area (SVRA)
- California Department of Fish and Game (CDF)

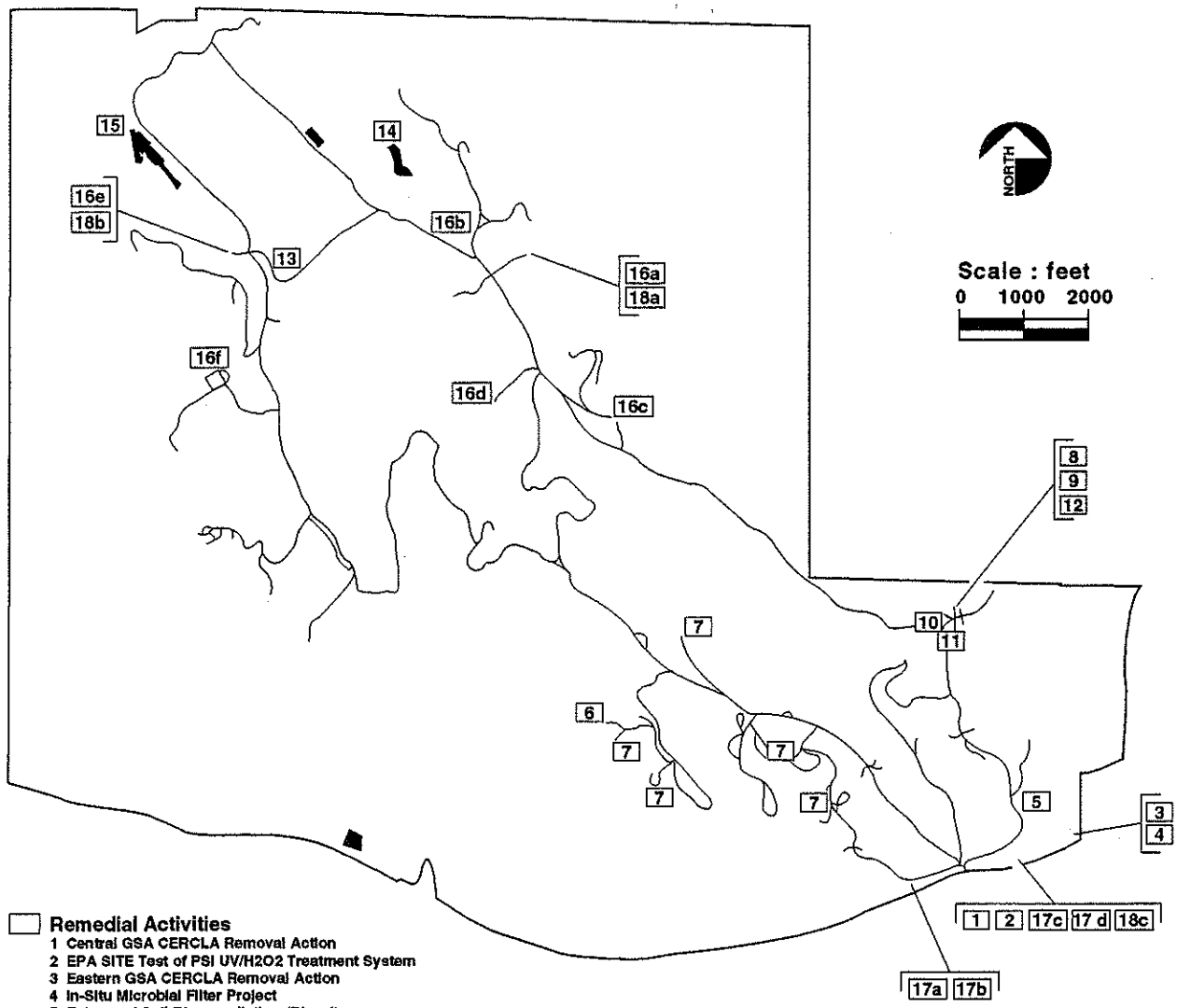
G = Gallo Ranch
C = Connolly Ranch
M = Mulqueeney Ranch
Y = Yroz Ranch land
V = Vieira Ranch land (proposed Tracy Hills Development)
O = Other ranch land
PI = Physics International
SRI = SRI International

- Castle Rock fire station (CDF)
- Hetch Hetchy aqueduct
- Interstate 580
- Broadcasting tower

Scale : feet
0 2000 4000

ERD-FS-All-3032

Figure 1-4. Land use in the vicinity of Site 300.



Remedial Activities

1 Central GSA CERCLA Removal Action
2 EPA SITE Test of PSI UV/H2O2 Treatment System
3 Eastern GSA CERCLA Removal Action
4 In-Situ Microbial Filter Project
5 Enhanced Soil Bioremediation (Diesel)
6 High Explosive Burn Pit Facility RCRA Closure
7 High Explosive Rinse-Water Lagoon Closures
8 Building 834 Complex Interim Remediation
9 EPA SITE Test of PURUS Pulsed UV System
10 Electrical Soil Heating Project
11 Electron Accelerator Demonstration Project
12 Fiber Optic Monitoring of Remediation
13 Pilot Tritium Evaporator
14 RCRA Capping of Pit 1
15 RCRA Capping of Pit 7
16 Removal/Replacement of Firing Table Gravels
16a - Building 801 (removed and replaced)
16b - Building 802 (removed)
16c - Building 812 (removed)
16d - Building 845 (removed)
16e - Building 850 (removed and replaced)
16f - Building 851 (removed and replaced)
17 Sealing/Abandonment of Water-Supply Wells
17a - Well 4
17b - Well 6
17c - Well 7
17d - Well 19
18 Underground Fuel Storage Tank Removal/Remediation
18a - Building 801
18b - Building 850
18c - Building 874

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Figure 1-5. Corrective actions and facility upgrades at LLNL Site 300.

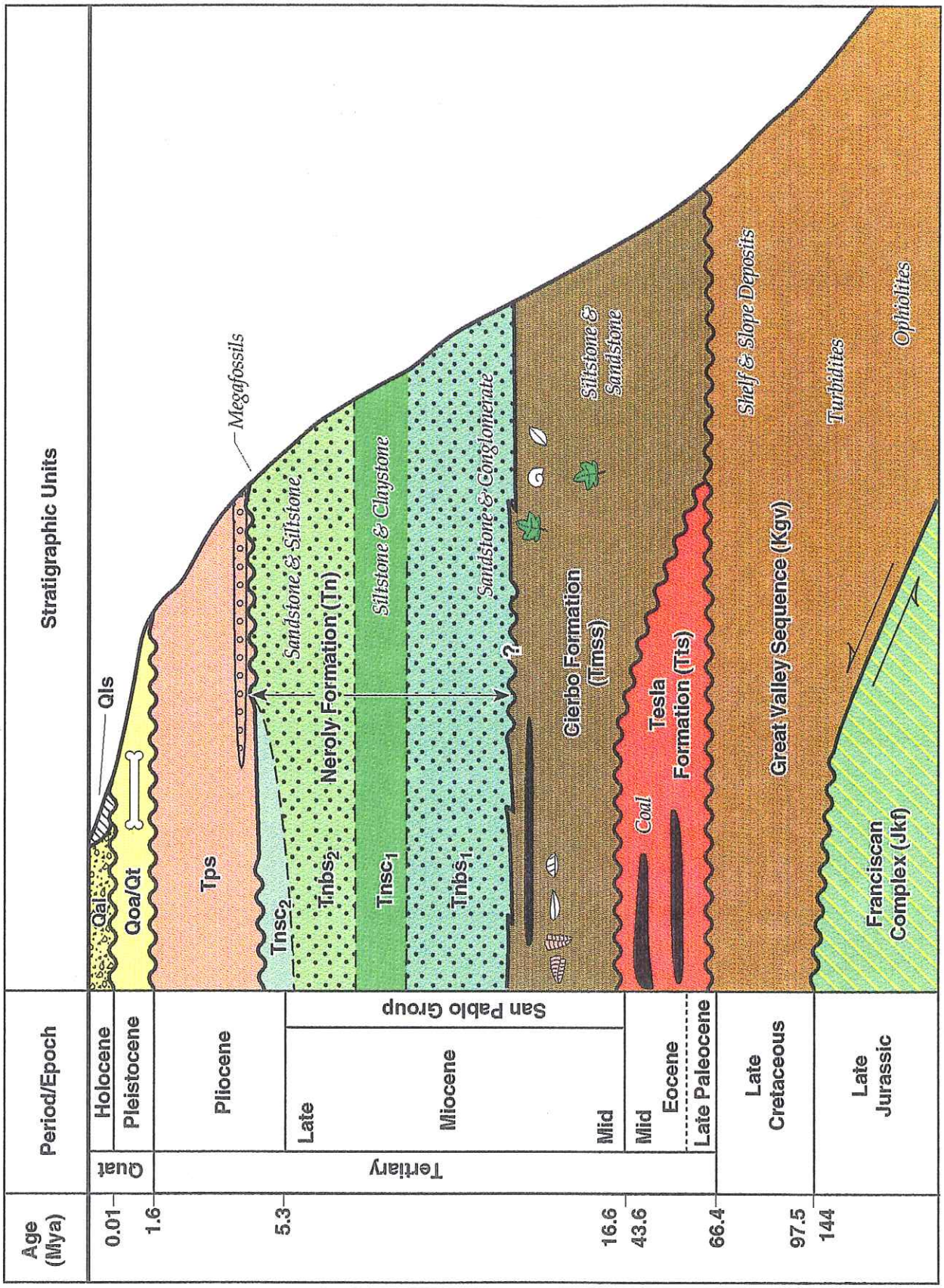

Figure 1-6. Schematic stratigraphy of Site 300.

Figure 1-6

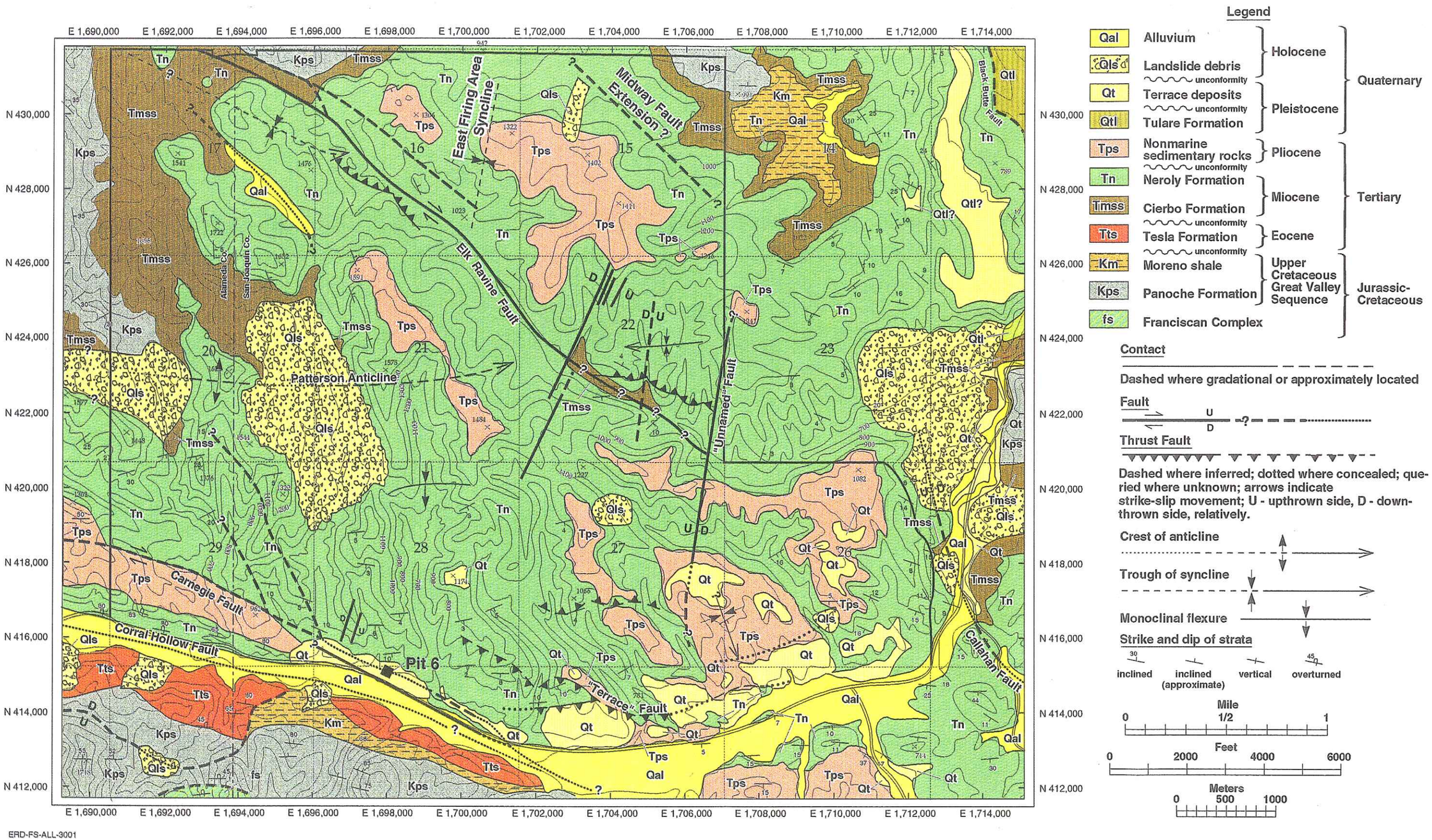

Figure 1-7. Geologic map of Site 300 area (modified from Dibblee, 1980a; Raymond, 1969; and Dugan and Mateik, 1990).

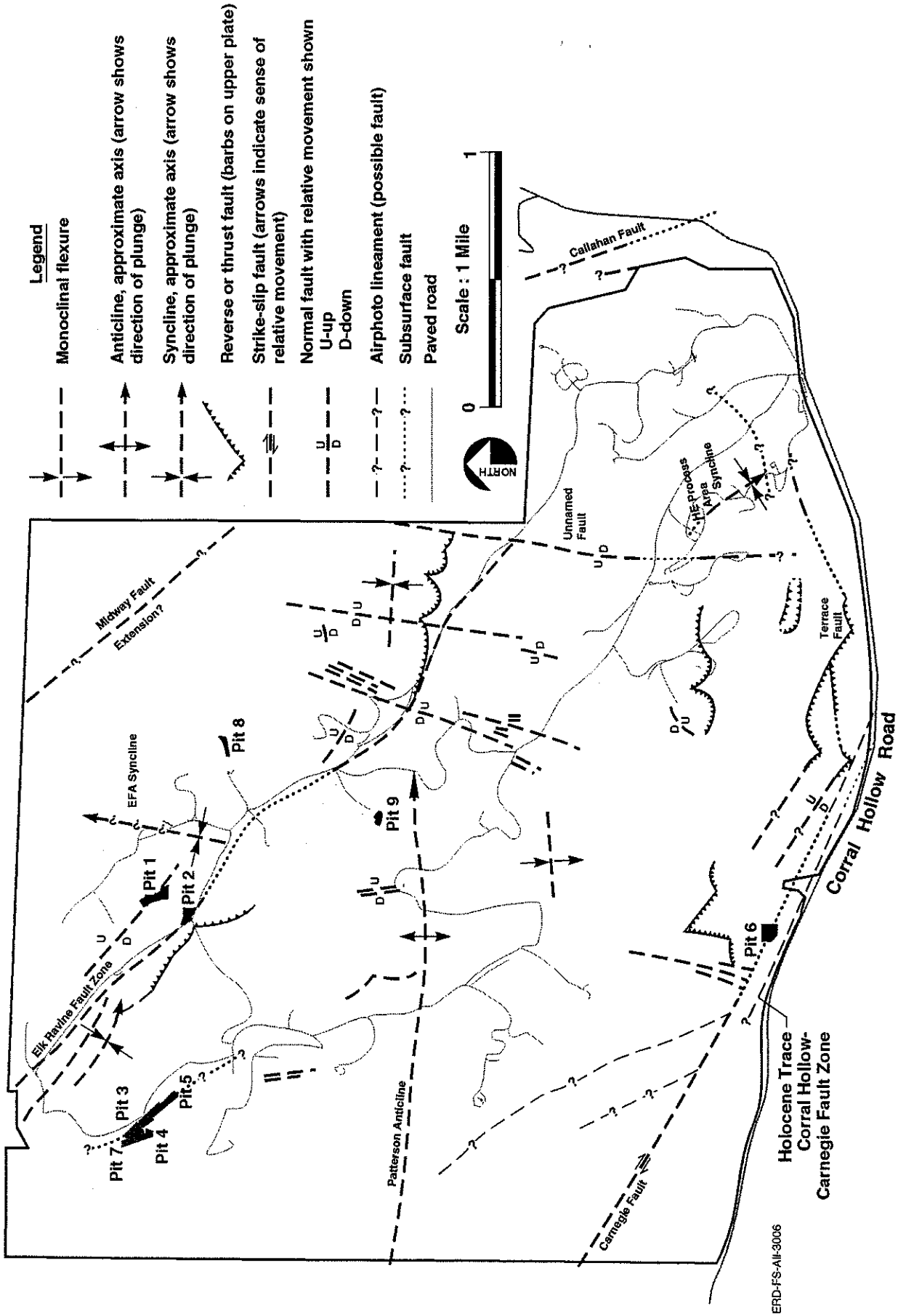

Figure 1-8. Map showing principal folds and faults, Site 300.

Figure 1-8

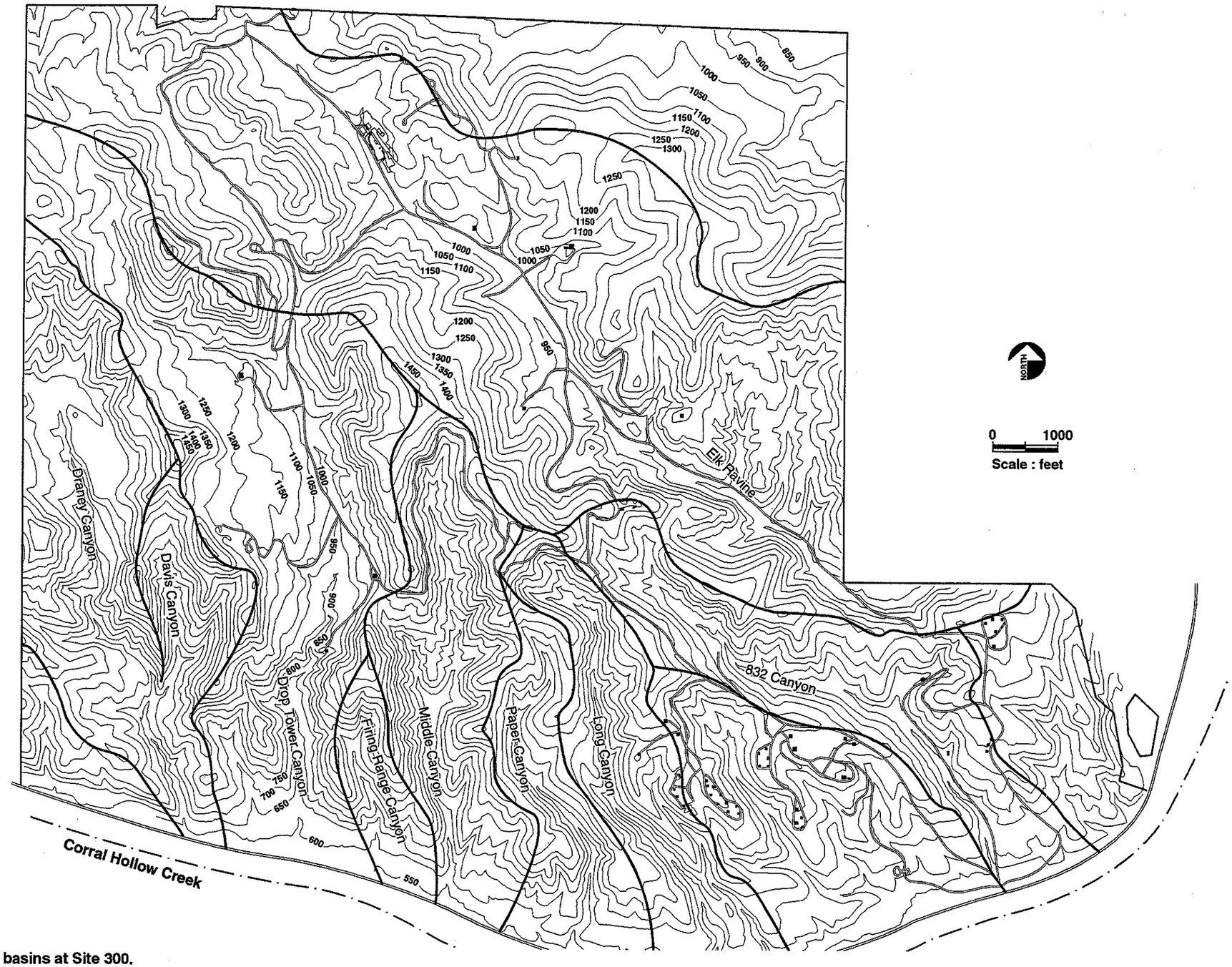

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Figure 1-9. Surface water drainage basins at Site 300.

Figure 1-9

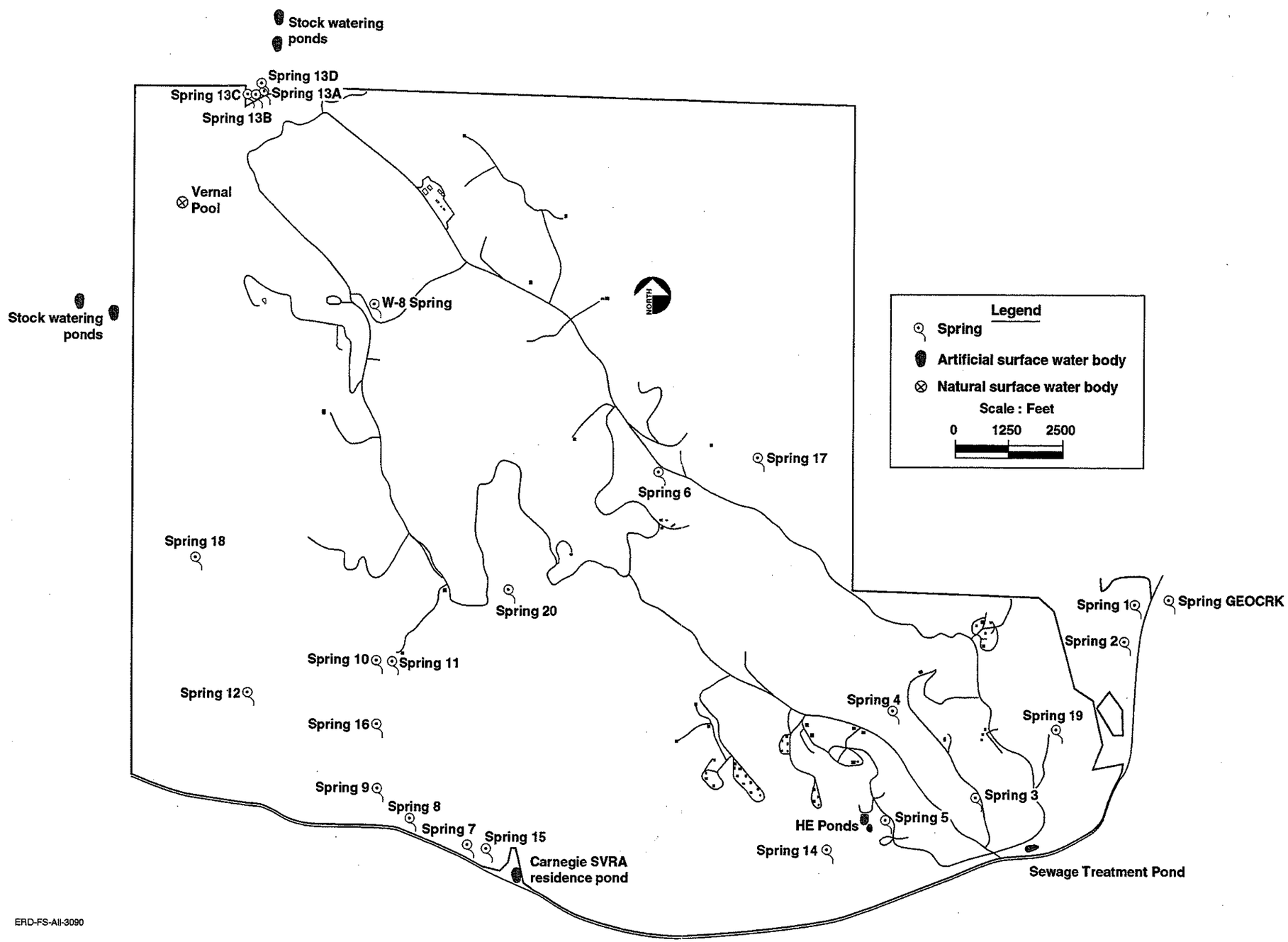
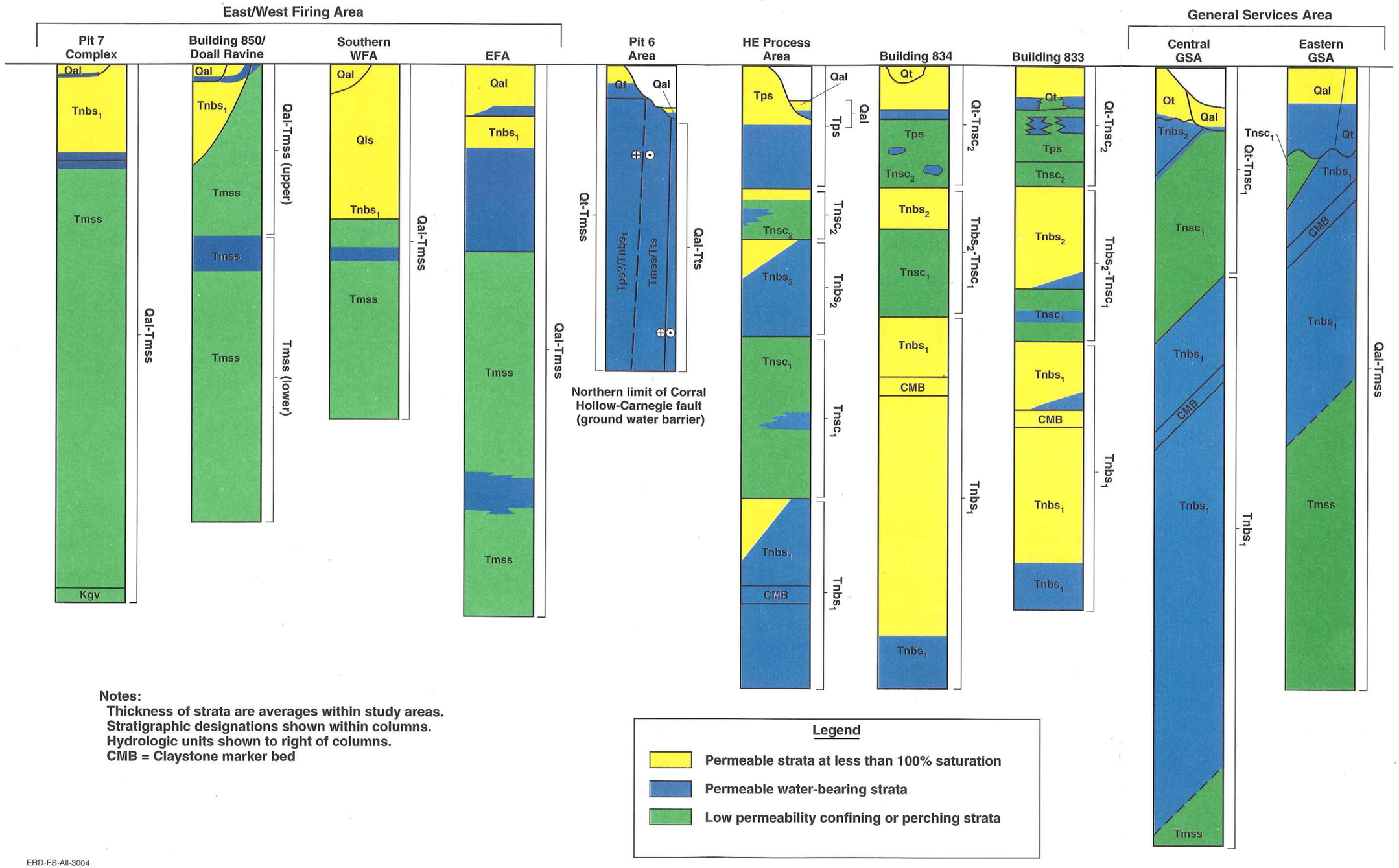


Figure 1-10. Surface water at Site 300.



Notes:
Thickness of strata are averages within study areas.
Stratigraphic designations shown within columns.
Hydrologic units shown to right of columns.
CMB = Claystone marker bed

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Figure 1-11. Stratigraphic and hydrologic units within the study areas at Site 300.

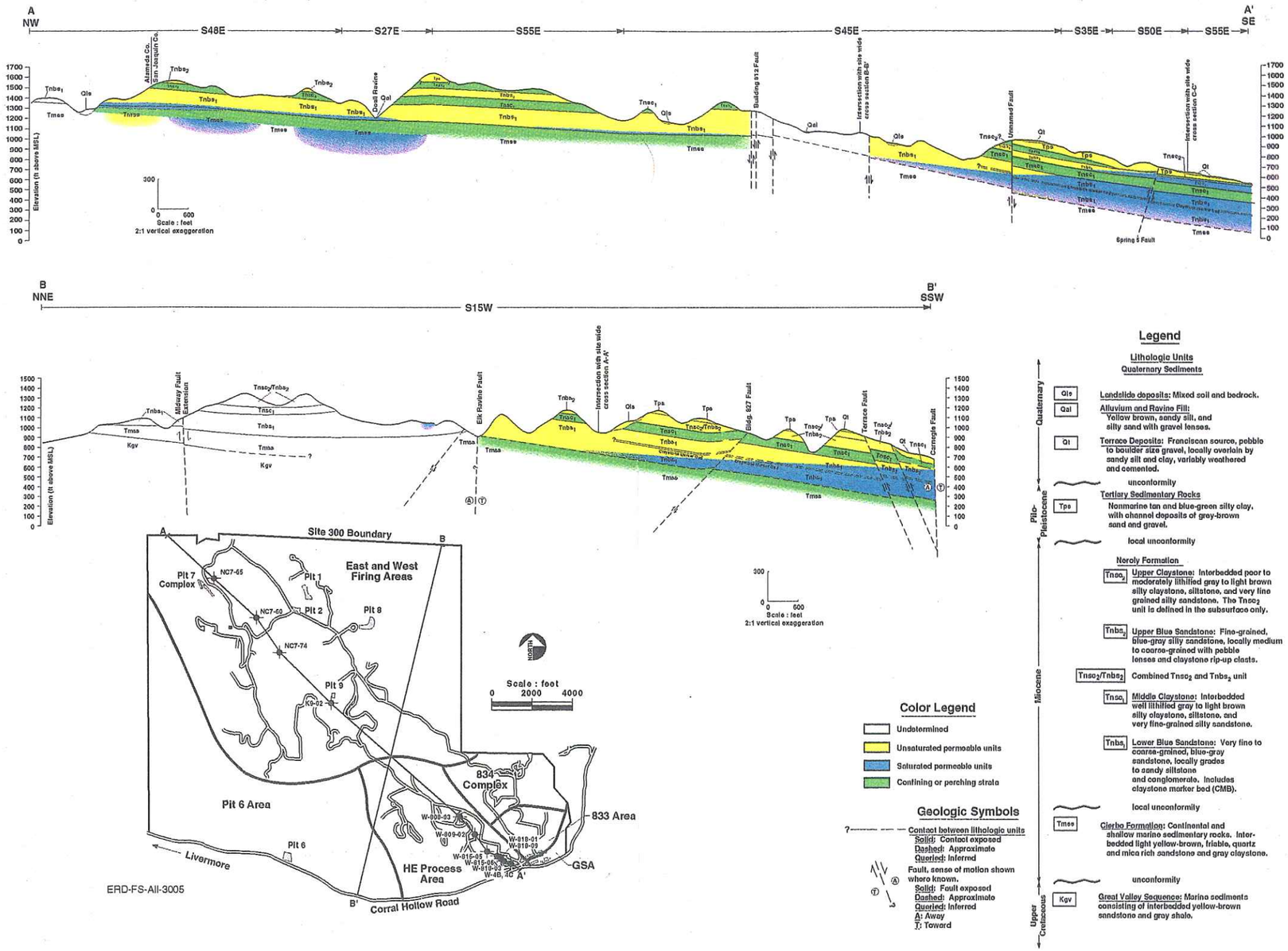
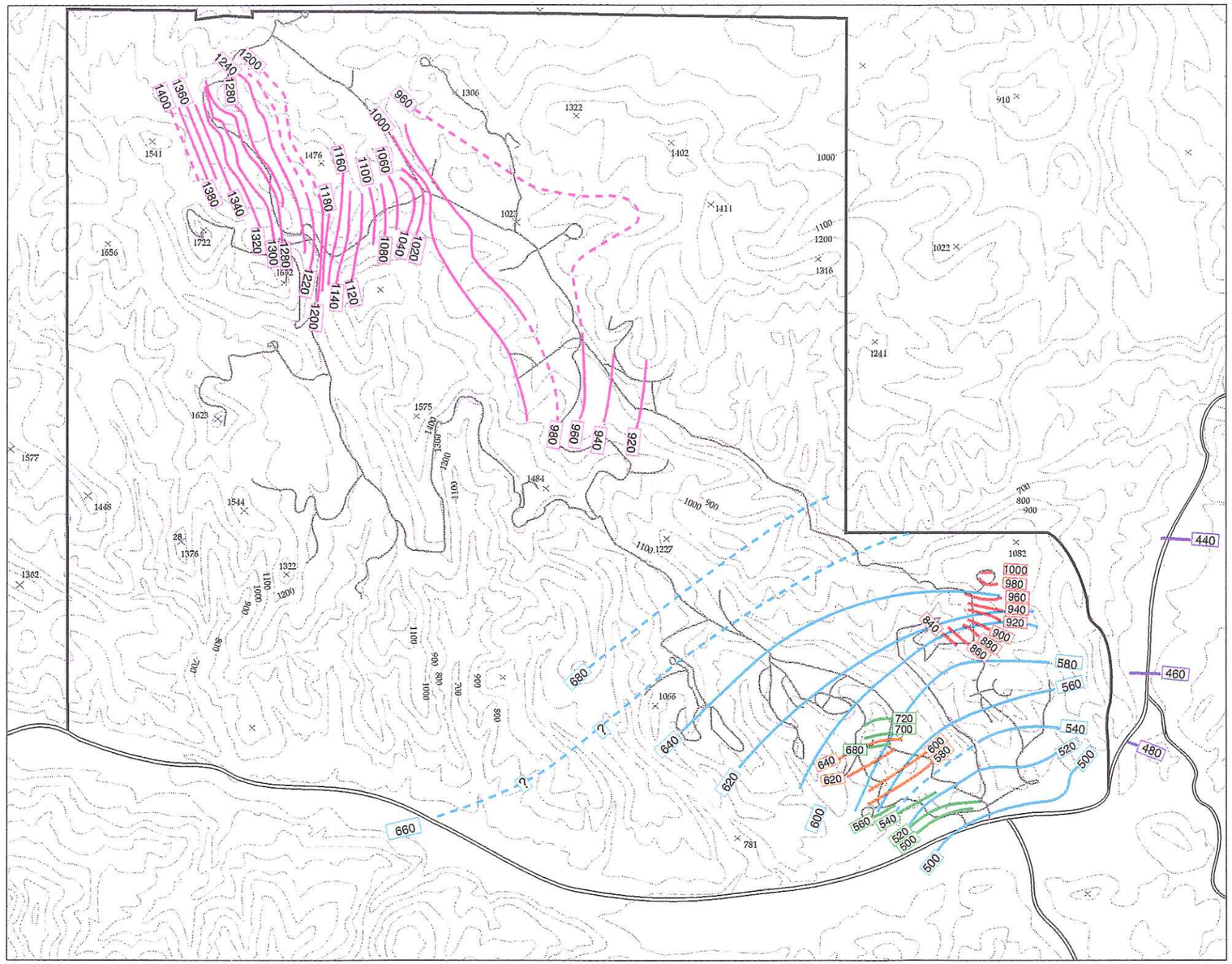


Figure 1-12. Site-wide hydrogeologic cross sections A-A' and B-B'.



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Legend

Potentiometric surface contours of principal water-bearing hydrogeologic units

Qt-Tnsc$_1$ (Central GSA) and Qal-Tmss (Eastern GSA)

Contours are shown for the first water-bearing zone within the Corral Hollow Creek alluvium and terrace deposits, and include some shallow bedrock wells. Ground water in this aquifer is semi-confined to unconfined. Ground water in the Qt-Tnsc$_1$ unit in the central GSA is partially derived from outflow from bedrock aquifer north of the GSA. All bedrock strata that subcrops beneath the Quaternary alluvium (Qal) in the Corral Hollow Creek stream channel are in hydraulic communication via the alluvium.

Qal-Tmss Hydrologic Units (Northwest Site 300)

Contours include data from wells completed in the Doall Ravine alluvium, and from some wells completed in bedrock, primarily the Neroly Formation lower blue sandstone (Tnbs$_1$) and the Cierbo Formation (Tmss), which is in direct contact with the alluvium. Hydraulic continuity of the Tnbs$_1$ regional aquifer with the southern portion of Site 300 is not established. Hydraulic continuity may be intermittent, and dependent on temporal variations in recharge.

Hydrologic Tps (Building 834)

Contours based on data from shallow wells completed in the perched water-bearing zone within the Pliocene nonmarine unit (Tps). The perched zone outcrops and discharges on the hillslopes.

Tps Hydrologic Unit (HE Process Area)

Potentiometric surface contours are based on water levels measured in ground water monitor wells completed in the Pliocene nonmarine unit (Tps). Ground water in the Tps unit is perched in the northern part of the HE Process Area. Saturation in the Tps strata increases southward, and ground water is under artesin conditions near the southern boundary of Site 300.

Tnbs$_2$ Hydrologic Unit (HE Process Area)

Data contoured are from wells completed in the Neroly Formation upper blue sandstone (Tnbs$_2$) unit. The Tnbs$_2$ aquifer is saturated only in the HE Process Area in southeastern Site 300. Hydraulic conditions range from unconfined in the northern HE Process Area to flowing artesian to the south near Corral Hollow Road. This unit serves as a local off-site water-supply aquifer.

Tnbs$_1$ Hydrologic Unit (Southern Site 300)

Contours based on data from wells completed in the Neroly Lower Blue Sandstone (Tnbs$_1$) regional water-supply aquifer. The Tnbs$_1$ unit is unsaturated in the central portion of the site. Ground water in the Tnbs$_1$ is under flowing artesian conditions near Corral Hollow Road. The Tnbs$_1$ unit is in hydraulic communication with the Qt-Tnsc$_1$ and other water-bearing units in the southeastern portion of the site, either through direct contact or through mutual communication with the Corral Hollow Creek alluvium (Qal). This unit serves as a water-supply aquifer both on and off site.

Ground water potentiometric surface elevation countour in feet above mean sea level, dashed were approximately located and queried where uncertain

Notes:

1) Ground water elevation data from December 1991
2) Potintiometric contours shown on this plate are taken from figures presented in the hydrogeology sections of Chapters 9—14 in the SWRI report. Wells and water level data used to generate potentiometric contours are included in those sections.

Feet: 0 2000 4000 6000

Meters: 0 500 1000

Figure 1-13. Potentiometric surface elevation map of major water-bearing units at Site 300.

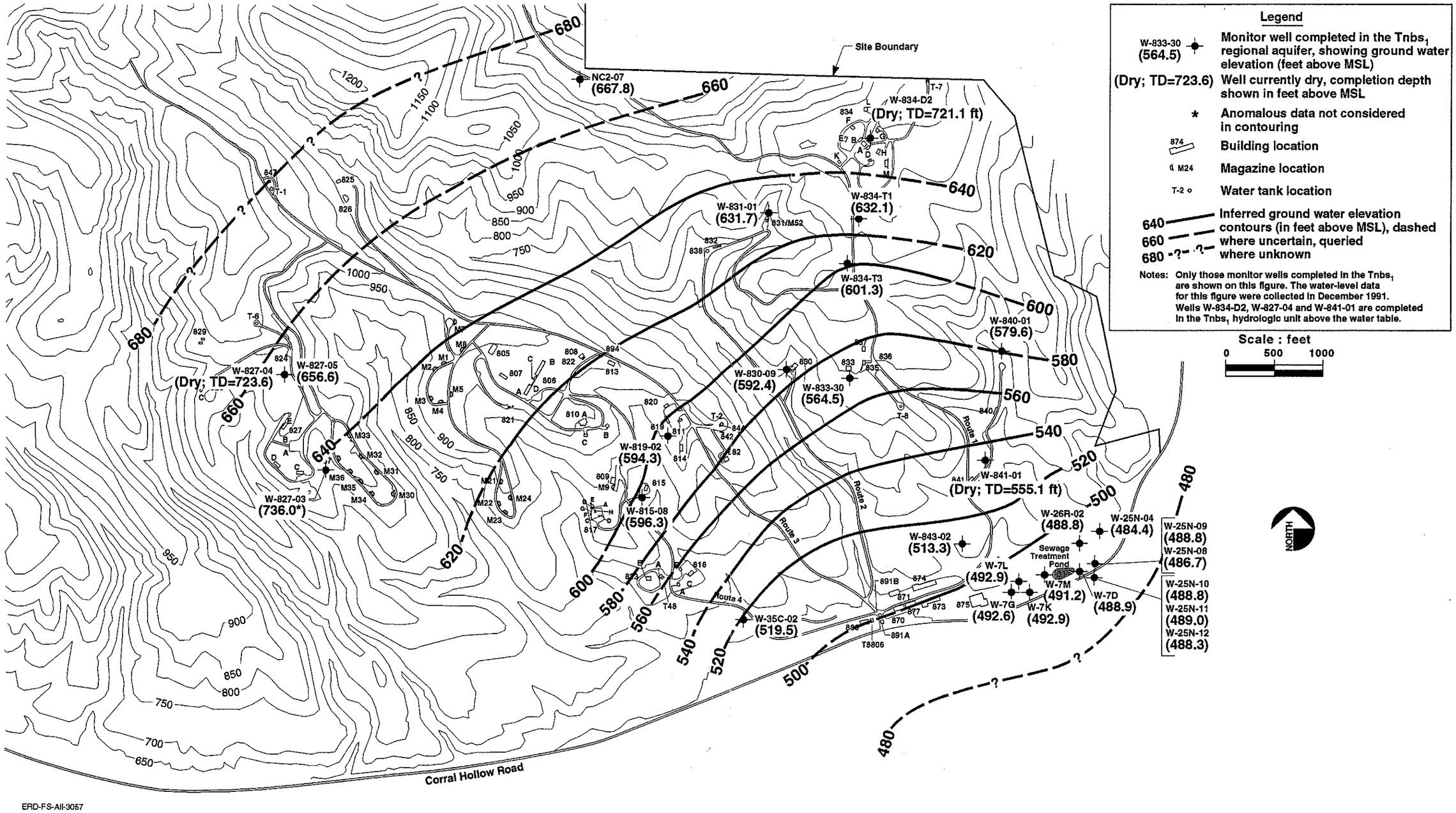

Figure 1-14. Potentiometric map of ground water for the $Tnbs_1$ regional aquifer in southeastern Site 300 (December 1991 data).

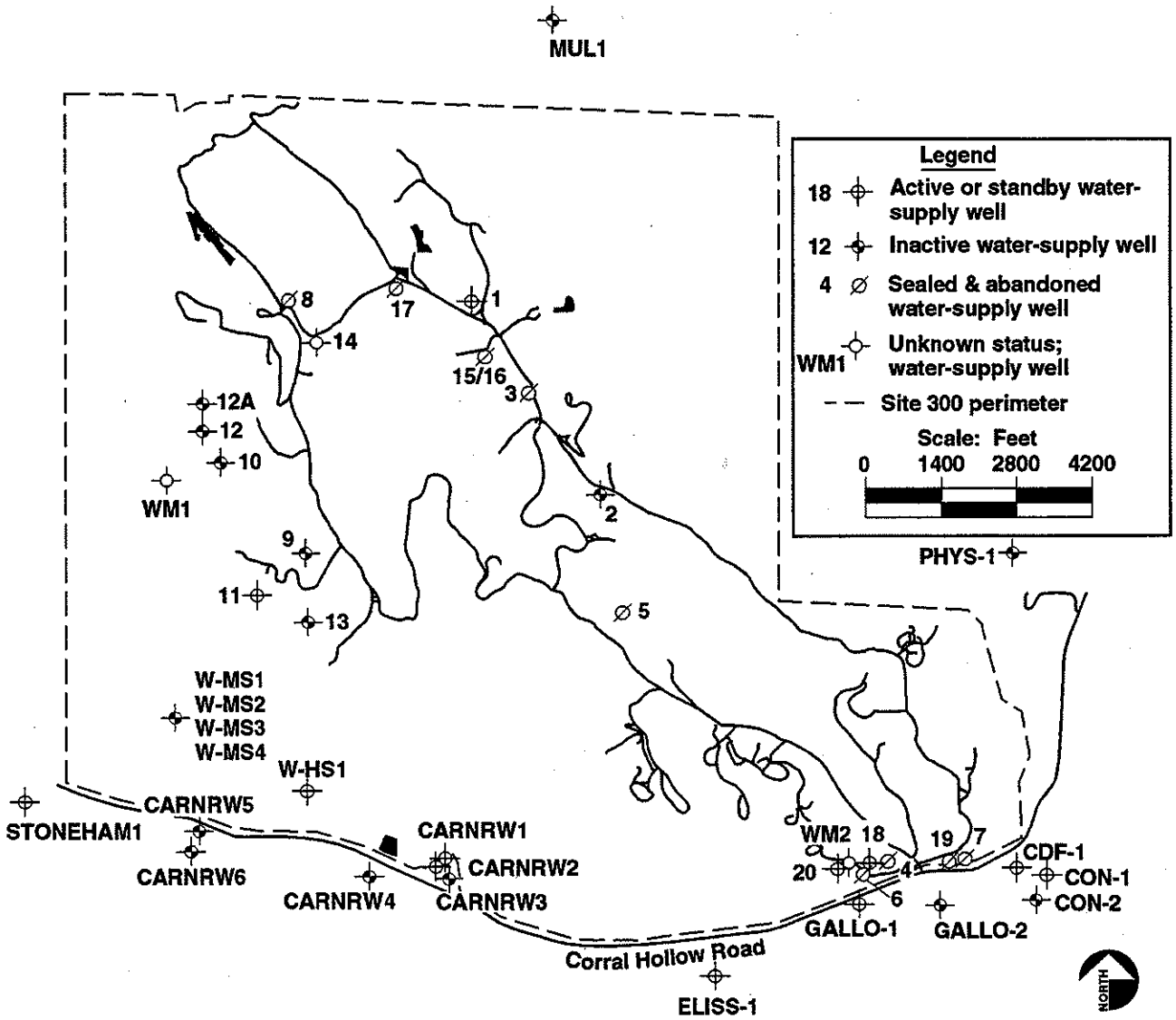

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Figure 1-15. Water-supply wells at and within 0.5 mi of Site 300.

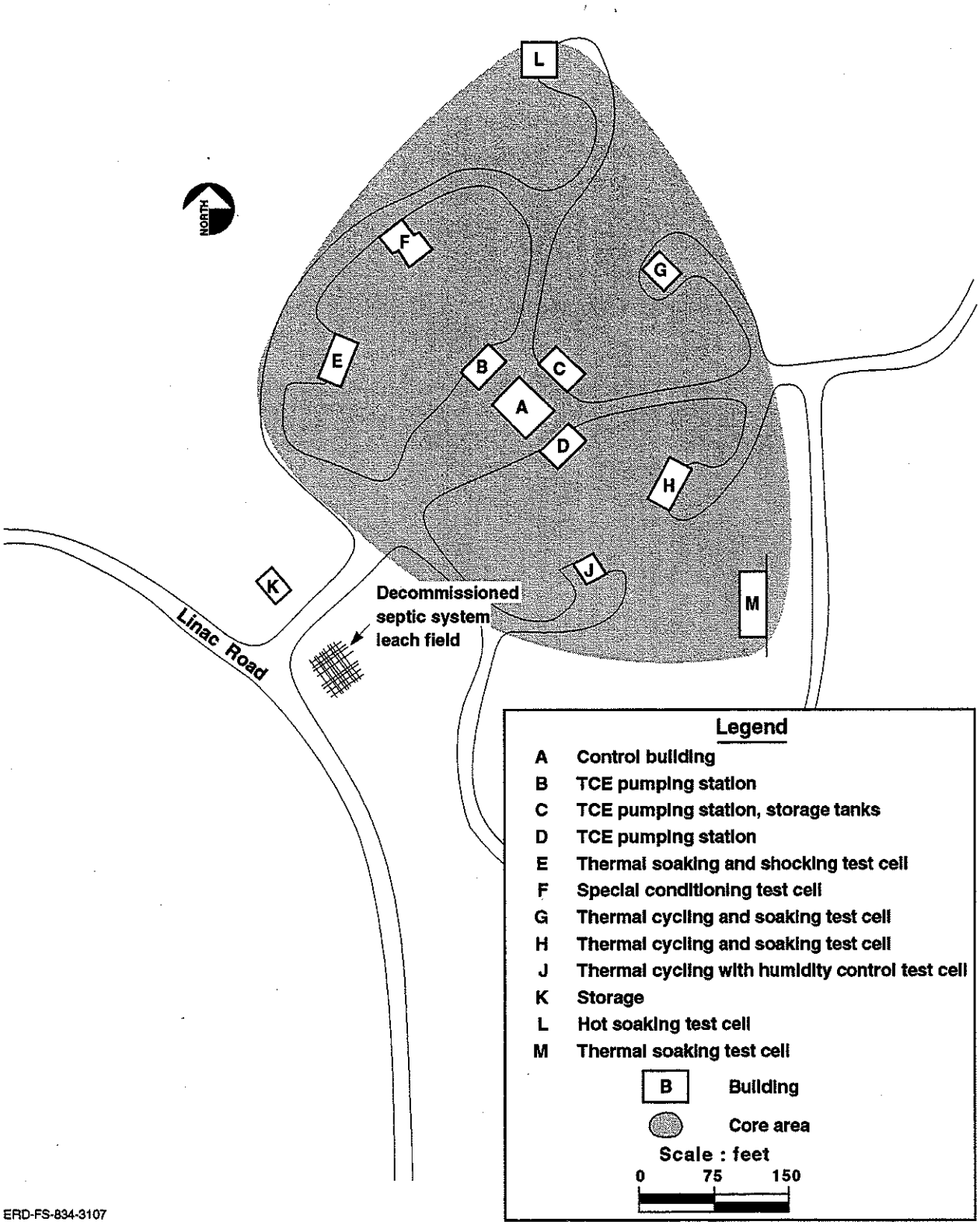

Figure 1-16. Functions of the buildings at the Building 834 Complex.

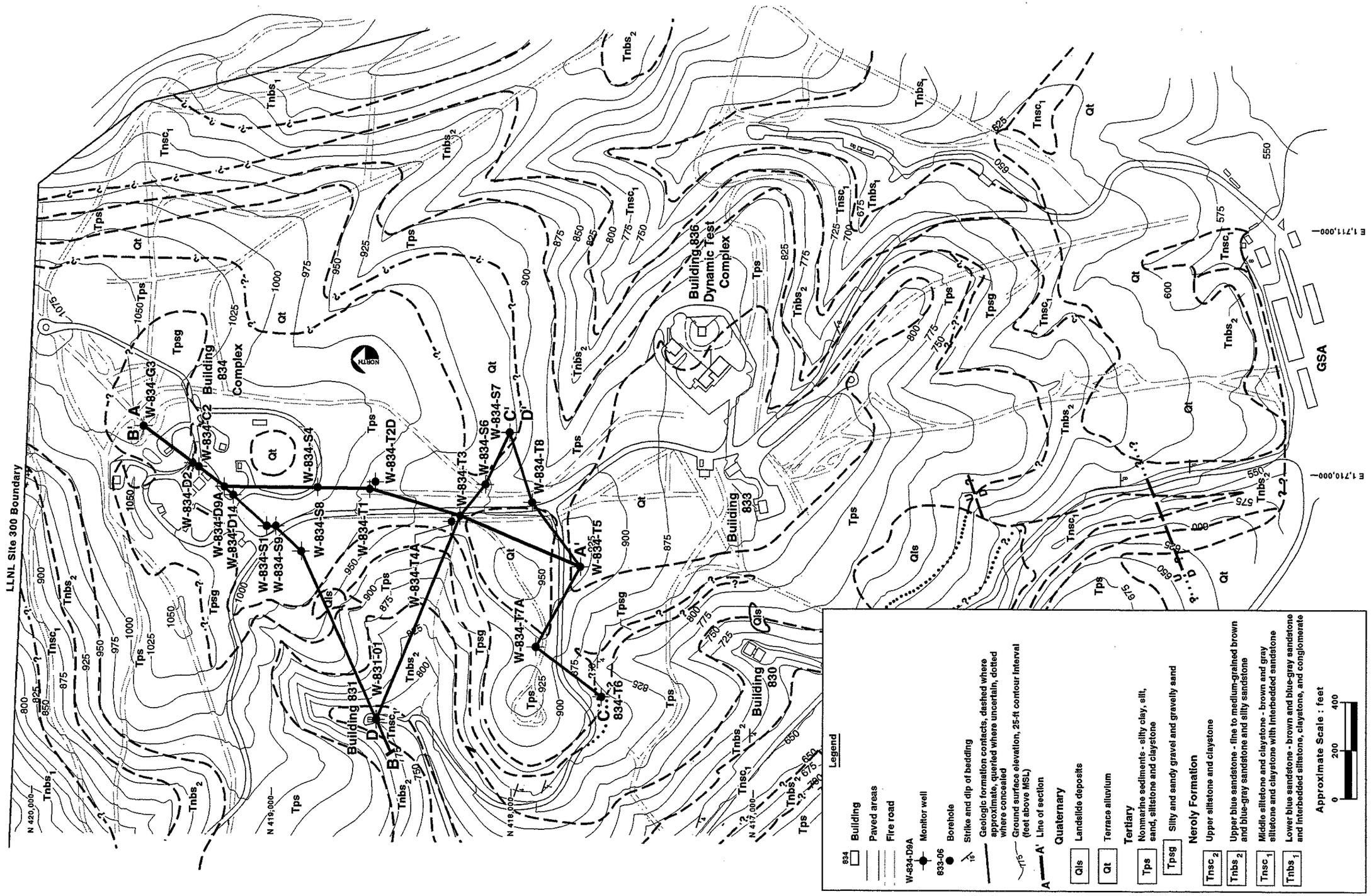

Figure 1-17

Figure 1-17. Geologic and topographic map of Building 834 and vicinity with hydrologic cross section locations.

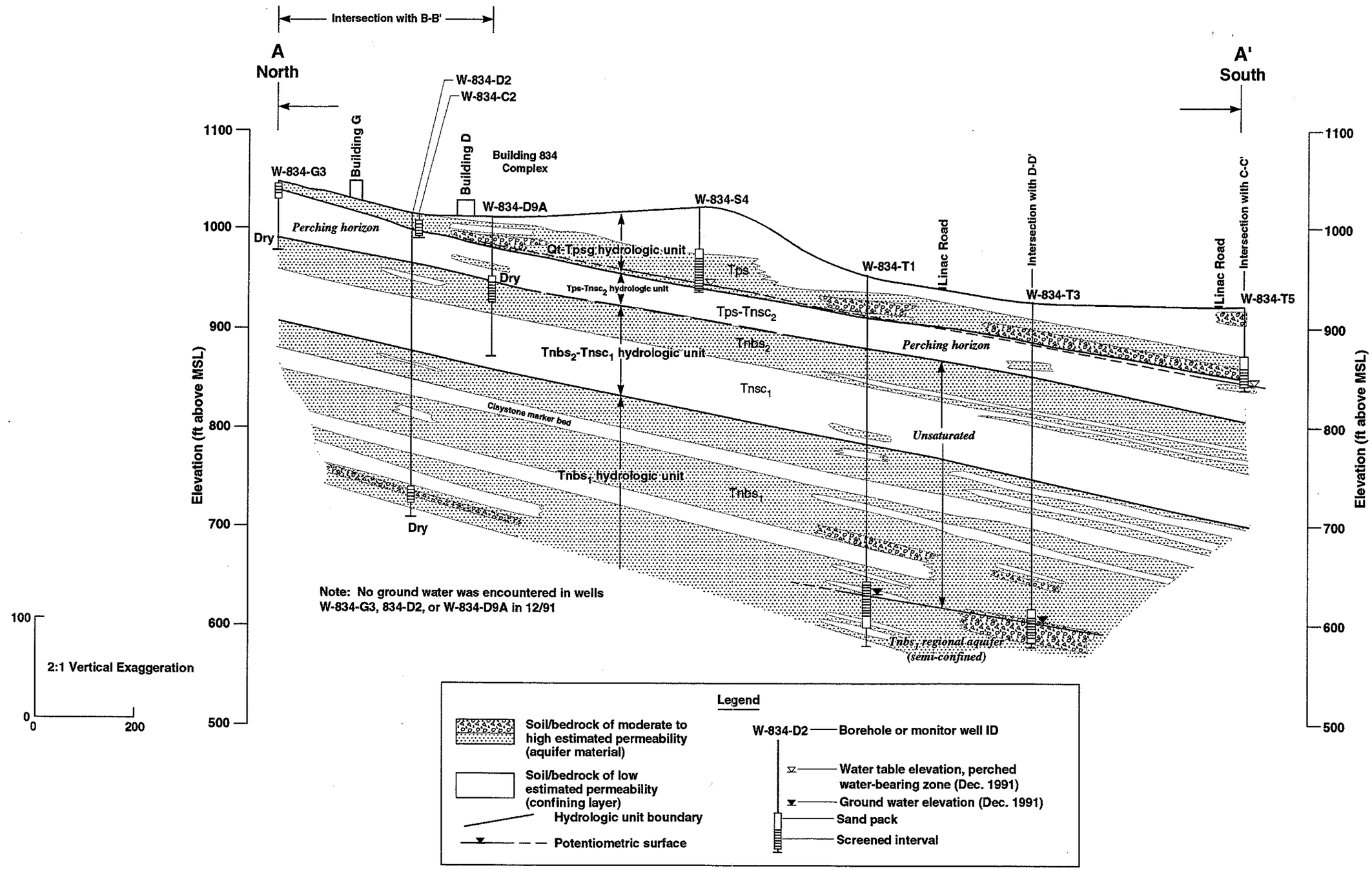

Figure 1-18. North-south hydrologic cross-section A-A' of the area between Buildings 833 and 834.

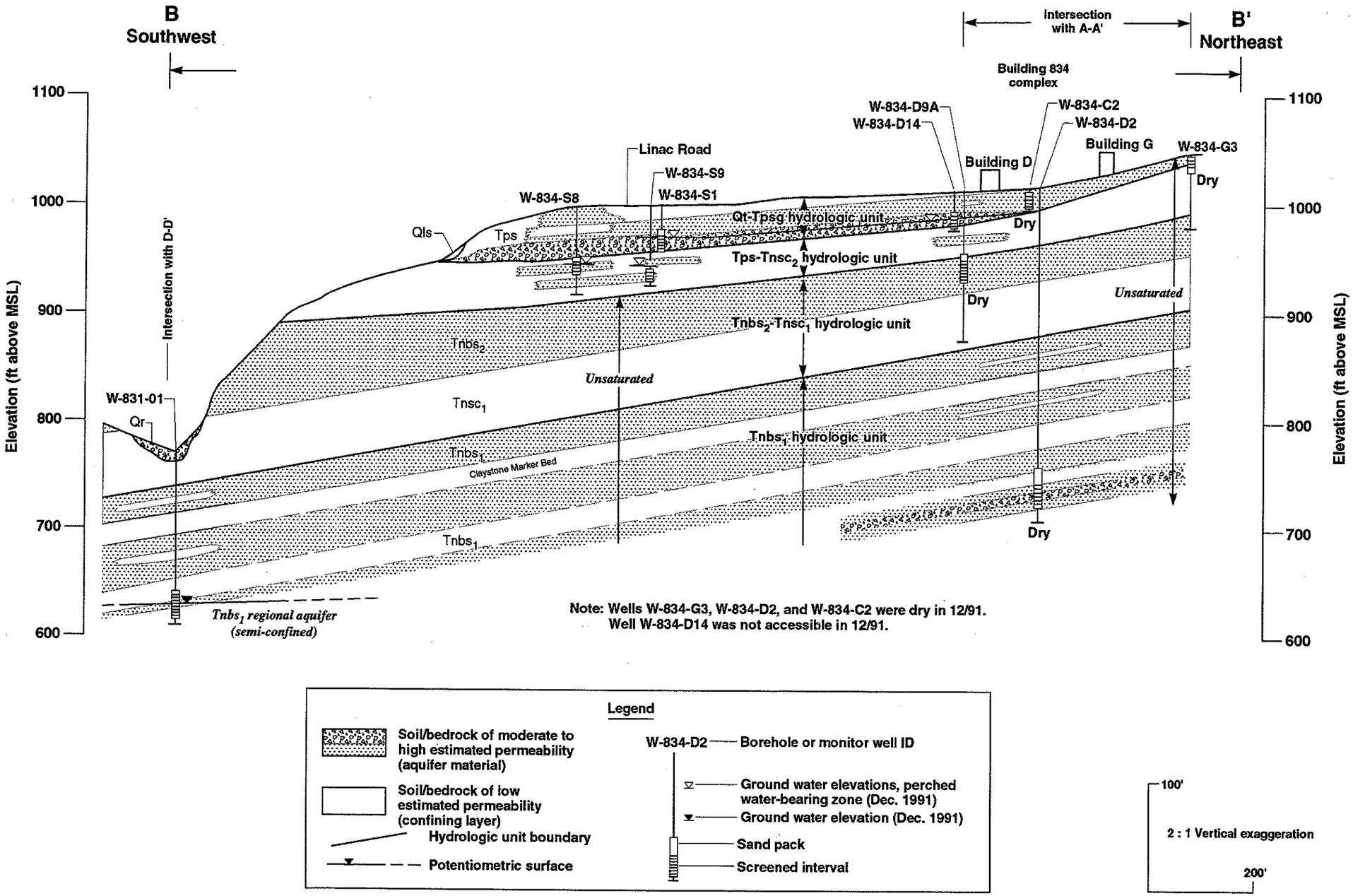

Figure 1-19. Southwest-northeast cross-section B-B', Building 834 Complex.

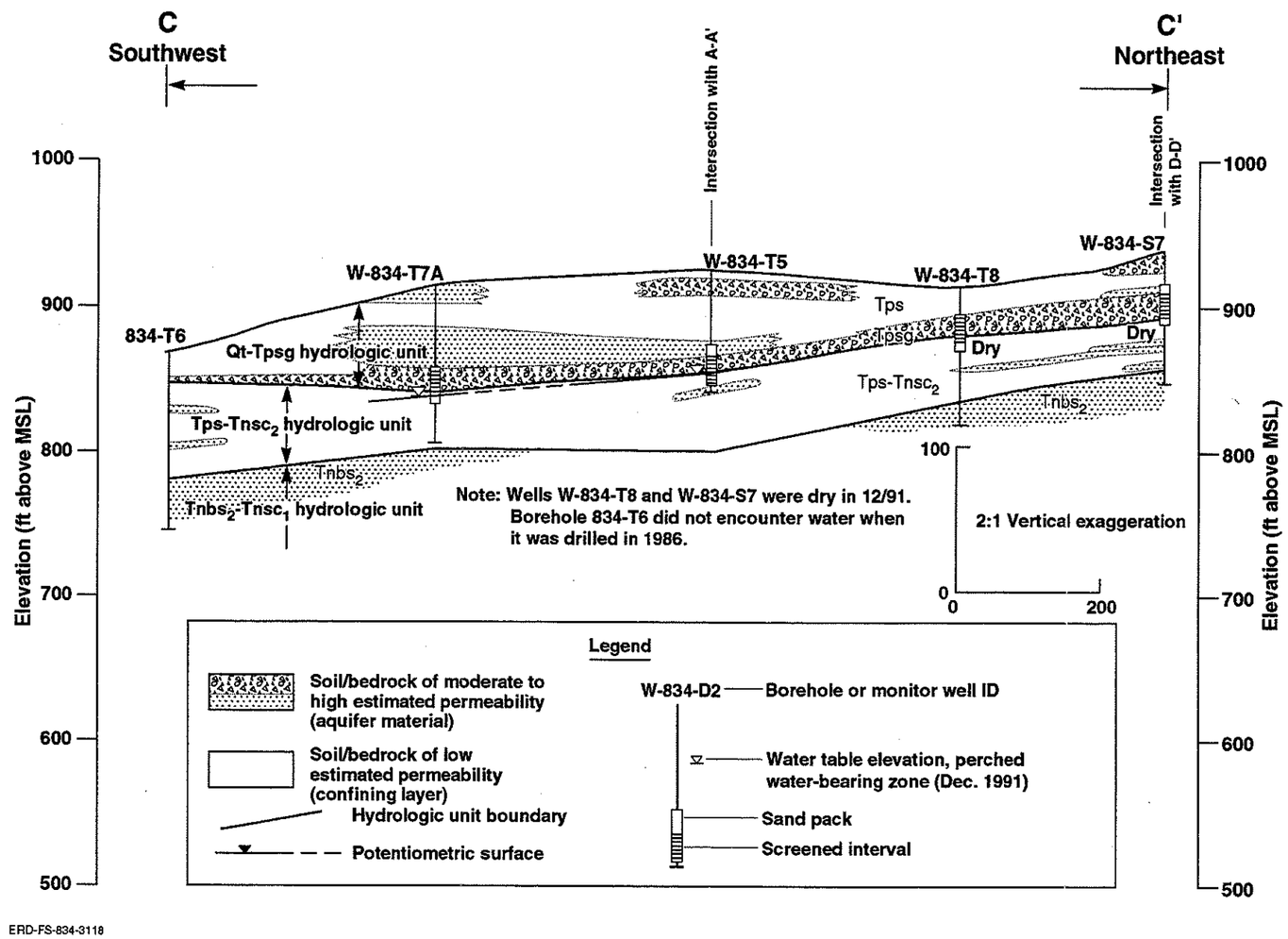

Figure 1-20. Southwest-northeast hydrologic cross-section C-C', Building 834 Complex.

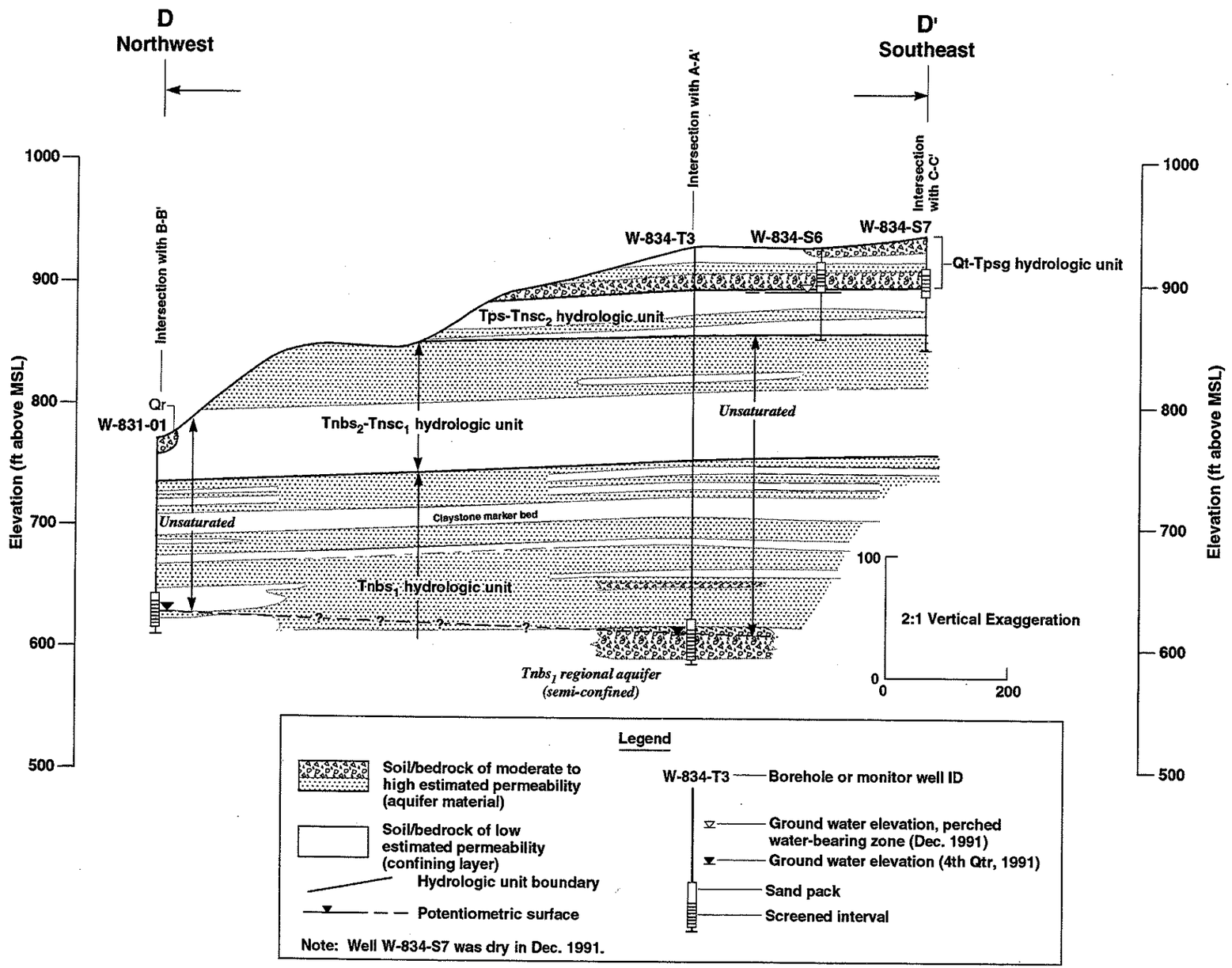

Figure 1-21. Hydrologic cross-section D-D', Building 834 Complex.

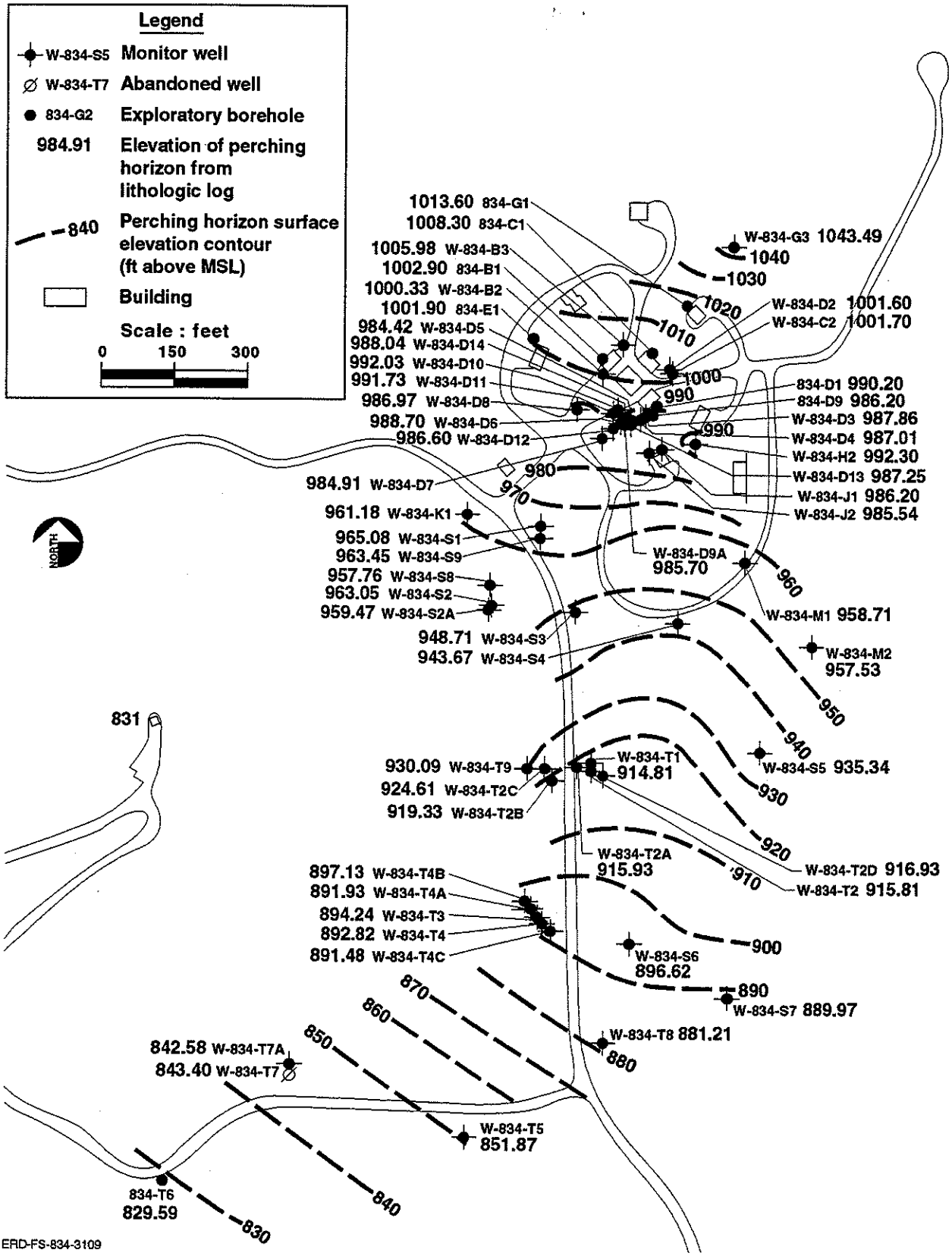

Figure 1-22. Elevation contour map of perching horizon surface (top of Tps-Tnsc$_2$ hydrologic unit) at the Building 834 Complex site.

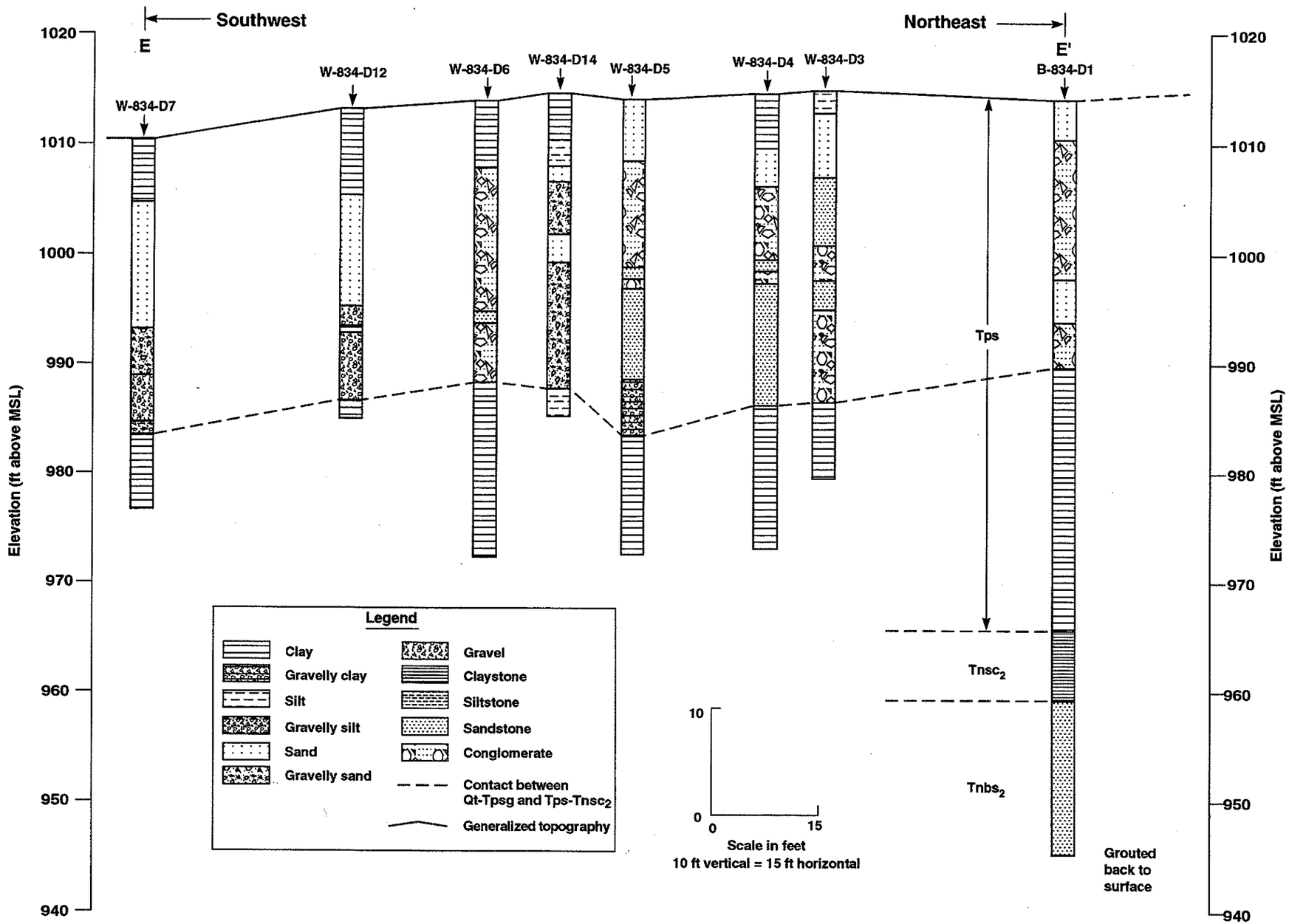

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Figure 1-23. Vertical and lateral heterogeneity of fluvial depositional units near Building 834D. (See Figure 1-24 for location map.)

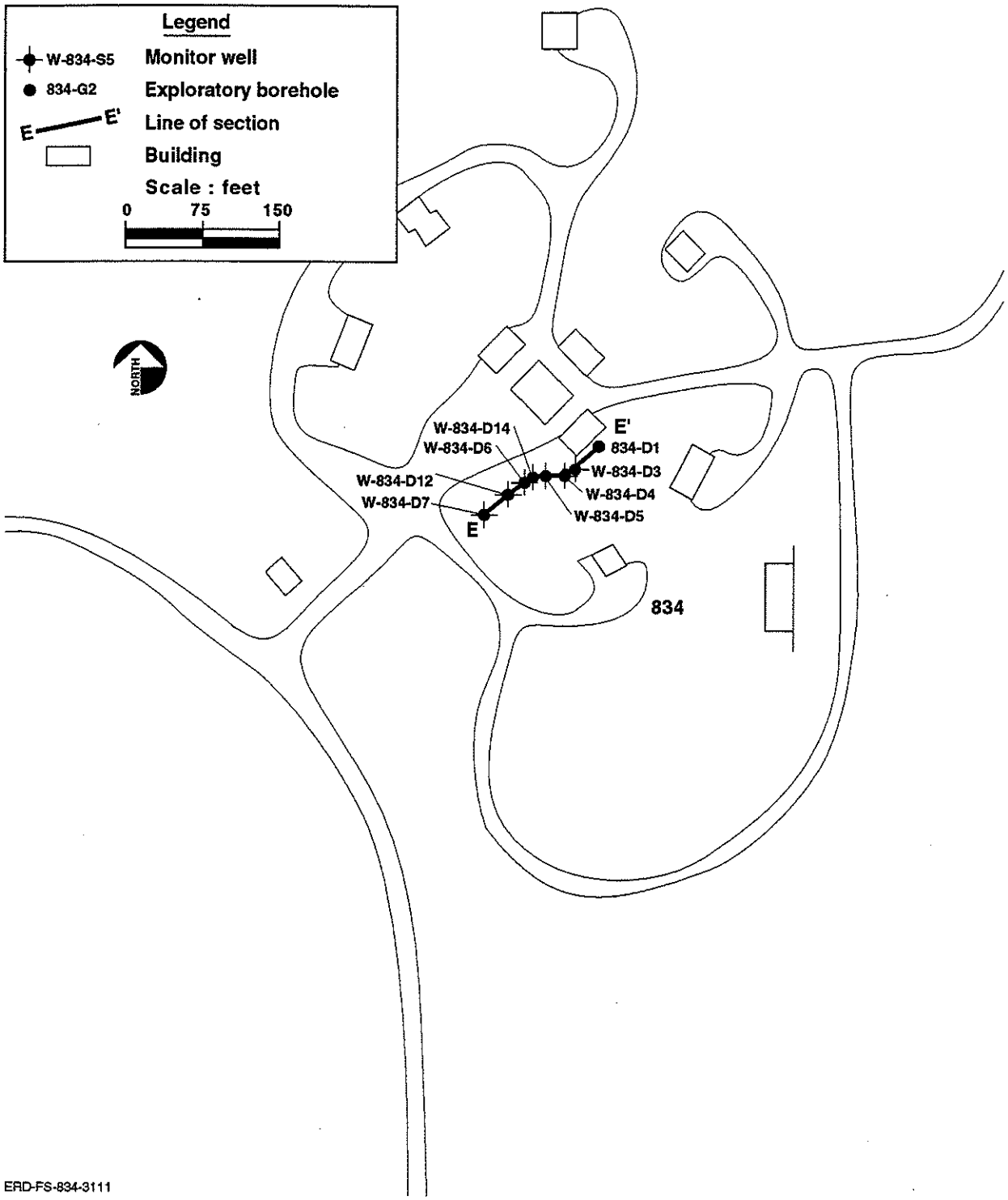

Figure 1-24. Location map for illustration of vertical and lateral heterogeneity of fluvial depositional units adjacent to Building 834D.

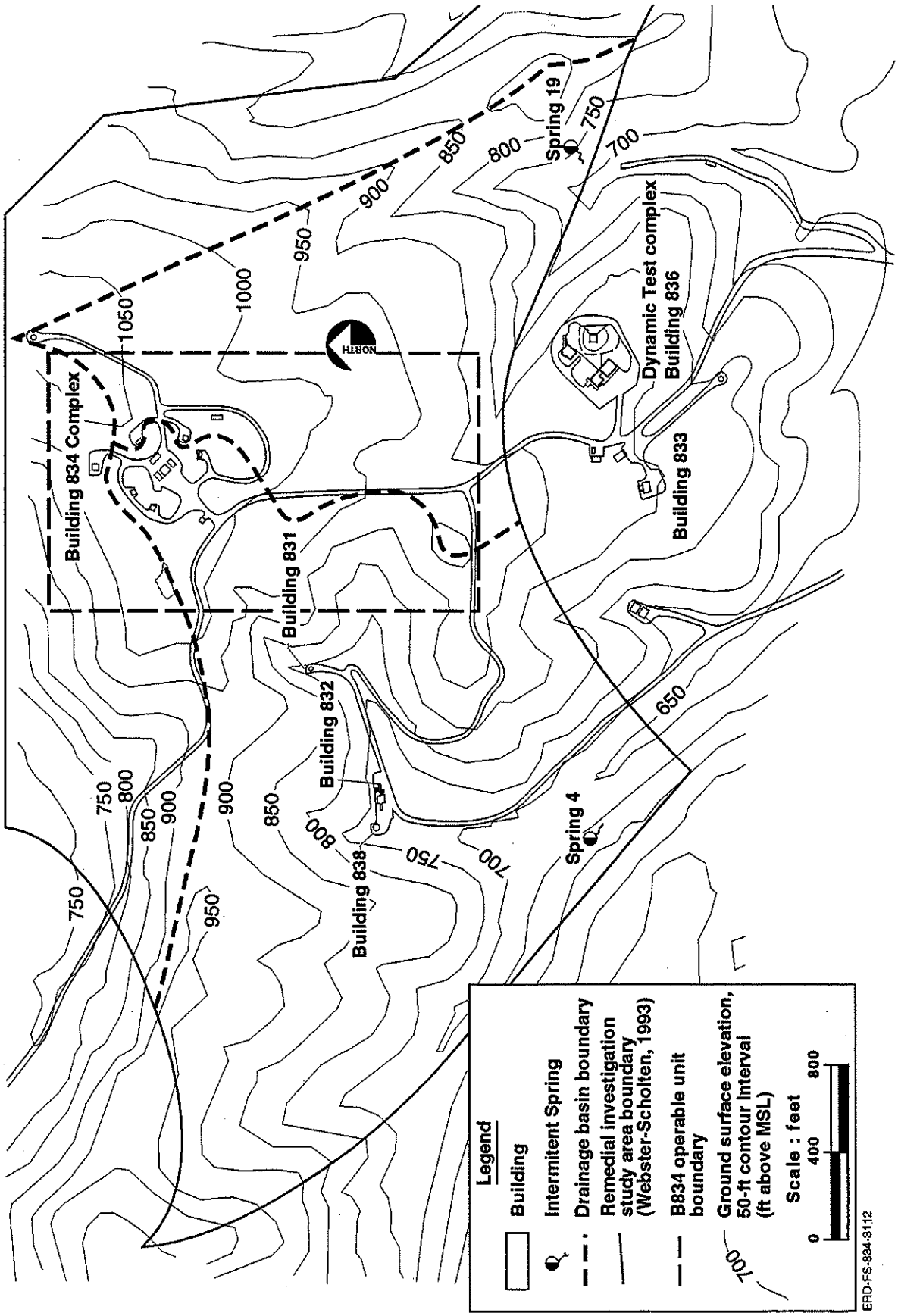

Figure 1-25. Drainage basins and intermittent springs in the vicinity of the Building 834 operable unit.

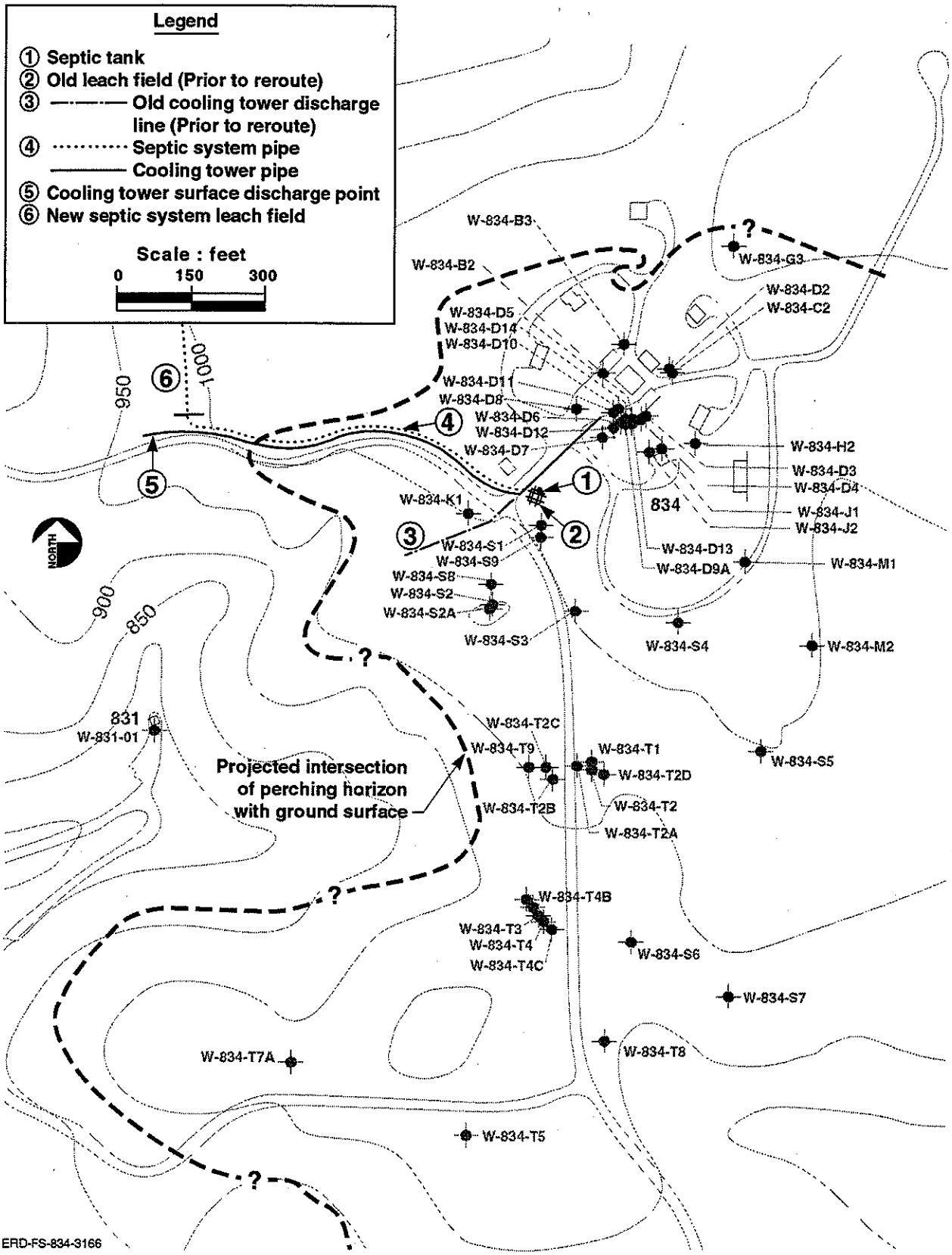

Figure 1-26. Building 834 cooling tower and septic tank system reroute.

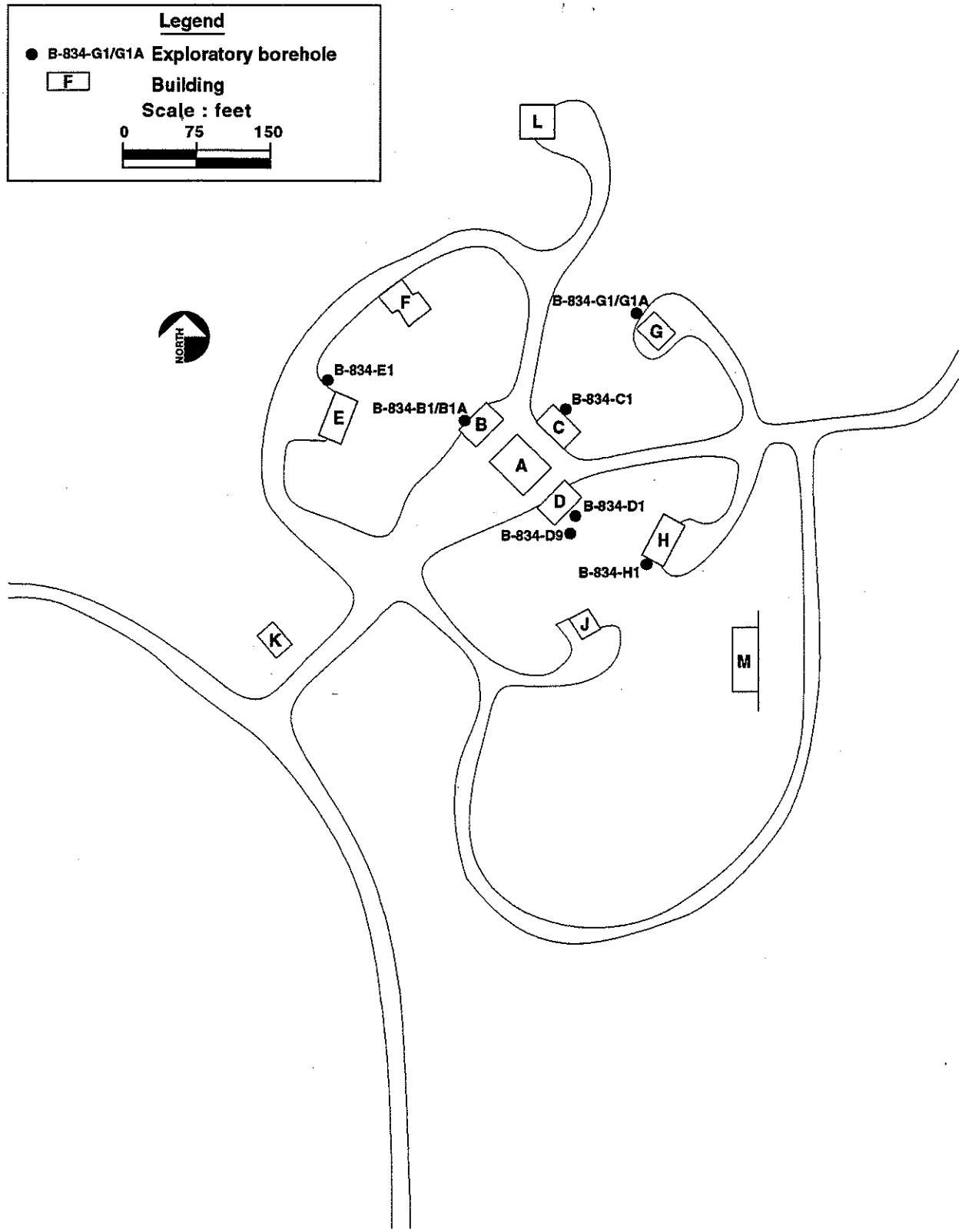

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Figure 1-27. Exploratory boreholes at the Building 834 Complex.

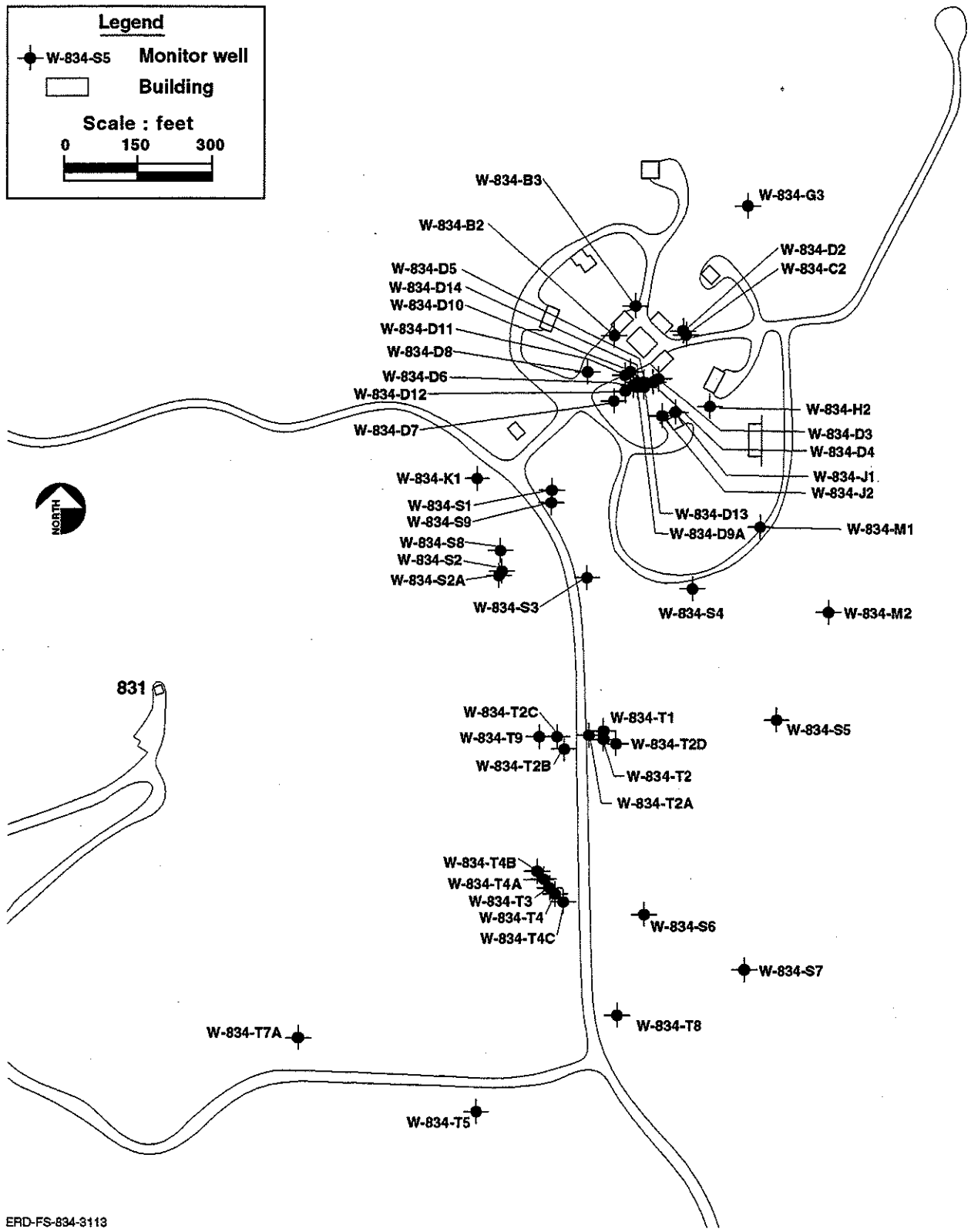
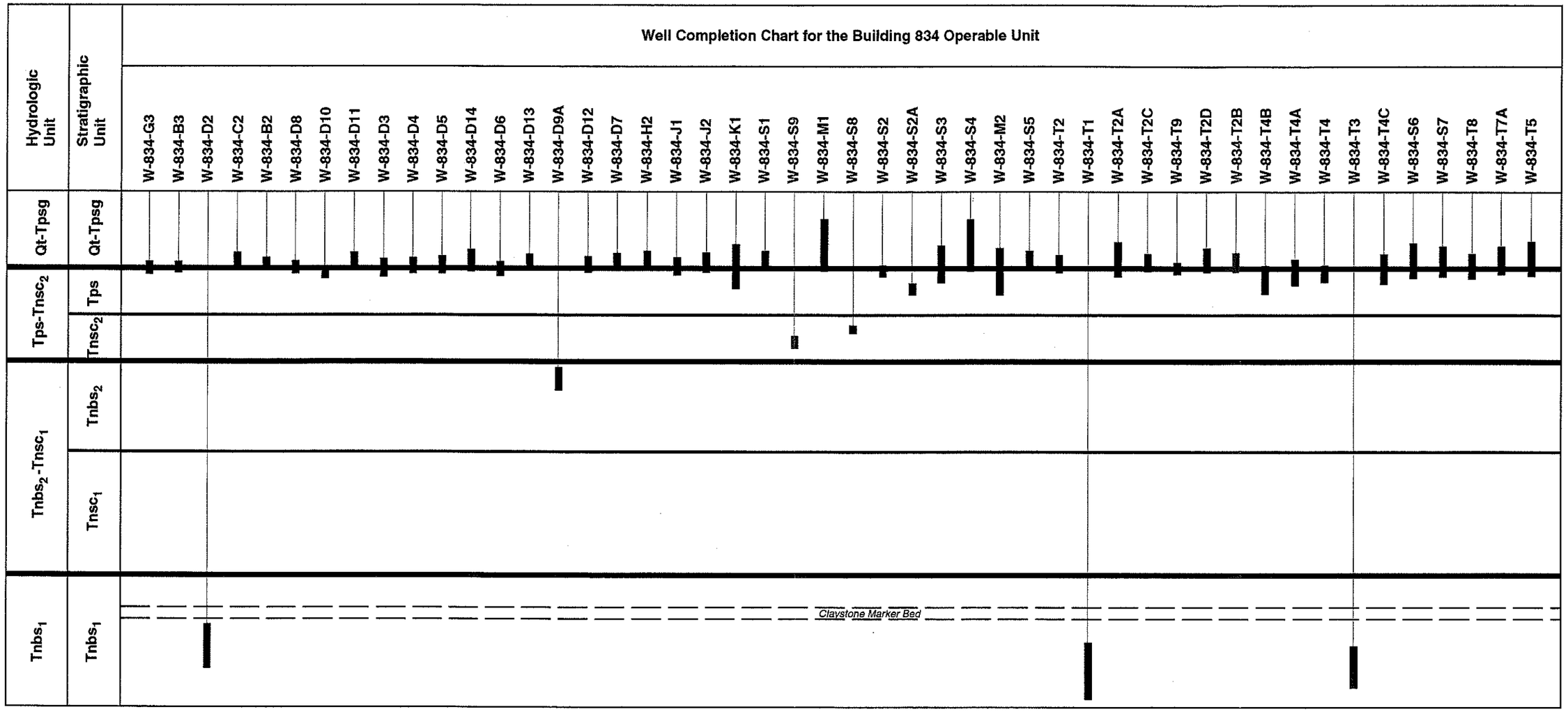


Figure 1-28. Monitor wells in the Building 834 operable unit in December 1991.



▌	Sand pack interval
Qt-Tpsg	Quaternary terrace alluvium and gravel member of the non-marine Tps
Tps	Tertiary non-marine clay and claystone
$Tnsc_2$	Neroly Formation upper siltstone/claystone
$Tnbs_2$	Neroly Formation upper blue sandstone
$Tnsc_1$	Neroly Formation middle siltstone/claystone
$Tnbs_1$	Neroly Formation lower blue sandstone

Notes:
1) Wells are generally shown from north to south
2) Distances and sand pack intervals are not to scale

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Figure 1-29. Well completion chart for the Building 834 operable unit.

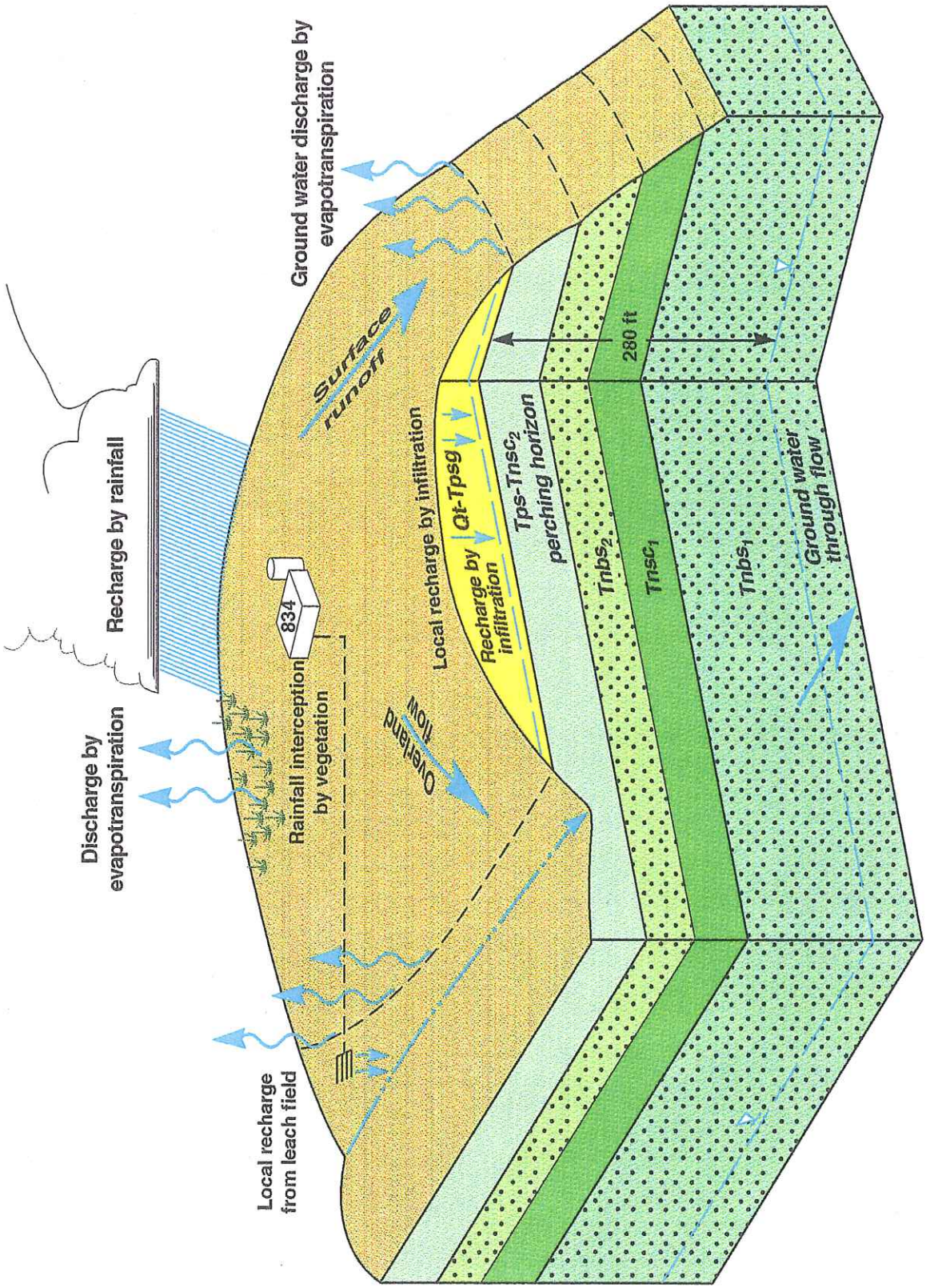

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Figure 1-30. Conceptual hydrologic model of the Building 834 operable unit.

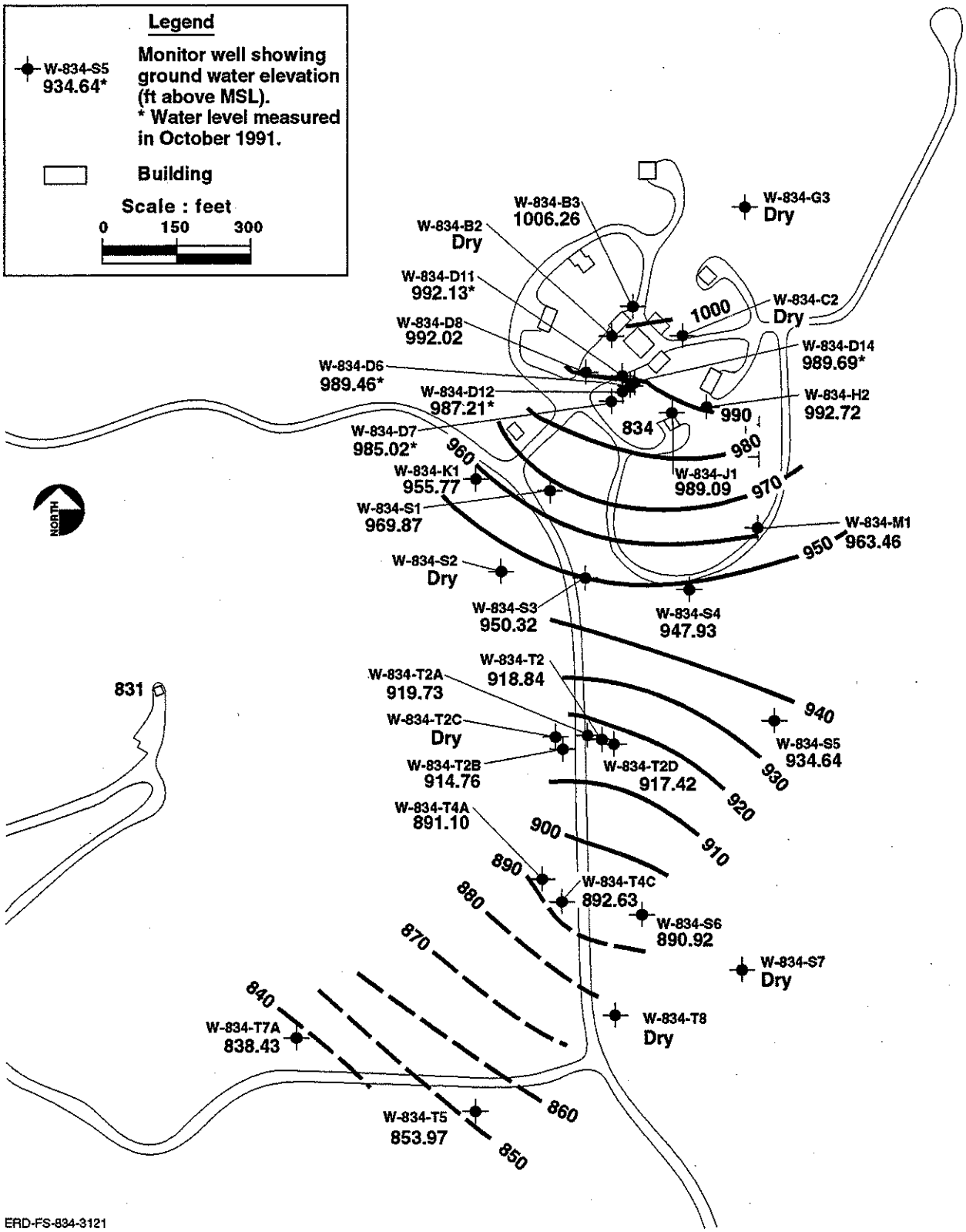

Figure 1-31. Elevation of perched ground water table at the Building 834 Complex site in December 1991.

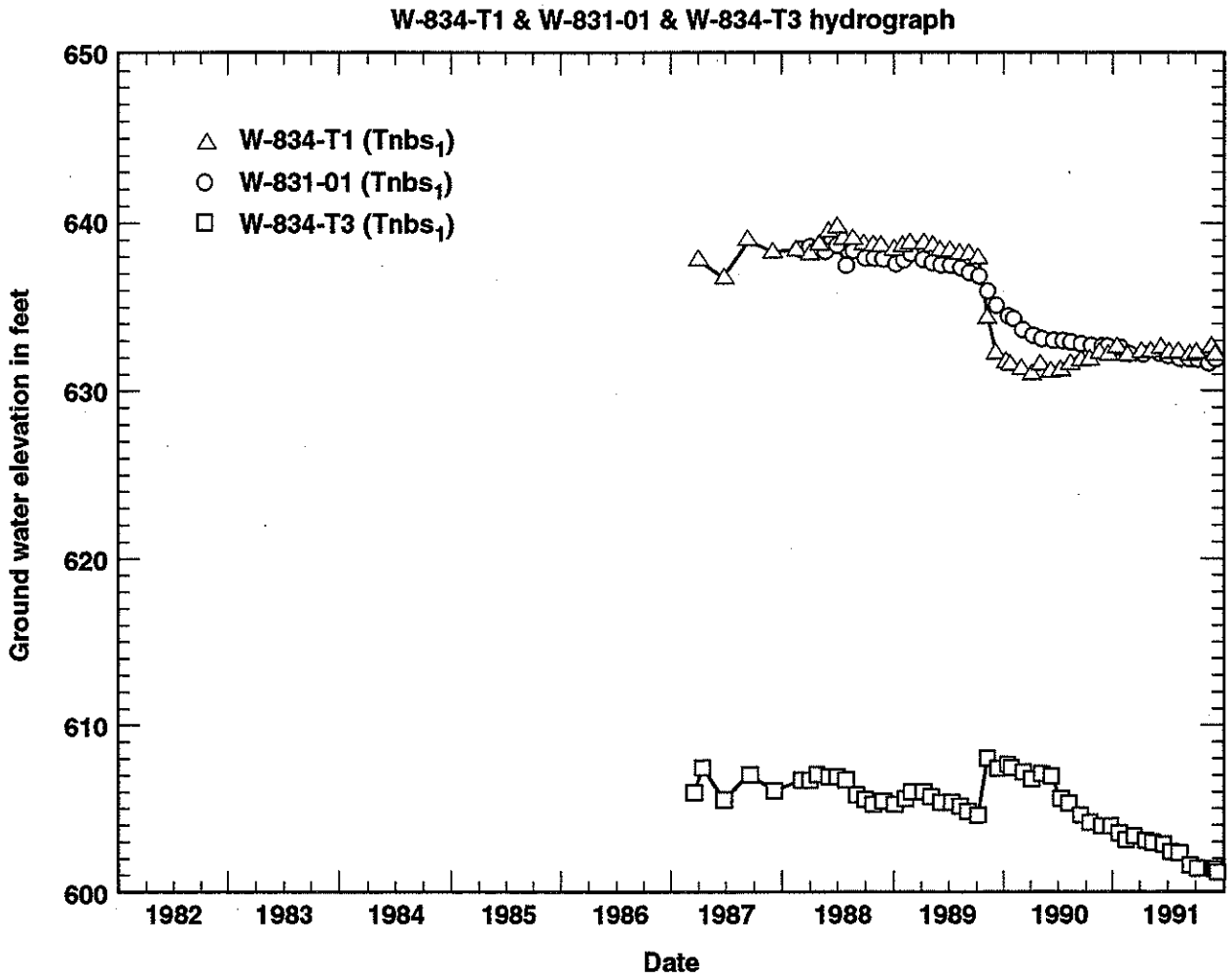

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Figure 1-32. Hydrographs for regional aquifer ($Tnbs_1$) wells in the Building 834 operable unit.

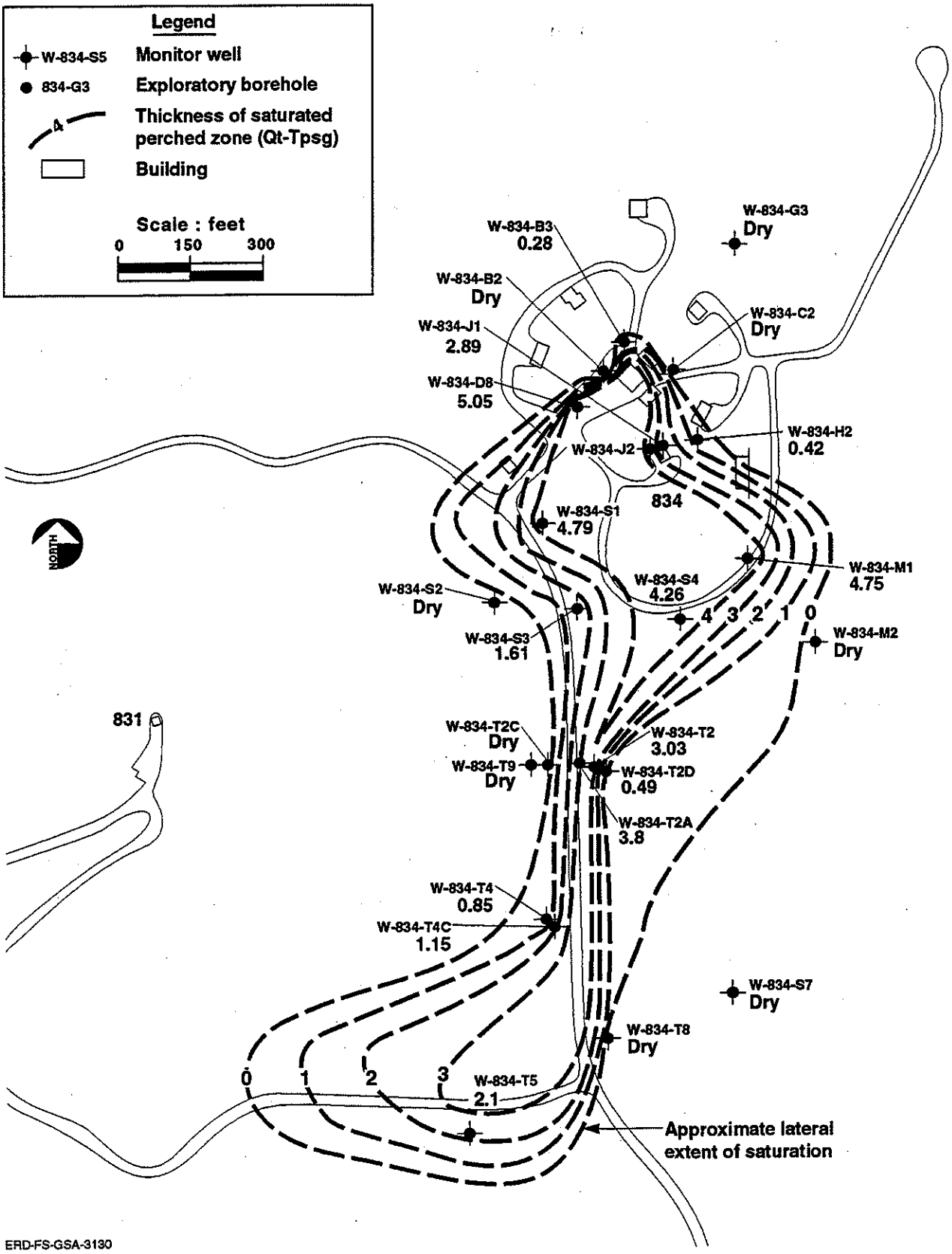

Figure 1-33. Thickness of the saturated portion of the perched zone (Qt-Tpsg/Tps-Tns$_2$ hydrologic units) in December 1991.

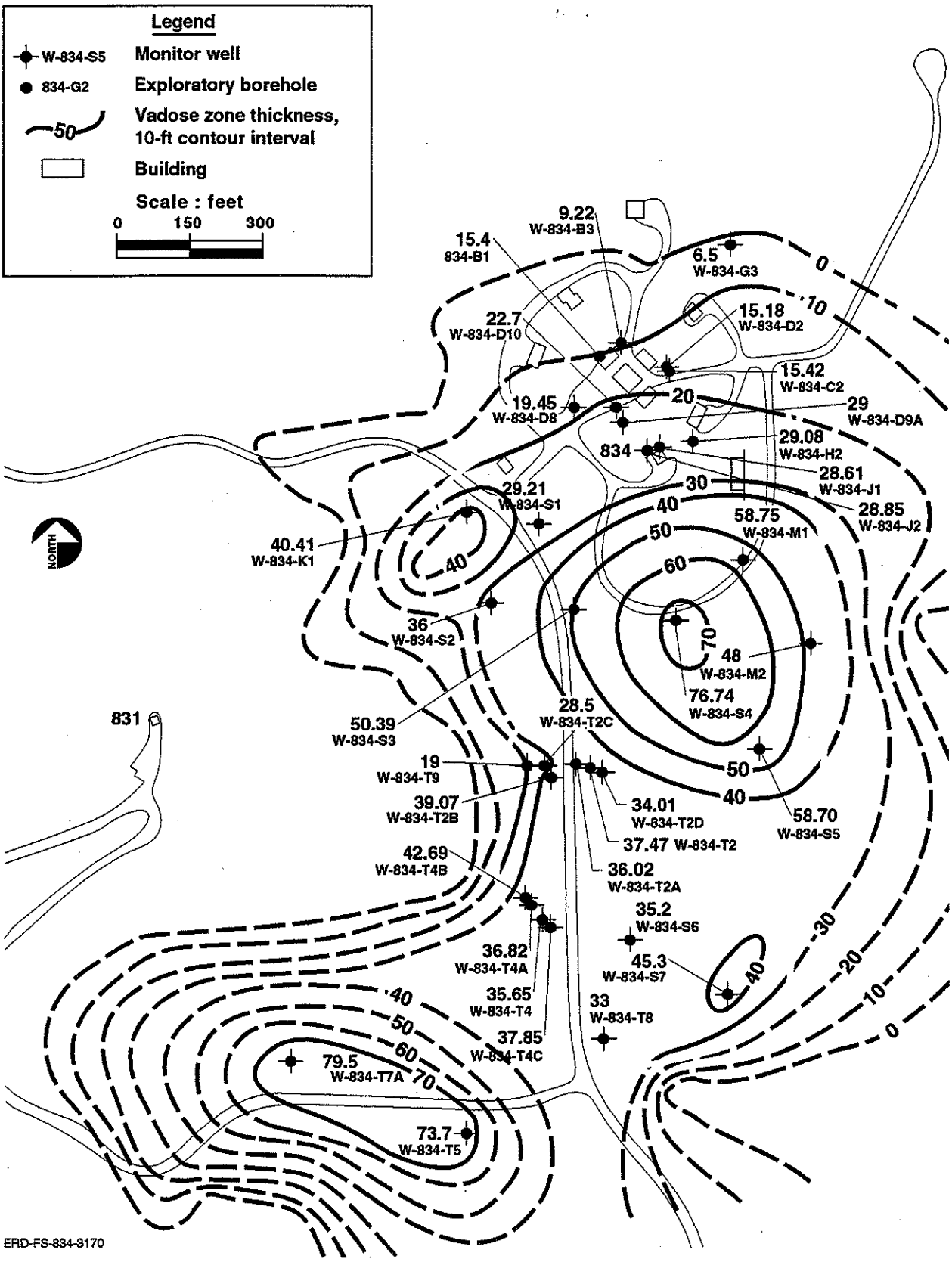

Figure 1-34. Thickness of vadose zone above the perching horizon (Tps-Tnsc$_2$) at the Building 834 Complex site.

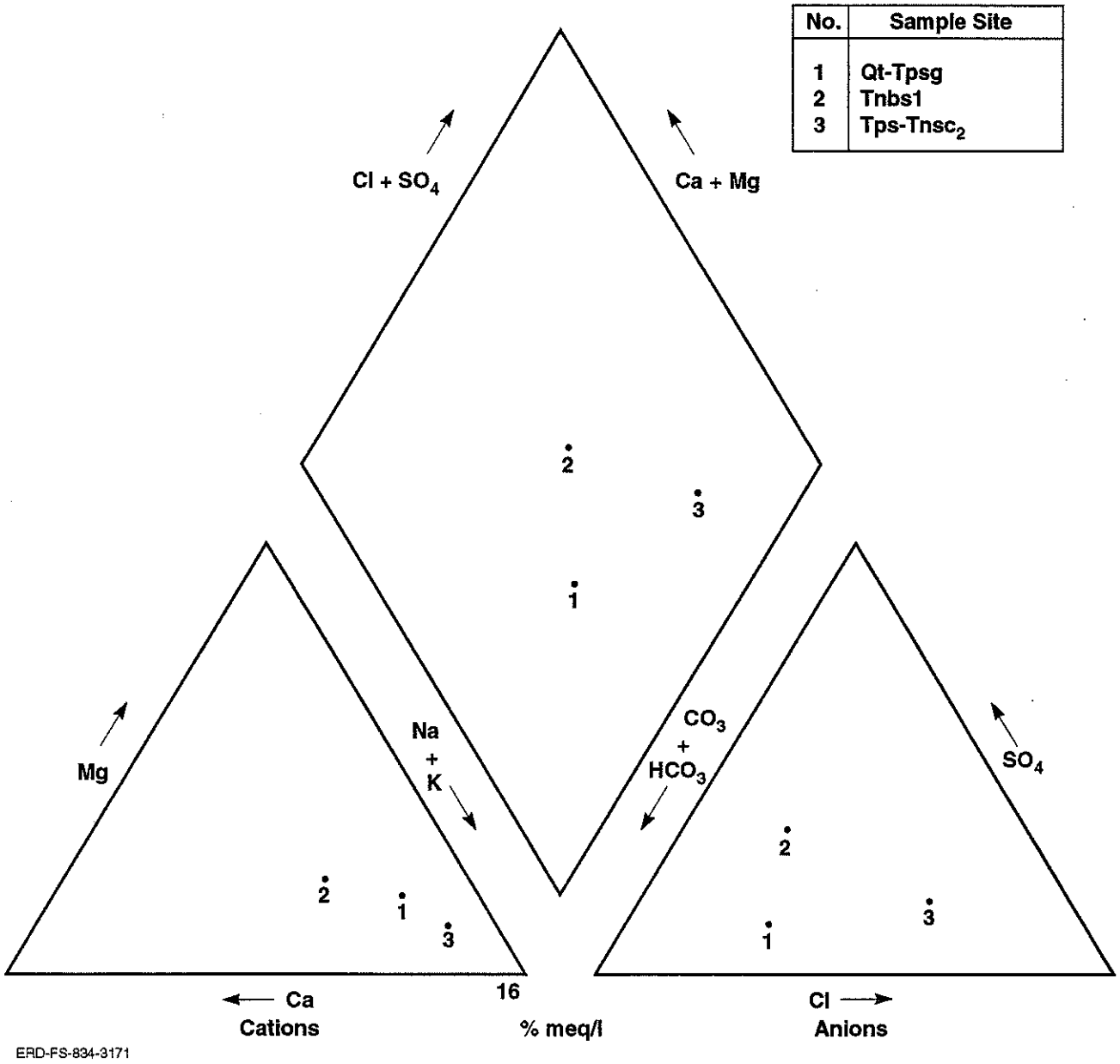

Figure 1-35. Piper diagram of the average major ground water ions for each hydrologic unit at the Building 834 operable unit.

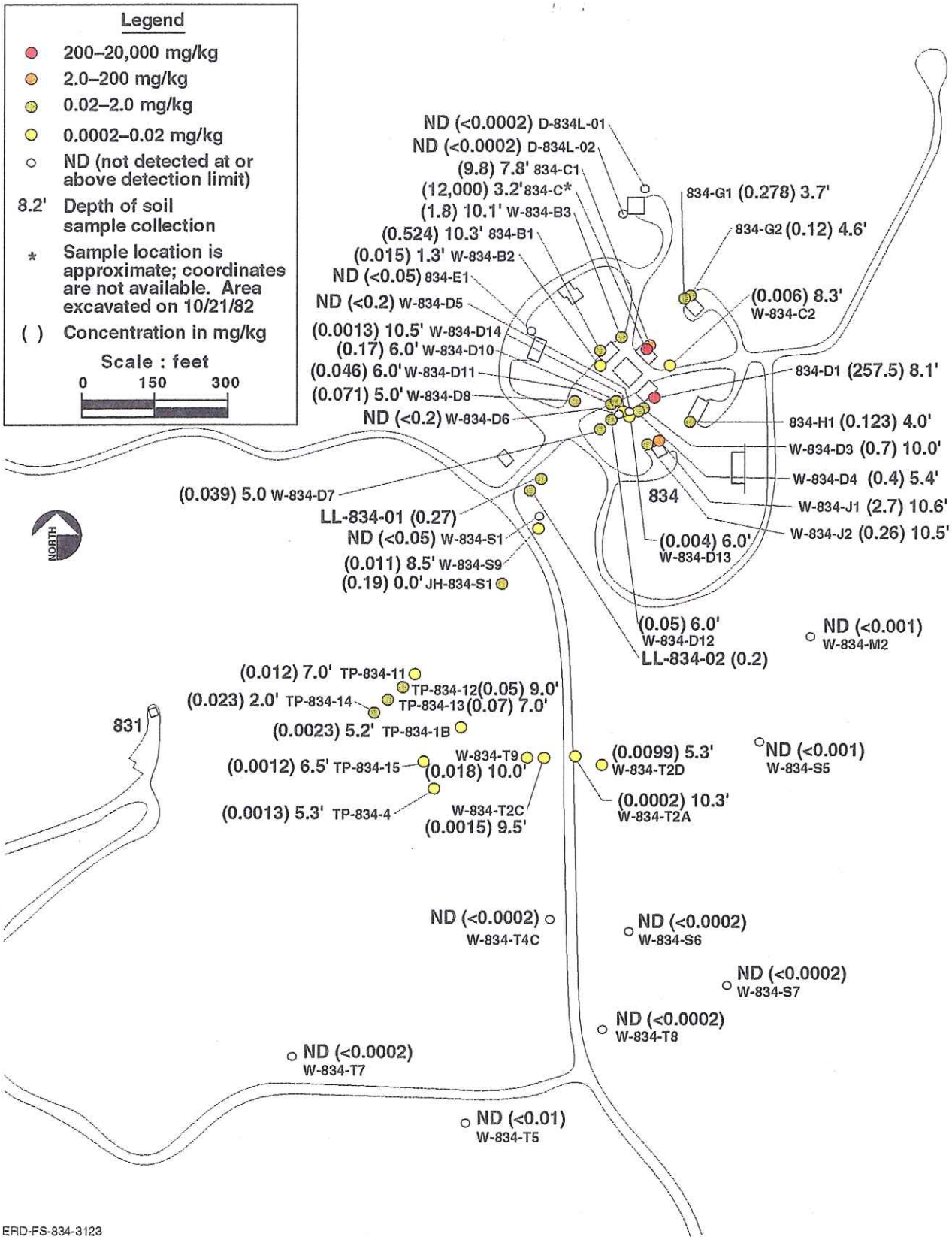

Figure 1-36. Maximum TCE concentration, 0 to 12 ft, in soil and rock samples in the Building 834 operable unit. Unsampled boreholes are not depicted.

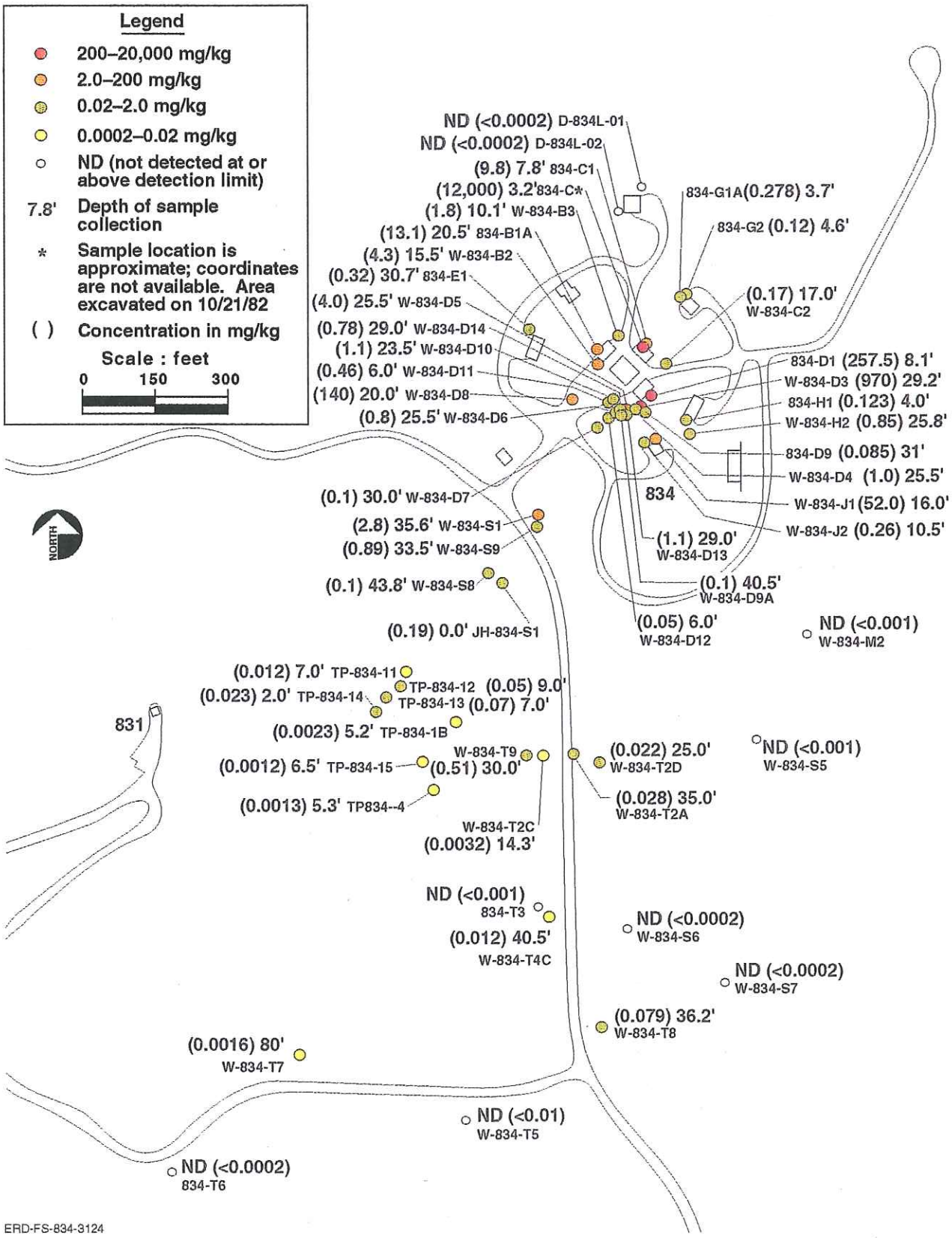

Figure 1-37. Maximum TCE concentration in soil and rock samples in the Building 834 Complex site. Unsampled boreholes are not depicted.

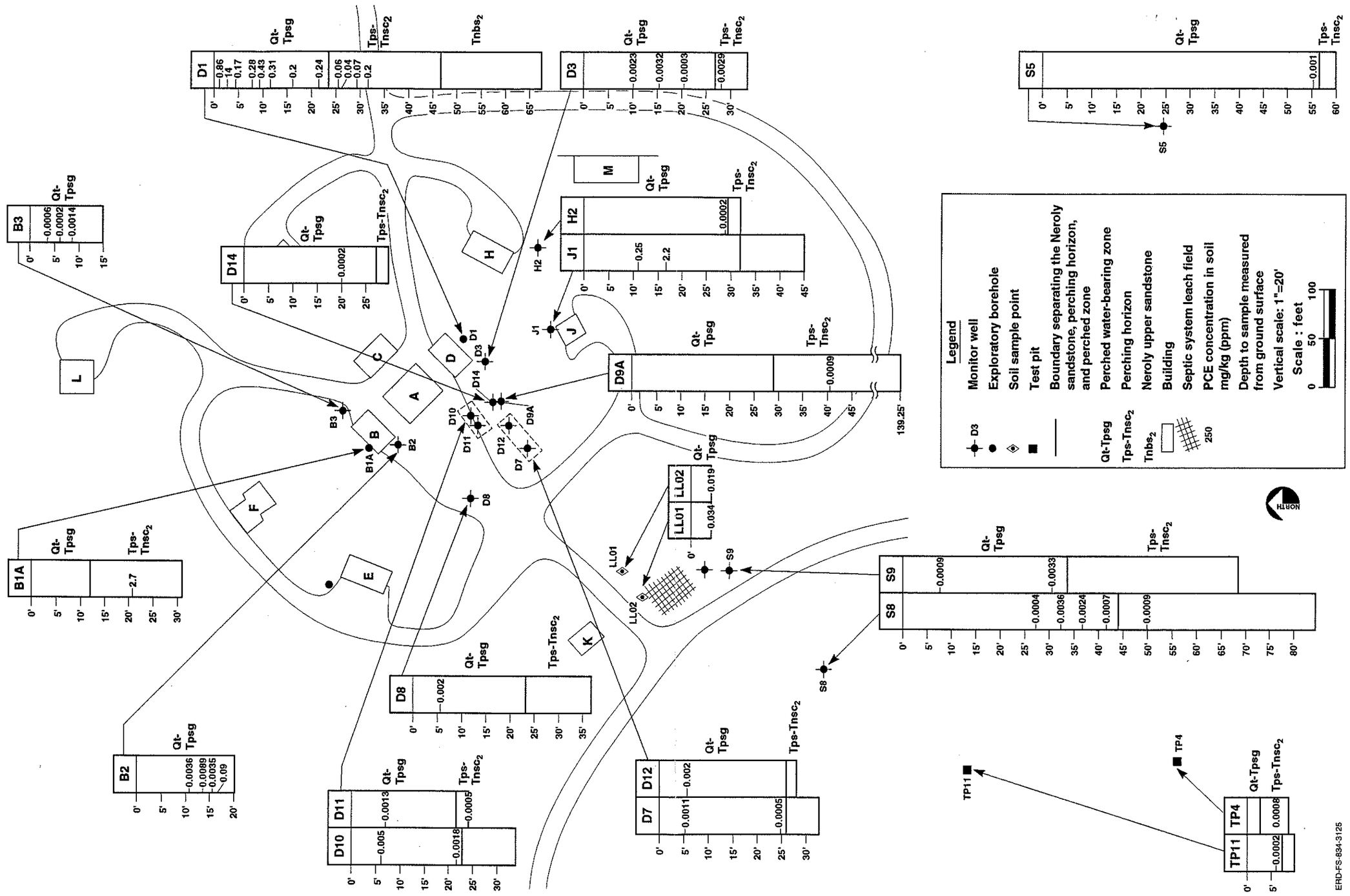

Figure 1-38

Figure 1-38. PCE concentrations in soil samples collected at the Building 834 Complex. Samples in which PCE was not detected are not depicted.

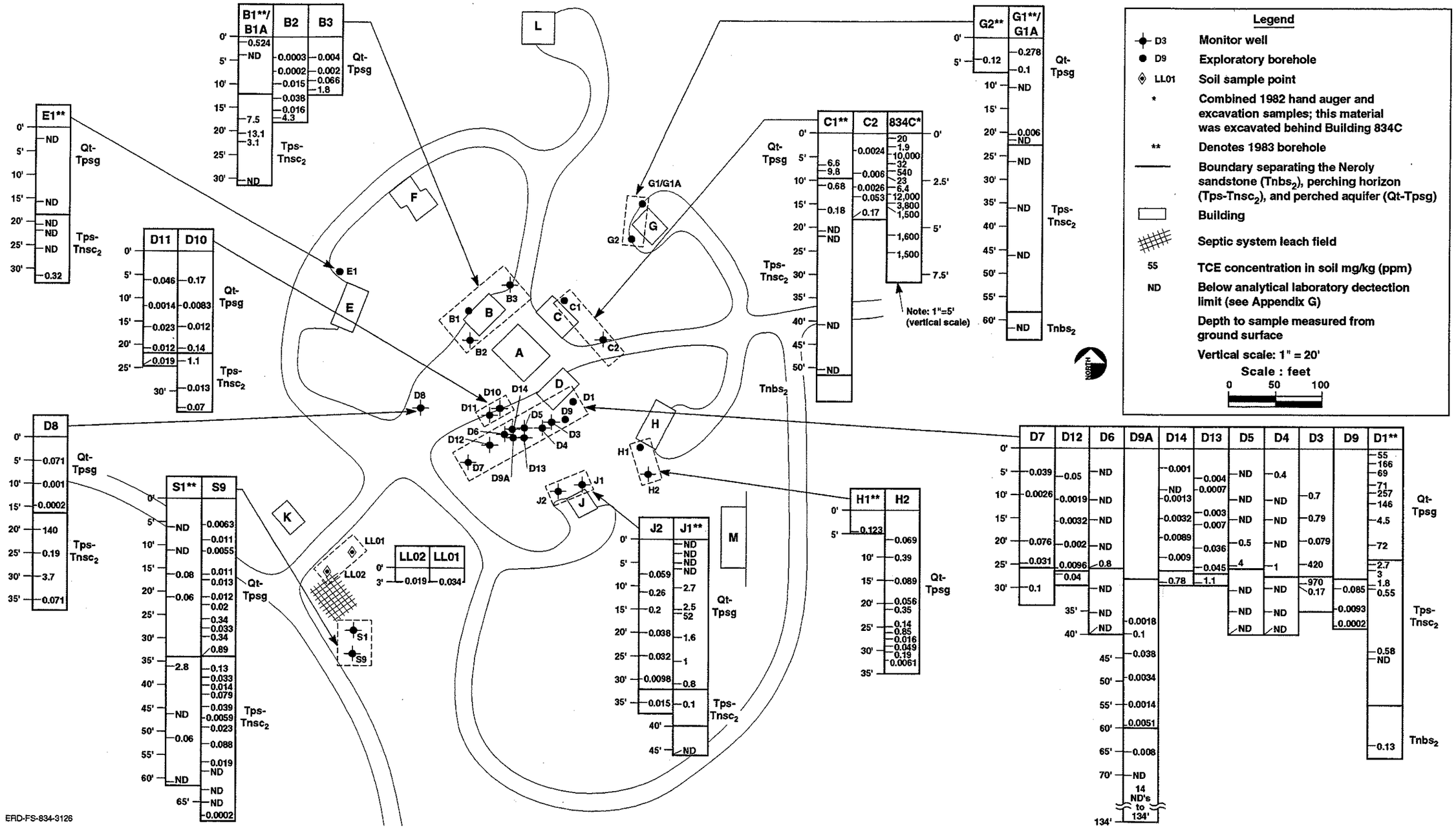

Figure 1-39. TCE concentrations in soil samples collected at the Building 834 Complex.

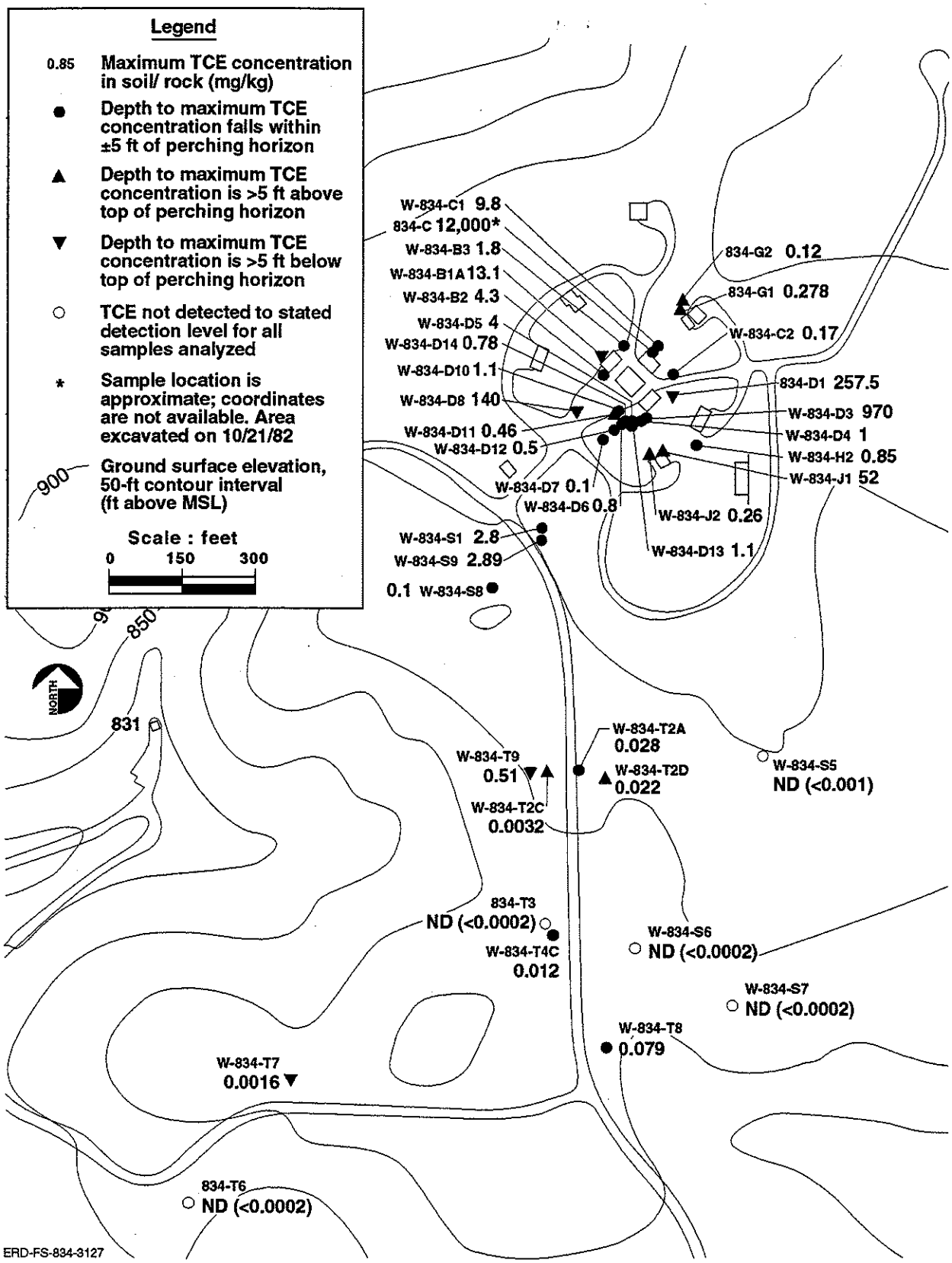

Figure 1-40. Soil and rock TCE maxima; most maxima occur within 5 ft of the perched water-bearing zone/perching horizon contact.

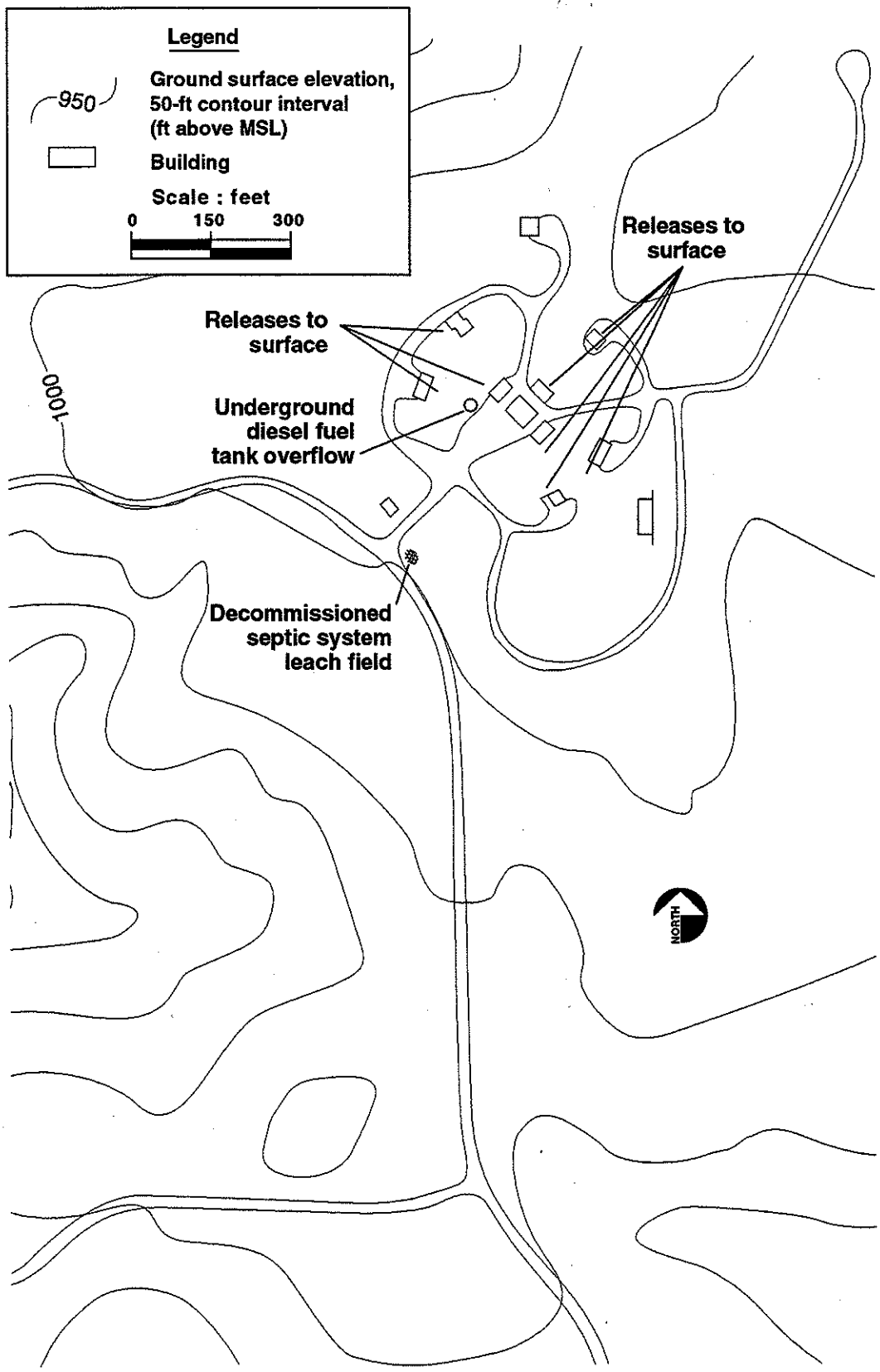

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Figure 1-41. Confirmed release sites in the Building 834 operable unit.

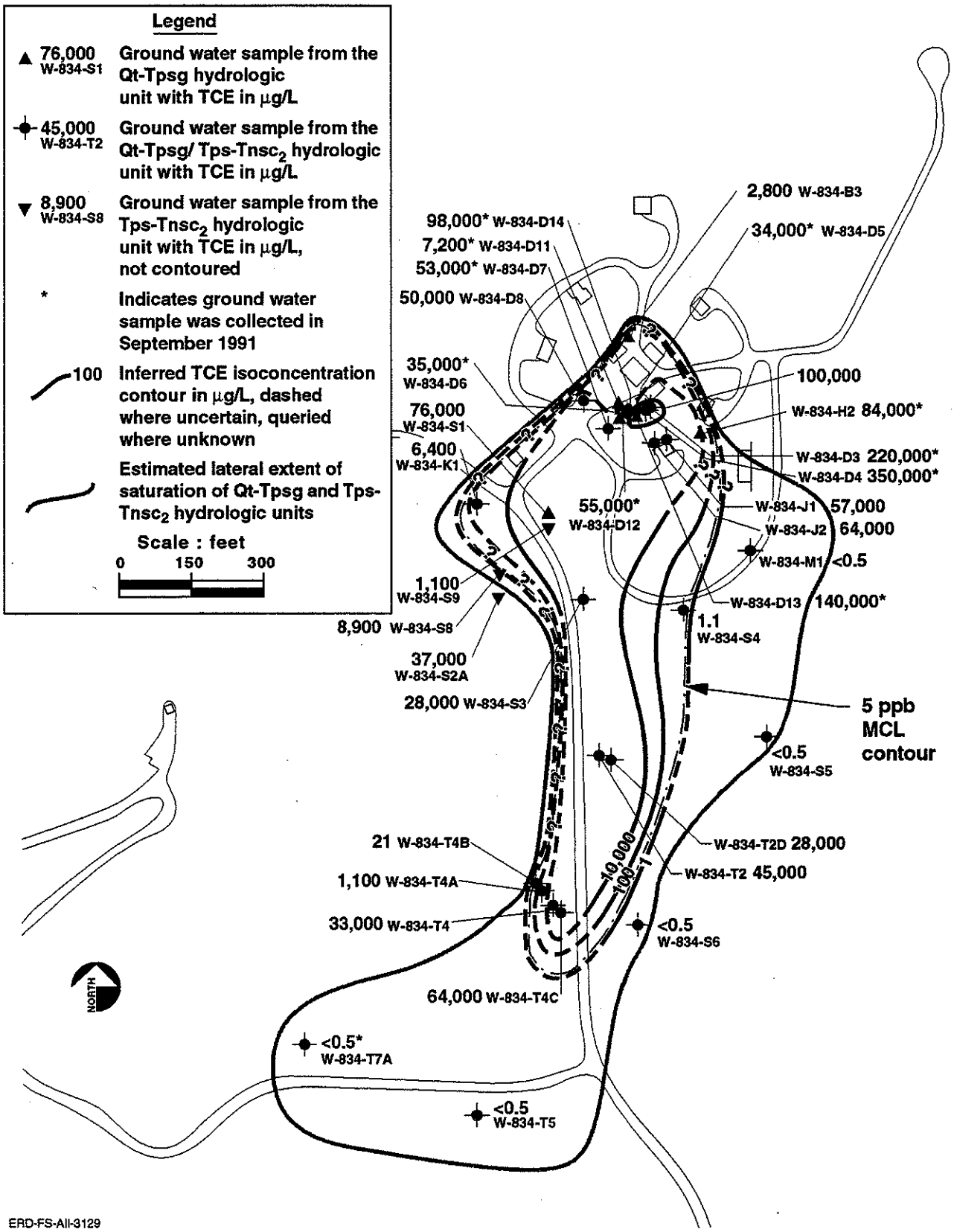

Figure 1-42. Distribution of TCE in perched ground water in the Qt-Tpsg/Tps-Tns$_2$ hydrologic units, December 1991.

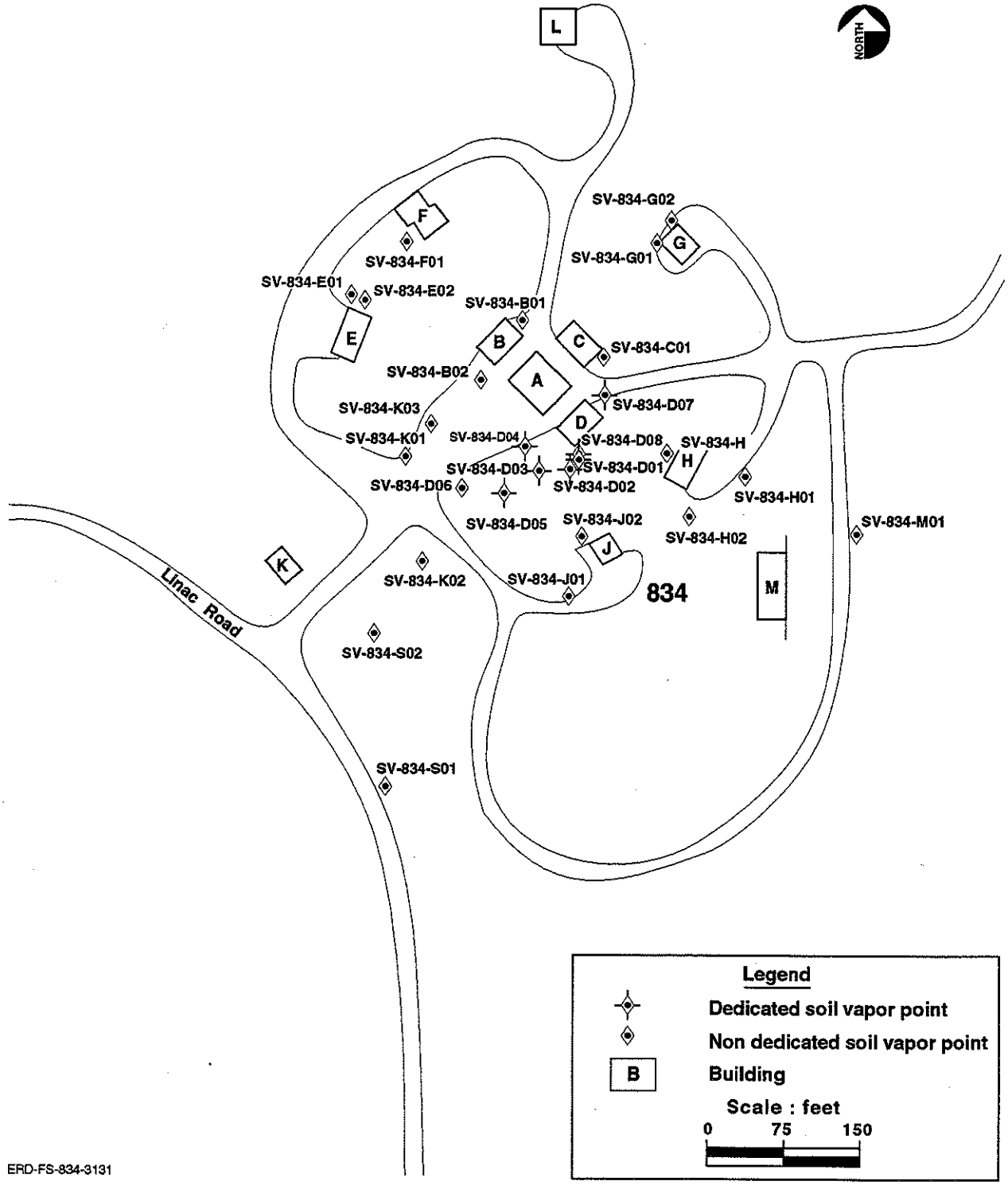

Figure 1-43. Location map of the Building 834 Complex, SVS points, and the dedicated soil vapor monitoring points.

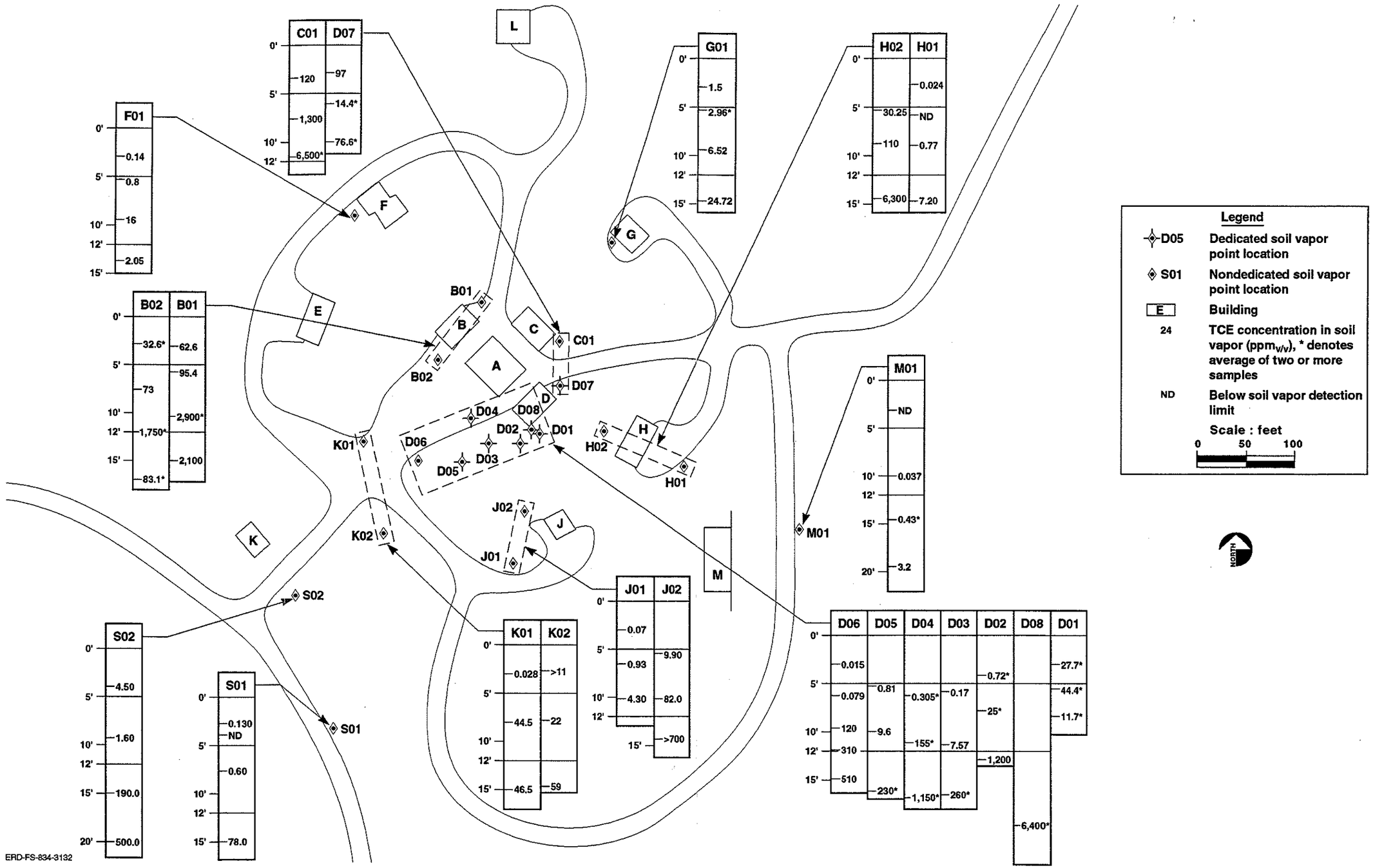

Figure 1-44. Vertical distribution of TCE in soil vapor at the Building 834 Complex (ppm$_{v/v}$).

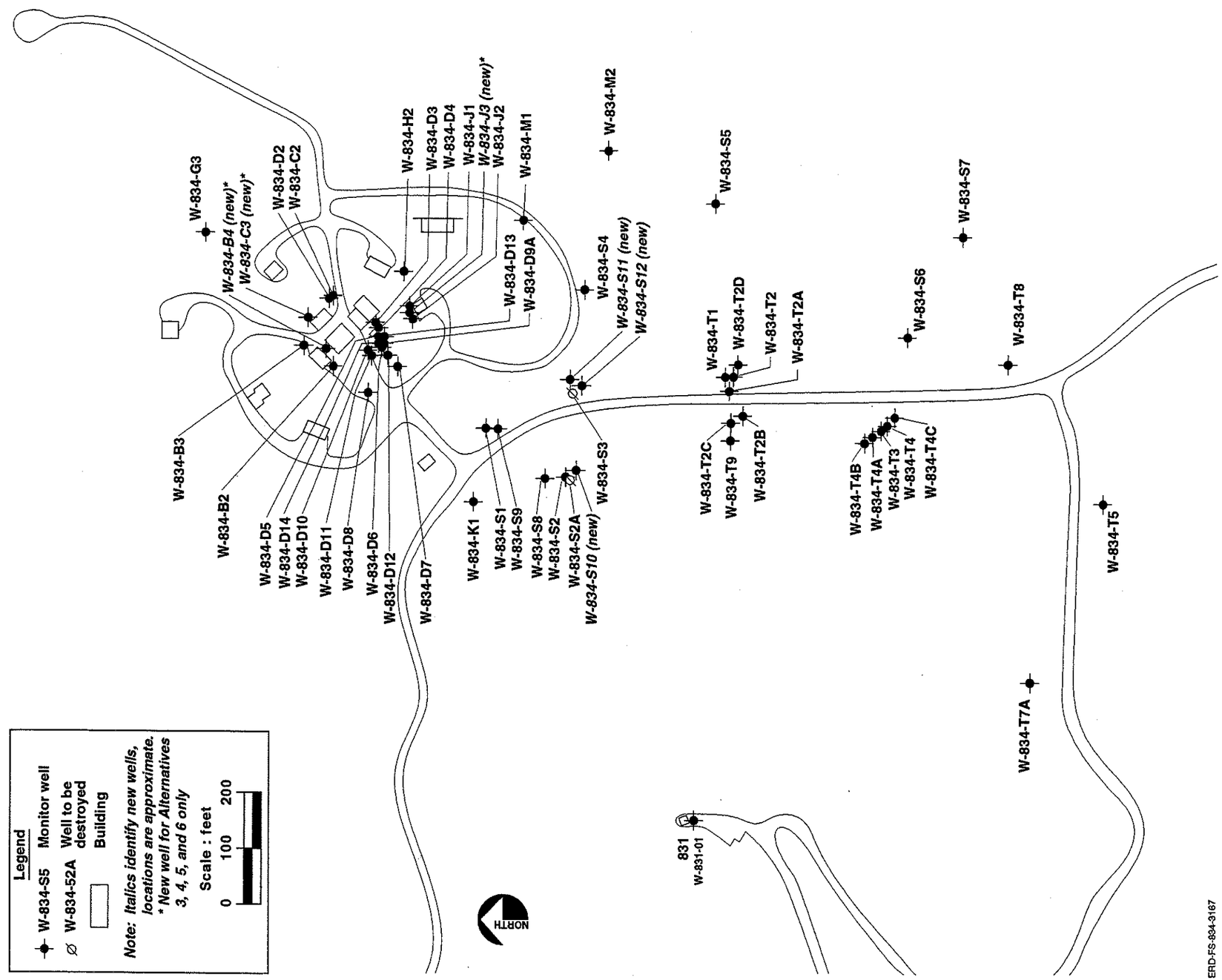

Figure 4-1. Location of existing and proposed monitor wells in the Building 834 Complex.

Figure 4-1

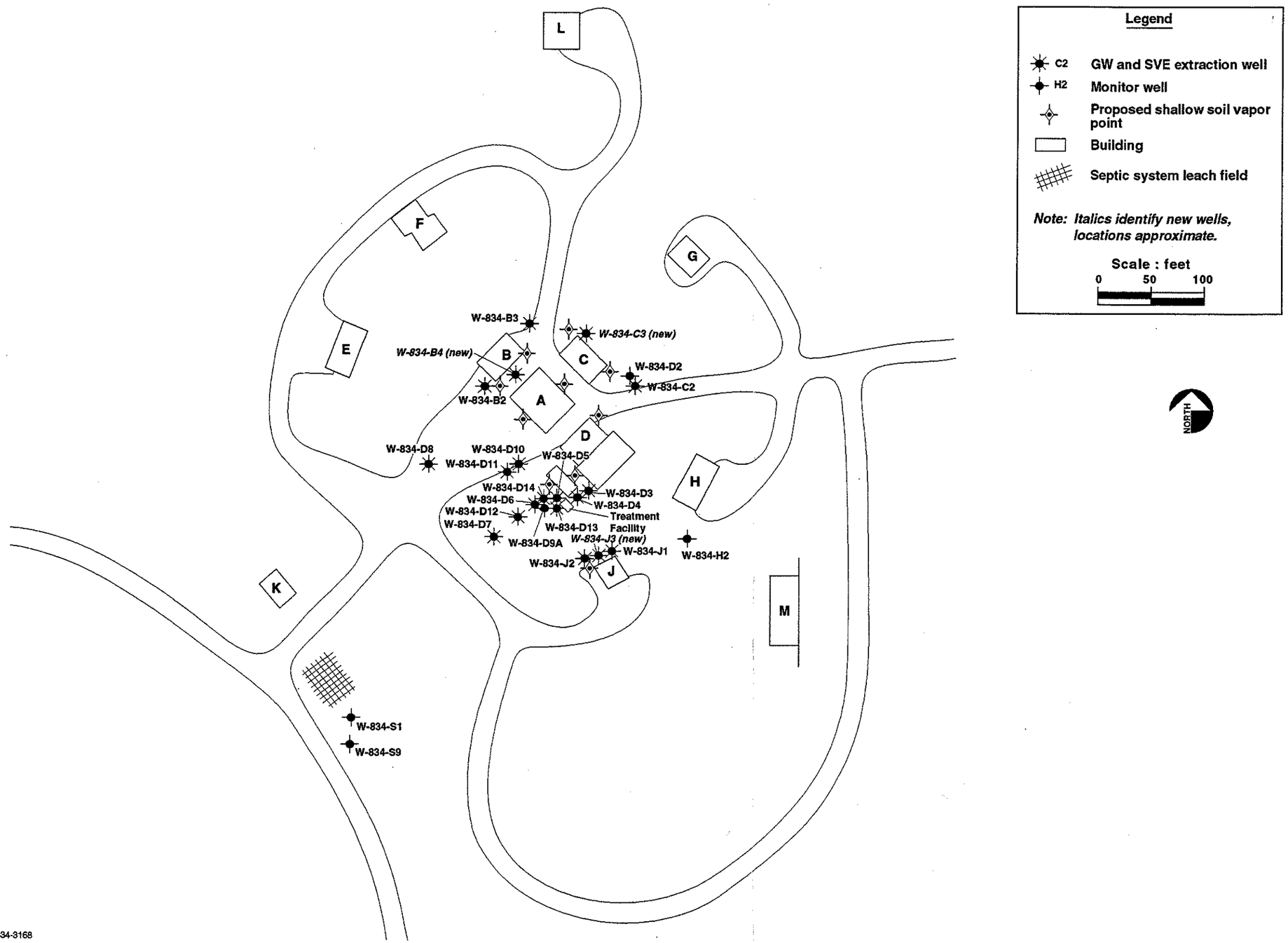

Figure 4-2. Location of extraction wells and treatment facility in the Building 834 Complex for Alternatives 3 and 4.

Figure 4-2

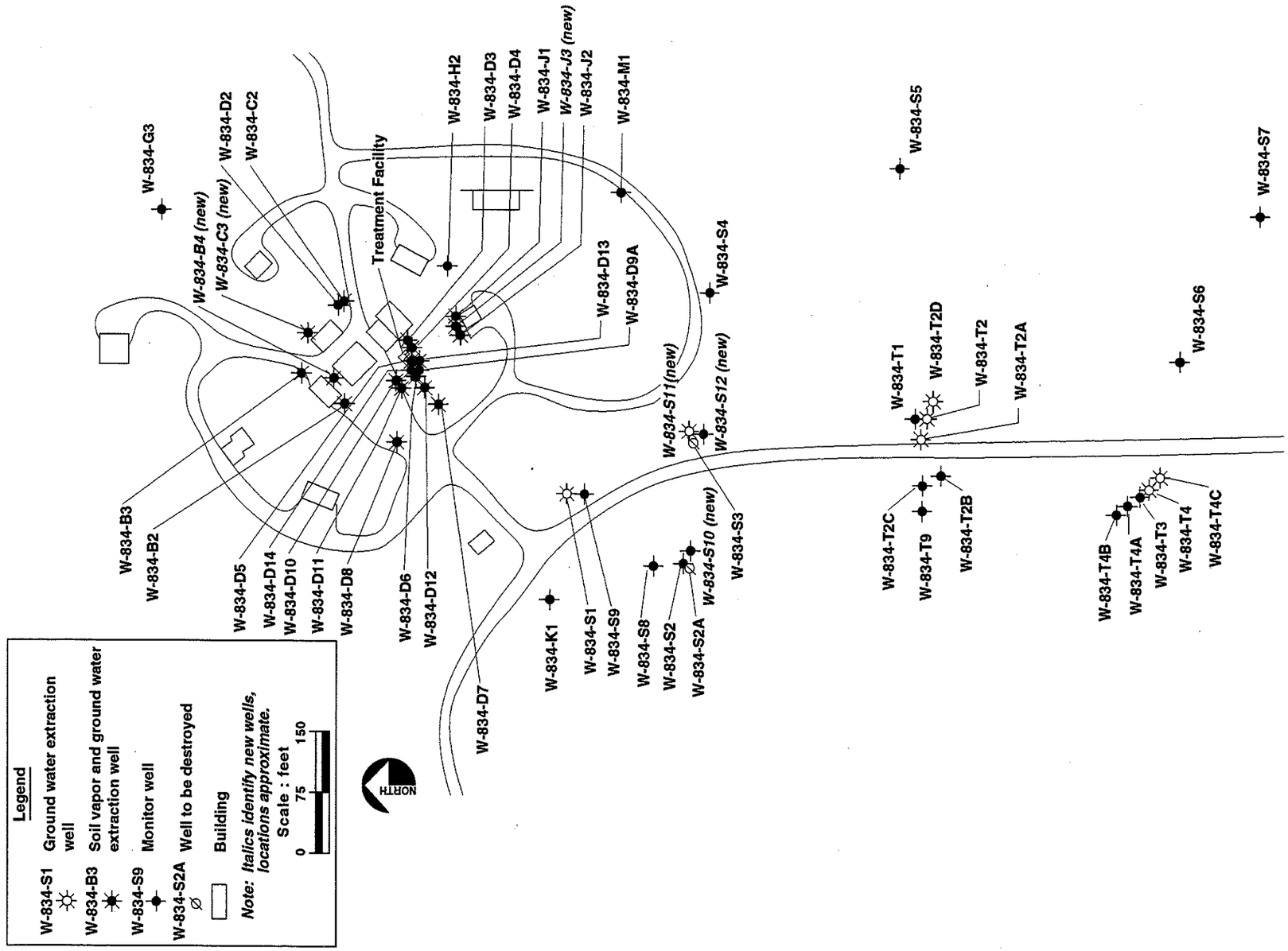

Figure 4-3. Location of extraction wells and treatment facility in the Building 834 Complex for Alternative 5.

Figure 4-3

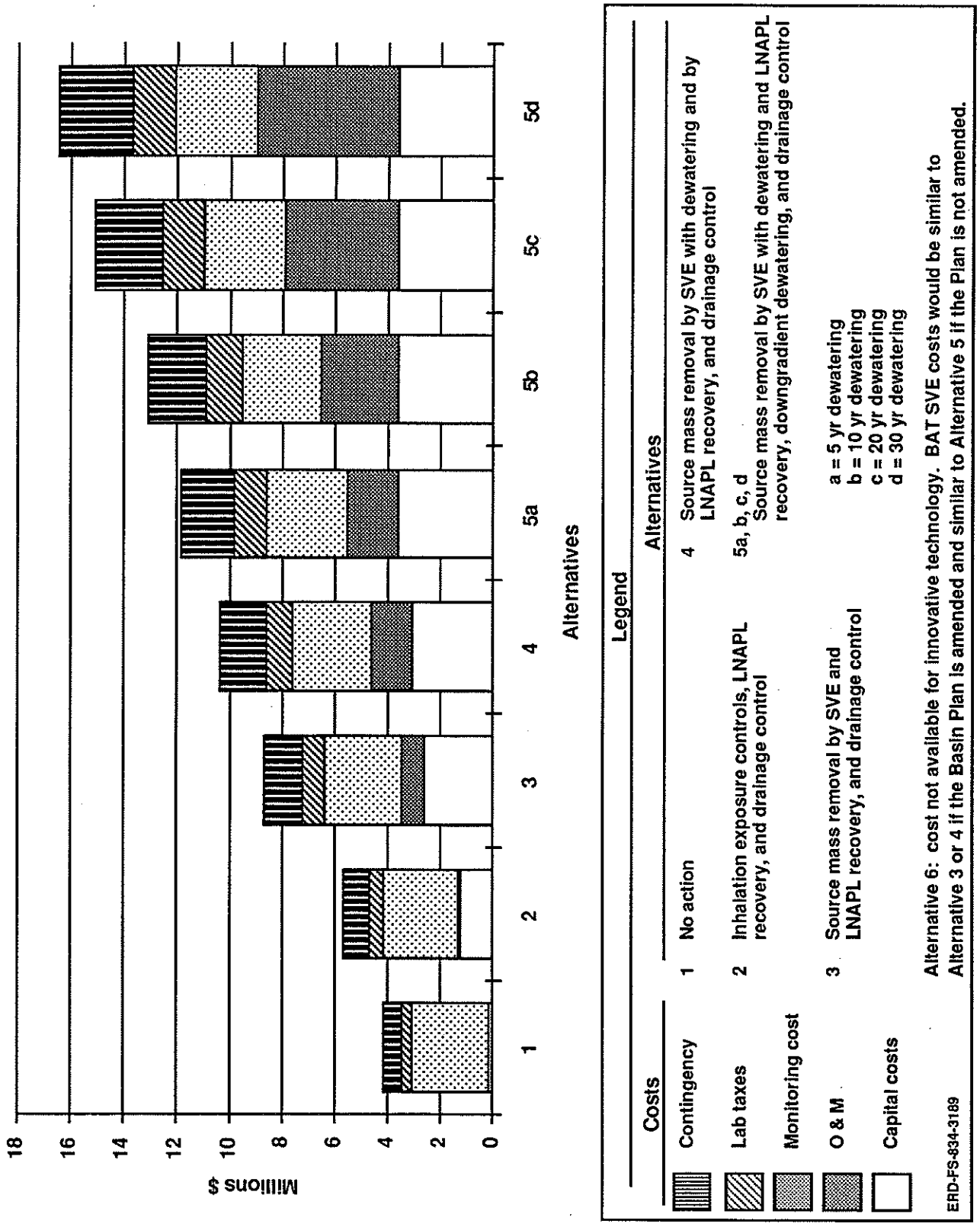

Figure 5-1. Building 834 remedial alternative cost summary chart.

Tables

Table 1-1. Stratigraphic characteristics of geologic units, LLNL Site 300.

Epoch	Geologic unit	Depositional environment	Lithologic characteristics
Holocene	Colluvium, alluvium and valley fills (Qal), landslides (Ls/Qls)	Continental, mass wasting, fluviatile	Silty clay, sand, gravel, landslides heterogeneous.
Pleistocene	Older alluvium (Qoa) and landslides (Qls), terrace deposits (Qt)	Continental, predominantly fluviatile	Silty clay, silt, sand, gravel, often partly cemented.
Pliocene	Pliocene nonmarine unit of Dibblee (1980) (Tps)	Continental fluviatile, lacustrine	Pebble conglomerate, greenish gray, brown and red clay, silty sand and some marl interbeds.
Late Miocene	Neroly Formation	Continental, fluviatile, lacustrine	Volcanic source terrain; immature sandstone, conglomerate, tuffaceous shale and claystone, slightly to well-lithified, within Site 300 subdivided into following informal lithologic members: $Tnbs_2$ upper blue sandstone (predominantly fine-coarse grained, blue-gray and brown silty sandstone, conglomerate lenses, tuffaceous claystone interbeds; beds of claystone, sandstone, heterogeneous conglomerate [$Tnsc_2$] discontinuously present at top of sequence and mappable locally). $Tnsc_1$ middle claystone, siltstone (interbedded claystone, siltstone, fine sandstone). $Tnbs_1$ lower blue sandstone (predominantly fine to coarse-grained, blue-gray silty sandstone, tuffaceous claystone and siltstone interbeds, conglomerate lenses.
	Cierbo Formation (Tmss)	Littoral, varying from shallow marine to continental	Friable, yellow-gray quartz-rich sandstone, chert pebble conglomerate, gray claystone, locally tuffaceous.
Late Paleocene-Eocene	Tesla Formation (Tts)	Brackish water to marine	Quartz-mica sandstone and carbonaceous clay, subordinate chert pebble conglomerate and lignite coal. Not encountered in Building 834 operable unit.
Late Jurassic-Cretaceous	Great Valley Sequence (Kgv) (Panoche Formation)	Deep oceanic trough floor grading up to subsea fans, forearc basin setting	Arkosic sandstone with large concretions, micaceous clay interbeds. Not encountered in the Building 834 operable unit.

Table 1-2. Principal active and potentially active faults in the San Francisco Bay Region and in the Altamont Hills and Central Valley margin areas.

Fault	Distance (mi)[a] and direction	Max historic earthquake magnitude (yr)	Slip rate (mm/yr)[b]		Max earthquake magnitude	
			Geodetic	Geologic	Probable	Credible
Corral Hollow-Carnegie	1.5 (SW)	None known[c]	—	0.7[d]	6.3–6.7[d]	7.1[d]
Midway	2 (NE)	3.5 (no date)[e]	—	0.05[f]	—	6.0[f]
Tesla	2.5 (S)	4.6 (1977)[e]	—	0.2[f]	—	6.25[f]
Patterson Pass	3 (W)	4.6 (after 1900)[e]	—	NA	—	5.9[g]
Black Butte	4 (NE)	None known[c]	—	0.2[f]	—	6.5[f]
Greenville	6 (SW)	5.8 (1980)[c]	—	0.5–0.75[h]	—	6.6 ± 0.2[h]
Las Positas	10 (SW)	5.5 (1903)[c]	—	0.4[h]	—	6.0 ± 0.5[h]
Ortigalita	17 (SSE)[i]	5± (1926) 3.7 (1981)[k]	—	0.1[j]	—	6.8[j]
Calaveras	20 (SW)	6± (1861)[l] 6.2 (1984)[o]	7[m]	5.3[n]	—	7.0 ± 0.25[g]
Hayward	25 (SW)	7± (1868)[p]	7[m]	3.5–9[q]	7.0[p]	7.5[p]
San Andreas	42 (SW)	8.25 (1906)[l] 7.1 (1989)[r]	12.2 ±3.9[m]	10–30[n]	—	8.3[l]
San Gregorio-Seal Cove-Hosgri	54 (SW)	6.1 (1926)[l]	—	6–13[n]	—	7.4[l]

[a] Distance from approximate center of Site 300.
[b] 25.4 mm = 1 in.
[c] Reported microseismicity with general spatial correlation.
[d] Carpenter et al. (1991).
[e] CDWR (1979).
[f] Tera Corporation (1984).
[g] Calculated using total fault length method in Slemmons and Chung (1982).
[h] Carpenter et al. (1984).
[i] To northern tip, activity mainly farther south.
[j] Shedlock et al. (1980).
[k] Laforge and Lee (1982). Location of M = 5 event is near southern end of mapped trace but location accuracy uncertain.
[l] Wesson et al. (1975), for San Andreas Fault, North Coast segment; other faults not segmented.
[m] Prescott et al. (1981).
[n] Page (1982).
[o] Oppenheimer et al. (1990).
[p] Steinbrugge et al. (1987).
[q] Lienkaemper et al. (1991).
[r] Plafker and Galloway (1989), Santa Cruz Mountains segment.
— = Not available.

Table 1-3. Stratigraphic units encountered in the Building 834 operable unit.

Stratigraphic unit: Quaternary deposits: Landslide deposits (Qls/Ls), Terrace deposits (Qt)	
Range of thickness	Qls/Ls: Approximately 9 ft where partially penetrated by test pit TP-834-T6. (The test pits were originally designated "TR" in the Building 834 Complex Remedial Investigation/Feasibility Study report (Bryn et al., 1990). The sample designation was changed to TP for the SWRI report and subsequent reports. Qt: Variable, ranging from absent at the surface to 13 ft in well W-834-S7; contact difficult to differentiate from Tps in augered boreholes.
Lithology	Qls: (Mixed with colluvium) silty gravel to gravelly silt (GM/ML); medium brown with red-brown mottling; dense/stiff; 20–30% very fine to very coarse sand; 30–50% subrounded pebbles to 2.5 in. diam, medium plasticity fine-grained material; low to moderate estimated hydraulic conductivity. Qt: Silty clay, silty sand; silty gravel with subangular to rounded pebbles to 3.5 in., 10–30% silt, 10–20% fine to medium sand, tan, dry, unindurated; Franciscan source, including red chert and dark metamorphic pebbles.
Extent of unit	Qls: Three landslides exist within the study area, ranging in areal extent from about 60,000 to 300,000 ft^2. Qt: Occurs in semicircular exposures of about 63,000 and 160,000 ft^2, capping two hilltops; as a band 200 to 600 ft in width, semiparallel to the 950 ft elevation contour on the easternmost-facing ridge in the study area; and capping the north-south trending ridge in the southern part of the study area.
Stratigraphic unit: Pliocene deposits: Pliocene nonmarine sequence (Tps)	
Range of thickness	Tps: 9.5 to 81 ft.
Lithology	Tps: Pliocene nonmarine sediments. Dense silty clay gradational to claystone and siltstone, silty sand gradational to silty sandstone, some gravel. Clays green, red, brown. Claystone, siltstone, and sandstone greenish-gray to greenish-yellow. Contains silty sand and silty gravel channel deposits comprising the Tpsg member of unit Tps. Member Tpsg: Yellow-brown, red-brown or green-brown, silty sand, and sandy, silty gravel, dense to loose depending on percentage of silt, generally matrix-supported, locally grading to conglomerate (concretionary). Rounded pebbles a mixture of Neroly Formation meta-volcanics and chert of the Franciscan Complex.
Extent of unit	Caps the ridge tops. Exposed at the surface for most of the study area.
Stratigraphic unit: Miocene Neroly Formation: Upper siltstone/claystone ($Tnsc_2$)	
Range of thickness	13.3 to 24.4 ft.
Lithology	Well-indurated, gray-green, tan, brown or gray-brown, siltstone, claystone and silty sandstone.

Table 1-3. (Continued)

Stratigraphic unit: Miocene Neroly Formation: Upper siltstone/claystone ($Tnsc_2$)	
Extent of unit	Presumed to discontinuously overlie the Neroly upper sandstone throughout the study area. Not resistant; assumed to occur in narrow band running subparallel to topography along study area hillsides. Very difficult to distinguish from Tps in some boreholes; chief criterion is degree of induration.
Stratigraphic unit: Miocene Neroly Formation: Upper sandstone ($Tnbs_2$)	
Range of thickness	40 to 70 ft.
Lithology	"Upper blue sandstone," well lithified fine to medium silty graywacke, locally coarse-grained, pebbly, with occasional thin claystone interbeds and rip-up clasts. Brown, weathers blue-gray, volcanic source.
Extent of unit	Present beneath the entire study area except where eroded away in canyons. Exposed as resistant benches beneath the Tps, trending subparallel to the topography along the study area hillsides.
Stratigraphic unit: Miocene Neroly Formation: Middle siltstone/claystone ($Tnsc_1$)	
Range of thickness	35.7 to 68.0 ft.
Lithology	Predominantly moderately to well-lithified claystone, siltstone, interbeds of fine silty-clayey graywacke. Core contains fractured zones. Light gray to yellow and greenish brown, sandstone weathers blue-gray to brown.
Extent of unit	Present beneath the entire study area. Crops out along canyon bottoms.
Stratigraphic unit: Miocene Neroly Formation: Lower sandstone ($Tnbs_1$)	
Range of thickness	Thickness penetrated by borehole W-834-T1 is 217 ft, and W-834-T3 is 184 ft.
Lithology	Consolidated, medium- to fine-grained graywacke sandstone, predominantly volcaniclastic source. Interbedded with siltstone and claystone. Two claystone beds are traceable in the subsurface across the study area. Includes less frequent conglomerate. Core dries blue-gray.
Extent of unit	Present beneath the entire study area.
Stratigraphic unit: Mid-Miocene Cierbo Formation (Tmss)	
Range of thickness	Study area boreholes do not penetrate this unit.
Lithology	Study area boreholes do not penetrate this unit, nor does it crop out in this area.
Extent of unit	Believed to extend throughout the study area in the subsurface.

Table 1-4. Depth (below ground surface) of stratigraphic contacts used to construct geologic cross-section A-A' that connects the Building 833 and Building 834 operable units.

Well/ borehole	Total depth (ft)	Surface elevation (ft)	Qt[a] (ft)	Qal (ft)	Qls (ft)	Tps (ft)	$Tnsc_2$ (ft)	$Tnbs_2$ (ft)	$Tnsc_1$ (ft)	$Tnbs_1$ Unit above CMB (ft)	$Tnbs_1$ CMB (ft)	$Tnbs_1$ Unit below CMB (ft)	Tmss (ft)	Tts (ft)	Kgv (ft)
W-834-D2	308	1,017.08	NP	NP	NP	Surface	42.5	51.3	82.7	139.1	165.7	177.2	—	—	—
W-834-D3	35	1,016.16	NP	NP	NP	Surface	28	—	—	—	—	—	—	—	—
W-834-D9A	139.3	1,015.00	NP	NP	NP	Surface	37	61	94.5	—	—	—	—	—	—
W-834-T1	373.5	955.92	NP	NP	NP	Surface	47.1	71.5	104.7	168.9	205.8	220.3	—	—	—
W-834-T2D	41	951.73	NP	NP	NP	Surface	—	—	—	—	—	—	—	—	—
W-834-T4A	53	928.23	NP	NP	NP	Surface	—	—	—	—	—	—	—	—	—
W-834-T3	354.2	929.54	NP	NP	NP	Surface	59.2	75.1	113.8	174.6	213.7	221.0	—	—	—
W-834-T8	95	914.51	NP	NP	NP	Surface	58	73	—	—	—	—	—	—	—
833-42	66	873.00	Surface	NP	NP	24	—	—	—	—	—	—	—	—	—
W-833-28	61	853.80	Surface	NP	NP	19.5	—	—	—	—	—	—	—	—	—
W-833-34	45.8	849.00	Surface	NP	NP	15	—	—	—	—	—	—	—	—	—
833-06	125	848.78	Surface	NP	NP	15	56	81.2	—	—	—	—	—	—	—
W-833-30	318	848.20	Surface	NP	NP	17.5	70	80.8	130.2	204.1	250.6	259.8	—	—	—
833-20	50.8	848.30	Surface	NP	NP	24.5	—	—	—	—	—	—	—	—	—
833-21	52	848.30	Surface	NP	NP	24.5	—	—	—	—	—	—	—	—	—

[a] Stratigraphic units are defined in text.

CMB = Claystone marker bed.

NP = Not present at this location.

— = Well/borehole was not drilled deep enough to intercept this unit.

? = Depth uncertain.

Table 1-5. Depth (below ground surface) of stratigraphic contacts used to construct geologic cross-section B-B' in the Building 834 operable unit.

Well/ borehole	Total depth (ft)	Surface elevation (ft)	Qc[a] (ft)	Qr[b] (ft)	Qt[c] (ft)	Tps[d] (ft)	$Tnsc_2$ (ft)	$Tnbs_2$ (ft)	$Tnsc_1$ (ft)	$Tnbs_1$ Unit above CMB (ft)	$Tnbs_1$ CMB (ft)	$Tnbs_1$ Unit below CMB (ft)	Tmss (ft)	Tts (ft)	Kgv (ft)
W-831-01	159	770.49	NP	Surface	NP	NP	NP	NP	10.8	37	57	75	—	—	—
W-834-S8	85	1,000.06	Surface	NP	NP	6.5	45.1	—	—	—	—	—	—	—	—
W-834-S9	68	997.83	Surface	NP	NP	1.5	35	—	—	—	—	—	—	—	—
W-834-S1	60.67	999.38	Surface	NP	NP	10.5	NP?	—	—	—	—	—	—	—	—
W-834-D14	29.5	1,015.34	Surface	NP	NP	4.3	—	—	—	—	—	—	—	—	—
W-834-D9A	139.3	1,015.00	NP	NP	NP	Surface	37	61	94.5	—	—	—	—	—	—
W-834-C2	18.5	1,017.42	NP	NP	NP	Surface	—	—	—	—	—	—	—	—	—
W-834-D2	308	1,017.08	NP	NP	NP	Surface	42.5	51.3	82.7	139.1	165.7	177.2	—	—	—
W-834-G3	70	1,050.29	NP	NP	NP	Surface	46?	58	—	—	—	—	—	—	—

[a] Quaternary colluvium. Unit not depicted in cross sections. May also include emplaced fill dirt at the core of the Building 834 Complex.

[b] Quaternary ravine fill. Unit persent only at well W-831-01.

[c] Quaternary terrace deposits. Present in Building 834 operable unit, but not crossed by geologic cross sections.

[d] Other stratigraphic units are defined in text.

CMB = Claystone marker bed.

NP = Not present at this location.

— = Well/borehole was not drilled deep enough to intercept this unit.

? = Depth uncertain.

Table 1-6. Building 834 operable unit hydraulic test results.

Hydrologic unit/well	Date tested	Aquifer thickness (ft)	Maximum pumping rate (gpm) [m^3/sec]	Test type[a]	Test phase[b]	Analysis[c]	Transmissivity (gpd/ft)	Hydraulic conductivity (gpd/ft^2)	Hydraulic conductivity (cm/sec)	Data quality[d]
Qt-Tpsg										
W-834-S1	04/16/87[e]	3.5	NA	Slug	Slug	Modified Papadopulos (cyl.)	57	16	7.5×10^{-4}	P
Qt-Tpsg/Tps-Tnsc2										
W-834-D3	10/16/86[e]	8.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	29	3.6	1.7×10^{-4}	P
	04/16/87	8.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	45	5.6	2.6×10^{-4}	F
W-834-K1	10/16/86[e]	1.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	5.7	5.7	2.7×10^{-4}	P
W-834-M2	02/19/87[e]	5.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	4.6	>0.9	4.2×10^{-5}	G
W-834-S3	10/16/86[e]	2.2	NA	Slug	Slug	Modified Papadopulos (cyl.)	28	13	6.1×10^{-4}	G
W-834-S5	02/19/87[e]	4.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	0.2	0.04	1.9×10^{-6}	F
W-834-T2	01/08/87[e]	5.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	18	3.6	1.7×10^{-4}	F
	04/15/87	5.0	NA	Slug	Slug	Modified Papadopulos (cyl.)	14	2.9	1.4×10^{-4}	F
W-834-T4	01/07/86[e]	2.0	NA	Slug	Slug	Papadopulos (cyl.)	40	20	9.4×10^{-4}	E
Tps-Tnsc2										
W-834-S8	03/30/89	8.3	NA	Slug	Slug	Papadopulos (cyl.)	0.38	0.05	2.4×10^{-6}	F
W-834-S9	03/02/89	5.0	NA	Slug	Slug	Papadopulos (cyl.)	0.19	0.038	1.8×10^{-6}	E
Tnsb1										
W-834-T1	04/07/87[e]	18.0	4.9	DD1R	DD	Theis	710	39	1.8×10^{-3}	G
			[3.1×10^{-4}]		DD	Cooper	760	42	2.0×10^{-3}	G
					R	Theis	710	39	1.8×10^{-3}	F
					DD	Specific Discharge Approx.	1,200	65	3.0×10^{-3}	—
W-834-T3	04/08/87[e]	5.0	2.2	DD1R	DD	Theis	84	17	8.0×10^{-4}	F
			[1.4×10^{-4}]		R	Theis	61	12	5.7×10^{-4}	P
					DD	Specific Discharge Approx.	460	92	4.3×10^{-3}	—

NA = not applicable.

[a] DD1 = Single Step Drawdown.
DD2 = Two Step Drawdown.
DD3 = Three Step Drawdown.
R = Recovery Monitored.
Slug = displacement of a known quantity of water.

[b] DD = Drawdown.
1 = Drawdown Step 1.
2 = Drawdown Step 2.
3 = Drawdown Step 3.
4 = Drawdown Step 4.
R = Recovery.
Slug = Displacement of a known quantity of water.

[c] Cooper et al. (1967).
Papadopulos et al. (1973) (cylindrical curves).
Theis (1935).

[d] E = Excellent: High confidence that solution is unique. Data are smooth and flow rate will controlled.
G = Good: Some confidence that solution is unique. Data are not too "noisy." Well bore storage effects, if present, do not significantly interfere with test interpretation. Bondary effects can be separated from properties of the pumped zone.
F = Fair: Low confidence that solution is unique. Data are "noisy." Multiple leakiness and other boundary effects tend to obscure the curve match.
P = Poor: Unique solution cannot be obtained due to multiple boundaries, well bore storage, uneven flow rate, or equipment problems. Usually the test is repeated.

[e] Weiss Assoc. (1988).

Table 1-7. Well completions in the Building 834 operable unit.

Well	Stratigraphic unit	Hydrologic unit	Comments
W-834-B2	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
W-834-B3	Tpsg/Tps	Qt-Tpsg	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-C2	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
W-834-D2	$Tnbs_1$	$Tnbs_1$	
W-834-D3	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-D4	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-D5	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-D6	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-D7	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-D8	Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.
W-834-D9A	$Tnbs_2$	$Tnbs_2$-$Tnsc_1$	Not completed in the $Tnsc_1$ stratigraphic unit.
W-834-D10	Tps	Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.
W-834-D11	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
W-834-D12	Tpsg/Tps	Qt-Tpsg	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-D13	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
W-834-D14	Tpsg/Tps	Qt-Tpsg	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-G3	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-H2	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
W-834-J1	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-J2	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-K1	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-M1	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-M2	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S1	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
W-834-S2	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S2A	Tps/$Tnsc_2$	Tps-$Tnsc_2$	Completed exclusively in the perching horizon.
W-834-S3	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S4	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S5	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S6	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S7	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-S8	$Tnsc_2$	Tps-$Tnsc_2$	Not completed in the Tps stratigraphic unit.
W-834-S9	$Tnsc_2$	Tps-$Tnsc_2$	Not completed in the Tps stratigraphic unit.
W-834-T1	$Tnsb_1$	$Tnsb_1$	Completed in regional aquifer.
W-834-T2	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T2A	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.

Table 1-7. (Continued)

Well	Stratigraphic unit	Hydrologic unit	Comments
W-834-T2B	Tpsg/Tps	Qt-Tpsg	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T2C	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T2D	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T3	$Tnsb_1$	$Tnsb_1$	Completed in regional aquifer.
W-834-T4	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T4A	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T4B	Tps	Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.
W-834-T4C	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T5	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T7	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T7A	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T8	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
W-834-T9	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
TP-834-T1B	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
TP-834-T7	Tps	Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.
TP-834-T9B	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
TP-834-T10A	Tpsg	Qt-Tpsg	Not completed in the Qt stratigraphic unit.
TP-834-T10B	Tps	Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.
TP-834-T11	Tpsg/Tps	Qt-Tpsg/Tps-$Tnsc_2$	Not completed in the Qt and $Tnsc_2$ stratigraphic units.
TP-834-T13	Tps	Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.
TP-834-T15	Tps	Tps-$Tnsc_2$	Not completed in the $Tnsc_2$ stratigraphic unit.

Table 1-8. Methods used at boreholes and monitor wells in the Building 834 operable unit.

Monitor well or borehole	Installation type[a]	Drilling method[b]	Zone of completion	Dates drilled	Borehole geophysical logs[c]	Hydraulic tests			Ground water sample collection			Dry out
						Slug bail	Step DD	Cont. rate	Bail	Blad. pump	Elec. sub pump	
834-B1	BH	1,5	NA	6/10–7/15/83	none	NA	NA	NA	NA	NA	NA	NA
W-834-B2	MW	1	Qt-Tpsg	7/25/90	EMI, NL	NO	NO	NO	YES	NO	NO	YES
W-834-B3	MW	1	Qt-Tpsg	8/9/90	none	NO	NO	NO	YES	NO	NO	YES
834-C1	BH	1,5	NA	7/5–6/83	none	NA	NA	NA	NA	NA	NA	NA
W-834-C2	MW	1	Qt-Tpsg	8/8/90	none	NO	NO	NO	YES	NO	NO	YES
834-D1	BH	1,5	NA	6/23–7/1/83	none	NA	NA	NA	NA	NA	NA	NA
W-834-D2	MW	5	$Tnbs_1$	11/25–12/11/85	NGL, RL, SPRL, EMI, NL,	NO	NO	NO	YES	NO	NO	DRY[d]
W-834-D3	MW	1	Qt-Tpsg/ $Tps\text{-}Tnsc_2$	6/9–10/86	none	YES	NO	NO	YES	NO	NO	YES
W-834-D4	MW	1	Qt-Tpsg/ $Tps\text{-}Tnsc_2$	10/10/86, 11/10–11/86	none	NO	NO	NO	YES	NO	NO	YES
W-834-D5	MW	1	Qt-Tpsg/ $Tps\text{-}Tnsc_2$	10/13/86, 11/11/86	none	NO	NO	NO	YES	NO	NO	YES
W-834-D6	MW	1	Qt-Tpsg/ $Tps\text{-}Tnsc_2$	10/13–14/86, 11/11/86	none	NO	NO	NO	YES	NO	NO	YES
W-834-D7	MW	1	Qt-Tpsg/ $Tps\text{-}Tnsc_2$	4/12/88	none	NO	NO	NO	YES	NO	NO	YES
W-834-D8	MW	1	Qt-Tpsg/ $Tps\text{-}Tnsc_2$	4/13/88	none	NO	NO	NO	NO	YES	NO	YES
834-D9	BH	1,5	NA	6/24–7/11/88	none	NA	NA	NA	NA	NA	NA	NA
W-834-D9A[d]	MW	1,5	$Tnbs_2\text{-}Tnsc_1$	7/12–8/10/88	NGL, EMI, NL	NA[2]	NA[2]	NA[2]	NO	NO	NO	NA
W-834-D10	MW	1	$Tps\text{-}Tnsc_2$	1/17–18/89	none	NO	NO	NO	YES	NO	NO	YES

Table 1-8. (Continued)

Monitor well or borehole	Installation type[a]	Drilling method[b]	Zone of completion	Dates drilled	Borehole geophysical logs[c]	Hydraulic tests			Ground water sample collection			Dry out
						Slug bail	Step DD	Cont. rate	Bail	Blad. pump	Elec. sub pump	
W-834-D11	MW	1	Qt-Tpsg	3/16/89	none	NO	NO	NO	YES	NO	NO	YES
W-834-D12	MW	1	Qt-Tpsg	3/16–21/89	none	NO	NO	NO	YES	NO	NO	YES
W-834-D13	MW	1	Qt-Tpsg	3/22/89	none	NO	NO	NO	YES	NO	NO	YES
W-834-D14	MW	1	Qt-Tpsg	3/23/89	none	NO	NO	NO	YES	NO	NO	YES
834-E1	BH	1,5	NA	7/13–14/83	none	NA	NA	NA	NA	NA	NA	NA
834-G1	BH	1,5	NA	6/9/83, 7/7–8/83	none	NA	NA	NA	NA	NA	NA	NA
834-G2	BH	8	NA	7/26/83	none	NA	NA	NA	NA	NA	NA	NA
834-G3	BH	8	NA	6/9/83	none	NA	NA	NA	NA	NA	NA	NA
W-834-G3	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/22/85	none	NO	NO	NO	YES	NO	NO	YES
834-H1	BH	8	NA	6/10/83	none	NA	NA	NA	NA	NA	NA	NA
W-834-H2	MW	1	Qt-Tpsg	7/25/90	none	NO	NO	NO	YES	NO	NO	YES
W-834-J1	MW	1,5	Qt-Tpsg/ Tps-Tnsc$_2$	7/11–12/83	none	NO	NO	NO	YES	NO	NO	YES
W-834-J2	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	3/3–4/1/88	none	NO	NO	NO	YES	NO	NO	YES
W-834-K1	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/18/85	none	YES	NO	NO	YES	NO	NO	YES
W-834-M1	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/21/85	none	NO	NO	NO	NO	YES	NO	YES
W-834-M2	MW	1,5,1	Qt-Tpsg/ Tps-Tnsc$_2$	11/12–13/86	none	YES	NO	NO	NO	YES	NO	YES
W-834-S1	MW	1,5	Qt-Tpsg	7/15–19/83	none	YES	NO	NO	YES	NO	NO	YES

Table 1-8. (Continued)

Monitor well or borehole	Installation type[a]	Drilling method[b]	Zone of completion	Dates drilled	Borehole geophysical logs[c]	Hydraulic tests			Ground water sample collection			Dry out
						Slug bail	Step DD	Cont. rate	Bail	Blad. pump	Elec. sub pump	
W-834-S2	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/12–13/85	EMI, NL	NO	NO	NO	YES	NO	NO	YES
W-834-S2A	MW	1	Tps-Tnsc$_2$	3/3–17/86	none	NO	NO	NO	NO	YES	NO	YES
W-834-S3	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/15/85	none	YES	NO	NO	NO	YES	NO	YES
W-834-S4	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/19/85	none	NO	NO	NO	YES	NO	NO	YES
W-834-S5	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	11/14–17/86	none	YES	NO	NO	YES	NO	NO	YES
W-834-S6	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	1/22–23/87	none	NO	NO	NO	YES	NO	NO	YES
W-834-S7	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	11/17–19/87	none	NO	NO	NO	YES	NO	NO	YES
W-834-S8	MW		Tps-Tnsc$_2$		none	YES	NO	NO	NO	YES	NO	YES
W-834-S9	MW		Tps-Tnsc$_2$		none	YES	NO	NO	YES	NO	NO	YES
W-834-T1	MW	5	Tnbs$_1$	10/15–11/10/86	NGL, RL, SPRL, SPL, CL	NO	YES	NO	NO	NO	YES	NO
W-834-T2	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	10/17–21/86	none	YES	NO	NO	NO	YES	NO	YES
W-834-T2A	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	5/26/88	none	NO	NO	NO	YES	NO	NO	UNK
W-834-T2B	MW	5	Qt-Tpsg	5/31–6/2/88	none	NO	NO	NO	YES	NO	NO	UNK
W-834-T2C	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	5/25/88	none	NO	NO	NO	YES	NO	NO	YES

Table 1-8. (Continued)

Monitor well or borehole	Installation type[a]	Drilling method[b]	Zone of completion	Dates drilled	Borehole geophysical logs[c]	Hydraulic tests			Ground water sample collection			Dry out
						Slug bail	Step DD	Cont. rate	Bail	Blad. pump	Elec. sub pump	
W-834-T2D	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	6/20–21/88	none	NO	NO	NO	NO	YES	NO	YES
W-834-T3	MW	5	Tnbs$_1$	11/11–12/8/86	EMI, NGL, RL, SPRL, SPL, NL, CL	NO	YES	NO	NO	NO	YES	NO
W-834-T4	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	12/8–9/86	none	YES	NO	NO	YES	NO	NO	YES
W-834-T4A	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	4/7–8/88	none	NO	NO	NO	YES	NO	NO	YES
W-834-T4B	MW	5	Tps-Tnsc$_2$	4/6–7/88	none	NO	NO	NO	YES	NO	NO	YES
W-834-T4C	MW	1,5	Qt-Tpsg/ Tps-Tnsc$_2$	4/4–6/88	none	NO	NO	NO	YES	NO	NO	YES
W-834-T5	MW	1,5	Qt-Tpsg/ Tps-Tnsc$_2$	12/4–5/86	none	NO	NO	NO	NO	YES	NO	YES
834-T6	BH	1	NA	12/9–11/86	none	NA	NA	NA	NA	NA	NA	NA
834-T7	BH	1,5	NA	11/2–9/87	none	NA	NA	NA	NA	NA	NA	NA
W-834-T7A	MW	5	Qt-Tpsg/ Tps-Tnsc$_2$	3/22–31/88	none	NO	NO	NO	YES	NO	NO	YES
W-834-T8	MW	1,5	Qt-Tpsg/ Tps-Tnsc$_2$	11/10–17/87	none	NO	NO	NO	YES	NO	NO	YES
W-834-T9	MW	1	Qt-Tpsg/ Tps-Tnsc$_2$	1/12–13/88	none	NO	NO	NO	YES	NO	NO	YES
834-T10	BH	1	NA	11/1–4/91	none	NA	NA	NA	NA	NA	NA	NA

Note: Footnotes on following page.

Table 1-8. (Continued)

[a] *Installation Type:*

A-WSW	=	Active water-supply well
BC	=	Barcad sampler
BH	=	Borehole
DS	=	Destroyed well
GR	=	Grouted
I-MW	=	Inactive mine ventilation well
I-WSW	=	Inactive water-supply well
LY	=	Lysimeter
MC	=	Multiple completion
MP	=	Monitor point
MW	=	Monitor well
NP	=	Neutron probe access tube
PZ	=	Piezometer
WCD	=	Well currently dry
WSW	=	Water-supply well

[b] *Drilling Method:*

1 Hollow stem auger
2 Flight auger
3 Air-mist rotary coring
4 Mud rotary coring
5 Air-mist rotary, rock or other bit
6 Mud rotary, rock or other bit
7 Well installed in vertical mine shaft
8 Hand auger
9 Cable tool
10 Dug with shovel
* Abandoned well

[c] *Geophysical Logs Available* (see note):

A	=	Acoustic
BVL	=	Borehole Video Logs
C	=	Caliper
CL	=	Three-Arm Caliper Logs
DL	=	Density Logs
EMI	=	Electromagnetic Induction Logs
FEC	=	Fluid Electrical Conductivity
FWAL	=	Full Wave Form Acoustic Logs
LL	=	Lateral Log
NGL	=	Natural Gamma Logs
NL	=	Neutron Logs
RL	=	Normal Resistivity Logs
SPL	=	Spontaneous Potential Logs
SPRL	=	Single Point Resistance Logs
SV	=	Seismic Velocity Survey
TL	=	Temperature Logs

[d] Well W-834-D9A has never contained ground water. A straddle packer hydraulic test was performed.
[e] Secondary zone of completion

Miscellaneous Abbreviations:

Blad.	=	Bladder
Cont. rate	=	Constant rate
DD	=	Drawdown
Elec. sub.	=	Electric submersible
NA	=	Not applicable
UNK	=	Unknown

Note: Logging methods are discussed in Webster-Scholten (1993); geophysical logs are illustrated in Toney and Crow (1988), Crow and Toney (1991), and Crow and McConihe (1993).

Table 1-9. Description of hydrologic units in the Building 834 operable unit.

Hydrologic unit Qt-Tpsg, perched water-bearing zone: Quaternary terrace deposits (Qt) and Tertiary channel deposits (Tpsg)	
Occurrence and extent of saturation	Depth to water table of perched water-bearing zone varies from 20 to 70 ft. The areal extent of saturation in December 1991 was 8.7×10^5 ft^2, and the saturated thickness varied from 0 to 5 ft. The total thickness of the perched zone varies from 6 to 81 ft, with an average of 34 ft.
Hydraulic condition	Perched, unconfined water-bearing zone.
Hydraulic conductivity	The hydraulic conductivity obtained by slug testing well W-834-S1 is 7.5×10^{-4} cm/sec (15.7 gal/day/ft^2)
Ground water flow direction, gradient, and velocity	Ground water flows generally north to south then changes to a northeast to southwest direction about 600 ft south of Building 834. The average hydraulic gradient is 0.1 ft/ft. The average linear pore velocity is 155 ft/yr, ranging from 0.8 to 389 ft/yr, with an assumed porosity of 20%.
Relationship to adjacent hydrologic units	The perched zone is underlain by a 10- to 80-ft thick interval of clay, siltstone, and claystone ($Tps/Tnsc_2$) that impedes downward movement of liquids. Perimeter of saturated zone "daylights" on hillsides. Regional potential evapotranspiration is 40–50 in. Evapotranspiration is the inferred mechanism of discharge (Bryn et al., 1990).
Typical well yields	Most wells yield less than 4.3×10^{-8} m^3/sec (1 gpd). Nonvacuum-enhanced yield on a pair of wells, 1.1×10^{-6} m^3/sec (25 gpd) (W-834-D4 and -D5, screened across $Qt\text{-}Tpsg/Tps\text{-}Tnsc_2$). Vacuum-enhanced production rates on pairs of wells: 3.5×10^{-6} m^3/sec (80 gpd) (W-834-D4 and -D5), 4.4×10^{-6} m^3/sec (110 gpd) (W-834-T4 and -T4C, screened across $Qt\text{-}Tpsg/Tps\text{-}Tnsc_2$).
Beneficial uses	None. Water in the perched aquifer is not considered suitable or potentially suitable under California SWRCB Resolution No. 88-63, which specifies that a municipal or domestic water supply must be able to produce a sustained yield of 200 gpd from a single well. Furthermore, San Joaquin County Health Ordinance No. 1862 requires that any water-supply well be grouted to a depth of 100 ft, which renders the perched aquifer unusable.
Hydrologic unit $Tps\text{-}Tnsc_2$, "perching horizon": Pliocene nonmarine deposits (Tps), and Neroly upper mudstone ($Tnsc_2$)	
Occurrence and extent of saturation	Impedes downward movement of liquids, because it is composed of clay, siltstone, and claystone. Thickness varies from 10 to 80 ft. Localized silty sandstone lenses and stringers may yield minor quantities of water to wells.
Hydraulic condition	Perching horizon, aquitard. The water level in a third well was above the screen (W-834-S9).

Table 1-9. (Continued)

Hydraulic conductivity	The hydraulic conductivity of the more permeable sandstone beds in the perching horizon is approximately two orders of magnitude less than that of the perched water-bearing zone, based on slug test results. The hydraulic conductivities obtained by slug tests made in two perching horizon wells, screened in sandstone, range from 1.8×10^{-6} to 2.4×10^{-6} cm/sec (0.038 to 0.05 gal/day/ft^2). The saturated hydraulic conductivities, obtained from three perching horizon intervals by infiltration packer testing, range from 1.6×10^{-7} to 2.8×10^{-7} cm/sec (0.0034 to 0.0059 gal/day/ft^2). The value of 2.8×10^{-7} cm/sec was obtained from an interval selected because it was significantly fractured.
Ground water flow direction, gradient, and velocity	NA
Relationship to adjacent hydrologic units	Impedes downward migration of percolation, resulting in water perched near the surface. Leaky boundary between Qt-Tpsg and Tps-Tnsc$_2$. Lack of matrix suction between the base of the Tps-Tnsc$_2$ and the top of the Tnbs$_2$-Tnsc$_1$ serves as impediment to downward flow of liquids.
Typical well yields	Less than 4.3×10^{-8} m^3/sec (1 gpd).
Beneficial uses	None. San Joaquin County Health Ordinance No. 1862 prevents use of this water. Yields too low for any well to serve as a source of municipal or domestic supply under California SWRCB Resolution No. 88-63.
Hydrologic unit Tnbs$_2$-Tnsc$_1$: Miocene Neroly Formation (upper blue sandstone/middle siltstone-claystone)	
Occurrence and extent of saturation	No known saturated area in Tnbs$_2$ within the study area. No springs have been observed discharging from the Tnbs$_2$ where it crops out along study area hillsides. Inconclusive evidence for Tnbs$_2$ moisture is noted in geologic logs for wells drilled in the far southeastern corner of the Building 834 Complex site.
Hydraulic condition	Not fully saturated, based on available evidence.
Hydraulic conductivity	Attempt to test unsaturated Neroly upper sandstone by infiltration packer test unsuccessful due to washout of borehole walls and loss of packer seal. Estimated saturated hydraulic conductivity greater than 1.0×10^{-5} cm/sec (0.212 gal/day/ft^2). No testing conducted on Tnsc$_1$.
Ground water flow direction, gradient, and velocity	NA
Relationship to adjacent hydrologic units	Saturation/permeability contrast at the top of the Neroly upper blue sandstone acts as an impediment to downward flow from the Tps-Tnsc$_2$ hydrologic unit at the core of the Building 834 Complex site.

Table 1-9. (Continued)

Typical well yields	Well W-834-D9A has yielded no water from the Neroly upper blue sandstone ($Tnbs_2$) since completion in August 1988.
Beneficial uses	NA
	Hydrologic unit $Tnbs_1$, "regional aquifer": Miocene Neroly lower blue sandstone
Occurrence and extent of saturation	Due to the variable elevation in the study area, the surface of the saturated portion of the $Tnbs_1$ is identified at depths ranging from about 130 to 280 ft. The $Tnbs_1$ saturated zone is inferred to extend to the study area boundaries. Its thickness is unknown because study area wells are not fully penetrating.
Hydraulic condition	NA
Hydraulic conductivity	Hydraulic conductivity values range from 2.0×10^{-3} cm/sec to 5.7×10^{-4} cm/sec.
Ground water flow direction, gradient, and velocity	Ground water flows generally southward, with orientation varying from west to east depending on location. The gradient is approximately 0.03 ft/ft. The average linear pore velocity is 78 ft/yr.
Relationship to adjacent hydrologic units	Subsurface inflow at the study area boundary is the inferred mechanism of recharge. Discharge is inferred to occur by subsurface outflow at the downgradient study area boundary.
Typical well yields	Yields obtained from pumping tests on wells W-834-T1 and -T3 were between 3.1×10^{-4} and 1.4×10^{-4} m^3/sec (2 and 5 gpm). Hydraulic characteristics for well W-831-01 resulting from a slug test indicated even lower yields.
Beneficial uses	No current beneficial uses in the study area. Elsewhere at Site 300, the $Tnbs_1$ regional aquifer is used as a fire fighting and drinking water supply. The $Tnbs_1$ also supplies offsite municipal and domestic water uses. The arsenic occurring in the water is inferred to have leached from arsenopyrite in the Neroly Formation.

Table 1-10. Natural ground water geochemical characteristics of the hydrologic units in the Building 834 operable unit.[a]

Hydrologic unit	pH	TDS (mg/L) (ppm)	Specific conductivity (μmhos/cm)	Natural background metaloids (mg/L) (ppm)		Natural background iron (mg/L) (ppm)
				Arsenic	Selenium	
Qt-Tpsg	7.4–8.2 (2)	760–910 (2)	1,020–1,400 (2)	0.015–0.018 (2)	<0.002 (2)	<0.1–47 (7)
Tps-Tnsc$_2$	7.9–9.5 (4)	680–1,400 (4)	1,000–2,430 (4)	ND	ND	<0.1–6.7 (6)
Qt-Tpsg/Tps Tnsc$_2$	7.4–9.7 (21)	380–1,800 (21)	630–2,890 (21)	0.009 (1)	0.001 (1)	<0.04–3.8 (14)
Tnbs$_2$-Tnsc$_1$	NW	NW	NW	NW	NW	NW
Tnbs$_1$	7.7–7.9 (4)	440–470 (4)	640–710 (4)	0.023–0.058 (2)	<0.001 (2)	<0.03–0.05 (4)

[a] This table presents a summary of natural ground water chemical constituents available for each well sampled (Webster-Scholten, 1993); not all wells have been sampled.

( ) = Parenthetic entries are sample counts.

Range = Historical range.

ND = Data not available, no samples analyzed.

NW = No water present in well completed in this hydrologic unit.

Table 1-11. Well cluster at the Building 834 Complex site (data collected in December 1991).

Well	Hydrologic unit	Water elevation (ft above MSL[a])	Distance of water level above (+) or below (–) screen (ft)	TCE detected (μg/L) (ppb)
W-834-S1	Qt-Tpsg	969.87	–1.71	76,000
W-834-S9	Tps-Tnsc$_2$	945.62	+6.19	1,100

[a] MSL = mean sea level.

Table 1-12. Source screening information in the Building 834 operable unit.[a]

Control building—Building 834A	
Investigations performed	Records search. Interviews with former and present employees. Building inspection.
Summary of results	*Historical operations summary* Building 834A is the control room for the Building 834 Complex testing facility; it contains a sink and toilet. Based on interviews, no chemicals were used or stored in this building.
Conclusions	The Building 834A area is not considered to be a release site.
Pump stations—Buildings 834B, C, and D	
Investigations performed	Records search. Interviews with former and present employees. Building inspections and field observations. Soil analyses from boreholes. Ground water analyses from monitor wells. AVI SVS
Summary of results	*Historical operations summary* Building 834B was used as a TCE conditioning station for the test cells in Building 834E and 834F from approximately 1960 to July 1985. Since the late 1970s, it is believed that several releases have occurred in front of and behind Building 834B. One of the most recent TCE releases occurred in February 1987, when an estimated 2 to 5 gal. spilled onto the soil berm behind the building. Building 834C was used to condition TCE to heat the thermal cycling and soaking test cell in Building 834G. Building 834C was in use from approximately 1960 to 1986. Most of the TCE releases at 834C occurred in the mid- to late 1960s as the result of leaking TCE pump seals. Equipment in Building 834D is used to pump TCE to the test cells in Building 834H and 834J, and was also used to pump TCE to the test cell in Building 834E when 834B was deactivated. The 834D TCE system presently contains approximately 3,400 gal. of TCE. It is estimated that somewhat less than half as much TCE was released at 834D as at 834C. The soil with the highest TCE concentrations was removed in June 1983. At that time, about 40 yd^3 of soil was excavated behind Building 834D, which removed all soil within a 20-ft radius of TCE-stained soil. In May 1994, the TCE transfer system was completely dismantled and removed from the Building 834 Complex.

Table 1-12. (Continued)

Summary of results (continued)	*Data summary* TCE was detected at the following locations: Building 834B Borehole samples: 0.524–13.1 ppm Soil vapor samples: 32.6–2,900 ppm Building 834C Borehole samples: 1.9–12,000 ppm Soil vapor samples: 0.18–9.8 ppm Soil samples: 120–6,500 ppm Building 834D Borehole samples: 0.13–257 ppm Soil vapor samples: 14.4–97 ppm Soil and rock samples: 0.0007–970 ppm Perched ground water samples: approximately 330,000 ppb. Maximum TCE concentration reported in the SWRI was 510,000 ppb. A new maximum TCE concentration of 800,000 ppb was reported in February 1993.
Conclusions	The Building 834B, C, and D areas are principal release areas.
TCE system test cells—Buildings 834E, F, G, H, and J	
Investigations performed	Records search. Interviews with former and present employees. Building inspections and field observations. Soil analyses from boreholes. AVI SVS. Ground water analyses from monitor wells.

Table 1-12. (Continued)

Summary of results	*Historical operations summary* Building 834E is a thermal soaking shocking test cell. TCE used in 834E is currently pumped from 834D, but was pumped from 834B before 834B was deactivated in July 1985. Leakage of TCE through pump seals and valves was known to have occurred at 834E. TCE stains have also been noted high up on a wall near 834E, suggesting that TCE under pressure may have sprayed from a leaking pump seal or pipe. However, after TCE pump seals were replaced, any leaks occurred only as droplets. Building 834F is a special test cell controlled by 834B. TCE was used at 834F from approximately 1961 to the late 1960s, possibly into the early 1970s. It is believed that little, if any, TCE was released at Building 834F. However, some compressor oil may have leaked near the building. Building 834G is a thermal cycling and soaking cell that receives TCE from Building 834C. Some TCE was released via leaking seals at Building 834G. In May 1983, 50 to 60 gal of TCE were released from the system due to a blown Teflon seal. All but 10 gal were contained, and it is estimated that only about 1.5 gal flowed onto bare ground. A second release, consisting of 2 to 20 gal, occurred sometime between 1983 and 1987. Building 834H is a thermal cycling and soaking test cell that receives TCE from Building 834D. Because no TCE pumps were located outside the back of Building 834H, it is believed that no TCE leaked on the northwest side of the building. Building 834J is a thermal cycling test cell with humidity control. Between approximately 1964 and 1985, TCE was used there as a heat-transfer medium. TCE sporadically leaked onto the soil surface from two pumps located outside 834J, near monitor well W-834-J1. The spills are believed to be smaller in magnitude than those that occurred at pump stations 834C, 834D, and 834B (Stupfel, 1988a). "Substantial" TCE soil stains were documented near the northern corner of 834J (McConachie, 1982). In May 1994, the TCE transfer system was completely dismantled and removed from the Building 834 Complex.

Table 1-12. (Continued)

Summary of results (continued)	*Data summary* TCE was detected at the following locations: Building 834E Borehole samples: ND–0.32 ppm Building 834F Soil vapor samples: 0.14–16 ppm Building 834G Borehole samples: 0.006–0.278 ppm Soil vapor samples: 1.5–24.7 ppm Building 834H Borehole samples: 0.123 ppm Well sample: 84,000 ppb Soil vapor samples: 0.024–6,300 ppm Building 834J Borehole samples: 0.1–52 ppm Well samples: 750–64,000 ppb Soil vapor samples: 0.07–>700 ppm
Conclusions	The Building 834E, F, G, and H areas are sites of lesser releases of TCE. The Building 834J area is a principal release site.
Other test cells—Buildings 834K, L, and M	
Investigations performed	Records search. Interviews with former and present employees. Field observations. AVI SVS.

Table 1-12. (Continued)

Summary of results	*Historical operations summary* Building 834K has no history of use or storage of chemicals. Building 834L was a thermal soaking test cell located north of the core of the Building 834 Complex. It used electricity for heating and refrigeration for cooling. It is reported that "no TCE has been in or around" Building 834L (Stupfel, 1988a). As a result, sampling to detect releases of TCE has not been conducted at Building 834L, nor has any soil been excavated. Testing is no longer performed in this cell. Building 834M is a thermal soaking test cell. The cell uses solar energy as its principal heat source. It was reported that "no TCE has been in or around" this building. No boreholes have been drilled, nor have any soil samples been collected at this building. Borehole W-834-M2, drilled about 375 ft southeast of Building 834M, had no detections of TCE in 14 samples analyzed (collected from 5.5 ft–90.5 ft in depth). *Data summary* TCE was detected at the following locations: Building 834K Soil vapor samples: 0.028–59 ppm Building 834L No samples taken. Building 834M Borehole samples: ND Soil vapor samples: 0.037–3.2 ppm
Conclusions	The Building 834K, L, and M areas are not considered to be release sites.
	Septic system leach field
Investigations performed	Records search. Interviews with former and present employees. Field observations. Soil analyses from boreholes and leach-line trench. Ground water analyses from monitor wells.

Table 1-12. (Continued)

Summary of results	*Historical operations summary* Prior to 1978, concrete floor drains in pump stations 834B, C, and D were connected to the septic system leach field. After that time, the drains were sealed. In February 1989, the discharge to the leach field was rerouted to an area outside of the TCE plume in perched ground water to prevent recharge to the plume. *Data summary* TCE was detected at the following locations: Well W-834-S1 Borehole samples: 0.004–2.8 ppm Ground water samples: 2,200–170,000 ppb Pipe trench sample LL-834-01 Borehole samples: 0.27 ppm No ground water samples taken. Pipe trench sample LL-834-02 Borehole samples: 0.2 ppm No ground water samples taken.
Conclusions	The septic system leach field is a principal release site.
Underground diesel tank—core of Building 834 Complex	
Investigations performed	Records search. Interviews with former and present employees. Soil analyses from boreholes. Ground water analyses from monitor wells.

Table 1-12. (Continued)

Summary of results	*Historical operations summary* The most recent annual integrity testing of tank 834-D1U1 and associated lines was conducted on May 16, 1991. No leaks were found. We identified total fuel hydrocarbons and hydrocarbons (by IR method in perched ground water) and total petroleum hydrocarbons in a borehole rock sample. We attribute the presence of these compounds to releases from accidental overfilling of the tank. *Data summary* The following chemicals were detected in samples from well W-834-D8: TCE Borehole samples 0.0002–140 ppm Ground water samples: 39,000–120,000 ppb TPH Borehole samples: 100 ppm Ground water samples: 25,000–150,000 ppm BTEX Borehole samples: 0.0003–0.0021 ppm Ground water samples: ND
Conclusions	The underground diesel tank is a release site.
Retention tank and dry well—Building 834 L	
Investigations performed	Records search. Interviews with former and present employees. Field observations. Soil analyses from boreholes.
Summary of results	*Historical operations summary* These facilities have been investigated and closed (Lamarre et al., 1989a, and two unpublished addenda).
Conclusions	The Building 834L retention tank and dry well are not confirmed release sites.

Table 1-12. (Continued)

Cooling towers—Building 834 Complex	
Investigations performed	Records search. Interviews with former and present employees. Field observations. Surface water discharge samples.
Summary of results	*Historical operations summary* The discharge from the Building 834 cooling towers is regulated under NPDES permit No. CA 0081396 and Waste Discharge Order 82105. The discharge is in compliance.
Conclusions	The discharge from the Building 834 Complex cooling towers is not considered to be a confirmed release.

[a] Source screening data for study area Buildings 831, 832, and 838 are presented in SWRI Chapter 10.

Table 1-13. Building 834 Remedial Investigation summary.

Confirmed release sites (Building 834 Complex)	Primary chemical(s) of potential concern	Fate and transport modeling	Risk assessment	Comments/recommendations
Buildings 834B, C, D, E, F, G, H, and J Underground diesel fuel tank (834-D1U1) Building 834A former septic tank leach field	TCE Cadmium	*Surface soil* Contaminants bound to resuspended soil particles in general study area. *Subsurface soil* VOC flux through soil, ambient air in vicinity of Building 834D, and through concrete slab into Building 834D. *Ground water* VOC transport through vadose zone to regional aquifer, assumed to reach well CDF-1. *Ecological exposure* Fauna exposure to contaminants in surface and subsurface soil, outdoor air, and subsurface air.	*Human health risk assessment* Adult on-site exposures Range of risk at Building 834D: 6×10^{-4} to 1×10^{-3} Range of risk at other locations: 4×10^{-10} to 4×10^{-7} Range of HIs at Building 834D: 22 to 36 Range of HIs at other locations: 7.2×10^{-5} to 1.1×10^{-2} Residential exposure associated with use of contaminated ground water Risk ~ 7×10^{-11} HI = 2.7×10^{-6} *Ecological risk assessment* Range of HIs: California ground squirrel (adult and juvenile): 17.6 to 31.9 (PCE), 338 to 614 (TCE), and 1.38 to 13.3 (cadmium) San Joaquin kit fox (adult and juvenile): 17.6 to 31.9 (PCE), 338 to 614 (TCE), and 1.38 to 13.3 (cadmium)	Values of risk and HI for Building 834D indicate there is a potential for unacceptable levels of risk and noncancer hazard associated with long-term exposure at this location. Data suggest that the California ground squirrel population at Site 300 has not been negatively impacted by contaminants of concern (COCs). Insufficient data prevent full assessment of the impact of COCs on black-tailed deer population. San Joaquin kit fox may be at risk from COCs should they den at the study area in the future.

Table 1-14. Contaminants of potential concern in surface soil (0–0.5 ft) in the Building 834 operable unit.

Contaminant	Maximum concentration mg/kg (ppm)	Mean concentration[a]	95% UCL[b] mg/kg (ppm)
Acetone	7.0×10^{-2}	3.21×10^{-2}	5.63×10^{-2}
Cadmium	1.6×10^{1}	NA[c]	1.6×10^{1}[c]
Trichloroethylene	1.9×10^{-1}	2.59×10^{-2}	7.03×10^{-2}
Trichlorofluoromethane	2.1×10^{-2}	5.24×10^{-3}	1.28×10^{-2}
Trichlorotrifluoroethane	9.5×10^{-2}	1.49×10^{-2}	3.66×10^{-2}
Xylenes (total isomers)	5.0×10^{-3}	2.86×10^{-3}	3.55×10^{-3}

a Estimate of the arithmetic mean of the underlying log-normal distribution.

b UCL = upper confidence limit.

c Because there was only a single sample and a single detection of this substance, a 95% UCL could not be calculated. The value given is the only measured concentration.

Table 1-15. Contaminants of potential concern in subsurface soil (>0.5–12.0 ft) at Building 834D.

Contaminant	Maximum concentration mg/kg (ppm)	Mean concentration[a]	95% UCL[b] mg/kg (ppm)
Benzene	2.0×10^{-4}[c]	NA[c]	2.00×10^{-4}[c]
Ethylbenzene	1.3×10^{-3}	2.55×10^{-4}	6.16×10^{-4}
Tetrachloroethylene	1.4×10^{1}	5.95×10^{-1}	1.44×10^{0}
Toluene	1.2×10^{-3}[c]	NA[c]	1.20×10^{-3}[c]
Trichloroethylene	2.6×10^{2}	2.74×10^{1}	4.76×10^{1}
Trichlorofluoromethane	2.0×10^{-1}	3.21×10^{-2}	5.29×10^{-2}
Xylenes (total isomers)	1.7×10^{-2}	4.93×10^{-3}	1.45×10^{-2}

a Estimate of the arithmetic mean of the underlying log-normal distribution.

b UCL = upper confidence limit.

c No statistical calculations were made for this substance. The value given is the maximum measured concentration.

Table 1-16. Contaminants of potential concern in ground water in the Building 834 operable unit.[e]

Contaminant	Maximum concentration µg/L (ppb)	Mean concentration[a]	95% UCL[b] µg/L (ppb)
1, 1, 1-Trichloroethane	3.3×10^4	3.02×10^3	1.87×10^4
1, 1-Dichloroethylene	9.0×10^2	2.10×10^1	8.47×10^1
cis-1,2-Dichloroethylene[c]	5.4×10^5	1.62×10^4	1.41×10^5
Acetone	5.5×10^1	NA[c]	5.5×10^1[c]
Benzene	1.4×10^1	NA[c]	1.4×10^1[c]
Chloroform	9.5×10^2	3.31×10^1	1.06×10^2
Ethylbenzene	2.1×10^1	4.59×10^0	1.27×10^1
Methylene chloride	5.1×10^3	2.02×10^2	2.50×10^2
Tetrachloroethylene	6.3×10^3	4.30×10^2	9.08×10^2
Toluene	6.2×10^1	2.13×10^1	5.65×10^1
Trichloroethylene	5.1×10^5	1.38×10^5	1.90×10^5
Trichlorotrifluoroethane	1.3×10^3	2.37×10^1	3.60×10^2
Xylenes (total isomers)	4.0×10^1	NA[d]	4.0×10^1[c]

[a] Estimate of the arithmetic mean of the underlying log-normal distribution.

[b] UCL = upper confidence limit.

[c] The chemical 1, 2-dichloroethylene (1,2-DCE) exists as two isomers, cis-1,2-DCE and trans-1,2-DCE. At various times throughout the 9 years of ground water analysis at Site 300, this chemical has been analyzed for as 1,2-DCE (total), as one or both of the specific isomers, or as all three. When concentration data were available for one or both isomers, we used those values and omitted the less specific analysis for 1,2-DCE (total) from further consideration. The exceptions to this were in cases where the concentration reported for 1,2-DCE (total) was greater than that reported for one or both isomers.

[d] This contaminant has only been detected a single time; consequently, neither a mean concentration nor a 95% UCL were calculated.

[e] Analytical data originally presented in the SWRI report (data prior to December 31, 1991).

Table 1-17. Deepest TCE concentrations detected in rock samples collected from boreholes at the Building 834 operable unit.

Borehole	Total depth (ft)	Maximum depth of TCE detected in soil (ft)	Concentration of TCE detected in soil (mg/kg [ppm])	Stratigraphic unit
W-834-D1	67.5	66.6	0.13	$Tnbs_2$
W-834-D9A	139.3	65.3	0.008	$Tnbs_2$
W-834-S8	85	79.7	0.0016	$Tnsc_2$
W-834-S9	68	67.5	0.0002	$Tnsc_2$
W-834-T7	85	80.3	0.0016	Tps
W-834-T8	95	75.9	0.0012	$Tnsc_2$

Table 1-18. Compounds other than TCE reported in borehole soil and rock samples from the Building 834 operable unit.

Chemical	Maximum concentration detected in mg/kg (ppm)	No. of detections				
		Perched zone	Perching horizon	Neroly upper sandstone	Neroly aquitard	Neroly lower sandstone
Tetrachloroethylene (PCE)	14	30	11	0	0	0
1,1-Dichloroethylene (1,1-DCE)	0.0037	2	3	0	0	0
1,2-Dichloroethylene (1,2-DCE) (Total)	0.017	17	3	0	0	0
1,1,1-Trichloroethane (1,1,1-TCA)	0.0004	0	2	0	0	0
Trichlorofluoromethane (Freon 11)	0.2	4	1	0	1	0
Trichlorotrifluoroethane (Freon 113)	0.004	10	0	0	0	0
Dibromochloromethane	0.0004	1	0	0	0	0
Ethylbenzene	0.0035	13	1	0	0	0
Benzene	0.0013	11	3	0	0	0
Toluene	0.052	18	4	0	0	0
Xylene isomers	0.017	13	3	0	0	0
Total petroleum hydrocarbons	100	0	1	0	0	0
Chloroform	0.024	11	8	0	0	0
Carbon tetrachloride	0.0009	0	1	0	0	0
Methylene chloride	0.0028	3	0	0	1	0
HMX	0.0002	0	1	0	0	0
RDX	0.02	0	2	0	0	0

Table 1-19. Summary of TCE in ground water from July 1983 to December 1991 in the Building 834 operable unit.

Location	Hydrologic unit(s)	Total no. of monitor wells	Total no. of wells with TCE	Maximum concentration in µg/L (ppb)
Building 834	Qt-Tpsg	10	9	190,000
	Qt-Tpsg/Tps-$Tnsc_2$	29	23	510,000[b]
	Tps-$Tnsc_2$	5	4	37,000
	$Tnbs_1$	3[a]	1	1.1

[a] One well, W-834-D2, has not produced water.

[b] A ground water sample collected from well W-834-D3 on February 9, 1993 (after the SWRI data cutoff) reported a new maximum TCE concentration of 800,000 µg/L.

Table 1-20. Comparison (in µg/L [ppb]) of TCE, PCE, 1,2-DCE, and 1,1,1-TCA in perched zone[a] ground water samples from the Building 834 operable unit, third quarter 1991.

Well	TCE	PCE	1,2-DCE	1,1,1-TCA
Perched water-bearing zone				
W-834-B3	34,000	<200	<200	<200
W-834-S1	560,000	2,600	800	<200
Perched zone				
W-834-D4	350,000	<2,000	210,000	<2,000
W-834-D5	34,000	<200	44,000	<200
W-834-D6	35,000	<200	7,200	<200
W-834-K1	6,100	<20	<20	60
Perching horizon				
W-834-S2A	27,000	100	<100	<100
W-834-S8	9,200	110	<50	<20

[a] Includes both perched water-bearing zone (Qt-Tpsg) and perching horizon (Tps-$Tnsc_2$) hydrologic units.

Table 1-21. Summary of VOCs detected in regional aquifer wells for the period of record[a] in the Building 834 operable unit.

Analytes	W-834-T1		W-834-T3	
	µg/L (ppb)	Sampling date	µg/L (ppb)	Sampling date
Chloroform	0.5	12/19/86	ND	PR
Chloromethane	15	12/09/91	ND	PR
Freon 113	1.0	03/08/88	1.1	12/10/87
	2.0	12/19/86		
Methylene chloride	ND	PR	2.5	03/19/87
PCE	0.9	03/19/87	ND	PR
Toluene[b]	ND	PR	1.0	07/01/87
1,1,1-TCA	ND	PR	1.0	12/10/87
TCE	0.7	03/19/87	ND	PR
	1.1	12/19/86		

[a] Period of record: Well W-834-T1 (December 1986 to December 1991) and well W-834-T3 (March 1987 to December 1991).

[b] Toluene not analyzed in all samples.

ND = Not detected.

PR = Not detected in all quarterly samples analyzed for that chemical in the period of record.

Table 1-22. Maximum concentrations of TCE encountered in soil vapor at the Building 834 operable unit.

Sample location	Depth (ft)	Maximum TCE concentration ($ppm_{v/v}$)
SVS-834-B01	10.2	3,800 and 2,000[a]
SVS-834-B02	11.8	1,800 and 1,700[a]
SVS-834-C01	11.5	6,600 and 6,400[a]
SVS-834-D01	6.0	45 and 43[a]
SVS-834-D02	12.6	1,200 and 1,200[a]
SVS-834-D03	16.2	310 and 3109[a]
SVS-834-D04	16.4	1,300 and 1,000[a]
SVS-834-D05	15.5	270 and 160[a]
SVS-834-D06	15.0	510
SVS-834-D07	3.0	97
SVS-834-D08	20.0	6,300 and 6,500[a]
SVS-834-F01	9.4	16
SVS-834-G01	14.3	25
SVS-834-H01	14.7	7
SVS-834-H02	13.7	6,300
SVS-834-J01	10.0	4
SVS-834-J02	14.7	>700
SVS-834-M01	19.2	3.19

Notes:

[a] One of these concentrations is a duplicate sample result.

1. A general increase occurred in the concentration of TCE soil vapor with depth in each borehole (Webster-Scholten, 1994). In only 7 out of 22 sampling locations was there a deviation from this pattern. (Every sample was lower in concentration than those collected beneath it.)
2. In only 1 sampling location out of 22 was the maximum concentration at a depth of less than 5 ft. This occurred at location SVS-834-D07, about 18 ft to the northeast of pump station Building 834D. The concentration at a depth of 3 ft was 96.8 $ppm_{v/v}$ (v/v = on a volume-per-volume basis).
3. The overall maximum concentrations at a depth of less than 5 ft were as follows: 120 $ppm_{v/v}$ at 3.5-ft depth, SVS-834-C01, about 10 ft to the southeast of pump station Building 834C; 96.8 $ppm_{v/v}$ at 3-ft depth, SVS-834-D07; and 62.6 $ppm_{v/v}$ at 3-ft depth, SVS-834-B01, about 15 ft to the north of pump station Building 834B.
4. At 6 out of 22 sampling locations, the maximum concentrations were at depths of from 5.1 to 12 ft. These are: SVS-834-B01, SVS-834-B02, SVS-834-C01, SVS-834-D01, and SVS-834-J01.
5. The overall maximum concentrations considering all depths were adjacent to pump station Buildings 834C and D, and about 18 ft west of test cell 834H.
6. The second highest overall maxima at any depth were at pump station Buildings 834B, C, and D.
7. Although concentrations tend to increase with depth, the increases are not identical. Similar sample depths in adjacent sample locations do not necessarily have similar concentrations. The lateral variability in the magnitude of soil vapor concentrations is attributed to the variability in lithologic and moisture content of the perched zone.
8. It is inferred that two mechanisms may be exerting control on the distribution of TCE in soil vapor at the core of the Building 834 operable unit: (1) diffusion of TCE vapor from the upper surface of the TCE plume in ground water; and (2) the "settling" of TCE in soil vapor onto a less permeable surface (in this case the unsaturated/saturated soil interface), due to the density of TCE vapor relative to air.

Table 1-23. Summary of the fate and transport models applied to estimate human exposure-point concentrations in the Building 834 operable unit.

Media/process release area(s)	Model and/or method	Potential exposure point(s)	Chemicals of concern	Maximum concentration at release area(s)	95% UCL	Estimated exposure-point concentrations
Fugitive (airborne) dust; contaminants bound to resuspended soil particles						
Data evaluated are from surface soil samples collected throughout the study area.	Mass-loading (Anspaugh et al., 1975).	Throughout the operable unit.	Acetone	0.07 mg/kg[a]	0.0563 mg/kg[a]	1.29×10^{-9} mg/m^3[b]
			Cadmium	16 mg/kg[a]	16 mg/kg[a]	3.68×10^{-7} mg/m^3[b]
			TCE	0.19 mg/kg[a]	0.0703 mg/kg[a]	1.62×10^{-9} mg/m^3[b]
			Freon 11	0.021 mg/kg[a]	0.0128 mg/kg[a]	2.94×10^{-10} mg/m^3[b]
			Freon 113	0.095 mg/kg[a]	0.0366 mg/kg[a]	8.42×10^{-10} mg/m^3[b]
			Xylenes (total isomers)	0.005 mg/kg[a]	0.00355 mg/kg[a]	8.17×10^{-11} mg/m^3[b]
Direct contact with surface soil (<0.5 ft).	Measured concentration of contaminant in surface soil.	Throughout the operable unit (Exposure routes: incidental ingestion and direct dermal contact.)	Acetone	0.07 mg/kg[a]	0.0563 mg/kg[a]	5.63×10^{-2} mg/kg[a]
			Cadmium	16 mg/kg[a]	16 mg/kg[a]	1.60×10^{1} mg/kg[a]
			TCE	0.19 mg/kg[a]	0.0703 mg/kg[a]	7.03×10^{-2} mg/kg[a]
			Freon 11	0.021 mg/kg[a]	0.0128 mg/kg[a]	1.28×10^{-2} mg/kg[a]
			Freon 113	0.095 mg/kg[a]	0.0366 mg/kg[a]	3.66×10^{-2} mg/kg[a]
			Xylenes (total isomers)	0.005 mg/kg[a]	0.00355 mg/kg[a]	3.55×10^{-3} mg/kg[a]
Volatilization of contaminants from subsurface soil to air within a building and to the atmosphere						
Area adjacent to pump station Building 834D.	Volatilization from subsurface soil and diffusion into a building (McKone, 1992).	Inside Building 834D.	Benzene	0.00020 mg/kg[c]	0.00020 mg/kg[c]	5.92×10^{-6} mg/m^3[d] 3.46×10^{-6} mg/m^3[e]
			Ethylbenzene	0.0013 mg/kg[c]	0.000616 mg/kg[c]	5.62×10^{-6} mg/m^3[d] 5.38×10^{-6} mg/m^3[e]
	Volatilization from the soil to the atmosphere (Hwang et al., 1986).	In the vicinity of Building 834D.	PCE	14 mg/kg[c]	1.44 mg/kg[c]	3.64×10^{-2} mg/m^3[d] 2.29×10^{-2} mg/m^3[e]
			Toluene	0.0012 mg/kg[c]	0.00120 mg/kg[c]	2.03×10^{-5} mg/m^3[d] 1.49×10^{-5} mg/m^3[e]
			TCE	260 mg/kg[c]	47.6 mg/kg[c]	1.32×10^{0} mg/m^3[d] 7.98×10^{-1} mg/m^3[e]
			Freon 11	0.20 mg/kg[c]	0.0529 mg/kg[c]	1.18×10^{-2} mg/m^3[d] 5.47×10^{-3} mg/m^3[e]
			Xylenes (total isomers)	0.017 mg/kg[c]	0.0145 mg/kg[c]	1.22×10^{-4} mg/m^3[d] 1.21×10^{-4} mg/m^3[e]

Table 1-23. (Continued)

Media/process release area(s)	Model and/or method	Potential exposure point(s)	Chemicals of concern	Maximum concentration at release area(s)	95% UCL	Estimated exposure-point concentrations
Soil/rock and ground water						
Core of the Building 834 Complex.	Perched zone; VLEACH (U.S. EPA, 1981).	Well CDF-1, completed in the regional aquifer, 4,100 ft downgradient from the Building 834 Complex and outside the Site 300 boundary.	Primarily TCE; co-contaminants detected in ground water samples in the study area also considered. These include: 1,1-DCE, cis-1,2-DCE, 1,1,1-TCA, acetone, benzene, chloroform, ethylbenzene, methylene chloride, PCE, toluene, Freon 113, and xylenes (total isomers).	510,000 µg/L TCE[f]	Assumed source term for VLEACH is 1,100 mg/L (ppm) TCE	1.6×10^{-4} µg/L TCE (maximum concentration contributed from perched zone). Maximum 70-y average TCE concentration predicted in well CDF-1 from the perched zone is 1.5×10^{-4} µg/L. Concentrations of co-contaminants from the perched zone in the range of 10^{-9} to 10^{-4} µg/L.
	Regional aquifer; PLUME (In-Situ, Inc., 1986).	Well CDF-1, completed in the regional aquifer, 4,100 ft downgradient from the Building 834 Complex and outside the Site 300 boundary.	1,1,1-TCA, chloroform, methylene chloride, PCE, toluene, Freon 113, and TCE.	3.5 µg/L (ppb)[f]	Assumed source term for PLUME is all detected VOC concentrations from regional aquifer wells: W-834-T1, W-834-T3, and W-831-01 These were treated as instantaneous point sources.	Concentrations of VOCs predicted to arrive at CDF-1 from regional aquifer wells W-031-01, W-834-T1, and W-834-T3 range from 10^{-13} to 10^{-12} µg/L (ppb). The exposure-point concentrations in ground water withdrawn from CDF-1.

[a] Surface soil (0–0.5 ft).
[b] Air.
[c] Subsurface soil (0.5–12.0 ft).
[d] Indoor air.
[e] Outdoor air.
[f] Ground water.

Table 1-24. Estimated incremental lifetime cancer risk and noncancer hazard index associated with potential adult on-site exposure in the Building 834 operable unit (overall operable unit: inhalation of particulates resuspended from surface soil).

Chemical	Contaminant concentration $C_{p(ss)}$ (mg/m^3)[a]	Individual lifetime cancer risk		Hazard index (Dose/RfD)
Acetone	1.29×10^{-9}	Not carcinogenic		2.54×10^{-9}
Cadmium	3.68×10^{-7}	3.86×10^{-7}		7.21×10^{-5}
Trichloroethylene	1.62×10^{-9}	1.13×10^{-12}		4.31×10^{-8}
Trichlorofluoromethane	2.94×10^{-10}	Not carcinogenic		2.88×10^{-10}
Trichlorotrifluoroethane	8.42×10^{-10}	Not carcinogenic		5.50×10^{-12}
Xylenes	8.17×10^{-11}	Not carcinogenic		8.00×10^{-12}
	Σ Risk =	4×10^{-7}	Σ Hazard index =	7.2×10^{-5}

[a] $C_{p(ss)}$ refers to the concentration (C) of contaminant on resuspended particulates in air (p) (the exposure medium), resulting directly from the presence of contaminant in surface soil (ss).

Table 1-25. Estimated incremental lifetime cancer risk and noncancer hazard index associated with potential adult on-site exposure in the Building 834 operable unit (overall operable unit: ingestion and dermal adsorption from surface soil).

Chemical	Contaminant concentration $C_{s(ss)}$ (mg/kg)[a]	Individual lifetime cancer risk		Hazard index (Dose/RfD)
Acetone	5.63×10^{-2}	Not carcinogenic		6.09×10^{-7}
Cadmium	1.60×10^{1}	Not available[b]		1.10×10^{-2}
Trichloroethylene	7.03×10^{-2}	4.07×10^{-10}		1.04×10^{-5}
Trichlorofluoromethane	1.28×10^{-2}	Not carcinogenic		4.61×10^{-8}
Trichlorotrifluoroethane	3.66×10^{-2}	Not carcinogenic		1.32×10^{-9}
Xylenes	3.55×10^{-3}	Not carcinogenic		1.92×10^{-9}
	Σ Risk =	4×10^{-10}	Σ Hazard index =	1.1×10^{-2}

[a] $C_{s(ss)}$ refers to the concentration (C) of contaminant in surface soil (S) (the exposure medium), resulting directly from the presence of contaminant in surface soil (ss).

[b] A slope factor for ingestion or dermal exposure to cadmium is not available.

Table 1-26. Estimated incremental lifetime cancer risk and noncancer hazard index associated with potential adult on-site exposure in the Building 834 operable unit (pump station Building 834D: inhalation of VOCs that volatilize from subsurface soil to indoor air).

Chemical	Contaminant concentration $C_{voc(sbs)}$ (mg/m^3)[a]	Individual lifetime cancer risk		Hazard index (Dose/RfD)
Benzene	5.92×10^{-6}	4.14×10^{-8}		Not available[b]
Ethylbenzene	5.62×10^{-6}	Not carcinogenic		1.10×10^{-5}
Tetrachloroethylene	3.64×10^{-2}	1.30×10^{-4}		7.14×10^{-1}
Toluene	2.03×10^{-5}	Not carcinogenic		3.52×10^{1}
Trichloroethylene	1.32×10^{0}	9.23×10^{-4}		1.15×10^{-2}
Trichlorofluoromethane	1.18×10^{-2}	Not carcinogenic		1.99×10^{-5}
Xylenes	1.22×10^{-4}	Not carcinogenic		1.20×10^{-5}
	Σ Risk =	1×10^{-3}	Σ Hazard index =	36

[a] $C_{voc(sbs)}$ refers to the concentration (C) of volatile organic compound in indoor air (voc) (the exposure medium), resulting directly from the presence of contaminant in subsurface soil (sbs).

[b] A reference dose (Rfd) is not available.

Table 1-27. Estimated incremental lifetime cancer risk and noncancer hazard index associated with potential adult on-site exposure in the Building 834 operable unit (vicinity of pump station Building 834D: inhalation of VOCs that volatilize from subsurface soil to air).

Chemical	Contaminant concentration $C_{a(sbs)}$ (mg/m^3)[a]	Individual lifetime cancer risk		Hazard index (Dose/RfD)
Benzene	3.46×10^{-6}	2.42×10^{-8}		Not available[b]
Ethylbenzene	5.38×10^{-6}	Not carcinogenic		1.05×10^{-5}
Tetrachloroethylene	2.29×10^{-2}	8.17×10^{-5}		4.49×10^{-1}
Toluene	1.49×10^{-5}	Not carcinogenic		1.46×10^{-5}
Trichloroethylene	7.98×10^{-1}	5.58×10^{-4}		2.13×10^{1}
Trichlorofluoromethane	5.47×10^{-3}	Not carcinogenic		5.36×10^{-3}
Xylenes	1.21×10^{-4}	Not carcinogenic		1.19×10^{-5}
	Σ Risk =	6×10^{-4}	Σ Hazard index =	22

[a] $C_{a(sbs)}$ refers to the concentration (C) of contaminant in air (a) (the exposure medium), resulting directly from the presence of contaminant in subsurface soil (sbs).

[b] A reference dose (Rfd) is not available.

Table 1-28. Estimated incremental lifetime cancer risk and noncancer hazard index associated with potential residential exposures to contaminated ground water that originates in the Building 834 operable unit (well CDF-1).

	Contaminant concentration $C_{w(gw)}$ (mg/L)[a]	Individual lifetime cancer risk		Hazard index (Dose/RfD)
1,1,1-Trichloroethane	1.32×10^{-8}	Not carcinogenic		7.24×10^{-9}
1,1-Dichloroethylene	6.00×10^{-11}	2.77×10^{-12}		6.89×10^{-10}
Acetone	3.90×10^{-11}	Not carcinogenic		2.85×10^{-11}
Benzene	9.90×10^{-12}	4.37×10^{-14}		Not available[b]
Chloroform	7.48×10^{-11}	2.00×10^{-13}		7.00×10^{-10}
cis-1,2-Dichloroethylene	9.99×10^{-8}	Not carcinogenic		1.01×10^{-6}
Ethylbenzene	8.98×10^{-12}	Not carcinogenic		9.45×10^{-12}
Methylene chloride	1.77×10^{-10}	5.21×10^{-14}		3.10×10^{-10}
Tetrachloroethylene	6.44×10^{-10}	1.49×10^{-12}		6.60×10^{-9}
Toluene	4.01×10^{-11}	Not carcinogenic		1.98×10^{-11}
Trichloroethylene	1.35×10^{-7}	6.38×10^{-11}		1.67×10^{-6}
Trichlorotrifluoroethane	2.55×10^{-10}	Not carcinogenic		8.44×10^{-13}
Xylenes	2.84×10^{-11}	Not carcinogenic		1.53×10^{-12}
	Σ Risk =	7×10^{-11}	Σ Hazard index =	2.8×10^{-6}

[a] $C_{w(gw)}$ refers to the concentration (C) of contaminant in water (w). Water is the exposure medium for ingestion and dermal absorption of contaminants, and also is the transfer medium for exposures that result from ingestion of homegrown beef, milk, and fruits and vegetables that are raised with contaminated ground water (gw).

[b] A reference dose (RfD) is not available.

Table 1-29. Summary of hazard indices for ground squirrel in the Building 834 operable unit.

Analyte	Inhalation			Combined oral and inhalation		
	RfD mg/(kg•d)	HI Adult	HI Juvenile	RfD mg/(kg•d)	HI Adult	HI Juvenile
VOCs						
Trichlorofluoromethane	3.49×10^{2}	2.52×10^{-1}	6.12×10^{-1}	3.49×10^{2}	2.52×10^{-1}	6.12×10^{-1}
Trichlorotrifluoroethane	5.70×10^{3}	7.12×10^{-15}	—	5.70×10^{3}	2.85×10^{-7}	6.03×10^{-13}
Ethyl benzene	9.71×10^{1}	2.86×10^{-4}	6.95×10^{-4}	9.71×10^{1}	2.86×10^{-4}	6.95×10^{-4}
Benzene	5.00×10^{1}	4.74×10^{-4}	1.15×10^{-3}	5.00×10^{1}	4.75×10^{-4}	1.15×10^{-3}
Toluene	4.46×10^{2}	2.17×10^{-4}	5.28×10^{-4}	4.46×10^{2}	2.17×10^{-4}	5.28×10^{-4}
Xylene	2.50×10^{2}	2.65×10^{-3}	6.45×10^{-3}	2.50×10^{2}	2.66×10^{-3}	6.45×10^{-3}
Acetone	1.00×10^{2}	6.24×10^{-13}	—	1.00×10^{2}	2.25×10^{-3}	1.89×10^{-12}
Tetrachloroethene	1.40×10^{1}	1.22×10^{1}	2.96×10^{1}	1.40×10^{1}	1.22×10^{1}	2.96×10^{1}
Trichloroethene	2.40×10^{1}	2.34×10^{2}	5.68×10^{2}	2.40×10^{1}	2.34×10^{2}	5.68×10^{2}
Total	—	2.46×10^{2}	5.99×10^{2}	—	2.47×10^{2}	5.99×10^{2}
Metals						
Cadmium	5.50×10^{-3}	3.23×10^{-6}	—	5.50×10^{-3}	6.88×10^{1}	7.84×10^{-4}
Total	—	3.23×10^{-6}	—	—	6.88×10^{1}	7.84×10^{-4}

Table 1-30. Summary of hazard indices for deer in the Building 834 operable unit.

Analyte	Inhalation			Combined oral and inhalation		
	RfD mg/(kg•d)	HI Adult	HI Juvenile	RfD mg/(kg•d)	HI Adult	HI Juvenile
VOCs						
Trichlorofluoromethane	3.49×10^{2}	4.79×10^{-5}	8.65×10^{-5}	3.49×10^{2}	5.07×10^{-5}	8.66×10^{-5}
Trichlorotrifluoroethane	5.70×10^{3}	2.66×10^{-14}	4.80×10^{-14}	5.70×10^{3}	5.31×10^{-8}	1.73×10^{-8}
Ethyl benzene	9.71×10^{1}	1.69×10^{-7}	3.06×10^{-7}	9.71×10^{1}	2.19×10^{-7}	3.06×10^{-7}
Benzene	5.00×10^{1}	2.12×10^{-7}	3.82×10^{-7}	5.00×10^{1}	3.34×10^{-7}	3.82×10^{-7}
Toluene	4.46×10^{2}	1.02×10^{-7}	1.84×10^{-7}	4.46×10^{2}	1.42×10^{-7}	1.84×10^{-7}
Xylene	2.50×10^{2}	1.49×10^{-6}	2.69×10^{-6}	2.50×10^{2}	1.92×10^{-6}	2.73×10^{-6}
Acetone	1.00×10^{2}	2.33×10^{-12}	4.21×10^{-12}	1.00×10^{2}	4.03×10^{-4}	1.52×10^{-6}
Tetrachloroethene	1.40×10^{1}	5.01×10^{-3}	9.05×10^{-3}	1.40×10^{1}	5.60×10^{-3}	9.06×10^{-3}
Trichloroethene	2.40×10^{1}	1.02×10^{-1}	1.84×10^{-1}	2.40×10^{1}	1.43×10^{-1}	1.84×10^{-1}
Total		1.07×10^{-1}	1.93×10^{-1}		1.49×10^{-1}	1.93×10^{-1}
Metals						
Cadmium	5.50×10^{-3}	1.20×10^{-5}	2.17×10^{-5}	5.50×10^{-3}	1.33×10^{1}	7.87×10^{0}
Total		1.20×10^{-5}	2.17×10^{-5}		1.33×10^{1}	7.87×10^{0}

Table 1-31. Summary of hazard indices for kit fox in the Building 834 operable unit.

Analyte	Inhalation			Combined oral and inhalation		
	RfD mg/(kg•d)	HI Adult	HI Juvenile	RfD mg/(kg•d)	HI Adult	HI Juvenile
VOCs						
Trichlorofluoromethane	3.49×10^{2}	3.65×10^{-1}	6.62×10^{-1}	3.49×10^{2}	3.65×10^{-1}	6.62×10^{-1}
Trichlorotrifluoroethane	5.70×10^{3}	1.03×10^{-14}	—	5.70×10^{3}	2.93×10^{-9}	9.43×10^{-15}
Ethyl benzene	9.71×10^{1}	4.14×10^{-4}	7.51×10^{-4}	9.71×10^{1}	4.14×10^{-4}	7.51×10^{-4}
Benzene	5.00×10^{1}	6.87×10^{-4}	1.25×10^{-3}	5.00×10^{1}	6.87×10^{-4}	1.25×10^{-3}
Toluene	4.46×10^{2}	3.14×10^{-4}	5.70×10^{-4}	4.46×10^{2}	3.14×10^{-4}	5.70×10^{-4}
Xylene	2.50×10^{2}	3.84×10^{-3}	6.97×10^{-3}	2.50×10^{2}	3.84×10^{-3}	6.97×10^{-3}
Acetone	1.00×10^{2}	9.03×10^{-13}	—	1.00×10^{2}	2.56×10^{-7}	3.29×10^{-16}
Tetrachloroethene	1.40×10^{1}	1.76×10^{1}	3.19×10^{1}	1.40×10^{1}	1.76×10^{1}	3.19×10^{1}
Trichloroethene	2.40×10^{1}	3.38×10^{2}	6.14×10^{2}	2.40×10^{1}	3.38×10^{2}	6.14×10^{2}
Total	—	3.56×10^{2}	6.47×10^{2}	—	3.56×10^{2}	6.47×10^{2}
Metals						
Cadmium	5.50×10^{-3}	4.67×10^{-6}	—	5.50×10^{-3}	1.38×10^{0}	2.39×10^{-5}
Total	—	4.67×10^{-6}	—	—	1.38×10^{0}	2.39×10^{-5}

Table 1-32. Remedial actions to date at the Building 834 Complex site.

Date	Remedial actions	References
June–July 1983	Excavated and aerated about 100 yd^3 of soil containing TCE at the Building 834 Complex.	Carpenter et al., 1983; Lindeken et al., 1986; Bryn et al., 1990; McConachie, 1990
August 1986	Conducted a short vacuum extraction test on well W-834-D3 at the Building 834 Complex.	Buddemeier et al., 1987; Bryn et al., 1990
October–December 1987	Conducted two short vacuum extraction tests on well W-834-D4 at the Building 834 Complex.	Bryn et al., 1990
February–April 1988	Conducted water and vacuum extraction tests on three wells at the Building 834 Complex.	McIlvride et al., 1988; Field, 1989; Bryn et al., 1990
October–November 1988	Operated a dual-tank bubbler and vacuum extraction system at the Building 834 Complex.	Field, 1989; Bryn et al., 1990; HAZWRAP Progress Report for May, 1989
November 1988–June 1989	Operated a dual-tank bubbler and vacuum extraction system at wells W-834-T4 and -T4C.	Field, 1989; Bryn et al., 1990; HAZWRAP Progress Report for May, 1989
May 1989–June 1989	Evaluated the feasibility of vacuum extraction at the Building 834 Complex by ground water extraction at three shallow wells; induced venting at ten wells; sampled vapor stream and measured vacuum radius of influence; and treated TCE-bearing water by aeration.	Bryn et al., 1990
June–November 1989	Installed one borehole adjacent to each of the two dry wells (i.e., one dry well and one concrete retention tank) adjacent to Building 834L to determine if these dry wells are a source of soil or ground water contamination.	Lamarre et al., 1989
August 1990	Evaluated the TCE yield from vacuum extraction in the release area and southward by conducting single well tests and seven manifold tests.	Lamarre, 1990
November–December 1991	Under funding from the DOE Office of Technology Development (OTD), used an electron accelerator to destroy TCE in air produced from the vacuum extraction system at Building 834D. Of the ingoing TCE, 90% was destroyed at a cost of approximately $15/kg.	Matthews, 1992
January–March 1992	Under funding from the EPA/SITE Program Emerging Technology Program, used an ultraviolet flashlamp system to destroy TCE in air from the vacuum extraction system at the Building 834 Complex. Of the ingoing TCE, 99% was destroyed, though by-product analyses showed oxidation was not complete.	Johnson et al., 1992; Blystone et al, 1991
September 1993–May 1994	TCE transfer system entirely dismantled and removed from Building 834 Complex.	

Table 2-1. Potential federal, state, and local ARARs for the Building 834 operable unit.

Regulation	Comments	Alternative no.[a]	ARAR category[b]
Federal chemical-specific requirements			
Safe Drinking Water Act (SDWA) [42 USCA 300 [40 CFR 141.11–141.16; 141.50–141.51]	This law establishes chemical-specific standards for public drinking water by setting Maximum Contaminant Levels (MCLs) and nonzero Maximum Contaminant Level Goals (MCLGs). The perched water-bearing zone is not capable of producing adequate quantities of ground water (i.e., <200 gpd per well) for domestic or municipal drinking water supply, and therefore standards for public drinking water do not apply. However, if the regional aquifer is impacted in the future, these chemical-specific standards may apply.	1–5	RAR
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 Alternatives 3 through 5 include oil-water separators and granular activated carbon (GAC) vapor treatment to prevent emissions from exceeding CAA limits.	3–5	A
Federal action-specific requirements			
Action: Closure			
Hazardous Waste Control Act Closure Requirements, Health and Safety Code Sections 25150–25245 [22 CCR 66264.111–120]	Requires that hazardous waste management facilities be closed in a manner that minimizes the need for further maintenance and is protective of human health and the environment.	1–5	A
Health and Safety Code Section 25159 [22 CCR 66264.178]	Requires removal of all hazardous waste and waste residues from containment systems. Although the treatment facilities are not considered containment systems, this closure requirement will be considered RAR.	1–5	RAR

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
Action: Pump and treat			
Health and Safety Code Sections 25150–25159 [22 CCR 66264.190–192]	Design and operating standards for tank systems. Tank systems may be used for oil-water separators, dewatering alternatives, and possibly for potential resin treatment processes.	3–5	A
Action: Discharge of treatment system effluent			
Clean Water Act (CWA) [33 USCA 1251–1376] NPDES [40 CFR 122–125]	Both on- and off-site 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]. WDR and NPDES permits are not required for on-site discharges of treated water.	4,5	A[c]
Action: Air stripping			
OSWER Directive 9355.0–28	Establishes guidance on the control of air emissions from air strippers used at CERCLA sites for ground water treatment. This is a nonpromulgated directive.	3–5	TBC
Action (Potential): Electron Accelerator			
DOE Order 5400.5	Prescribes protection for radiation emmissions. This is a DOE policy to implement legally applicable radiation protection standards and to protect the environment from radioactive contamination to the extent practical.	IT[d]	A
General action-specific ARARs			
DOE Order 5400.4	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.	1–5	TBC
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.	1–5	A

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
Federal location-specific requirements			
Endangered Species Act of 1973 16 USC Section 1531 et seq. 50 CFR Part 200, 50 CFR Part 402 [40 CFR 257.3-2]	Facilities or practices shall not cause or contribute to the taking of any endangered or threatened species of plants, fish, or wildlife. Even though no federally-designated endangered species have been found within the operable unit, there is potential habitat for the San Joaquin kit fox. Specific mitigation measures for these species will be met prior to any construction. All of these requirements will be additionally met through NEPA and DOE implementing requirements.	1–5	A
National Historic Preservation Act of 1966 (16 USC 470 et seq.), Public Law 89-665 and amendments of 1980, Public Law 96-515	Requires federal agencies to take into account the effects of their projects on historic properties listed, or eligible for listing, on the National Register of Historic Properties and to afford the Advisory Council a reasonable opportunity to comment on them. A historical records search indicates no historic properties were located within the operable unit. Other areas of potential impact will be surveyed prior to project activity to ensure that no historic properties will be affected by the proposed project.	1–5	A
Archaeological Resource Protection Act of 1979 (16 USC 470), Public Law 96-96	Requires federal land managers to provide protection for archaeological resources located on public and Indian lands. Construction personnel will be advised of the laws and penalties for disturbing or collecting cultural resources located on Site 300 property.	1–5	A
American Indian Religious Freedom Act (1978). (42 USC 1996), Public Law 95-341	Requires federal land managers to consult directly with local Indian groups, including religious and political leaders, to insure Native American access to religious sites, and to protect and preserve Native American cultural rights and practices. On June 10, 1993, the California Native American Heritage Council was contacted by telephone with a request for assistance in locating Native American groups or individuals to provide input into cultural resource planning. The Council requirement of a written request for this information was complied with on June 21, 1993.	1–5	A[c]

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
Native American Graves Protection and Repatriation Act of 1990 (25 USC 3001), Public Law 101-601	Requires federal agencies to provide for the protection of Native American graves and associated cultural objects and to repatriate sacred objects, burials, and associated funerary objects to Native American groups. In the event that interested local Native Americans are identified and burial sites or artifacts are discovered, identified local Native Americans will be contacted. Project construction personnel will be advised of the possibility of buried cultural deposits and be alerted to likely indicators. If a human burial is discovered during project construction, all work will be halted in the vicinity of the discovery and the archaeologist and the County Coroner will be called immediately.	1–5	A
State and local chemical-specific requirements			
Health and Safety Code, Sections 25100–25395, CCR, Title 22, ch. 30: Minimum Standards for Management of Hazardous and Extremely Hazardous Wastes	HWCA 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, including potential innovative technologies.	1–5	A
Criteria for Identifying Hazardous Wastes [Title 22, 66261. 21–33]	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 including potential innovative technologies, use these criteria.	1–5	A
Persistent and Bioaccumulative Toxic Substances [Title 22, 66261.113]	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, including potential innovative technologies, use these criteria.	1–5	A

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
Porter-Cologne Water Quality Control Act [WC13260–13272], as administered by the State Water Resources Control Board (SWRCB) and the nine Regional Water Quality Control Boards (RWQCB) under CCR Title 23, subch. 15, 2510–2559	Establishes authority for state and regional water boards to determine site-specific discharge requirements and to regulate disposal of waste to land. Contains corrective action requirements which state that a constituent of concern shall have a concentration limit not to exceed background unless it can be shown that it is technologically and economically infeasible to achieve the background value and that the constituent will not pose a substantial present or potential hazard to human health or the environment. This policy is applicable for potential surface discharges related to oil-water separators, recovery of diesel and T-BOS floating product and DNAPLs, and ground water treatment alternatives for dewatering.	4,5	A[c]
Water Quality Control Plan (Basin Plan) for the Central Valley Regional Water Quality Control Board (CVRWQCB)	Describes water basins in the Central Valley Region, establishes beneficial uses of ground and surface waters, establishes beneficial uses of ground and surface waters, establishes water quality objectives, establishes implementation plans to meet water quality objectives, protects beneficial uses, and incorporates statewide water quality control plans and policies.	1–5	A
State Water Resources Control Board Resolution 68-16	The state board's policy for maintaining the high quality of California's waters (as applied to discharged water) implies that ground water cleanup should continue to achieve background conditions if it can be shown that it is technically feasible, cost effective, and more protective of human health and the environment to do so. The resolution also allows alternative cleanup levels if Site 300 can demonstrate that nondegradation cannot be practically achieved and that the alternative is protective of human health and the environment.	4,5	A
State Water Resources Control Board Resolution 92-49	The state board's policies and procedures for the oversight of investigations and cleanup and abatement activities resulting from discharges of waste that affect or threaten water quality. This resolution is not promulgated and is therefore TBC.	1–5	A
State Water Resources Control Board Resolution 88-63	The state board's policy concerning potential sources of drinking water. This policy specifies that a municipal or domestic water supply must be able to produce a sustained yield of 200 gpd from a single well. The sustained yield for single wells completed in the perched zone in the Building 834 Complex is approximately 100 gpd.	1–5	RAR

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
California Safe Drinking Water Act, Health and Safety Code, Section 2549.5	Regulations and standards for public water systems (CA MCLs), which are enforceable in California. There are no beneficial uses of ground water from the perched water-bearing zone, and the regional aquifer has not been affected. However, should the presence of any chemicals be confirmed in the regional aquifer in the future, these standards will apply.	1–5	RAR
State and local action-specific requirements			
Action: General treatment of hazardous waste			
Health and Safety Code, Sections 25100–25395 [22 CCR 66264.1–77]	Requirements for general operations of interim status and permitted facilities, including preparedness and prevention [66264.30–37], contingency plans and emergency procedures [66264.50–55], and manifesting and monitoring requirements [66264.70–77].	1–5	A
Hazardous Waste Control Act Land Disposal Restrictions [22 CCR 66268.1–124]	This law requires that certain hazardous wastes meet minimum treatment standards prior to disposal at a landfill. Alternatives 2–5 produce waste through recovery of diesel and T-BOS floating product and DNAPLs, and Alternatives 3–5 produce waste through regeneration of GAC. Waste may be produced by potential innovative technologies; waste products could include regenerated resin from a Padre unit or possible by-products from an electron accelerator.	2–5	A
Hazardous Materials Release Response Plans and Inventory (Health and Safety Code, Div. 20, ch. 6.95) [19 CCR, ch. 3, subch. 3]	This law requires businesses handling hazardous materials to plan for emergency response actions.	1–5	A

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
Action: Transportation			
Hazardous Waste Control Act Hauler Registration Requirements and Requirements for Transporters of Hazardous Waste [22 CCR 66263.10–31]	Standards applicable to transporters of hazardous waste. Establishes transporter operating standards (66263.23) registration requirements (66263.11–12), record keeping procedures (66263.15), and immediate action and discharge cleanup requirements for an accidental discharge of hazardous waste (66263.30–31). Generated waste being transported to an off-site disposal facility would be subject to these requirements. Alternatives 2–5 produce waste through recovery of diesel and T-BOS floating product and DNAPLs, and Alternatives 2–5 produce waste through regeneration of GAC. Waste may be produced by potential innovative technologies; waste products could include regenerated resin from a Padre unit or possible by-products from an electron accelerator.	2–5	A
Requirements for Generators of Hazardous Waste [Title 22 66262.10]	Owners or operators who ship hazardous waste from a TSD facility shall comply with the generator standards in these regulations. These standards include keeping of manifests [66261.21], submission of manifest to CDHS within 30 days of shipment [66262.23], preparation of a biennial report [66262.41], and a maximum 90-day accumulation time [66262.34]. These regulations are applicable to transportation and off-site disposal of hazardous waste. Alternatives 3–5 produce waste through recovery of diesel and T-BOS floating product and DNAPLs, and Alternatives 2–5 produce waste through regeneration of GAC. Waste may be produced by potential innovative technologies; waste products could include regenerated resin from a resin Padre unit or possible by-products from an electron accelerator.	2–5	A

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
Action: Discharge of treatment system effluent			
Porter-Cologne Water Quality Control Act [WC 13260–13272], as administered by the State Water Resources Control Board and the nine Regional Water Quality Control Boards under CCR Title 23, subch. 15, 2510–2559	Establishes authority for State and Regional Water Boards to determine site-specific discharge requirements and to regulate disposal of waste to land.	4,5	A[c]
Action: Air stripping/air sparging			
Air Resources Act (Health and Safety Code, Section 3900 et. seq.)	Establishes allowable discharge standards for point sources within each air pollution control district, and establishes ambient air quality standards. Alternatives 3–5 employ soil vapor extraction with vapor-phase GAC treatment. Treatment processes from Alternatives 4 and 5 employ oil-water separators and air stripping or air sparging as primary or secondary treatment of ground water for dewatering purposes. These requirements are, therefore, applicable.	3–5	A
San Joaquin Unified Air Pollution Control District [Rule 2201]	Requires permitting of VOC air discharges (e.g., from oil-water separators or an air-stripping unit). Alternatives 3–5 employ soil vapor extraction with vapor-phase GAC treatment. Treatment processes from Alternatives 4 and 5 employ air stripping treatment of ground water for dewatering. These requirements are, therefore, applicable.	3–5	A

Table 2-1. (Continued)

Regulation	Comments	Alternative No.[a]	ARAR Category[b]
State location-specific requirements			
California Endangered Species Act California Fish and Game Code Sections 2050–2068	Requires action to preserve endangered species or threatened species. Even though no California-designated endangered species have been found within the operable unit, there is potential habitat for the San Joaquin kit fox. Prior to conducting any ground-disturbing activities, surveys will be conducted for the San Joaquin kit fox.	1–5	A

a 1—No action.

2—Exposure control including building venting, institutional controls, and drainage control.

3—Risk-based source mass removal at core of complex, including soil vapor extraction with GAC and recovery of diesel and T-BOS floating product.

4—Risk-based source mass removal at core of complex, including soil vapor extraction, dewatering with air stripping, and GAC.

5—Source mass removal at complex core including dewatering with air stripping, soil vapor extraction, and GAC; plume control at septic system release site, and the T2 and T4 well clusters, including dewatering with air stripping and GAC.

b A = Applicable.
RAR = Relevant and appropriate.
TBC = To be considered.

c Only off-site CERCLA discharges to surface waters must be NPDES-permitted.

d The electron accelerator is an innovative technology for the treatment of VOC-contaminated media. LLNL is considering this technology to potentially supplement BAT treatment processes for the Building 834 operable unit.

Table 2-2. Summary comparison of corresponding ARARs and factors to be considered for the Building 834 operable unit.

Regulation	Alternative[a]				
	B834 1	B834 2	B834 3	B834 4	B834 5
Federal chemical-specific requirements					
Safe Drinking Water Act (SDWA) [42 USCA 300] [40 CFR 141.11–141.16; 141.50–141.51]	RAR	RAR	RAR	RAR	RAR
Clean Air Act (CAA) [42 USCA 7401–7642] [40 CFR 50–69]	—	—	A	A	A
Federal action-specific requirements					
Action: Closure					
Health and Safety Code, Sections 25150–25245 [22 CCR 66264.111–120]	A	A	A	A	A
Health and Safety Code, Section 25159 [22 CCR 66264.178]	RAR	RAR	RAR	RAR	RAR
Action: Pump and treat					
Health and Safety Code, Sections 25150–25159 [22 CCR 66264.190–92]	—	—	A	A	A
Action: Discharge of treatment system effluent					
Clean Water Act, [33 USCA 1251–1376] NPDES [40 CFR 122–125]	—	—	—	A	A
Action: Air stripping					
OSWER Directive 9355.0–28	—	—	TBC	TBC	TBC
Action (Potential): Electron accelerator[b]					
DOE Order 5400.5	—	—	—	—	—
General action-specific ARARs					
DOE Order 5400.4	TBC	TBC	TBC	TBC	TBC
29 CFR 1910 et seq. Noise Control Act of 1972, as amended by the Quiet Communities Act of 1978 [40 CFR 204, 205, 211]	A	A	A	A	A
Federal location-specific requirements					
Endangered Species Act of 1973 16 USC Section 1531 et seq. 50 CFR Part 200, 50 CFR Part 402 [40 CFR 257.3-2]	A	A	A	A	A
National Historic Preservation Act of 1966 (16 USC 470 et seq.), Public Law 89-665 and amendments of 1980, Public Law 96-515	A	A	A	A	A
Archaeological Resource Protection Act of 1979 (16 USC 470), Public Law 96-96	A	A	A	A	A

Table 2-2. (Continued)

Regulation	Alternative[a]				
	B834 1	B834 2	B834 3	B834 4	B834 5
American Indian Religious Freedom Act (1978), Public Law 95-341	A	A	A	A	A
Native American Graves Protection and Repatriation Act of 1990 (25 USC 3001), Public Law 101-601	A	A	A	A	A
State and local chemical-specific requirements					
Health and Safety Code, Sections 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, 66261.21–33]	A	A	A	A	A
Persistent and Bioaccumulative Toxic Substances [Title 22, 66261.113]	A	A	A	A	A
Porter-Cologne Water Quality Control Act [WC 13260–13272], as administered by the State Water Resources Control Board (SWRCB) and the nine Regional Water Quality Control Boards (RWQCB) under CCR Title 23, subch. 15, 2510–2559	—	—	—	A	A
Water Quality Control Plan (Basin Plan) for the Central Valley Regional Water Quality Control Board	A	A	A	A	A
State Water Resources Control Board Resolution 68-16	—	—	—	A	A
State Water Resources Control Board Resolution 92-49	TBC	TBC	TBC	TBC	TBC
State Water Resources Control Board Resolution 88-63	RAR	RAR	RAR	RAR	RAR
California Safe Drinking Water Act, Health and Safety Code, Section 2549.5	RAR	RAR	RAR	RAR	RAR
State and local action-specific requirements					
Action: General treatment of hazardous waste					
Health and Safety Code, Sections 25100–25395 [22 CCR 66264.1–77]	A	A	A	A	A
Hazardous Waste Control Act Land Disposal Restrictions [22 CCR 66268.1–124]	—	A	A	A	A
Hazardous Materials Release Response Plans and Inventory (Health and Safety Code, Div. 20, ch. 6.95) [19 CCR, ch. 3, subch. 3]	A	A	A	A	A

Table 2-2. (Continued)

Regulation	Alternative[a]				
	B834 1	B834 2	B834 3	B834 4	B834 5
Action: Transportation					
Hazardous Waste Control Act Hauler Registration Requirements and Requirements for Transporters of Hazardous Waste [22 CCR 66263.10–31]	—	A	A	A	A
Requirements for Generators of Hazardous Waste [Title 22 66262.10]	—	A	A	A	A
Action: Discharge of treatment system effluent					
Porter-Cologne Water Quality Control Act [WC 13260–13272], as administered by the State Water Resources Control Board and the nine Regional Water Quality Control Boards under CCR Title 23, subch. 15, 2510–2559	—	—	—	A	A
Action: Air stripping/air sparging					
Air Resources Act (Health and Safety Code, Section 3900 et. seq.)	—	—	A	A	A
San Joaquin Unified Air Pollution Control District [Rule 2201]	—	—	A	A	A
State location-specific requirements					
California Endangered Species Act California Fish and Game Code Sections 2050–2068	A	A	A	A	A

[a] 1—No action.

2—Exposure control including building venting, institutional controls, and drainage control.

3—Risk-based source mass removal at core of complex, including soil vapor extraction with GAC and recovery of diesel and T-BOS floating product.

4—Risk-based source mass removal at core of complex, including soil vapor extraction, dewatering with air stripping, and GAC.

5—Source mass removal with at complex core, including dewatering with air stripping, soil vapor extraction, and GAC; plume control at septic system release site and the T2 and T4 well clusters, including dewatering with air stripping and GAC.

[b] The electron accelerator is an innovative technology for the treatment of VOC-contaminated media. LLNL is considering this technology to potentially supplement BAT treatment at processes for the Building 834 operable unit.

A = Applicable.

RAR = Relevant and appropriate.

TBC = To be considered.

— = Not ARAR or TBC.

Table 2-3. Health-based concentrations and soil vapor restoration levels (SVRLs) for the Building 834 operable unit.[a]

Chemical	Health-based concentration[b] (mg/kg)	SVRLs ($ppm_{v/v}$)
Trichloroethylene (TCE)[c]		
Indoor air	1.3	150
Outdoor air	2.2	250

[a] The health-based concentrations of TCE presented in this table were determined based on an estimate of exposure, risk, and hazard associated with the predicted movement of TCE from subsurface soil to air inside Building 834D and to outdoor air in the vicinity of Building 834D (Appendix C). However, building ventilation systems (Chapter 4) will be designed to reduce indoor air concentrations to estimated ambient concentrations and, with filtration, to the lower acceptable target concentrations.

[b] Concentration in soil corresponding to a hazard index (HI) of 1.0. This is an estimated concentration, which reflects HIs from potential exposure to all contaminants present at a given exposure location. This value was calculated based on an adult on-site exposure scenario (e.g., 25 years).

[c] Indicator chemical.

Table 2-4. Remedial action objectives (RAOs), cleanup goals, and general response actions (GRAs) for the Building 834 operable unit.

	Ground water			Soil[a]			Air		
Alternatives	RAO[b]	Cleanup goal	GRA	RAO[c]	Cleanup goal[d]	GRA	RAO[c]	Cleanup goal	GRA
Alternative 1	MCL	None	• No action • Monitoring	10^{-4}–10^{-6} risk or HI<1	None	• No action • Monitoring	10^{-4}–10^{-6} risk or HI<1	None	• No action • Monitoring
Alternative 2	MCL	None	• Hydraulic containment • Treatment • Institutional/ administrative controls • Monitoring	10^{-4}–10^{-6} risk or HI<1	None	• Institutional/ administrative controls • Monitoring	10^{-4} risk or HI<1	None	• Enhanced air flow • Institutional/ administrative controls • Monitoring
Alternative 3	MCL	None	• Hydraulic containment • Treatment • Institutional/ administrative controls • Monitoring	10^{-4}–10^{-6} risk or HI<1	2.2 mg/kg	• Soil vapor extraction • Treatment • Institutional/ administrative controls • Monitoring	10^{-4} risk or HI<1	None	• Enhanced air flow • Institutional/ administrative controls • Monitoring
Alternative 4	MCL	None	• Hydraulic containment • Treatment • Institutional/ administrative controls • Monitoring	10^{-4}–10^{-6} risk or HI<1	2.2 mg/kg	• Extraction • Treatment • Institutional/ administrative controls • Monitoring	10^{-4} risk or HI<1	None	• Enhanced air flow • Institutional/ administrative controls • Monitoring
Alternative 5	MCL	None	• Hydraulic containment • Treatment • Institutional/ administrative controls • Monitoring	10^{-4}–10^{-6} risk or HI<1	2.2 mg/kg	• Extraction • Treatment • Institutional/ administrative controls • Monitoring	10^{-4} risk or HI<1	None	• Enhanced air flow • Institutional/ administrative controls • Monitoring

[a] Includes soil vapor off gas from soil.

[b] RAO is to prevent human exposure to chemicals in ground water above maximum contaminant levels (MCLs).

[c] RAO is to prevent human exposure to VOCs that may volatilize from subsurface soil into ambient and indoor air above the 10^{-4}–10^{-6} risk level or hazard level >1, whichever is more conservative. Exposure estimates are based on adult on-site exposure (8 h/d) to VOCs over the course of a 25-y career.

[d] The soil cleanup concentration (2.2 mg/kg) for the indicator chemical, TCE, was determined based on estimates of exposure and hazard associated with the predicted movement of TCE from subsurface soil to outdoor air in the vicinity of Building 834D (Appendix C, Chapter 4). The baseline risk assessment presented in the SWRI indicates that an unacceptable level of risk is associated with subsurface soil in the vicinity of Building 834D. The estimated risks are 6×10^{-4} and 1×10^{-3}, and the estimated hazard indices are 22 and 36 associated with VOCs that volatilize from subsurface soil to the atmosphere and to the air inside of Building 834D, respectively.

Notes:

- Ground water, soil, and air are the only environmental media affected in the Building 834 operable unit.
- General response actions are discussed in detail in Chapter 3.
- Cleanup levels are discussed in detail in Chapter 4.
- Remedial action alternatives are evaluated in Chapter 5.

Table 3-1. Description of General Response Actions.

General Response Action	Description
No action	Present remedial action programs would be terminated. Only natural degradation, dispersion, and adsorption would take place.
Containment	Restriction of contaminant movement by physical and/or hydraulic measures.
Enhanced air flow	VOC concentrations in confined spaces are lowered by enhancing the air flow through the space.
Extraction/excavation	Removal of contaminated soil vapor, soil/rock, and/or ground water.
In situ treatment	In-place degradation, detoxification, destruction, or immobilization of contaminants.
Treatment	Degradation, detoxification, destruction, or removal of contaminants present in extracted vapor, excavated soil/rock, and/or extracted ground water on site or at an off-site permitted facility.
Disposal	Disposal of treated air emissions, ground water, or extracted contaminants on or off site.
Institutional/administrative controls	Limit or restrict access to and use of areas of contaminated soil and/or ground water or exposure to hazards.

Table 3-2. Response action screening and evaluation.

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
No action	None	Natural degradation, dispersion, and adsorption	Applicable	Could impact perched ground water. Minimal impact to regional aquifer. May not be protective of human health and the environment.	Implementable	No additional cost	Yes
Containment	Drainage control	Asphalt surfacing	Applicable	Retards leaching from soil. Minimizes short circuiting of airflow from surface, and reduces VOC flux to atmosphere.	Implementable. Partial asphalt cover exists in core area.	Low–medium	Yes
		Lined ditches	Applicable	Effective when combined with other technologies. Minimizes short circuiting of airflow from surface, and reduces VOC flux to atmosphere.	Implementable	Low–medium	Yes
		Synthetic membrane liners	Applicable	Minimizes short circuiting of airflow from surface, and reduces VOC flux to atmosphere.	Implementable. Surface construction.	High	No
	Ground water removal from wells	Dewatering	Applicable	Effective migration control.	Implementable	Medium–high	Yes

Table 3-2. (Continued)

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
	Migration barrier	Slurry wall/grout curtain	Applicable	Limited effectiveness due to maturity of plume	NCF	NCF	No
Enhanced air flow	Enhanced building ventilation	Reengineer building ventilation systems	Applicable	Effective in controlling exposure risk. No mass removal.	Implementable. Some ventilation in place.	Low	Yes
Extraction	Venting	Soil vapor extraction	Applicable. Source control and removal for Building 834 Complex.	Effective. Removes contaminants. May not reach low SVRLs.	Implementable. Soil vapor extraction system in place. Expansion feasible.	Low	Yes
		Dynamic underground stripping	Innovative technology	Effectiveness unknown	Not implementable. Integrity of underground utility lines and tanks questionable when heated.	High	No
		Joule-heating	Innovative technology	Effectiveness considered to be extremely localized.	Not implementable. Integrity of underground utility lines and tanks questionable when heated.	Medium–high	No
	Ground water removal from wells	Partial dewatering	Applicable	Exposes greater soil column for vadose zone remedial actions.	Implementable	Low–medium	Yes
	LNAPL removal	Skimming	Applicable	Effective. Removes contaminants from subsurface.	Implementable	Low	Yes

Table 3-2. (Continued)

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
	Excavation	Soil removal	Applicable for small, shallow volumes. Most contaminants are deep and widespread.	Effective when combined with other technologies such as thermal treatment of soil to destroy VOCs. Removes contaminants and source of inhalation risks. Backfilling required.	Extensive excavation. Excavations would mostly include bedrock. Underground utilities may present excavation hazard. Requires disposal of contaminated soil/rock. Safety precautions necessary to prevent worker exposure during excavation. Requires decommissioning of weapons facility. Would also require removal of buildings as well as underground utilities.	High	No
Treatment	Soil vapor treatment/air emissions control	GAC	Applicable	Effective	Implementable. Carbon requires regeneration or disposal.	Low–medium	Yes
		Thermal oxidation	Applicable	Effective. Destroys VOCs.	Implementable. Fire permit required. Fire safety concerns.	NCF	No
		Catalytic oxidation	Not applicable	Not effective for VOCs. Produces more toxic daughter compounds.	NCF	NCF	No

Table 3-2. (Continued)

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
		Electron accelerator	Applicable. Innovative technology.	Effective	Potentially implementable. Possible high energy consumption.	High	Yes (RITD)
		PADRE™ resin	Innovative technology	Effective	Potentially implementable	NC	Yes (RITD)
		UV/oxidation	Applicable. Innovative technology.	Effective at destroying TCE. Produces off-gas products.	Potentially implementable	High	Yes (RITD)
	Ground water treatment	GAC	Applicable	Effective for VOCs at low flow rates and low VOC concentrations (e.g., polishing).	Implementable. Potentially high O&M due to carbonate precipitation and vessel clogging. Dispose/regenerate spent carbon.	High	Yes
		Air stripping	Applicable. Air permit required.	Effective. Possible reduced efficiency due to carbonate precipitation.	Implementable. Potentially high O&M due to carbonate precipitation and reduced efficiency. Design to prevent scaling.	Medium	Yes
		Air sparging	Applicable. Air permit required.	Effective. Possible reduced efficiency due to carbonate precipitation.	Implementable. Potentially high O&M due to carbonate precipitation and reduced efficiency. Design to prevent scaling.	Medium	Yes

Table 3-2. (Continued)

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
		UV/oxidation	Applicable	Effective, destroys VOCs. Possible reduced efficiency due to carbonate precipitation.	Implementable	High	No
		Biological treatment	Technology not proven	Not proven effective for VOCs given low discharge limits.	VOC concentrations may make technology difficult to implement.	High	No
		Electron accelerator	Innovative technology	Effective	Potentially implementable. Possible high energy consumption.	High	Yes (RITD)
In situ treatment	*In situ* soil treatment	Biological enhancement	Innovative technology	NCF	NCF	NCF	No
		Radio frequency	Not applicable. Innovative technology.	Effectiveness unknown	NCF	NCF	No
	In situ ground water treatment	Air sparging	Applicable to LNAPL VOCs, but less applicable to DNAPLs such as TCE and PCE.	Effective. Can increase VOC mass removal rates and reduce cleanup times.	Difficult to control movement and capture of sparged VOCs in fractured bedrock.	NC	Yes (RITD)
		Surfactants	Innovative technology. Applicable when combined with ground water extraction.	Can increase mobility of DNAPLs.	Implementable	NC	Yes (RITD)
		Biological enhancement	Innovative technology	Unknown	May already be occurring at septic tank release site.	NC	Yes (RITD)

Table 3-2. (Continued)

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
Disposal	Treated ground water disposal	Permitted discharge to sanitary sewer	Not applicable. Existing sewage pond could not handle flow rates.	NCF	NCF	NCF	No
		On-site surface discharge	Applicable. Infiltration areas or irrigation spray.	Effectiveness is function of flow rates and infiltration rates.	Implementable. Pumping required for discharge to area not impacted by VOCs.	Low	Yes
		Air misting	Applicable	Effective for low flows.	Implementable	Low	Yes
		Reinjection	Applicable. Difficult to permit.	Effective. May be designed to flush contaminants toward extraction wells/trenches.	Must ensure that recharge does not adversely affect subsurface (e.g., migration of VOCs). Low permeability subsurface may make this difficult to implement.	Low–medium	Yes
		On-site recycling/reuse	Not applicable. Inadequate demand.	Effective	Difficult. Need to replumb users. Limited demand for water.	NCF	No
	LNAPL disposal	Off-site incineration/ recycling	Applicable	Effective	Coordinate with hazardous materials program.	Medium	Yes
Institutional/ administrative controls	Restrict access and use	Building and worker use restrictions	Limited worker use in buildings and outdoor areas where contaminated soils present a risk of inhalation exposure.	Effective	Difficult. Hard to predict the needs of Site 300 over the next 30 years. Implementable over the short term.	Low	Yes

Table 3-2. (Continued)

General Response Action	Remediation technology type	Technology (process options)	Screening comments	Effectiveness	Implementability	Cost	Retained
		Fencing and signs	Applicable to deter the long-term exposure concerns.	Effective, since long-term exposure is primary concern.	Readily implementable. Already exist for Site 300 portions of the area.	Low	Yes
		Security guards/patrols	Applicable	Effective	Implementable	High	Yes
	DOE/Lab policy	Restrict building placement and/or construction and soil disturbance activities in the complex.	Applicable	Effective	Implementable	Low	Yes

NCF = Not considered further.

N = Not considered.

RITD = Retained for innovative technology development.

Table 3-3. Retained General Response Actions and remedial technologies.

General Response Action/ technology	Effectiveness	Cost
No action		
No action	Could impact perched ground water. Minimal impact to regional aquifer. May not be protective of human health and the environment.	No additional cost
Containment		
Asphalt surfacing	Retards infiltration and VOCs leaching from soil.	Low–medium
Lined ditches	Drainage control effective when combined with other technologies.	Low–medium
Dewatering	Prevents downgradient migration of contaminant plume in ground water	High
Enhanced air flow/enhanced building ventilation	Effective in controlling exposure risk. No mass removal.	Low
Extraction		
Soil vapor extraction	Effective. Removes contaminants.	Low
Partial dewatering	Exposes greater soil column for vadose zone remedial actions.	Low–medium
LNAPL skimming	Effective. Removes contaminants from subsurface.	Low
Treatment		
GAC—Soil vapor	Effective	Low–medium
GAC—Ground water	Effective for VOCs at low flow rates and low VOC concentrations (e.g., polishing).	High
Air stripping	Effective. Possible reduced efficiency due to carbonate precipitation.	Medium
Air sparging	Effective. Possible reduced efficiency due to carbonate precipitation and power requirements.	Medium
Disposal		
On-site surface discharge	Effective	Low
Air misting	Effective	Low
Reinjection	Effective. May be designed to flush contaminants toward extraction wells/trenches.	Low–medium
Off-site incineration	Effective	Medium
Institutional/administrative controls		
Builder and worker use restrictions	Effective	Low

Table 3-3. (Continued)

General Response Action/ technology	Effectiveness	Cost
Fencing and signs	Effective, since long-term exposure is primary concern.	Low
Security guards/patrols	Effective	High
DOE/Lab policy	Effective	Low

Table 4-1. Summary of Building 834 Complex remedial alternatives.

Alternative 1—No action	Sampling/water-level measurement Quarterly water-level measurements of 50 monitor wells. Biannual soil vapor sampling of 16 wells for five years, followed by annual sampling of 11 wells for 25 years. For the first five years, ground water samples would be collected and analyzed quarterly in 8 wells, biannually in 11 wells, and annually in 31 wells. Annual ground water sampling and analysis of 50 wells would continue for an additional 25 years. QA/QC samples. Other Well and pump maintenance. Reporting. Project management. Database management. QA/QC. Project life: 30 years of soil vapor and ground water monitoring.
Alternative 2—Exposure control	Sampling/water-level measurement Quarterly water-level measurements of 50 monitor wells. Soil vapor samples would be collected and analyzed biannually in 16 soil vapor wells for five years, followed by annual sampling of 11 wells for 25 years. For the first five years, ground water samples would be collected and analyzed quarterly in 12 wells, biannually in 8 wells, and annually in 30 wells. Annual ground water sampling and analysis of 50 wells would continue for an additional 25 years. Exposure controls Modification of building ventilation in Buildings 834A, D, O, and J to provide increased circulation. Additional drainage controls, such as alsphalt paving and diversion channels at the Building 834 Complex core area. Institutional controls Implementation of institutional controls, including fences, warning signs, restricted access, and revised construction procedures, to limit exposure to VOCs within potential risk areas defined by the SWRI risk assessment (Webster-Scholten, 1994). LNAPL removal and disposal Passive skimming of T-BOS/oil from wells W-834-D3, -4, and -5, and of diesel from well W-834-D8 for up to two years. Other Well and pump maintenance. Reporting. Project management. Database management. QA/QC. Project life: 2 years LNAPL removal, 30 years of soil vapor and ground water monitoring.

Table 4-1. (Continued)

Alternative 3—Source mass removal at complex through soil vapor extraction, and treatment to ARL risk-based concentrations (1×10^{-4})	Sampling/water-level measurement Quarterly water-level measurements of 54 monitor wells. Soil vapor samples would be collected and analyzed quarterly for the first year and biannually for the next four years in 19 soil vapor wells in the Building 834 Complex core area. Soil vapor monitoring would be reduced to annual sampling of 19 wells and would continue for an addtional five years. For the first year, ground water samples would be collected and analyzed quarterly in 27 wells, biannually in 7 wells, and annually in 20 wells. For the next four years, ground water samples would be collected and analyzed quarterly in 8 wells, biannually in 26 wells, and annually in 20 wells, followed by 25 years of post-remediation annual ground water sampling and analysis of 54 wells. Exposure, institutional controls, and LNAPL removal and disposal Same as Alternative 2. Soil vapor extraction and treatment Extract soil vapor from 16 existing and 3 new extraction wells. Soil vapor treatment with existing SVE system for up to five years. Extract soil vapor until VOC concentrations in vadose zone are reduced to acceptable health-based concentrations (HI = 1.0) and risk levels below 1×10^{-4}. Conduct soil sampling to determine when the remedial action goals have been achieved so soil vapor remediation could be discontinued. Treatment system effluent discharge Discharge treated soil vapor to atmosphere via an air misting system. Other Permitting. Optional development and testing of innovative technology. Well and pump maintenance. SVE system maintenance. Reporting. Project management. Database management. QA/QC. Project life: 2 years LNAPL removal, 5 years SVE, 30 years (25 years post-closure) soil vapor and ground water monitoring.
Alternative 4—Source mass removal in core area through soil vapor extraction, ground water dewatering, and treatment; LNAPL removal to ARL risk-based concentrations (1×10^{-4})	Sampling/water-level measurement Quarterly water-level measurements of 54 monitor wells. Soil vapor monitoring would be the same as monitoring in Alternative 3. For the first five years, ground water samples would be collected and analyzed quarterly in 27 wells, biannually in 7 wells, and annually in 20 wells. Annual ground water sampling and analysis of 54 wells would continue for an additional 25 years. Exposure and institutional controls Same as Alternative 2. Soil vapor extraction and treatment Extract soil vapor from 16 existing and 3 new extraction wells. Soil vapor treatment with existing SVE system for up to five years.

Table 4-1. (Continued)

Alternative 4—(Continued)	Extract soil vapor until VOC concentrations in vadose zone are reduced to acceptable health-based concentrations (HI = 1.0) and risk levels below 1×10^{-4}. Conduct soil sampling to determine when the remedial action goals have been achieved so soil vapor remediation could be discontinued. Ground water dewatering Extract ground water from 16 existing and 3 new ground water extraction wells in the Building 834 Complex core area. Install new on-site air stripping ground water treatment facility in the core area, with adsorption of vapor phase VOCs by GAC. Design flow rate would be 1.4 gpm. Pump ground water from 19 extraction wells to air stripping treatment system. Treatment system effluent discharge Discharge treated water from air stripping treatment system to an air misting system. LNAPL removal and disposal Active LNAPL removal by total fluids pumping T-BOS/oil from wells W-834-D3, 4, and 5, and diesel from well W-834-D8 for up to two years. Other Permitting. Optional development of innovative technology. Well and pump maintenance. Ground water treatment system and SVE system maintenance. Reporting. Project management. Database management. QA/QC. Project life: 2 years LNAPL removal, 5 years SVE, 5 years ground water extraction, 30 years (25 years post-closure) soil vapor and ground water monitoring.
Alternative 5—Source mass removal in complex core area through soil vapor extraction, ground water dewatering, and treatment; LNAPL removal; plume control through ground water extraction; and treatment to ARL risk-based concentrations (1×10^{-4})	Sampling/water-level measurement Quarterly water-level measurements of 54 monitor wells. Soil vapor monitoring would be the same as monitoring in Alternative 3. For the first five years ground water samples would be collected and analyzed quarterly in 41 wells and annually in 13 wells, followed by 25 years of biannual ground water sampling in 38 wells and annual sampling in 16 wells. Exposure and institutional controls Same as Alternative 2. Soil vapor extraction and treatment Extract soil vapor from 16 existing and 3 new extraction wells. Soil vapor treatment with existing SVE system for up to five years.

Table 4-1. (Continued)

Alternative 5—(Continued)	Extract soil vapor until VOC concentrations in vadose zone are reduced to acceptable health-based concentrations (1×10^{-4}). Conduct soil sampling to determine when the remedial action goals have been achieved, so soil vapor remediation could be discontinued. Ground water dewatering Extract ground water from 16 existing and 3 new ground water extraction wells in the Building 834 Complex core area and 7 ground water extraction wells in the septic tank, W-834-T2 and -T4 areas. Install new on-site air stripping ground water treatment Facility A in the core area, with adsorption of vapor-phase VOCs by GAC. Design flow rate would be 1.4 gpm. Install new on-site air stripping ground water treatment Facility B in the W-834-T4 area, with adsorption of vapor-phase VOCs by GAC. Design flow rate would be 0.5 gpm. Pump ground water from 26 extraction wells to air stripping treatment systems. Treatment system effluent discharge Discharge treated water from air stripping treatment systems A and B to an air mist system. LNAPL removal and disposal Active LNAPL removal by total fluids pumping of T-BOS/oil from wells W-834-D3, 4, and 5, and of diesel from well W-834-D8 for up to two years. Other Permitting. Optional development of innovative technology. Well and pump maintenance. Ground water treatment system and SVE system maintenance. Reporting. Project management. Database management. QA/QC. Project life: 2 years LNAPL removal, 5 years SVE, 5–30 years ground water extraction (dewatering and plume migration control), 30 years soil vapor and ground water monitoring.
Alternative 6—Remediation using innovation technology(s)	<u>If perched zone is delisted from CVRWQCB Basin Plan:</u> Innovative technology with same sampling and water level measurement plan as Alternative 3, and interim soil vapor extraction and treatment. Technology and associated operating procedures will be the same as Alternative 3 or 4 if innovative technology does not meet remediation criteria. <u>If perched zone is not delisted from CVRWQCB Basin Plan:</u> Innovative technology with same sampling and water level measurement plan as Alternative 5, and contingent soil vapor extraction and treatment. Technology and associated operating procedures will be the same as Alternative 5 if innovative technology does not meet remediation criteria.

Table 4-2. Construction details for proposed extraction wells at the Building 834 Complex.

Well	Function		Well casing depth (ft below grade)	Screened interval (ft below grade)	Sand pack interval (ft below grade)
	SVE	GWE			
W-834-B2	3, 4, 5	4, 5	14.5	7.0–14.5	4.1–14.5
W-834-B3	3, 4, 5	4, 5	10.2	5.5–10.2	4.2–10.2
W-834-B4 (new)	3, 4, 5	4, 5	NA	NA	NA
W-834-C2	3, 4, 5	4, 5	15.8	6.0–15.8	3.8–15.8
W-834-C3 (new)	3, 4, 5	4, 5	NA	NA	NA
W-834-D3	3, 4, 5	4, 5	34.0	19.0–29.0	17.0–35.0
W-834-D4	3, 4, 5	4, 5	34.0	19.0–29.0	17.0–34.0
W-834-D5	3, 4, 5	4, 5	34.0	19.0–29.0	17.0–34.0
W-834-D6	3, 4, 5	4, 5	34.0	19.0–29.0	17.0–34.0
W-834-D7	3, 4, 5	4, 5	31.0	16.0–26.0	11.0–29.0
W-834-D8	3, 4, 5	4, 5	36.0	21.0–31.0	15.0–33.0
W-834-D10	3, 4, 5	4, 5	32.5	25.6–32.5	22.5–32.5
W-834-D11	3, 4, 5	4, 5	22.1	11.9–21.9	7.5–22.1
W-834-D12	3, 4, 5	4, 5	27.3	17.0–27.0	13.8–27.3
W-834-D13	3, 4, 5	4, 5	27.4	17.1–27.1	12.7–27.5
W-834-D14	3, 4, 5	4, 5	27.6	17.3–27.3	10.9–27.6
W-834-J1	3, 4, 5	4, 5	30.0	25.0–30.0	21.0–34.0
W-834-J2	3, 4, 5	4, 5	37.0	22.0–32.0	18.5–33.0
W-834-S1		5	32.5	27.5–32.5	18.0–34.0
W-834-S11 (new)		5	NA	NA	NA
W-834-T2		5	47.0	32.0–42.0	28.0–44.0
W-834-T2A		5	42.5	17.5–37.5	17.5–42.5
W-834-T2D		5	40.8	25.8–35.8	16.0–36.0
W-834-T4		5	47.5	37.7–47.5	33.5–49.0
W-834-T4C		5	52.0	32.0–47.0	26.0–50.0
W-834-J3 (new)	3, 4, 5	4, 5	NA	NA	NA

SVE = Soil vapor extraction.

GWE = Ground water extraction (for dewatering and/or plume migration control).

3 = Alternative 3.

4 = Alternative 4 (and/or Alternative 6).

5 = Alternative 5 (and/or Alternative 6).

NA = Data not available because well has not been installed.

Table 4-3. Estimated well yield and ground water total VOC concentrations in Alternative 4 extraction wells.

Well	Approximate maximum yield (gpd)	Total VOC concentrations (µg/L)	
		Maximum observed	Second quarter 1993
W-834-B2	100	32,400	30,300
W-834-B3	100	81,000	11,300
W-834-B4 (new)	100	NA	NA
W-834-C2	100	29,000	20,000[a]
W-834-C3 (new)	100	NA	NA
W-834-D3	100	1,051,000	238,000
W-834-D4	100	633,000	230,000
W-834-D5	100	500,000	5,200
W-834-D6	100	84,000	84,000
W-834-D7	100	56,000	13,000
W-834-D8	100	120,640	34,000
W-834-D10	100	NA	NA
W-834-D11	100	58,000	15,000
W-834-D12	100	120,000	41,000
W-834-D13	100	190,000	1,700[a]
W-834-D14	100	170,000	100,200
W-834-J1	100	94,000	NA
W-834-J2	100	64,000	22,000
W-834-J3 (new)	100	NA	NA

[a] First quarter 1993 value; well not sampled second quarter 1993.

NA = Data not available either because well has not been installed or was not sampled.

Table 4-4. Estimated well yield and ground water total VOC concentrations in Alternative 5 extraction wells.

Well	Approximate maximum yield (gpd)	Total VOC concentrations (µg/L)	
		Maximum observed	Second quarter 1993
W-834-B2	100	32,400	30,300
W-834-B3	100	81,000	11,300
W-834-B4 (new)	100	NA	NA
W-834-C2	100	29,000	20,000[a]
W-834-C3 (new)	100	NA	NA
W-834-D3	100	1,051,000	238,000
W-834-D4	100	633,000	230,000
W-834-D5	100	500,000	5,200
W-834-D6	100	84,000	84,000
W-834-D7	100	56,000	13,000
W-834-D8	100	120,640	34,000
W-834-D10	100	NA	NA
W-834-D11	100	58,000	15,000
W-834-D12	100	120,000	41,000
W-834-D13	100	190,000	1,700[a]
W-834-D14	100	170,000	100,200
W-834-J1	100	94,000	NA
W-834-J2	100	64,000	22,000
W-834-J3 (new)	100	NA	NA
W-834-S1	100	179,200	81,460
W-834-S11 (new)	100	NA	NA
W-834-T2	100	66,000	61,000
W-834-T2A	100	NA	NA
W-834-T2D	100	41,000	31,050
W-834-T4	100	55,000	36,000
W-834-T4C	100	64,000	48,000

[a] First quarter 1993 value; well not sampled second quarter 1993.

NA = Data not available either because well has not been installed or was not sampled.

Table 5-1. Detailed evaluation of remedial alternatives for the Building 834 Complex.

Remedial alternative	Evaluation criteria					
	Overall protection of human health and the environment	Compliance with ARARs	Long-term effectiveness and permanence	Reduction in volume, toxicity, and mobility	Short-term effectiveness	Implementability
Alternative 1 No action	Is not protective of human health and the environment at the Building 834 Complex. Maintains acceptable risk associated with off-site downgradient water-supply wells completed in the regional aquifer.	Perched water-bearing zone is not a drinking water supply per SWRCB Policy 88-63.[a] Does not follow procedures of SWRCB Policy 92-49 (TBC).	Does not reduce VOCs in soil vapor to SVRLs.	Volume, mobility, and toxicity of VOCs not reduced. Subsurface restoration depends on natural degradation, dispersion, and evapotranspiration of VOCs.	No impact to general public. Possible exposure of workers during drilling and monitoring. Use of protective procedures, clothing, and equipment will mitigate risk.	Implementable. Ongoing monitoring would be reduced.
Alternative 2 Inhalation exposure controls, LNAPL recovery, and drainage control[b]	Exposures to human health risks reduced to EPA-accepted levels inside buildings but not outside. No air emissions. Maintains acceptable risk associated with off-site downgradient water-supply wells completed in the regional aquifer.	Perched water-bearing zone is not a drinking water supply per SWRCB Policy 88-63.[a] Does not follow procedures of SWRCB Policy 92-49 (TBC). LNAPL disposal in accordance with ARARs.	Localized infiltration and drainage control will prevent migration of VOCs from source areas. Building ventilation and institutional controls will reduce inhalation health risks to workers in Building 834 Complex buildings to EPA-accepted levels. Does not reduce VOCs in soil vapor to SVRLs.	LNAPLs removed from site. Volume and toxicity of VOCs in soil and ground water not reduced. Infiltration control will reduce mobility. Source mass reduction depends on natural degradation, dispersion, and evapotranspiration of VOCs.	No impact to general public. Short-term impact to workers and access to Building 834 facilities during drilling and construction. Coordinate short-term shutdown of Building 834 facilities. Possible exposure of workers during monitoring, LNAPL recovery, and surface grading. Use of protective procedures, clothing, and equipment will mitigate risk. Costs provided for LNAPL recovery for 2-y duration.	Implementable. Building ventilation would maintain air concentrations at acceptable levels. Hardware is readily available. Standard design and construction techniques and materials used for drainage control. Passive skimmers readily available. Recovered LNAPLs will be managed as a hazardous waste. Low maintenance, long-term effectiveness, low cost.
Alternative 3 Source mass removal by SVE and LNAPL recovery, and drainage control[b]	Exposures to human health risks reduced to EPA-accepted levels. Adverse impacts to environment from VOCs are substantially reduced. Results in negligible risk to employees and the public from system operation or exposure to air emissions. Maintains acceptable exposure risk associated with off-site downgradient water-supply wells completed in the regional aquifer.	Air emissions meet ARARs. Perched water-bearing zone is not a drinking water supply per SWRCB Policy 88-63. Does not follow procedures of SWRCB Policy 92-49 (TBC). GAC and LNAPL disposal in accordance with ARARs.	Removes VOCs. SVE and treatment system operated until soil vapor concentrations indicate that SVRLs have been achieved or effectiveness of the technology is expired (estimated 5 y). Mass removal reduces potential for VOC migration to regional aquifer. Spent GAC is regenerated off site. LNAPLs are recycled or disposed of off site. Localized infiltration and drainage control will prevent migration of VOCs from source areas. Building ventilation and institutional controls will reduce inhalation health risks to workers in Building 834 core area buildings.	Volume and toxicity of VOCs reduced by LNAPL recovery, SVE and treatment. VOC vapor migration controlled by SVE. Off-site thermal regeneration of spent GAC destroys VOCs. VOC solubilities and diffusion rates limit total mass removal of VOCs dissolved in ground water or from probable DNAPLs. Natural degradation and evapotranspiration of VOCs continues.	No impact to general public. GAC used to control air emissions from SVE, preventing impact on community. Provides option to conduct pilot tests and implement promising innovative technologies using BAT to ensure that no releases occur. Possible exposure of workers during monitoring, LNAPL recovery, drilling, and construction of piping and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. Remediation costed for 5-y duration.	Implementable. SVE and air emissions control using GAC are BAT for removing VOCs from vadose zone. Subsurface hydrogeology is appropriate for SVE. LLNL has permits for construction and operation of SVE treatment system. Services and materials for system construction, O&M, and off-site regeneration of GAC are available. Substantial portion of the system is in place and operating. Skimming LNAPLs is a standard technology. Building ventilation would maintain air concentrations at acceptable levels. Hardware is readily available. Standard design and construction techniques and materials used for drainage control.

Table 5-1. (Continued)

Remedial alternative	Evaluation criteria					
	Overall protection of human health and the environment	Compliance with ARARs	Long-term effectiveness and permanence	Reduction in volume, toxicity, and mobility	Short-term effectiveness	Implementability
Alternative 3—Continued			Current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources. Provides option to conduct pilot tests and implement promising innovative technologies. Soil vapor and ground water monitoring continue after remediation to ensure permanence of shallow vadose-zone cleanup.	Possible reduction in volume, toxicity, and mobility due to bioremediation augmented by SVE.		
Alternative 4 Source mass removal by SVE with dewatering and by DNAPL and LNAPL recovery, and drainage control[c]	Exposures to human health risks reduced to EPA-accepted levels. Adverse impacts to environment from VOCs are substantially reduced. Results in negligible risk to employees and the public from system operation or exposure to discharged treated water or air emissions. Maintains acceptable exposure risk associated with off-site downgradient water-supply wells completed in the regional aquifer.	Effluent and emissions meet ARARs. GAC, DNAPL, and LNAPL disposal in accordance with ARARs. Perched water-bearing zone is not a drinking water supply per SWRCB Policy 88-63. Does not follow procedures of SWRCB Policy 92-49 (TBC).	Removes VOCs. Soil vapor extraction and treatment system operated until soil vapor concentrations indicate that SVRLs have been achieved or effectiveness of technology is expired (estimated 5 y). Dewatering increases SVE effectiveness and mass removal. Mass removal reduces potential for VOC migration to regional aquifer. Spent GAC is regenerated off site. DNAPLs and LNAPLs are recycled or disposed of off site. Localized infiltration and drainage control will prevent migration of VOCs from source areas. Building ventilation and institutional controls will reduce inhalation health risks to workers in Building 834 core area buildings. Current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources. Provides option to conduct pilot tests and implement promising innovative technologies. Soil vapor and ground water monitoring continue after remediation to ensure permanence of shallow vadose-zone cleanup.	Volume and toxicity of VOCs reduced by SVE, dewatering, and treatment. VOC vapor migration controlled by SVE. VOC mobility at complex reduced by hydraulic control during dewatering. VOC solubilities and diffusion rates limit total mass removal of VOCs dissolved in ground water or from probable DNAPLs. Off-site thermal regeneration of spent GAC destroys VOCs. Natural degradation and evapotranspiration of VOCs continues. Possible reduction in volume, toxicity, and mobility due to bioremediation augmented by SVE. Infiltration control will reduce mobility.	No impact to general public. GAC used to control air emissions from air stripper and SVE, preventing impact on community. Provides capability to conduct pilot tests and implement promising innovative technologies using BAT to ensure that no releases occur. Possible exposure of workers during monitoring, LNAPL recovery, drilling, and construction of piping and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. SVE and dewatering costed for 5-y duration.	Implementable. SVE and air emissions control using GAC are BAT for removing VOCs from vadose zone. Subsurface hydrogeology is appropriate for SVE. Dewatering in the core area will expose more soil and enhance mass removal by SVE. LLNL has permits for construction and operation of SVE treatment system. Air stripping is BAT for removing VOCs in ground water. Tray aeration eliminates adverse visual impact of packed towers. Recarbonation system reduces O&M due to carbonate precipitation. Services and materials for system construction, O&M, and off-site regeneration of GAC are available. Substantial portion of the system is in place and operating. Standard requirements for treated ground water discharge would be met. Recovered DNAPLs and LNAPLs will be managed as a hazardous waste. Building ventilation would maintain air concentrations at acceptable levels. Hardware is readily available. Standard design and construction techniques and materials used for drainage control.

Table 5-1. (Continued)

Remedial alternative	Evaluation criteria					
	Overall protection of human health and the environment	Compliance with ARARs	Long-term effectiveness and permanence	Reduction in volume, toxicity, and mobility	Short-term effectiveness	Implementability
Alternative 5 Source mass removal by SVE with dewatering and by DNAPL and LNAPL recovery; plume control downgradient by ground water extraction; and drainage control[b]	Exposures to human health risks reduced to EPA-accepted levels. Adverse impacts to environment from VOCs are substantially reduced. Results in negligible risk to employees and the public from system operation or exposure to discharged treated water or air emissions. Maintains acceptable exposure risk associated with off-site downgradient water supply wells completed in the regional aquifer.	Effluent and emissions meet ARARs. GAC, DNAPL, and LNAPL disposal in accordance with ARARs. Perched water-bearing zone is not a drinking water supply per SWRCB Policy 88-63.[a] Does not follow procedures of SWRCB Policy 92-49 (TBC).	SVE and treatment system operated until soil vapor concentrations indicate that SRLs may be achieved. Soil confirmation sampling would be conducted to demonstrate that SRLs have been achieved and system would be shut off. Dewatering increases SVE effectiveness and mass removal. Downgradient ground water extraction and treatment operated until TCE concentrations reach asymptotic levels or MCLs, whichever is higher (estimated 30 y). Mass removal reduces potential for VOC migration to regional aquifer. Spent GAC is regenerated off site. DNAPLs and LNAPLs are recycled or disposed off site. Localized infiltration and drainage controls will prevent migration of contaminants of concern from source areas. Building ventilation and institutional controls will reduce inhalation health risks to workers in Building 834 core area buildings. Current industrial health, safety, and hygiene and hazardous materials handling practices are designed to prevent creation of new sources. Provides option to conduct pilot tests and implement promising innovative technologies. Soil vapor and ground water monitoring continue after remediation to ensure permanence of shallow vadose-zone cleanup	Volume and toxicity of VOCs reduced by LNAPL recovery, SVE and treatment, dewatering and treatment, and downgradient ground water extraction. VOC vapor migration controlled by SVE. VOC mobility reduced by hydraulic control. VOC solubilities and diffusion rates limit total mass removal of VOCs dissolved in ground water or probable DNAPLs. Off-site thermal regeneration of spent GAC destroys VOCs. Natural degradation and evapotranspiration of VOCs continues. Possible reduction in volume, toxicity, and mobility due to bioremediation augmented by SVE. Infiltration control may eventually reduce volume.	No impact to community during construction. Use of GAC to control air emissions from air stripper and SVE will prevent impact on community. Provides capability to conduct pilot tests and implement promising innovative technologies using BAT to ensure that no releases occur. Possible exposure of workers during monitoring, LNAPL recovery, drilling, and construction of piping and treatment systems. Use of protective procedures, clothing, and equipment will mitigate risk. SVE costed for 5-y duration. Ground water extraction costed for 5-, 10-, 20-, and 30-y durations.	Implementable. SVE and air emissions control using GAC are proven remedial technologies for removing VOCs from vadose zone and controlling air emissions. Dewatering in the core area will expose more soil and enhance mass removal by SVE. Subsurface hydrogeology is appropriate for SVE. LLNL has permits for construction and operation of SVE treatment system. Substantial portion of treatment facility is constructed and operating. Operating and discharge permits will be obtained for treatment facility. Air stripping is proven for treatment of VOCs in ground water. Tray aeration eliminates adverse visual impact of packed towers. Recarbonation system reduces O&M due to carbonate precipitation. Services and materials for system construction, O&M, and for off-site regeneration of GAC are readily available. Recovered DNAPLs and LNAPLs will be managed as a hazardous waste. Building ventilation would maintain air concentrations at acceptable levels. Hardware is readily available. Standard design and construction techniques and materials used for drainage control.

Table 5-1. (Continued)

Remedial alternative	Evaluation criteria					
	Overall protection of human health and the environment	Compliance with ARARs	Long-term effectiveness and permanence	Reduction in volume, toxicity, and mobility	Short-term effectiveness	Implementability
Alternative 6[d] Remediation using innovative technology						

[a] LLNL/DOE is currently pursuing CVRWQCB listing of the perched zone from the Basin Plan.

[b] Exposure controls include building ventilation and institutional controls.

[c] Alternatives 4 and 5 include exposure controls and drainage controls presented in Alternative 2.

[d] Innovative technology coupled with soil vapor extraction (enhanced by ground water extraction, as needed) will address all evaluation criteria similarly to Alternative 3 or 4 if perched zone is excluded from Basin Plan. Innovative technology coupled with soil vapor extraction (and contingent Alternative 5 BAT) will address all evaluation criteria similarly to Alternative 3 or 4 if perched zone is not excluded from Basin Plan.

TBC = To be considered.

Table 5-2. Summary of present worth costs for the Building 834 Complex remedial alternatives (in millions of 1994 dollars).

Remedial alternative	Capital costs[a]	Operation and maintenance costs	Monitoring costs[b]	LLNL taxes[c]	Subtotal[d]	Contingency (20%)	Total present worth[d]
Alternative 1 No action	0.22	0	2.84	0.43	3.49	0.70	4.19
Alternative 2 Inhalation exposure controls, LNAPL recovery, and drainage control[e]	1.25	0.06	2.84	0.58	4.74	0.95	5.69
Alternative 3 Source mass removal by SVE and LNAPL recovery, and drainage control[e]	2.61	0.85	2.92	0.89	7.27	1.45	8.72
Alternative 4 Source mass removal by SVE with dewatering and LNAPL recovery, and drainage control[g]	3.08	1.57	2.94	1.06	8.65	1.73	10.38
Alternative 5 Source mass removal by SVE with dewatering and LNAPL recovery, downgradient dewatering, and drainage controls							
5a (5 years pumping)	3.66	1.92	3.05	1.20	9.84	1.97	11.80
5b (10 years pumping)	3.66	2.85	3.05	1.33	10.90	2.18	13.08
5c (20 years pumping)	3.66	4.30	3.05	1.54	12.54	2.51	15.05
5d (30 years pumping)	3.66	5.32	3.05	1.68	13.71	2.74	16.45
Alternative 6[g] Remediation using innovative technology with SVE							

Note: Footnotes appear on the following page.

Table 5-2. (Continued)

[a] Capital costs include engineering design, construction and management of remediation systems, ventilation retrofit projects, and drainage control projects.

[b] Monitoring costs include ground water and soil vapor monitoring.

[c] LLNL taxes include LLNL General & Administrative tax at 7.5% and Lab-Directed Research & Development tax at 6.0%.

[d] Rounding may cause subtotal or total to appear incorrect by ±0.01 million dollars. Subtotals and totals are taken directly from Tables G1–G5.

[e] Exposure controls include ventilation and institutional controls.

[f] Alternative includes exposure controls and drainage controls presented in Alternative 2.

[g] Costs not available for innovative technology. SVE costs would be similar to Alternatives 3 and 4 if perched zone is excluded from the Basin Plan and similar to Alternative 5 if not excluded.

Table 5-3. Comparative evaluation of remedial alternatives for the Building 834 Complex.

Alternative	Overall protection of human health and environment	Compliance with ARARs[a]	Long-term effectiveness and permanence	Reduction in volume, toxicity, and mobility	Short-term effectiveness	Implementability	Relative Cost	State acceptance	Community acceptance
Alternative 1	Human health: No Environment: No	Criteria met	Not effective	Dependent on natural degradation	Not effective	Implementable	Low	TBD	TBD
Alternative 2	Human health: Inside: Yes Outside: No Environment: No	Criteria met	Effective	Limited reduction in core area LNAPL contamination	Effective	Implementable	Moderate	TBD	TBD
Alternative 3	Human health: Yes Environment: Yes	Criteria met	Effective	Reduction in core area vadose zone and LNAPL contamination	Effective	Implementable	High	TBD	TBD
Alternative 4	Human health: Yes Environment: Yes	Criteria met	Effective	Reduction in core area vadose zone, perched zone, and LNAPL contamination	Very effective	Implementable	High	TBD	TBD
Alternative 5	Human health: Yes Environment: Yes	Criteria met	Very effective	Reduction in core area vadose zone, perched zone, and LNAPL contamination and downgradient perched zone contamination	Very effective	Implementable	Very high[b]	TBD	TBD
Alternative 6									
If perched zone excluded from Basin Plan	Same as Alternative 3 or 4						TBD	Same as Alternative 3 or 4	
If perched zone not excluded from Basin Plan	Same as Alternative 5						TBD	Same as Alternative 5	

TBD = To be determined.

a Alternatives do not meet TBC ARARs. DOE/LLNL is currently pursuing a CVRWQCB Basin Plan amendment to exclude the shallow perched water-bearing zone.

b Overall cost is highly dependent on the required length of pumping time.

Appendix A

Area and Volume Estimates and Calculation Sensitivities

Appendix A

Area and Volume Estimates and Calculation Sensitivities

A-1. Estimates of Area and Volume

This appendix presents estimates of the volume of TCE in soil and perched ground water at the Building 834 Complex and shows how these estimates are derived.

Tables A-1 and A-2 display our estimated areas and volumes of contaminated soil and ground water. Figure A-1 shows the areas defined by the isoconcentration contours of TCE in the perched water-bearing zone.

As described in Chapter 1, TCE has the highest concentration of any VOC detected in the Building 834 operable unit soil and ground water at this operable unit. Other chemicals of concern detected are present at much lower concentrations relative to TCE. Because TCE has been identified as the most prominant chemical of potential concern in soil and ground water, we use TCE as the primary indicator chemical. Thus, TCE is used to delineate areas and volumes of contamination at the Building 834 Complex.

To calculate total volume of TCE in soil, a concentration of 47.6 mg/kg (a conservative 95% UCL) was applied to three volumes, each defined by a circle at Buildings 834D, J, B, and C with a maximum radius of 50 ft (from the approximate center of each spill area), and a depth from the surface to the bottom of the saturated zone of 25 ft. Our calculations are approximations.

In calculating our estimates, we used a conservative porosity of 0.25 (dimensionless) (Freeze and Cherry, 1979), a soil bulk density of 1.85 (g/cc), and a TCE density of 1.46 (g/cc) (Windholz, 1983). Although a value of 0.20 for porosity is displayed in the SWRI hydrogeologic characteristic tables, we chose a more conservative porosity of 0.25 to ensure that we accounted for heterogeneities. The concentrations used in our ground water estimates were derived from our most recent sampling data (first and second quarter 1993). For TCE in ground water, isoconcentration contours were used to define the areas affected. We assumed complete vertical mixing of contaminants in ground water. The saturated thickness contours for the quarters ending in April 1993 (Fig. A-2) and July 1993 (Fig. A-3) were used to calculate average saturated thicknesses of 3.3 and 3 ft, respectively. These values represent the highest saturated thicknesses up- and downgradient, respectively, after the winter storms of 1992/1993. We used the more conservative of the two values, 3.3 ft, to calculate ground water estimates. To calculate total volume of TCE in ground water, a logarithmic mean of the TCE concentrations was assigned to the volume between adjacent contours, (e.g., the volume between 1,000 µg/L and 10,000 µg/L isocontours was assigned a concentration value of 3,162 µg/L).

Due to the age of the spills (30 + years) and the uncertainty regarding the initial spill volumes, the estimates of 270 and 27 gallons of TCE in soil and ground water (Tables A-1 and A-2), respectively, should be accepted as order-of-magnitude estimates. Given these large

uncertainties, it is unlikely that these estimates can account for all released TCE. The following issues also need to be noted when accounting for released TCE in the Building 834 Complex:

- Soil suspected of containing the highest concentrations of released TCE has been excavated (approximately 10 ft deep) from the vicinity of several complex buildings.
- Some of the TCE spilled inside facility buildings was cleaned up before leaking outside the building and never penetrated the soil surface.
- A portion of the released TCE probably volatilized before it could deeply penetrate the soil.
- Treatability studies have been conducted at the Building 834 Complex, and several hundred pounds of TCE mass was removed from the subsurface.
- Low concentration of TCE vapor may be actively fluxing from soil in the Building 834 core area, thereby decreasing the TCE mass.
- Field data suggest that natural biodegradation is occurring, further reducing TCE mass in the subsurface.

A-2. Sensitivity Study for TCE Estimates

We have four variables to consider for our volume estimates of TCE in ground water and the vadose zone: area, depth to saturation (vadose zone) and depth of saturation (ground water), bulk soil density (vadose zone), and porosity (vadose zone). The sensitivities of these four variables are discussed below.

A-2.1. Area

We used areas in our calculations which are based on a conservative interpretation of the distribution of TCE in soil and ground water. Figure A-4 shows the linear relationship between area and volume of TCE in soil calculations; a decrease in area results in a decrease in TCE in soil volume estimates.

A-2.2. Depth to Saturation (Vadose Zone) and Depth of Saturation (Ground Water)

We used 3.3 ft average saturated thickness, which is the more conservative area-weighted value calculated using the saturated thickness contours shown on Figure A-2. Water-level data was also used to determine an average vadose zone thickness of 25 ft at the core of the complex. Figures A-5 and A-6 show the linear relationships between depth and TCE volume calculations; an increase in thickness results in an increase in TCE volume estimates.

A-2.3. Porosity

We used current literature to establish a conservative porosity value of 0.25 for the perched water-bearing zone (Freeze and Cherry, 1979). Figure A-7 shows the linear relationship between porosity and the calculated estimate of the volume of TCE in ground water; an increase in porosity results in an increase in the estimated volume of TCE in ground water.

A-2.4. Bulk Soil Density

We assumed a bulk density at 1.85 (g/cc). Figure A-8 shows the linear relationship between soil bulk density and the calculated volume of TCE in soil; an increase in soil bulk density results in an increased estimate of the volume of TCE in soil.

A-3. References

Freeze, R. A., and J. A. Cherry (1979), *Groundwater* (Prentice-Hall, Englewood Cliffs, N.J.).

Windholz, M., Ed. (1983), *The Merck Index, 10th Edition* (Merck & Co., Rahway, N.J.).

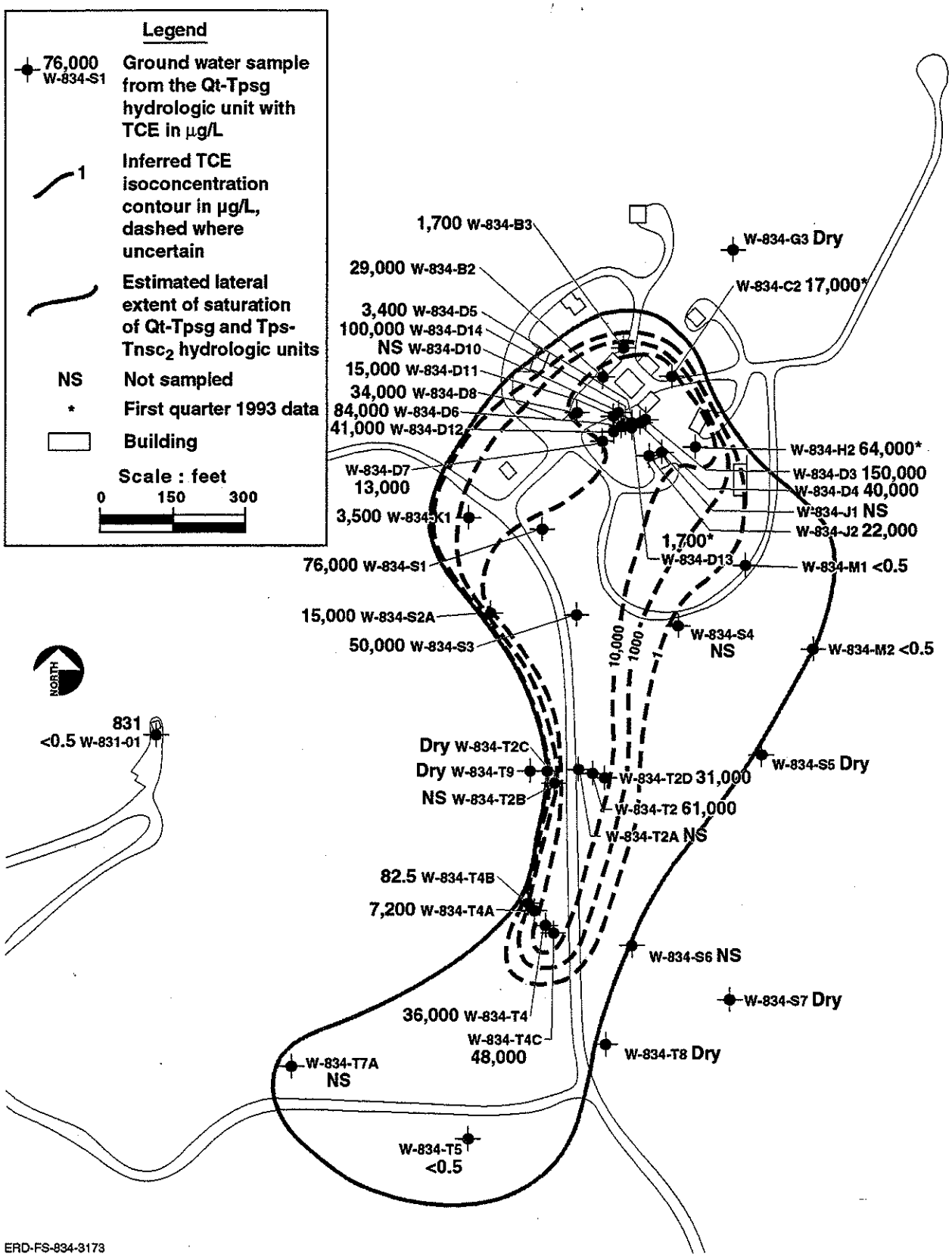

Figure A-1. Distribution of TCE in perched ground water (Qt-Tpsg/Tps$_2$) at the Building 834 Complex, first and second quarter 1993.

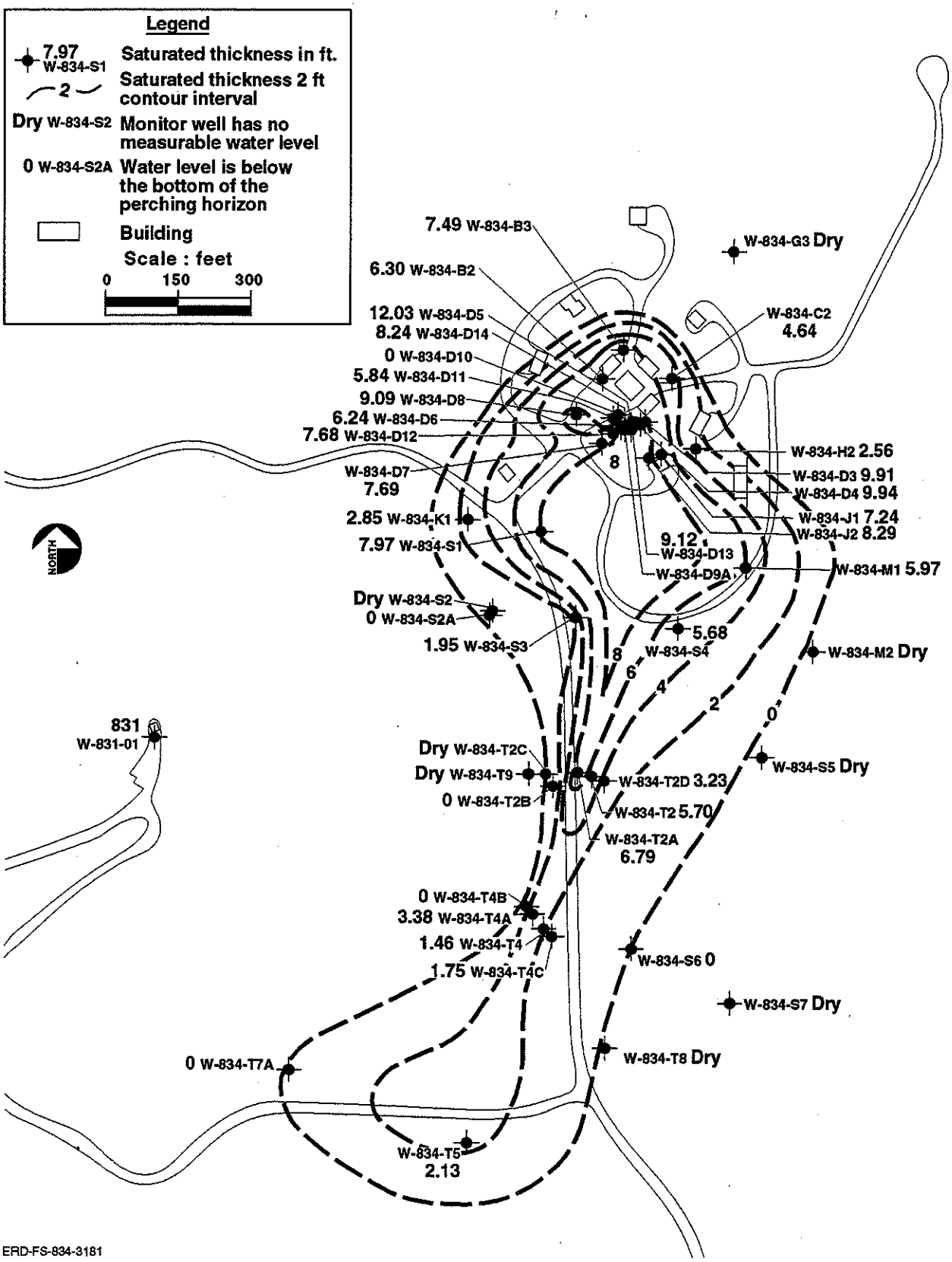

Figure A-2. Saturated thickness of the perched zone (Qt-Tpsg/Tps-Tnsc$_2$ hydrologic units), April 1993.

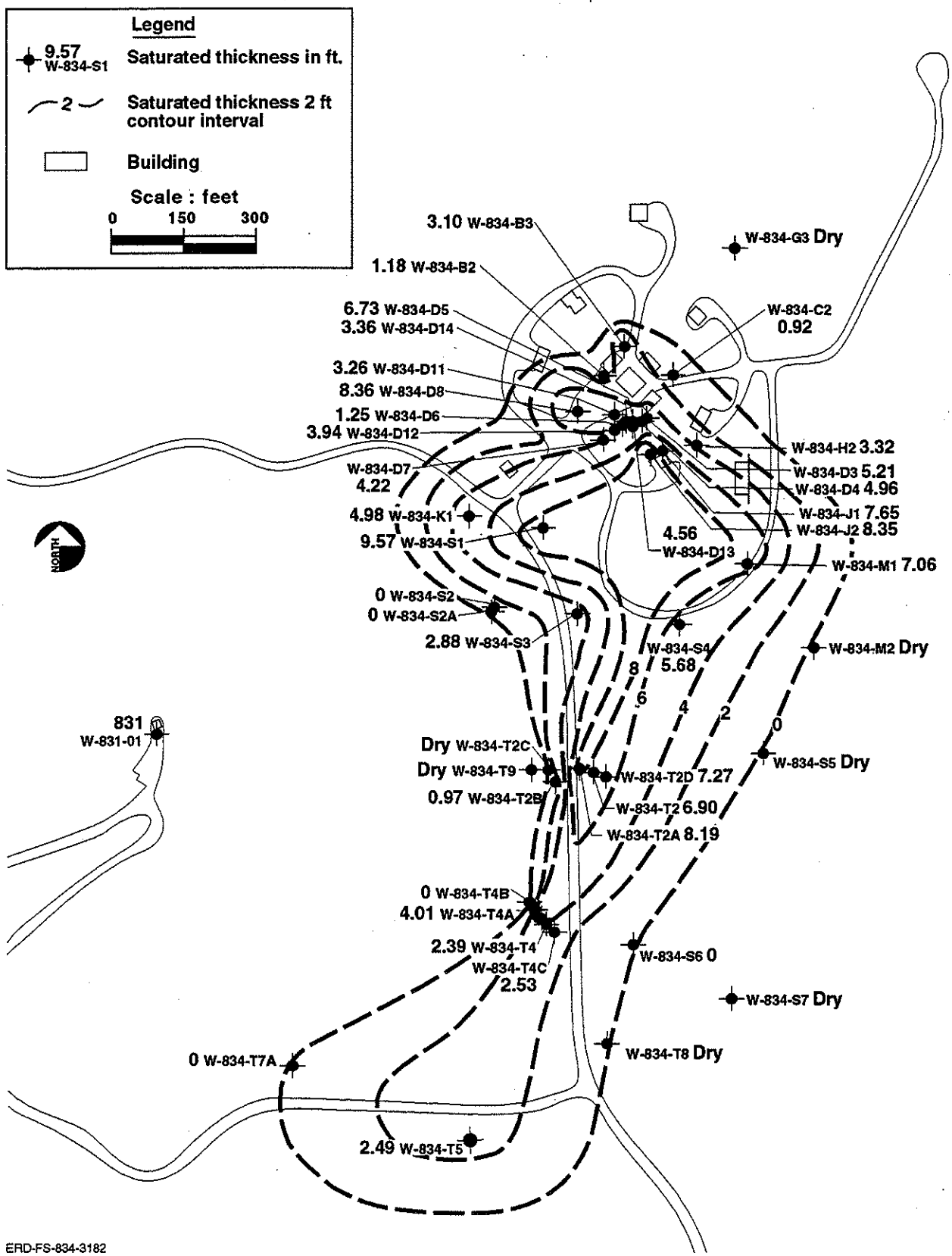

Figure A-3. Saturated thickness of the perched zone (Qr-Tpsg/Tps-Tnsc$_2$ hydrologic units), July 1993.

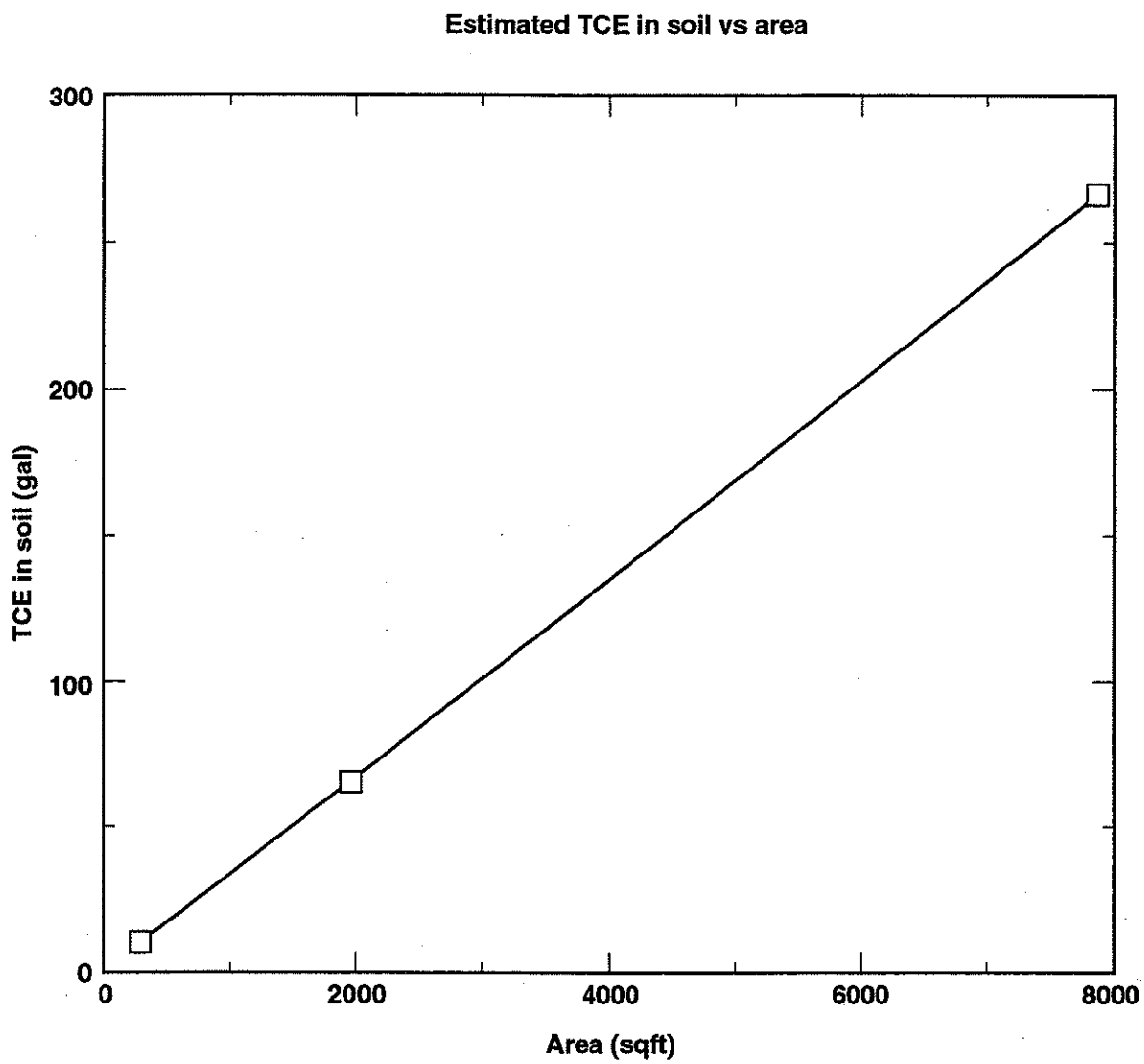

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Figure A-4. TCE in soil with variations in area.

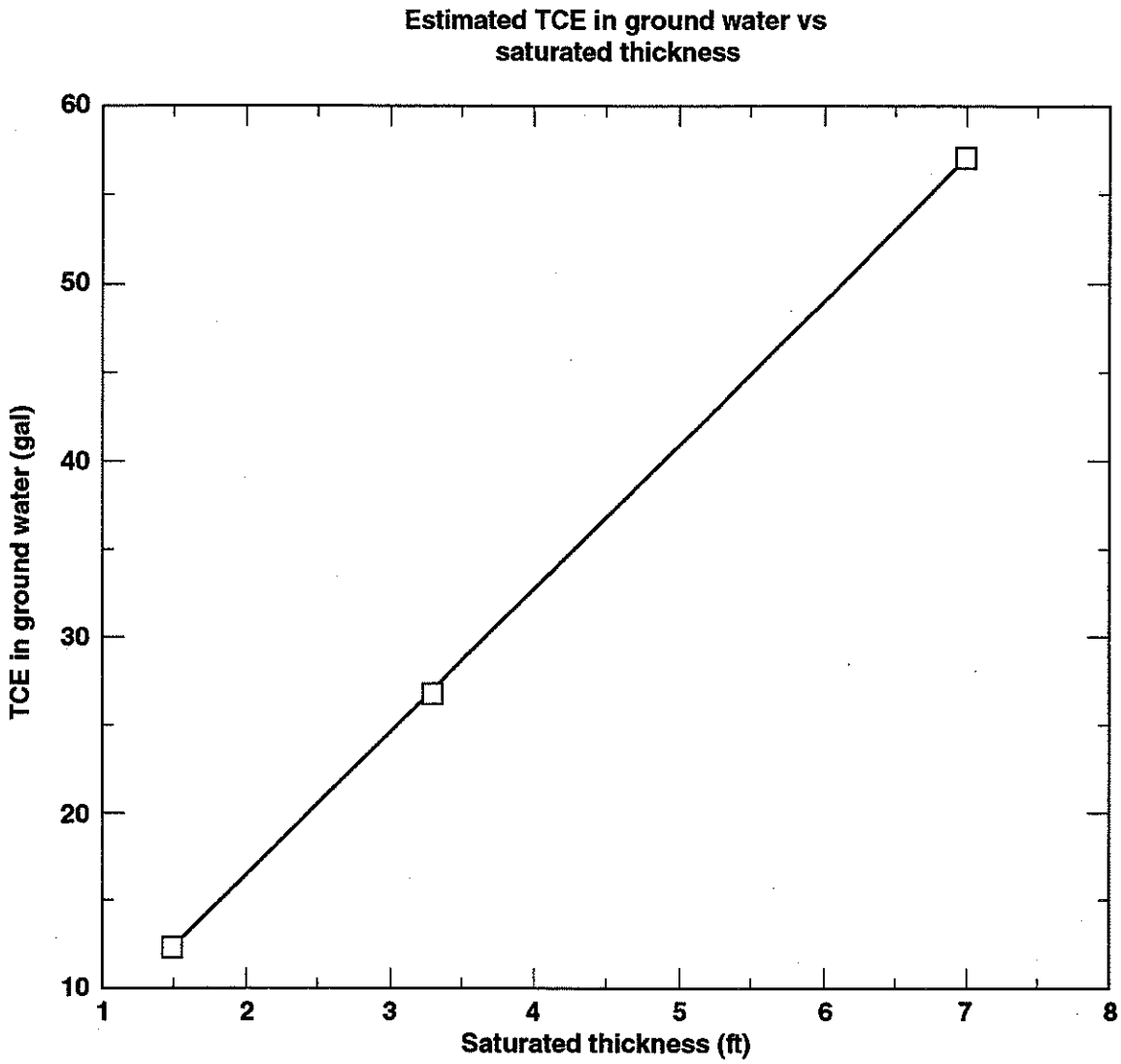

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Figure A-5. TCE in ground water with variations in saturated thickness.

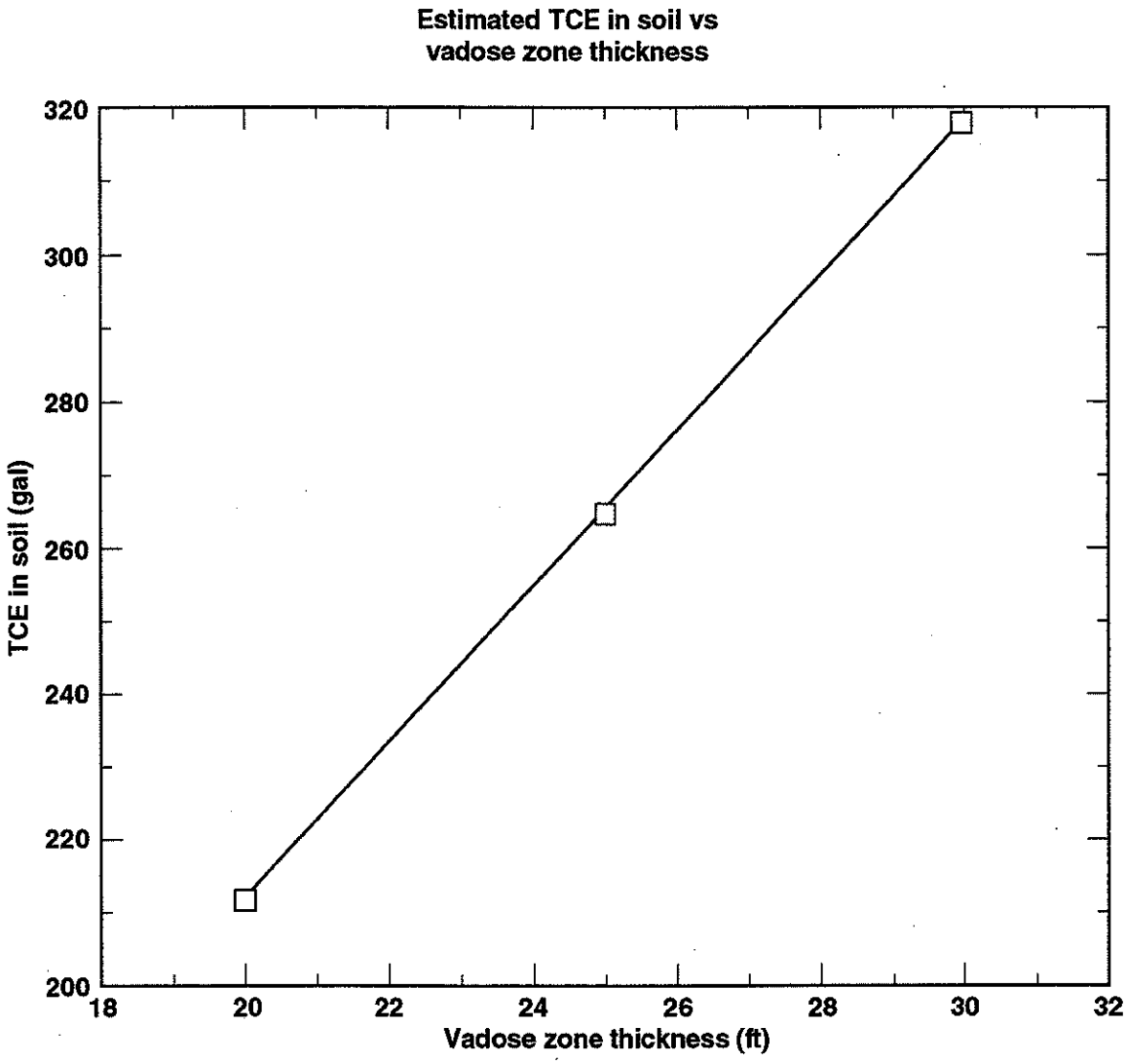

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Figure A-6. TCE in soil with variations in vadose zone thickness.

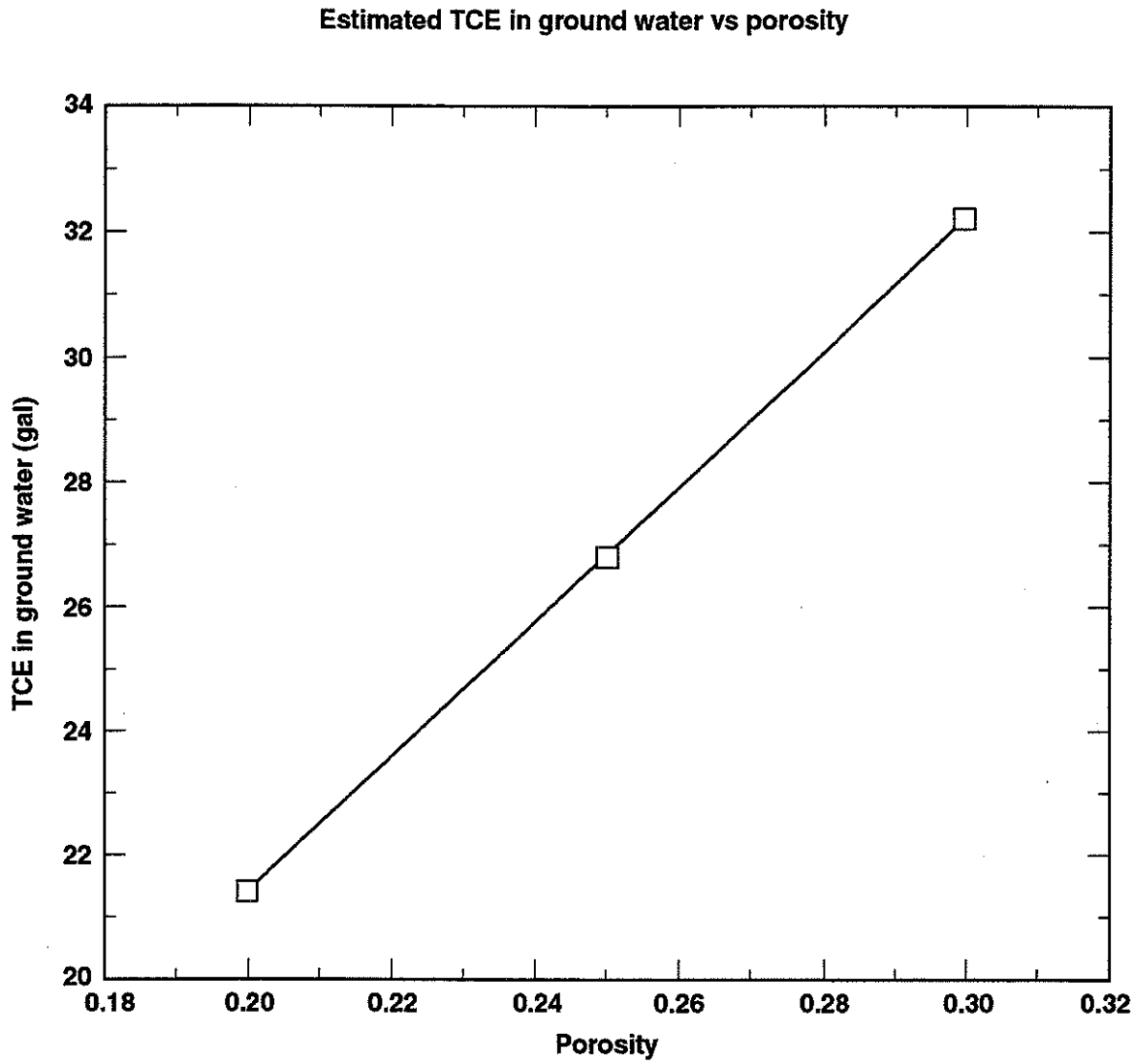

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Figure A-7. TCE in ground water with variations in porosity.

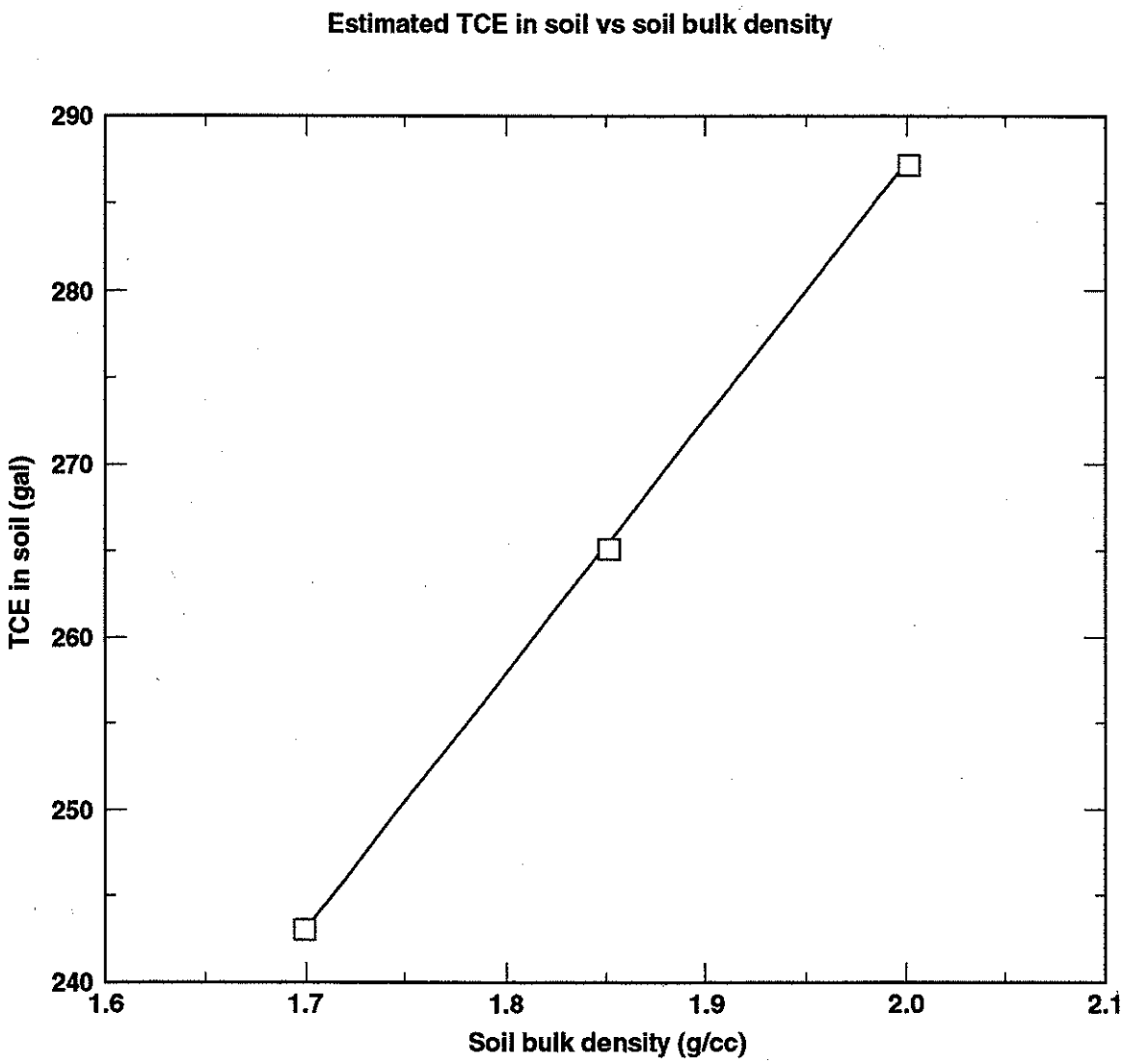

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Figure A-8. TCE in soil with variations in soil bulk density.

Table A-1. Estimated volume of TCE in soil beneath the Building 834 Complex.

Approximate unsaturated thickness (ft)	Approximate area affected (ft^2)	Bulk contaminated volume (ft^3)	Volume of TCE (gal.)
25	24,000	590,000	270

Table A-2. Estimated volume of TCE in perched ground water beneath the Building 834 Complex.

Approximate average saturated thicknesses (ft)	Approximate area affected (ft^2)	Volume of contaminated ground water (gal.)[a]	Volume of TCE (gal.)
3.3	400,000	2,400,000	27

[a] Porosity assumed to be 0.25.

Appendix B

Comparative Statistical Analysis—Baseline and Post-SWRI Data Cutoff

Appendix B

Comparative Statistical Analysis—Baseline and Post-SWRI Data Cutoff

This Appendix presents an evaluation of data obtained for the Building 834 operable unit between the data cutoff date for the SWRI (Webster-Scholten, 1994) of December 31, 1991 and August 3, 1993. The principal purpose of this evaluation is to determine, to the extent possible, whether our current understanding of environmental contamination in the Building 834 Complex differs substantially from our understanding of that contamination at the time the SWRI was prepared. This comparison of SWRI and post-SWRI data is limited to ground water due to the fact that no samples of surface soil or subsurface soil have been collected in the complex other than those reported in the SWRI report.

B-1. Detections of VOCs in Wells Installed in the Regional Aquifer

Several issues arose regarding ground water contamination in the Building 834 Complex near the time of the SWRI data cutoff. Of particular interest was a detection of chloromethane (15 µg/L) on December 9, 1991, in the regional aquifer well W-834-T1. Chloromethane had not been detected previously in ground water in the complex, and, as a consequence of its low frequency of detection (<2%), chloromethane was not included as a contaminant of potential concern. Well W-834-T1 has been sampled in each of the six quarters subsequent to December 31, 1991; chloromethane has not been detected again. Other VOCs (e.g., TCE and PCE) had also been sporadically detected in regional aquifer wells in the Building 834 Complex prior to December 31, 1991. However, no detections of VOCs have been reported from these wells since then.

B-2. Tetra 2-ethylbutylorthosilicate

The SWRI report documented the presence of tetra 2-ethylbutylorthosilicate (T-BOS) in well W-834-D3. T-BOS is a viscous, relatively insoluble LNAPL used as a lubricant in the thermodynamic testing apparatus at the Building 834 Complex. The identification of T-BOS was made in February 1992. No additional analyses for this compound have been completed to date.

B-3. Substances Detected in Ground Water in the Building 834 Complex Since the SWRI

We examined ground water data obtained between December 31, 1991 and August 3, 1993, to determine if any substances, other than those identified as contaminants of potential concern, had been detected in ground water during that 20-month period. This examination yielded

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Comparative Statistical Analysis—Baseline and Post-SWRI Data Cutoff

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We examined ground water data obtained between December 31, 1991 and August 3, 1993, to determine if any substances, other than those identified as contaminants of potential concern, had been detected in ground water during that 20-month period. This examination yielded

evidence of a single detection of three separate isomers of chlorobenzene in well W-834-C2 (all from a single sample taken February 21, 1992), a single detection of 1,2-dichloropropane in well W-834-T4A on June 25, 1992, and a number of detections of diesel hydrocarbons. These results are summarized in Table B-1. We have not added any of these substances to our list of contaminants of potential concern in ground water for the Building 834 Complex. With respect to the chlorobenzenes and 1,2-dichloropropane, this decision was based on the low frequency of detection (<2%) and the fact that the presence of these compounds has not been confirmed by subsequent analyses. It is apparent, however, that the perched aquifer in the core area is contaminated with diesel hydrocarbons. Nonetheless, in the absence of quantitative identification of the constituent compounds, we do not have sufficient data to characterize potential risk or hazard associated with exposure to these substances.

B-4. Comparison of Contaminants of Potential Concern in Ground Water Between Baseline and Post-SWRI Data

For the SWRI report, we calculated the 95% upper confidence limit of the mean concentration (95% UCL) of ground water contaminants in the Building 834 Complex. These calculations pertain to contaminant concentration data obtained from a subset of wells in the perched zone of the complex that characterize the VOC plume. These wells are listed in Table B-2. (Although we also examined the detection history of contaminants in the three wells installed in the regional aquifer, contaminant concentration data from these wells were not used in our estimates of the 95% UCLs.) Table B-3 presents summary statistics for ground water contaminants in the perched zone plume within the Building 834 Complex; these data were originally presented in Chapters 4 and 10 of the SWRI report.

To determine whether the mean concentrations of these VOCs have changed over time, we recalculated the 95% UCLs using data collected through August 3, 1993. Table B-4 presents the summary statistics that resulted from these calculations. A comparison of values between Tables B-3 and B-4 indicates that, for most compounds, the maximum measured concentration remains unchanged, and the 95% UCL has decreased relative to the values originally presented in the SWRI. The exceptions to this are chloroform, PCE, and TCE.

The maximum measured concentration of 950 μg/L for chloroform reported in the SWRI remains unchanged. However, the 95% UCL has increased from 1.06×10^2 to 1.35×10^2 μg/L, apparently due to one additional detection since the SWRI data cutoff. A plot of detections of chloroform in ground water over time in the plume subset of wells (Table B-2) is provided in Figure B-1.

The maximum measured concentrations of both PCE and TCE have increased substantially relative to data available for the SWRI. These increases are due in both cases to the results from a relatively recent sample (February 2, 1993) obtained from well W-834-D3. Laboratory analysis of this sample yielded a concentration of TCE of 8.0×10^5 μg/L and a concentration of PCE of 1.0×10^4 μg/L. The sample in question was subjected to a 10,000-fold dilution (Brown and Caldwell, 1993a) prior to laboratory analysis, which potentially introduced a degree of error into these results. However, the field notes sent to the analytical laboratory noted that there was visible product in the sample (Brown and Caldwell, 1993b), indicating that there are high levels of these VOCs present in well W-834-D3. Although the TCE maximum concentration increased

as noted, the 95% UCL decreased (from 1.90×10^5 µg/L to 1.82×10^5 µg/L), presumably due to a number of relatively low detections of TCE in the set of wells that characterize the plume. The current 95% UCL for PCE is 1.59×10^3 µg/L, an increase from 9.07×10^2 µg/L originally calculated for the SWRI. A plot of detections of TCE in ground water over time in the plume subset of wells (Table B-2) is provided in Figure B-2; an analogous plot for PCE is presented in Figure B-3.

B-5. Cancer Risk and Noncancer Hazard Associated with Use of Ground Water from the Building 834 Complex

From the methodology presented in Chapter 10 (section 10-5) of the SWRI, we estimated concentrations of VOCs in ground water at the off-site well CDF-1 (the hypothetical exposure point for ground water contaminants that originate in the Building 834 Complex). These estimates were made using the concentration data presented in Table B-4 (pertaining to the VOC plume in the perched zone), as well as accounting for contaminant concentrations measured in the regional aquifer. Because no VOC detections in the regional aquifer have been documented since the SWRI data cutoff, the concentrations of VOCs originally estimated to reach well CDF-1 from the regional aquifer are unchanged from those originally presented in the SWRI. Table B-5 lists the predicted 70-yr average estimated concentrations of VOCs at CDF-1.

We used the data, methodology, pathway exposure factors, and toxicity values presented in Chapter 6 and Appendix P of the SWRI in conjunction with the newly estimated VOC concentrations at CDF-1 (Table B-5) to calculate the potential incremental excess cancer risk and noncancer hazard associated with residential use of ground water at CDF-1. These calculations yielded an estimate of cancer risk of 7×10^{-11} and a noncancer hazard index (HI) of 2.5×10^{-6}, values that are either identical or extremely close to the values originally calculated for the SWRI (the original estimate of cancer risk was 7×10^{-11}, and the HI was 2.8×10^{-6}).

B-6. References

Brown and Caldwell (1993a), *Report of Analytical Results, Groundwater Sample Number 9302227*5*, sent to Albert Lamarre, Lawrence Livermore National Laboratory on April 1, 1993, Brown and Caldwell Analytical, Emeryville, Calif.

Brown and Caldwell (1993b), *LLNL Groundwater Sampling Data, Brown and Caldwell Log No. 9302227*, Chain of Custody Document No., A1-50, February 9, 1993, Brown and Caldwell Analytical, Emeryville, Calif.

Webster-Scholten, C. P., Ed. (1994), *Final Site-Wide Remedial Investigation Report, Lawrence Livermore National Laboratory Site 300,* Lawrence Livermore National Laboratory, Livermore, Calif. (UCRL-AR-108131).

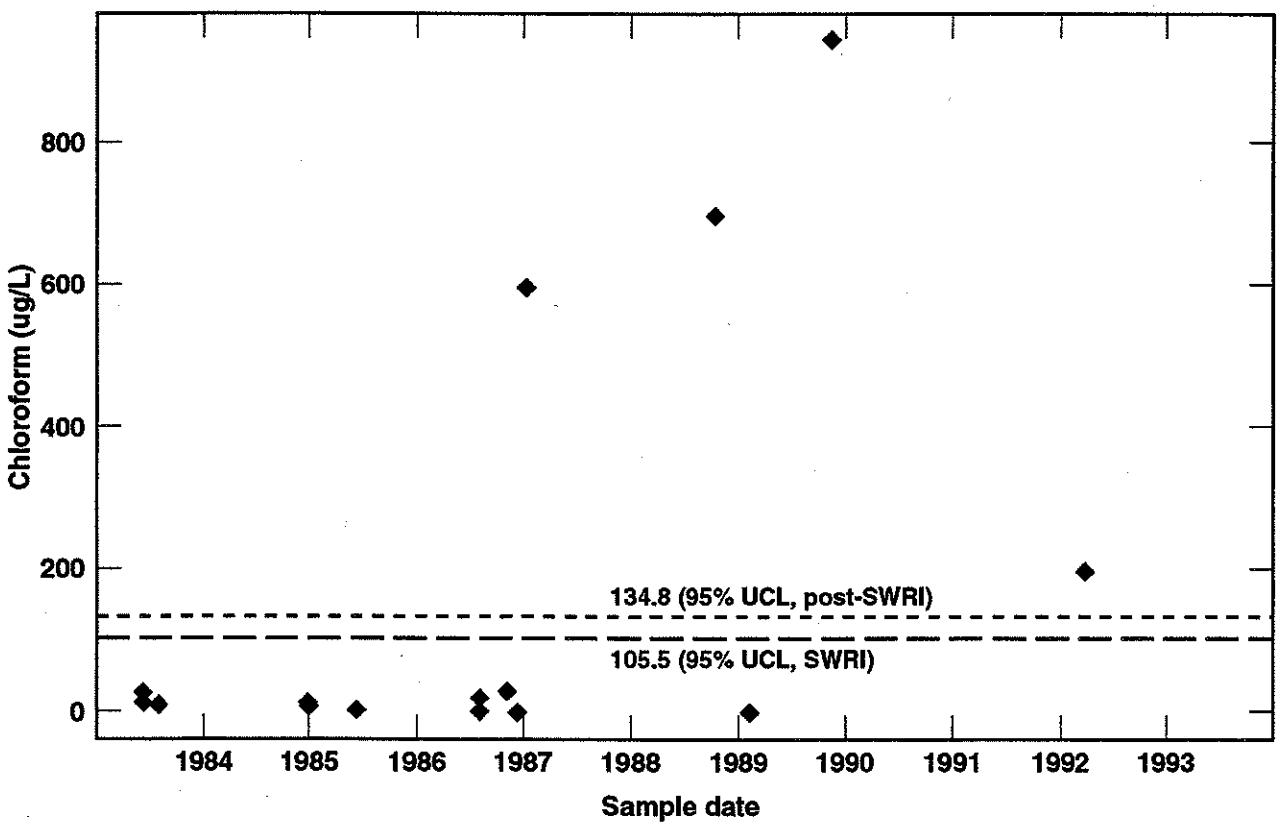

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Figure B-1. Detections of chloroform over time in ground water in a VOC-plume-specific set of wells in the Building 834 operable unit.

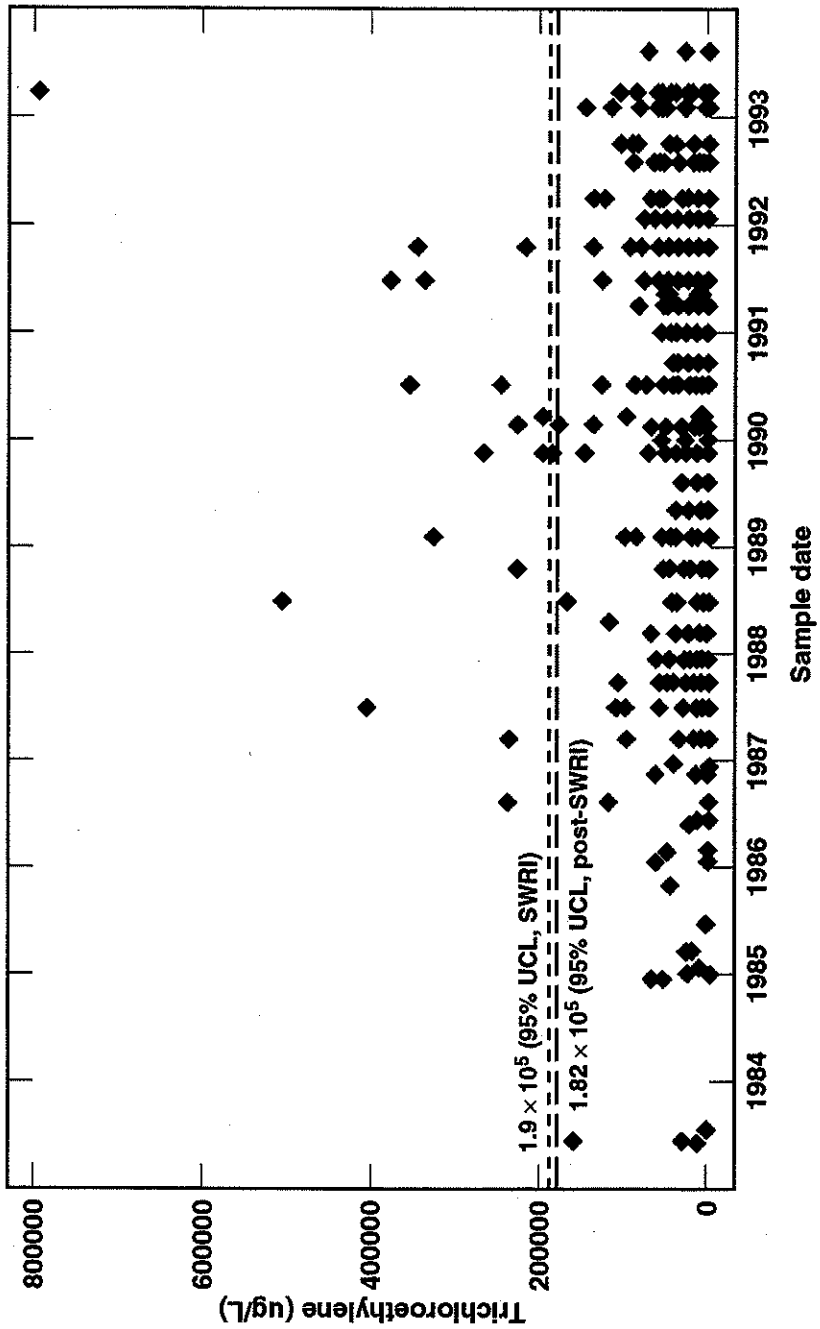

Figure B-2. Detections of trichloroethylene over time in a VOC-plume specific set of wells in the Building 834 operable unit.

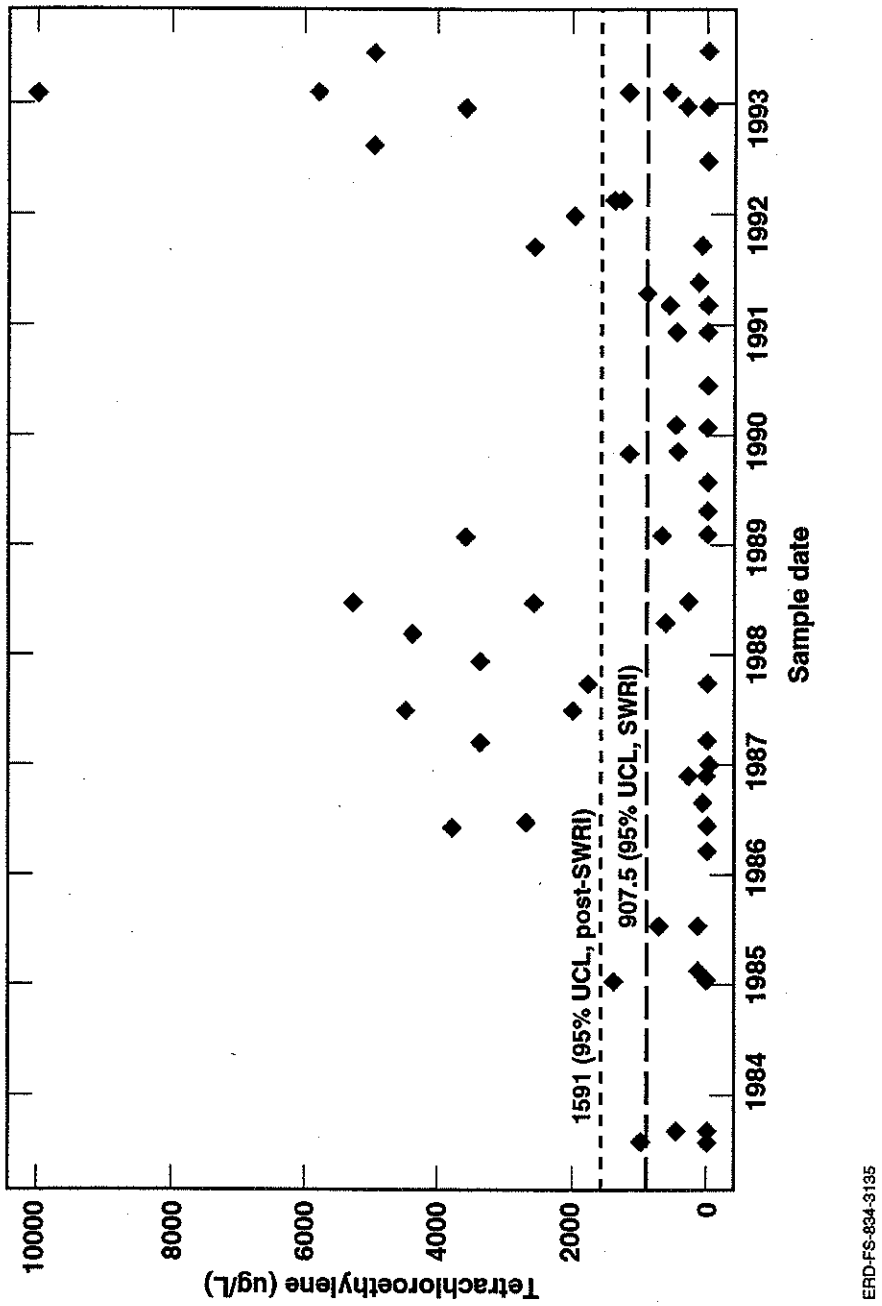

Figure B-3. Detections of tetrachloroethylene over time in ground water in a VOC-plume-specific set of wells in the Building 834 operable unit.

Table B-1. Substances detected in ground water in the Building 834 Complex after December 31, 1991, that are not considered to be chemicals of potential concern.

Chemical	Concentration (µg/L)	Well number	Sample date
1,2-Dichlorobenzene	8.0×10^2	W-834-C2	02-21-92
1,3-Dichlorobenzene	4.0×10^2	W-834-C2	02-21-92
1,4-Dichlorobenzene	9.0×10^2	W-834-C2	02-21-92
1,2-Dichloropropane	7.0×10^1	W-834-T4A	06-25-92
C10–C22 Hydrocarbons as diesel	1.2×10^3	W-834-D8	03-04-92
C10–C22 Hydrocarbons as diesel	3.0×10^3	W-834-D8	08-21-92
C10–C22 Hydrocarbons as diesel	1.0×10^2	W-834-S1	12-18-92
C10–C22 Hydrocarbons as diesel	1.0×10^2	W-834-D14	12-22-92
C10–C22 Hydrocarbons as diesel	2.3×10^4	W-834-D8	12-22-92
C10–C22 Hydrocarbons as diesel	1.3×10^2	W-834-D12	12-23-92
C10–C22 Hydrocarbons as diesel	7.3×10^1	W-834-J1	12-23-92
C10–C22 Hydrocarbons as diesel	1.9×10^4	W-834-D8	02-09-93

Table B-2. Designation of wells that characterize the principal region of ground water contamination in the perched zone of the Building 834 Complex.

W-834-B2	W-834-D12	W-834-S4
W-834-B3	W-834-D13	W-834-S8
W-834-C2	W-834-D14	W-834-S9
W-834-D3	W-834-H2	W-834-T2
W-834-D4	W-834-J1	W-834-T2D
W-834-D5	W-834-J2	W-834-T4
W-834-D6	W-834-K1	W-834-T4A
W-834-D7	W-834-S1	W-834-T4B
W-834-D8	W-834-S2A	W-834-T4C
W-834-D11	W-834-S3	W-834-T9

Table B-3. Summary statistics for contaminants of potential concern in ground water in the Building 834 Complex, SWRI data set.[a]

Contaminant	Frequency of detection	No. detections/ no. samples	Maximum concentration (μg/L)	Mean concentration (μg/L)[b]	95% UCL (μg/L)
1,1,1-Trichloroethane	5.2	16/307	3.3×10^4	3.02×10	1.87×10^4
1,1-Dichloroethylene	2.9	9/307	9.0×10^2	2.10×10	8.47×10^1
cis-1,2-Dichloroethylene	9.0	15/166	5.4×10^5	1.62×10^4	1.41×10^5
Acetone	7.7	1/13	5.5×10^1	NA[c]	5.5×10^1[c]
Benzene	4.2	1/24	1.4×10^1	NA[c]	1.4×10^1[c]
Chloroform	4.9	15/307	9.5×10^2	3.31×10^1	1.06×10^2
Ethylbenzene	16.7	4/24	2.1×10^1	4.59×10^0	1.27×10^1
Methylene chloride	2.9	9/307	5.1×10^3	2.02×10^2	2.50×10^2
Tetrachloroethylene	17.3	53/307	6.3×10^3	4.30×10^2	9.08×10^2
Toluene	25.0	6/24	6.2×10^1	2.13×10^1	5.65×10^1
Trichloroethylene	94.2	292/310	5.1×10^5	1.38×10^5	1.90×10^5
Trichlorotrifluoroethane	2.5	7/285	1.3×10^3	2.37×10^1	3.60×10^2
Xylenes (total isomers)	5.9	1/17	4.0×10^1	NA[c]	4.00×10^1[b]

[a] Data pertain to 30 wells that characterize the perched zone (Table B-2). Values include data collected through December 31, 1991.

[b] Estimate of the arithmetic mean of the underlying log-normal distribution.

[c] For certain contaminant data sets where there were relatively few detections of a substance (e.g., acetone, benzene, and xylenes), the calculated 95% UCL was greater than the maximum measured value. In those cases, no mean was calculated, and the maximum measured value is given instead of the 95% UCL.

Table B-4. Summary statistics for contaminants of potential concern in ground water in the Building 834 Complex, post-SWRI data set.[a]

Contaminant	Frequency of detection	No. detections/ no. samples	Maximum concentration (µg/L)	Mean concentration (µg/L)[b]	95% UCL (µg/L)
1,1,1-Trichloroethane	4.2	16/382	3.3×10^4	2.90×10^3	1.83×10^4
1,1-Dichloroethylene	2.6	10/382	9.0×10^2	1.59×10^1	5.95×10^1
cis-1,2-Dichloroethylene	12.9	31/241	5.4×10^5	1.99×10^4	9.33×10^4
Acetone	7.7	1/13	5.5×10^1	NA[c]	5.5×10^1[c]
Benzene	4.2	1/24	1.4×10^1	NA[c]	1.4×10^1[c]
Chloroform	4.2	16/382	9.5×10^2	4.05×10^1	1.35×10^2
Ethylbenzene	16.7	4/24	2.1×10^1	4.59×10^0	1.27×10^1
Methylene chloride	2.4	9/382	5.1×10^3	1.96×10^2	2.36×10^2
Tetrachloroethylene	17.3	66/382	1.0×10^4	7.43×10^2	1.59×10^3
Toluene	25.0	6/24	6.2×10^1	2.13×10^1	5.65×10^1
Trichloroethylene	95.0	365/385	8.0×10^5	1.37×10^5	1.82×10^5
Trichlorotrifluoroethane	2.0	7/360	1.3×10^3	1.88×10^1	2.85×10^2
Xylenes (total isomers)	5.9	1/17	4.0×10^1	NA[c]	4.0×10^1[c]

[a] Data pertain to 30 wells that characterize the perched zone (Table B-2). Values include data collected through August 3, 1993.

[b] Estimate of the arithmetic mean of the underlying log-normal distribution.

[c] For certain contaminant data sets where there were relatively few detections of a substance (e.g., acetone, benzene, xylenes), the calculated 95% UCL was greater than the maximum measured value. In those cases, no mean was calculated, and the maximum measured value is given instead of the 95% UCL. No analyses of ground water have been completed for acetone, benzene, ethylbenzene, or xylenes (total isomers) since the SWRI data cutoff of December 31, 1991.

Table B-5. Predicted 70-yr average concentrations of VOCs withdrawn from the off-site well CDF-1 that originate in the Building 834 Complex.

Chemical	Predicted concentration (μg/L)
1,1,1-Trichloroethane[a]	1.35×10^{-5}
1,1-Dichloroethylene[b]	4.43×10^{-8}
cis-1,2-Dichloroethylene[b]	6.90×10^{-5}
Acetone[b]	4.07×10^{-8}
Benzene[b]	1.04×10^{-8}
Chloroform[a]	9.89×10^{-8}
Ethylbenzene[b]	9.38×10^{-9}
Methylene chloride[a]	1.75×10^{-7}
Tetrachloroethylene[a]	1.18×10^{-6}
Toluene[a]	4.18×10^{-8}
Trichloroethylene[a]	1.35×10^{-4}
Trichlorotrifluoroethane[a]	2.11×10^{-7}
Xylenes (total isomers)[b]	2.96×10^{-8}

[a] These chemicals have been detected in both the perched zone and in the regional aquifer.

[b] These chemicals have been detected only in the perched zone.

Appendix C

Assessment of Incremental Cancer Risk and Noncancer Hazard Indices Associated with Potential Remediation of Soil at the Building 834 Complex

Appendix C

Assessment of Incremental Cancer Risk and Noncancer Hazard Indices Associated with Potential Remediation of Soil at the Building 834 Complex

In this appendix, we provide data and analyses of issues related to human health risks and hazards relevant to the Building 834 operable unit. We first present the results of calculations of potential exposure, risk, and hazard, that pertain to two buildings in the core area of the Building 834 Complex, which were not considered in the Baseline Public Health Assessment (Chapter 6 of the SWRI report [Webster-Scholten, 1994]). Following a discussion of these results, the data and methods used to calculate health-based concentrations (HBCs) and soil vapor restoration levels (SVRLs), presented in Chapter 2 of this document, are provided.

C-1. Background

The SWRI report identifies subsurface soil (0.5–12.0 ft) as the only contaminated environmental medium in the Building 834 operable unit associated with an unacceptable level of risk and/or hazard. The National Contingency Plan (40 CFR Part 300) states that excess cancer risks greater than 10^{-4} are unacceptable, while excess cancer risks less than or equal to 10^{-6} are generally acceptable; U.S. EPA (1989) indicates than a hazard index (HI) greater than 1.0 may be associated with noncarcinogenic adverse health effects. Calculations presented in the SWRI report indicated that individuals who may work either outdoors in the immediate vicinity of Building 834D or inside the building may be exposed to potentially hazardous concentrations of VOCs that volatilize from contaminated subsurface soil in the vicinity of the building.

Of the various buildings in the core of the Building 834 Complex that have a history of VOC use, site characterization data retained in the MONITOR database indicate that Building 834D appears to be located directly adjacent to (and possibly on top of) the region of maximum or near-maximum subsurface soil contamination in the operable unit. As described in the SWRI report, we evaluated potential adult on-site exposure to this contamination in two different ways: (1) by calculating the risk and hazard associated with inhalation of VOCs that volatilize from subsurface soil to the atmosphere in the immediate vicinity of Building 834D, and (2) by completing parallel calculations associated with inhalation of VOCs that volatilize from subsurface soil underneath the building, followed by diffusion into building air. The same set of contaminant concentration data (obtained from boreholes in the vicinity of the building) were used as the starting point for both sets of calculations. As noted above, both series of calculations (potential exposure either inside or outside of Building 834D) yielded estimates of risk and hazard that exceeded acceptable levels.

Our baseline estimates of risk and hazard for potential adult on-site exposure to VOCs present in subsurface soil near Building 834D did not consider two other nearby buildings that

are also in the vicinity of the maximum subsurface soil contamination. These buildings, designated Building 834O, and the Building 834D rain shed (hereafter referred to as the rain shed), were initially considered to be temporary structures that would not remain in use and/or existence for an extended period of time. Since completion of the draft SWRI, however, these two buildings have apparently become relatively permanent structures. As a consequence of the change in status, we also calculated the potential risk and hazard for an adult on-site who may work in either of these buildings on a regular basis over the course of a career at Site 300 (Chapter 6 of the SWRI report presents a description of the adult on-site exposure scenario).

In section C-4 of this appendix, we also examine the risk and hazard associated with potential residential exposure at the nearest site boundary to VOCs that volatilize from subsurface soil in the vicinity of Building 834D. We completed this evaluation in recognition of the possibility that residential development may take place in this region within the next five to ten years (City of Tracy, 1993).

C-2. Cancer Risk and Noncancer Hazard Associated with the Rain Shed

The rain shed is located directly adjacent to the east side of Building 834D. Building dimensions, determined by direct measurement, are as follows: length, 13.11 m; average height, 5.79 m; and width, 6.10 m (Lima, 1993). This metal building has a concrete floor (approximately 0.15 m thick), that is separated from the ground surface by an average distance of 0.488 m (Lima, 1993). The area between the ground surface and the floor of the building is not enclosed.

Due to the proximity of the rain shed to Building 834D, we used the same set of VOC concentration data to estimate exposure, risk, and hazard as we used in our original calculations for Building 834D (section 10-5 of the SWRI report). The model of Hwang et al. (1986), described in Appendix A-2.2 and section 10-5 of the SWRI report, served as the basis of our estimates of flux of VOCs from subsurface soil to the air underneath the rain shed. (These flux values are identical to those presented in section 10-5 of the SWRI report.)

A simple box model was used to translate the calculated flux values into estimates of VOC concentrations in the air space underneath the rain shed (Paustenbach et al., 1991). The concentration of a VOC in the airspace was calculated from the relation

$$C_{air} = \frac{N_S \times SA}{W \times \mu \times L} \qquad \text{(C-1)}$$

where

C_{air} = concentration of VOC in the airspace underneath the rain shed (mg/m^3);

N_S = the flux of VOC ($mg/cm^2 \cdot s$);

SA = surface area of contaminated soil directly underneath the rain shed, assumed to be equal to the surface area of the building floor, 7.89×10^5 cm^2;

W = width of the contaminated area perpendicular to the wind direction, 6.10 m;

μ = predominant wind speed at Site 300, 1.0 m/s (Sims et al., 1991);

L = estimated average height of the mixing zone, 0.488 m. (The value of L corresponds to the height of the rain shed floor above the ground surface.)

The calculated concentrations of VOCs in the airspace underneath the rain shed are given in Table C-1.

The flux of the VOCs through the concrete floor of the rain shed was calculated from the model of McKone (1992), previously presented in Appendix A-2.2 and section 10-5 of the SWRI report. (Note that the term C_{air} is substituted for the term $C_{s\text{-}gas}$ described in the SWRI report.) The flux of VOCs across a concrete building slab is converted to an exposure concentration based on the relation

$$C_{VOC} = \frac{N_c \times SA}{V_r} \tag{C-2}$$

where

C_{VOC} = concentration of VOC in air inside of the building (mg/m^3);

N_c = flux of VOC per unit area of concrete slab (mg/m^2 • s);

SA = surface area of the concrete slab of the rain shed, 79.89 m^2;

V_r = ventilation rate of the building (m^3/s).

In the absence of information on specific building air exchange rates, we assumed that one volume of air is replaced every hour (i.e., 3,600 s). The building volume is 462.67 m^3 (Lima, 1993). Values of N_c and C_{VOC} are given in Table C-2.

Tables C-3 and C-4 present the variables used to calculate incremental cancer risk and noncancer hazard associated with inhalation exposure inside the rain shed. The variables and the methodology used to select and/or derive them were presented in Chapter 6 of the SWRI report. As indicated in Tables C-3 and C-4, our calculations yielded an estimated cancer risk of 1×10^{-9} and an HI of 4.7×10^{-5}. Both of these values are considerably less than the values of risk (1×10^{-3} and 6×10^{-4}) and hazard (36×10^{1} and 22×10^{1}) originally calculated for potential exposure associated with Building 834D.

C-3. Cancer Risk and Noncancer Hazard Associated with Building 834O

Building 834O is a portable structure located approximately 100 ft to the west of Building 834D. Like many portable structures, it does not have a concrete slab foundation. Instead, the building sits some distance above the ground on piers. The region between the ground and the subfloor of the building has been enclosed with wood siding.

To calculate the magnitude of potential exposure to VOCs associated with long-term use of this building, we again used the same set of VOC concentration data as we used in our original calculations for Building 834D (section 10-5 of the SWRI report). We relied on the model of

Hwang et al. (1986) to estimate flux of VOCs from subsurface soil to the air under the building (chemical-specific flux values are presented in SWRI section 10-5).

Nazaroff and Doyle (1985) developed a model that characterizes the transport of radon (Rn) vapor from soil, through a vented crawl space, and into the living space of a single family home. According to their model, the indoor air concentration of Rn at steady state can be calculated as

$$I = \frac{\sigma}{\lambda v} + I_o \qquad \text{(C-3)}$$

where

I = indoor air concentration of Rn,

σ = rate of Rn entry into the residence per unit volume,

λv = air exchange volume in the residence per unit time,

I_o = outdoor air concentration of Rn.

If we assume that this relationship can be extrapolated directly to VOCs, and revise the nomenclature to correspond to that used in the SWRI, Equation C-3 becomes

$$C_{VOC} = \frac{\sigma}{\lambda v} + C_a \qquad \text{(C-4)}$$

where

C_{VOC} = indoor air concentration of a VOC (mg/m^3),

σ = rate of entry of a VOC into the building per unit volume ($mg/m^3 \bullet s$),

λv = air exchange volume in the building per unit time, assumed to be equal to one volume of air per hour (i.e., 3,600 s),

C_a = annual-average ground-level concentration of VOC outdoors (mg/m^3).

The term σ is calculated from the relation

$$\sigma = f \times \frac{N_s}{\frac{V}{SA}} \qquad \text{(C-5)}$$

where

f = fraction of soil flux transmitted to indoor air (dimensionless),

N_S = calculated flux of VOC from subsurface soil to crawl space air ($mg/m^2 \bullet s$),

V = building volume (72.77 m^3),

SA = surface area of the building floor (25.81 m^2).

Building parameters were obtained by direct measurement (Lima, 1993). For our calculations, we selected a value of 0.65 for f. That value is close to the maximum value measured in SF_6 tracer gas experiments reported by Nazaroff and Doyle (1985). C_a was calculated from the model of Turner (1982) (Appendix A-2.2 of the SWRI) with a mixing height of 500 m. Table C-5 shows the calculated values of N_s, σ, C_a, and C_{VOC}.

Tables C-6 and C-7 present the variables used to calculate incremental cancer risk and noncancer hazard associated with inhalation exposure inside Building 834O. These variables and the methodology used to select and/or derive them were presented in Chapter 6 of the SWRI. As indicated in Tables C-6 and C-7, our calculations yielded an estimated cancer risk of 2×10^{-3} and an HI of 6.2×10^{1}. Both of these values are somewhat greater than the values of risk (1×10^{-3} and 6×10^{-4}) and hazard (36×10^{1} and 22×10^{1}) originally calculated for Building 834D.

C-4. Cancer Risk and Noncancer Hazard Associated with Potential Residential Exposure to VOCs in Air

The nearest site boundary is approximately 1,200 ft (0.37 km) from the core of the Building 834 Complex (where Building 834D is located), along an axis that follows the prevailing winds to the north-northeast.

To calculate the magnitude of potential exposure to a resident who may occupy a home directly adjacent to the site boundary, we calculated the flux of VOCs from subsurface soil to air in the vicinity of Building 834D. These calculations were made using the VOC concentration data obtained from boreholes in the vicinity of this building and the contaminant flux model of Hwang et al. (1986). The VOC concentration data and calculated flux values were presented in section 10-5 of the SWRI report.

A gaussian air dispersion model for a continuous source was used to calculate the concentration of VOCs at the nearest site boundary (in the direction of the prevailing winds). At steady-state, the general form of the model is

$$C_a(x,y,z) = \frac{Q_s}{2\pi\sigma_y(x)\sigma_z(x)\mu} e^{\frac{-y^2}{2\sigma y^2}} x \left(e^{\frac{-(z-h)^2}{2\sigma z^2}} + e^{\frac{-(z+h)^2}{2\sigma z^2}} \right) \qquad \text{(C-6)}$$

where

C_a = calculated concentration of VOC at the site boundary (mg/m^3),

Q_s = emission rate of VOC from soil (g/s) (presented in section 10-5 of the SWRI report),

h = height of the plume rise above the ground surface (m),

μ = wind speed,

x, y, and z = directional cartesian coordinates.

Specifically, the origin of the plume is considered to be at ground level, with the x-axis of the plume extending horizontally in the direction of the wind; the y-axis is in the horizontal plane perpendicular to the x-axis, and the z-axis extends vertically.

Tables C-8 and C-9 present the modeled VOC concentrations at the site boundary, and the variables used to calculate incremental cancer risk and noncancer hazard associated with inhalation exposure of residents to VOCs that volatilize from subsurface soil near Building 834D. The variables given in these tables, and the methodology used to select and/or derive them, are presented in Chapter 6 of the SWRI report. As indicated in these tables, our calculations yielded an estimate of risk of 1×10^{-6} and an HI of 3.1×10^{-2}. These values of risk and hazard are less than those calculated for adult on-site exposure outdoors in the vicinity of Building 834D (6×10^{-4} and 2.2×10^{1}, respectively), and reflect lower concentrations of VOCs at the site boundary (relative to those estimated near the building) as a consequence of atmospheric dilution and dispersion.

C-5. Calculation of Health-Based Concentrations for Subsurface Soil

This section describes the methodology we used to calculate HBCs for contaminants in subsurface soil. These methods are applied to each of the three exposure scenarios associated with unacceptable levels of risk and hazard, and yield a range of HBCs for each contaminant.

To calculate HBCs for contaminants present in subsurface soil in the Building 834 operable unit, we began by identifying two target risk levels, 1.0×10^{-4} and 1.0×10^{-6}, based on the range of acceptable risk (40 CFR Part 300). For each carcinogen present in subsurface soil in the vicinity of Building 834D, the fractional contribution to total risk for the baseline case was calculated as

$$R_{T(F)} = \frac{R_t}{R_T} \tag{C-7}$$

where

R_t = chemical-specific risk for a particular exposure location and exposure scenario (e.g., adult on-site exposure inside of Building 834D),

R_T = total risk attributable to all chemicals present at that exposure location,

$R_{T(F)}$ = fractional contribution to total risk for a specific chemical for the baseline case.

We multiplied the values of $R_{T(F)}$ by each of the target risk levels (e.g., 1.0×10^{-4} and 1.0×10^{-6}), in turn, to obtain the estimated allowable chemical-specific contribution to risk for HBCs of contaminants in soil, $R_{t(HBC)}$.

We also identified a target HI of 1.0 based on U.S. EPA (1989). For each substance with noncarcinogenic effects present in subsurface soil near Building 834D, the fractional contribution to the HI for the baseline case was calculated as

$$HI_{(F)} = \frac{HQ}{HI} \tag{C-8}$$

where

HQ = hazard quotient for a chemical for a particular exposure location and exposure scenario (e.g., adult on-site exposure inside of Building 834D),

HI = hazard index, the sum of the hazard quotients attributable to all chemicals present at that exposure location,

$HI_{(F)}$ = fractional contribution to the hazard index for a specific chemical for the baseline case.

We multiplied the values of $HI_{(F)}$ by the target HI of 1.0 to obtain the estimated allowable chemical-specific contribution to hazard for HBCs of contaminants in soil, $HQ_{(HBC)}$. Table C-10 lists the chemical-specific values of risk and hazard for potential exposure inside of Building 834D (baseline case), as well as the values of $R_{T(F)}$ and $HI_{(F)}$. Table C-11 gives the estimated allowable chemical-specific values of risk and hazard associated with HBCs of contaminants in subsurface soil based on exposure inside of Building 834D.

To develop estimated allowable values of risk and hazard based on adult on-site exposure outside Building 834D, we completed a set of calculations analogous to those just described for exposure inside of Building 834D. Tables C-12 and C-13 list the chemical-specific values of risk and hazard, and $RT_{(F)}$ and $HI_{(F)}$ for the baseline case, as well as the estimated allowable chemical-specific values of risk and hazard for HBCs, respectively, for exposure outside of Building 834D. A similar process was completed for Building 834O based on exposure inside the building. The data are presented in Tables C-14 and C-15.

For each value of $R_{t(HBC)}$ and $HQ_{(HBC)}$, we then completed a series of calculations, working backwards through the set of models used to calculate the baseline estimates of risk and hazard, to obtain concentrations of contaminants in subsurface soil that represent HBCs. For example, to calculate an HBC for TCE in soil based on exposure inside Building 834D, we began with the estimated allowable chemical-specific value of risk $R_{t(HBC)}$ for one of the two target risk levels (1.0×10^{-4} or 1.0×10^{-6}). We rearranged, then solved, Equation 6-5 in SWRI to obtain C_{VOC}. The value C_{VOC} was used to solve for N_c after rearranging Equation 10-8 in SWRI. Similarly, N_S, applied to Equation 10-7 in SWRI gave the value $C_{s\text{-}gas}$, which is the last variable needed to solve for C_s (Equation 10-6 in SWRI), the HBC. A similar set of calculations was completed for all chemicals, for each of the target risk levels, as well as for the target HI of 1.0. The parameters we calculated for each target level of risk and/or hazard, including values of C_s (the HBCs), are presented in Tables C-16 through C-24.

We then used the HBCs associated with a target HI of 1.0 and potential exposure outside Building 834D, given in Table C-24, to calculate the magnitude of potential exposure to VOCs associated with long-term use of Buildings 834D and 834O. We applied Equations 10-6, 10-7,

and 10-8 (from the SWRI report) to estimate the concentration of each VOC (C_{VOC}) present in air inside Building 834D when the soil concentration, C_s (mg/kg), is equal to the HBC. In addition, we solved for C_{VOC} in Building 834O using the model presented in section C-3 of this appendix (Eqs. C-3, C-4, and C-5). The HBCs, C_s (mg/kg), and related parameters for Buildings 834D and 834O are presented in Tables C-25 and C-26, respectively.

Tables C-27 and C-28 present the incremental cancer risk and noncancer hazard associated with inhalation exposure inside Buildings 834D and 834O when the VOC concentrations in soil equal the HBCs. The variables used to estimate the cancer risk and hazard values are presented in Tables C-6 and C-7. The methodology used to select and/or derive these values were presented in Chapter 6 of the SWRI report. As indicated in Table C-27, our calculations for inhalation exposure inside Building 834D yielded an estimated cancer risk of 5×10^{-5} and an HI of 1.7. As presented in Table C-28, our calculations for inhalation exposure inside Building 834O yielded an estimated cancer risk of 8×10^{-5} and an HI of 2.9.

C-6. Calculation of Soil Vapor Restoration Levels

The HBCs of TCE in soil associated with a target HI of 1.0 and potential exposure outside and inside Building 834D were used to derive the SVRLs. The methodologies used to select the HBCs and SVRLs are discussed in Chapter 2; the HBCs, given as C_s (mg/kg) and corresponding SVRLs are presented in Table C-29.

The SVRLs were derived using Equation 10-6 in SWRI (Webster-Scholten, 1994). Applying this equation, the HBCs for TCE (C_s [mg/kg]) were used to solve for $C_{s\text{-}gas}$ (mg/m^3), the soil gas concentration of TCE at the soil surface underneath Building 834D. The parameters used in Equation 10-6 are presented in Table C-30.

$C_{s\text{-}gas}$ was then converted from soil gas concentrations in mass per volume (mg/m^3) to concentrations in parts per million volume per volume ($ppm_{v/v}$). The following method description is taken from Verschueren (1983).

The physical state of gaseous air pollutants at atmospheric concentrations may be described generally by the ideal gas law:

$$pv = nRT \tag{C-9}$$

where

p = absolute pressure of gas,

v = volume of gas,

n = number of moles of gas,

T = absolute temperature (degrees K),

R = universal gas constant.

The number of moles (n) may be calculated from the weight of pollutant (W) and its molecular weight (m) by:

$$n = \frac{W}{m} \tag{C-10}$$

Substituting Equation (C-10) into Equation (C-9) and rearranging yields:

$$v = \frac{WRT}{pm} \tag{C-11}$$

Parts per million refers to the volume of pollutant (v) per million volumes of air (V):

$$ppm_{v/v} = \frac{W}{V}\frac{RT}{pm10^6} \tag{C-12}$$

Using Equation C-12 and the following values, we convert soil gas concentrations from mg/m^3 to $ppm_{v/v}$.

T = 298°K (25°C),

p = 1 atm,

m = 131.4 g/mol (molecular weight of TCE),

R = 8.206×10^{-5} atm•m^3/mol–°K,

V = 1 m^3,

$C_{s\text{-}gas}$ = 1.348×10^3, and 8.15×10^2 mg/m^3.

The SVRLs, derived from these equations, correspond to the HBCs of TCE in soil of 2.2 and 1.3 mg/kg and are presented in Table C-29.

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Table C-1. Calculated rates of flux from subsurface soil (N_s) and estimated concentrations of VOCs (C_{air}) in the air space underneath the Building 834D rain shed.

Chemical	N_s (mg/cm^2•s)	C_{air} (mg/m^3)
Benzene	1.19×10^{-12}	3.20×10^{-7}
Ethylbenzene	1.84×10^{-12}	4.94×10^{-7}
Tetrachloroethylene	7.89×10^{-9}	2.12×10^{-3}
Toluene	5.09×10^{-12}	1.37×10^{-6}
Trichloroethylene	2.73×10^{-7}	7.33×10^{-2}
Trichlorofluoromethane	1.87×10^{-9}	5.02×10^{-4}
Xylenes (total isomers)	4.17×10^{-11}	1.12×10^{-5}

Table C-2. Calculated rates of flux across the floor (N_c) and estimated concentrations of VOCs (C_{VOC}) in the air inside the Building 834D rain shed.

Chemical	N_c (mg/m^2•s)	C_{VOC} (mg/m^3)
Benzene	1.30×10^{-14}	8.11×10^{-12}
Ethylbenzene	1.63×10^{-14}	1.01×10^{-11}
Tetrachloroethylene	7.39×10^{-11}	4.59×10^{-8}
Toluene	5.09×10^{-14}	3.16×10^{-11}
Trichloroethylene	2.81×10^{-9}	1.74×10^{-6}
Trichlorofluoromethane	1.10×10^{-11}	6.82×10^{-9}
Xylenes (total isomers)	3.37×10^{-13}	2.10×10^{-10}

Table C-3. Variables used to calculate excess lifetime cancer risk associated with inhalation exposure to VOCs inside the Building 834D rain shed.

Chemical	C_{VOC} (mg/m^3)	PEF (m^3/kg•d)[a]	Dose (mg/kg•d)[b]	Cancer potency factor (mg/kg•d)$^{-1}$[c]	Excess lifetime cancer risk
Benzene	8.11×10^{-12}	6.99×10^{-2}	5.67×10^{-13}	1.00×10^{-1}[d]	5.67×10^{-14}
Ethylbenzene	1.01×10^{-11}	1.96×10^{-1}	1.98×10^{-12}	Not carcinogenic	NA
Tetrachloroethylene	4.59×10^{-8}	6.99×10^{-2}	3.21×10^{-9}	5.10×10^{-2}[d]	1.64×10^{-10}
Toluene	3.16×10^{-11}	1.96×10^{-1}	6.19×10^{-12}	Not carcinogenic	NA
Trichloroethylene	1.74×10^{-6}	6.99×10^{-2}	1.22×10^{-7}	1.00×10^{-2}[d]	1.22×10^{-9}
Trichlorofluoromethane	6.82×10^{-9}	1.96×10^{-1}	1.34×10^{-9}	Not carcinogenic	NA
Xylenes (total isomers)	2.10×10^{-10}	1.96×10^{-1}	4.12×10^{-11}	Not carcinogenic	NA
					Σ Risk = 1×10^{-9}

[a] PEF is the pathway exposure factor and is derived in Chapter 6 of the SWRI.

[b] Calculated as the product of C_{VOC} and PEF.

[c] Cancer potency factor is the increased tumorigenic response per dose rate.

[d] California Environmental Protection Agency (1992).

NA = not applicable.

Table C-4. Variables used to calculate noncancer hazard associated with inhalation exposure to VOCs inside the Building 834D rain shed.

Chemical	C_{VOC} (mg/m^3)	PEF (m^3/kg•d)[a]	Dose (mg/kg•d)[b]	RfD (mg/kg•d)[c]	Hazard quotient (Dose/RfD)
Benzene	8.11×10^{-12}	1.96×10^{-1}	1.59×10^{-12}	Not available	Not available
Ethylbenzene	1.01×10^{-11}	1.96×10^{-1}	1.98×10^{-12}	1.00×10^{-1}[d]	1.98×10^{-11}
Tetrachloroethylene	4.59×10^{-8}	1.96×10^{-1}	9.00×10^{-9}	1.00×10^{-2}[d]	9.00×10^{-7}
Toluene	3.16×10^{-11}	1.96×10^{-1}	6.19×10^{-12}	2.00×10^{-1}[d]	3.10×10^{-11}
Trichloroethylene	1.74×10^{-6}	1.96×10^{-1}	3.41×10^{-7}	7.35×10^{-3}[e]	4.64×10^{-5}
Trichlorofluoromethane	6.82×10^{-9}	1.96×10^{-1}	1.34×10^{-9}	2.00×10^{-1}[f]	6.68×10^{-9}
Xylenes (total isomers)	2.10×10^{-10}	1.96×10^{-1}	4.12×10^{-11}	2.00×10^{0}[d]	2.06×10^{-11}
					HI = 4.7×10^{-5}

[a] PEF is the pathway exposure factor and is derived in Chapter 6 of the SWRI.

[b] Calculated as the product of C_{VOC} and PEF.

[c] RfD is the reference dose, and is generally calculated as the ratio of the experimentally-determined no-observed-adverse-effect-level to an uncertainty factor (typically 10 to 1,000) (Chapter 6 of the SWRI).

[d] IRIS (U.S. EPA, 1992a).

[e] California Environmental Protection Agency (1992).

[f] HEAST (U.S. EPA 1992b, 1993).

Table C-5. Calculated parameters used to estimate the concentration of VOCs in air inside Building 834O.

Chemical	N_s (mg/m^2•s)	σ (mg/m^3•s)	C_a (mg/m^3)	C_{VOC} (mg/m^3)
Benzene	1.19×10^{-8}	2.74×10^{-9}	1.18×10^{-8}	9.88×10^{-6}
Ethylbenzene	1.84×10^{-8}	4.24×10^{-9}	1.83×10^{-8}	1.53×10^{-5}
Tetrachloroethylene	7.89×10^{-5}	1.82×10^{-5}	7.84×10^{-5}	6.55×10^{-2}
Toluene	5.09×10^{-8}	1.17×10^{-8}	5.06×10^{-8}	4.22×10^{-5}
Trichloroethylene	2.73×10^{-3}	6.29×10^{-4}	2.71×10^{-3}	2.27×10^{0}
Trichlorofluoromethane	1.87×10^{-5}	4.31×10^{-6}	1.86×10^{-5}	1.55×10^{-2}
Xylenes (total isomers)	4.17×10^{-7}	9.61×10^{-8}	4.15×10^{-7}	3.46×10^{-4}

Table C-6. Variables used to calculate excess lifetime cancer risk associated with inhalation exposure to VOCs inside Building 834O.

Chemical	C_{VOC} (mg/m^3)	PEF ($m^3/kg \bullet d$)[a]	Dose ($mg/kg \bullet d$)[b]	Cancer potency factor $(mg/kg \bullet d)^{-1}$[c]	Excess lifetime cancer risk
Benzene	9.88×10^{-6}	6.99×10^{-2}	6.91×10^{-7}	1.00×10^{-1}[d]	6.91×10^{-8}
Ethylbenzene	1.53×10^{-5}	1.96×10^{-1}	3.00×10^{-6}	Not carcinogenic	NA
Tetrachloroethylene	6.55×10^{-2}	6.99×10^{-2}	4.58×10^{-3}	5.10×10^{-2}[d]	2.34×10^{-4}
Toluene	4.22×10^{-5}	1.96×10^{-1}	8.27×10^{-6}	Not carcinogenic	NA
Trichloroethylene	2.27×10^{0}	6.99×10^{-2}	1.59×10^{-1}	1.00×10^{-2}[d]	1.59×10^{-3}
Trichlorofluoromethane	1.55×10^{-2}	1.96×10^{-1}	3.04×10^{-3}	Not carcinogenic	NA
Xylenes (total isomers)	3.46×10^{-4}	1.96×10^{-1}	6.78×10^{-5}	Not carcinogenic	NA
					Σ Risk = 2×10^{-3}

[a] PEF is the pathway exposure factor and is derived in Chapter 6 of the SWRI.

[b] Calculated as the product of C_{VOC} and PEF.

[c] The cancer potency factor is the increased tumorigenic response per dose rate.

[d] California Environmental Protection Agency (1992).

NA = not applicable.

Table C-7. Variables used to calculate noncancer hazard associated with inhalation exposure to VOCs inside Building 834O.

Chemical	C_{VOC} (mg/m^3)	PEF (m^3/kg•d)[a]	Dose (mg/kg•d)[b]	RfD (mg/kg•d)[c]	Hazard quotient (Dose/RfD)
Benzene	9.88×10^{-6}	1.96×10^{-1}	1.94×10^{-6}	Not available	Not available
Ethylbenzene	1.53×10^{-5}	1.96×10^{-1}	3.00×10^{-6}	1.00×10^{-1}[d]	3.00×10^{-5}
Tetrachloroethylene	6.55×10^{-2}	1.96×10^{-1}	1.28×10^{-2}	1.00×10^{-2}[d]	1.28×10^{0}
Toluene	4.22×10^{-5}	1.96×10^{-1}	8.27×10^{-6}	2.00×10^{-1}[d]	4.14×10^{-5}
Trichloroethylene	2.27×10^{0}	1.96×10^{-1}	4.45×10^{-1}	7.35×10^{-3}[e]	6.05×10^{1}
Trichlorofluoromethane	1.55×10^{-2}	1.96×10^{-1}	3.04×10^{-3}	2.00×10^{-1}[f]	1.52×10^{-2}
Xylenes (total isomers)	3.46×10^{-4}	1.96×10^{-1}	6.78×10^{-5}	2.00×10^{0}[d]	3.39×10^{-5}
					HI = 6.2×10^{1}

[a] PEF is the pathway exposure factor and is derived in Chapter 6 of the SWRI.

[b] Calculated as the product of C_{VOC} and PEF.

[c] RfD is the reference dose, and is generally calculated as the ratio of the experimentally-determined no-observed-adverse-effect-level to an uncertainty factor (typically 10 to 1,000) (Chapter 6 of the SWRI).

[d] IRIS (U.S. EPA, 1992a).

[e] California Environmental Protection Agency (1992).

[f] HEAST (U.S. EPA 1992b, 1993).

Table C-8. Variables used to calculate excess lifetime cancer risk associated with residential exposure to VOCs at the Building 834 operable unit site boundary.

Chemical	Ca (mg/m^3)	PEF[a] (m^3/kg•d)[a]	Dose[b] (mg/kg•d)[b]	Cancer potency factor[c] (mg/kg•d)$^{-1}$	Excess lifetime cancer risk
Benzene	3.6×10^{-9}	1.17×10^{-1}	4.21×10^{-10}	1.00×10^{-1}[d]	4.2×10^{-11}
Ethylbenzene	5.5×10^{-9}	2.74×10^{-1}	1.08×10^{-9}	Not carcinogenic	NA
Tetrachloroethylene	2.4×10^{-5}	1.17×10^{-1}	2.81×10^{-6}	5.10×10^{-2}[d]	1.43×10^{-7}
Toluene	1.5×10^{-8}	2.74×10^{-1}	2.94×10^{-9}	Not carcinogenic	NA
Trichloroethylene	8.2×10^{-4}	1.17×10^{-1}	9.59×10^{-5}	1.00×10^{-2}[d]	9.59×10^{-7}
Trichlorofluoromethane	5.6×10^{-6}	2.74×10^{-1}	1.10×10^{-6}	Not carcinogenic	NA
Xylenes (total isomers)	1.3×10^{-7}	2.74×10^{-1}	2.55×10^{-8}	Not carcinogenic	NA
					Σ Risk = 1×10^{-6}

[a] PEF is the pathway exposure factor and is derived in Chapter 6 of the SWRI report.

[b] Calculated as the product of C_a and PEF.

[c] Cancer potency factor is the increased tumorigenic response per dose rate.

[d] California Environmental Protection Agency (1992).

NA = not applicable.

Table C-9. Variables used to calculate noncancer hazard associated with residential exposure to VOCs at the Building 834 operable unit site boundary.

Chemical	Ca (mg/m^3)	PEF[a] ($m^3/kg \cdot d$)	Dose[b] ($mg/kg \cdot d$)	RfD[c] ($mg/kg \cdot d$)	Hazard quotient (Dose/RfD)
Benzene	3.6×10^{-9}	2.74×10^{-1}	9.86×10^{-10}	Not available	Not available
Ethylbenzene	5.5×10^{-9}	2.74×10^{-1}	1.51×10^{-9}	1.00×10^{-1}[d]	1.51×10^{-8}
Tetrachloroethylene	2.4×10^{-5}	2.74×10^{-1}	6.58×10^{-6}	1.00×10^{-2}[d]	6.58×10^{-4}
Toluene	1.5×10^{-8}	2.74×10^{-1}	4.11×10^{-9}	2.00×10^{-1}[d]	2.06×10^{-8}
Trichloroethylene	8.2×10^{-4}	2.74×10^{-1}	2.25×10^{-4}	7.35×10^{-3}[e]	3.06×10^{-2}
Trichlorofluoromethane	5.6×10^{-6}	2.74×10^{-1}	1.53×10^{-6}	2.00×10^{-1}[f]	7.67×10^{-6}
Xylenes (total isomers)	1.3×10^{-7}	2.74×10^{-1}	3.56×10^{-8}	2.00×10^{0}[d]	1.78×10^{-8}
					HI = 3.1×10^{-2}

[a] PEF is the pathway exposure factor and is derived in Chapter 6 of the SWRI report.

[b] Calculated as the product of C_a and PEF.

[c] RfD is the reference dose and is generally calculated as the ratio of the experimentally determined no-observed-adverse-effect level to an uncertainty factor (typically 10 to 1,000), as described in Chapter 6 of Webster-Scholten (1993).

[d] IRIS (U.S. EPA, 1992a).

[e] California Environmental Protection Agency (1992).

[f] HEAST (U.S. EPA, 1992b and 1993).

Table C-10. Calculated values of risk and hazard for potential adult on-site exposure inside Building 834D for the baseline case (Webster-Scholten, 1994).

Chemical	Baseline chemical-specific risk (R_t)	Chemical-specific fraction, baseline total risk ($RT_{(F)}$)	Baseline hazard quotient (HQ)[a]	Chemical-specific fraction, baseline hazard index ($HI_{(F)}$)
Benzene	4.14×10^{-8}	3.94×10^{-5}	Not available	Not available
Ethylbenzene	Not carcinogenic	NA	1.10×10^{-5}	3.06×10^{-7}
Tetrachloroethylene (PCE)	1.30×10^{-4}	1.24×10^{-1}	7.14×10^{-1}	1.99×10^{-2}
Toluene	Not carcinogenic	NA	1.99×10^{-5}	5.54×10^{-7}
Trichloroethylene (TCE)	9.23×10^{-4}	8.79×10^{-1}	3.52×10^{1}	9.81×10^{-1}
Trichlorofluoromethane	Not carcinogenic	NA	1.15×10^{-2}	3.20×10^{-4}
Xylenes (total isomers)	Not carcinogenic	NA	1.20×10^{-5}	3.34×10^{-7}
	$R_T = 1 \times 10^{-3}$		HI = 35.9	

[a] Originally presented in Chapter 6 of the SWRI report.

NA = not applicable.

Table C-11. Estimated allowable chemical-specific values of risk and hazard for health-based concentrations (HBCs) of contaminants in subsurface soil near Building 834D. Values are based on potential adult on-site exposure inside Building 834D.

Chemical	$R_{t(HBC)}$ (target risk = 1.0×10^{-4})	$R_{t(HBC)}$ (target risk = 1.0×10^{-6})	Hazard quotient (HBC) (target HI = 1.0)
Benzene	3.94×10^{-9}	3.94×10^{-11}	Not available
Ethylbenzene	Not carcinogenic	Not carcinogenic	3.06×10^{-7}
Tetrachloroethylene (PCE)	1.24×10^{-5}	1.24×10^{-7}	1.99×10^{-2}
Toluene	Not carcinogenic	Not carcinogenic	5.54×10^{-7}
Trichloroethylene (TCE)	8.79×10^{-5}	8.79×10^{-7}	9.81×10^{-1}
Trichlorofluoromethane	Not carcinogenic	Not carcinogenic	3.20×10^{-4}
Xylenes (total isomers)	Not carcinogenic	Not carcinogenic	3.34×10^{-7}

Table C-12. Calculated values of risk and hazard for potential adult on-site exposure outside of Building 834D.

Chemical	Baseline chemical-specific risk (R_t)[a]	Chemical-specific fraction, baseline total risk ($RT_{(F)}$)	Baseline hazard quotient (HQ)[a]	Chemical-specific fraction, baseline hazard index ($HI_{(F)}$)
Benzene	2.42×10^{-8}	3.78×10^{-5}	Not available	Not available
Ethylbenzene	Not carcinogenic	NA	1.05×10^{-5}	4.77×10^{-7}
Tetrachloroethylene (PCE)	8.17×10^{-5}	1.28×10^{-1}	4.49×10^{-1}	2.04×10^{-2}
Toluene	Not carcinogenic	NA	1.46×10^{-5}	6.64×10^{-7}
Trichloroethylene (TCE)	5.58×10^{-4}	8.72×10^{-1}	2.13×10^{1}	9.68×10^{-1}
Trichlorofluoromethane	Not carcinogenic	NA	5.36×10^{-3}	2.44×10^{-4}
Xylenes (total isomers)	Not carcinogenic	NA	1.19×10^{-5}	5.41×10^{-7}
	$R_T = 6.4 \times 10^{-4}$		HI = 22	

[a] Originally presented in Chapter 6 of the SWRI report.

NA = not applicable.

Table C-13. Estimated allowable chemical-specific values of risk and hazard for HBCs of contaminants in subsurface soil near Building 834D. Values are based on potential adult on site exposure inside Building 834D.

Chemical	$R_{t(HBC)}$ (target risk = 1.0×10^{-4})	$R_{t(HBC)}$ (target risk = 1.0×10^{-6})	Hazard quotient (HBC) (target HI = 1.0)
Benzene	3.78×10^{-9}	3.78×10^{-11}	Not available
Ethylbenzene	Not carcinogenic	Not carcinogenic	4.77×10^{-7}
Tetrachloroethylene (PCE)	1.28×10^{-5}	1.28×10^{-7}	2.04×10^{-2}
Toluene	Not carcinogenic	Not carcinogenic	6.64×10^{-7}
Trichloroethylene (TCE)	8.72×10^{-5}	8.72×10^{-7}	9.68×10^{-1}
Trichlorofluoromethane	Not carcinogenic	Not carcinogenic	2.44×10^{-4}
Xylenes (total isomers)	Not carcinogenic	Not carcinogenic	5.41×10^{-7}

Table C-14. Calculated values of risk and hazard for potential adult on-site exposure inside Building 834O (section C-3 of this appendix).

Chemical	Baseline chemical-specific risk (R_t)	Chemical-specific fraction, baseline total risk ($RT_{(F)}$)	Baseline hazard quotient (HQ)	Chemical-specific fraction, baseline hazard index ($HI_{(F)}$)
Benzene	6.91×10^{-8}	3.80×10^{-5}	Not available	Not available
Ethylbenzene	Not carcinogenic	NA	3.00×10^{-5}	4.85×10^{-7}
Tetrachloroethylene (PCE)	2.34×10^{-4}	1.29×10^{-1}	1.28×10^{0}	2.08×10^{-2}
Toluene	Not carcinogenic	NA	4.14×10^{-5}	6.69×10^{-7}
Trichloroethylene (TCE)	1.59×10^{-3}	8.74×10^{-1}	6.05×10^{1}	9.79×10^{-1}
Trichlorofluoromethane	Not carcinogenic	NA	1.52×10^{-2}	2.46×10^{-4}
Xylenes (total isomers)	Not carcinogenic	NA	3.39×10^{-5}	5.48×10^{-7}
	$R_T = 2 \times 10^{-3}$		HI = 61.8	

NA = not applicable.

Table C-15. Estimated allowable chemical-specific values of risk and hazard for HBCs of contaminants in subsurface soil near Building 834O. Values are based on potential adult on site exposure inside Building 834O.

Chemical	$R_{t(HBC)}$ (target risk = 1.0×10^{-4})	$R_{t(HBC)}$ (target risk = 1.0×10^{-6})	Hazard quotient (HBC) (target HI = 1.0)
Benzene	3.8×10^{-9}	3.8×10^{-11}	Not available
Ethylbenzene	Not carcinogenic	Not carcinogenic	4.85×10^{-7}
Tetrachloroethylene (PCE)	1.29×10^{-5}	1.29×10^{-7}	2.08×10^{-2}
Toluene	Not carcinogenic	Not carcinogenic	6.69×10^{-7}
Trichloroethylene (TCE)	8.74×10^{-5}	8.74×10^{-7}	9.79×10^{-1}
Trichlorofluoromethane	Not carcinogenic	Not carcinogenic	2.46×10^{-4}
Xylenes (total isomers)	Not carcinogenic	Not carcinogenic	5.48×10^{-7}

Table C-16. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target risk of 1×10^{-4} and potential exposure inside Building 834D.

Chemical	C_{VOC} (mg/m^3)[a]	N_c (mg/m^2•s)[b]	$C_{s\text{-}gas}$ (mg/m^3)[c]	C_s (mg/kg)[d]
Benzene	5.64×10^{-7}	4.78×10^{-10}	1.17×10^{-2}	1.91×10^{-5}
Ethylbenzene	Not carcinogenic	NA	NA	NA
Tetrachloroethylene (PCE)	3.47×10^{-3}	2.94×10^{-6}	8.43×10^{1}	1.37×10^{-1}
Toluene	Not carcinogenic	NA	NA	NA
Trichloroethylene (TCE)	1.26×10^{-1}	1.07×10^{-4}	2.79×10^{3}	4.56×10^{0}
Trichlorofluoromethane	Not carcinogenic	NA	NA	NA
Xylenes (total isomers)	Not carcinogenic	NA	NA	NA

[a] C_{VOC} (mg/m^3) is the calculated concentration of VOC in building air.

[b] N_c (mg/m^2•s) is the calculated flux of VOC per unit area of concrete slab.

[c] $C_{s\text{-}gas}$ (mg/m^3) is the calculated soil gas concentration of VOC at the soil surface underneath the building.

[d] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

NA = not applicable.

Table C-17. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target risk of 1×10^{-6} and potential exposure inside Building 834D.

Chemical	C_{VOC} (mg/m^3)[a]	N_c (mg/m^2•s)[b]	$C_{s\text{-}gas}$ (mg/m^3)[c]	C_s (mg/kg)[d]
Benzene	5.64×10^{-9}	4.78×10^{-12}	1.17×10^{-4}	1.91×10^{-7}
Ethylbenzene	Not carcinogenic	NA	NA	NA
Tetrachloroethylene	3.47×10^{-5}	2.94×10^{-8}	8.43×10^{-1}	1.37×10^{-3}
Toluene	Not carcinogenic	NA	NA	NA
Trichloroethylene	1.26×10^{-3}	1.07×10^{-6}	2.79×10^{1}	4.56×10^{-2}
Trichlorofluoromethane	Not carcinogenic	NA	NA	NA
Xylenes (total isomers)	Not carcinogenic	NA	NA	NA

[a] C_{VOC} (mg/m^3) is the calculated concentration of VOC in building air.

[b] N_c (mg/m^2•s) is the calculated flux of VOC per unit area of concrete slab.

[c] $C_{s\text{-}gas}$ (mg/m^3) is the calculated soil gas concentration of VOC at the soil surface underneath the building.

[d] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

NA = not applicable.

Table C-18. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target HI of 1.0 and potential exposure inside Building 834D.

Chemical	C_{VOC} (mg/m^3)[a]	N_c (mg/m^2•s)[b]	$C_{s\text{-}gas}$ (mg/m^3)[c]	C_s (mg/kg)[d]
Benzene	Not available	Not available	Not available	Not available
Ethylbenzene	1.56×10^{-7}	1.32×10^{-10}	4.00×10^{-3}	1.71×10^{-5}
Tetrachloroethylene	1.01×10^{-3}	8.55×10^{-7}	2.45×10^{1}	3.99×10^{-2}
Toluene	5.65×10^{-7}	4.78×10^{-10}	1.29×10^{-2}	3.34×10^{-5}
Trichloroethylene	3.68×10^{-2}	3.12×10^{-5}	8.14×10^{2}	1.33×10^{0}
Trichlorofluoromethane	3.27×10^{-2}	2.77×10^{-5}	1.27×10^{3}	1.47×10^{-1}
Xylenes (total isomers)	3.41×10^{-6}	2.89×10^{-9}	9.59×10^{-2}	4.04×10^{-4}

[a] C_{VOC} (mg/m^3) is the calculated concentration of VOC in building air.

[b] N_c (mg/m^2•s) is the calculated flux of VOC per unit area of concrete slab.

[c] $C_{s\text{-}gas}$ (mg/m^3) is the calculated soil gas concentration of VOC at the soil surface underneath the building.

[d] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

Table C-19. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target risk of 1×10^{-4} and potential exposure inside Building 834O.

Chemical	C_{VOC} (mg/m^3)[a]	σ (mg/m^3•s)[b]	C_a (mg/m^3)[c]	N_s (g/cm^2•s)[d]	C_s (mg/kg)[e]
Benzene	5.44×10^{-7}	1.51×10^{-10}	6.51×10^{-10}	6.56×10^{-17}	1.11×10^{-5}
Ethylbenzene	Not carcinogenic	NA	NA	NA	NA
Tetrachloroethylene	3.62×10^{-3}	1.01×10^{-6}	4.33×10^{-6}	4.36×10^{-13}	7.95×10^{-2}
Toluene	Not carcinogenic	NA	NA	NA	NA
Trichloroethylene	1.25×10^{-1}	3.47×10^{-5}	1.49×10^{-4}	1.51×10^{-11}	2.63×10^{0}
Trichlorofluoromethane	Not carcinogenic	NA	NA	NA	NA
Xylenes (total isomers)	Not carcinogenic	NA	NA	NA	NA

[a] C_{VOC} (mg/m^3) is the calculated concentration of VOC in building air.

[b] σ (mg/m^3•s) is the calculated rate of entry of VOC into the building, per unit volume.

[c] C_a (mg/m^3) is the calculated concentration of VOC in air outside the building.

[d] N_s (g/cm^2•s) is the calculated flux of VOC from subsurface soil to crawl space air.

[e] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

NA = not applicable.

Table C-20. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target risk of 1×10^{-6} and potential exposure inside Building 834O.

Chemical	C_{VOC} (mg/m^3)[a]	σ (mg/m^3•s)[b]	C_a (mg/m^3)[c]	N_s (g/cm^2•s)[d]	C_s (mg/kg)[e]
Benzene	5.44×10^{-9}	1.51×10^{-12}	6.51×10^{-12}	6.56×10^{-19}	1.11×10^{-3}
Ethylbenzene	Not carcinogenic	NA	NA	NA	NA
Tetrachloroethylene	3.62×10^{-5}	1.01×10^{-8}	4.34×10^{-8}	4.37×10^{-15}	7.95×10^{-4}
Toluene	Not carcinogenic	NA	NA	NA	NA
Trichloroethylene	1.25×10^{-3}	3.47×10^{-7}	1.49×10^{-6}	1.51×10^{-13}	2.63×10^{-2}
Trichlorofluoromethane	Not carcinogenic	NA	NA	NA	NA
Xylenes (total isomers)	Not carcinogenic	NA	NA	NA	NA

[a] C_{VOC} (mg/m^3) is the calculated concentration of VOC in building air.

[b] σ (mg/m^3•s) is the calculated rate of entry of VOC into the building, per unit volume.

[c] C_a (mg/m^3) is the calculated concentration of VOC in air outside the building.

[d] N_s (g/cm^2•s) is the calculated flux of VOC from subsurface soil to crawl space air.

[e] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

NA = not applicable.

Table C-21. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target HI of 1.0 and potential exposure inside Building 834O.

Chemical	C_{VOC} (mg/m^3)[a]	σ (mg/m^3•s)[b]	C_a (mg/m^3)[c]	N_s (g/cm^2•s)[d]	C_s (mg/kg)[e]
Benzene	Not available	Not available	Not available	Not available	Not available
Ethylbenzene	2.47×10^{-7}	6.86×10^{-11}	2.95×10^{-10}	2.48×10^{-17}	9.96×10^{-6}
Tetrachloroethylene	1.06×10^{-3}	2.94×10^{-7}	1.27×10^{-6}	1.28×10^{-13}	2.33×10^{-2}
Toluene	6.82×10^{-7}	1.89×10^{-10}	8.16×10^{-10}	8.22×10^{-17}	1.94×10^{-5}
Trichloroethylene	3.67×10^{-2}	1.02×10^{-5}	4.39×10^{-5}	4.42×10^{-12}	7.70×10^{-1}
Trichlorofluoromethane	2.51×10^{-4}	6.97×10^{-8}	3.00×10^{-7}	3.02×10^{-14}	8.52×10^{-4}
Xylenes (total isomers)	5.60×10^{-6}	1.56×10^{-9}	6.70×10^{-9}	6.75×10^{-16}	2.34×10^{-4}

[a] C_{VOC} (mg/m^3) is the calculated concentration of VOC in building air.

[b] σ (mg/m^3•s) is the calculated rate of entry of VOC into the building, per unit volume.

[c] C_a (mg/m^3) is the calculated concentration of VOC in air outside the building.

[d] N_s (g/cm^2•s) is the calculated flux of VOC from subsurface soil to crawl space air.

[e] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

Table C-22. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target risk of 1×10^{-4} and potential exposure outside of Building 834D.

Chemical	C_a (mg/m^3)[a]	Q_s (g/s)[b]	N_s (g/cm^2•s)[c]	C_s (mg/kg)[d]
Benzene	5.41×10^{-7}	3.61×10^{-10}	1.85×10^{-16}	3.12×10^{-5}
Ethylbenzene	Not carcinogenic	NA	NA	NA
Tetrachloroethylene (PCE)	3.59×10^{-3}	2.40×10^{-6}	1.23×10^{-12}	2.24×10^{-1}
Toluene	Not carcinogenic	NA	NA	NA
Trichloroethylene (TCE)	1.25×10^{-1}	8.34×10^{-5}	4.27×10^{-11}	7.45×10^{0}
Trichlorofluoromethane	Not carcinogenic	NA	NA	NA
Xylenes (total isomers)	Not carcinogenic	NA	NA	NA

[a] C_a (mg/m^3) is the calculated annual-average ground level concentration of VOC.

[b] Q_s (g/s) is the calculated emission rate of VOC from soil.

[c] N_s (g/cm^2•s) is the calculated flux rate of VOC from soil.

[d] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

NA = not applicable.

Table C-23. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target risk of 1×10^{-6} and potential exposure outside of Building 834D.

Chemical	C_a (mg/m^3)[a]	Q_s (g/s)[b]	N_s (g/cm^2•s)[c]	C_s (mg/kg)[d]
Benzene	5.41×10^{-9}	3.61×10^{-12}	1.85×10^{-18}	3.12×10^{-7}
Ethylbenzene	Not carcinogenic	NA	NA	NA
Tetrachloroethylene (PCE)	3.59×10^{-5}	2.40×10^{-8}	1.23×10^{-14}	2.24×10^{-3}
Toluene	Not carcinogenic	NA	NA	NA
Trichloroethylene (TCE)	1.25×10^{-3}	8.34×10^{-7}	4.27×10^{-13}	7.45×10^{-2}
Trichlorofluoromethane	Not carcinogenic	NA	NA	NA
Xylenes (total isomers)	Not carcinogenic	NA	NA	NA

[a] C_a (mg/m^3) is the calculated annual-average ground level concentration of VOC.

[b] Q_s (g/s) is the calculated emission rate of VOC from soil.

[c] N_s (g/cm^2•s) is the calculated flux rate of VOC from soil.

[d] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

NA = not applicable.

Table C-24. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. Values are based on a target HI of 1.0 and potential exposure outside of Building 834D.

Chemical	C_a (mg/m^3)[a]	Q_s (g/s)[b]	N_s (g/cm^2•s)[c]	C_s (mg/kg)[d]
Benzene	Not available	Not available	Not available	Not available
Ethylbenzene	2.43×10^{-7}	1.62×10^{-10}	8.30×10^{-17}	2.78×10^{-5}
Tetrachloroethylene (PCE)	1.04×10^{-3}	6.94×10^{-7}	3.56×10^{-13}	6.49×10^{-2}
Toluene	6.78×10^{-7}	4.53×10^{-10}	2.32×10^{-16}	5.47×10^{-5}
Trichloroethylene (TCE)	3.63×10^{-2}	2.42×10^{-5}	1.24×10^{-11}	2.16×10^{0}
Trichlorofluoromethane	2.49×10^{-4}	1.66×10^{-7}	8.51×10^{-14}	2.40×10^{-3}
Xylenes (total isomers)	5.52×10^{-6}	3.69×10^{-9}	1.89×10^{-15}	6.57×10^{-4}

[a] C_a (mg/m^3) is the calculated annual-average ground level concentration of VOC.

[b] Q_s (g/s) is the calculated emission rate of VOC from soil.

[c] N_s (g/cm^2•s) is the calculated flux rate of VOC from soil.

[d] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a specific target risk or hazard, and represents an HBC.

Table C-25. HBCs, C_s (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. The values are based on potential exposure inside Building 834D when C_s (mg/kg) is the concentration in soil associated with a target HI of 1.0 and potential exposure outside Building 834D.

Chemical	C_s (mg/kg)[a]	$C_{s\text{-}gas}$ (mg/m^3)[b]	N_c (mg/m^2•s)[c]	C_{VOC} (mg/m^3)[d]
Benzene	Not available	Not available	Not available	Not available
Ethylbenzene	2.78×10^{-5}	6.51×10^{-3}	2.15×10^{-10}	2.54×10^{-7}
Tetrachloroethylene (PCE)	6.49×10^{-2}	3.98×10^{1}	1.39×10^{-6}	1.64×10^{-3}
Toluene	5.47×10^{-5}	2.11×10^{-2}	7.84×10^{-10}	9.25×10^{-7}
Trichloroethylene (TCE)	2.20×10^{0}	1.35×10^{3}	5.17×10^{-5}	6.10×10^{-2}
Trichlorofluoromethane	2.40×10^{-3}	2.07×10^{1}	4.53×10^{-7}	5.35×10^{-4}
Xylenes (total isomers)	6.57×10^{-4}	1.56×10^{-1}	4.70×10^{-9}	5.54×10^{-6}

[a] C_s (mg/kg) is the calculated concentration of VOC in soil associated with a target HI of 1.0 and potential exposure in the vicinity of Building 834D (Table C-24).

[b] $C_{s\text{-}gas}$ (mg/m^3) is the calculated soil gas concentration of VOC at the soil surface beneath Building 834D.

[c] N_c (mg/m^2•s) is the calculated flux of VOC per unit area of concrete slab.

[d] C_{VOC} (mg/m^3) is the calculated concentration of VOC in Building 834D air.

Table C-26. HBCs, C_S (mg/kg), and related parameters for VOCs in soil in the Building 834 Complex. The values are based on potential exposure inside Building 834O when C_S (mg/kg) is the concentration in soil associated with a target HI of 1.0 and potential exposure outside Building 834D.

Chemical	C_S (mg/kg)[a]	N_S (g/cm^2•s)[b]	σ (mg/m^3•s)[c]	C_{VOC} (mg/m^3)[d]
Benzene	Not available	Not available	Not available	Not available
Ethylbenzene	2.78×10^{-5}	8.31×10^{-17}	1.92×10^{-10}	6.90×10^{-7}
Tetrachloroethylene (PCE)	6.49×10^{-2}	3.56×10^{-13}	8.21×10^{-7}	2.95×10^{-3}
Toluene	5.47×10^{-5}	2.32×10^{-16}	5.35×10^{-10}	1.93×10^{-6}
Trichloroethylene (TCE)	2.20×10^{0}	1.26×10^{-11}	2.90×10^{-5}	1.05×10^{-1}
Trichlorofluoromethane	2.40×10^{-3}	8.50×10^{-14}	1.96×10^{-7}	7.05×10^{-4}
Xylenes (total isomers)	6.57×10^{-4}	1.89×10^{-15}	4.36×10^{-9}	1.57×10^{-5}

[a] C_S (mg/kg) is the calculated concentration of VOC in soil associated with a target HI of 1.0 and potential exposure in the vicinity of Building 834D.

[b] N_S (g/cm^2•s) is the calculated flux of VOC from subsurface soil to crawl space air.

[c] σ (mg/m^3•s) is the calculated rate of entry of VOC into Building 834O, per unit volume.

[d] C_{VOC} (mg/m^3) is the calculated concentration of VOC in Building 834O air.

Table C-27. Predicted incremental lifetime cancer risk and HI attributable to inhalation of VOCs that volatilize from subsurface soil into the indoor air of Building 834D (adult on-site exposure).

Chemical	HBCs (mg/kg)[a]	C_{VOC} (mg/m^3)[b]	Individual lifetime cancer risk	Hazard quotient
Benzene	Not available	Not available	Not available	Not available
Ethylbenzene	2.78×10^{-5}	2.54×10^{-7}	Not carcinogenic	4.98×10^{-7}
Tetrachloroethylene (PCE)	6.49×10^{-2}	1.64×10^{-3}	5.85×10^{-6}	3.21×10^{-2}
Toluene	5.47×10^{-5}	9.25×10^{-7}	Not carcinogenic	9.07×10^{-7}
Trichloroethylene (TCE)	2.20×10^{0}	6.10×10^{-2}	4.26×10^{-5}	1.63×10^{0}
Trichlorofluoromethane	2.40×10^{-3}	5.35×10^{-4}	Not carcinogenic	5.24×10^{-4}
Xylenes (total isomers)	6.57×10^{-4}	5.54×10^{-6}	Not carcinogenic	5.43×10^{-7}
			Σ Risk = 5×10^{-5}	HI = 1.7

[a] HBCs (mg/kg) are the calculated concentration of VOC in soil associated with a target HI of 1.0 and potential exposure outside Building 834D.

[b] C_{VOC} (mg/m^3) is the calculated concentration of VOC in Building 834D air.

Table C-28. Predicted incremental lifetime cancer risk and HI attributable to inhalation of VOCs that volatilize from subsurface soil into the indoor air of Building 834O (adult on-site exposure).

Chemical	HBCs (mg/kg)[a]	C_{VOC} (mg/m^3)[b]	Individual lifetime cancer risk	Hazard quotient
Benzene	Not available	Not available	Not available	Not available
Ethylbenzene	2.78×10^{-5}	6.90×10^{-7}	Not carcinogenic	1.35×10^{-6}
Tetrachloroethylene (PCE)	6.49×10^{-2}	2.95×10^{-3}	1.05×10^{-5}	5.78×10^{-2}
Toluene	5.47×10^{-5}	1.93×10^{-6}	Not carcinogenic	1.89×10^{-6}
Trichloroethylene (TCE)	2.20×10^{0}	1.05×10^{-1}	7.34×10^{-5}	2.80×10^{0}
Trichlorofluoromethane	2.40×10^{-3}	7.05×10^{-4}	Not carcinogenic	6.91×10^{-4}
Xylenes (total isomers)	6.57×10^{-4}	1.57×10^{-5}	Not carcinogenic	1.54×10^{-6}
			Σ Risk = 8×10^{-5}	HI = 2.9

[a] HBCs (mg/kg) are the calculated concentration of VOC in soil associated with a target HI of 1.0 and potential exposure outside Building 834D.

[b] C_{VOC} (mg/m^3) is the calculated concentration of VOC in Building 834O air.

Table C-29. HBCs (C_s [mg/kg]) for TCE in soil, the calculated values of $C_{s\text{-}gas}$, and the corresponding SVRLs. HBC values are based on a target HI of 1.0 and correspond to a risk of 3×10^{-5}.

HBCs C_s (mg/kg)	$C_{s\text{-}gas}$ (mg/m^3)	SRVL (ppm$_{v/v}$)
2.2	1.35×10^{3}	250
1.3	8.15×10^{2}	150

Table C-30. HBCs (C_s [mg/kg]) for TCE and parameters used to calculate the soil gas concentration of TCE at the soil surface beneath Building 834D.

HBCs C_s (mg/kg)	Adsorption coefficient Kd (L/kg)	Henry's law constant H (atm·m^3/mol)	Gas constant R (atm•m^3/mol•T)	Temperature T (K)	$C_{s\text{-}gas}$ (mg/m^3)
2.2	$6..4 \times 10^{-1}$	9.58×10^{-3}	8.2×10^{-5}	298	1.35×10^{-3}
1.3	$6..4 \times 10^{-1}$	9.58×10^{-3}	8.2×10^{-5}	298	8.15×10^{-2}

Appendix D

Treatability Studies

Appendix D

Treatability Studies

D-1. Background

This appendix is a compilation of the methods and results of treatability studies conducted at the Building 834 Complex to date. It presents the information previously included in Chapter 7 of Bryn et al. (1990) and more recent reports on the three studies conducted after 1990: Joule heating, electron acceleration, and the EPA SITE test of the Purus™ photo-oxidation treatment system.

D-2. References

Bryn, S. M., R. K. Landgraf, and S. E. Booth (1990), *Draft Remedial Investigation and Feasibility Study for the Lawrence Livermore National Laboratory Site 300 Building 834 Complex,* Lawrence Livermore National Laboratory, Livermore, Calif. (UCRL-ID-103963).

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Johnson, M. D., W. Haag, and P. G. Blystone of Purus, Inc., and P. F. Daley of Lawrence Livermore National Laboratory (1992), "Destruction of Organic Contaminants in Air Using Advanced Ultraviolet Flashlamps," Risk Reduction Engineering Laboratory, Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio (Contract no. CR818209-01-0).

Matthews, S. M., A. J. Bolgel, D. W. Camp, R. A. Caulfield, J. O. Cunningham, P. F. Daley, J. J. Greci, M. C. Jovanovich, J. A. Loftis, and P. D. Soran (1992), "Remediation of a TCE Ground Spill Using an Electron Accelerator," *Proceedings, Nuclear and Hazardous Waste Management, Spectrum '92,* August 23–27, 1992, Boise, Idaho.

Chapter 7. Trichloroethylene (TCE) Pilot Remediation Study

From August 1986 through June 1989, a series of pilot remediation tests were conducted at the Building 834 Complex to evaluate soil vapor and ground water extraction methods of removing TCE from the subsurface, and to test a prototype ground water treatment system. The tests were conducted at two locations:

- Near the main TCE release area using wells W-834-D3, -D4, -D5, -D6, and nearby wells (D-wells area), and
- About 1000 ft downgradient of the TCE release area using wells W-834-T4, -T4A, -T4B, and -T4C (T4 wells area) (Fig. 7-1).

A cross section of the D-wells area is shown in Figure 7-2; a cross section of the T4 wells area is shown in Figure 7-3. The test schedules and configurations were as follows:

- August 1986: Soil vapor extraction testing at the D-wells;
- October through December 1987: Soil vapor extraction testing at the D-wells;
- February to April and October to November 1988: Soil vapor and ground water extraction testing and ground water treatment at the D-wells;
- November 1988 to June 1989: Soil vapor and ground water extraction testing and ground water treatment at the T4 wells;
- May to June 1989: Soil vapor and ground water extraction testing with expanded monitoring network, and operation of a second ground water treatment unit at the D-wells.

Figure 7-4 provides a timeline for these test intervals. The pilot-test designs, equipment, and results are discussed in the following sections.

7.1. 1986–1987 Tests—Soil Vapor Extraction

The first soil-vapor extraction test was conducted in August 1986 using a positive-displacement vacuum pump connected to well W-834-D3 (Fig. 7-2). The pump, rated at 5 in. Hg vacuum, produced a vapor flow of about 27 cu ft/minute (cfm) with a TCE concentration averaging about 2500 ppm on a volume-to-volume basis ($ppm_{v/v}$) (Buddemeier *et al.,* 1987).

From October through December 1987, additional soil-vapor extraction was conducted using monitor wells W-834-D3, W-834-D4, W-834-D5, and W-834-D6 (Ruggieri et al, 1987). In the first test, a vacuum was applied with a high-volume blower to well W-834-D4. Wells W-834-D3, W-834-D5, and W-834-D6 were monitored for pressure changes. The blower was able to induce a 20 in. Hg vacuum on well W-834-D4. Simple uncalibrated manometers (U-tubes filled with water) were attached to special, sealed well heads on the other wells. Well W-834-D3, located only 10 ft from the pumping well, showed an almost immediate pressure response to pumping in well W-834-D4. The other two wells, located 20 and 40 ft from the pumping well, responded within 45 minutes. For all three monitor wells, the pressure response was small (less than 1/2 in. response in manometers with approximately 4 in. of water in them). The first test was conducted twice: once for about 2 hours and then for 6 hours. Steady state

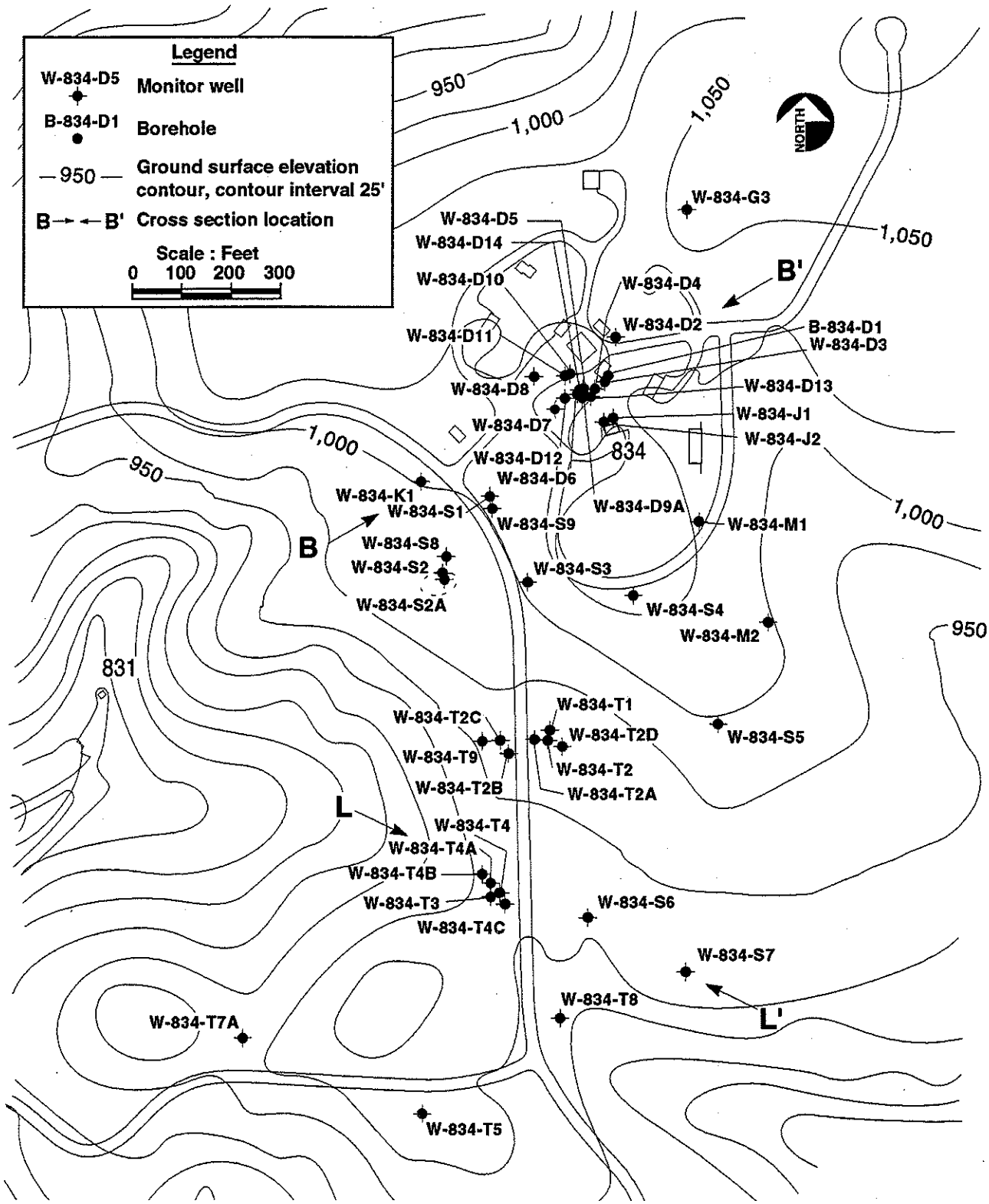

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Figure 7-1. Location of wells at the Building 834 Complex and vicinity, and cross sections through pilot remediation areas.

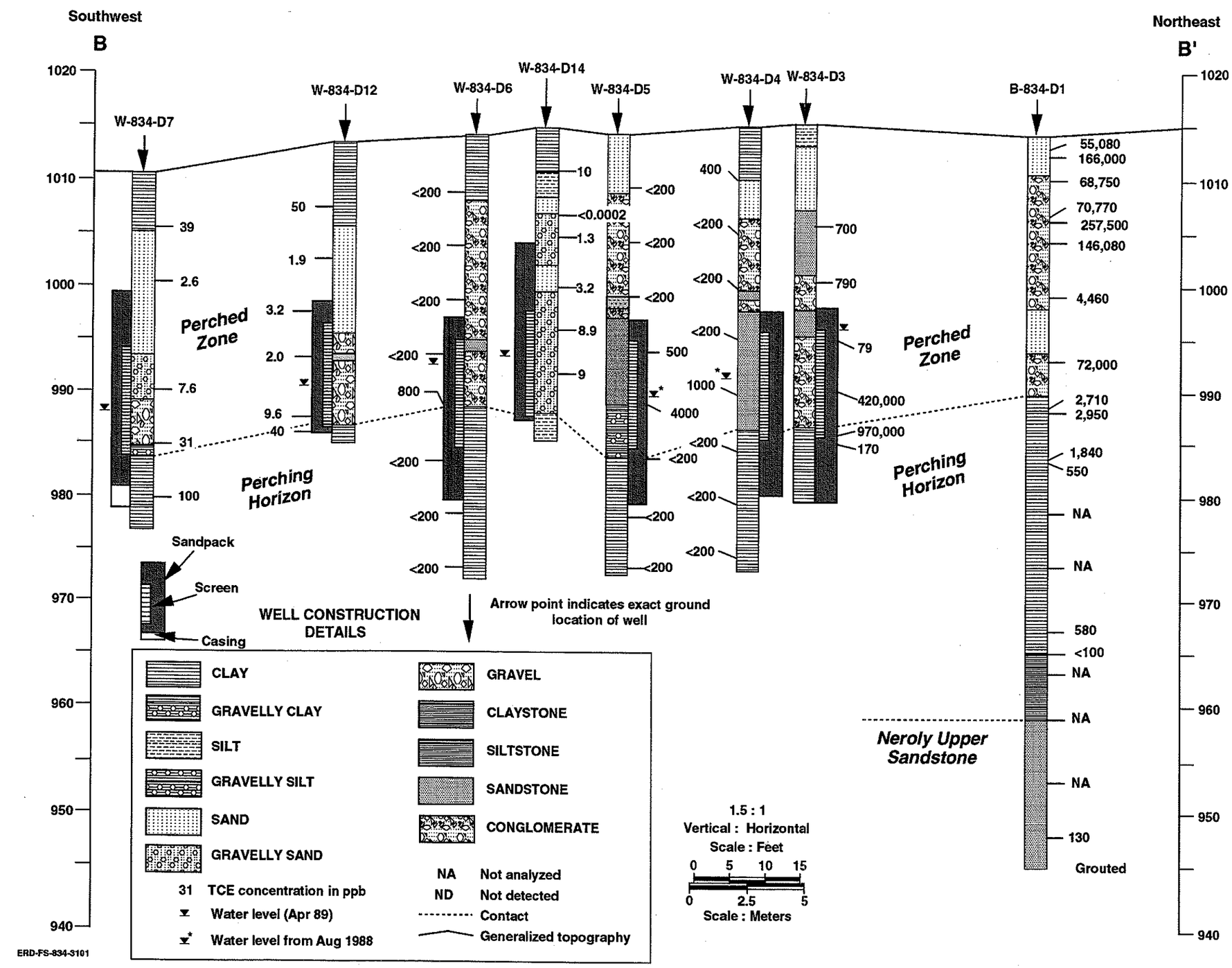

Figure 7-2. Building 834 Complex core area hydrogeologic cross section B-B'.

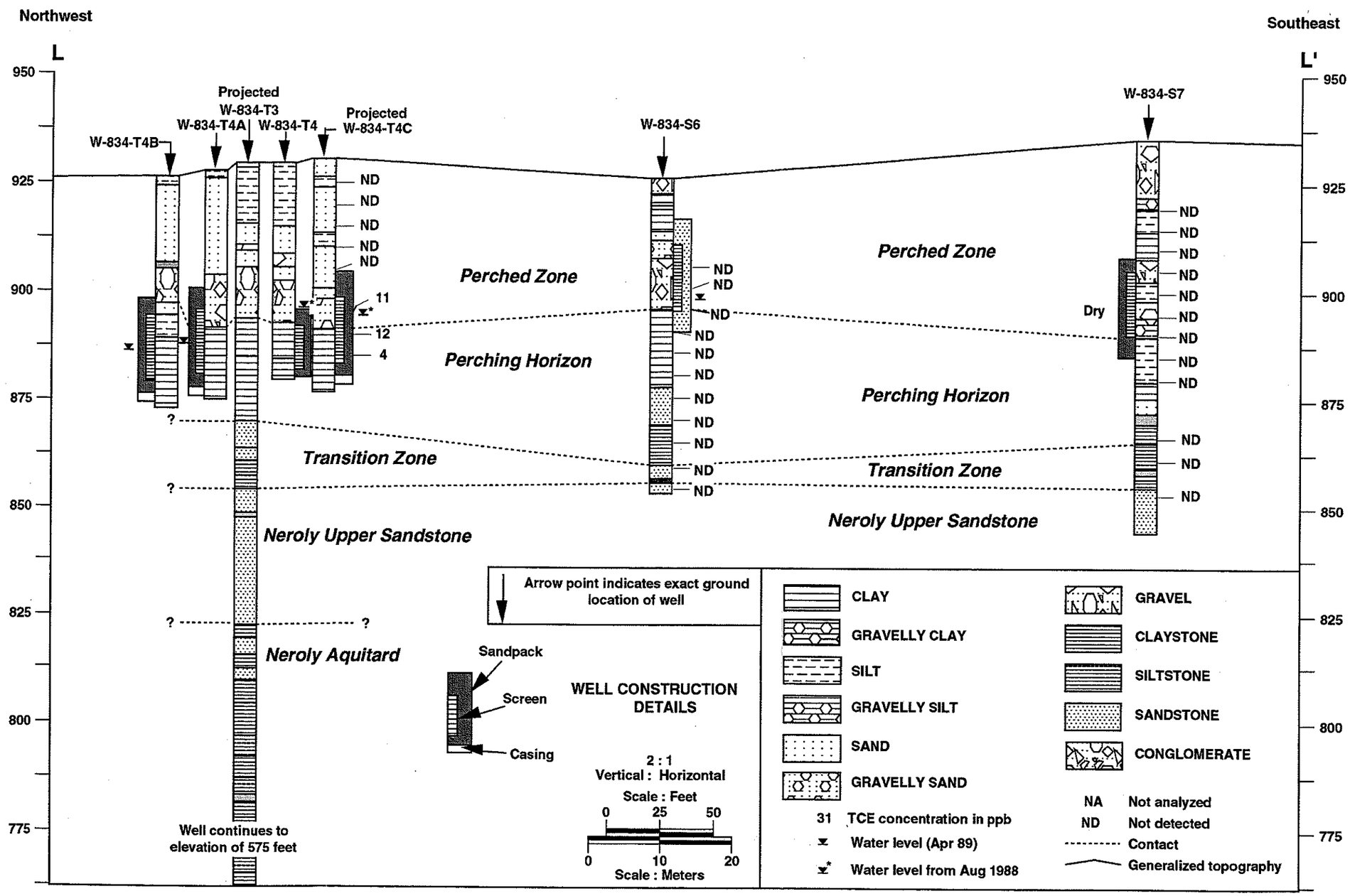

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Figure 7-3. Building 834 Complex hydrogeologic cross section L-L'.

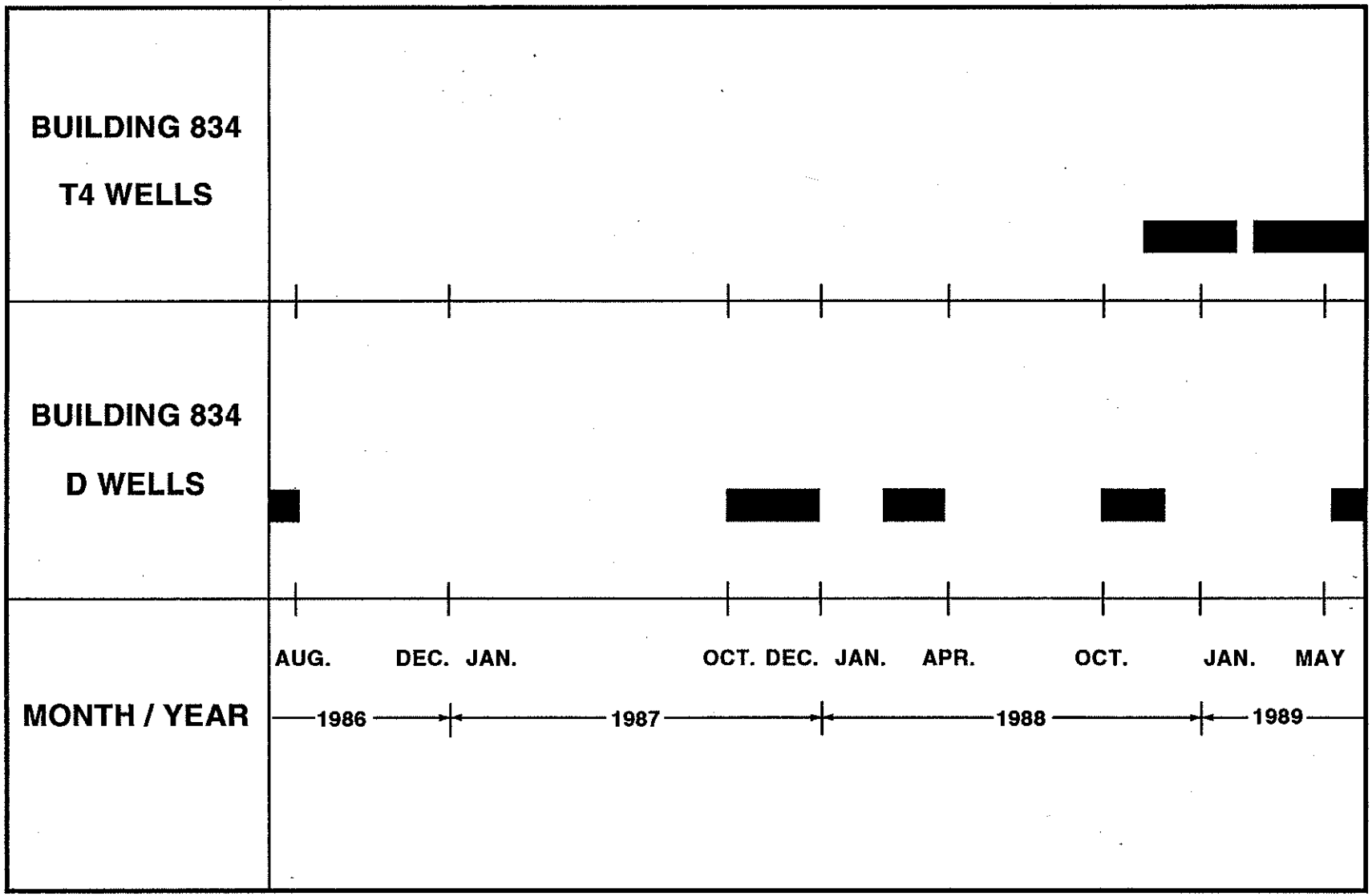

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Figure 7-4. Timeline for pilot Remediation Activities.

(that is, no further manometer response) was reached in less than 1 hour from the start of the pumping.

A second test was conducted with the same arrangement of wells but with a water-lubricated (liquid-ring) vacuum pump that induced a vacuum of about 28 in. Hg on well W-834-D4. The results were similar to those of the first test. The first and strongest response was from well W-834-D3, located 10 ft from the pumping well. As in the first test, steady-state conditions were achieved within 1 hour.

TCE concentrations were not measured in the effluent air from either test. In the first test, the blower initially produced air that smelled of TCE. No TCE odor was present after a few minutes of pumping, however. The blower throughput was tens of cfm, diluted by ambient air bled into the vacuum line to prevent the blower from running too roughly. This ambient air diluted the TCE concentration. In the second test, the vacuum-pump exhaust smelled strongly of TCE throughout the length of the test, but the TCE concentrations were not measured.

7.2. 1988 D-Wells Tests—Soil Vapor and Ground Water Extraction with Water Treatment

From February to April and October to November 1988, pilot remediation tests were conducted to determine:

- Rates of potential ground water and soil vapor extraction;
- Amounts of resulting TCE vapors that would be vented into the atmosphere if recovery were not attempted; and
- Design parameters for the full-scale remediation systems, such as extraction well spacing, vacuum pump capacity, and treatment system capacity.

The pilot tests were conducted at wells W-834-D3, W-834-D4, W-834-D5, and W-834-D6 (Fig. 7-2). Wells W-834-D4 and W-834-D5 were equipped with submersible pumps for ground water extraction and connected to a liquid-ring vacuum pump.

7.2.1. February–April 1988 Test

During the February to April test, water was initially removed from wells W-834-D4 and W-834-D5 at a rate of about 88 gal/5-hour day, but declined to less than 60 gal by the conclusion of testing. The vacuum pump produced vapors at about 42.5 cfm and also increased the rate of water extraction by a factor of two. The vapors were vented into the atmosphere. Water and vapor samples were collected every few days and sent to Brown and Caldwell, Emeryville, California, for analysis. Extracted ground water was treated by air stripping in a bubbling tank until TCE concentrations declined below 0.5μg/L; it was then discharged to the ground.

Table 7.2.1-1 summarizes the TCE concentrations found in extracted water and vapor. Based on TCE concentrations in vapor and vapor extraction rates, we conclude that most of the TCE is contained in the vadose zone and must be removed as vapor. The pilot testing indicated that 400 gal of water could be removed per 24-hour day, and the average TCE concentration is 400 mg/L (ppm). Therefore, about 1.2 lb of TCE can be removed per day from ground water in the vicinity of wells W-834-D4 and -D5. At 1000 $ppm_{v/v}$ and 42 cfm, the TCE vapor emission was calculated to be about 1.16 lb/hour or about 28 lb/day. Thus, total emissions were estimated to be about 30 lb/day. However, long-term results were believed to be only 10% of the initial results, or 3 lb/day (Connor, 1988).

Table 7.2.1-1. Trichloroethylene (TCE) concentrations from water and vapor samples from wells W-834-D3, W-834-D4, W-834-D5, and W-834-D6 (McIlvride *et al.*, 1988).

Total water removed (gals)	TCE in water samples (mg/L)					TCE in vapor (ppm, by vol)
	Well D3	Well D4	Well D5	Well D6	Average (D4+D5)/2	D4 + D5
50	140	150	230	96	190	-
250	220	200	240	-	220	-
500	340	450	1100	470	775	350
750	-	330	340	-	335	930
1000	-	410	390	-	400	1200
Average TCE	-		308	460	384	-

Use of the bubbling tank showed that 400 mg/L (ppm) of TCE in ground water could be reduced to less than 40 µg/L (ppb) after 24 hours of vigorous air sparging. After 48 hours, the concentration of TCE was reduced to less than 1 µg/L (ppb).

7.2.2. October–November 1988 Test

During the October to November 1988 pilot remediation, we tested a Dual-Tank Air-Stripping Pilot Remediation System for treatment of ground water extracted at the Building 834 Complex. The system was designed to be self-contained, requiring only a constant 220V power source and periodic maintenance. A microprocessor control board monitors and controls not only the treatment system but also the soil vapor and ground water extraction pumps. The microprocessor control board can be programmed to site-specific requirements such as aeration time.

Operation of the Dual-Tank Air-Stripping system is discussed below and illustrated in Figure 7-5. The system is designed to pump the TCE-containing water and vapor from one or more wells screened in the perched water-bearing zone. Since water flow rates from wells at the Building 834 Complex are quite low and do not permit continuous pumping, electric "conductive" switches were installed to turn on the pump(s) after water-level recovery and turn off the pump(s) before daylight. The water-level range of the pumping wells was kept to about 1 ft. Meters were installed on the discharge line of each pumping well to measure flows.

When the Dual-Tank Air-Stripping system is started, the control board checks the system status. If both tanks are empty, tank 1 (default) begins to fill, the vacuum pump is turned on and begins to extract vapor from the pumping wells, which are screened in both the saturated and unsaturated zones. The controller stops filling the first tank when it is filled, and checks the empty tank outflow valve. If the valve is closed, he begins to fill the empty tank. As the second tank begins to fill, the air compressor is monitored for air pressure. If the air pressure is low, the control board turns on the air compressor; if the air pressure is normal, an electronically controlled air valve is opened at the bottom of the first (full) tank and the water is aerated for a predetermined time (72 hours). After the first tank is aerated, the air compressor shuts off, the electronically controlled air valve on the first tank closes, and an electronically controlled valve at the bottom of the first tank opens to let the tank drain. The effluent is diverted away from the site where it will not recharge the perched zone. Once the tank is drained, the drain valve closes, and the first tank begins filling after the second tank is full. However, if the second tank is filled before the first tank has finished aerating (72 hours), the water extraction pumps shut off until the first tank has finished aerating and has drained.

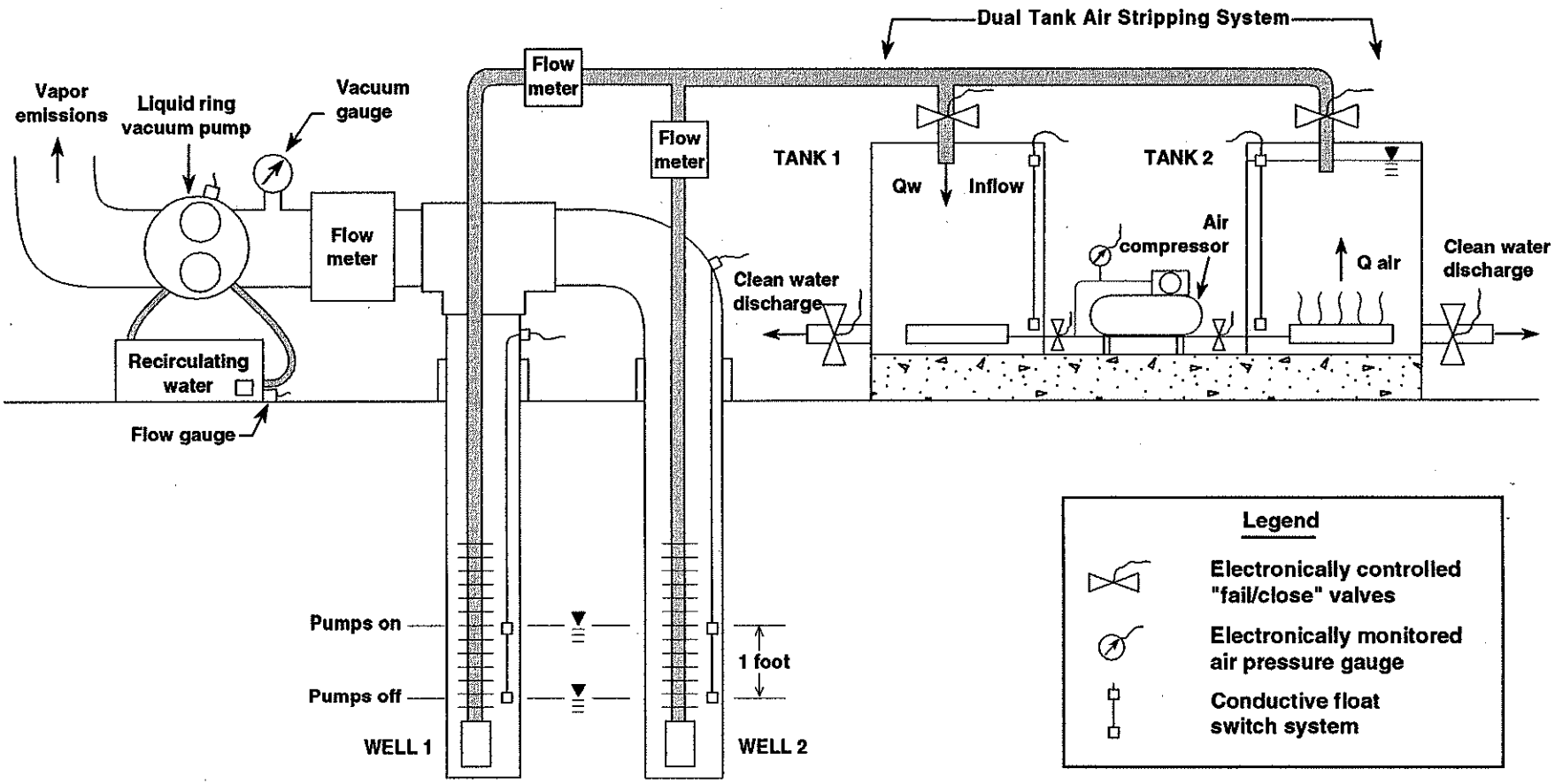

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Figure 7-5 Schematic of the soil vapor and ground water extraction and water treatment system.

All of the electronically controlled valves are "fail-close" valves, therefore, if the system fails, all valves close and contaminated water will not accidentally be discharged. When the system is restarted after a system failure, the control board analyzes the tank status and begins to aerate any full tank(s) (default = tank 1). The control board is programmed so that a tank cannot be drained with less than 72 hours of aeration, and water cannot be pumped unless at least one tank is empty.

The water tank bubbling time was determined by a time-series water-sampling test. First, a tank was filled with TCE-bearing water pumped from extraction wells W-834-D4 and W-834-D5, located in an area of high concentrations in the plume at the Building 834 Complex. Once the tank was filled, a water sample was collected from the tank and analyzed for VOCs to measure the initial TCE concentration in water, and the air compressor was used to continuously aerate the contaminated water. Water samples were collected once a day for 3 days during the continuous aeration process and analyzed for VOCs to measure the effectiveness of the aeration system. Then the tank aeration time was determined from startup to the first water sample taken with VOCs below California Department of Health Services action limits. We observed that almost all of the TCE was removed after 24 hours of continuous aeration, when the TCE concentration decreased from 140 ppm to 3.2 ppb (Chaing, 1988). We used a safety factor of three to determine the system aeration time of 72 hours (3×24 hours).

For the October to November 1988 tests, the extraction and treatment system was operated for about 4 weeks at wells W-834-D3, W-834-D4, W-834-D5, and W-834-D6. W-834-D4 and W-834-D5 served as ground water and vapor extraction wells, and W-834-D3 and -D6 were left uncovered to serve as air inlets. About 1000 gal of water were extracted during the test. Initially, no vacuum was used and the combined ground water extraction rate from both wells was about 25 gal/day (gpd). When the vacuum was applied, the ground water extraction rate increased to about 80 gpd. This rate was significantly less than the 400 gpd prediction that was made from the February to April 1988 test data. At the end of the test, the water level in well W-834-D3 had fallen 30 inches. Several days later it had recovered to within seven inches of its initial level.

We extracted TCE-containing soil vapors for 8 consecutive days at a rate averaging about 30 lb of TCE per day. The TCE concentrations in water were about 200 ppm during the test. The dual-tank treatment system operated successfully. The treated water was discharged at the same location as the cooling tower blowdown discharge. (In the future, under the NPDES permit, the treated water will be discharged on the eastern side of the ridge.)

During the extraction and recovery phases of pilot remediation in the W-834-D well group series, six wells near the core of the Building 834 Complex were monitored by pressure transducers to evaluate the effects on water levels of ground water and vapor extraction from wells W-834-D4 and W-834-D5 and to evaluate the hydrogeologic system at the Complex. The monitored wells included W-834-D6, W-834-D7, W-834-J1, W-834-J2, W-834-K1, and W-834-S1.

In the extraction phase of the test, well W-834-D6 showed the most response, nearly 0.6 ft of drawdown. At the other locations, less drawdown was observed. No correlation was discerned between the short-term water level responses and the on-off records for the vacuum and water extraction system. Wells W-834-J1 and W-834-J2 displayed a significant amount of barometric influence. Wells W-834-K1 and W-834-S1 showed unexplained cyclical water-level patterns, which may have masked influences from the pilot test.

The most noise-free water-level record was obtained from well W-834-D7. It showed a relatively steady water-level decline of nearly 1 ft from October through December 1988. It is not certain if this was in response to the ground water extraction.

7.3. 1988-1989 T4 Wells Test—Soil Vapor and Ground Water Extraction with Water Treatment

For this phase of pilot testing, the Dual-Tank Air-Stripping System was moved to the W-834-T4 series wells. Ground water extraction began at wells W-834-T4 and W-834-T4C on November 21, 1988 and continued through June 1989 (Lamarre *et al.,* 1988, 1989a, 1989b). The vacuum was also operated to increase ground water flow to the wells and to remove TCE from the dewatered soils.

Ground water flow data taken from the extraction wells recorded during the first 400 hours of the test, indicate that the initial total extraction rate was about 0.44 gpm, which gradually declined to a near-steady state rate of 0.11 gpm. About 75% of the flow came from well W-834-T4C and 25% from well W-834-T4.

Wells W-834-T4A and W-834-T4B were monitored to evaluate the hydrogeologic effects of the ground water and soil vapor extraction at wells W-834-T4 and W-834-T4C. Well W-834-T4A (Fig. 7-3) is screened in both the sandy gravel aquifer and the silty-clay perching horizon. It showed greater response than well W-834-T4B. Initially the water level in well W-834-T4A fell rapidly—nearly 0.7 ft/day by early December. As the test progressed, the rate of drawdown decreased. By late December 1988, it had dropped to 0.07 ft/day. The water level at well W-834-T4A fell a total of 9 ft between the start of the test on November 15, 1988, and the end of the test in December 1988. Well W-834-T4B is primarily screened in the silty-clay perching horizon. This well showed less response to extraction than well W-834-T4A, with water levels declining as little as 0.03 ft/day by late December 1988 (Lamarre *et al.,* 1988).

By the end of May 1989, about 20,000 gal of ground water had been extracted from wells W-834-T4 and W-834-T4C. The water table was drawn down to a depth of about 42 ft below ground surface to the base of the gravelly water-bearing materials. The combined yield of the extraction wells stabilized at about 110 gpd (0.07 gpm). The dewatering exposed the formerly saturated, water-bearing materials to air, increasing the amount of TCE removed via the vacuum extraction system.

During the testing period, TCE concentrations in ground water showed an overall declining trend, while TCE concentrations in vapor showed an overall increasing trend, as shown in Table 7.3-1.

7.4. 1989 D-Wells Test—Continued Soil Vapor and Ground Water Extraction and Water Treatment, with Enhanced Monitoring

In May and June 1989, pilot testing resumed at the Building 834 D-wells area using the same ground water and soil vapor extraction equipment and an identical Dual-Tank Air-Stripping System as were used in the October to November 1988 tests. The primary goals of this test were:

- To establish how far the soil vapor vacuum and ground water cone of depression extended away from the extraction wells,
- How quickly TCE could be removed from the saturated and unsaturated subsurface materials, and
- What degree of cleanup could be achieved.

To meet these objectives, an extensive subsurface monitoring network was installed. Seven dedicated soil-vapor monitoring points were installed at depths of 12 to 18 ft near extraction

wells W-834-D4 and W-834-D5 (Figs. 7-6 and 7-7). Vapors from the soil vapor points were periodically sampled for TCE concentrations during water and vapor extraction. Several wells in the vicinity of W-834-D4 and W-834-D5 were fitted with specially-designed well caps for use with a calibrated electronic vacuum gauge and digital data logger to monitor the radius of influence of the vacuum extraction system. In addition, 12 wells within 420 ft of the two extraction wells were outfitted with electronic water-level pressure transducers and digital data loggers to record perched water-bearing zone water levels during the test.

Table 7.3-1. TCE concentrations in ground water and soil vapor during pilot remediation in the T4 wells area.

	TCE concentration (ppm)	
Date	Water	Vapor
12-05-88	19	0.04
12-12-88	11	0.31
01-04-89	2.2	2.1
01-10-89	1.7	2.0
01-17-89	2.0	11
01-23-89	2.0	5.6
01-30-89	0.48	6.1
02-21-89	2.1	4.0
03-06-89	0.12	2.0
03-13-89	0.85	13
03-21-89	0.44	9.6
04-89 through 06-89	0.19 (average)	8.3 (average)

7.4.1. Vacuum Sensors and Test Results

Vacuum sensing devices were developed to characterize the extent of vacuum influence (both radially, and if possible, with depth) and the rate of venting. They had sufficient sensitivity to detect the soil vacuum, and their output was compatible with data logging. A similar device was developed to continuously monitor soil-gas flow at the vacuum pump.

A Validyne model DP15 differential pressure transducer, the first vacuum sensor tested, was borrowed from the LLNL vacuum-calibration shop. This commercially packaged transducer has interchangeable diaphragms for different ranges; we used both a 0-10 in. (inches of water relative to ambient, unless otherwise specified) and a 0-54 in. water diaphragm. A housing was constructed that permitted rapid connection of the sensor to a valved cap that was sealed to the 4.5-in. diameter standard monitor well casing (Fig. 7-8), and also allowed venting of the transducer to ambient air. Calibration of all sensors was performed in the field with a specially made water manometer; all measurements were referenced against prevailing ambient atmospheric pressure. Well caps were sealed with Dow Corning 3145 RTV low-volatile silicone adhesive/sealant, after the inside of the cap was coated with Apiezon N high-vacuum grease. This prevented any contact between the well atmosphere and residual volatiles in the RTV. The monitor wells were capped and the valves on the caps were left closed to allow vacuum to build to a maximum equilibrium level.

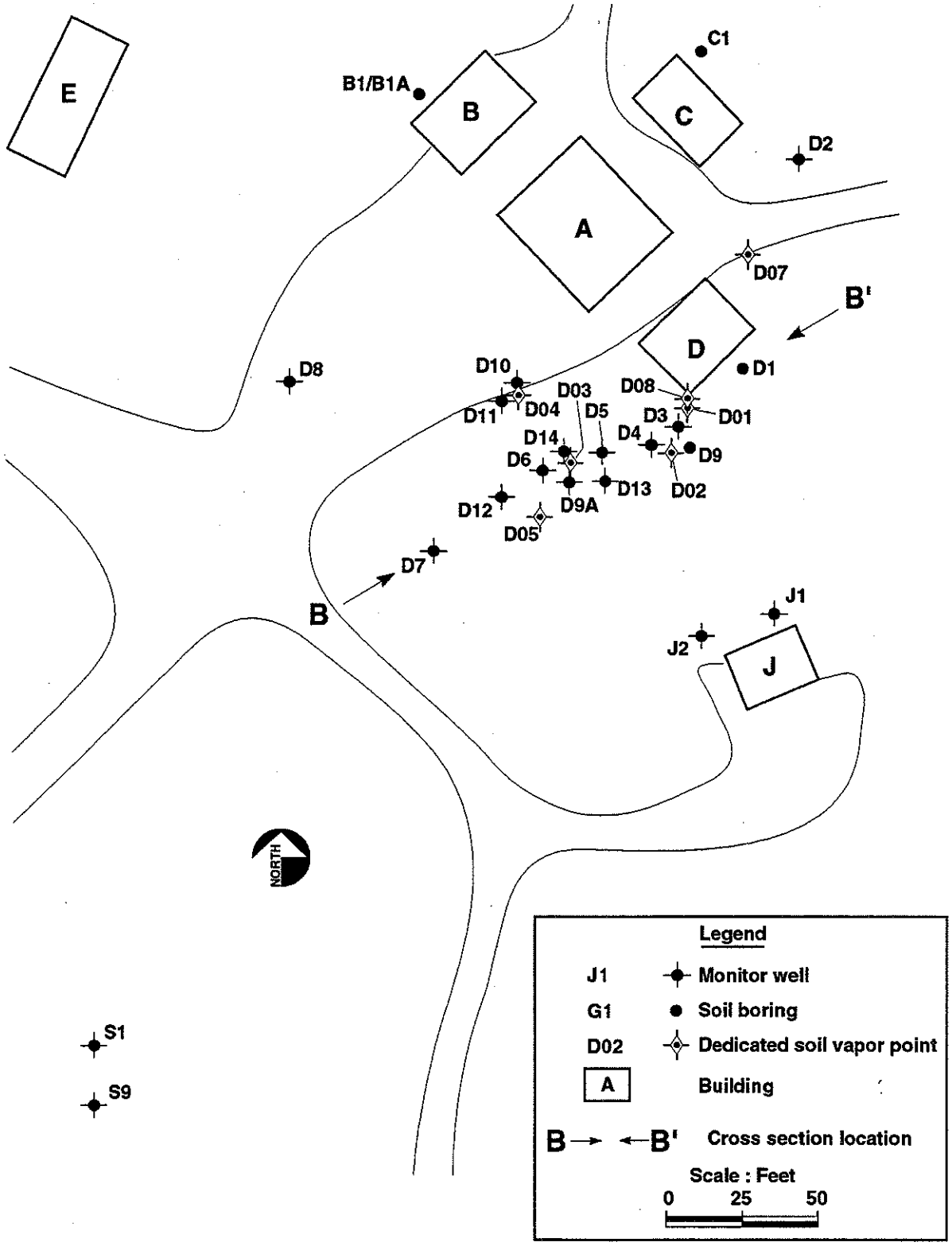

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Figure 7-6. Location of wells and dedicated soil vapor monitor points at the Building 834 Complex.

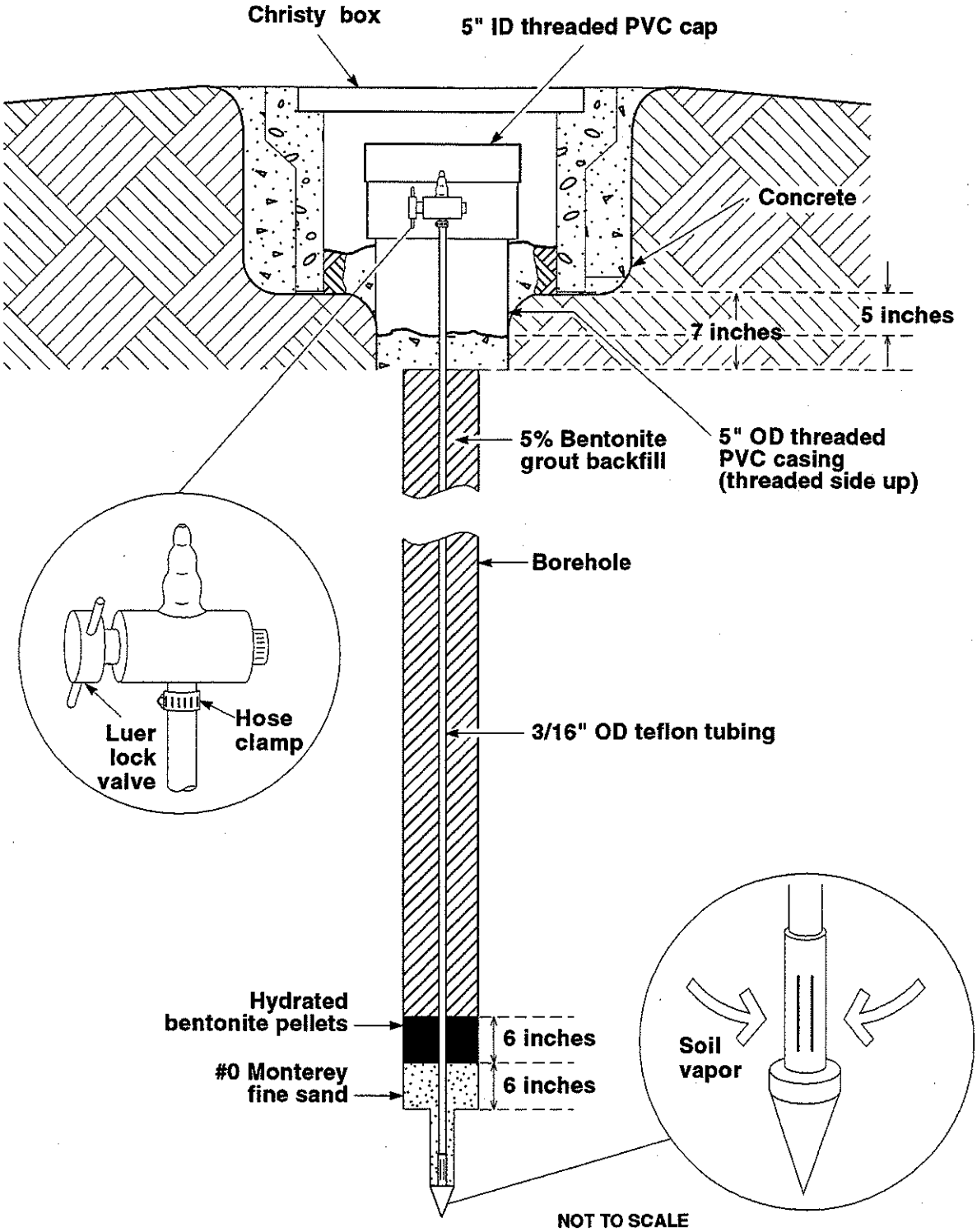

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Figure 7-7. Dedicated soil vapor monitor point completion diagram.

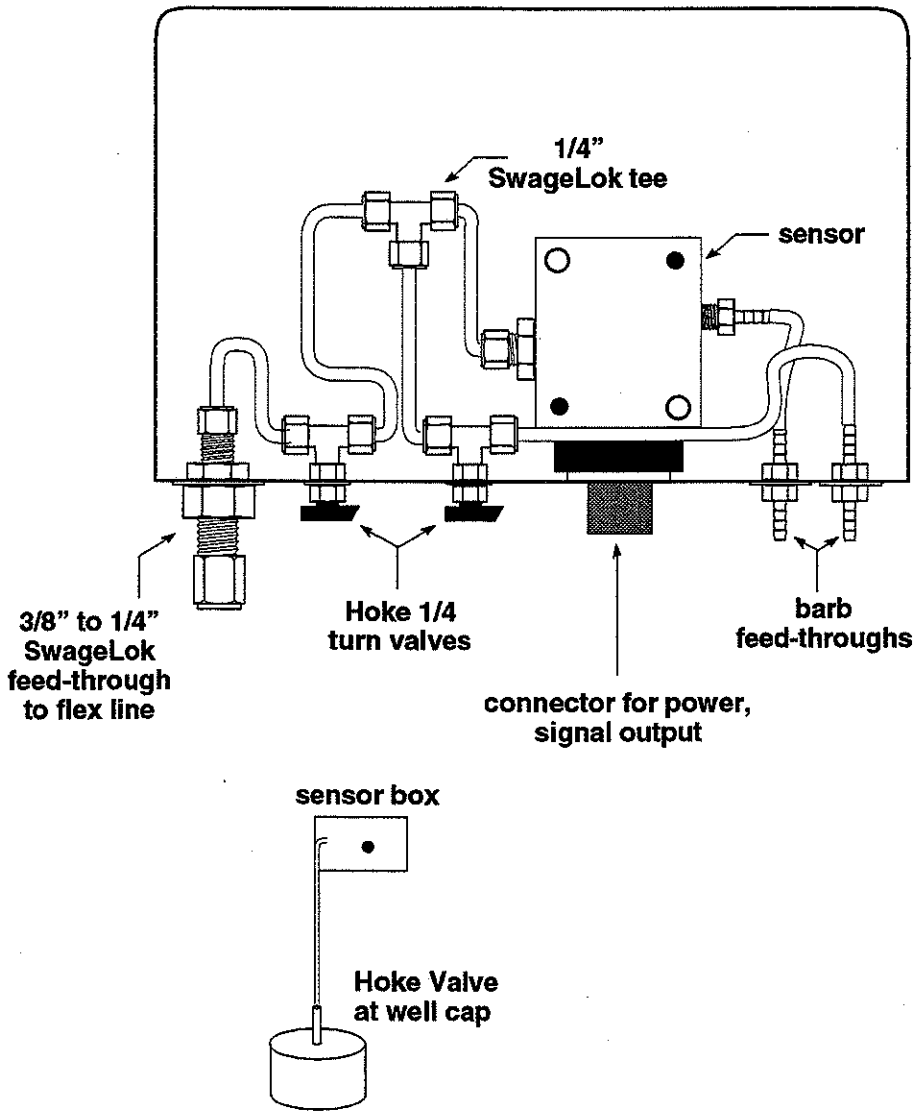

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Figure 7-8. Plumbing schematic for the Validyne pressure transducer.

7.4.1.1. Initial Tests at T4-Wells Area

The equipment was first tested in the T4-wells area by measuring soil vacuum at monitor wells W-834-T4A and W-834-T4B during the November 1988 to June 1989 T4-wells tests (see Fig. 7-5 for a schematic diagram of the venting system). The sensors were attached and valved so the steady-state vacuum buildup could be read. To allow air back into the well, the sensor enclosure's air vent valve was opened. Following 15 minutes of air bleeding, the vent was closed to examine how quickly equilibrium was re-established.

At well W-834-T4A, about 25 ft from the extraction wells, a steady-state vacuum of 22 in. was achieved (Fig. 7-9). Sustained venting through the small ports of the sensor housing resulted in greater than 17 in. Hg (≈204 in. water) present at the water-seal pump, for a residual of about 10% at a radius of 25 ft.

Well W-834-T4B reached only about half the level of vacuum of W-834-T4A, and responded more dramatically to venting. Nevertheless, it recovered to a steady state in about the same amount of time as T4A. Although these measurements established an expected magnitude of vacuum for the vapor extraction system, the actual magnitude observed in the D-wells area was in fact much lower, as discussed in Section 7.4.1.2.

7.4.1.2. D-Wells Area Test

Two additional vacuum sensors were developed for testing at the D-wells area using low-cost fixed-range differential vacuum transducers. Special care was taken in the supporting circuitry design to ensure linearity at low vacuum levels. The ranges were 0-14 in. and 0-28 in.; along with the Validyne sensor, these were deployed at three wells for continuous logging at substantial distances from soil vapor extraction wells D3, D4, and D5. At intervals during the test, one of the transducers was moved to monitor additional capped wells and dedicated soil-vapor sampling points (Figs. 7-6 and 7-7), and read with a multimeter when steady state values were achieved. A vacuum contour map for this facility is shown later in Section 7.4.3.

The continuous logging indicated that at distances of from 50 to 75 ft from the well being pumped, vacuum could be detected within 30-45 minutes of the onset of pumping. However, well W-834-D11 (Fig. 7-6), completed in the perching horizon, did not develop vacuum, revealing that vertical propagation of the vacuum was effectively blocked by clay layers. Well W-834-D6, completed in the perched zone, also did not develop vacuum, but the well's casing had experienced damage at the surface and may not have had a good seal below grade. As a result, its data were not analyzed further.

7.4.2. Vapor Sampling and Estimate of Mass Flow

7.4.2.1. Vacuum System Flow Sensors

The soil venting vacuum pump systems were equipped with Meriam flow gauges to measure air flow through the systems. The gauges were installed between the wellhead manifolds and the liquid-ring pumps. These gauges have a precision capillary element that creates a small differential pressure that is factory-calibrated against air flow through the unit. At the W-834-T4 well installation, the differential pressure was manually logged on inspection of a Magnahelic pressure gauge; while at the D-series area, the differential was logged from an Omega Instruments differential vacuum transducer (PX 154, 0-5-in. water range) that was calibrated in the field with the same water manometer used to calibrate the other vacuum sensors.

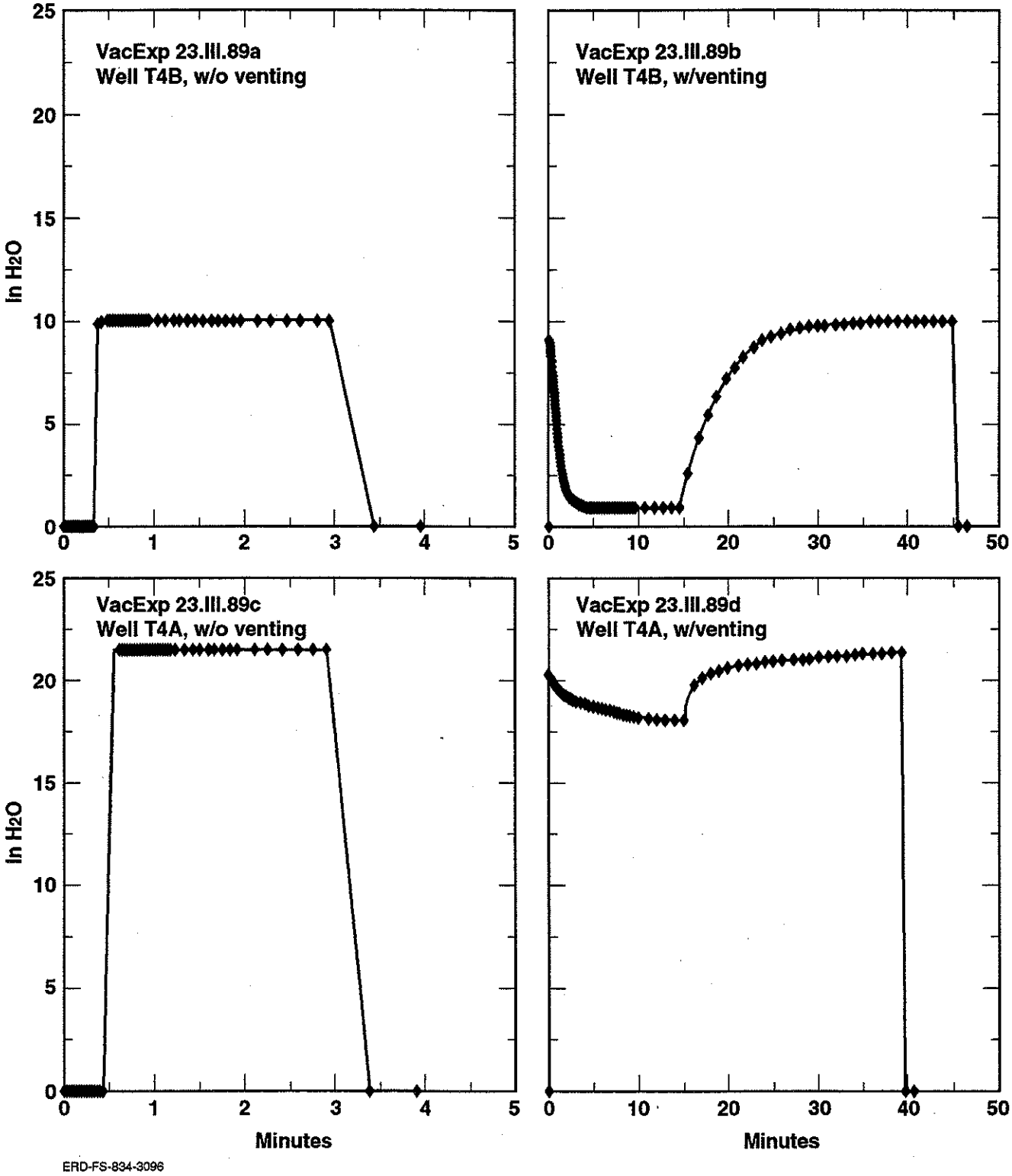

Figure 7-9. Soil vacuum induced by pumping on adjacent wells with a water seal pump. Equilibrium vacuum measured without venting, shown on the left. Response to venting, shown on the right.

7.4.2.2. VOC measurements

Air samples were extracted at regular intervals from the exhaust of the water-seal pump. Samples were collected into Tedlar bags and analyzed with a Photovac gas chromatograph equipped with a photoionization detector (Table 7.4.2.2-1). When the system was started on May 10, 1989, each of the three wells attached to the pump manifold were individually sampled following 5 minutes of pumping; then the valves were closed on wells D3 and D4 to permit pumping from D5 alone. Its TCE concentrations ranged from 200 to 260 $ppm_{v/v}$ in the ensuing 40 day test. When wells D3 and D4 were opened on June 5, 1989, emission levels climbed to approximately 460 $ppm_{v/v}$.

Table 7.4.2.2-1. TCE concentration in effluent air from the soil venting system at Building 834 D-wells Area, May to June 1989.

Date	TCE ($ppm_{v/v}$) in effluent vapor	Comments
5/10/89	850	D3 only, day of test start-up, 5 min. pumping
5/10/89	920	D4 only, day of test start-up, 5 min. pumping
5/10/89	230	D5 only, day of test start-up, 5 min. pumping
5/10/89	200	D5 only, day of test start-up, 30 min. pumping
5/15/89	220	D5 only, continuous pumping
5/22/89	260	D5 only, continuous pumping
5/30/89	240	D5 only, continuous pumping
6/05/89	200	D5 only, continuous pumping
6/05/89	460	D3, D4 and D5, continuous pumping
6/12/89	460	D3, D4 and D5, continuous pumping

7.4.2.3. Estimates of VOC Mass Flow

Flow rates were calculated using the Meriam gauge factory calibration coefficients and the vacuum sensor readings. These calculations were combined with regularly collected TCE concentration data to estimate total poundage of TCE emitted (Fig. 7-10). Apart from two periods of system shutdown, emissions were relatively steady during continuous pumping. For the 37 days of the pumping at the D-series wells in May and June 1989, we estimate that 204 lb of TCE were removed by soil venting and 8 lb by water extraction.

7.4.3. Area of Vacuum Influence

The continuously logged values and the short-term measurements were used to establish the vacuum contour plot shown in Figure 7-11. At the end of the first part of the tests (where vacuum was placed on a single well), approximately 250 ft^2 were under a 2 in. vacuum, with an additional 2000 ft^2 between 1 and 2 in., 4500 additional square feet between 0.5 and 1 in., and about 8500 ft^2 between 0.1 and 0.5 in. of vacuum. The thickness of the affected zone is about 30 ft, and the radial extent of vacuum influence from the pumping of well W-834-D5 was from 60 to 85 ft (Fig. 7-11).

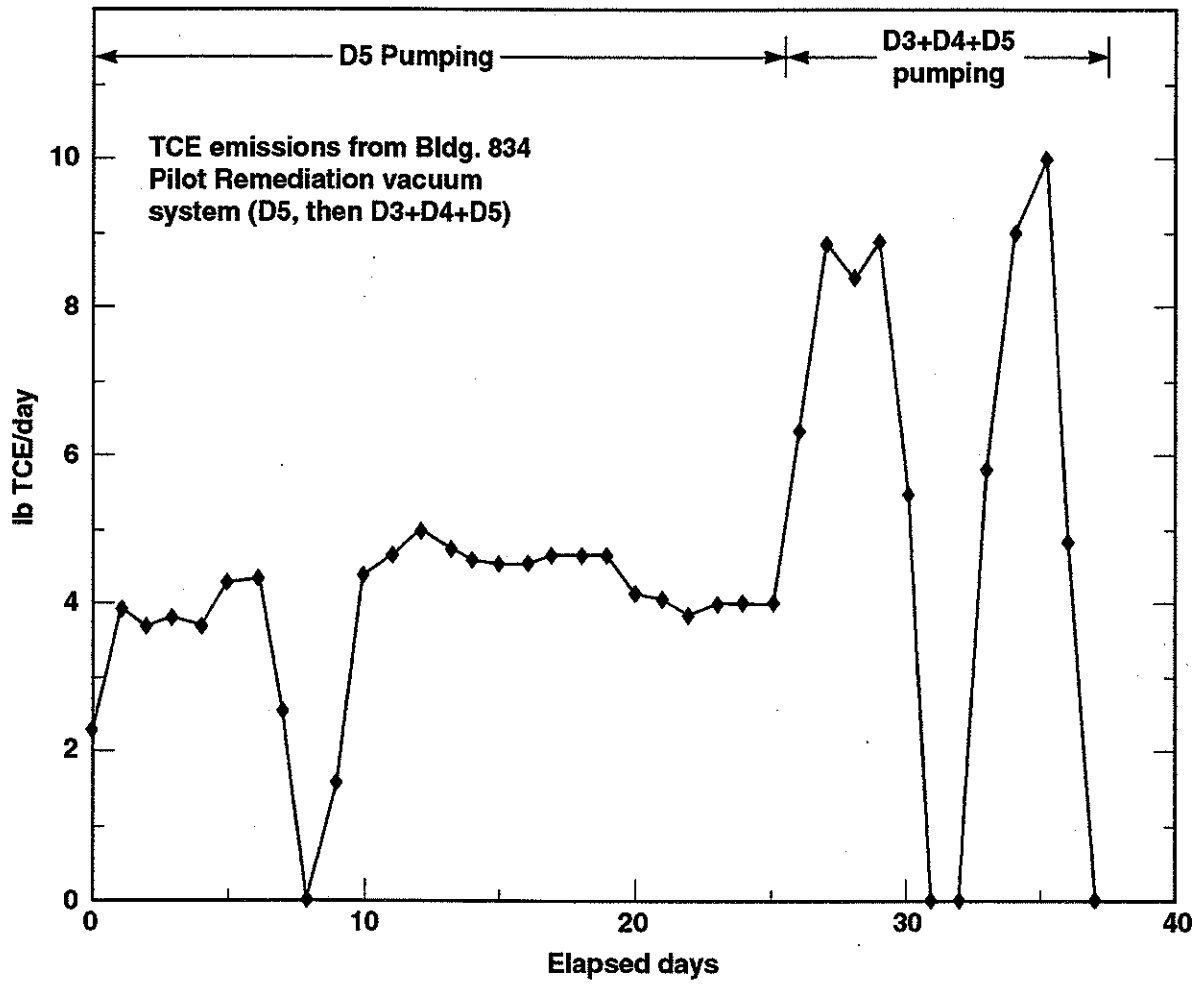

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Figure 7-10. Daily TCE emissions for soil gas venting at the Building 834 Complex between May 10 and June 16, 1989.

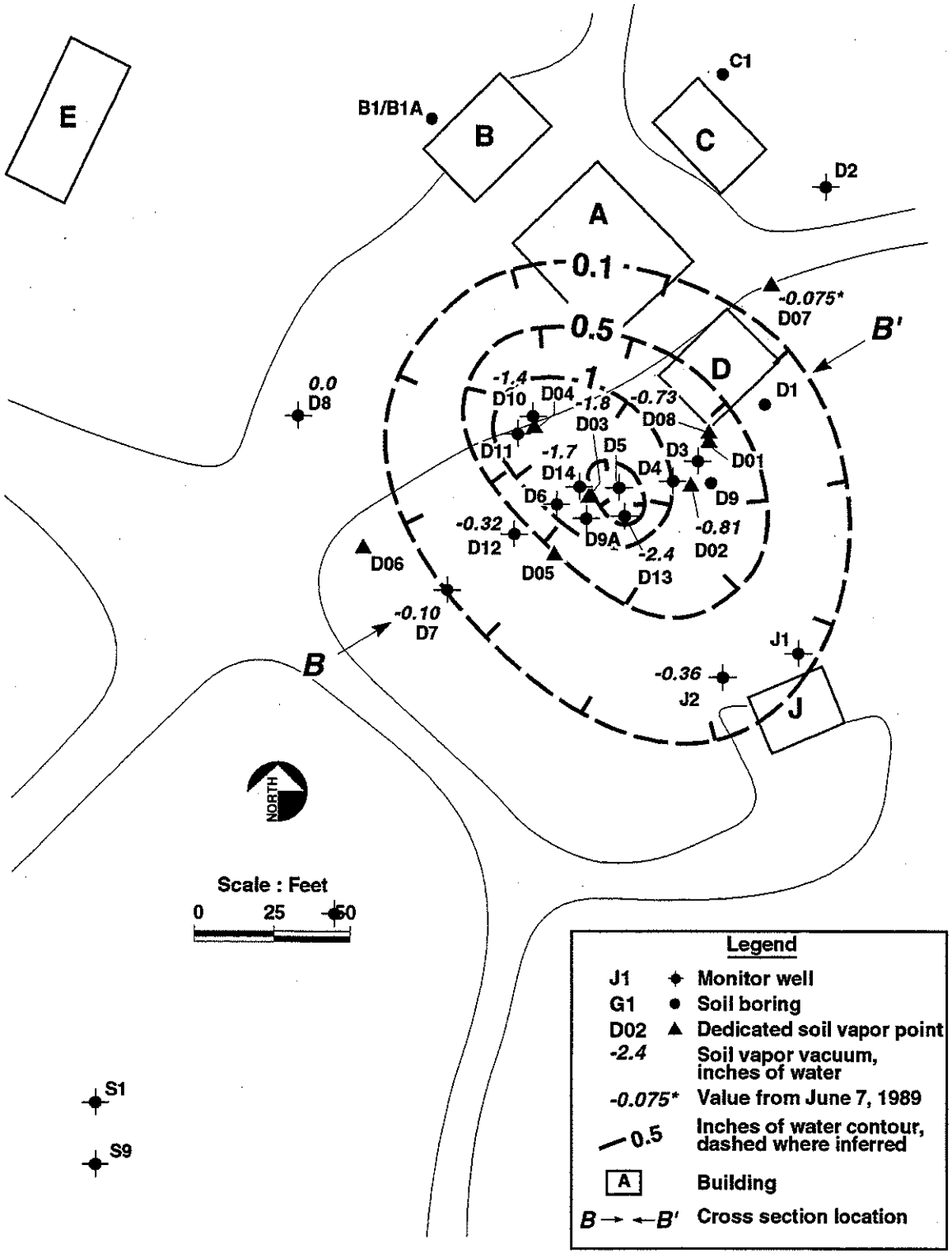

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Figure 7-11. Approximate soil vapor vacuum, June 2, 1989, during pilot testing at the Building 834 Complex.

7.4.4. Changes in TCE Concentrations

To determine the effect of soil vapor extraction on the concentration of TCE in the unsaturated zone, vapor samples were collected at dedicated soil vapor points: D01, D02, D03, D04, D05, D07, and D08 during 1 week in February and on April 25, May 22, and June 5, 1989. Vacuum extraction began on May 10, 1989.

7.4.4.1. Soil Vapor Sampling

The February 1989 soil vapor samples were collected using a constant-flow sample pump and clean glass syringe, described in Section 3.1.3. After the initial sampling, soil vapor samples were collected using a clean Tedlar sample bag, a vacuum desiccator, and a constant-flow sample pump. These subsequent samples were collected using the following procedure:

- A constant-flow sampling pump was connected to the dedicated soil vapor point and run for 25 seconds at 2 L/minutes to purge the sample line;
- A vacuum desiccator was connected to the dedicated soil vapor point and a clean 1 liter Tedlar bag was placed in the vacuum jar. The constant-flow sampling pump was connected to the vacuum jar to evacuate the jar and draw soil vapor into the Tedlar bag;
- When the Tedlar sample bag was filled, it was removed from the vacuum jar and immediately transported to a Photovac GC (gas chromatograph); and
- A vapor sample was obtained from the bag using a clean, gas-tight, glass syringe and injected directly into the Photovac GC and analyzed for TCE.

All soil vapor samples were analyzed for TCE with the Photovac GC, equipped with a photoionization detector. See Section 3.1.3 for a description of the GC analytical procedures.

The results of this sampling are presented in Table 7.4.4.1-1. At all vapor monitoring points, TCE concentration decreased, some up to two to three orders of magnitude, even in sampling points up to 60 ft away from the vapor extraction wells. This indicates that the vacuum extraction is capturing most, if not all, of the soil vapor within the 0.1 in. of water-vacuum contour, which lies between 60 and 80 ft away from the extraction wells. This is not surprising if the volume of soil vapor is compared to the extraction rate. Assuming an area of soil of 15,000 ft^2, 20-ft soil thickness, and porosity of 0.25, the volume of vapor within the 0.1 contour is 75,000 ft^3. At an extraction rate of 40 cfm, 1.5 million ft^3 of vapor were extracted during the first 26 days of the test—about 20 times the volume within the 0.1 in. of water vacuum contour.

7.4.5. Ground Water Capture

The potential effectiveness of ground water extraction can be evaluated either by estimating how much ground water is removed in comparison to the amount flowing through the perched zone, or by plotting water levels and measuring the size of the cones of depression created by pumping. The latter method is difficult to apply to the Building 834 Complex, because either vacuum was used during pumping and representative water-level measurements could not be obtained, or observation wells were not spaced closely enough to define the cones of depression. However, we can compare volumes pumped to the amount of water estimated to be flowing through the perched zone.

Table 7.4.4.1-1. TCE $ppm_{v/v}$ Concentrations at dedicated soil vapor monitoring points in the Building 834 Complex D-Wells Area (Vacuum Extraction Test start 5/10/89).

Monitoring Point Number	D01	D02	D03	D04	D05	D07	D08
Depth (ft)	8.7	12.6	16.2	16.3	15.5	9.8	20
Date: 2/22-2/28/89	>8	1200	260	1300	270	76.1	6500
4/25/89	43.2	1200	74.9	130	130	20.7	9500
5/22/89	NA	2.7	6.1	89.7	11.7	3.4	1086
6/05/89	20.1	0.7	0.7	2.5	2.2	3.2	1950

NA Not Available

Ground water flow from the recharge area to the discharge area (flow through the perched zone) can be roughly estimated at about 100,000 ft^3/year; it could be as low as 50,000 ft^3/year or as high as 150,000 ft^3/year depending on what assumptions are used in the calculation (Section 5.3.1.5), but it probably lies within that range. Vacuum enhanced ground water extraction from wells W-834-T4 and -T4C was about 20,000 gal in 6 months (Section 7.3), for a rate of about 5,000 ft^3/year. Comparing this to the estimated throughput of 50,000 to 150,000 ft^3/year yields an estimate that the T4 extraction wells were capturing about 3 to 10% of the ground water flow through the perched zone.

During the October to November 1988 test at wells W-834-D-4 and -D5, up to 80 gal of ground water per day were removed by vacuum enhanced pumping. Since this rate probably could not be sustained indefinitely, a lower flow, on the order of 60 gpd, will be assumed for long-term pumping. Pumping constantly at 60 gpd would yield about 3000 ft^3/year. This is about 2 to 6% of the estimated ground water flow through the perched zone.

These percentages indicate that if complete capture of the ground water by pumping in the perched zone is desired, several times the current number of extraction wells will have to be pumped.

7.4.6. Problems Encountered with Water Treatment

During the May to June 1989 operation of the Dual-Tank Air-Stripping System in the D-wells area, a potential problem was identified in the treatment of water being pumped from the vapor extraction wells. This stream was being transferred to one of a pair of 500-gal plastic tanks, where it was aerated (from a single compressor) batchwise, until it could be shown (by rapid turn-around GC analysis with an on-site Photovac GC) to have been stripped of TCE to below detectable levels (<5µg/L).

At the outset of the pumping test started in mid-May, the time required for batch aeration was approximately 80 hours. However, by the end of June, this had gradually lengthened to more than 350 hours, even though the input TCE concentrations had not changed appreciably. Routine operation of the system was stopped until the reason for the extended aeration requirement had been identified. The following additional observations on the system were made before a series of simple experiments isolated the problem:

- Algae growth had occurred in the bubbling tanks, particularly during long filling cycles before the vacuum extraction system was started. To reduce this problem, a shed with turbine ventilators in its roof was erected over the tanks, to shade the tanks and suppress algae photosynthesis. This did alleviate the algal bloom, but provided a barrier for air circulation around the tanks. Also the air compressor intake was not initially rerouted outside the shed, so recirculation of the bubbled TCE may have been possible. We are

replacing the compressor with blowers (one per bubbling tank) with outdoor intakes. The waste-air will be directed (not needed for bubbling) through the turbine ventilators to actively drive them and increase forced ventilation in the shed.

- TCE is known to permeate through some plastics, particularly PTFE (Teflon®) tubing (Dorothy Bishop, LLNL, personal communication). We hypothesized that since the tanks were not bubbled until filled, that TCE might be dissolving into the plastic material of the tanks, only to slowly leach back into the water as the tank contents were stripped by aeration. To test this hypothesis, we filled a tank with contaminated well water in the "normal" way, and allowed it to stand without bubbling for at least 2 days, then we sampled the water and pumped it into a second tank. The first tank was quickly rinsed with clean water three times, and then filled with a charge of clean water, and resampled. This clean water was allowed to stand, and was resampled after 4 days, to determine the extent TCE might have leached in. Operational remedies may include bubbling while filling the tank, different tank geometry (wide-mouth or trough shapes) or, in a worst case, using metal tanks.

- The shed cooled the water in the tanks somewhat, lowering the vapor pressure of the TCE. In conjunction with the "TCE-leaching" experiment described above, we filled tanks outside the shed, and monitored temperatures in parallel with thermocouples and data logging. This was done to quantify the actual differential so that we could calculate the possible extent of temperature influence. The results of the tests are described below.

The shelters enclosing the tanks cooled the water, achieving about 5°C lower maximum temperatures each day (Fig. 7-12), which would tend to slow volatilization of TCE by only a relatively small amount. Refer to Table 7.4.6-1 for the following:

- The concentrations of TCE in the water used to fill the plastic tank,
- The concentration after standing 4 days,
- The analysis of the in-going domestic water used for washing,
- The first wash-water concentration, and
- The concentration of TCE leached into the clean water that filled the tank.

When the tank was emptied (from the tank bottom) and rinsed, a strong jet from a hose was needed to dislodge the oily scum which clung to the walls; residual water and sludge were vacuumed from the tank bottom with a wet-dry shop vacuum. While a significant concentration of TCE was present in the first rinse water, this fraction contained water that had not been vacuumed out, as well as floating oily material. The second and third washes ran clear. If the efficiency of TCE removal by washing was the same for the second and third washing, the last rinse water would have had concentrations well below 100 μg/L (ppb). Clearly the tank itself contributed several hundred parts per billion of TCE over the period of this test.

The oily material was collected and analyzed by GC/MS by Brian Andersen of the LLNL Chemistry and Materials Sciences Department (Fig. 7-13). TCE was identified with greater than 90% probability in the early eluting volatile fraction, as was t-butanol. The peaks from 15.8 to 36 minutes were a complex mixture representing the bulk of the oily material. However, although the MS analysis revealed hydrocarbon fragments in many of these compounds, the overall signature was not one of a hydrocarbon lubricating oil. Moreover, several of the compounds possessed fragments that suggested the presence of silicon. Interviews with a retired technical supervisor at the site (Dale Stupfel) revealed that the TCE used at the Building 834 Complex had for some time in the past been used in a mixture with silicon-oil heat exchange fluids (until the latter 1970s, in particular T-BOS, tetra 2-ethylbutylorthosilicate, NIOSH #VV9400000, CAS RN: 78137). Although this material has not yet been unequivocally

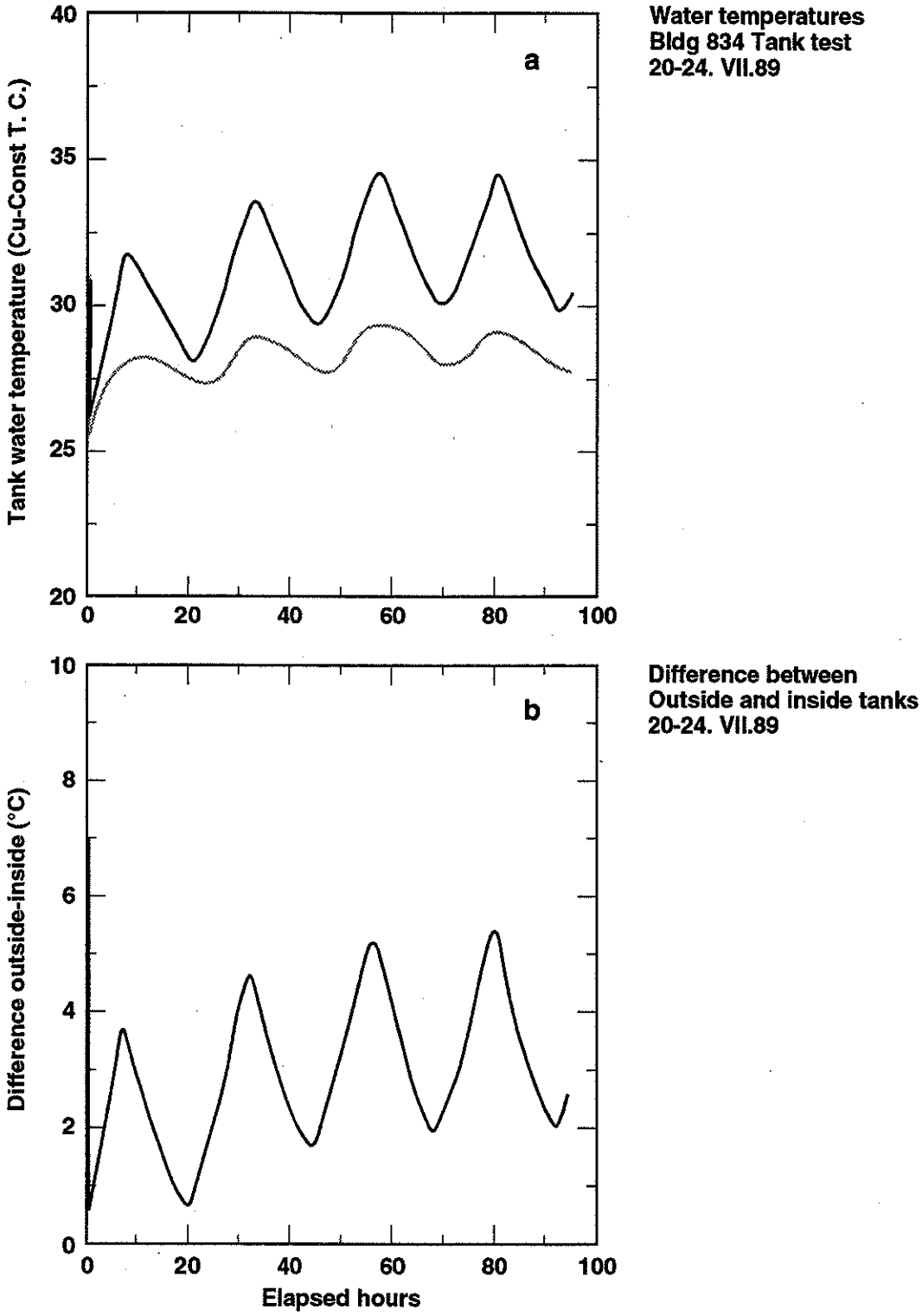

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Figure 7-12. Water temperatures measured in bubbling tanks outdoors (upper trace) and in enclosure, shown in frame "a." Temperature differential between the two tanks, shown in frame "b."

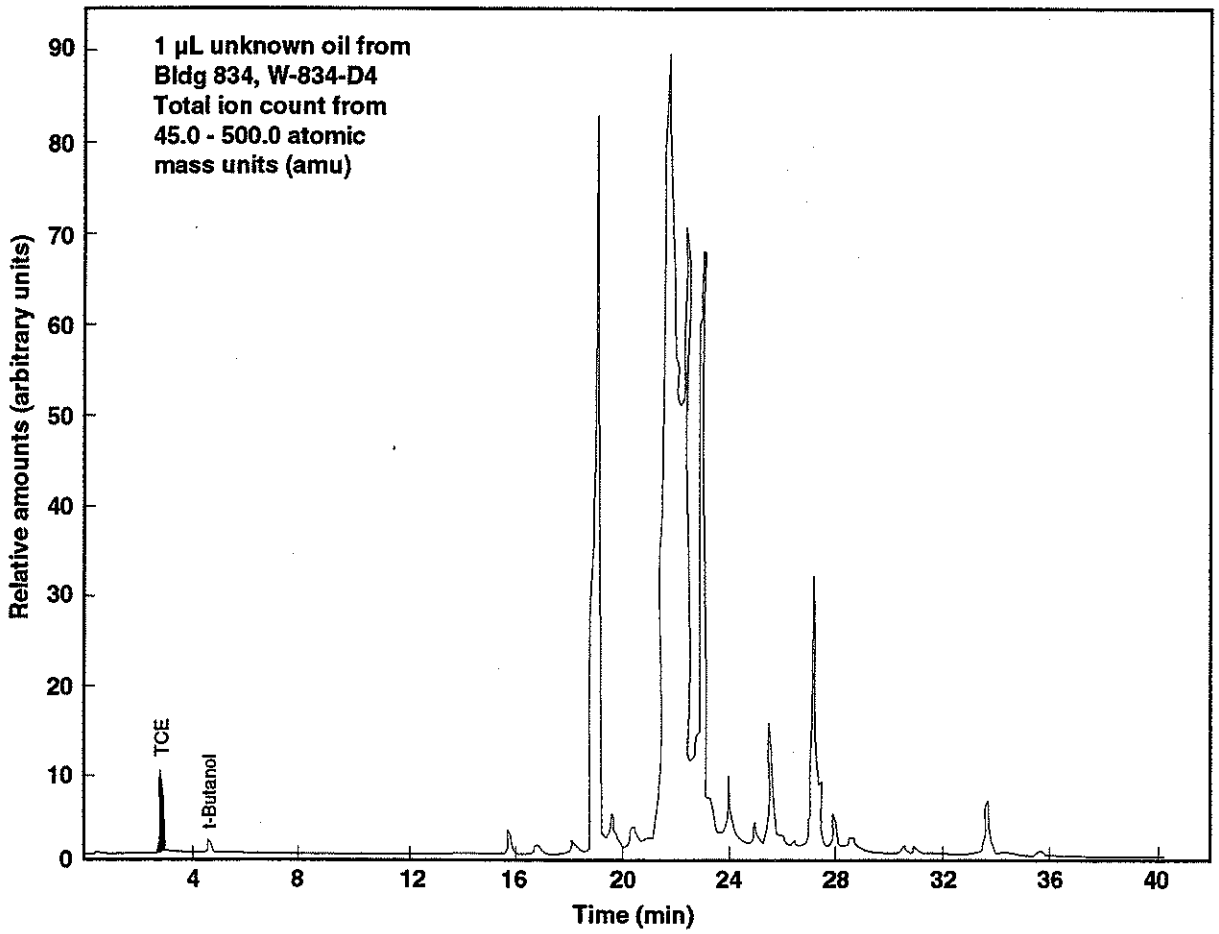

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Figure 7-13. GC/MS analysis of unknown oil skimmed from the top of the bubbling tank.

Table 7.4.6-1. Analytical results for TCE from test for solvent permeation into the plastic of bubbling tanks.

Sample description	TCE (μg/L)	Comments
In-going water pumped from wells	180,000	Close to other TCE values observed in May to June 1989 tests
Well water after standing in unbubbled tank for 4 days	21,000	
Lab water used to rinse and fill tank	<0.5	
First wash of tank	3,300	~1.5 L of an oily substance skimmed from the top of the tank; first rinse water was still turbid; second and third ran clear
"Clean" water after 4 days in tank	760	

identified from the mass-spectral data, since the t-butanol is a likely hydrolysis product of T-BOS, we conclude that this floating product is likely to be residual heat-exchange oil.

Based on the analysis of peak areas from this chromatogram, the TCE peak was estimated to be 0.52% of the total mixture, or approximately 5200 μg/L (ppm) TCE. This is roughly 28 times the TCE concentration of the incoming well water as the tank was filled, and 250 times the concentration after the water stood in the tank for 4 days (when the oil was recovered). Since the oily material also clings to the walls of the tank when drained, this oily material provides another route for possible carryover of TCE from one batch to the next.

Although simple aeration of the well water from this installation appears to be a potentially efficient method for remediation, the presence of heavy, non-volatile components presents a significant complicating factor. We have concluded from the "TCE permeation test" that the tanks used for bubbling will probably have to be replaced with metal tanks that do not take up the solvent, unless continuous aeration during filling prevents uptake. We further conclude that tanks with conical bottoms may be needed and more efficient floor drains used to facilitate removal of any sludges that might build up. A floating-product separator will have to be interposed between the wells and the bubbling tanks, or down the wells to remove oils from well water. Alternative means of dealing with this problem are being reviewed.

7.5. Conclusions

Pilot remediation for TCE at the Building 834 Complex has centered on developing and testing soil vapor and ground water extraction systems and an air-stripping system for water treatment. Soil-vapor extraction with a 40 cfm liquid-ring vacuum pump capable of developing a 28-in. Hg vacuum appears to be successful, capturing soil vapor with TCE from a 60 to 80 ft radius of extraction wells in the D-wells area. Within 2 to 4 weeks of vacuum extraction, TCE concentrations in areas away from the TCE release site near well W-834-D3 dropped one to three orders of magnitude to less than 3 $ppm_{v/v}$. This indicates that substantial cleanup of these areas is achievable in a matter of weeks to a few months. TCE concentrations in monitoring points near the release area, D01 and D08 dropped from a high of 43.2 $ppm_{v/v}$ to 20.1 $ppm_{v/v}$, and from a high of 9500 $ppm_{v/v}$ to a low of 1950 $ppm_{v/v}$, respectively. The stabilization of TCE concentrations at relatively high levels at these points reflects a limit that is probably controlled by partitioning of TCE from soil and water to the gas phase. This suggests that it will take several months or longer to clean up TCE where it is present in high concentrations at the release area.

We estimated total poundage of TCE emitted by using flow rates calculated with the Meriam-gauge factory-calibration coefficients and the differential vacuum sensor readings, combined with regularly collected TCE concentration data (Fig. 7.4.2.3-1). Apart from two periods of system shutdown, emissions were relatively steady during continuous pumping. For the 37 days of pumping during May and June 1989, we estimate that 204 lb of TCE were removed by soil venting, and 8 lb were removed by water extraction.

During initial operation, the Dual-Tank Air-Stripping system operated effectively. As pumping continued, however, TCE began sorbing into the walls of the plastic tanks, aided by an oily substance that was being removed from the extraction wells. To overcome these problems, the full-scale system will employ an oil-water separator to keep oil out of the tanks and may employ steel tanks. The submersible turbine pumps used for ground water extraction will be replaced with positive displacement pumps to reduce emulsification of the oil and water, thereby improving the efficiency of the oil-water separator.

Cleaning Contaminated Soil Using Electrical Heating and Air Stripping

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Abstract: In the summer of 1992 we conducted an engineering demonstration of direct electrical soil heating for enhancing the removal of a volatile organic contaminant, trichloroethylene (TCE), when compared to standard air stripping methods. Six electrodes were buried in shallow boreholes so that a region about 7 m in diameter and 4 m in height was heated by ohmic dissipation of powerline-frequency electrical currents supplied by a diesel generator. Air stripping of TCE contamination from the same region was accomplished from a single well at the center of the heated volume. Prior to heating the TCE concentration in the vapor was about 60 parts per million by volume (ppm_V). Some concentration data were lost shortly after electrical heating began, but the highest concentration during heating was about 130 ppm_V, measured just when sampling data was restored, after which the concentration dropped rapidly to around 5 ppm_V over a period of about 25 days.

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Introduction

Air stripping is an established technique for removing volatile organic contamination from soil. Experience with the method has come from mathematical modeling (e.g., Massmann, 1989; Wilson *et al.*, 1987; Johnson *et al.*, 1990; Lingineni and Dhir, 1992), from physical model studies in the laboratory (Brown *et al.*, 1987; Marley and Hoag, 1984; Thornton *et al.*, 1984; Hoag *et al.*, 1987; Crow *et al.*, 1987) and from field demonstrations(e.g., Agrelot *et al.*, 1985; Batchelder *et al*, 1986; Crow *et al.*, 1987; Hoag *et al.*, 1987; Thornton and Wootan, 1982; Blake and Gates, 1986; Fall and Pickens, 1988). It is a technique where surface air is moved through the *in situ* subsurface soil. As the compounds evaporate at the air-product interface, the air stream carries the vapors away from their source to a borehole where they are removed from the ground. Removal of the vapor from the air stream is accomplished by a number of means at the surface. What is important is that this is a simple and inexpensive way to clean volatiles from soils in place.

The purpose of the work reported herein is to demonstrate thermally enhanced air stripping by *in situ* electrical heating of the soil or rock mass that is being air stripped. If direct electrical heating is shown to enhance air stripping of VOCs from soil in an economically beneficial way, the technique should have application for remediation of many contaminated industrial and governmental sites.

The rationale for combining heating and air stripping may at first seem obvious; the vapor pressure of all organic compounds (as well as that of water) increases with temperature. Thus at elevated temperatures an air stream should remove contaminant vapors at a higher rate (Johnson *et al.*, 1990). However, many processes are operative in air stripping and it is not obvious how much heating will enhance VOC removal. For example, based on one dimensional calculations and physical modeling, Lingineni and Dhir (1992) assert that heating the inlet air will enhance extraction rates only for less volatile contaminants for which the evaporation front moves slower than the thermal front in the soil. Direct electrical heating of a heterogeneous soil is likely to have a different effect than such simple calculations suggest.

We will discuss three aspects of air stripping in the context of the work we are to report herein: 1) The rate of volatile removal is strongly dependent on the temperature. 2) Air will move through the subsurface only within the most permeable parts of the soil leaving the less permeable regions of soil contaminated. 3) Air stripping is possible only in the unsaturated zone. We will now discuss how each of these points relates to moderate heating of the soil being treated.

For many organic compounds the relation between vapor pressure and temperature can be expressed as

$$\log p = b - (0.05223\ a/T)$$

where p is the pressure in mm of mercury of the saturated vapor at absolute temperature T with constants a and b depending on the compound. Figure 1 shows the relationship for a few compounds of interest (Weast, 1989). Using this relationship alone to calculate vapor pressures in contaminated soil is an oversimplification. Surface tension, solubility in water and sorption on solid surfaces affect the actual vapor pressure. However, to explore the possible effects of heating on vapor removal we will assume these effects are small.

Carbon tetrachloride is a good example of a highly volatile compound. Between 20°C and 40°C the vapor pressure increases from 91 to 221 mm Hg--nearly a 2.5-fold increase for a modest 20 degree temperature rise. If the vapor above a free surface is continuously swept free of carbon tetrachloride, which is the goal for air stripping, then the above data translates into an increase in evaporation rate, and extraction rate, of about 2.5 times for the electrically heated case as compared to air stripping alone. This effect is the principle benefit and the basic rationale for heating the soil to enhance air stripping.

Air stripping is not typically considered an option for removing so called nonvolatile hydrocarbons from soil. An important benefit to thermally enhanced air stripping may be the ability to remove so called non-volatiles. Consider toluene as an example with a vapor pressure of only 22 mm Hg at 20°C. At 40°C the pressure is 61.5 mm Hg which is comparable to the value of volatile hydrocarbons at ambient temperature. The point is that heating the subsurface may make air stripping of nonvolatile compounds practical.

One limitation of conventional air stripping results from the natural heterogeneity of soil. The gas permeability of typical unsaturated soil can vary many orders of magnitude on a spatial scale of centimeters or kilometers. Of course, forced air movement is controlled by this heterogeneity. Our only significant control over where fluids flow underground is by drilling--we can force flow along a well bore but once the fluid leaves the well we have little control. The result for air stripping is that air pumped underground follows isolated paths of least resistance which are often a small part of the volume to be cleaned. Figure 2a is a conceptual representation of this operation of air stripping in normal soils. As surface air with a low relative humidity displaces the existing pore air with a higher relative humidity, the pore water (and VOCs) evaporate and the relative gas permeability increases. Therefore, the longer air is pumped underground, the larger the permeability contrasts become making it even more difficult to get air flow into the tighter parts of the soil. This is an unfortunate state of affairs since two mechanisms conspire to concentrate the VOCs in the low permeable regions where the air flow cannot reach them. First, capillary tension is higher so water content is higher as is any dissolved contaminant. Second, soil particle surface area is greater so that much more material can be held by surface adsorption.

In a typical inhomogeneous vadose soil, gas permeability is often anti-correlated with grain size - the coarse units have higher permeability, the fines a lower permeability. It is also true that the fine grained soils tend to have the lower electrical resistivity. This is true because of two effects. First capillarity in the smaller pores is higher so that in the vadose zone these units hold more water than the coarser-grained soil. Often the effect that dominates the electrical properties is the presence of clay minerals which are preferentially found in the fine-grained, low-permeability soils. Electrical conduction in clays is controlled by surface conduction along the charged double layer (Keller and Frischknecht, 1966) The point is that there is a natural tendency for electrical current and air to move separately through the subsurface; gas moves through the highly permeable coarse material and electrical current moves through the less permeable fine-grained material. This coincidence can be exploited to enhance air stripping.

The distribution of energy deposited in the ground is controlled by the current distribution and its resistivity according to the volume integral

$$P = \int \bar{J} \cdot \bar{E} \, dv$$

where P is the power dissipation, $\bar{J}$ is the current density, and $\bar{E}$ is the electric field. Since the current is channeled preferentially in the low permeability paths these are the regions that are preferentially heated. As the temperature rises in these units the vapor pressure increases. The volatiles then move down the pressure gradient, out of the tight material, to a cooler, more permeable zone. But this region is subject to advective movement from the air stripping. In short the volatiles are driven from the fines via pressure gradients generated by the resistive heating and then removed from the permeable zones by the time-tested process of air stripping. The process is represented conceptually in Figure 2b. It is not often than Mother Nature provides such circumstances which we can exploit.

Another limitation of air stripping is that it can only be done above the water table where the gas permeability exists to allow air flow. Sometimes an insoluble contaminant which is initially in the unsaturated zone is trapped in the saturated zone as the water table rises. A standard protocol is to dewater the region and then proceed with air stripping. Johnson (1989) has shown important experimental results that contradict the intuitive appeal of this approach. In a large physical model study 205 liters of synthetic gasoline were released into unsaturated soil and eventually settled onto the water table. Vapor concentrations within the unsaturated zone were very high. Then, the water level was lowered about 0.4 m but soon after raised to its original position. The free product was trapped in the saturated zone and the vadose vapor concentrations soon fell to near zero. In an effort to re-expose the contaminant, the water level was lowered again about 0.4 m. However vapor concentrations remained near zero. Johnson concludes that at least for small spills like he studied: 1) significant quantities of product can become trapped as

residual blobs in the groundwater zone; 2) these blobs are not readily re-exposed to pore air by lowering the water table; 3) the effectiveness of soil vapor extraction for removing this trapped residual is poor; and 4) the trapped product can provide a long-term source of groundwater contamination.

Raising the temperature in such a situation may make air stripping practical. At higher temperatures the trapped blobs will be re-exposed to the air stream as the confining water layer evaporates away. This process will happen much more quickly at elevated temperature than at ambient.

Background

Electrical heating of soil is not a new idea. Both powerline-frequency (60 Hz) and radio-frequency (a few MHz) heating have been used in the oil industry to reduce the viscosity of the bitumen to the point where oil can be recovered from the formation. An excellent article by Chute et al (1988) presents a survey of laboratory and field applications of electromagnetic reservoir heating. They conclude that in general powerline-frequency methods are preferable when 1) the desired temperatures are lower than the *in-situ* steam temperature, and 2) when the formation contains sufficient water so that inter-well resistances are low enough to permit acceptable heating rates at applied voltages of less than a few thousand volts.

In contrast radio-frequency induction methods should be considered when 1) the formation is to be heated to temperatures above the *in-situ* steam temperature, and/or 2) where the formation contains very little initial moisture. However, there can be substantial capital costs associated with the conversion of powerline-frequency energy to radio-frequency energy. In simple terms, 1 watt of 60 Hz power is much cheaper than 1 watt of radio-frequency power. Additionally 60 Hz power transmission and distribution equipment is much easier and cheaper to maintain. The reader should see Bridges et al (1988) for a field example of radio-frequency heating.

Powerline-frequency heating methods for remediation of volatile organic compounds in soil and groundwater are known to be under investigation by two groups in the United States. Electrical soil heating was successfully demonstrated by LLNL in the field on an engineering scale in 1991 (Buettner *.et al.*, 1992 and Aines *et al.*, 1992), and some modeling and a laboratory-scale experiment was conducted at Pacific Northwest Laboratory (Heath, 1992). This paper describes work currently being done at the LLNL and to the authors' knowledge represents the first demonstration of the use of powerline-frequency electrical heating in combination with vacuum venting for remediation of VOCs.

Prior to this demonstration, we conducted an engineering test of some of the design ideas at a site in the Livermore Valley, CA that was not contaminated. The purpose was to

refine the design (make our mistakes) before working at a contaminated site. The test was designed to check the elements of the electrical heating system, therefore, no vacuum extraction was performed. However, the arrangement of heating electrodes, the level of power delivered and operating procedures were very similar. Several borehole completion schemes were tried in order to optimize the coupling efficiency between the electrodes and the ground. This design information was used in the demonstration that followed.

This engineering test ran for 15 days during which 14,920 kW hr of energy was dissipated in the soil. Temperatures at the center of the pattern rose from 19°C to 44°C by the end of heating for an average increase of 1.7 $^{\circ}C\ day^{-1}$. The central temperature continued to rise for several days afterward to reach a peak of 54°C. The result was a figure of merit for the heating process of 1.34 kW hr/$^{\circ}$C m^3. The heating rates agreed well with those predicted based on simple calculations. This test is reported in more detail by Buettner *et al.* (1992).

Concept and Theory

Joule heating is conceptually very simple. When electric currents flow through soil, power will be dissipated through ohmic losses, and this is manifested by heating of the soil. This process is analogous to the operation of the heating element in a simple home space heater or the heating element of an electric range. If one chooses to use powerline frequency heating, then power sources are readily available from the commercial power grid or motor-generators.

We describe here the simple theory for such heating. We will confine the analysis to the case of a two-dimensional model with homogenous electrical and thermal properties. In addition the effects of phase changes and fluid flow through the soil are ignored.

Expected initial heating rates are based on solutions to the heat equation

$$\frac{\partial T}{\partial t} = \frac{k}{c\rho}\nabla^2 T + \frac{U}{c\rho} \qquad (1)$$

where T is the temperature, k is the thermal conductivity (joule/m·°C·sec), c is the specific heat (joule/kg·°C), ρ is the density of the soil (kg/m^3), and U is the heat source term (W/m^3). The source term is given by

$$U = \sigma\left|\bar{E}^2\right| \qquad (2)$$

where σ is the electrical conductivity (S/m) and $\bar{E}$ is the electric field (v/m). The

electric field is found from the gradient of the electric potential ,V(x,y), which is the solution to Laplace's equation. It is not difficult to show that the solution in two dimensions for line source currents has the form (see Appendix A of this page for details of the analysis)

$$V(x,y) = -(2\pi\sigma)^{-1}[\ \pm I_1 \ln(r_1) \pm I_2 \ln(r_2) \ldots \pm I_n \ln(r_n)] \qquad (3)$$

where I_i is the current per unit length at the ith location, the positive sign is assigned to current sources, the negative sign to current sinks, and r_i is the distance from some observation point (x,y) to the source or sink at the ith location.

Our calculations for the heating rate are for early time when the first term on the right-hand side of equation (1) is small compared to the second. When the current is first turned on this will be true since the temperature distribution is uniform ($\nabla^2 T = 0$). In early time then the temperature will vary linearly with time according to

$$T = T_o + \frac{U}{c\rho}\Delta t \qquad (4)$$

where T_o is the starting temperature and Δt is the elapsed time. Even at later times the linear relationship can hold provided that the "Laplacian" term of equation (1) remains small compared to the heat source term. The validity of this assumption can be tested by examining the time behavior of the temperature readings for linearity.

We now show some plots of the calculated spatial distribution of heating rates based on equations (2), (3), and (4). Two cases are considered: 1) a 6-spot pattern with 6-phase currents, 2) a 6-spot pattern with 3-phase currents where the electrical phases are periodically shifted between electrodes so that the "cold spot" between two adjacent electrodes connected to the same phase is turned into a current flow path when these electrodes are connected to different phases. From here on case 2) will be denoted as 6-spot, 3-phase, composite. In case 1) the phase angles of the currents as one proceeds around the circular pattern are 0, 60, 120, 180, 240, and 300 degrees while in case 2) they would alternate between say 0, 0, 120, 120, 240, 240 degrees and 0, 120, 120, 240, 240, 0 degrees. Because heating takes place on a time scale of days or weeks changing the phasing every few days as in case 2) is quite practical.
The calculations are based on equal total power inputs to the ground. The current injected at each electrode is 10 A/m, the electrical conductivity is taken to be 0.1 S/m (typical for Livermore soils), the volumetric heat capacity ($c\rho$) for average soil is $2X10^6$ joule/m^3°C (Carslaw and Jaeger, 1959), and the diameter of the circular pattern is 6.1 m. The result of these calculations is shown in figures 3a and 3b respectively. In each case 3-dimensional surface plots of the $\log_{10}$ of the heating rate are shown.

There are some features worth noting in these plots. The heating rate distribution for the 6-spot, 6-phase case is slightly more uniform than for the 6-spot, 3-phase, composite case, however the differences are small. This is readily apparent from an examination of figures 3a and 3b. Specifically, at the center of the pattern the heating rate is only 25% less for the 6-spot, 3-phase, composite heating case, and at the periphery of the pattern, midway between wells, the heating rate is less than 3% different.. At first glance a 25% difference might be considered to be very great. However, this difference must be viewed in light of the natural variability in soil conditions. The soil electrical conductivity at a site might easily vary by nearly an order of magnitude over small distances so that the actual fine-scale distribution of energy deposition is really controlled more by soil conditions than electrode configuration and phasing.

As a practical matter, three-phase heating has significant advantages over six-phase heating in that the power generating and handling equipment is readily available and affordable. Three-phase power is available directly from electric utility companies and from motor-generators which one can rent or buy. The slight advantage that 6-spot, 6-phase heating has in uniformity over 6-spot, 3-phase, composite heating may not be worth the extra investment required to produce 6-phase power.

Experiment Design

The demonstration was conducted at a facility of the Lawrence Livermore National Laboratory (LLNL) known as Site 300, located just outside Livermore, CA. At the building 834 complex, TCE had leaked from surface piping during the mid 1960's resulting in a contaminated, shallow perched unsaturated zone less than 30 m deep. The highest measured concentrations of TCE in the sediments are 970 to 12,000 mg/kg (ppm) and in ground water from 170,000 to 510,000 μg/L (ppb). The total release of TCE was estimated to be 2079 L. Small amounts of other VOCs have been detected at the site.

The hydrostratigraphy in the area consists of six units: a perched zone, a perching horizon, transition zone, Neroly upper sandstone, Neroly aquitard and Neroly lower sandstone (regional aquifer). The clay, siltstone and claystone perching horizon is 8 to 13 m thick. It is the first barrier to ground water from the perched zone to the lower Neroly sandstone 93 m below. The second barrier to water from the surface is a saturation and permeability contrast across the contact at the base of the perching horizon and the top of the upper Neroly sandstone. The third barrier is the Neroly aquitard which is 13 to 23 m of siltstone and claystone. There are isolated, saturated sandstone lenses in the perching horizon which appear to be hydraulically confined. The site is geologically heterogeneous with units of high permeability contrast.

The only natural source of recharge is precipitation, which is only about 25 cm per year. Evapotranspiration of the perched zone ground water is thought to be high enough to

remove perched zone ground water at about 5 to 15 times the amount of recharge and through flow. Therefore, evapotranspiration is likely more than adequate to dissipate ground water discharge for the perched zone without any downward flow. A more detailed description of the site geology, hydrology and contamination is reported by Bryn *et al.*, (1990).

The region adjacent to well W-834-S2, about 250 m from the contaminate source, was chosen for the demonstration. Figure 4a shows the well construction and lithology from geologist's logs in W-834-S2 and two nearby wells. The TCE soil concentrations measured in one of the wells ranges up to only 100 ppb although there is anecdotal evidence that the odor of TCE was noticeable at the collar of W-834-S2 before the demonstration. In early 1988 the TCE concentration in the perched ground water near well W-834-S2 was 12,000 ppb but in 1991 no perched water was detected when we drilled to 12 m depth to install heating electrodes.

Five of the six electrodes were equally spaced around the extraction well W-834-S2 as shown in Figure 4b. The sixth well, JH-834-S2, was offset from the pattern because it had to be redrilled after a drill bit was lost during drilling in the original location. The wells were completed with sand backfill and a bentonite plug near the top (figure 4a). The 12 m depth was chosen to coincide with the screened depth in the extraction well and the higher concentrations of TCE found in nearby wells at that depth. The top of the perching horizon was at about 11 m depth. This geometry allowed for the heating of a volume of soil approximately 154 m^3 (roughly 7m in diameter and 4 m high) centered on the extraction well screen. The goal was an average temperature increase in this target volume of 20 to 30°C.

In each heating well a small diameter tube was used to provide water to the electrode from a surface source. This was needed to keep the resistivity at a reasonable low level immediately adjacent to each electrode; the current density was high enough very near the electrode to boil off the water, produce a resistive sheath around the electrode and force the current to small values. A thermocouple was placed in each heating well at the top of the electrode and two were put in the extraction well, one at 14.6 m and one at 8.5 m, to measure the air stream temperature.

Three phase electrical power for heating was supplied by a 125 KVA diesel generator operated at a nominal constant voltage of about 400 VAC between phases. Pairs of adjacent electrodes were connected to each phase. Operation was only during the day for continuous heating of periods as long as 16 hours.

Safety was a major concern. The principle danger was the electrical shock hazard which was mitigated by several physical and administrative controls. The physical controls included a six foot fence with a single entrance. A "kill" switch that turned off the generator was located at the gate. The administrative controls included restriction to the

fenced area only when the power was off and through measurement of touch potentials (e.g., voltage between the generator and ground) and step potentials (i.e., voltage between two points on the surface separated by a stride) outside the fence. An operational safety procedure enumerating all the controls was used to define the detailed operating policies. The demonstration was conducted without incident.

The TCE vapors were removed from the central well in the pattern (W-834-S2) at a typical suction of 8 pounds per square inch (psi). and conducted by a 4-inch diameter PVC pipe to a system for removing the contamination using activated carbon canisters. Effluent flow rate was measured automatically and at regular intervals by a laminar flow type meter located in the 4-inch diameter PVC pipe between the extraction well and the canisters. To measure the TCE concentration in the effluent, a gas sample was pumped from the 4-inch diameter line through a small diameter stainless tube to a gas chromatograph. Sampling, measuring, and data storage operations for both flow rate and TCE concentration were under computer control. Around day 62 of the demonstration we discovered that the stainless steel sampling tube between the 4 inch line and the gas chromatograph had become plugged so that we began supplementing the automatically sampled data with samples collected in a syringe from the 4-inch pipe. The vapor sampling system is described in more detail by Daley (1992).

Results and Discussion

Air stripping began on April 23, 1992 and electrical heating began 36 days later on May 28. Nearly continuous heating (during the day) and air stripping (day and night) continued for the next 47 days until July 14. Air stripping was terminated the day after heating stopped. TCE concentration versus time in the air removed from the extraction well is plotted in figure 5. The cumulative electrical energy delivered to the electrodes and temperatures in the extraction well are shown in figure 6. The discontinuous nature of the plot reflects daytime-only operation. Air temperature within the extraction well, on the same plot, begins at 16°C and reaches 38°C at the end of heating. The temporal behavior clearly follows the smoothed energy input curve. Temperatures at the heating electrodes (not shown) were within a few degrees of boiling by day 12 of heating. Figures 5 and 6 constitute the bulk of the experimental data.

A total of 9600 kWhr (3.46×10^6 joules) of electrical energy was dissipated during the demonstration. If we assume that all of this energy was used to raise the temperature of the 154 m^3 target volume inside and immediately adjacent to the electrodes, then the average temperature increase for average soil should have been 112°C. At the end of heating extraction well temperature was about 38°C and the periphery near boiling but the temperature began relaxing at the end of heating as the thermal front diffused inward from the hotter electrode region. The average final temperature in the target volume is not known because our array of sampling thermocouples was inadequate, but it lies somewhere between 38°C and 100°C. If we assume that this final temperature was 50°C,

then the average temperature increase was 34°C, and thus approximately 34/112 or 30% of the energy actually went into heating the target volume. The "missing" 70% of the energy can be accounted for by realizing that some of our assumptions may be in error and that we have neglected 1) the energy that is dissipated outside the target volume (significant currents flow outside the volume), 2) the energy used to vaporize water and TCE, and 3) the energy losses in the power delivery system.

Even though there were differences in the electrical heating part of this demonstration and the heating test performed earlier, the results of the two compare favorably. For example, a factor of 1.6 times the energy was deposited during the earlier test as compared to this demonstration. This extra energy resulted in a temperature change at the test that was 1.7 times that of the demonstration. Heating rates were also higher at the test since we had the capability of running continuously day and night--on the average the rate of energy deposition at the test was 4.9 times that of the demonstration so that the average temperature increase was 5.2 times higher.

Prior to heating the concentration of TCE was gradually decreasing from about 80 ppm_v and it had reached 60 ppm_v when heating started (see figure 5). This trend was reversed as soon as heating commenced. Around day 48 the sampling line to the gas chromatograph became clogged. Since the acquisition system was running automatically, this was not noticed until day 62. Unfortunately all concentration data in that period was lost. There is evidence that a small diameter stainless steel line between the pumping line and the gas chromatograph was plugged by condensed water vapor. We strongly suspect that the relative humidity of the warmed air exiting the ground was 100% and water condensed in the stainless tubing cooled by the evening temperatures. The problem was solved by moving the gas sample through the tubing with a pump that developed sufficient pressure to displace the water. When the measurement system was modified on day 62 the concentration was 130 ppm_v, more than double the concentration when heating began. After day 62 the extraction rate fell off rapidly until on day 86, 51 days from the start of heating, the TCE concentration in the air stream at well W-834-S2 was below measurable levels. We estimate that a total of 12 kg of TCE was removed from the extraction well during the period of electrical heating. This calculation was performed by using the concentration data of figure 5 along with measured flow rate data. The result is clearly an underestimate since we neglected the TCE removed between days 48 and 62 where the data were lost.

Lingineni and Dhir (1992) used an analytical model to calculate the effects of temperature on air venting extraction rates. Their model was for an initially isothermal system which was allowed to change temperature from evaporation, condensation and the energy carried by an incoming heated air stream. They found that for their model, little improvement in extraction rate is realized by heating the inlet air to 70°C. This occurred because the temperature increase in the soil caused by deposition of energy from the inflowing air lagged behind the evaporation front. Presumably all the energy available to

advance the thermal front was used to heat the soil behind the evaporation front and evaporate the volatile but not raise the temperature downstream in the system. This was a consequence of two conditions. First, the relatively large concentration of liquids to be volitalized in the system; the soil was saturated with the liquid and then allowed to drain under a small pressure difference (2 in. Hg). Second, the small energy available from the air stream. DePaoli *et al.* (1991) report a field test of a case similar to that used for the calculations: the inlet air used for air stripping of JP-4 jet fuel was heated from the stack of a catalytic incinerator emissions control device. Contrary to the model calculations, hydrocarbon removal during the period of heating was increased by 9% over the period when the inlet air was not heated.

Direct comparison of our results and the modeling of Lingineni and Dhir or to the experiment of DePaoli and coworkers is not appropriate since the conditions are different. First, the concentration and type of liquid to be volatilized is much different. In our case that liquid is water with traces of dissolved TCE. Second, the energy density available to the system is much higher during direct electrical heating and it is delivered on both sides of the evaporation front, allowing for a thermal front which is little affected by the evaporation front.

Our demonstration was of short duration and the supporting diagnostics incomplete. Therefore, our conclusions are conservative about the effects of direct heating on air stripping of VOCs. We believe that this work demonstrated the potential of the approach for increasing the rate of TCE removal at this site. It also helped establish engineering design parameters for such a technique as well as operating practice for its implementation. Table 1 summarizes the results of the demonstration.

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Key words: Environmental engineering, hazardous waste, thermal remediation, electrical soil heating, air stripping, waste site cleanup

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TABLE 1
Summary of results

Location	Lawrence Livermore National Laboratory, Site 300
Dates	April-July, 1992
Electrical energy	9600 kW hr
Target volume	154 m^3
Duration of heating	47 days
Total TCE removed during heating	12 kg
TCE concentrations:	
Before heating	60 ppm_v
Peak during heating	130 ppm_v
End of heating	less than 5 ppm_v
Cost	
Electrical Energy*	$528

*assuming a typical industrial rate of $0.055 (k Whr)$^{-1}$.

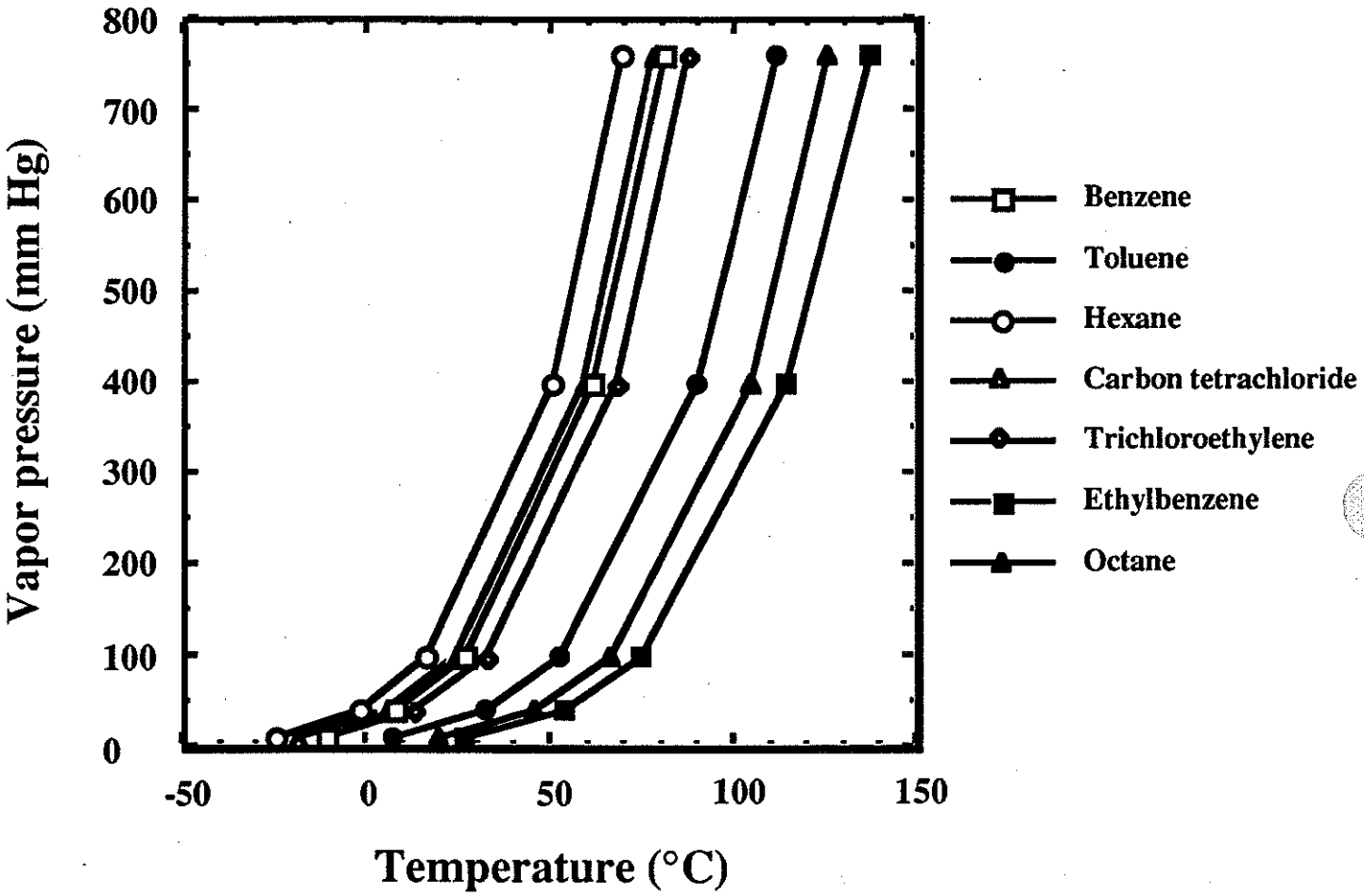

Figure 1. Vapor pressure as a function of temperature for some compounds of interest.

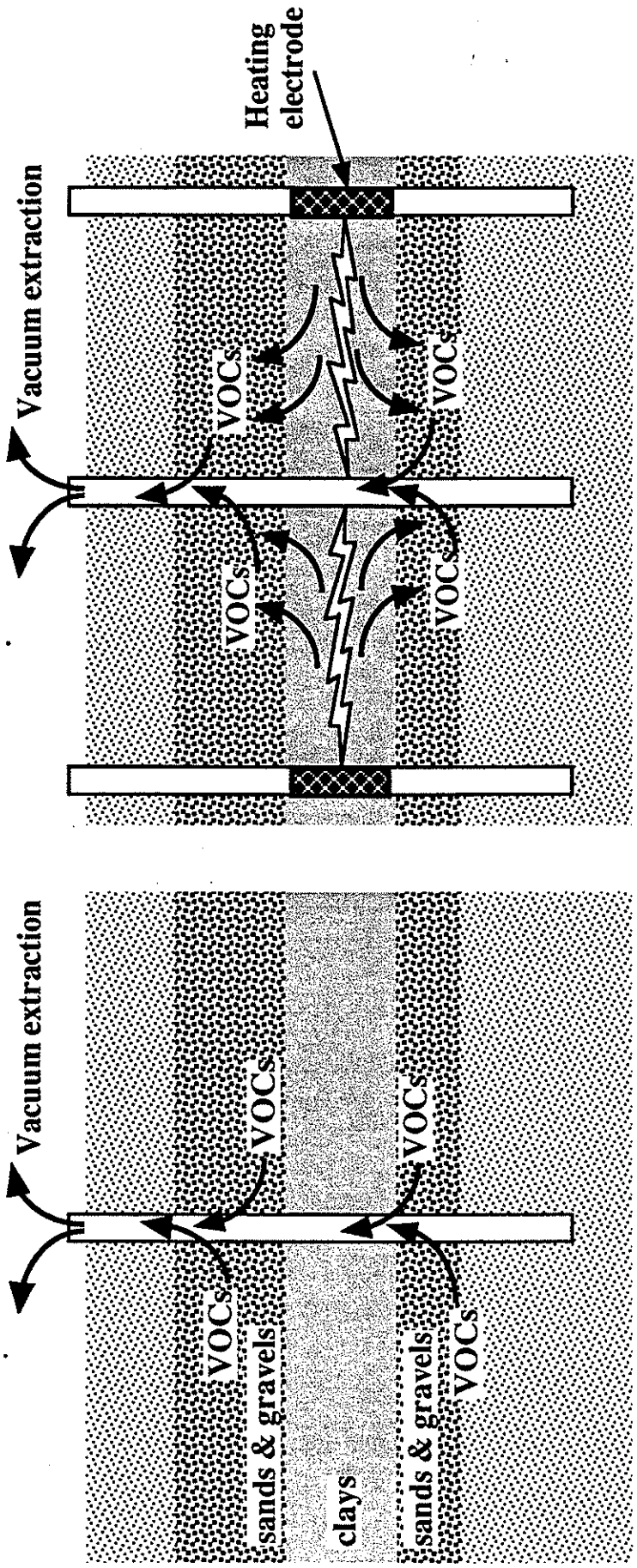

Figure 2. A conceptual view of the effects of soil heterogeneity on air stripping. (a) Air stripping is effective for the more permeable regions because the air flow is through these regions with little or no air flow in the regions of lower permeability. (b) Electrical heating will tend to heat the regions of lower permeability. As the vaporized contaminant moves down pressure gradient to the more permeable region, it can be removed by air stripping.

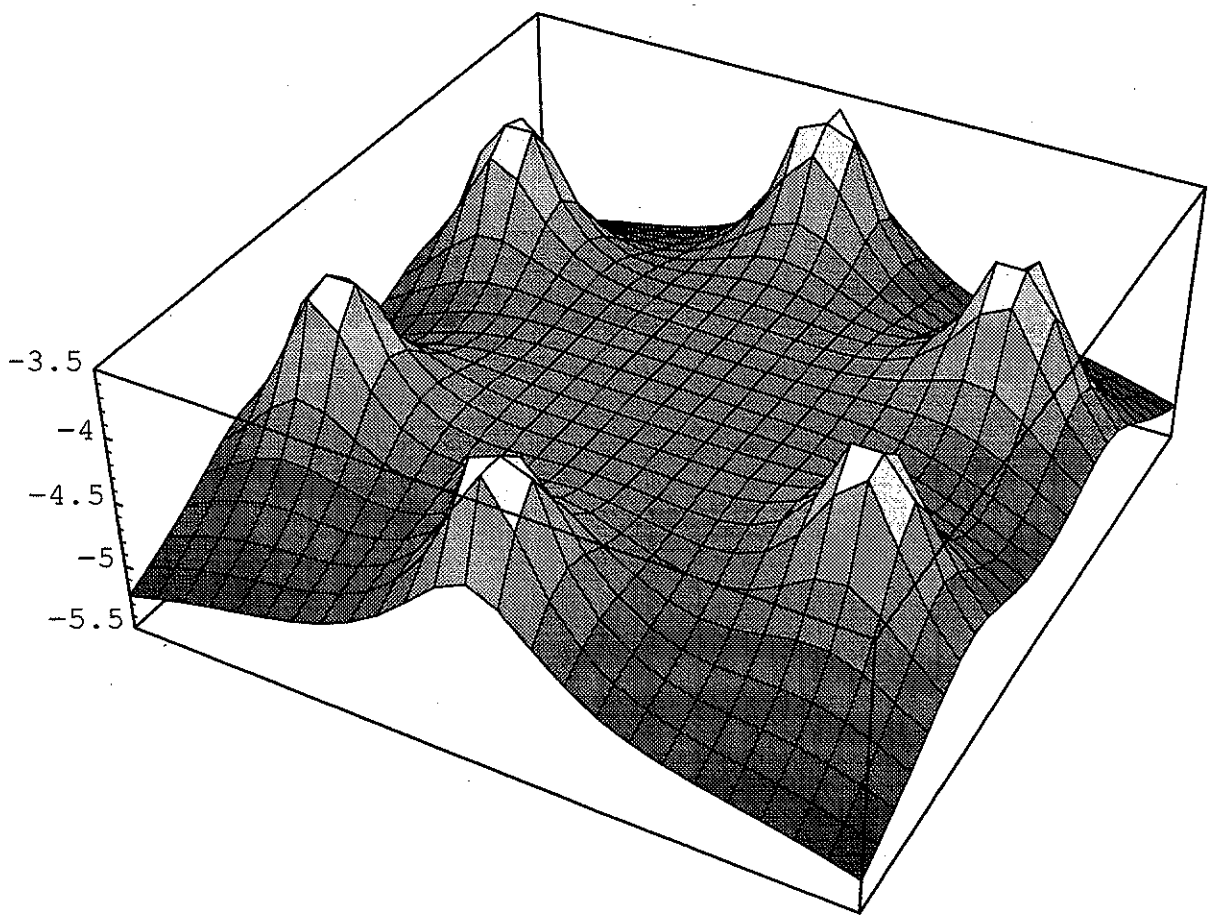

Figure 3a. Initial heating rate for homogeneoous soil. These are 3-dimensional surface plots of the $\log_{10}$ of the heating rate: Heating rate distribution for a 6-spot, 6-phase pattern.

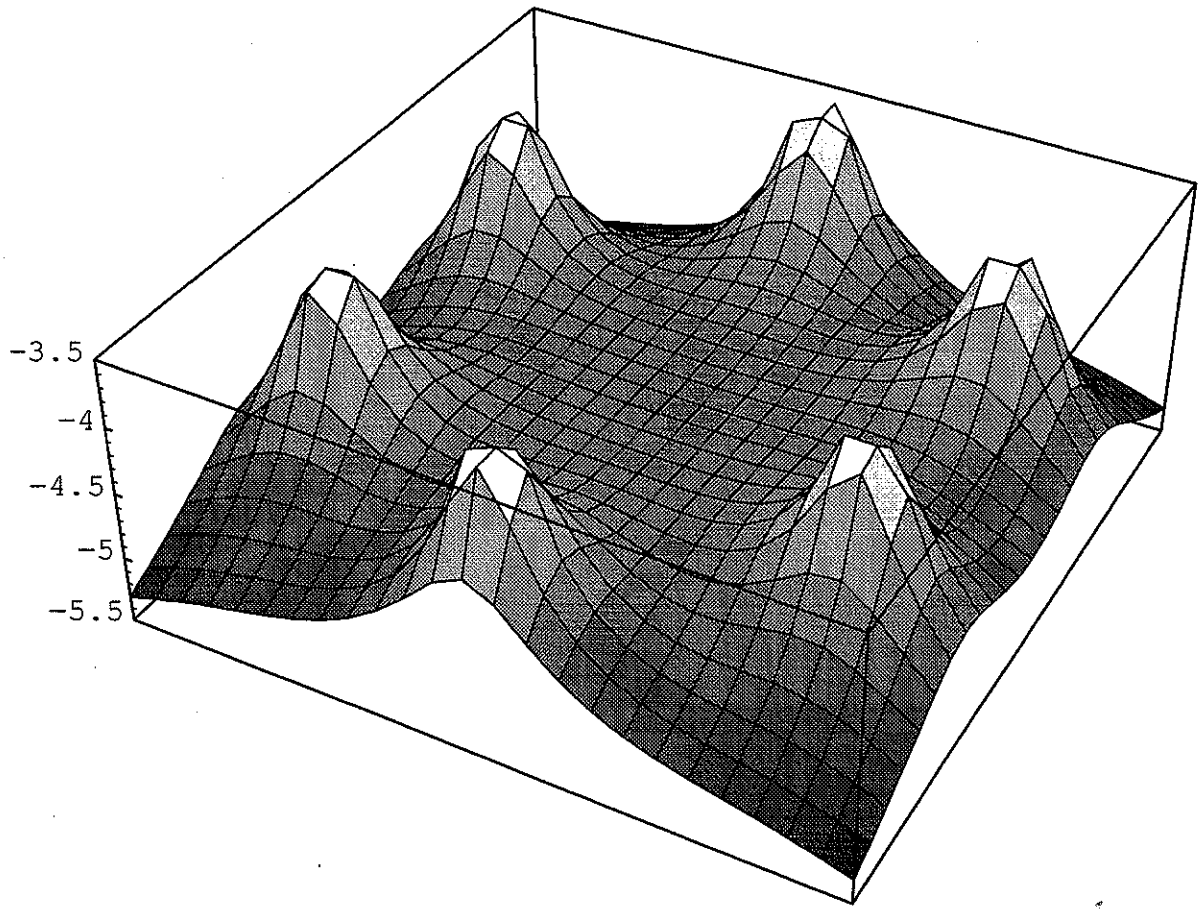

Figure 3b. Initial heating rate for homogeneoous soil. These are 3-dimensional surface plots of the $\log_{10}$ of the heating rate: Heating rate distribution for a 6-spot 3-phase, composite pattern where the three phases are driving 3 non-adjacent electrodes but are periodically connected to the other non-adjacent electrodes.

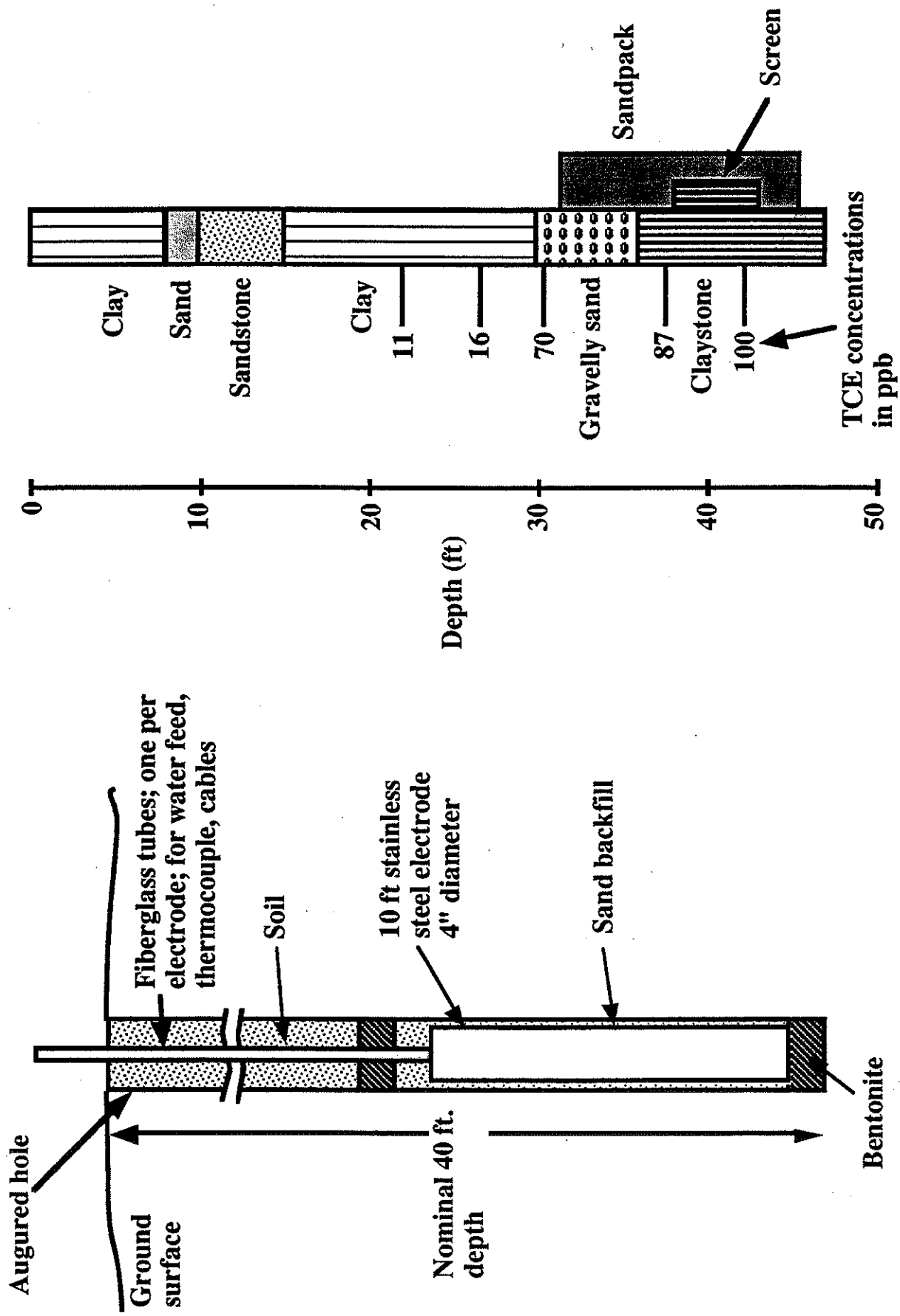

Figure 4. Experimental layout. (a) Construction of the electrical heating wells and for W-834-S2 which was used as the extraction well. TCE concentrations are given for W-834-S8 about 20 m away from well W-834-S2.

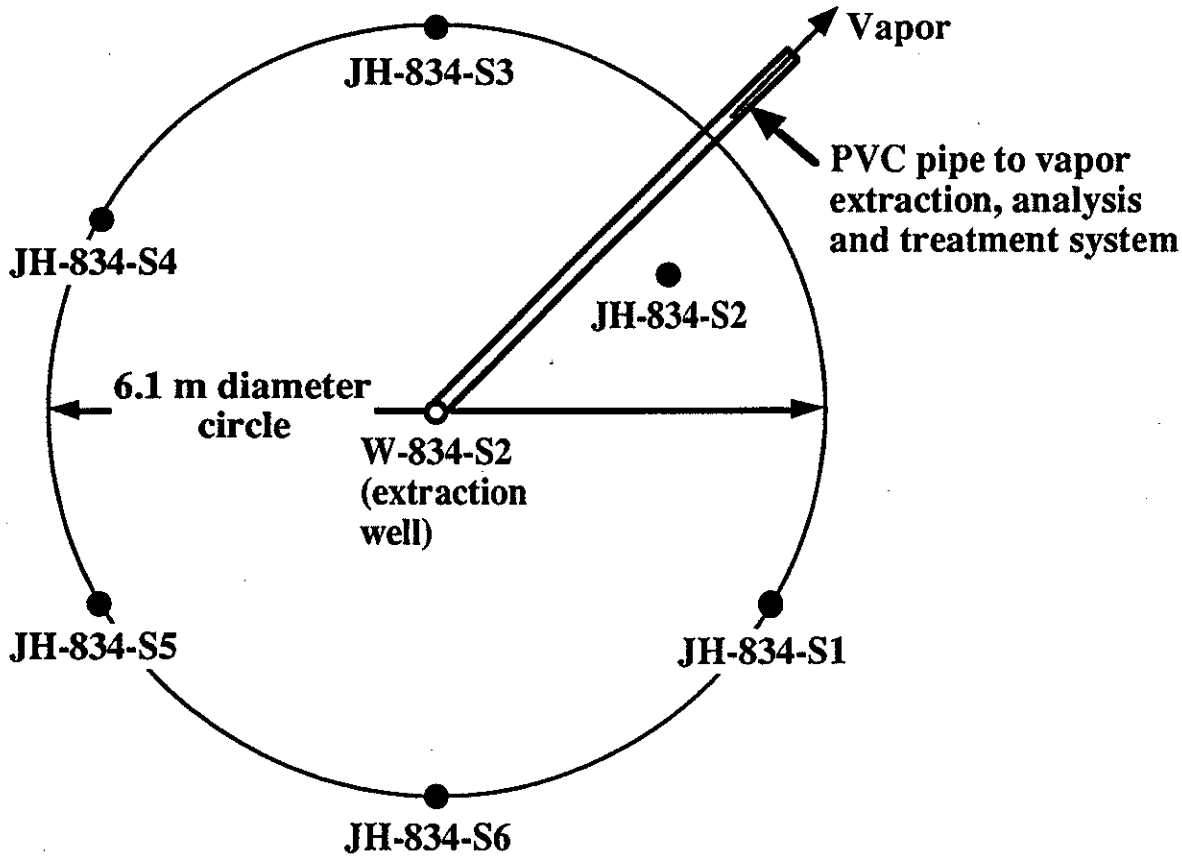

Figure 4b. Experimental layout. Borehole layout for electrical heating and for air stripping. One heating well is offset from the pattern because it had to be moved and redrilled after a drill bit was lost on the first attempt to drill the hole.

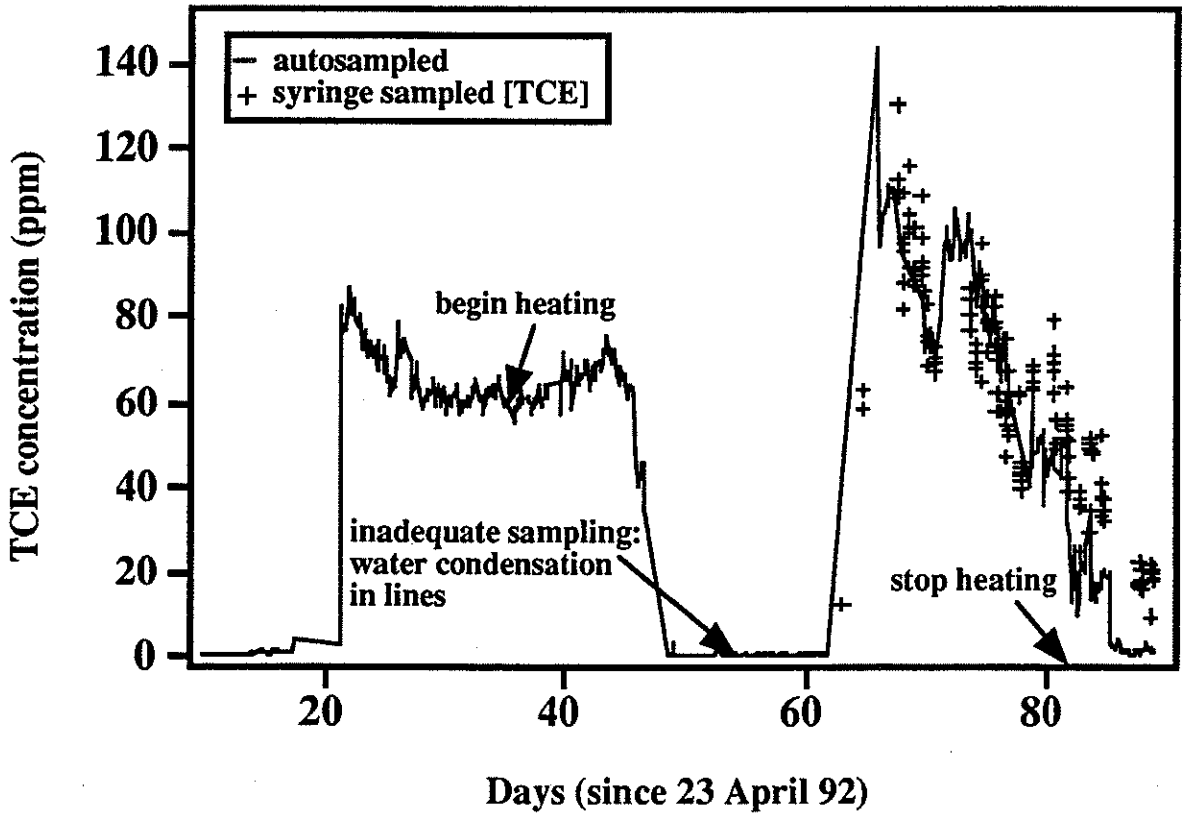

Figure 5. Concentration of TCE as a function of time in the exit air stream from W-834-S2.

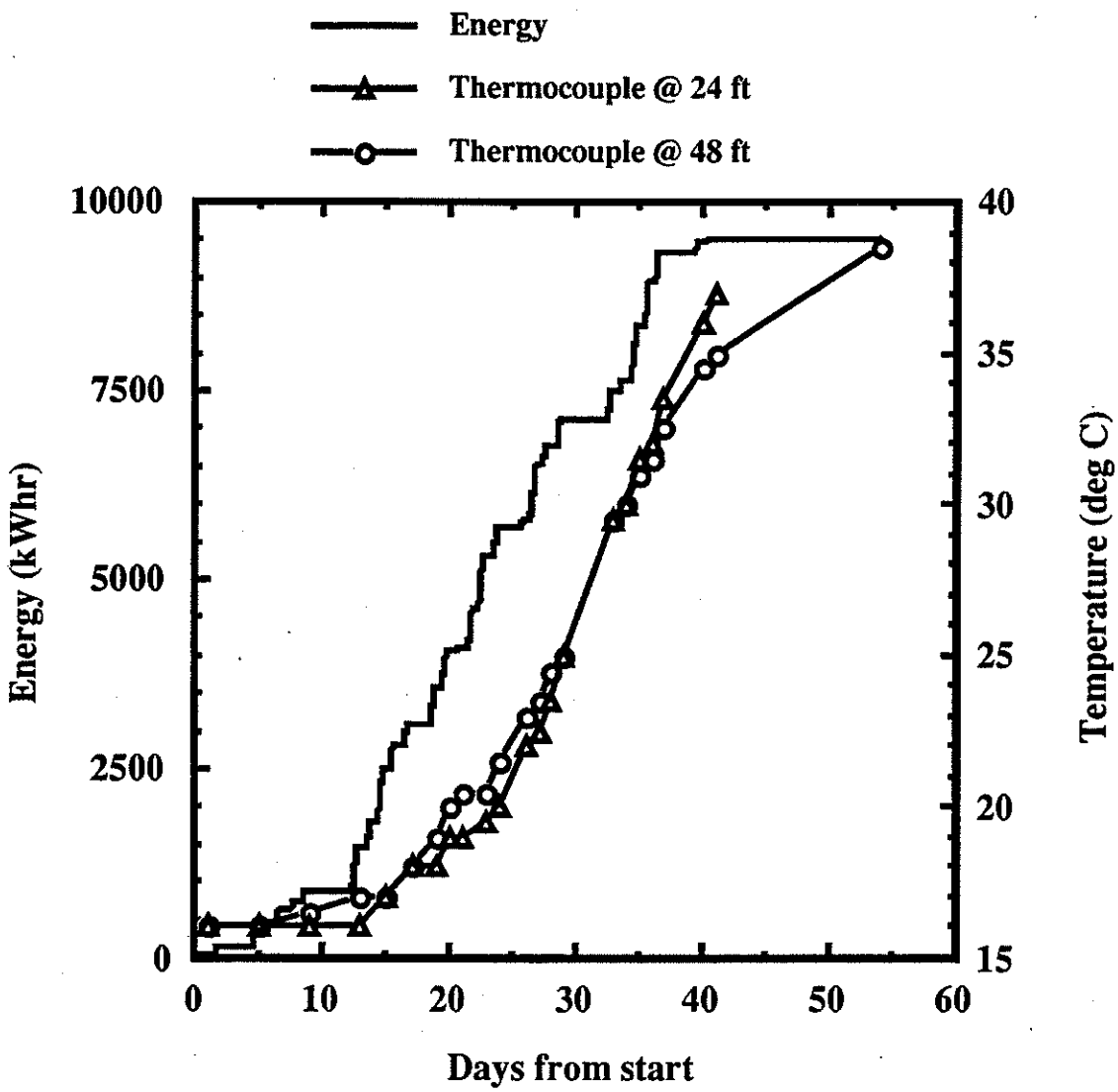

Figure 6. Total electrical energy and selected thermocouple measurements as a function of time.

APPENDIX A

Since this paper deals with powerline frequency heating, the currents, potentials and field are time-harmonic with a frequency of 60 Hz. We shall adopt the convention of expressing the current at the ith location as

$$\text{current at i th location} = I_i \, \mathrm{Re}\left[\exp[j(\omega t - \phi_i)] \right]$$

where Re denotes the real part of a complex quantity, ω is the angular frequency, ϕ_i is the phase of the ith source or sink, and $j = \sqrt{-1}$.

In two dimensions for circular coordinates Laplace's Equation for the potential is

$$\nabla^2 V = \frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right) = 0$$

and thus

$$\frac{dV}{dr} = \frac{A}{r}$$

where A is a constant. Integration yields

$$V = A \ln r + B$$

where B is a constant.

When there are current sources and sinks, the appropriate boundary conditions are 1) that $V \rightarrow 0$ as $r \rightarrow \infty$, and 2) that the integral of the current density over a closed surface which just surrounds a source (sink) equals the current that flows in (out). That is

$$\int_s \bar{J}\cdot\overline{dS} = \int_s \sigma\bar{E}\cdot\overline{dS} = \int_s -\sigma\bar{\nabla}V\cdot\overline{dS} = I$$

For example in the case of a current source of strength I/l per unit length and a sink of -I/l per unit length as shown in Fig. A1 below, we set $A = I/2\pi\sigma l$ and $B = 0$ and thus

$$V(x,y) = \frac{I}{2\pi\sigma l}\left(\ln r_1 - \ln r_2\right) \qquad \text{(A1)}$$

where $r_1 = [x^2 + (y+d)^2]^{1/2}$ and $r_2 = [x^2 + (y-d)^2]^{1/2}$. It is a simple matter to show that Eq. A1 satisfies Laplace's Equation and the boundary conditions

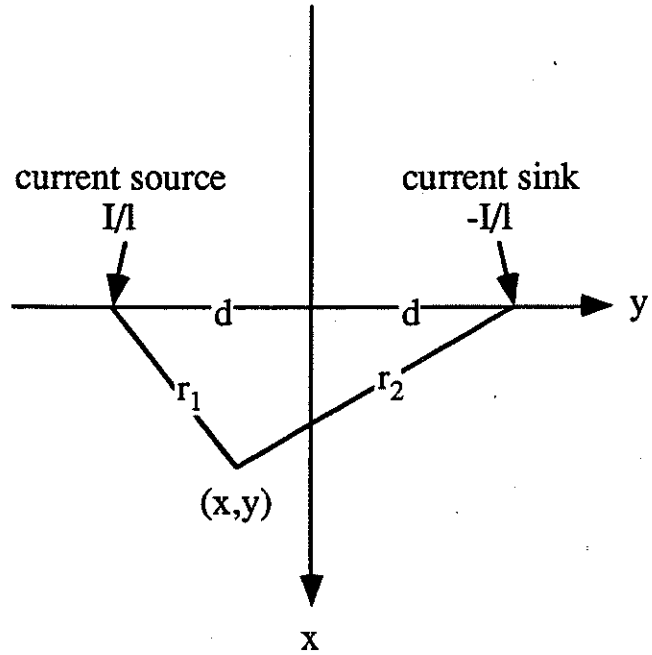

Fig. A1 Layout for sample solution to Laplace's Equation

Now in the general case of N current sources and sinks where the ith source (or sink) has coordinates (x_i,y_i), magnitude I_i, and phase ϕ_i, the electric potential is written as

$$V(x,y,t) = \mathrm{Re}\left[-\frac{\exp(j\omega t)}{2\pi\sigma l} \sum_{i=1}^{N} I_i \ \exp(-j\phi_i)\ln r_i \right]$$

$$\text{and } \overline{E}\ (x,y,t) = -\overline{\nabla} V(x,y,t)$$

$$= \mathrm{Re}\left[\frac{\exp(j\omega t)}{2\pi\sigma l} \left[\hat{x} \sum_{i=1}^{N} \frac{I_i\,(x - x_i)\exp(-j\phi_i)}{r_i^2} + \hat{y} \sum_{i=1}^{N} \frac{I_i\,(y - y_i)\exp(-j\phi_i)}{r_i^2} \right] \right] \qquad \text{(A2)}$$

$\hat{x}$ and $\hat{y}$ are unit vectors in the x and y directions respectively and $r_i^2 = (x - x_i)^2 + (y - y_i)^2$.

The source term, U, in the heat equation is the time average of $\sigma\ |\overline{E}|^2$, but this is the same as $\frac{1}{2}\sigma\,\overline{E}\cdot\overline{E}^*$ where $\overline{E}^*$ is the complex conjugate of $\overline{E}$.

Thus

$$U = \frac{1}{2\sigma(2\pi l)^2}\left[\left[\mathrm{Re}\sum_x\right]^2 + \left[\mathrm{Im}\sum_x\right]^2 + \left[\mathrm{Re}\sum_y\right]^2 + \left[\mathrm{Im}\sum_y\right]^2\right] \qquad \text{(A3)}$$

where Re and Im denote the real and imaginary parts of a complex quantity and

$$\sum_x = \sum_{i=1}^{N} \frac{I_i\,(x - x_i)\exp(-j\phi_i)}{r_i^2} \;;\; \sum_y = \sum_{i=1}^{N} \frac{I_i\,(y - y_i)\exp(-j\phi_i)}{r_i^2}$$

The heating rates displayed in Figs. 3a and 3b are computed from Eq. 4 with U given by Eq. A3. For all cases the electrodes are distributed symmetrically around a circle whose radius is 3.05 m. For case 1) $\phi_1 = 0°$, $\phi_2 = 60°$, $\phi_3 = 120°$, $\phi_4 = 180°$, $\phi_5 = 240°$, $\phi_6 = 300°$, while for case 2) the phases alternate between $\phi_1 = \phi_2 = 0°$, $\phi_3 = \phi_4 = 120°$, $\phi_5 = \phi_6 = 240°$, and $\phi_1 = 0°$, $\phi_2 = \phi_3 = 120°$, $\phi_4 = \phi_5 = 240°$, and $\phi_6 = 0°$.

APPENDIX B

In Appendix A we computed heating rates based on the assumption that joule heating would dominate conduction heating. We seek now to be more quantitative about this by comparing the relative importance of the joule heating term to the conduction heating term. Thus recall the heat equation

$$\frac{\partial T}{\partial t} = \frac{k}{c\rho}\nabla^2 T + \frac{U}{c\rho} \qquad \text{(B1)}$$

and the joule heating term

$$U = \sigma\left|\overline{E}^2\right| \qquad \text{(B2)}$$

When the current is first turned on, the temperature will vary linearly with time because the Laplacian of the initial temperature distribution is zero, and thus

$$T = T_o + \frac{U}{c\rho}\Delta t \qquad \text{(B3)}$$

where T is the temperature at the end of the time interval Δt and T_o is the initial temperature distribution (assumed constant). Clearly the new temperature distribution depends on time and the spatial coordinates because the joule heating term varies spatially.

If one solved equation B1 by stepping along in time, the initial temperature would be T_o everywhere, and at the end of the first time step Δt, the temperature would be given by equation B3. From equation B1 the rate of change of temperature at the end of the first time step would be given by

$$\frac{\partial T}{\partial t} = \frac{k}{c\rho}\frac{\sigma\Delta t}{c\rho}\nabla^2\left|\overline{E}^2\right| + \frac{\sigma\left|\overline{E}^2\right|}{c\rho} \qquad \text{(B4)}$$

So at the end of the first time step the rate of change of the temperature is equal to the sum of the joule heating term (varies as the square of the electric field) and the conduction term (varies as the Laplacian of the square of the field). We can now compare the joule heating term to the conduction term to arrive at an estimate of when conduction becomes comparable to joule heating. Thus equating the two terms on the right hand side of B4 gives

$$\Delta t = \frac{c\rho \left|\overline{E}^2\right|}{k\, \nabla^2 \left|\overline{E}^2\right|} \qquad \text{(B5)}$$

Equation B5 tells us that for a given spatial distribution of electric field and thermal properties and at some particular location there is a time interval Δt during which the heating will be dominated by joule heating. For times greater than this both terms will be important. In fact even if the current is turned off there can still be significant heating by conduction provided enough time has elapsed.

For purposes of illustration consider the simple case of heating from a line source of current. This two-dimensional case corresponds to that of a line electrode embedded in a conducting layer which is separated from other conducting layers by insulating layers. For example the case of a clay layer with insulating gravels above and below all of which are above the water table is well modeled by this case.

In the two-dimensional case the electric field is given by

$$\left|\overline{E}\right| = \frac{I}{2\pi\sigma r} \qquad \text{(B6)}$$

where r is the radial distance from the line source of current. Thus the square of the field term is

$$\left|\overline{E}\right|^2 = \left(\frac{I}{2\pi\sigma r}\right)^2 \qquad \text{(B7)}$$

With variations in r only the Laplacian is given by

$$\nabla^2 = \frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\right) \qquad \text{(B8)}$$

and thus

$$\nabla^2\left|\overline{E}\right|^2 = \left(\frac{I}{\pi\sigma}\right)^2 r^{-4} \qquad \text{(B9)}$$

and substitution of B7 and B9 into B5 yields

$$\Delta t = \frac{c\rho r^2}{4k} \qquad \text{(B10)}$$

Substitution of some typical values of the thermal properties of soils into B10 allows us to estimate the time Δt. We use values of $c\rho$ and k from Carslaw and Jaeger for average soil, namely $c\rho = 2X10^6$ joule/m^3°C and k = 1 W/m°C. Thus

$$\Delta t = 5X10^5 r^2 \qquad \text{(B10)}$$

For example at a distance of 1 meter, Δt is $5X10^5$ seconds or 5.79 days, at 2 meters, the time is 23.1 days, at 3.05 meters (as in our experiment) the time is 53.8 days, and finally at 10 meters, it is 579 days.

These calculations have important implications for the design of an electrical heating-assisted vapor extraction cleanup. For example in a remediation scenario where the heating is to take place over two months, conduction heating will not be significant unless the area to be heated is less than about 3 m from a heating electrode. If, however, the time frame is extended to 18 months, then the electrodes could be as much as 10 m from the region to be heated.

This analysis has neglected the effects of heterogeneous soil properties and the benefits of using arrays of heating electrodes rather than one, but the basic conclusions should still be valid.

APPENDIX C. NOTATION

$\underline{p}$ = pressure
$\bar{E}$ = electric field
I_i = current source per unit length at i th location
Im = the imaginary part of a complex quantity
$\bar{J}$ = current density
P = ohmic power dissipation
Re = the real part of a complex quantity
T = temperature (absolute in pressure-temperature equation, Celsius elsewhere)
U = power dissipation per unit volume due to ohmic heating
V = electrical potential
a, b = constants in pressure-temperature equation
c = specific heat of soil
d = distance from the origin to current source or sink for sample solution to Laplace's Equation
k = thermal conductivity of soil
ϕ_i = phase of the current at the i th location
r_i = distance from the current source at the i th location to the origin
ρ = soil density
σ = electrical conductivity of soil
ω = angular frequency

DESTRUCTION OF ORGANIC CONTAMINANTS IN AIR USING ADVANCED ULTRAVIOLET FLASHLAMPS

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FOREWORD

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The purpose of the Program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards which require greater reliance on permanent remedies. A key part of EPA's effort is its research into our environmental problems to find new and innovative solutions.

The Risk Reduction Engineering Laboratory (RREL) is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The SITE Program is part of EPA's research into cleanup methods for hazardous waste sites around the nation. Through cooperative agreements with developers, alternative or innovative technologies are refined at the bench-and pilot-scale level then demonstrated at actual sites. EPA collects and evaluates extensive performance data on each technology to use in remediation decision-making for hazardous waste sites.

This report documents Purus Inc.'s laboratory and field studies of the use of photolytic oxidation for destruction of volatile organic compounds (VOCs) in air. Field tests were performed at the Lawrence Livermore National Laboratory Superfund site in Livermore, California on soil zones contaminated with trichloroethene (TCE).

Copies of this report can be purchased from the National Technical Information Service, Ravensworth Bldg., Springfield, VA, 22161, 703-487-4600. You can also call the SITE Clearinghouse hotline at 1-800-424-9346 or 202-382-3000 in Washington, D.C. to inquire about the availability of other reports.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This paper describes a new process for photo-oxidation of volatile organic compounds (VOCs) in air using an advanced ultraviolet source, a Purus xenon flashlamp. The flashlamps have greater output at 200-250 nm than medium-pressuer mercury lamps at the same power and therefore cause much more rapid direct photolysis of VOCs , including methylene chloride (CH_2Cl_2), chloroform ($CHCl_3$), carbon tetrachloride (CCl_4) , 1,2-dichloroethane (1, 2-DCA), 1,1, 1-trichloroethane (TCA), Freon 113 and benzene . The observation of quantum yields greater than unity indicate the involvement of chain reactions for trichloroethene (TCE), perchloroethene (PCE), 1,1-dichloroethene (DCE), chloroform, and methylene chloride.

TCE was examined more closely because of its widespread occurrence and very high destruction rate. Two full scale air emission control systems for TCE were constructed at Purus and tested at a Lawrence Livermore National Laboratory (LLNL) Superfund Site. The systems were operated at flash frequencies of 1 - 30 Hz, temperatures of 33 - 60 °C, flows up to 300 scfm (260 ppmv TCE) and concentrations up to 10,600 ppmv (100 scfm). Residence times ranged from 5 to 75 seconds. In all cases except at the lowest flash frequency, greater than 99% removal of TCE was observed. Careful attention was paid to product formation and mass balances. The main initial photo-oxidation product of TCE was dichloroacetyl chloride (DCAC), which upon further photolysis was converted in part to dichlorocarbonyl (phosgene or DCC) and possibly formyl chloride, and ultimately to HCl and CO_2. Further treatment of photo-oxidation products is recommended for full-scale operation.

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SECTION 1

INTRODUCTION

Many environmental remediation sites suffer from pollution with volatile organic compounds (VOCs). Some of these sites are amenable to remediation by vacuum-induced soil venting and groundwater air stripping methods. However, treatment of off-gases from such operations can be problematic. Because of environmental legislation, air quality management districts require VOC air emission controls at restoration activities. Activated carbon adsorption is often utilized to control emissions. However, once breakthrough occurs, the spent carbon must be regenerated on-site or transported to the limited number of disposal or regeneration locations. In addition, this practice can be costly for sites that contain VOCs like methylene chloride or acetone with low adsorption characteristics, thereby requiring large amounts of carbon. A permanent treatment would involve complete oxidation of the VOC, so that subsequent disposal would be unnecessary. Remediation technologies that destroy VOCs on-site, such as thermal and catalytic combustion, also have limitations, particularly for sites with chlorinated VOCs.

Oxidation of organic molecules can be initiated by photolysis. Unlike thermally initiated oxidation, very little is known about the feasibility of photo-oxidation of VOCs in air as a commercial process. The lack of an intense and highly efficient light source that emits in the deep ultraviolet (<250 nm) is the reason that this has not been investigated as a process. Previously, the only light source that was routinely used for ultraviolet photolyses on a large scale was the mercury discharge lamp. Flash lamps can also be made to emit high intensities of ultraviolet light, but their use as sources for initiating photo-oxidation has previously been limited to the laboratory.

Pulsed inert-gas lamps (flashlamps) have been used for many applications including pump sources for lasers (EG&G, 1988). Lasers themselves have relatively low overall efficiency and therefore are not likely to find application in large-scale commercial or treatment processes. A flashlamp is an arc lamp that operates in the pulsed mode by alternately storing electrical energy in a capacitor and discharging it through a gas contained in a chamber of UV transmissive quartz (EG&G, 1988). The discharge quickly heats the gas to a very high temperature (≥ 13,000 K) and pressure, causing ionization and creating a plasma that emits light. The spectral properties of the plasma approach those of an ideal black body radiator which has a peak emission wavelength defined by its characteristic temperature. Increasing energy discharged into the plasma increases its

temperature, which lowers the wavelength of its emission maximum.

As opposed to non-specific blackbody radiation, most continuous sources emit lines that are characteristic of the electronic transitions of the unionized fill gas. For example, almost all the radiation emitted by a low pressure mercury lamp is resonance radiation of mercury vapor at 254 and 185 nm, arising from the electronic transitions $6^3P_1 \rightarrow 6^1S_0$ and $6^1P_1 \rightarrow 6^1S_0$ (Phillips, 1963). A major advantage of mercury lamps for low power applications is that they are very efficient at these two wavelengths. A disadvantage of continuous sources is that they can only be operated at relatively low intensities because the number of photons emitted is proportional to the fill gas pressure. Because the photons are in resonance with electronic transitions, they can be reabsorbed by the fill gas.

We report the application of a xenon plasma flashlamp as a UV light source for the photo-oxidation of some VOCs in air. Initially, laboratory experiments were performed on saturated and unsaturated chlorinated hydrocarbons in air to screen compounds for treatability. The kinetics of photo-oxidation were studied, and apparent quantum yields were determined for the disappearance. Efforts were made to characterize the photo-oxidation products of one of these chlorinated hydrocarbons, trichloroethene (TCE).

A full scale photoreactor was built for the photo-oxidation of TCE and was tested at Lawrence Livermore National Laboratory (LLNL) Site 300. This report contains a summary of the laboratory screening studies and performance data collected at the LLNL site on the photochemical treatment process for trichloroethene (TCE). The TCE destruction effectiveness and the yields of the main oxidation products were characterized under various operating conditions, including:

- Process flow: 100 to 290 cfm
- TCE concentration: 30 to 10,000 ppmv
- Flash lamp frequency: 1 to 30 Hz
- Temperature: 33-60 °C

These results, in combination with toxicological data, were used to estimate the operating conditions suitable for reducing the total toxicity from TCE and residual products by 99% using UV photolysis alone.

SECTION 2

CONCLUSIONS

KINETICS OF VOC PHOTO-OXIDATIONS

The low-wavelength emission of the pulsed xenon lamps (λ_{max} = 230 nm) allows direct photolysis of many VOCs, particularly chlorinated compounds and freons, that was not possible with commercial mercury lamps. The quantum yields for photolyses of simple carbon-chlorine bonds are quite high, near unity. Nevertheless, light absorption by such compounds is still weak enough at 230 nm that either photosensitization or an even lower-wavelength source is needed for the photolyses to be rapid enough for commercialization at present. On the other hand, very rapid destruction is observed for compounds that undergo chain reactions initiated by light, notably TCE, PCE, DCE, chloroform and methylene chloride (in order). Therefore, full-scale reactors were designed for the treatment of the chloro-olefins DCE, TCE and PCE.

TCE PHOTO-OXIDATION

The initial steps of TCE photo-oxidation involve a chlorine atom propagated chain reaction Sanhueza, *et al.*, 1976, Blystone *et al.*, 1991). The apparent quantum yield for this process is about 31, which makes the disappearance of TCE extremely rapid and efficient (Blystone *et al.*, 1991). The main product (> 85%) from this chain photo-oxidation is dichloroacetyl chloride (DCAC). Products from the initial photolysis of TCE are insignificant because most of the products are formed via Cl· atom attack.

Further oxidation of DCAC is approximately 100 times slower than the photolysis of TCE. The concentration of DCAC decays exponentially with dose, and may be a result of both direct photolysis and chlorine atom reactions. The products of further photo-oxidation after DCAC is fully formed include dichlorocarbonyl (DCC) in about 20% yield, trichloroacetyl chloride (≤ 2%), $CHCl_3$ (~0.65%), CCl_4 (~0.15%), CH_2Cl_2 (~0.05%), and possibly formyl chloride and dichloroacetic acid. The yield of DCC can be substantially enhanced by the addition of chlorine, indicating that this product may be formed by chlorine atom reaction with DCAC. At even higher light doses, DCC also decays, suggesting that the low yield is a result of its concurrent formation and destruction. Evidence was found that the carbon-containing products are eventually converted to CO_2 with enough exposure.

ESTIMATION OF PROCESS PARAMETERS FOR REMEDIATION

Although both full-scale reactors demonstrated very efficient removal of TCE, remediation of the LLNL site to toxicity level goals was not attained because of the formation of intermediate toxic products. A reduction in toxicity for TCE of 99% requires that the residual DCAC concentration be 0.026% the TCE input concentration, and the DCC concentration must be 0.45% the TCE input concentration. While it is possible to estimate the UV dose required to eliminate DCAC to this level, sufficient data does not exist to determine the dosage at which the concentration of DCC is reduced to the required level.

The maximum flow rate that meets the DCAC reduction goal under standard lamp operating conditions is between 13 and 20 cfm. At this level of treatment, the DCC concentration would still be excessive and additional treatment would be needed. Scrubbing with water under these conditions would rapidly hydrolyze the DCC to CO_2 and HCl and the DCAC to dichloroacetic acid (DCAA) and HCl. However, the accumulation of even a trace dichloroacetic acid may result in a disposal problem for the water because the expected EPA drinking water limit for DCAA is so low (~0.2 ppb; Bull R., University of Washington, personal communication, 1991).

SECTION 3

RECOMMENDATIONS

Further studies on the use of low-wavelength lamps for the destruction of VOCs should be directed at 1) examining the use of shorter-wavelength UV lamps or catalysts for photolysis of a broader range of VOCs, 2) in the oxidation of chloro-olefins, verify the effectiveness of dry or wet scrubbers for removing acidic photo-oxidation products, and 3) developing methods for post-treatment of products such as DCAA present in the water after scrubbing. Purus will examine some of these issues together with Argonne National Laboratory in continued demonstrations at the Department of Energy Savannah River site.

SECTION 4

EXPERIMENTAL METHODS

LABORATORY EXPERIMENTS

Chemicals

The following chemicals were used without further purification and were obtained from the following sources: from Aldrich trichloroethene 99+%, tetrachloroethene HPLC grade, 1,1,1-trichloroethane 99%, 1,2- dichloroethane HPLC grade, dichloromethane HPLC grade, trichlorofluoromethane 99+% , dichloroacetyl chloride 99%, and chloroform HPLC grade were obtained; from Chem Service 1,1,2-trichloro-1,2,2-trifluoroethane, and 1,1-dichloroethene were obtained; and carbon tetrachloride AR grade was purchased from Mallinkrodt.

Dichloroacetanilide was synthesized by reaction of excess aniline with dichloroacetyl chloride in toluene. The precipitated product was filtered, washed with 0.1 M HCl, recrystallized from methanol/water, and its identity verified by GC/MS.

Lamp Spectra

Flashlamp emission spectra were measured on an Oriel InstaSpec III 1024 diode-array detector fitted with a 77410 MultiSpec Grating. A Molectron J25 pyroelectric calorimeter was used for absolute intensity determinations. Total lamp output at $\lambda < 300$ nm was measured by H_2O_2 actinometry (Nicole *et al.*, 1990).

Bench-Scale Photolyses

Photolyses were carried out in specially made 32-mL (10 cm in length, 2 cm in diameter) cylindrical quartz spectrophotometer cell, which had a Teflon stopcock sealed on one end and a threaded glass adapter sealed on the other. The threaded glass adapter was capped with a Teflon lined septum. Liquid TCE or dichloroacetyl chloride (DCAC) aliquots were injected into the cell by microliter syringe through the septum and were allowed to evaporate. The front face of the cell was then placed 4 cm from a xenon flash lamp, and the sample was irradiated. TCE concentrations were determined by drawing a sample with a gas tight syringe and directly injecting into a gas chromatograph. Acid chloride products were analyzed by derivitization with methanol, which was

injected into the cell after irradiation. Gas chromatography with electron capture or electrolytic conductivity detection was used for quantitation. DCC was analyzed by derivatization with aniline using a modification EPA method TO-6 (Winberry *et al.*, 1990). A 2% v/v aniline/toluene solution was injected into the cell following irradiation. The solution was rinsed from the spectrophotometer cell, blown to dryness, and diluted to 1.2 mL with acetonitrile. Carbanilide, the product of the reaction of DCC with aniline, was analyzed by HPLC with UV detection at 254 nm.

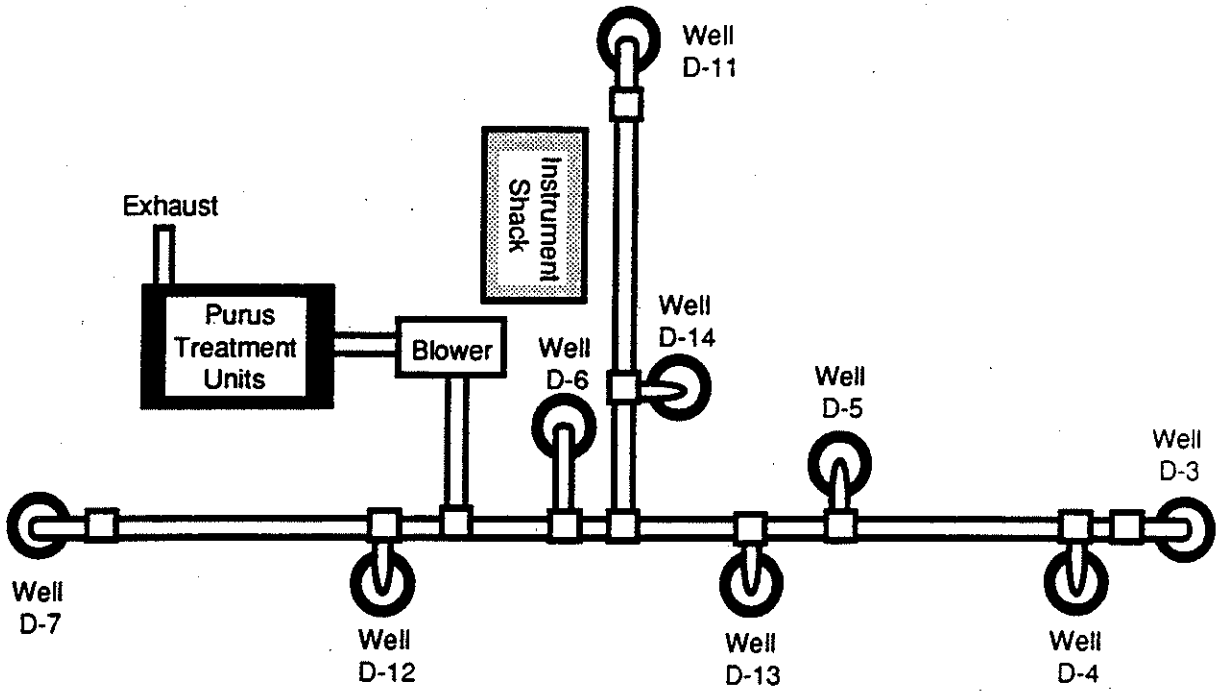
Pilot-Scale Photolyses

Air mixtures were irradiated in a 208-liter steel cylindrical reactor. A high intensity six-inch xenon flash lamp was inserted in the middle of the reactor through its side. The reactor contained two electric fans inside to facilitate mixing. All photolyses were performed at atmospheric pressure, and the gas temperature ranged from 300 K to approximately 340 K.

Known volumes of reagents were injected into the reactor by syringe, and were given time to evaporate and mix. Analyses of reactant concentrations were performed by gas chromatography after successive exposures of known duration. Samples were drawn from the reactor by gas tight syringe after turning off the lamp. No reaction was observed in laboratory light or in the reactor with the lamp off. Samples were directly injected into an HP5890 model 2 gas chromatograph equipped with a 30-m J&W model 624 fused silica column and using either photoionization or electron capture detection. CO_2 measurements were made in one run using a Horiba PIR-2000 CO_2 monitor.

FIELD MEASUREMENTS

Figure 1 is a schematic diagram of the Building 834 Complex chosen for the field studies at the southeast portion of Site 300 at Lawrence Livermore National Laboratory (LLNL). The process stream was pumped from the wells at Site 300 using the blower located as shown in Figure 1. Figure 2 gives details of the connections to the photoreactors. The air stream was passed through a heat exchanger to cool, and sent into two types of photoreactors (Figures 3 and 4). Air-2 is a large steel cylinder 4 feet in diameter by 8 feet in length with a volume of 101 cu. ft. Four xenon lamps are distributed about the center of the cylinder and point radially inward. The process stream flows from one end of the cylinder to the other. Air-3 is a Purus-patented reactor consisting of four disc shaped stainless steel chambers. Each chamber is 42 in. in diameter by 6.1 in. high with a volume of 4.1 cu. ft. exposed to the light source. The lamps in Air-3 are positioned in the center axis of each chamber. The process flow enters the bottom of each chamber, around a deflection plate, in towards the lamp, and then out the top. The chambers in Air-3 are configured



Well ID	Maximum Flow (scfm)	Maximum [TCE] (ppmv)
D3	70	420
D4	9	30
D5	15	14
D13	19	19
D14	19	10
D3, D4, D5	23	150
D3, D4, D5, D14	30	100
D13, D14	35	25
All	> 250	11

Figure 1. Lawrence Livermore Site 300 Building 834 soil venting apparatus

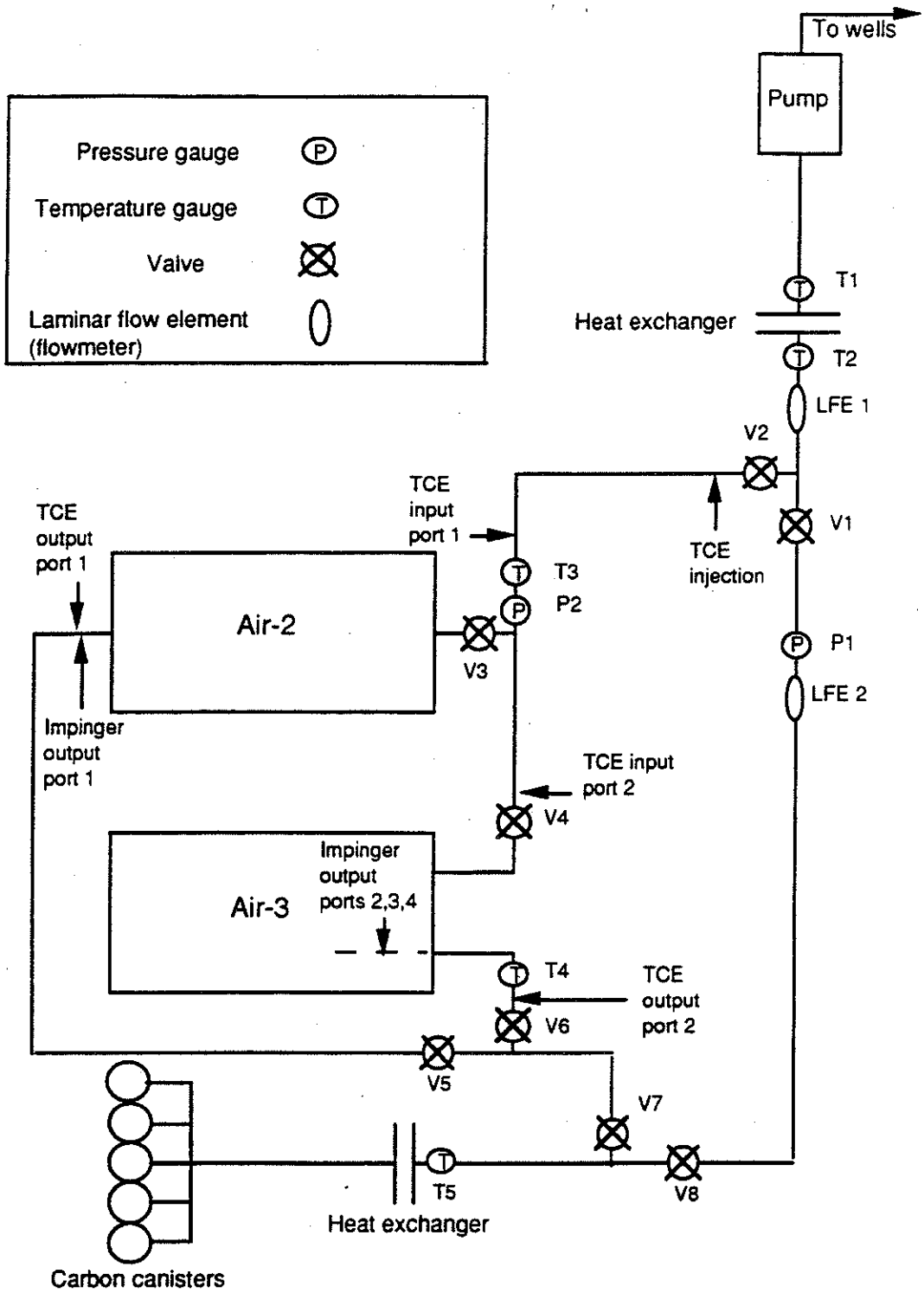


Figure 2. Details of plumbing connections to the photoreactors

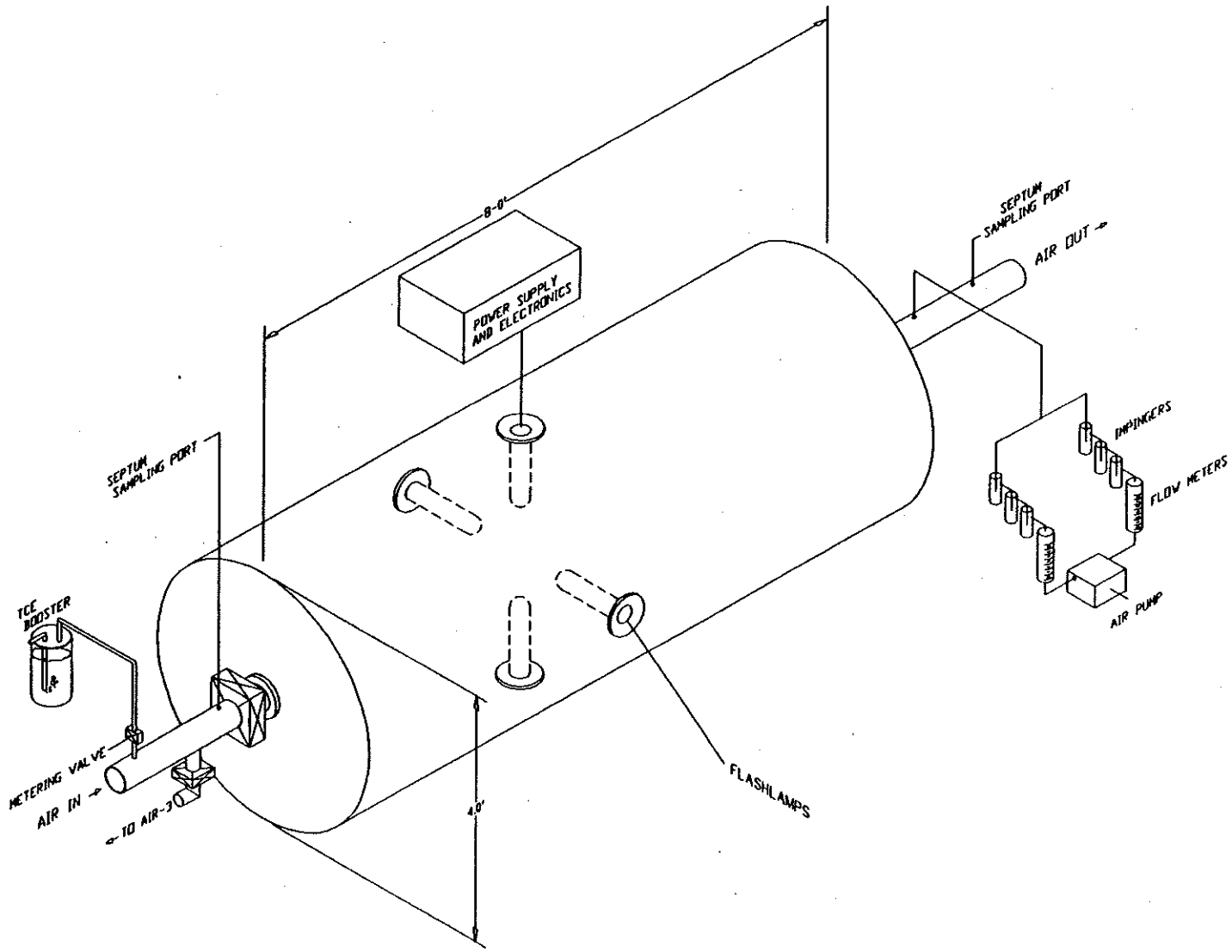


Figure 3. Schematic of Air-2 photochemical reactor

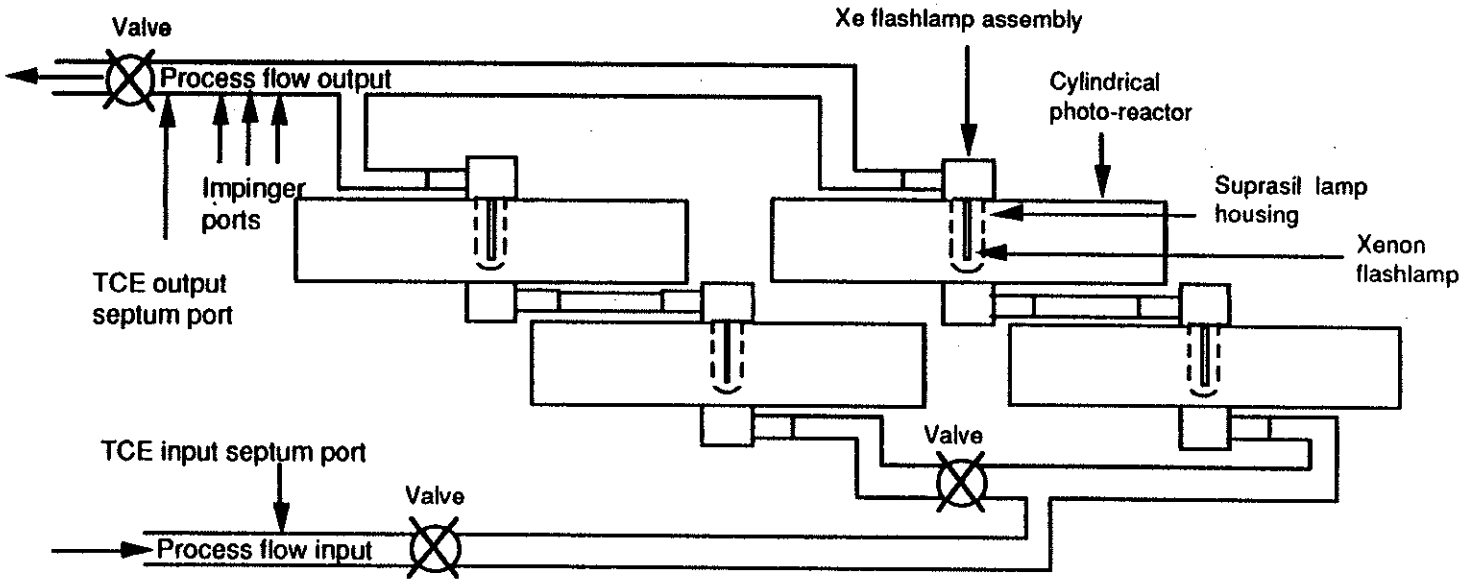


Figure 4. Schematic of Air-3 photochemical reactor

so that the flow is split through two sets of chambers in series. Some experiments were conducted with an enriched TCE air stream by gas injection from a pressurized liquid TCE-filled stainless steel bubbler before the reaction chambers.

The process flow rate was measured on LFE-2 (Figure 2), a Meriam Model 50 MC2-4 laminar flow element. Initially, the entire output from the pump was measured by closing valve V2, thus sending the entire flow around the reactors and into the carbon cans. The flow was then sent through either Air-2 or Air-3 by opening V2. Valve V1 was set so part of the flow was sent through the bypass. The flow rate through the reactors was thus the difference between the full capacity and the residual flow through the bypass when valve V1 was partly closed.

A typical sampling session involved setting the process flow rate, adjusting the TCE concentration, and alternately taking at least three input and output TCE samples while photolyzing. The impinger samples were collected during the monitoring of the TCE concentration, and were usually run for 30 minutes at a flow rate of approximately 100 mL/min. For the sampling performed in Air-2, the impingers were connected to the reactor port by 0.25-inch i.d. Teflon tubing that was split by a Teflon tee into two sets of impingers. The total length of tubing was approximately 1 meter. Even when warmed with heat tape, water tended to condense on the internal surface of the tubing, which might have prevented some of the reactive compounds from reaching the impingers. In order to minimize this problem, the impingers that were used on the tests performed on Air-3 had separate connections to the sampling ports that were less than 3 cm in length .

TCE

Trichloroethene was analyzed by gas chromatography with photoionization detection. Samples were drawn by gas tight syringe at septum sealed sample ports where the process flow entered or exited the reactor. They were injected into a Hewlett-Packard model 5890-2 gas chromatograph equipped with a 30-m J&W 624 capillary column and a photoionization detector. TCE standards were prepared in volume-calibrated glass sampling bulbs by injecting liquid TCE into the bulbs. The TCE detection limit was approximately 0.01 ppmv.

DCC

Dichlorocarbonyl was analyzed by EPA method TO-6 (Winberry *et al.*, 1990). A small fraction of the process stream was split off through a Teflon tube into two impingers connected in series. The impingers were filled with 30 mL of a 2% v/v aniline/toluene solution, which reacts with DCC to give carbanilide. The flow was measured by a rotameter placed after the impingers

and before the pump. Volumes were determined by taking the product of the flow rate with the acquisition time. The rotameter was calibrated with a bubble flowmeter. Typical flow rates were about 100 mL/min, and typical gas volumes sampled were about 3 liters.

Samples for TO-6 analyses were evaporated to dryness at 60 °C under a stream of nitrogen and taken up in 1 or 10 mL of acetonitrile. Carbanilide was determined by high pressure liquid chromatography (HPLC) on a Perkin Elmer 410 instrument with a 15-cm octadecylsilyl column and a UV detector set at 254 nm. The eluent, a 37/63 v/v acetonitrile/water solution, was run at 0.3 mL/min. Injections of 5 µL gave a detection limit of about 0.02 ppmv DCC, when the samples were diluted with 10 mL of acetonitrile. The average recovery of carbanilide based upon standard samples run through the blow down procedure was 106 ± 19% (95% confidence interval).

DCAC

Analyses of dichloroacetyl chloride (DCAC) for experiments in Air-2 were performed as part of the TO-6, with care taken to not blow the samples completely to dryness. Under these conditions, DCAC reacts with aniline to form dichloroacetanilide, which was measured by HPLC in the same runs as for DCC. The estimated detection limit was 0.1 ppmv DCAC. Recovery based upon standard samples run through the blow-down procedure was 104 ± 69% (95% CI). These large variations in yield were probably a result of volatilization losses, which were minimized by not blowing the samples down to complete dryness. However, this approach left some aniline in the samples, which gave a large HPLC peak and which may have given a positive error in the DCAC measurement.

For these reasons the methanol trap method was used in the subsequent testing of Air-3. Two methanol impingers were used in series, and flow rates and acquisition volumes were similar to the DCC method. The methyl dichloroacetate that formed was analyzed by gas chromatography with electrolytic conductivity detection. The detection limit for this method, for gas volumes of about 3 liters and 30 mL of methanol in each trap, was approximately 0.05 ppmv DCAC.

Chloride and Hydrolyzable Chlorine

Another impinger method was used to measure free HCl plus the sum of all carbonyl chloride bonds, which hydrolyze in water to yield HCl. A set of three (Air-2) or four (Air-3) impingers were filled with deionized water and connected in series. Chloride was analyzed using EPA method 325.3, a titrimetric method using mercury nitrate.

VOCs

Volatile organic compounds were analyzed in one set of experiments by EPA method TO-14, a whole air sampling method (Winberry, *et al.*, 1990). The evacuated stainless steel (SUMMA) canisters, which were obtained from Coast to Coast Analytical Services, San Luis Obispo, CA, were filled during an experiment by connecting a 1-foot long 0.25-inch OD Teflon tube to the swagelock fittings of the canister and the reactor port. Two samples were taken of the process flow with and without the lamps operating. A third sample was taken from a 20.0 ppmv standard cylinder of TCE obtained from Scott Specialty Gases. After filling, the canisters were sent to Coast to Coast Analytical Services for analysis. Agreement was reasonable; the Purus analyses agreed with the standard within 10% and the Coast to Coast analyses within 25% (see VOC results below)

SECTION 5

RESULTS AND DISCUSSION

LABORATORY EXPERIMENTS

Flashlamp Emission Spectrum

Figure 5 compares the emission spectrum of a 6-inch Purus 3675-W xenon flashlamp with that of a 7500-W medium pressure mercury lamp taken from the Peroxidation Systems, Inc. (Tuscon, AZ) literature. The data are presented as the output power integrated over the total area of the lamp and normalized to the same input power. The xenon flashlamp has a maximum at 230 nm and significant output at wavelengths as low as 200 nm, whereas the mercury lamp has most of its output at wavelengths above 250 nm. Using peroxide actinometry, we determined an overall electrical efficiency of 18.6% for generation of light below 300 nm by the Purus lamp, compared to 11.4% for the commercial Hg lamp used in UV oxidation. For the same power, the flashlamp allows a seven-fold smaller reaction chamber and thus has an advantage in capital costs. Lamp life for both lamps is on the order of 1000 hours.

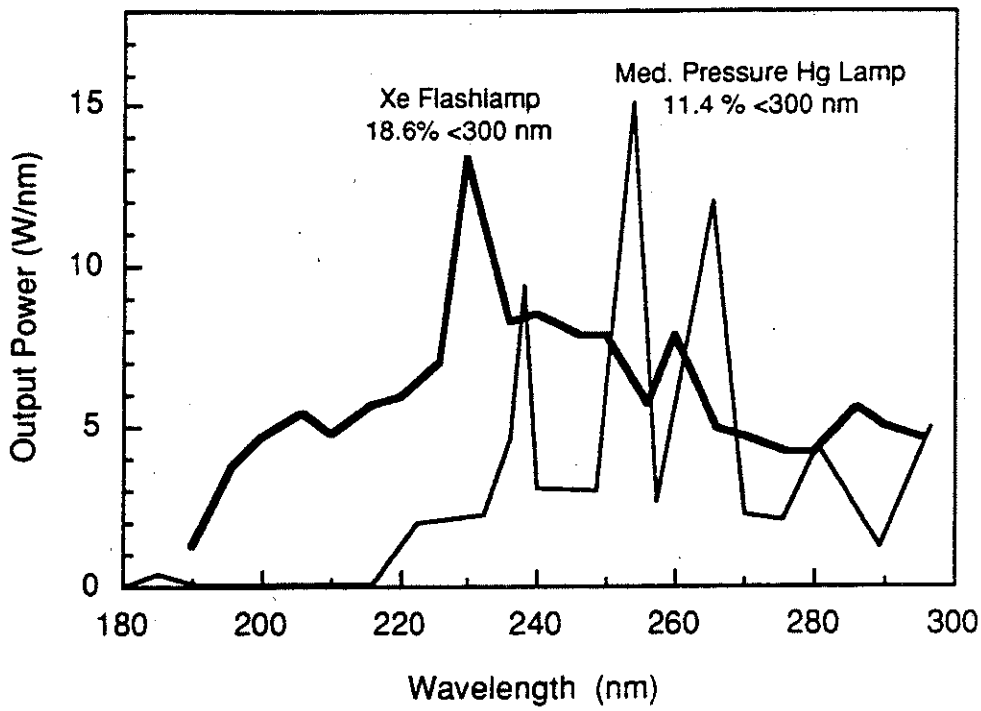


Figure 5. Emission spectrum for a mercury lamp vs. a xenon flashlamp. (All lamps corrected to 3675 W input).

Figure 6 compares the emission spectrum of the flashlamp with the absorption spectra of several VOCs (Baulch *et al.*, 1980, Hubrich and Stuhl, 1980). Note that the lamp spectrum is given on a linear scale while the absorption spectra are on a logarithmic scale. The halomethanes and TCA are weak absorbers, whereas TCE and other chloro-olefins absorb strongly in the deep UV region. The VOCs all absorb strongly below 200 nm. A shift in peak output from 254 to 230 nm is significant because it corresponds to a 1 to 2 order of magnitude increase in absorptivity of many VOCs, thereby greatly enhancing the rates of direct photolysis.

Photolysis Kinetics

At low total absorbance (< 0.1) the direct photolysis of a compound results in the exponential decrease in concentration of the compound with photolysis time (Zepp and Cline, 1977):

$$-\frac{d[C]}{dt} = 2.3 I_0 \Phi \varepsilon l [C] \qquad (1)$$

where I_0 is the incident light intensity, Φ is the apparent disappearance quantum yield, ε is the molar extinction coefficient, l is the light pathlength, and [C] is the contaminant concentration. For a fixed reactor size and light intensity, a simple first-order decrease in concentration of the photoreactant with irradiation time is consistent with a simple direct photoreaction. A non-exponential decay indicates that the loss of the reactant involves additional reactions whose efficiency is changing during the photolysis period.

The photolysis plots shown in Figures 7 and 8 display both exponential and non-exponential behavior. Compounds whose decay kinetics are first order include benzene, carbon

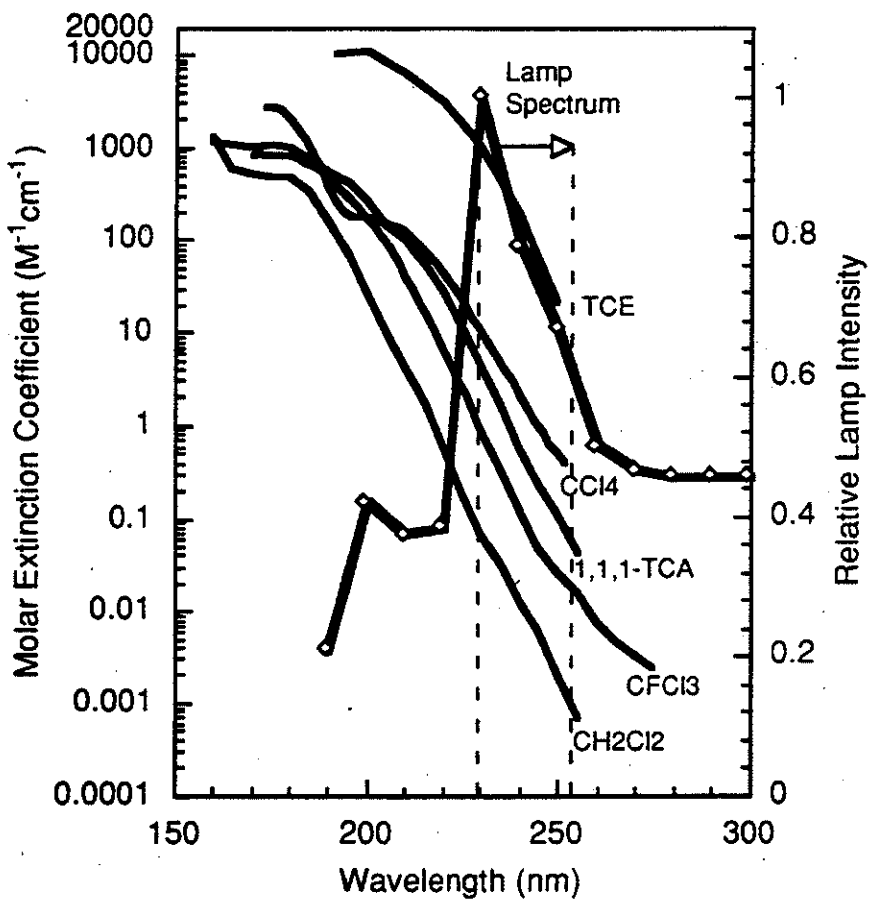


Figure 6. VOC absorbance spectra compared to xenon flashlamp spectrum.

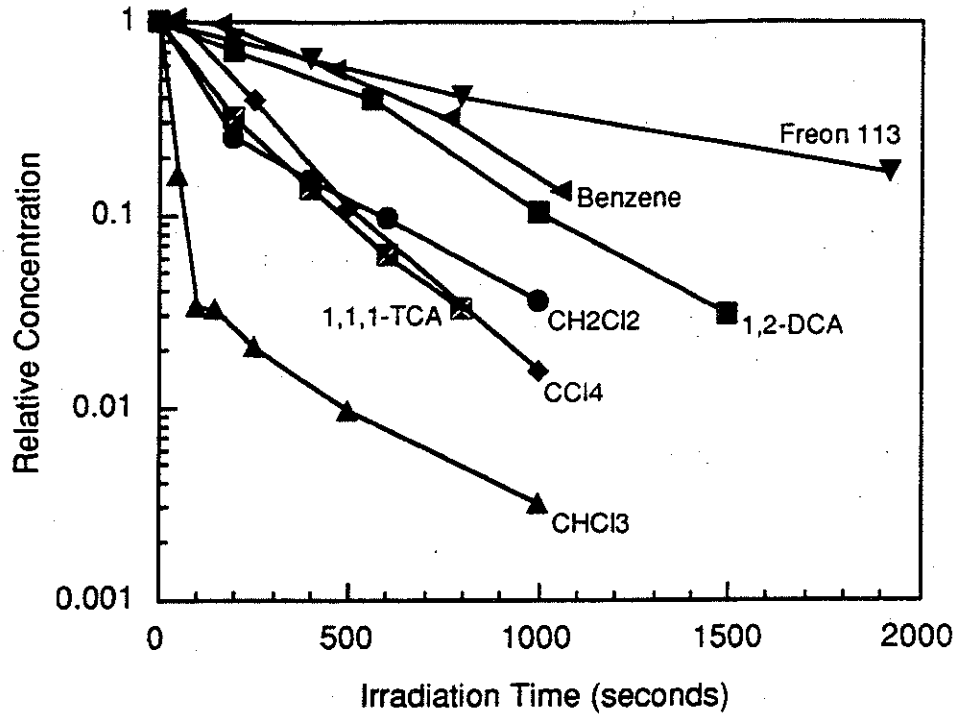


Figure 7. Photolysis plots for individual VOCs in the 208-L reactor.

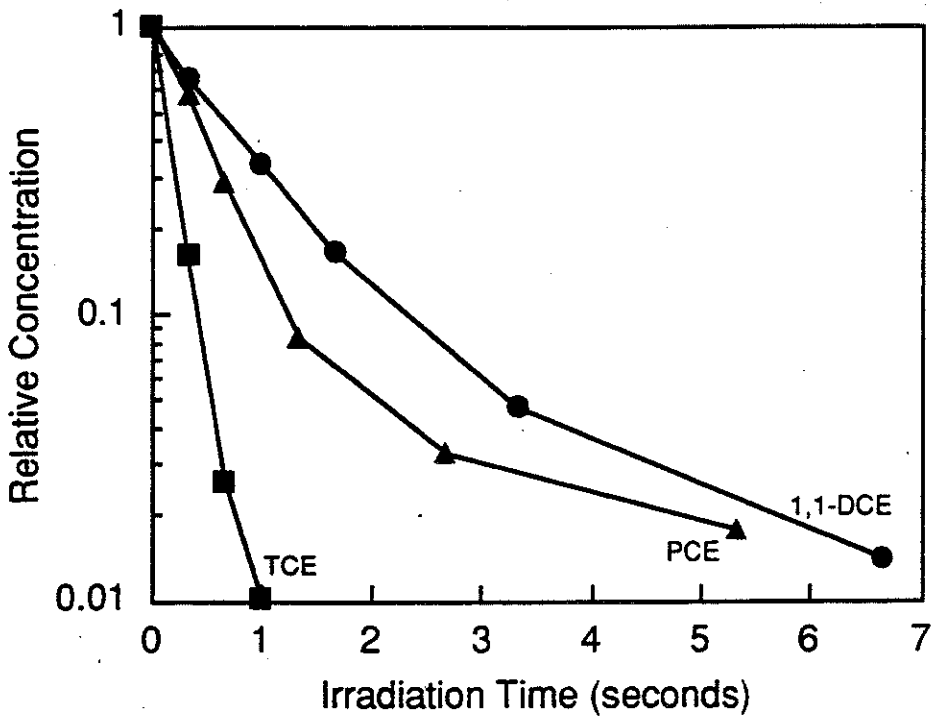


Figure 8. Photolysis plots for chloroolefins in the 208-L reactor.

tetrachloride, trichlorofluoromethane, 1,1,1-trichloroethane, 1,2-dichloroethane, and 1,1,2-trichloro-1,2,2-trifluoroethane. Non-first order decays were observed for methylene chloride, chloroform, tetrachloroethene, trichloroethene, and 1,1-dichloroethene. These differences in the decay behavior provide evidence that the photolysis mechanism for these sets of compounds is different.

Disappearance Quantum Yields

The magnitude of the quantum yield (Φ) for the elimination of the photoreactant also gives some mechanistic information. The ratio of the disappearance quantum yield divided by the primary yield would be unity in the case of a direct photoreaction that contains no subsequent reactions that consumes the reactant. This ratio is greater than unity when later dark reactions consume additional photoreactant, and is substantially greater than unity in the case of a chain reaction.

Table 1 shows apparent wavelength-averaged quantum yields for the compounds studied determined using carbon tetrachloride as an actinometer. From rate equation 1 for disappearance of the photoreactant in the low absorbance limit, the following expression for the quantum yield can be derived:

$$\frac{\sum I_\lambda \varepsilon_\lambda^{CCl_4}}{\sum I_\lambda \varepsilon_\lambda^{VOC}} \times \frac{k_{VOC}}{k_{CCl_4}} = \Phi_{VOC} \qquad (2)$$

Because a broad band source was used for the excitation light, this expression incorporates the summation over the emission band of the lamp multiplied with the corresponding extinction coefficients of the compound. The disappearance quantum yield for carbon tetrachloride was taken as 1.0, based on the literature data at 214 nm (Rebbert and Ausloos, 1976). For compounds that displayed non-first order decay, the quantum yield was calculated from the initial rate determined from the first time point.

Comparison of the data in Table 1 and Figures 7 and 8 show that compounds that display non-first order decays also exhibit apparent quantum yields greater than unity. These compounds include CH_2Cl_2, $CHCl_3$, TCE, 1,1-DCE, and PCE. Furthermore, the other compounds including benzene, CCl_4, $CFCl_3$, 1,1,1-trichloroethane, 1,2-dichloroethane, and 1,1,2-trichloro-1,2,2-trifluoroethane, have decays that are first order and apparent quantum yields near unity. We

TABLE 1. FIRST ORDER DECAY COEFFICIENTS AND WAVELENGTH-AVERAGED DISAPPEARANCE QUANTUM YIELDS WITH A 2.756 kW XENON LAMP

Compound	k (sec^{-1})*	$\frac{\sum I_\lambda \varepsilon_\lambda^{CCl_4}}{\sum I_\lambda \varepsilon_\lambda^{VOC}}$	x	$\frac{k_{VOC}}{k_{CCl_4}}$	=	Apparent Φ
CCl_4	0.00432	1.0		1.0		1.0
CCl_2FCClF_2	0.00093	5.09		0.22		1.1
Benzene	0.0019	0.067		0.44		0.029
CH_2ClCH_2Cl	0.0024	N.D.#		N.D.		N.D.
$CFCl_3$	0.0036	1.18		0.84		0.99
CCl_3CH_3	0.0041	0.79		0.94		0.74
CH_2Cl_2	0.0070	4.60		1.62		7.5
$CHCl_3$	0.0366	1.79		8.47		15
1,1-DCE	1.24	0.0389		287		11
PCE	1.7	0.0134		394		5.3
TCE	5.5	0.0236		1300		31
TCE + ethene	0.075	0.0236		17		0.4

* Initial rate constants are taken for non-log-linear curves
# N.D.= not determined

believe that the five compounds in this study that show non-log-linear photo-oxidation kinetics and apparent quantum yields greater than unity react by a chlorine atom chain mechanism. The other compounds are believed to react purely by direct photolysis.

The ratio of the disappearance quantum yield to that of the primary yield provides a measure of the chain length. Primary quantum yields for C-Cl bond dissociation in chloroalkanes are usually near unity (as verified for $CFCl_3$, 1,1,1-trichloroethane, and 1,1,2-trichloro-1,2,2-trifluoroethane); therefore chain lengths for methylene chloride and chloroform are approximately 8 and 15. The TCE experiment with ethene added (see below) as a Cl• atom scavenger suggests that the primary quantum yield for TCE is near 0.4, which in turn yields a chain length of about 75.

Chain Photo-oxidation Mechanism

Heicklen and co-workers have found that chain induced photo-oxidation occurs for chloroform and all of the chlorinated ethenes except vinyl chloride (Sanhueza, *et al.*, 1976).

Although the reactions in their studies were initiated by Cl_2 sensitization as opposed to direct photodissociation, similar chain propagation steps should occur in both cases. Because most of the oxidation takes place in the chain steps, the types of products formed are essentially independent of whether the chain is initiated by direct photolysis or Cl_2 photolysis. In the case of TCE, the main carbon containing products were shown to be dichloroacetyl chloride (DCAC), dichlorocarbonyl (DCC), and carbon monoxide (Sanhuenza *et al.*, 1976). Chloroform, carbon tetrachloride, and trichloroethylene oxide were also identified but at much lower yields (Huybrechts and Meyers, 1966). Adopting their mechanisms as the most probable, we propose the following mechanisms for VOC photo-oxidation in air:

The pathways for photo-induced chain reactions are consistent with the observed decrease in efficiency as the reactant concentration drops, because the fourth steps have a second order dependence on the concentration of the peroxy radical intermediate. As their concentration drops, they become more likely to react in other ways that do not regenerate Cl•.

TCE Photo-induced Chain Reaction

$$HClC{=}CCl_2 + h\nu \longrightarrow HClC{=}CCl^{\bullet} + Cl^{\bullet}$$
$$Cl^{\bullet} + HClC{=}CCl_2 \longrightarrow HCl_2C\text{-}CCl_2^{\bullet}$$
$$HCl_2C\text{-}CCl_2^{\bullet} + O_2 \longrightarrow HCl_2C\text{-}CCl_2OO^{\bullet}$$
$$2HCl_2C\text{-}CCl_2OO^{\bullet} \longrightarrow 2HCl_2C\text{-}CCl_2O^{\bullet} + O_2$$
$$HCl_2C\text{-}CCl_2O^{\bullet} \longrightarrow HCl_2C\text{-}CClO + Cl^{\bullet} \longrightarrow$$
(DCAC)

CH_2Cl_2 Photo-induced Chain Reaction

$$CH_2Cl_2 + h\nu \longrightarrow CH_2Cl^{\bullet} + Cl^{\bullet}$$
$$Cl^{\bullet} + CH_2Cl_2 \longrightarrow CHCl_2^{\bullet} + HCl$$
$$CHCl_2^{\bullet} + O_2 \longrightarrow CHCl_2OO^{\bullet}$$
$$2CHCl_2OO^{\bullet} \longrightarrow 2CHCl_2O^{\bullet} + O_2$$
$$CHCl_2O^{\bullet} \longrightarrow HCOCl + Cl^{\bullet} \longrightarrow$$
(formyl chloride)

TCA Non-chain Photolysis

$$H_3C\text{-}CCl_3 + h\nu \longrightarrow H_3C\text{-}CCl_2^{\bullet} + Cl^{\bullet}$$
$$Cl^{\bullet} + Cl_3C\text{-}CH_3 \longrightarrow Cl_3C\text{-}CH_2^{\bullet} + HCl$$
$$Cl_3C\text{-}CH_2^{\bullet} + O_2 \longrightarrow Cl_3C\text{-}CH_2OO^{\bullet}$$
$$2Cl_3C\text{-}CH_2OO^{\bullet} \longrightarrow 2Cl_3C\text{-}CH_2O^{\bullet} + O_2$$
$$Cl_3C\text{-}CH_2O^{\bullet} + O_2 \longrightarrow Cl_3C\text{-}CHO + HO_2^{\bullet} \longrightarrow$$

(trichloroacetaldehyde)

A common feature of the mechanisms for TCE and methylene chloride is that Cl• atom reacts with them to generate a carbon-centered radical that has chlorine substitution. These carbon-centered radicals are then oxidized in two steps to alkoxy radicals that can then cleave a Cl• atom and propagate the chain. By contrast, the carbon radical formed from TCA has no chlorine substitution and upon oxidation it can only cleave HO_2• instead of Cl•. HO_2• is a much less reactive radical and engages predominantly in termination steps with itself and other radicals. All the compounds listed in Table 1 fit this general rule, with the exception of 1,2-DCA. 1,2-DCA appears to deviate from the rule because it gave first-order photo-oxidation kinetics, but the quantum yield is yet undetermined and may still prove to be greater than one. Cl• atoms do not react with C-Cl or C-F bonds and therefore freons and perchloroalkanes will not form a chain.

Photolysis of Chloro-olefin Mixtures

As a further test of the occurrence of a chain reaction with TCE, we photolyzed TCE in the presence of a 500-fold molar excess of ethene as a Cl• atom scavenger. Because ethene contains no chlorine, it cannot propagate a Cl• atom chain. Figure 9 and Table 1 show that the ethene decreased the TCE photolysis rate by a factor of about 75. Moreover, the rate constant in the absence of ethene decreased with time until at very long times ([TCE] <1 ppmv) it approached the rate constant in the presence of ethene (data not shown). Under both of these conditions chain propagation is inefficient and therefore we believe that the reaction observed in these cases is predominantly direct photolysis.

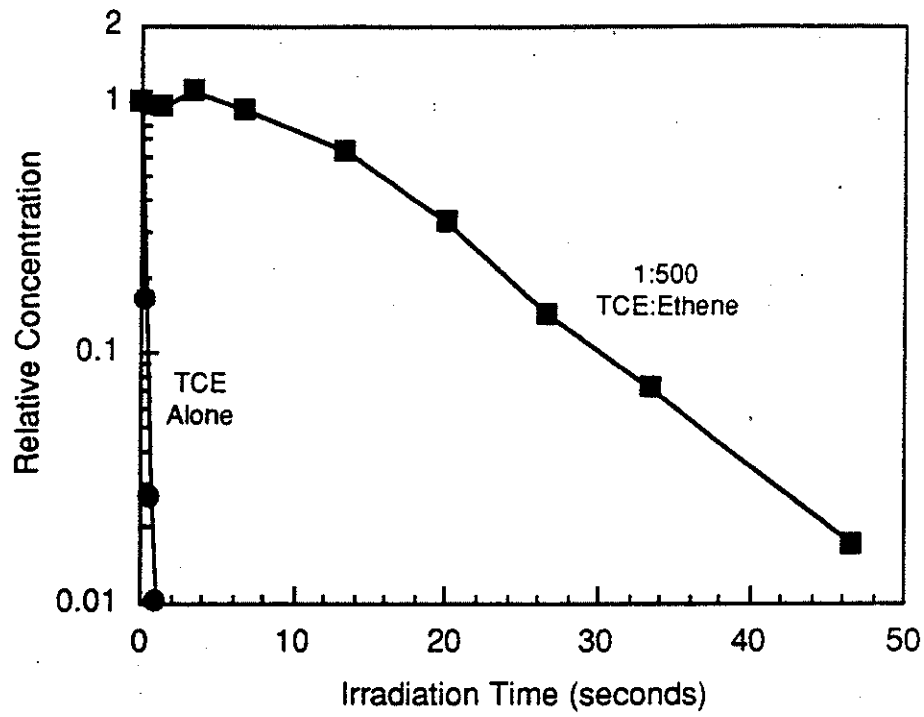


Figure 9. Chlorine atom scavenging with ethene in the 208-L reactor

Figure 10 shows a photolysis experiment with an equimolar mixture of TCE and 1,1-DCE. Comparing these results with those presented in Figure 8 shows that in the mixture the rate of TCE loss is slightly reduced but the rate of 1,1-DCE loss is considerably enhanced. We interpret this to be a result of photo-initiation predominantly by TCE because it absorbs UV light more strongly, but with chain propagation predominantly by 1,1-DCE because it reacts with chlorine atoms more rapidly (Atkinson and Aschmann, 1987):

$$Cl^{\bullet} + H_2C{=}CCl_2 \longrightarrow HClC\text{-}CCl_2^{\bullet} \qquad k_{DCE} = 14 \times 10^{-11}\ cm^3\ molec^{-1}\ s^{-1}$$
$$Cl^{\bullet} + HClC{=}CCl_2 \longrightarrow HCl_2C\text{-}CCl_2^{\bullet} \qquad k_{TCE} = 8.1 \times 10^{-11}\ cm^3\ molec^{-1}\ s^{-1}$$

When chains are long compared to the primary photolysis event, the relative rates of loss of 1,1-DCE and TCE should be in the same ratio as their Cl• atom reaction rate constants of 14/8.1 = 1.7. This value is in good agreement with the observed ratio of rates of 1.5 and presents further evidence that Cl• atom is the rate-limiting oxidant in the system.

The experiments with olefin mixtures demonstrate that co-contaminants can cause both

sensitization and inhibition of photolysis. Increasing chlorine substitution on the olefin results in stronger light absorption and thus more rapid chain initiation. On the other hand, greater chlorine substitution decreases the rate of the propagation reaction with Cl• atom thereby reducing chain length. Finally, as chlorine substitution decreases, the statistical chance of regenerating a free Cl• atom and propagating a chain drops sharply. Thus, TCE and PCE can be expected to sensitize the photo-oxidation of the dichloroethene isomers and vinyl chloride because the former are better light absorbers and the latter react with Cl• atom more readily. However, addition of chloroolefins will not sensitize the photoreactions of the chain promoters chloroform and dichloromethane, because the chloroolefins enhance the rate of Cl• atom scavenging as well as production. In principle, any chlorocarbon that photolyzes to form Cl• atom can be expected to sensitize the oxidation of another hydrocarbon, although the effect will be small if a chain reaction is not sustained or the reaction rate constant between Cl• atom and the hydrocarbon is low compared to that between Cl• atom and its precursor.

Photo-oxidation Products of TCE

Some products of the photo-oxidation of TCE in air were investigated by irradiating TCE in a Teflon-sealed, quartz spectrophotometer cell, to allow efficient collection of the reactive products. Methanol was injected into the cell following irradiation, which derivatized the main oxidation product DCAC to methyl dichloroacetate (MDCA). Analysis by GC/MS of the methanol solution revealed that at low UV doses, DCAC (measured as MDCA) was formed at a yield exceeding 90 mole % from TCE. The identity of MDCA peak was verified by mass spectrometry. Trichloroacetyl chloride (measured as methyl trichloroacetate) was also identified by GC/MS but the yield was < 2% of the DCAC yield based on the relative ion signal. Further photolysis of TCE in air revealed an approximately exponential decrease in the DCAC concentration (Figure 11). The pattern of the TCAC concentration suggests that it is formed from DCAC but then also photolyzes.

DCAC Photo-oxidation

Because the main intermediate product from TCE photo-oxidation is dichloroacetyl chloride, subsequent products are largely determined by the photochemistry of DCAC. One product formed from the photo-oxidation of DCAC is DCC, as shown in Figure 12. Note that these experiments were conducted by starting with DCAC instead of TCE in the spectrophotometer cell, and measuring the yield of DCC in the absence and presence of added Cl_2 gas. The DCC

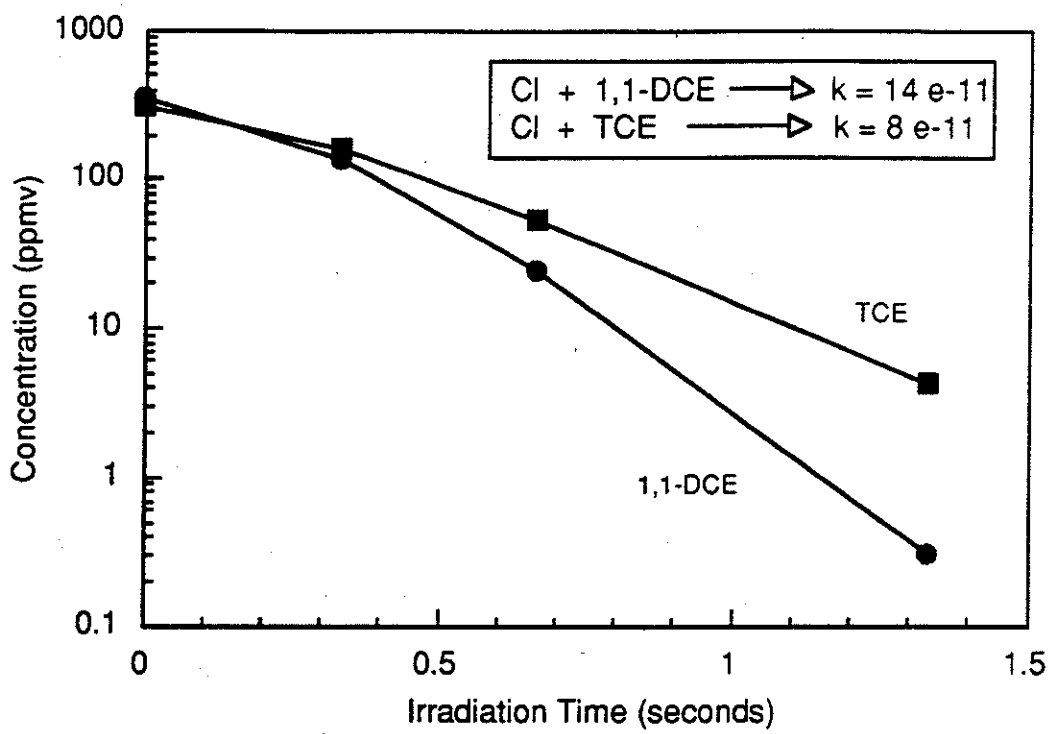


Figure 10. Photolysis of TCE and 1,1-DCE as a mixture in the 208-L reactor

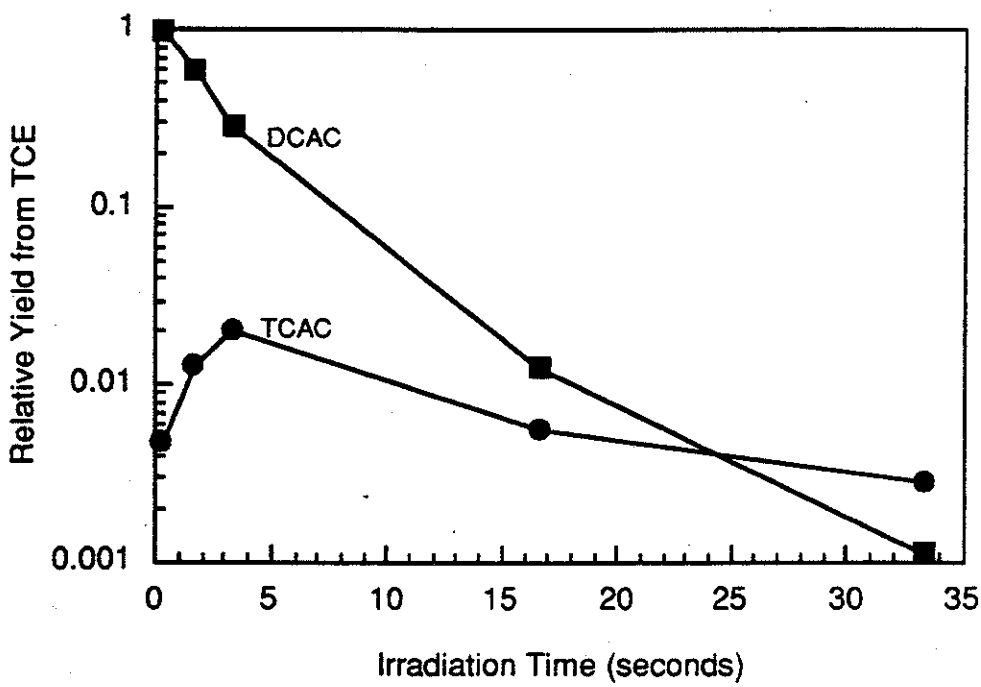


Figure 11. Product yields from the photo-oxidation of TCE in the spectrophotometer cell.

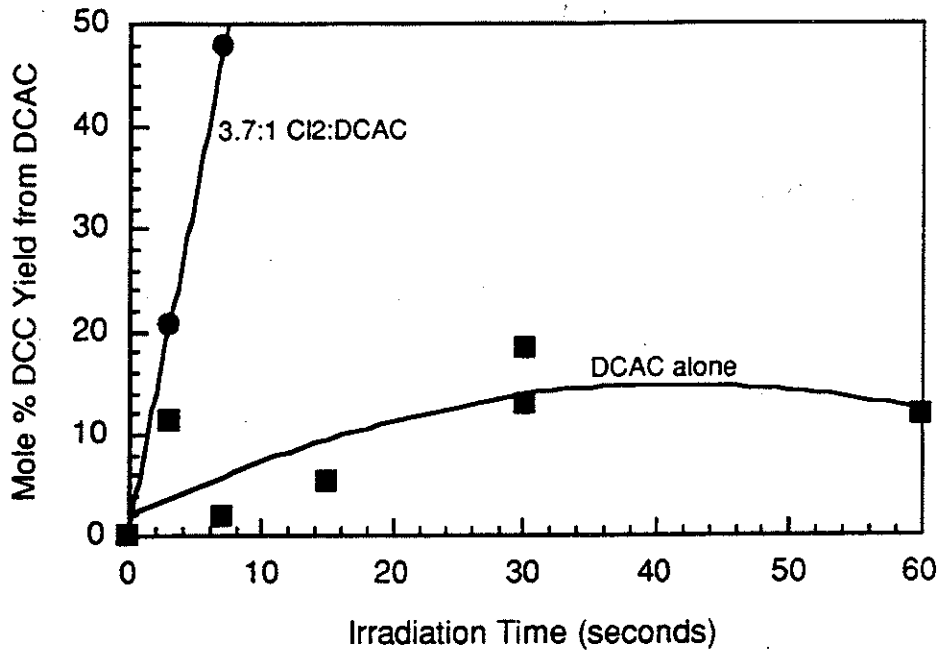


Figure 12. DCC yields from the photo-oxidation of DCAC in the spectrophotometer cell.

yield increases slowly to about 15 mole % and then begins to decrease with light dose. Addition of chlorine greatly increases the DCC yield by a factor of 24 when a 3.7:1 mole ratio of Cl_2 to DCAC is photolyzed for 7 seconds. Its formation might be caused by chlorine atom attack upon DCAC:

$$Cl^{\bullet} + \underset{(DCAC)}{Cl_2HC\text{-}C(O)Cl} \longrightarrow Cl(O)C\text{-}Cl_2C^{\bullet} + HCl$$

$$Cl(O)C\text{-}Cl_2C^{\bullet} + O_2 \longrightarrow Cl(O)C\text{-}Cl_2COO^{\bullet}$$

$$2\,Cl(O)C\text{-}Cl_2COO^{\bullet} \longrightarrow O_2 + 2\,Cl(O)C\text{-}Cl_2CO^{\bullet}$$

$$Cl(O)C\text{-}Cl_2CO^{\bullet} \longrightarrow \underset{(DCC)}{Cl_2CO} + OClC^{\bullet}$$

The low of DCC suggests that it is either photolyzed simultaneous with its production from DCAC, or that an additional DCAC reaction pathway exists that does not lead to DCC, or both. A possible additional mechanism involves photolytic cleavage of the chlorine-carbonyl bond followed by reaction with oxygen:

$$h\nu + Cl_2HC\text{-}C(O)Cl \longrightarrow Cl_2HC\text{-}C(O)^{\bullet} + Cl^{\bullet}$$
$$Cl_2HC\text{-}C(O)^{\bullet} + O_2 \longrightarrow Cl_2HC\text{-}C(O)OO^{\bullet}$$
$$2\,Cl_2HC\text{-}C(O)OO^{\bullet} \longrightarrow O_2 + 2\,Cl_2HC\text{-}C(O)O^{\bullet}$$
$$Cl_2HC\text{-}C(O)O^{\bullet} \longrightarrow Cl_2HC^{\bullet} + CO_2$$
$$Cl_2HC^{\bullet} + O_2 \longrightarrow Cl_2HCOO^{\bullet}$$
$$2\,Cl_2HCOO^{\bullet} \longrightarrow O_2 + 2\,Cl_2HCO^{\bullet}$$
$$Cl_2HCO^{\bullet} \longrightarrow \underset{\text{(formyl chloride)}}{ClHCO} + Cl^{\bullet}$$

This mechanism predicts CO_2 and formyl chloride as the carbon-containing products. A preliminary CO_2 measurement in the 208-L pilot reactor indicated ≥ 50% yield of CO_2 after 170 seconds of irradiation. Formyl chloride was not analyzed for, but it is the most likely missing product because it contains only hydrolyzable chlorine. The field data described below indicate that all of the chlorine not accounted for by DCAC is readily hydrolyzable, i.e., forms Cl^- rapidly on reaction with water. Formyl chloride hydrolyzes to give formic acid and HCl.

FIELD EXPERIMENTS

TCE disappearance data and product data from Air-2 and Air-3, are given in the Appendix. Most of the discussion will be limited to results from Air-3, because sampling conducted during the testing of Air-2 was impaired by high moisture levels in the system. Because the two principal oxidation products, DCAC and DCC, could react with water prior to sampling, they were readily lost on the reactor surface and sampling tubing. Measurements of TCE concentrations should not be influenced by this problem, however. As described in the Methods section, these difficulties were overcome before sampling for Air-3 measurements were begun.

TCE Removal Efficiency

Over the range of experimental variables covered, trichloroethene was photo-oxidized to >99% conversion except at the lowest flash frequencies and number of lamps. The tables in the Appendix give the extent of conversion under the different experimental conditions. Under the highest exposures and optimal conditions, conversions of 99.9996% were achieved. Estimation of the loss of trichloroethene was limited by the 0.01 ppmv detection limit of the gas chromatographic method.

Measured TCE Oxidation Products

Figure 13 shows the evolution of products during the photolysis of TCE in Air-3 at the field site. In order to compare total exposure levels in each reactor and to factor in flash frequency and process flow rate, a dose was calculated under each set of experimental conditions, defined as:

$$\text{Dose} = \text{Residence time} \times \text{Flash frequency} \times \text{No. of lamps} \times \text{Energy/flash} \qquad (3)$$

In the case of Air-3 the dose was calculated assuming two lamps, since the flow was split off and sent through two reactors in series. Again, the principal organic product from the TCE photo-oxidation observed in the field studies was dichloroacetyl chloride. At the lower exposure range (1.2 kJ dose) that is just sufficient to eliminate TCE, a conversion of 86 mole % DCAC and 6.9 mole % DCC was observed in Air-3. At a dose of about 70 kJ, we found a 28 mole % conversion to DCAC and 23 mole % to DCC. As the dose was increased, by increasing either the residence time or the flash frequency, the DCAC yield fell off exponentially (Figure 13), and the DCC concentration increased. The DCC yield did not equal the DCAC loss, presumably because of concomitant DCC photolysis or other pathways for DCAC loss, as observed in the laboratory studies.

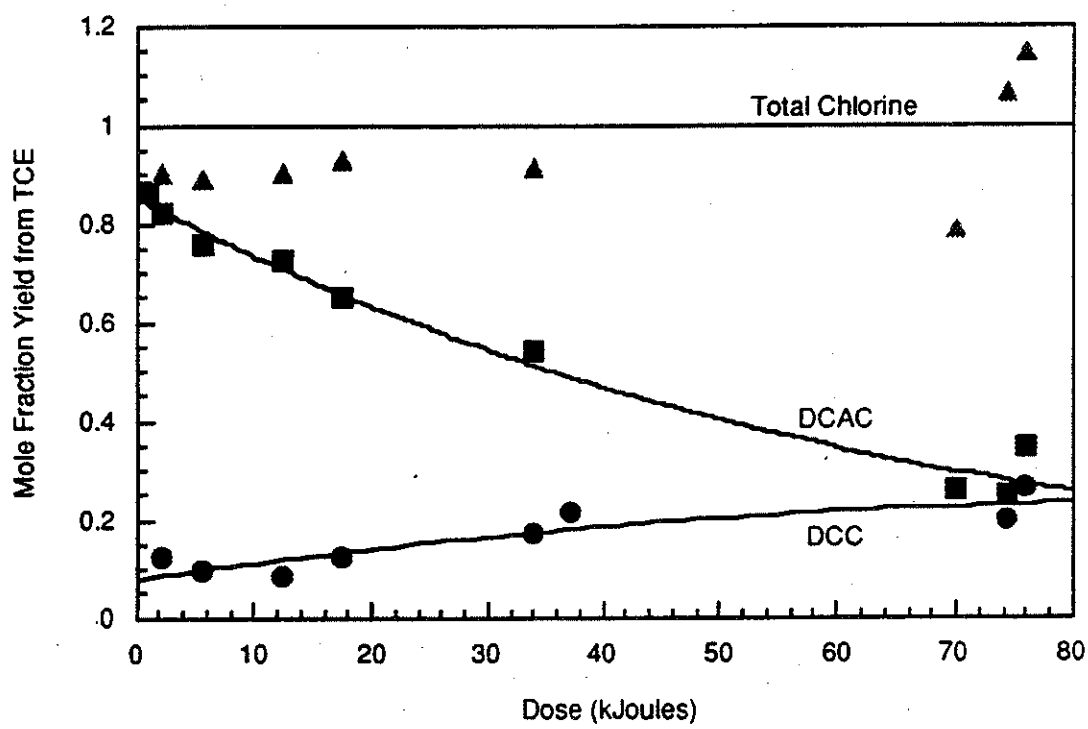


Figure 13. Product yields from the photolysis of TCE in Air-3.

A mass balance for chlorine can be estimated by using the yield obtained for DCAC and the total chloride yield. If, as the evidence suggests, DCAC is the only organic product with non-hydrolyzable chlorine atoms, then the chlorine mass balance may be calculated as follows:

Fraction chlorine recovered = (moles chloride + 2 x moles DCAC) / (3 x moles TCE lost) (4)

The chlorine recoveries taken from Air-3 ranged from 79 mole % to 115 mole % with the average about 93 ± 23 % (95% confidence interval). This high yield is constant throughout the experiment, as can be seen in Figure 1. Within the uncertainty of these measurements most of the chlorine is accounted for, indicating that all the chlorine other than one of those in DCAC is in hydrolyzable form, such as in DCC or formyl chloride. The chlorine balance in Air-2 experiments was more variable due to the higher humidity, causing sampling loss, as mentioned above.

The excellent chlorine balance implies that products such as carbon tetrachloride and chloroform, which have been detected previously in TCE photo-oxidation (Huybrechts and Meyers, 1966), are present in very low yield in our system. The TO-14 whole air sampling test results given in Table 2 confirm this. The chloroform yield was found to be 0.65 % of the TCE input, and the carbon tetrachloride yield 0.15%, and the methylene chloride yield 0.05%.

A mass balance for carbon cannot be determined based upon the measurements performed in this study. Potential carbon containing products from TCE photo-oxidation that were not examined in detail include CO, CO_2, formyl chloride and trichloroethylene oxide.

TABLE 2. TO-14 ANALYSIS SAMPLED ON 28 JAN 1992 AT 30 HZ FROM AIR-2

Sample	CCl_4 (ppmv)	$CHCl_3$ (ppmv)	CH_2Cl_2 (ppmv)	PCE (ppmv)	TCE (ppmv)
Input	≤0.002*	≤0.005	≤0.050	0.150 [0.002]*	130.0 [0.002] (182)†
Output	0.200	0.840	0.070	0.002	0.024 [0.001] (0.06)
20 ppmv Standard	≤0.001	≤0.001	≤0.010	≤0.001	15.0 [0.001] (18.3)

* Values in brackets or given as upper limits are detection limits. Detection limits for the output samples were the same as for the 20 ppmv standard.

† Values in parentheses were determined by Purus.

ESTIMATION OF PARAMETERS TO ACHIEVE RECOMMENDED TREATMENT LEVELS AT LLNL SITE 300

Because of the formation of toxic products, the efficacy of treatment at LLNL Site 300 cannot be measured simply in terms of TCE removal. Table 3 lists exposure limits for TCE and its photo-oxidation products, as estimated by Environ Corp., a consulting firm in Emeryville, CA (Tsai and Libicki, 1992). The estimate for DCAC assumes that this compound hydrolyzes rapidly in the environment or respiratory tract and thus has the same long-term toxicity as DCAA. It is clear from Table 3 that the major products are more toxic than TCE and thus would need to be removed by further photolysis or other post-treatment before emission to the atmosphere.

TABLE 3. EXPOSURE LIMITS FOR TCE AND ITS PHOTO-OXIDATION PRODUCTS

Chemical	Worker Exposure Limit* ($\mu g/m^3$)
TCE	26.8
DCAC	0.68
DCAA	0.68
DCC	12
CO	20.6

* Based on a lifetime cancer risk level 10^{-5}

Because the toxicity of DCAA is 40 times greater than that of TCE (Tsai and Libicki, 1992), the most DCAC one can emit is 1/4000 times the initial TCE concentration, or at most 0.025% DCAC remaining, to reach the goal of 99% reduction in initial toxicity. Similarly, the concentration of DCC would need to be less than 0.45% of the initial TCE concentration. To estimate the exposure time necessary to reach the required concentration of DCAC, an extrapolation must be made because no conditions used in this study reached these treatment goals. To do this we assume an exponential decrease with dose, as supported by the data over the parameters studied (Figures 11 and 13):

$$Y(t) = Y(o)\, e^{-kt} \qquad (5)$$

where Y = relative concentration, k = first order rate coefficient, and t = time. Because we want to

substitute for the dose, we let dose = Intensity (kJoules/sec) x time (sec), thus:

$$Y(t) = Y(o)\, e^{-(k/I)D} \qquad (6)$$

where D = dose and I = intensity.

Two important assumptions are made in deriving this expression. The first is that DCAC destruction is always first order, which may only be a good approximation if the mechanism for its removal is direct photolysis. This is not be the only possibility because preliminary experiments with added chlorine gas indicated that chlorine atom attack on DCAC can occur also. The second assumption is that DCAC is created instantly at zero time, which is a reasonable approximation when the rates of appearance and disappearance of DCAC are compared.

Table 4 gives the result of this extrapolation along with the first order rate constants obtained from the fits to three sets of data. The fit to data from Air-2 data includes only the highest yields over the dose range, because lower yields may have resulted from poor sampling recovery caused by water reactions. The data indicate that a flow rate of 13 - 20 cfm in Air-2 or Air-3 with four 3.7-kW lamps can achieve the desired DCAC reduction.

TABLE 4. TREATMENT PARAMETERS FOR 99% REDUCTION IN TOXICITY BY UV ALONE AT LLNL SITE 300

Data Source for Extrapolation	k (sec^{-1})	Calculated Residence Time (seconds)	Calculated Process Flow (cfm)	TCE Input Concentration (ppmv)
30 Hz Air-3	0.128	65	15.2	30
All Air-3	0.111	74.8	13.2	30
Highest Air-2	0.0267	301	20.2	30

Insufficient data are available to determine if the DCC concentration would be low enough when the DCAC treatment goal is reached. DCC could easily be removed with a water scrubber, where it would rapidly hydrolyze to CO_2 and HCl. However, traces of DCAC would also hydrolyze to dichloroacetic acid (DCAA) and HCl and, depending on the water flow, the residual

DCAA would still be at least an order of magnitude above the proposed drinking water limit of 0.2 ppb (Bull R., University of Washington, personal communication, 1991). A relatively dry scrubber, such as slaked lime is a possibility because it would trap both DCC and DCAC. However, DCAA is likely to leach out when the lime is landfilled. Promising approaches include using very small flows of water and treating them by incineration or other thermal processes.

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APPENDIX A

TABLE A-1. AIR-2 RESULTS

Freq. (Hz)	No. of Lamps	Flow (cfm)	Res. Time (sec)	[TCE] input (ppmv)	[TCE] output (ppmv)	TCE Destruction (%)	DCC Yield (ppmv)	DCAC Yield (ppmv)	Mole % DCC	Mole % DCAC	Mole % Cl^-	Chlorine Balance (Mole %)
30	4	289	21.0	256	4.34	98.3047	26.2	9.6	10.2	3.8	16.2	18.7
30	4	260	23.3	138	dl	≥ 99.99	26.7	41.9	19.3	30.4	47.8	68.0
30	4	199	30.5	144	0.082	99.9431	33.2	4.5	23.1	3.1	28.0	30.1
30	4	97	62.5	210	dl	≥ 99.995	186.5	29.5	88.8	14.0	61.7	71.1
30	4	103	58.8	31.8	0.28	99.1195	4.2	0.6	13.2	1.9	28.7	30.0
30	4	107	56.6	843	0.13	99.9846	418	4.2	49.6	0.5	75.1	75.4
30	4	104	58.3	10600	0.038	99.9996	959	42.5	9.0	0.4	6.6	6.9
30	4	104	58.3	182	0.06	99.9670	112	4	61.5	2.2	76.8	78.3
30	4	102	59.4	29.9	dl	≥ 99.97	nd	nd	nd	nd	nd	nd
15	4	294	20.6	113	dl	≥ 99.99	13	4.5	11.5	4.0	26.3	29.0
15	4	260	23.3	138	0.34	99.7536	15.2	36.6	11.0	26.5	34.7	52.4
15	4	199	30.5	149	0.21	99.8591	36.1	63.7	24.2	42.8	33.5	62.0
15	4	82	73.9	246	dl	≥ 99.995	167	60.7	67.9	24.7	42.9	59.3
15	4	104	58.3	166	0.06	99.9639	114	5.2	68.7	3.1	57.3	59.4
15	2	105	57.7	1575	0.06	99.9962	nd	nd	nd	nd	nd	nd
10	2	105	57.7	78.1	dl	≥ 99.99	nd	nd	nd	nd	nd	nd
10	4	105	57.7	1562	0.05	99.9968	nd	nd	nd	nd	nd	nd
10	2	105	57.7	1562	0.06	99.9962	nd	nd	nd	nd	nd	nd
5	4	294	20.6	132	dl	≥ 99.99	12.5	40.8	9.5	30.9	12.1	32.7
5	4	260	23.3	134	0.69	99.4851	11.6	33.6	8.7	25.1	34.8	51.5
5	4	198	30.6	167	1.9	98.8623	24.4	80.9	14.6	48.4	28.6	60.9
5	4	105	57.7	148	0.33	99.7770	16.6	12.4	11.2	8.4	17.1	22.7
5	4	107	56.6	113	0.41	99.6372	56.1	40.5	49.6	35.8	76.8	100.7
5	4	105	57.7	84.9	dl	≥ 99.99	nd	nd	nd	nd	nd	nd
5	2	105	57.7	84.9	0.87	98.9753	nd	nd	nd	nd	nd	nd
5	4	105	57.7	1236	0.13	99.9895	nd	nd	nd	nd	nd	nd
5	2	105	57.7	1236	27.8	97.7508	nd	nd	nd	nd	nd	nd

TABLE A-1. (CONT.'D) AIR-2 RESULTS

Freq. (Hz)	No. of Lamps	Flow (cfm)	Res. Time (sec)	[TCE] input (ppmv)	[TCE] output (ppmv)	TCE Destruction (%)	DCC Yield (ppmv)	DCAC Yield (ppmv)	Mole % DCC	Mole % DCAC	Mole % Cl^-	Chlorine Balance (Mole %)
1	4	284	21.3	149	23.6	84.1611	7.1	10.3	4.8	6.9	6.8	11.4
1	4	260	23.3	149	35.1	76.4430	10.5	17	7.0	11.4	13.9	21.5
1	4	195	31.1	115	25	78.2609	18.1	82.2	15.7	71.5	35.9	83.6
1	4	114	53.2	147	7.9	94.6259	7.9	24.4	5.4	16.6	30.9	42.0
1	4	103	58.8	40.2	0.96	97.6119	3.1	6.7	7.7	16.7	23.0	34.1
1	4	102	59.4	34.8	0.37	98.9368	nd	nd	nd	nd	nd	nd
1	4	99	61.2	773	166	78.5252	100.5	120.9	13.0	15.6	36.9	47.3
1	4	107	56.6	109	55	49.5413	49.3	76.7	45.2	70.4	85.6	132.5
1	4	104	58.3	3120	1330	57.3718	113	226	3.6	7.2	8.9	13.7
1	4	105.	57.7	105	22.8	78.2857	nd	nd	nd	nd	nd	nd
1	2	105	57.7	105	31.7	69.8095	nd	nd	nd	nd	nd	nd
1	4	105	57.7	1466	429	70.7367	nd	nd	nd	nd	nd	nd
1	2	105	57.7	1466	596	59.3452	nd	nd	nd	nd	nd	nd

TABLE A-2. AIR-3 RESULTS

Freq. (Hz)	No. of Chambers	Flow (cfm)	Res. Time (sec)	[TCE] input (ppmv)	[TCE] output (ppmv)	TCE Destruction (%)	DCC Yield (ppmv)	DCAC Yield (ppmv)	Mole % DCC	Mole % DCAC	Mole % Cl^-	Chlorine Balance (Mole %)
30	4	103	9.6	78.4	dl	≥ 99.99	nd	20.2	nd	25.8	61.6	78.8
30	4	97	10.1	108.5	dl	≥ 99.99	21.3	26.5	19.6	24.4	89.9	106.2
30	4	95	10.4	98.3	dl	≥ 99.99	25.6	34	26.0	34.6	91.4	114.5
30	2	106	4.6	91.7	0.07	99.92	15.9	49.2	17.3	53.7	55.3	91.1
15	4	97	10.1	106.8	dl	≥ 99.99	22.8	nd	21.3	nd	68.2	nd
15	2	103	4.8	101.3	dl	≥ 99.99	12.6	65.3	12.4	64.5	43.2	86.2
5	4	95	10.4	104.9	dl	≥ 99.99	8.7	75.7	8.3	72.2	41.9	90.0
5	2	103	4.8	101.4	dl	≥ 99.99	9.4	76.3	9.3	75.2	38.6	88.8
1	4	106	9.3	101.7	0.85	99.16	12.5	83.2	12.3	81.8	35.8	90.3
1	2	103	4.8	98.5	13.23	86.57	6.8	84.9	6.9	86.2	35.8	93.3

SPECTRUM '92

International Topical Meeting

NUCLEAR AND HAZARDOUS WASTE MANAGEMENT

VOL. 1

REMEDIATION OF A TCE GROUND SPILL USING AN ELECTRON ACCELERATOR[a]

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ABSTRACT

Radiolytic remediation of trichloroethylene (TCE) spilled into unsaturated soil has been demonstrated using an electron accelerator at Site-300. This site is on the National Priority List because of the large volume of TCE spilled there. Current remediation methods withdraw TCE vapor from the ground by vacuum extraction wells and then pass this effluent through activated charcoal filters. A small electron accelerator was brought to the site to treat the vapor effluent by irradiation before it passed through the charcoal filter. TCE vapor concentration was measured before and after treatment as a function of electron beam power. During operation the vacuum extraction well complex extracted TCE vapor at a concentration of 40 ppmv and flow rate of 270 CFM. The accelerator, operating at a beam power of 400 watts, reduced the TCE concentration from 40 ppmv to 0.1 ppmv. Five organic reaction byproducts were measured at concentrations down to the ppb level. These byproducts are chloromethane, dichloromethane, chloroform, acetone, and trimethylbenzene. These data are used to estimate the capital expenditure and operating costs of an electron accelerator facility for treatment of a vapor stream with TCE concentration of 500 ppmv and flow rate of 500 CFM. It is shown that the electron accelerator provides better treatment than activated charcoal and is more cost effective.

LABORATORY SAMPLE EXPOSURES

Radiolytic decomposition of TCE and other VOCs dissolved in groundwater and in the vapor phase has been demonstrated in the laboratory using bremsstrahlung radiation provided by an electron accelerator of several MeV energy.[1] Figure 1 shows the reduction of TCE concentration as a function of applied radiation dose in vapor obtained from a vacuum extraction well located at the TCE spill area of Site-300.

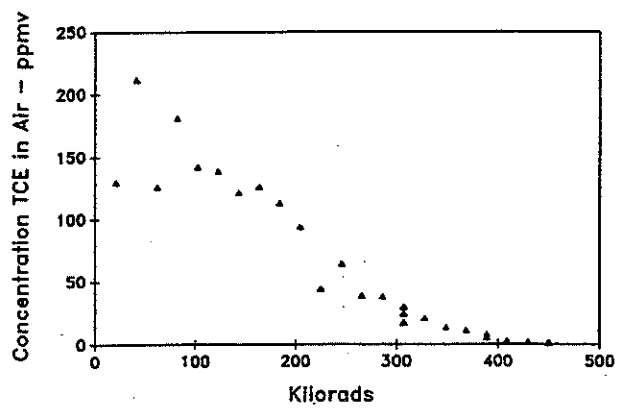

Figure 1 - Reduction of TCE concentration in air as a function of applied dose using 9 MeV bremsstrahlung on vapor obtained from Site-300 vacuum extraction well.

The vapor was collected within a hollow, initially evacuated eight inch diameter stainless steel sphere that was filled at the wellhead and brought to the laboratory for exposure to increasing amounts of 9 MeV bremsstrahlung. Small, microliter volume samples of vapor were withdrawn from the sphere at various intervals during the irradiation process and analyzed for TCE concentration. This was done

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using a gas tight syringe to extract the vapor samples through a rubber septum valve covering during brief periods while the accelerator was switched off. The samples were analyzed for TCE concentration using a Photo-Vac gas chromatograph. These data show that an applied dose of 450 kR reduces the TCE concentration from approximately 200 ppmv to less than 1 ppmv. Subsequent chemical analysis on the vapor residue remaining within the exposed sphere found no phosgene with a lower detection limit of 50 ppm and no organic compounds with a lower detection limit of 1 ppm.

FIELD EXPOSURES

The vacuum extraction well complex at Site-300 consists of nine vacuum extraction wells located within the TCE spill area. These wells are manifolded together in parallel to a common vacuum pump that extracts vapor at atmospheric pressure and ambient temperature of 70°F at a rate of 270 CFM. The TCE concentration in the extraction effluent is approximately 40 ppmv. The vapor is then passed through barrels of activated charcoal that filter and remove most of the TCE before release to the atmosphere. The vapor is piped through four inch diameter PVC piping which is used to connect the wells, the vacuum pump and activated charcoal filters together.

ELECTRON ACCELERATOR

A 2 MeV electron accelerator with a maximum beam power of 1 kW was brought to Site-300 and set up to irradiate the TCE vapor after extraction from the wells but before reaching the activated charcoal filter. The accelerator was packaged within a rectangular metal box approximately five feet high, three feet wide and three feet deep. A slight modification to the accelerator was required for use at Site-300 because it was originally constructed as an industrial x-ray unit. Installation consisted of cutting the vapor carrying PVC pipe between the vacuum pump and charcoal filter so that the accelerator could be plumbed into the system to irradiate the vapor.

The accelerator control module was mounted within a truck parked nearby and connected to the accelerator via fifty feet of electrical cable. An external 10 kW, 220 volt cable was connected to the control module and supplied electric power to run the accelerator. The accelerator operator was stationed at the control module and could vary the electron beam power and other accelerator parameters.

RADIATION SHIELDING

Protection of operating personnel against ionizing radiation is required when high voltage electron accelerating equipment is used. This was accomplished by stacking cement blocks around the accelerator to a height of about ten feet to enclose the accelerator within a primitive walled structure housing. A canvas tent was erected over the cement structure to protect the accelerator from rain. A warning light was placed on top of the accelerator housing and automatically activated when the beam was switched on. The area surrounding the accelerator was roped off at a distance of twenty-five feet from the cement block structure to provide further protection. The complete installation of the accelerator at the site, including replumbing the vapor carrying PVC pipes and construction of the cement block housing required one week.

During accelerator operation the background radiation field was measured at the rope barrier and found to be 0.5 mR/hr. This background is well within the DOE allowed limit for personnel exposure of 2.0 mR/hr. Furthermore, the 2 MeV beam energy used in this demonstration was well below the threshold for activation and therefore no residual radiation was measured when the accelerator was switched off. All concerns that the accelerator beam will make something radioactive are unfounded.

EXPERIMENTAL PROCEDURE

The demonstration measurements were made with the vacuum extraction system continuously operating at a flow rate of 270 CFM and pressure of one atmosphere. The vapor temperature was constant at 70°F. Vapor sampling ports located within the plumbing enabled sampling upstream and downstream of the accelerator. Samples were obtained first with the accelerator beam switched off, and then with the beam operating at 80 W. The accelerator power was increased by 80 W increments

to a maximum power of 400 W and was then switched off. The power level at each increment was held constant for approximately one hour while vapor samples were collected. This beam power level did not measurably increase the vapor temperature.

The radiation efficiency of the beam interaction with the vapor stream geometry was calculated to be 0.33 using a Monte Carlo radiation transport code. The radiation efficiency is that fraction of the beam power that actually deposits irradiation dose within the vapor. The accelerator deposited a dose of 88 kR into the vapor when operating at 400 W with the vapor flow rate set at 270 CFM. Since the flow rate was constant, the irradiation dose was proportional to the beam power.

Vapor obtained from the sampling ports was passed to an on-site GC through stainless steel tubing and TCE concentration measurements were made. Standard gases with known concentrations of TCE were used for calibration. Vapor samples were also collected in evacuated eight inch and four inch diameter stainless steel spheres and sent to two independent laboratories that were each approved by the EPA to perform a GC/MS Full Scan T0-14 analysis for organic compounds. Small amounts of vapor were first withdrawn from each sphere and analyzed at LLNL using a GC/MS.

EXPERIMENTAL MEASUREMENTS

The TCE concentration in the vapor is displayed as a function of beam power in Figure 2. These data show that the TCE concentration in the unirradiated vapor is approximately 40 ppmv and is reduced by increasing the accelerator power. Analysis of the vapor exposed to 400 W of beam power reveals the TCE concentration to be 0.1 ppmv (100 ppbv).

Five reaction products were measured in the irradiated gas at a maximum concentration of 400 ppbv. These were chloromethane, dichloromethane, chloroform, acetone, and trimethylbenzene.

Chloromethane and dichloromethane were detected in the unirradiated vapor at concentrations of several ppbv each. These were both increased by the radiation to maximum concentrations of 8 ppbv and 15 ppbv respectively in the vapor sample exposed to 400 W beam.

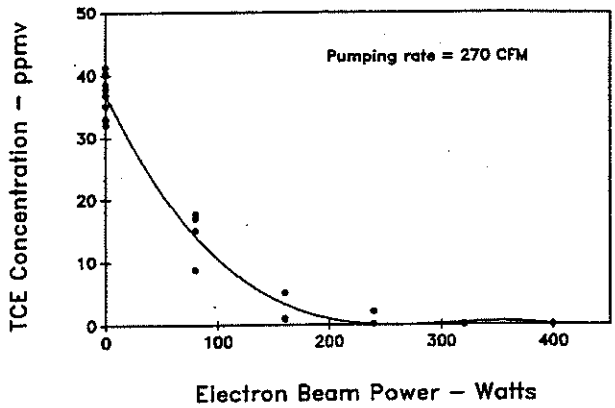

Figure 2 - TCE concentration as a function of accelerator beam power for vapor obtained downstream of the accelerator.

Chloroform was detected in the unirradiated vapor at a concentration of 10 ppbv. This concentration increased to a maximum of 100 ppbv in the sample exposed to the 400 W beam.

Acetone and trimethylbenzene were each found in the unexposed vapor at concentrations of 50 ppbv and 10 ppbv respectively. These concentrations increased to a maximum at intermediate beam powers and were reduced in the vapor sample exposed to 400 W. This indicates that these products were produced by small amounts of ionizing radiation but then began to decompose as the applied dose was increased. Peak acetone concentration was measured at 100 ppbv in the vapor sample irradiated at the 240 W power level. The acetone concentration in the 400 W sample was only 90 ppbv. Maximum trimethylbenzene concentration was found to be 400 ppbv in the vapor sample exposed at the 160 W power level. This concentration was reduced to 100 ppbv in the sample exposed at 400 W beam power. It was assumed that the trimethylbenzene production resulted from small amounts of diesel fuel present in the unirradiated vapor.

Carbon tetrachloride and PCE were both initially present in the vapor at initial concentrations

of 10 ppbv and 110 ppbv respectively. These concentrations continuously decreased with increasing beam power so they cannot be considered reaction products. The concentration of carbon tetrachloride in the vapor sample exposed to the 400 W beam was only slightly lower than in the unirradiated sample. However, the PCE concentration was reduced to about 2 ppbv in this vapor sample.

TREATMENT COST PROJECTIONS

A cost analysis was made for an accelerator facility designed to treat TCE vapor at a flow rate of 500 CFM and initial concentration of 500 ppmv. It is assumed that the facility operates with an annual up-time of 80% and treats 17.5 metric tons of TCE per year. The accelerator beam will reduce the TCE concentration from 500 ppmv to 0.1 ppmv. The analysis was made for the accelerator costs only and assumes that the vacuum extraction wells, vacuum pumps, vapor plumbing and activated charcoal filter are initially installed.

The capital cost of the accelerator used in this analysis is $500 K for a device that will produce a 3 kW beam power. Additional hardware and installation increase the initial capital cost to a total of $750 K.

The operating expenses assume 24 hour operation with four workers on duty at all times and labor costs of $600 K annually. (The DOE requires four workers when an electron accelerator is used however the accelerator could be operated remotely at a non DOE site with a considerable saving in labor costs.) Electric power is estimated to cost $15 K annually at a price of 9¢ per KWH. Annual facility maintenance expenses are assumed to be $75 K which is 10% of the initial capital investment. Total operating expenses are estimated at $750 K annually.

The accelerator facility expenses are compared to the cost of activated charcoal filtration. The price of activated charcoal is estimated at $5.67/lb and includes removal costs of the TCE loaded filter. This price also assumes that the charcoal is recycled once. The amount of charcoal required annually to reduce the TCE concentration in the assumed vapor flow from 500 ppmv to 1 ppmv is almost 1.4 million lbs and costs $7780 K. Thus the cost of the charcoal alone is more than an order of magnitude greater than either the initial capital expenditure of the accelerator facility or its annual operating expenses.

SUMMARY

An electron accelerator was used to remediate TCE vapor removed by vacuum extraction wells from subsurface soil where liquid TCE was spilled. The accelerator produced ionizing radiation that radiolytically decomposed the TCE from an initial concentration of 40 ppmv to 0.1 ppmv when operating at a beam power of 400 W. Organic reaction products were produced at very low concentrations compared to the initial TCE concentration. A cost analysis indicates that accelerator treatment of TCE vapor is cost effective compared to filtration using activated charcoal with a vapor stream flowing at 500 CFM and TCE concentration of 500 ppmv.

REFERENCES

1. S.M. MATTHEWS, A.J. BOEGEL, S.F.ECCLES, S.G. HOMANN, D.W. RICE, J.A. LOFTIS, M.C. JOVANOVICH and R.A. CAUFIELD, "High-Energy Irradiation of Chlorinated Hydrocarbons", American Nuclear Society International Topical Conference, Methods and Applications of Radioanalytical Chemistry II, Kona, April 21-27, 1991.

Appendix E

Remedial Technologies

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Remedial Technologies

This appendix presents detailed descriptions of the remedial technologies presented in Chapter 3. Sources for these descriptions are cited as references at the end of appropriate sections. Some of these technologies have already been used in previous pilot studies involving the extraction and/or treatment of ground water and/or soil vapor at the Building 834 Complex. These technologies are identified in the following discussion.

E-1. Clay, Asphalt, or Geomembrane Cover

Capping or surface sealing is part of a closure process in which a buried waste or contaminant plume is isolated to avoid surface water infiltration, thereby minimizing the generation of leachate. Capping may also be used to control the emission of gases and odors, reduce erosion, and improve aesthetics. Capping provides a stable surface that prevents direct contact with wastes, and is necessary when contaminated materials are to be buried or left in place at a site. In situations where the waste is entirely above the ground water table, a properly designed cover can prevent the entry of water into the closed landfill or into a surface impoundment that has been closed as a landfill. In general, capping is performed when extensive subsurface contamination at a site precludes excavation and removal of wastes due to potential hazards and/or unrealistic costs. Capping is often performed in connection with ground water extraction or containment technologies (i.e., physical barriers or hydraulic barriers) (U.S. EPA, 1991).

E-2. Soil Vapor Extraction

Soil vapor extraction consists of applying a vacuum to one or more extraction wells screened in the vadose zone. The vacuum induces air flow through the vadose zone. Volatile compounds are vaporized into this air flow and removed from the vadose zone 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 fuel hydrocarbons.

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 soil vapor extraction system. This technology would be used in conjunction with vapor-phase granular activated carbon (GAC) to prevent the release of hydrocarbon vapors and any VOC emissions to the atmosphere. Drawbacks to this and other extraction technologies include 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 operational expense (LLNL, 1991).

E-3. Dynamic Underground Stripping

Dynamic underground stripping is an innovative technology that has been developed and tested at LLNL. It uses an integrated process combining the complementary technologies of steam injection and electrical resistance heating. Steam injected through multiple wells on the perimeter of a plume volatilizes the contaminants in permeable zones and forces them towards a central vacuum-liquid extraction well. Electrical resistance heating volatilizes contaminants in low-permeability clay zones not penetrated by the steam. Current passes through the ground between electrodes installed in the permeable zones, where they are removed by vacuum extraction or subsequent steam floods (Siegel et al., 1992).

E-4. Joule-Heating

Joule-heating is an experimental method of soil heating developed by LLNL to enhance the removal of VOCs in soil. An experiment using this method to remove TCE was conducted at the Building 834 Complex in the summer of 1992. In this experiment, six electrodes were buried in shallow boreholes heating an area of approximately 7 m in diameter and 4 m in depth. The soil heating was accomplished by ohmic dissipation of powerline-frequency electrical currents supplied by a diesel generator. The result of heating was that TCE soil vapor concentrations dropped by approximately two orders of magnitude over a period of about one month. The highest soil vapor TCE concentration measured during the experiment was 130 $ppm_{v/v}$, which was reduced to about 5 $ppm_{v/v}$ over a period of 25 days (Buettner, 1993).

E-5. Ground Water Extraction from Wells

Extraction wells may be either well points, naturally developed wells, or gravel-packed wells. Well points typically are manifolded to a header pipe and pumped with a suction system. Larger-diameter wells are pumped most commonly with submersible electric pumps, although vertical turbine pumps may also be used. Extraction wells that are to be used in a ground water recirculation system would most likely be constructed near the leading edge of a plume. Extraction wells to be used for hydraulic gradient control would probably be installed upgradient of the plume (U.S. EPA, 1991).

E-6. Skimmer

A skimmer is a device that separates and recovers LNAPLs from ground water. A type of floating passive skimmer is designed to float on top of the ground water in the well and continually collect floating product down to a sheen (Keck, 1993).

E-7. Soil Removal—Excavation

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 PCBs or metals that cannot be treated *in situ*. Excavated materials can be treated on site or transported to an appropriate waste landfill.

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. In addition, the more indurated or cemented the sediment, the more difficult it is to excavate. Transport and disposal of excavated material can be very costly if large volumes are involved (LLNL, 1991).

E-8. Bioremediation

Bioremediation involves the use of microbes to degrade organic compounds in contaminated soils and/or ground water. Under favorable conditions, microorganisms may be capable of completely degrading many organic compounds into carbon dioxide and water or organic acids and methane.

The applicability of bioremediation depends on the biodegradability of site contaminants. Petroleum compounds, such as gasoline and diesel fuel, are known to be readily biodegradable. Other biodegradable contaminants include alcohols, phenols, esters, and ketones. Chlorinated compounds become more difficult to biodegrade as the number of chlorine molecules increases. The biodegradation rate, or half-life, of large, heavily chlorinated compounds such as PCBs is very slow. This makes bioremediation an impractical stabilization technology for soil contaminated with these compounds.

Bioremediation of contaminated soils is accomplished by the degradation of specific organic constituents, or "parent" compounds, to a number of intermediate compounds. It is a process that may involve many enzymes, many species of organisms, and many intermediate compounds before the parent compound is mineralized.

Mineralization is the complete degradation of organic compounds under aerobic conditions to CO_2, H_2O, inorganic compounds, and cell proteins or, under anaerobic conditions, to organic acids, methane, and/or hydrogen gas. Under normal degradation conditions, a constituent may not be completely mineralized but may be transformed to intermediate products, which may be just as hazardous as the parent compound. The goal of controlled on-site bioremediation is degradation of the parent compound to yield products that are not hazardous to human health or the environment.

Landfarming involves the aeration of soil and sludges containing oil and/or other hazardous materials by tilling or other cultivation methods, with the addition of nutrients. This method has been used by the oil refining industry for the disposal of oily sludges for many years. The methods can be applied *in situ*, where soil contamination is relatively shallow. Addition of microbial cultures can be used to augment the indigenous microbial population and speed up the rate of biodegradation.

In situ bioremediation of subsurface materials generally involves the simulation of naturally occurring, or indigenous, microorganisms to degrade organic contaminants. The microorganisms are stimulated by addition of agricultural fertilizers, such as manure, aqueous solutions of nutrients, such as ammonia and orthophosphate, and possibly an oxygen source, such as hydrogen peroxide. This is typically done by pumping ground water from the aquifer, treating it to remove contaminants, adding nutrients and an oxygen source, and then reinjecting it into the

aquifer. Water is withdrawn faster than it is reinjected, creating a pressure sink at the withdrawal point. The pressure sink hydraulically contains the contamination and increases the flow rate of nutrients through the aquifer. In some cases, other environmental parameters, such as pH and temperature, can be optimized to stimulate biological activity.

Both aerobic and anaerobic processes are applicable to the degradation of hazardous materials. Aerobic biodegradation, which relies on the presence of oxygen, is applicable to remediation of soils contaminated with nonchlorinated organics, such as fuel oil components, and some chlorinated materials.

Many chlorinated solvents, such as tetrachloroethene (PCE), trichloroethene (TCE), and 1,1,1-trichloroethane (TCA), are resistant to aerobic biodegradation. These compounds may, however, be degraded under anaerobic conditions. The degradation of these compounds involves reductive dehalogenation, in which chlorine is replaced with hydrogen, to form new compounds that may be more mobile and toxic than the original compound before being mineralized. Chlorinated alkenes have been mineralized by cometabolism, or methane-utilizing bacteria (methanotrophs). In other contaminated soil systems, some chlorinated compounds can be reductively dehalogenated to produce intermediate products that can then be degraded further aerobically. An example is the anaerobic reductive dehalogenation of 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) to 2,4-dichlorophenoxyacetic acid (2,4-D), which can then be treated aerobically.

Very often bioremediation is combined with other technologies, either by design as with pump-and-treat and *in situ* bioremediation, or as part of a treatment train, such as post-treatment following soil flushing or vacuum extraction (U.S. EPA, 1991).

E-9. *In Situ* Radio Frequency (IRF)

Radio frequency (RF) heating is an innovative technology intended to put energy into the *in situ* mass to give rapid uniform temperature rise. RF energy heats the soil with electrodes to the point where volatile and semivolatile compounds are vaporized from the soil matrix. The vapors can be collected by a soil vapor extraction system at the soil surface for subsequent treatment.

An exciter array introduces electromagnetic energy fields in the RF band into the soil to provide RF heating. The exciter array can consist of electrodes either inserted into boreholes or positioned on the soil surface. A modified radio transmitter using the industrial, scientific, and medical band serves as the power source. The actual operating frequency is chosen based on the dielectric properties of the soil and the areal extent of the contamination (Smith and Hinchee, 1993).

E-10. GAC—Soil Vapor Treatment

The use of GAC treatment for soil vapors is a well-established technology for the removal of VOCs from air streams. With few exceptions, most VOCs can be effectively removed from the vapor exhaust of a soil vapor extraction system using a fixed-bed GAC system. 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. High moisture content in the vapor can limit the sorptive capacity of carbon. The spent GAC may be regenerated on site or at a commercial facility in a furnace in which the VOCs are desorbed from the GAC and then completely oxidized. GAC treatment of the vapor phase is an applicable, effective, and implementable method to remove VOCs from vapors. Annual treatment costs associated with GAC are usually quite high initially; costs decrease as VOC concentrations in the soil vapor decrease over time (LLNL, 1991).

E-11. GAC—Ground Water Treatment

Granular activated carbon (GAC) adsorption is a well-established technology for ground water treatment that is generally effective for removing high-molecular-weight compounds and chlorinated solvents. Activated carbon removes contaminants from water by adsorbing them onto its surface. GAC units are made from a variety of carbonaceous materials. A GAC adsorption system consists of a packed column with a system to distribute the water evenly over the carbon bed. Organic compounds adsorb onto the surface of the GAC as the water flows through the fixed bed. The spent GAC may be thermally regenerated by heating the carbon in a natural gas-fired furnace. Regeneration is 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. After regeneration, the GAC is no longer considered a hazardous waste. The adsorptive capacity of GAC degrades from regeneration and the used material eventually must be disposed of and replaced. GAC is an applicable, effective, and implementable method to remove VOCs from either an aqueous or vapor medium. The cost is dependent upon flow rates and VOC concentrations. Generally, GAC is cost-effective for low flow and low concentration applications (LLNL, 1991).

E-12. Thermal Oxidation

The vapor emissions produced by soil vapor extraction of a vadose zone containing VOCs or fuel hydrocarbons can be controlled by passing the extracted vapor 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 fuel hydrocarbons in which the oxidation products 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 soil vapor extraction 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 on site. 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 (LLNL, 1991).

E-13. Catalytic Oxidation

Catalytic oxidation is a vapor treatment technology 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.

Catalytic oxidation is commonly used for the destruction of fuel hydrocarbon vapors. This method is not applicable to chlorinated solvents because toxic daughter products are created in the process (LLNL, 1991).

E-14. Electron Acceleration

Electron acceleration is an innovative technology used for the radiolytic remediation of TCE. In this process, a contaminated vapor stream is irradiated with a small electron accelerator, thereby reducing the concentration of TCE. The irradiation of contaminant in vapor is primarily a function of the power of the electron beam. In this process, organic by-products, such as chloromethane, dichloromethane, chloroform, acetone, and trimethylbenzene, may be formed at very low concentrations (Matthews et al., 1992). This technology was tested at the Building 834 Complex in November and December 1991. In this experiment, 90% of the ingoing TCE was destroyed at a cost of approximately $15/kg (Webster-Scholten, 1994).

A similar technology is now being developed for liquid phase contaminant destruction using electron acceleration. This technology is also considered innovative, and its cost-effectiveness is also based on contaminant concentration levels. The higher the contaminant concentration, the more power, and hence cost, required for irradiation.

E-15. Resin Adsorption-Regeneration

Resin adsorption-regeneration is an innovative vapor treatment system that traps VOC vapors on an adsorbent resin bed. The advantage of this system is its on-site regenerative capacity. Typically, a resin adsorption-regeneration system consists of one or more resin beds that are on line while another bed is being regenerated in a desorption cycle. The resin beds are automatically switched between adsorption and desorption cycles. Desorption is accomplished using a combination of temperature, pressure, and a carrier gas. During the desorption cycle, the VOCs trapped in the adsorbent resin material are removed, condensed, and transferred in liquid phase to a storage tank.

The resin adsorption-regeneration system has two advantages over the conventional carbon treatment system. Because the adsorbent material can be regenerated on site, the cost is much lower than GAC, which typically must be transported off site as hazardous waste for disposal or treatment. Although on-site carbon regeneration is feasible, the carbon has limited reuse capacity before replacement. Carbon regeneration also produces acids when treated for VOCs, thus causing corrosion problems. The claim for the resin adsorption-regeneration system is that

the adsorbent beds may be recycled in excess of 2,000 times with no measurable loss of adsorption capacity (Purus, 1993). In addition, activated carbon's capacity to adsorb VOCs is significantly affected by moisture. The resin adsorption-regeneration system adsorbent resin beds have a high tolerance to water vapor, thereby allowing treatment of vapor streams that have relative humidity greater than 90% with minimal impact on adsorption efficiency. These two factors would lower the operation and maintenance treatment costs and would make the resin resorption-regeneration system more cost effective and efficient for long term treatment.

E-16. UV/Oxidation

UV/oxidation uses an oxidizing agent, such as hydrogen peroxide or ozone, and ultraviolet (UV) light as an agent to augment the dissociation of the oxidizing agent to a hydroxyl radical. This is an applicable, effective, and implementable method to treat VOCs in ground water. By destroying the VOCs, UV/oxidation processes minimize the amount of waste that will require further treatment or disposal (LLNL, 1991).

A type of UV/oxidation technology is Perox-Pure™, a chemical oxidation technology that was demonstrated under the Superfund Innovative Technology Evaluation (SITE) program at the Building 834 Complex. Over a three-week period in September 1992, about 40,000 gallons of VOC-contaminated ground water was treated in the Perox-Pure™ system. For the SITE demonstration, the Perox-Pure™ system achieved TCE and PCE removal efficiencies of about 99.7 and 97.1%, respectively. In general, the system produced an effluent that contained TCE, PCE, and 1,1-dichloroethane (DCA) below detection limits, and chloroform and 1,1,1-TCA slightly above detection limits. The system also achieved chloroform, DCA, and TCA removal efficiencies of 93.1, 98.3, and 81.8%, respectively. The treatment system effluent met California drinking water action levels and federal drinking water maximum contaminant levels for TCE, PCE, chloroform, DCA, and TCA at the 95% confidence level (U.S. EPA, 1993).

E-17. Air Sparging

Air sparging consists of forcing air through coarse diffusers at the base of large tanks filled with contaminated water. The agitation of the water and contact with forced air promotes the volatilization of VOCs. Because of local air permit requirements, this technology would be used in conjunction with vapor phase GAC (LLNL, 1991). High calcium and magnesium hardness, which occurs at Site 300, can reduce efficiency, and increase operating costs.

Air sparging can also be used *in situ*. This requires either trenching to lay a shallow network of air injection and extraction piping and subsequent backfilling, or vertical and/or horizontal drilling to construct a deep subsurface network of piping. The difficulty in using this method is plume control. The air may diffuse away from collection points and mobilize the contaminants in an undesirable direction. This method also has an inherent expense when horizontal drilling is used, due to the specialized nature of horizontal drilling. Generally, aboveground air sparging is cost-effective for lower flow rates and high VOC concentrations, unless mineral content causes operating problems.

E-18. Surfactant Injection

Surfactant injection is a relatively new, *in situ* technique for remediation of DNAPLs. The technique is applied by pumping water, with surfactants, into the ground water zone via injection wells. The surfactants cause a significant increase in the solubility of the DNAPLs by forming colloidal clusters (called micelles) in which the DNAPLs are solubilized. The DNAPLs go into solution to concentrations several orders of magnitude greater than their normal water solubility. The resulting water/DNAPL mixture can be pumped to extraction wells without DNAPL becoming sorbed by soil particles, and treated with conventional ground water treatment systems (NETAC, 1992).

E-19. Air Stripping

Air stripping is a process in which VOCs are removed from water by bringing water into contact with air. Air stripping is similar to air sparging in that a large air-to-water ratio is used to provide mass transfer from water to air. Two types of air strippers are stripping towers and aeration trays. In conventional air strippers, ground water is sprayed into the top of an air stripping tower. As water cascades down through the tower, and through packing material within the tower, a high-powered blower forces an air stream upward through the water. Tray aeration is achieved by spraying extracted ground water into an inlet chamber. The water flows along baffled aeration trays and air is blown up through small-diameter holes in the trays. A froth forms, creating a large mass transfer surface. The high air-to-water ratio causes the organic contaminants to volatilize (evaporate) into air, leaving substantially reduced concentrations of VOCs in the water. Air stripper design operation, and maintenance must be tailored to the general water quality at the site. High calcium and magnesium hardness, which occurs at the Building 834 Complex, can clog the packed towers, reduce efficiency, and increase operating costs. CO_2 may be added to the influent water to prevent the precipitation of these minerals. To eliminate VOC discharge to the atmosphere, this technology would be used in conjunction with vapor-phase GAC. Packed-column or tray aeration counter-flow air stripping is an applicable, effective, and implementable method to remove VOCs by physical means from aqueous streams. The cost is dependent upon flow rates and VOC concentrations. Generally, air stripping is cost-effective for high flow rates and high VOC concentrations, unless mineral content causes operating problems (LLNL, 1991).

E-20. On-site Surface Discharge

We are presently discharging treated ground water from the central GSA on site, to the surface, as part of a CERCLA Removal Action. The treated water is collected in a Baker tank until 10,000 to 20,000 gallons have accumulated; then it is sprayed into a remote canyon at a rate of 100 gpm over an area of approximately 16,000 ft^2. This recharge rapidly infiltrates the exposed $Tnbs_1$ regional aquifer sandstone in the canyon.

E-21. Air Misting

Air misting is the atomization of treated ground water by forcing it through spray heads that separate the water into fine droplets as it is expelled into the air. This process allows maximum

areal dispersion of discharge. When operated during appropriate meteorologic conditions these droplets will evaporate before reaching the ground. This method of discharge prevents erosion that can result from normal surface discharge. A similar system is being considered for discharging treated ground water in the Building 834 Complex.

E-22. Hydraulic Barrier—Injection, Reinjection

Reinjection wells can function as a means to discharge treated ground water back into the aquifer being remediated, and/or a means to hydraulically control plume movement. This technology is more applicable to large aquifers than to limited water-bearing zones.

The reinjection of treated ground water can be an efficient cost-saving measure. However, the quality of this water is important because of potential for recontamination, and potential scaling from precipitates such as carbonate. Scaling can significantly reduce the efficiency of the injection well and increase O&M costs.

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Appendix F

Soil and Ground Water Modeling Analysis

Appendix F

Soil and Ground Water Modeling Analysis

F-1. Soil Vapor Modeling

F-1.1. Objective

To estimate TCE recovery from the vadose zone by soil vapor extraction (SVE) methods, we used the analytical program VENTING (Environmental Systems & Technologies, 1993).

F-1.2. Conceptual Model

Alternatives 3, 4, and 5, developed in Chapter 4, include SVE and the use of 19 wells in the core area of the Building 834 Complex to extract VOCs (primarily TCE) from the three TCE surface spill areas and one diesel release area. For modeling purposes, the spills are assumed to consist entirely of TCE. These wells typically are completed across the perched water-bearing zone and vadose zone with 10 ft of screen. The three volumes to be remediated are idealized as cylinders, assumed to be 25 ft long with radii of 50 ft. Continuous SVE is also assumed.

F-1.3. Model Description—VENTING

VENTING is an interactive PC-based program used to estimate rates of contaminant recovery from the unsaturated zone by vacuum extraction; the model is based on methods described by Johnson et al., 1990a and b. VENTING estimates recovery versus time during steady vapor flow at a specified total flow rate and a given temperature. It assumes equilibrium partitioning between the gas phase, water phase, nonaqueous liquid phase, and solid phase. The program enables evaluation of effects of soil properties, spill composition, temperature, and pumping rate on contaminant recovery.

VENTING performs a mass balance calculation for each chemical component in the system at discrete time steps. A mole balance of component i during the process of vapor extraction is given by:

$$\frac{dM_i}{dt} = \eta Q C_i^{eq} \tag{F-1}$$

where

M_i = total number of moles of component i in the soil [mole],

Q = total gas flow rate through the contaminated zone [$L^3\ T^{-1}$],

C_i^{eq} = equilibrium molar gas phase concentration of species i [mole L^{-3}],

η = an efficiency factor to account for nonequilibrium effects [dimensionless].

The balance equation can be solved if the relationship between M_i and C_i^{eq} is known. The required relations can be derived from equilibrium thermodynamic laws that consider partitioning among the gas, nonaqueous liquid, water, and solid (i.e., adsorbed) phases. The total number of moles of component i at equilibrium is given by:

$$M_i = z_i \frac{\theta_a PV}{RT} + x_i M^{VOC} + y_i \frac{\rho_w \theta_w V}{W_{H20}} + y_i k_i \frac{\rho_b V}{W_{H20}} \tag{F-2}$$

where

M_i = moles of species i in all phases [mole],

M^{VOC} = total moles of all species in the free nonaqueous liquid phase [mole],

V = total volume of the contaminated zone [L^3],

z_i = mole fraction of compound i in the gas phase [mole • $mole^{-1}$],

x_i = mole fraction of i in the nonaqueous liquid phase [mole • $mole^{-1}$],

y_i = mole fraction of i in the aqueous phase [mole • $mole^{-1}$],

ρ_w = density of water [M • L^3],

ρ_b = dry soil bulk density [M • L^{-3}],

θ_a = air-filled porosity [L^3 • L^{-3}],

θ_w = volumetric water content [L^3 • L^{-3}],

P = absolute total gas pressure [atm],

R = ideal gas constant (82.06 cm^3 atm $mole^{-1}$ deg^{-1}),

T = absolute temperature in the soil-water system [degrees Kelvin],

k_i = sorption coefficient for species i [M • M^{-1}],

W_{H20} = molecular weight of water [M • $mole^{-1}$].

Assuming the vapor phase behaves as an ideal gas, the free nonaqueous liquid phase acts as an ideal liquid mixture, and the aqueous phase is a non-ideal mixture, then the phase mole fractions may be related as:

$$z_i P = x_i P_i = \alpha_i y_i P_i = C_i^{eq} RT \tag{F-3}$$

where

P_i = vapor phase pressure of compound i at the ambient temperature,

α_i = aqueous-phase activity coefficient of compound i.

The vapor phase pressure P_i at ambient temperature T is computed from the vapor pressure P_i^R at reference temperature T_R (i.e., 20°C = 293°K) via the Clausius-Clapeyron equation as:

$$P_i(T) = P_i^R \exp\left\{\frac{T_B T_R}{T_B - T_R}\left(\frac{1}{T} - \frac{1}{T_R}\right)\ln\frac{P_i^R}{P_{atm}}\right\} \tag{F-4}$$

where

T_B = is the absolute temperature at the boiling point when the total pressure is P_{atm} (i.e., 1 atm).

Aqueous activity coefficients are estimated from tabulated solubility values. For species which are liquids or solids at the ambient temperature ($P_i \leq P_{atm}$), the relationship is:

$$\alpha_i = \frac{V_{mw} W_i}{S_i} \tag{F-5}$$

where

V_{mw} = molar volume of water [55.55 mole • L^{-1}],

W_i = molecular weight of species i [M • $mole^{-1}$],

S_i = solubility of pure species i in water.

For species which occur as gases at ambient temperature ($P_i > P_{atm}$), the activity coefficient is computed as:

$$\alpha_i = \frac{V_{mw} W_i P_{atm}}{S_i P_i} \tag{F-6}$$

The adsorption coefficient is assumed to be a linear function of the soil organic carbon content given by the empirical relation (Lyman et al., 1982):

$$k_i = 0.63 k_{ow_i} f_{oc} \tag{F-7}$$

where

k_{ow_i} = octanol-water partition coefficient [M M^{-1}],

f_{oc} = mass fraction of organic carbon in the soil [M M^{-1}].

Soil bulk density is related to the fluid content by:

$$\rho_r = \rho_s(1 - \theta_w - \theta_a) \tag{F-8}$$

where

ρ_s = particle density, assumed to be 2.65 g • cm^{-3}.

Substituting Equation F-3 in Equation F-2, Johnson et al. (1990a and b) gives:

$$M_i = x_i\left\{\frac{\theta_a P_i V}{RT} + M^{VOC} + \frac{\rho_w \theta_w V}{\alpha_i W_{H20}} + \frac{k_i \rho_b V}{\alpha_i W_{H20}}\right\}, \text{ for } \theta_w > 0 \text{ and } M^{VOC} > 0. \tag{F-9}$$

By definition, x_i is also

$$x_i = \frac{M_i^{VOC}}{M^{VOC}} \tag{F-10}$$

where

M_i^{VOC} = number of moles of species i in the nonaqueous liquid phase,

$M^{VOC} = \sum M_i^{VOC}$.

The equilibrium distribution of species between various phases is determined for any set of M_i by solving Equations F-9 and F-10 iteratively, subject to the constraint that $\sum x_i = 1$. When M_i is small for all species, a free nonaqueous liquid phase will cease to exist and contaminant will be distributed among aqueous, solid, and gas phases. Then, in lieu of Equation F-9, the appropriate relation is:

$$M_i = a_i y_i\left\{\frac{\theta_\alpha P_i V}{RT} + \frac{\rho_w \theta_w V}{\alpha_i W_{H20}} + \frac{k_i \rho_b V}{\alpha_i W_{H20}}\right\} \tag{F-11}$$

Equation F-11 is used instead of Equation F-10 when $\alpha_i y_i < 1$ is computed by Equation F-11 for all species. Integration of the mole balance Equation F-1 using a variable time-weighting scheme yields:

$$M_i^{t+\Delta t} = M_i^t \frac{1-(1-\mu)\eta Q \frac{P_i}{RTM_T}\Delta t}{1+\mu\eta Q \frac{P_i}{RTM_T}\Delta t} \tag{F-12}$$

where

Q = air flow rate [L^3/T];

t = previous time;

t + Δt = new time;

$M_T = \sum M_i$ = total moles of all components in the soil during the current timestep, which is approximated as the average of the corresponding values at the previous time t and at the end of previous iteration;

μ = time-weighting factor.

For $\mu = 0$ an explicit scheme is obtained, $\mu = 0.5$ corresponds to the Crank-Nicholson method, and $\mu = 1$ gives a fully implicit scheme. Values of μ between 0.5 and 1.0 are generally recommended.

The relationship between the equilibrium gas concentration and the actual well bore gas concentration is given by:

$$C_i^{well} = \eta C_i^{eq} \tag{F-13}$$

where

η = "venting efficiency factor."

The user may estimate efficiency factors from field data by matching observed and predicted well concentrations or mass recovery rates. Care should be taken to ensure that at least one pore volume of gas has been displaced prior to matching data, to overcome effects of initial conditions. The equilibrium concentration C_i^{eq} represents the value that would occur if the venting system is temporarily shut down and allowed to equilibrate. The overall efficiency factor is given by the ratio of concentration observed in the well prior to shutdown after pumping for an extended period to the concentration observed after shutdown, measured under near zero flow conditions $\left(\text{i.e.}, \eta = C_i^{well} / C_i^{eq}\right)$ (Environmental Systems & Technologies, 1993).

F-1.4. Parameter Selection

Table F-1 displays the subsurface properties we use to simulate contaminant removal from the Building 834 Complex core. Spill quantity and contaminant soil volumes are obtained from the conservative volume calculations in Appendix A. Ground water temperatures from Building 834 Complex monitor wells average about 20°C with seasonal variations of ±4 to 5°C. For a conservative estimate, we use a low temperature of 16°C. We use an organic carbon content of 0.001, obtained from Chapter 10 of Webster-Scholten (1994), and we assume a designed airflow rate of 250 scfm and a volumetric water content of 0.10. Although VENTING offers a biodecay calculation, we conservatively eliminated this feature by using a biodecay efficiency factor of 0.0.

A similar scenario developed in Johnson et al. (1990a) suggests a relatively high venting efficiency factor of 0.10. The present well completions in the Building 834 Complex would suggest a lower efficiency factor, since most of the screens are only 10 ft in length and are also completed in the perched water-bearing zone. Although the perched water-bearing zone will be dewatered before SVE commences, gas flow through the entire 25-ft deep vadose zone will be limited. Therefore, we estimate recovery rates using two venting efficiency factors, 0.10 and a relatively low factor of 0.01.

F-1.5. Results

For comparison, we use 68 kg as an estimate of the mass of remaining TCE. This value is the quantity of TCE remaining in a volume of 17,000 m^3 (Table F-1) if the calculated risk-based cleanup concentration of 2.2 mg/kg is achieved.

Using the two venting efficiency factors, the predicted removal time varies between 46 and 445 days to reach the 2.2 mg/kg TCE cleanup goal. Figure F-1 shows the results.

F-1.6. Sensitivity Analysis

In this section we analyze VENTING's sensitivity to various parameters by arbitrarily adjusting parameter values. A conservative venting efficiency factor of 0.01 is used in all parameter sensitivity analyses.

F-1.6.1. Temperature

We used three different temperatures (16, 18, and 20°C) to determine the effects of temperature on TCE recovery rates. Figure F-2 displays the results of the temperature sensitivity analysis. Venting periods of approximately 445, 410, and 385 days are required to reach the 2.2 mg/kg TCE soil cleanup level for temperatures of 16, 18, and 20°C, respectively. Recovery rates are least sensitive to this parameter.

F-1.6.2. Volumetric Water Content

We varied the volumetric water content while keeping total porosity constant at 0.25. Varying volumetric water content requires an inverse adjustment to air-filled porosity. Figure F-3 displays the results. Venting periods of approximately 390, 445, and 500 days are required to reach the 2.2 mg/kg TCE soil cleanup level for volumetric water content of 0.05, 0.10, and 0.15, respectively. Thus, a 30-fold increase in volumetric water content only yields a 1.3-fold increase in predicted venting time.

F-1.6.3. TCE Mass

We varied the initial mass of TCE in the soil while keeping the contaminated soil volume constant to evaluate the sensitivity to original mass. Figure F-4 displays the results. Venting periods of approximately 340, 445, and 500 days are required to reach the 2.2 mg/kg TCE soil cleanup level for initial TCE volumes of 133, 266, and 399 gallons, respectively. The original TCE mass has a more significant effect on removal rates earlier in the venting time. The effect of original TCE mass lessens significantly closer to the time of entire removal.

F-1.6.4. Soil Volume

We varied soil volume while keeping the initial mass constant to determine the model's sensitivity to soil volume. Figure F-5 displays the results. Venting periods of approximately 255, 445, and 660 days are required to reduce TCE mass to 68 kg for soil volumes of 8,000, 17,000, and 25,000 m^3, respectively. Recovery rates are very sensitive to this parameter.

F-1.6.5. Venting Efficiency Factor

Venting efficiency factors of 0.1 and 0.01 were used to evaluate a range of possible results. Venting periods of approximately 46 and 445 days are required to reach the 2.2 mg/kg TCE soil cleanup level for the venting efficiency factors of 0.01 and 0.10, respectively (Fig. F-1). Recovery rates appear to be most sensitive to this parameter.

F-1.7. Conclusions

The modeling results and sensitivity analyses, show TCE recovery rates consistent with the five years for cleanup that we estimated in Chapter 4. The results are used in the costing analysis presented in Appendix G.

F-2. Ground Water Modeling

This section presents the results of our investigation into the quantity of ground water in the Building 834 Complex and the effect of extracting the contaminated ground water for aboveground treatment. The ground water distribution, pumping rates, well placements, and water-bearing zone properties are used to estimate dewatering, extraction well drawdown, and extent of ground water capture. The objectives of our remedial design based on these results are to: (1) limit further migration of contaminated ground water and (2) augment a timely contaminant mass removal.

Our ground water modeling involves: (1) estimating the time required to dewater the core area and the perched water-bearing zone, (2) estimating necessary modeling/calculation parameters, and (3) predicting drawdown and estimating the maximum capture zone widths expected for the dewatering wells, as discussed below.

F-2.1. Dewatering of the Perched Water-Bearing Zone

The following estimates are used to approximate the quantity of ground water in the Building 834 Complex and the time required to remove it by pumping.

Two estimates are developed. The first is for the dewatering of the perched water-bearing zone in the core area only (subscript$_c$), and the second is for the dewatering of the entire perched water-bearing zone (subscript$_p$) at the Building 834 Complex. These estimates are in accordance with the Alternatives 4 and 5 scenarios, respectively, as presented in Chapter 4.

We calculate the volume of water to be removed by using the values in Table F-2. The core area is approximated by a circle with a 150-ft radius, and the entire perched water-bearing zone area is taken from Figure F-6. Using a porosity of 0.25, we estimate the volumes of ground water in the core area and the perched water-bearing zone to be 140,000 ft^3 (V_c) and 700,000 ft^3 (V_p), respectively.

The time (t) required to remove the ground water by pumping is estimated using values in Table F-3 and the following formulas:

$$t_c = V_c/(Q_c - Q_r) \qquad \text{(F-14)}$$

and

$$t_p = V_p / (Q_p - Q_r) \tag{F-15}$$

where

V_c = volume of ground water at the core area;

V_p = volume of ground water for the entire perched water-bearing zone;

Q_r = recharge rate (66 ft^3/d); this value was calculated by applying an infiltration rate of 0.092 ft/y [Chapter 10 of Webster-Scholten (1994)] to the recharge area of 260,000 ft^2 (Bryn et al., 1990);

Q_c = total pumping rate for the core (13.4 ft^3/d per well, for 19 wells);

Q_p = total pumping rate for the entire Building 834 Complex (13.4 ft^3/d per well, for 26 wells).

Thus:

t_c = 720 days, and

t_p = 2,500 days.

The results show that with an assumed continuous pumping rate of 100 gpd for each well, it will take approximately two years to dewater the core area and approximately seven years to dewater the entire perched water-bearing zone. The actual time required to dewater either the core or the entire perched water-bearing zone is likely to be greater than these estimates, because pumping rates will decrease as the water table is lowered.

F-2.2. Hydraulic Conductivities

In order to predict the extent of ground water capture, estimates of saturated hydraulic conductivities are necessary. Hydraulic conductivities (K) obtained from well slug/bail and pump tests (Chapter 10 of Webster-Scholten [1994]) are as follows for the three groups of dewatering wells:

- Well W-834-D3 (representative of core area wells): K = 0.48 ft/d (= 1.7×10^{-4} cm/s).
- Average for wells W-834-S1 and W-834-S3 (representative of downgradient W-834-S wells): K = 1.9 ft/d (= 6.8×10^{-4} cm/s).
- Average for wells W-834-T2 and T4 (representative of downgradient W-834-T wells): K = 1.6 ft/d (= 5.5×10^{-4} cm/s).

K can also be calculated by comparing the total estimated recharge flow with the flow through a complete cross section of the perched water-bearing zone. These calculations are similar to those used in the water budget presented in Bryn et al. (1990). The infiltration area value of 260,000 ft^2 is from the estimated active recharge area presented in that document. The estimated infiltration rate of 0.092 ft/year is from Chapter 10 of Webster-Scholten (1994). The resulting recharge rate (Q_r) is:

$Q_r = 66\ ft^3/d$

For the flow rate (Q_p) through the perched water-bearing zone we apply Darcy's Law:

$$Q_p = KiA \tag{F-16}$$

which can be rewritten as:

$$K = Q_p/(iA) \tag{F-17}$$

where

i = hydraulic gradient (0.1 ft/ft) (Chapter 10 of Webster-Scholten),

A = through-flow cross-sectional area (6,300 ft^2 = 900 ft × 7 ft [complete cross-sectional flow width, downgradient of the recharge area and perpendicular to the flow (taken from Fig. F-6) × the average saturated thickness at that width]).

If

$Q_p = Q_r$,

then

$$K = Q_r/(iA). \tag{F-18}$$

The results are:

$K = 0.10\ ft/d$

The K value obtained from recharge calculations is less than the K value obtained from the well W-834-D3 hydraulic tests. Both values are used to estimate capture widths. Predicted capture widths are shown in Table F-4.

F-2.3. Drawdown

F-2.3.1. Objectives

We used the program EQUIPLOT (Weiss Associates, 1986) to estimate the rate and magnitude of drawdown for the ground water extraction wells. We use EQUIPLOT as a screening tool in lieu of a more sophisticated and data-intensive numerical model, even though the Building 834 Complex perched water-bearing zone does not satisfy many of the assumptions required to use the program. The objective of using EQUIPLOT is to obtain a qualitative estimate of pumping responses before considering further modeling efforts.

F-2.3.2. Conceptual Model

The alternatives developed in Chapter 4 that include ground water extraction use either 19 core wells or 26 complex wells (19 core and 7 downgradient) for dewatering, containment, and/or removal, and to enhance the effectiveness of SVE. For Alternative 5, which includes downgradient ground water extraction, total dewatering is eventually expected to occur, since pumping rates are estimated to exceed recharge rates. Several of the wells in this alternative will be used for combined ground water and soil vapor extraction. These wells are typically completed across the perched water-bearing zone and vadose zone with 10 ft of screen. These wells tend to be clustered near the primary release sites (Buildings 834D, B, and C) in the core area.

F-2.3.3. Model Description—EQUIPLOT

EQUIPLOT calculates water level elevations at selected points by superimposing the drawdown of each pumping well onto a uniform piezometric surface. The water-bearing zone is assumed to be confined, nonleaky, isotropic, homogeneous, horizontal, and of constant thickness. Well drawdowns are calculated using a polynomial approximation of the Theis Well Function (Weiss Associates, 1986).

F-2.3.4. Parameter Selection

Input parameters are presented in Table F-4. The hydraulic gradient flow directions are obtained from Chapter 10 of Webster-Scholten (1994). Hydraulic conductivities are also from Webster-Scholten (1994) and Section F-2.2 of this appendix. We assume a storage coefficient of 0.001, and use a design pumping rate of 100 gpd for each well. Average saturated thicknesses are from monitor well water-level data following the 1992/1993 winter storms. The average saturated thickness value used for the entire perched water-bearing zone is an area-weighted based average using the saturated thickness contours in Figure F-6.

F-2.3.5. Results

The EQUIPLOT modeling results are presented in Table F-4. Although these are approximate predictions of drawdown, they indicate that the extraction wells may reach maximum drawdown quickly and, therefore, the saturated thickness of the perched zone will significantly decrease as a result of pumping. In light of the limited extent of the perched zone and other non-ideal conditions, such as anticipated changes in saturated thickness, capture estimates are very uncertain.

F-2.3.6. Sensitivity Discussion

The effects of input parameters on drawdown are:

- Drawdown is proportionally related to pumping rate Q. Therefore, if we increase Q, we increase drawdown by the same factor.
- Drawdown is less directly related to hydraulic conductivity K, but in general, the lower the K value, the greater the drawdown closer to the well.
- Saturated thickness is similar to hydraulic conductivity in its relation to drawdown.

- Hydraulic gradient and flow direction do not effect drawdown at the extraction well.
- As the storage coefficient is decreased, the rate of drawdown increases.

F-2.3.7. Conclusions

The uncertain nature of modeled capture zone estimates suggests a more simplified approach. In the following section, we present capture estimates based on Darcy's Law.

F-2.4. Capture Estimates

The following simple calculations are based on Darcy's Law, Q = KiA (Equation F-16). The following, then also applies:

$$Q = Kiwb \tag{F-19}$$

where

w = maximum capture zone width,

b = saturated thickness.

We take this approach to obtain a qualitative estimate of capture width, using a range of conductivities and gradients. Table F-5 presents the values used in these calculations and the results. Since we expect the hydraulic gradients to eventually lessen due to dewatering of the perched water-bearing zone, we also use a lower value to make estimates.

The resulting maximum capture zone widths for the core area, W-834-S wells, and W-834-T wells increase in value from tens to hundreds of feet as the gradient is lowered by one order of magnitude. The capture zone estimates based on parameters representative of the entire perched water-bearing zone are one order of magnitude higher, largely as a result of the lower estimated K and b. These differences may be a result of the heterogeneity that exists in the perched water-bearing zone.

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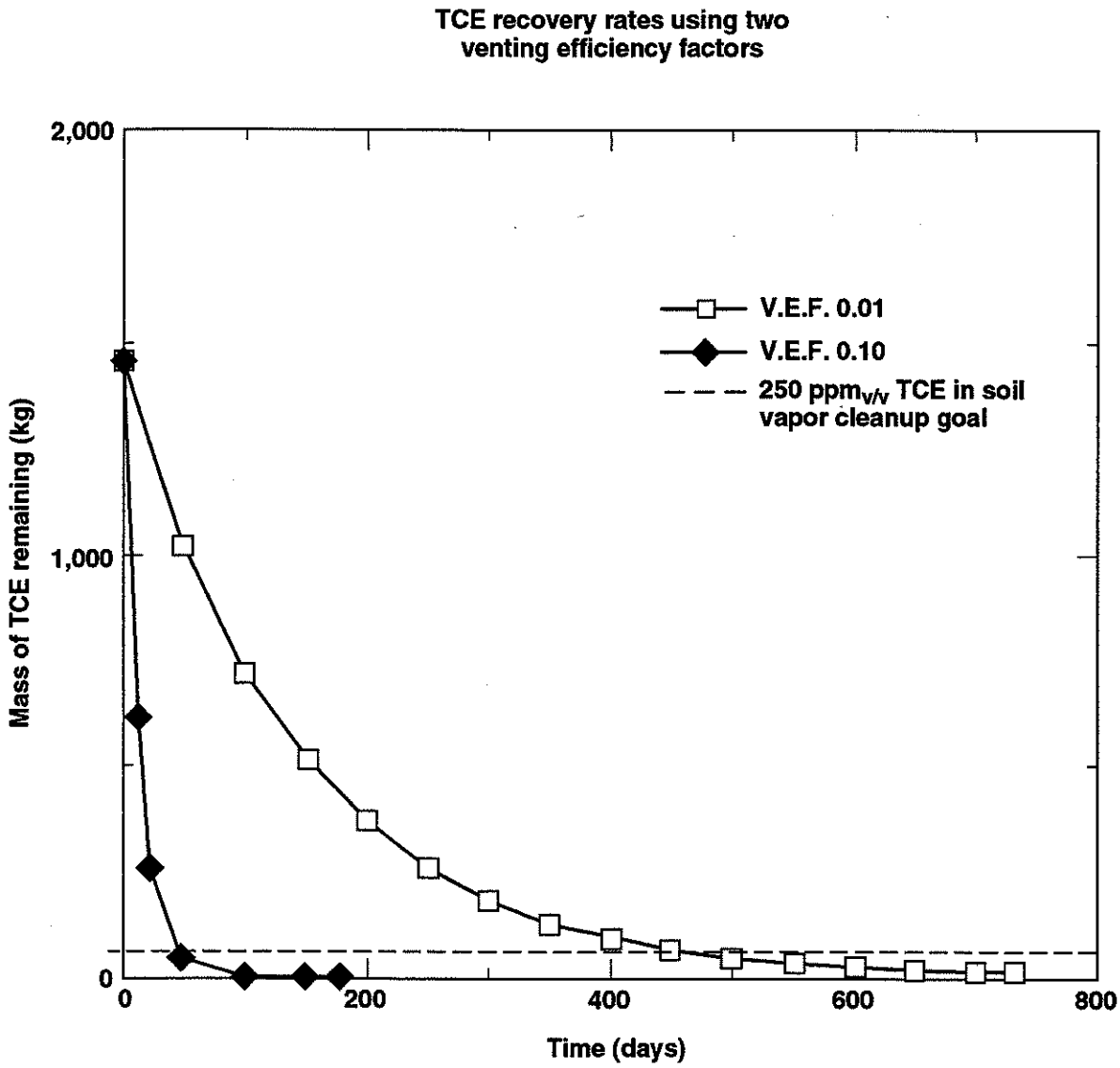

ERD-FS-834-3186

Figure F-1. TCE recovery rates using two venting efficiency factors.

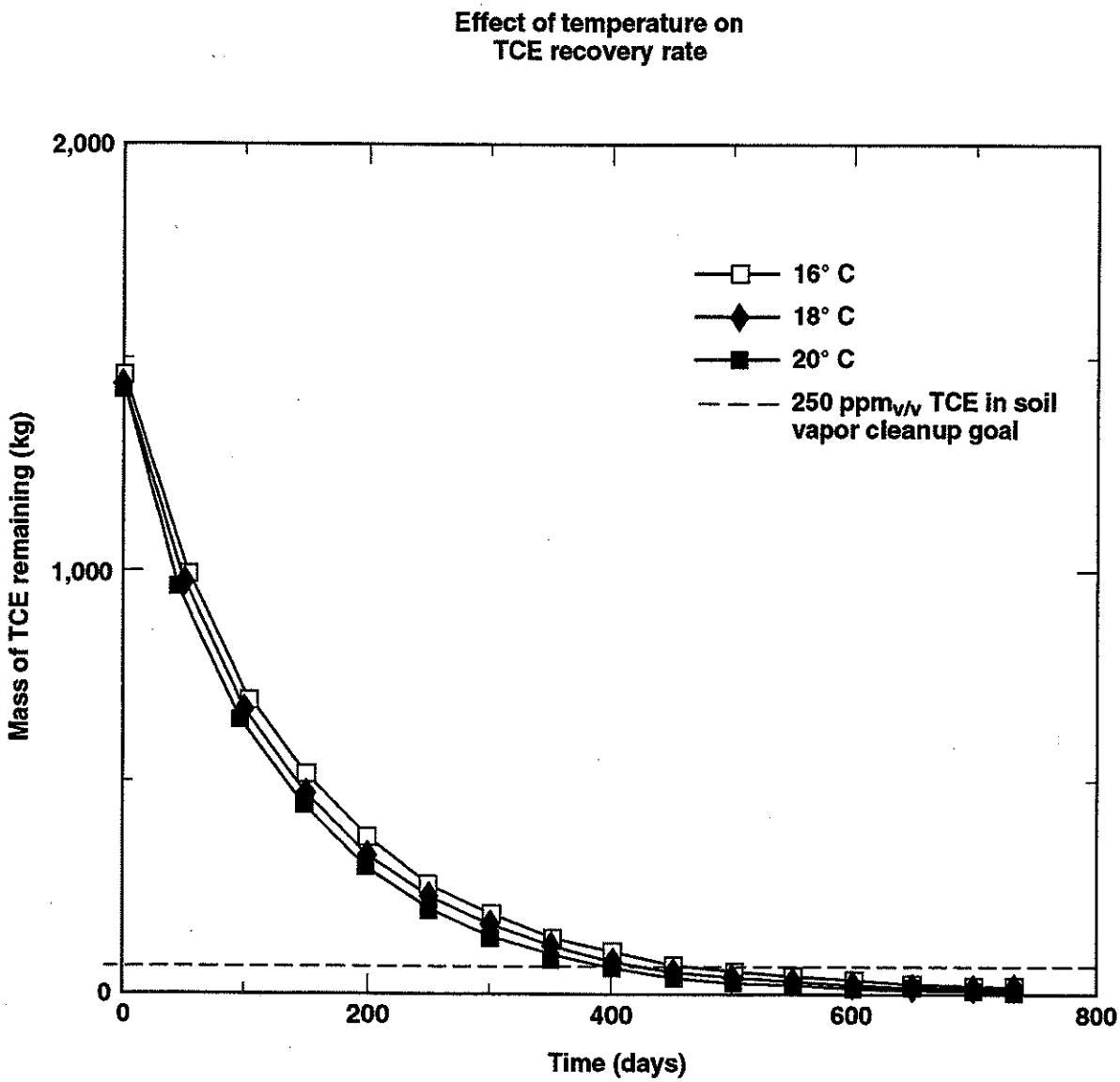

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Figure F-2. Effect of temperature on TCE recovery rates.

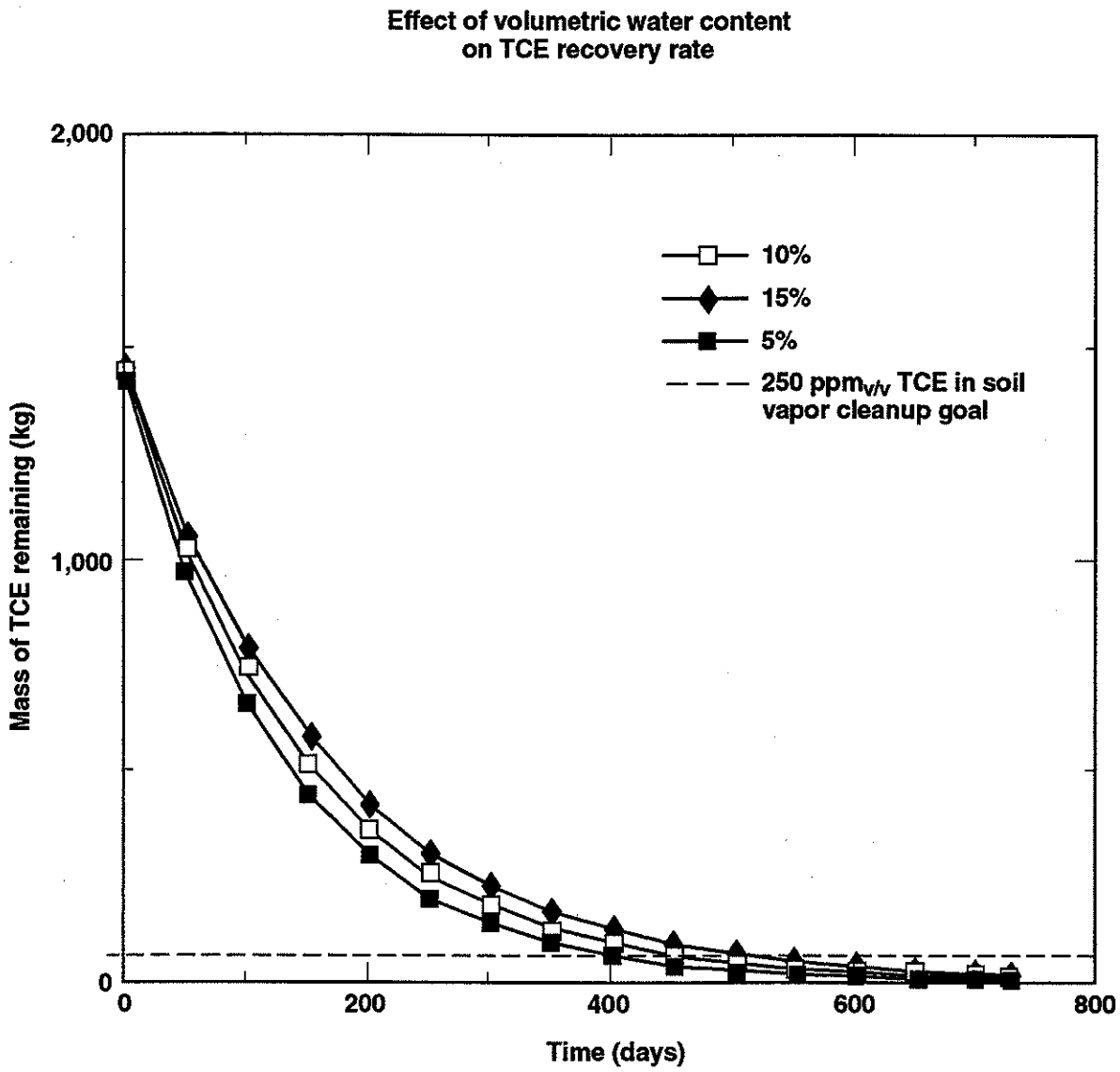

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Figure F-3. Effect of volumetric water content on TCE recovery rates.

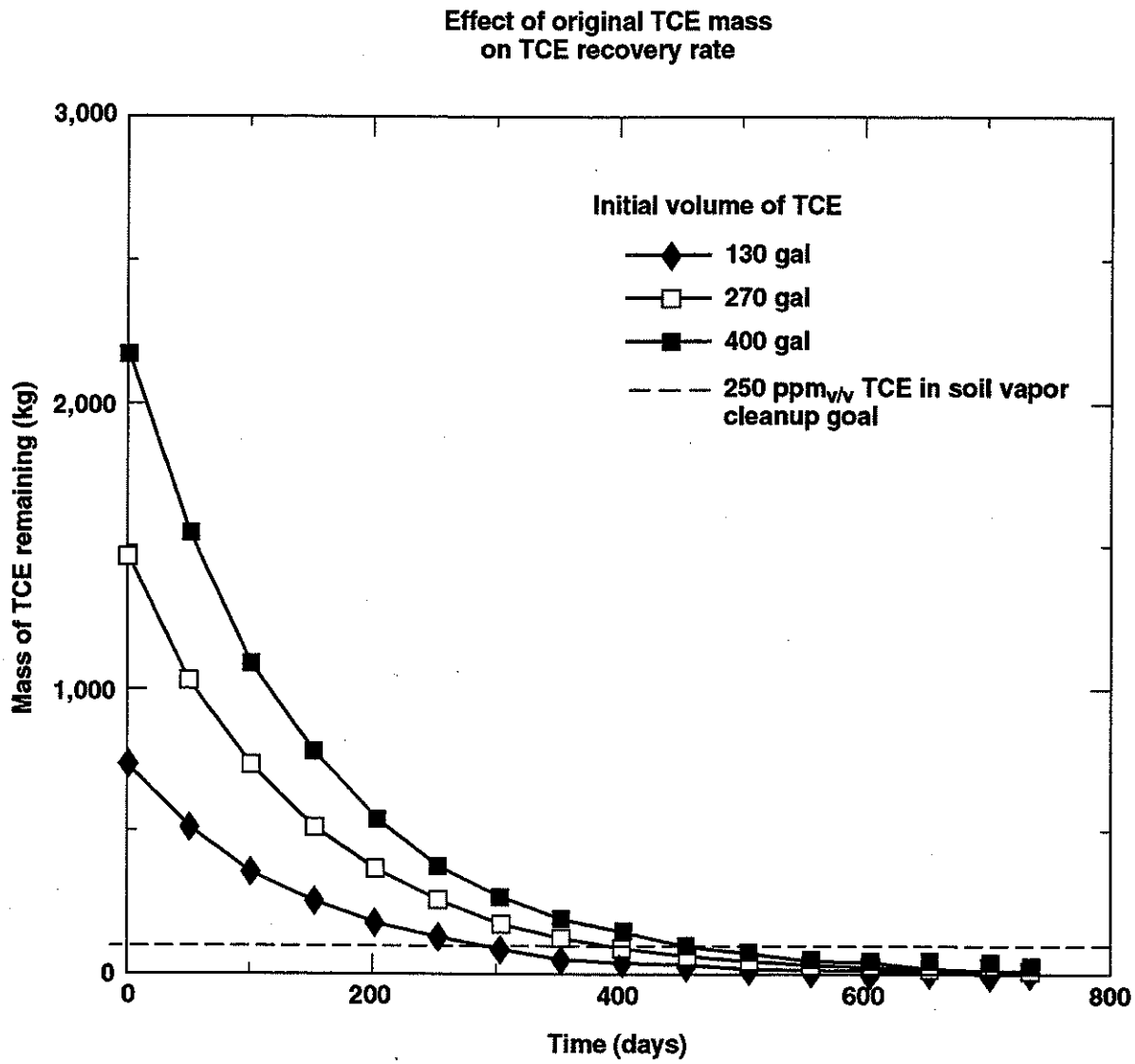

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Figure F-4. Effect of original TCE mass on TCE recovery rates.

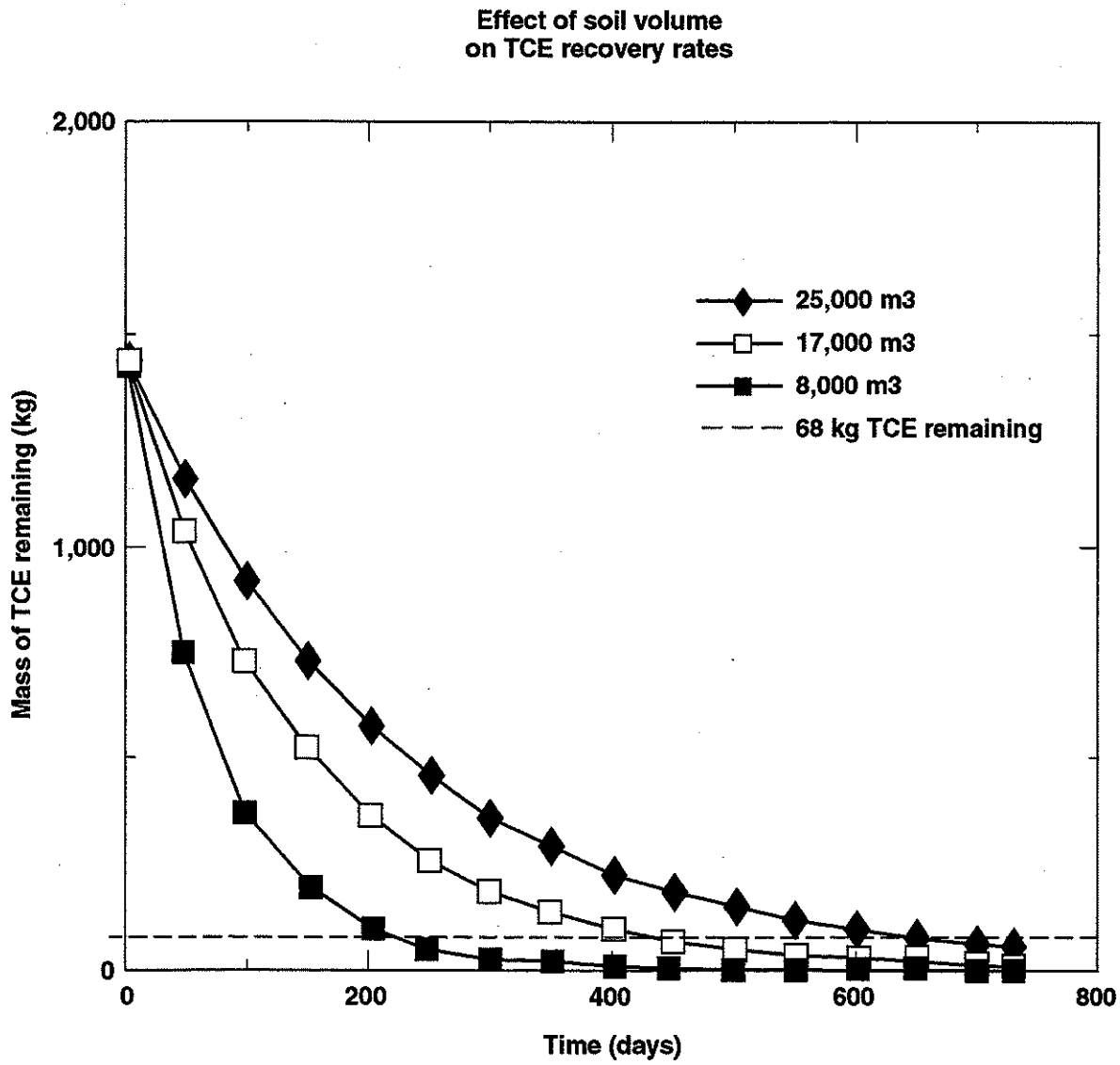

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Figure F-5. Effect of contaminated soil volume on TCE recovery rates.

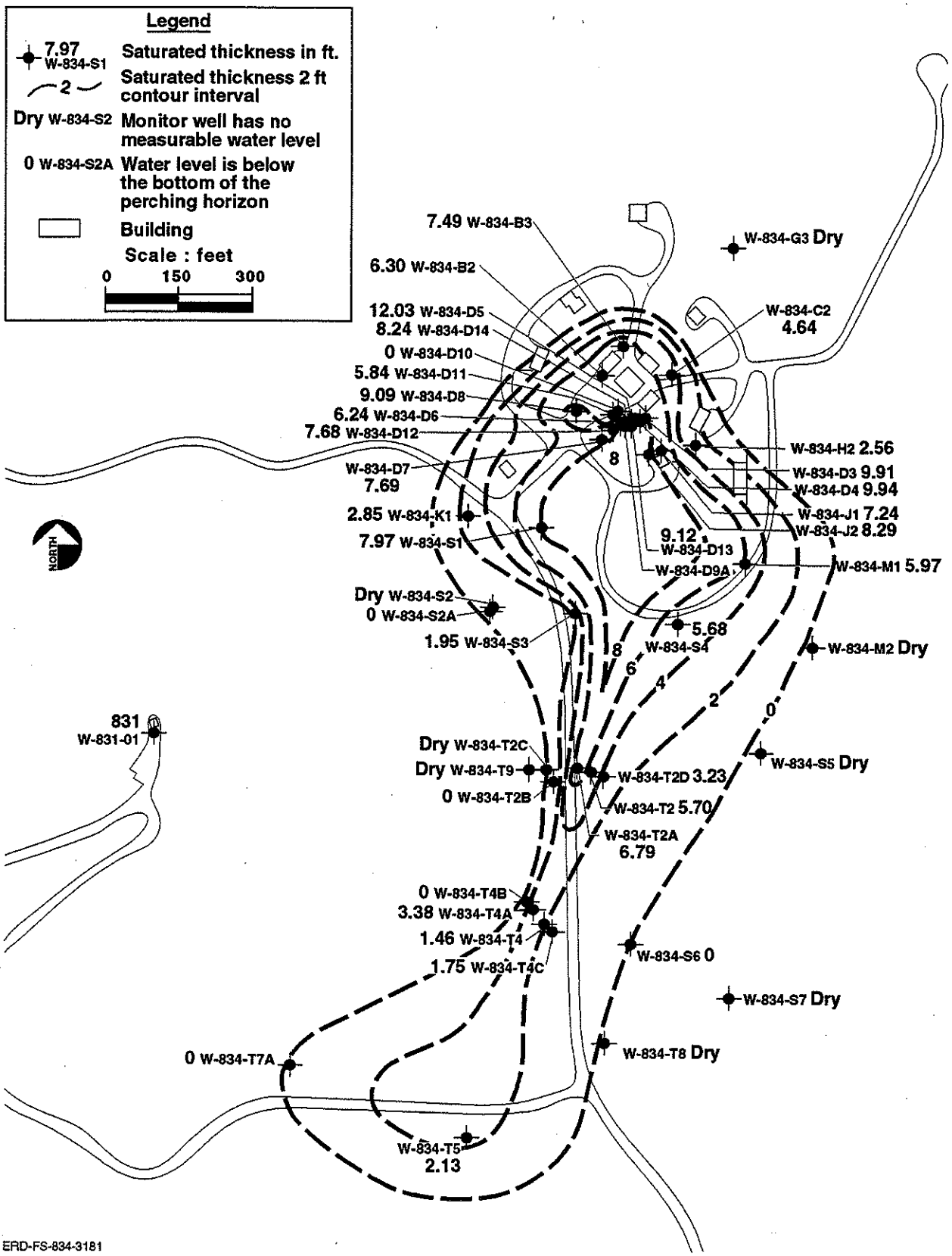


Figure F-6. Saturated thickness of the perched zone (Qt-Tpsg/Tps-Tnsc$_2$ hydrologic units), April 1993.

Table F-1. VENTING input parameters for the Building 834 Complex.

Parameter	Value
Air flow (L/m)	7,100
Spill quantity (gal.)	270
Temperature (°C)	16
Minimum time step (days)	1
Maximum time step (days)	10
Soil volume (m^3)	17,000
Organic carbon content	0.0010
Volumetric water content	0.10
Air-filled porosity	0.15
Venting efficiency factor	0.01, 0.10
Biodecay efficiency factor	0.0

Table F-2. Ground water volume estimates for the Building 834 Complex.

Description	Approximate area of interest (ft^2)	Approximate average saturated thickness (ft)	Porosity (dimensionless)	Volume of water (ft^3)
Core area	71,000	8	0.25	140,000
Entire perched water-bearing zone	850,000	3.3	0.25	700,000

Table F-3. Ground water removal time estimates for the Building 834 Complex.

Description	Volume of water to be removed (ft^3) [gal.]	Approximate pumping rate (ft^3/d)[a]	Approximate recharge rate (ft^3/d)[b]	Estimated time to dewater (yr)
Core area	140,000 [1,100,000]	260	66	2
Entire perched water-bearing zone	700,000 [5,200,000]	350	66	7

[a] Assuming a constant pumping rate of 100 gpd per well, and 19 and 26 wells in the core area and perched water-bearing zones, respectively.

[b] Recharge rate is the average yearly infiltration rate over the estimated recharge area of 260,000 ft^2 (Bryn et al., 1990).

Table F-4. EQUIPLOT input parameters and drawdown predictions.

Parameter	Core wells	W-834-S wells	W-834-T wells	Entire water-bearing zone
Hydraulic gradient (ft/ft)	0.1	0.1	0.1	0.1
Flow direction (° from north)	270	240	250	253
Pumping rate per well (gpd)	100	100	100	100
Hydraulic conductivity (ft/min)	3.3×10^{-4}	1.3×10^{-3}	1.1×10^{-3}	7.3×10^{-5}
Average saturated thickness (ft)	8.1	6.2	5.5	3.3
Storage coefficient	0.001	0.001	0.001	0.001
Pumping duration (days)	2	60	60	1
Average extraction well drawdown	>8.1	1.8	4.9	>8.1

Table F-5. Estimates of maximum capture zone widths.

Description	Pumping rate (ft^3/d)	Hydraulic conductivity (ft/d)	Hydraulic gradient	Average saturated thickness (ft)	Estimated maximum capture width (ft)
Core wells	13.4	0.48	0.1, 0.01	8.1	35 350
W-834-S wells	13.4	1.9	0.1, 0.01	6.2	11 110
W-834-T wells	13.4	1.6	0.1 0.01	5.5	15 150
Entire water-bearing zone	13.4	0.10	0.1, 0.01	3.3	410 4,100

Appendix G

Conceptual Designs and Cost Estimates for Building 834 Remedial Alternatives

Appendix G

Conceptual Designs and Cost Estimates for Building 834 Remedial Alternatives

Appendix G presents the technology and costs for selected alternatives for the Building 834 operable unit. Factors influencing alternatives and remedial designs and the assumptions applied to develop the capital and operating costs are also presented.

The comparative cost estimates presented in this report are for the purpose of analyzing and selecting the preferred remedial action alternative. These costs may be subject to:

- Variations in specific assumptions such as alternative implementation, construction, effectiveness, and system life.
- Changes in dollar value at the time of construction.
- Changes in available equipment and technology at the time of construction.
- Changes in assumed discount rate used in present-worth calculations.
- Uncertainties associated with the hydrogeologic characteristics, subsurface heterogeneities, estimated contaminant mass and volume, and estimated cleanup time.
- Estimated cost accuracy of –30% to +50%.

Although the alternative cost estimates are believed to be accurate and in accordance with U.S. EPA cost estimate guidelines (U.S. EPA, 1987 and 1988), they are subject to change and therefore should not be used for budgetary purposes. A more detailed cost analysis of the selected remedial action alternative will be presented in the Remedial Design (RD) report, following the Record of Decision (ROD) report.

An additional cost/benefits comparison between Alternative 3, which proposes a reduction in cancer risk to 3×10^{-5} (hazard index = 1.0) using soil vapor extraction, and the additional expense required to further reduce the cancer risk to 1×10^{-6} is presented in Berry and Landgraf (1994). The additional cost represented a 64 to 88% increase above the base present-worth cost of Alternative 3, and thus is deemed not justifiable.

G-1. Description of Remedial Alternatives and Associated Technologies

The cost data for the Building 834 area remedial alternatives are based on selected remedial actions and technologies for each remedial alternative described in Chapter 4. Costs for Alternatives 1 through 5 are based on an overall 30-year project life. Treatment facility life differs for each alternative depending on the extent of proposed remediation. Costs for Alternative 2 are based on two years of LNAPL recovery. Costs for Alternative 3 are based on two years of LNAPL recovery and five years of soil vapor extraction. Costs for Alternative 4 are

based on two years of LNAPL recovery and five years of soil vapor extraction with simultaneous dewatering in the core area. Costs for Alternative 5 are based on two years of LNAPL recovery, five years of soil vapor extraction, and 5, 10, 20, and 30 years of ground water pumping in the core area and from downgradient wells.

G-2. Ground Water and Soil Vapor Treatment Technologies

This section presents the alternative technologies for treatment of extracted ground water and soil vapor. General process descriptions are presented together with process flow diagrams for each technology. Factors influencing the design of each treatment system are discussed, as are the assumptions for the capital and operating costs.

G-2.1. LNAPL Removal by Downhole Skimming

Downhole skimming uses equipment placed in the well to skim LNAPLs from the ground water surface. Skimming can either be passive or active. Skimming systems proposed for Alternatives 2 and 3 are shown in Figure G-1. The passive skimmer proposed for well W-834-D8 in Alternatives 2 and 3 consists of a floating hydrophobic filter attached to a reservoir. The passive skimmer is placed in the well so that the filter intersects the LNAPL/water interface. The hydrophobic filter excludes the water but allows the diesel fuel to pass through and be collected in the reservoir. Periodically, the passive skimmer is removed manually from the well and emptied through a valve at the bottom of the reservoir.

Alternatives 2 and 3 include active skimming of T-BOS from wells W-834-D3, -D4, and -D5. Active skimming equipment uses a pneumatic pumping system to evacuate LNAPLs collected through a downhole hydrophobic filter. Because T-BOS is more viscous than diesel, the hydrophobic filter may prove to be ineffective. In this case, a specific-gravity float with a fluid inlet port on top can be substituted for the filter system at no additional cost.

All collected LNAPLs will be removed from the site by a licensed hauler and transported to a facility that has a Resource Conservation and Recovery Act (RCRA) permit for either incineration or recycling.

G-2.2. LNAPL and DNAPL Recovery by Total Fluids Pumping and Aboveground Phase Separation

In Alternatives 4 and 5, LNAPLs and DNAPLs would be collected by aboveground phase separation. Ground water and any entrained NAPLs are pumped from the wells to a chamber containing a series of baffles and weirs that cause NAPLs to coalesce and separate from the ground water. LNAPLs float to the surface and gravity-drain from a port near the top of the chamber, while DNAPLs collect in a bottom section of the chamber and also gravity-drain through a port. Gravity-drained NAPLs are collected in separate drums. Ground water gravity-drains from the chamber to a transfer drum to be pumped to additional treatment equipment. All collected NAPLs are removed from the site by a licensed hauler and transported to a RCRA-permitted facility for either incineration or recycling.

G-2.3. Soil Vapor Extraction (SVE)

SVE consists of applying a vacuum to one or more extraction wells with screens extending from the unsaturated zone down into the saturated zone. Dewatering may be conducted from the same wells to enhance the areal extent of the unsaturated zone. The vacuum induces a flow of air through the unsaturated sediment/rock, which causes volatile compounds to vaporize into this air flow. This technology is effective for compounds that are sufficiently volatile, and industry experience indicates that it is very effective for VOCs and volatile FHCs. The extracted gas is treated with vapor-phase GAC to prevent the release of volatile compounds to the atmosphere.

A process flow diagram for the SVE system is shown in Figure G-2. The mass of GAC required and the diameter and height of the adsorber are a function of the air-flow rate and the anticipated GAC saturation rate. Saturation rate is determined by air-flow rate and chemical concentrations. Breakthrough front (distance over which the concentrations change from zero to influent values) is generally very short for vapor-phase GAC beds. Therefore, near full use of the GAC can be achieved with the use of a single adsorber vessel. A second GAC bed will be placed in series with the first bed as a contingency in case of breakthrough. When the capacity of the first GAC bed has been exhausted, as indicated by detection of trace chemical concentrations in the air exiting the GAC unit, the GAC will be removed and replaced with fresh material. The GAC bed that was second in series will then become first in series. The spent GAC will be transported to a RCRA-permitted facility, either for thermal destruction of the chemicals or for recycling.

The higher adsorption capacity of the vapor-phase GAC treatment is significantly reduced if the air entering the adsorber is saturated with water vapor (100% relative humidity). This capacity loss can be prevented if the relative humidity is reduced to less than 50%. Because the exhaust from the air stripper will be saturated with water, a vapor knockout drum and a heater will be placed between the air stripper and the GAC unit to raise the temperature approximately 20° F. This will reduce the relative humidity to less than 50%. A blower also will be provided to overcome the pressure loss in the air heater and the vapor treatment GAC unit.

G-2.4. Air Stripping with Vapor-Phase Granular Activated Carbon (GAC)

This technology is suited for removing chemicals of moderate to high volatility from the ground water and, hence, is effective to treat VOCs. Treatment is achieved by contact between the water and air flow. In a shallow tray air stripper, water flows across a shallow baffled tray that has numerous small openings, and air is forced upward through the tray and through the water, forming a highly agitated froth and a very high air-to-water surface area contact ratio. The chemicals that are transferred to the air are adsorbed onto GAC in the vapor stream before being discharged to the atmosphere. In a traditional vertical tower air stripper, high surface area packing material facilitates 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 ShallowTray air strippers were the equipment of choice for maintenance and aesthetic reasons.

Air stripping the VOCs from water and vapor-phase adsorption onto GAC has an advantage over direct adsorption onto GAC from the liquid phase. The capacity of GAC treatment of the vapor phase (expressed as pounds of chemical adsorbed per pound of GAC) generally is

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 stripper and vapor-phase GAC adsorption.

The process flow diagram for air stripping with vapor-phase GAC is shown in Figure G-3. The air stripper design and sizing of pumps and blowers are based on flow rate of the extracted water, the influent chemical concentrations, and effluent concentration limits for the treated water discharge. For the ShallowTray air stripper, selection of the size unit is governed by the flow rate of water. The number of trays (and, therefore, the retention time) is based on required reduction in concentrations expressed as the ratio of influent to effluent concentrations for each chemical requiring treatment. Selection of the blower capacity and quantity of air flow is based on the water chemistry and flow rate. To minimize accumulation of sediment in the air stripper, a particulate filter will be installed in line, upstream of the air stripper.

The vapor from the air stripper is directed to a fixed bed of GAC for treatment. The design and operation considerations for treatment of vapors and air emissions control are the same as described in section G-2.3.

Two aqueous-phase GAC beds will be placed in series to treat the air stripper water effluent as a contingency for incomplete volatilization of diesel fuel. The mass of GAC required and the diameter and height of the fixed bed are a function of the water flow rate and the anticipated GAC saturation rate. The saturation rate is a function of the ground water flow rate and chemical concentration. The breakthrough front (the distance over which the chemical concentrations change from zero to the influent 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 at least two adsorber vessels in series.

When the capacity of the GAC to adsorb the chemicals from the water has been exhausted, as indicated by detection of elevated chemical concentrations 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 beds is reversed. In this way, the beds containing the least contaminated GAC will always be in the final polishing position. The spent GAC can be regenerated on site or transported to a RCRA-permitted facility, either for thermal destruction of the chemicals or for recycling.

G-3. Basis for Conceptual Designs and Cost Estimates of Remedial Alternatives

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, and (3) the basis for estimating operating costs over the project life.

G-3.1. Engineering Design Basis

The engineering designs that apply to the development of the conceptual treatment technologies for all alternatives are:

1. Building ventilation system retrofits included in Alternatives 2 through 5 include blowers, air filtration, and electrical connections. The goal of the ventilation retrofits for Buildings 834A, D, O, and J is to reduce indoor air concentrations to 0.036 mg/m^3 (Appendix C). Since Alternative 2 does not include soil remediation, we used the outdoor air concentration (0.798 mg/m^3 TCE) and subsurface air concentrations (1.32 mg/m^3 TCE for Buildings 834A, D, and J as calculated in the SWRI risk assessment, and 2.27 mg/m^3 TCE for Building 834O [Appendix C]) to design additional ventilation and air filtration systems. For Alternatives 3, 4, and 5, we assumed that soil remediation reduced concentrations to the 2.2 mg/kg cleanup level and air concentrations correlate to the reduced soil concentrations. Therefore, we applied an outdoor TCE air concentration of 0.0363 mg/kg TCE and subsurface air concentrations of 0.061 mg/m^3 for Buildings 834A, D, and J, and 0.105 mg/m^3 TCE for Building 834O (Appendix C).

2. Drainage control improvements specified in Alternatives 2 through 5 are designed to minimize infiltration and to channel surface runoff away from the Building 834 Complex.

3. Elements of drainage control include asphalt patching of exposed ground surfaces, construction of drainage curbs and culverts, and installation of a 2,100-ft drainage pipe from the Building 834 Complex to a natural drainage with a slope of less than 5%.

4. Ground water monitoring includes monthly water-level measurements, periodic water sampling and analysis, monitoring well maintenance, database maintenance, reporting and project management. Frequency of ground water sampling ranges from quarterly to annual and is dependent on well location and the alternative. The ground water sampling program is presented in Table G-1. Analytic costs for monitoring include an additional 10% for QA/QC analyses.

5. Soil vapor monitoring includes periodic measurements, using a flame-ionization detector (FID), for total VOCs from vapor extraction wells and shallow soil vapor monitor points. The soil vapor monitoring program is also presented in Table G-1. We assumed that vapor samples will be collected for laboratory analysis in conjunction with 20% of vapor measurements to provide additional QA/QC.

6. The conceptual design for the LNAPL skimming system in Alternatives 2 and 3 is based on measured LNAPL-thicknesses of less than three inches in wells W-834-D3, -D4, -D5, and -D8. Both alternatives assume that LNAPL skimming will be conducted for two years.

7. 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 LNAPLs, vapor, or water from the wells to the treatment facility, and to convey water from the facility to the point of discharge. The conceptual design of piping includes the necessary lengths of the specified type and size of pipes for aboveground and buried lines carrying LNAPLs, vapors, and untreated ground water. Schedule 80 polyvinyl chloride (PVC) is specified for all aboveground pipes, and Schedule 40 PVC for buried pipes. Double-contained pipe is specified for buried lines. Small-diameter nalgene tubing and high-pressure hose is specified for conveyance of fluids and for pneumatic air lines, respectively.

8. Conceptual design of newly installed extraction wells includes soil boring, well installation, and development. Completed well depths are assumed to be between 30 and 50 feet. Conceptual design of shallow soil vapor monitor points includes soil boring and well/point installation with completed depth between 5 and 12 feet.

9. The conceptual design for the soil vapor extraction and ground water extraction systems for the core area are based on upgrading the existing extraction and treatment systems. Equipment already installed that will be used for the proposed systems is designated as "previously installed" in the cost tables.

10. The conceptual design for the soil vapor extraction system for Alternatives 3, 4, and 5, include alternately extracting from up to ten of the proposed extraction wells at a time. The system would consist of the existing 350-cfm-capacity blower with a maximum vacuum of 11 inches of mercury, a water knock-out vessel, an air heater, two vapor-phase GAC vessels connected in series, piping, electrical supply and controls, and instrumentation. The system will be placed on a concrete pad in a small building (about 35 by 35 feet).

11. Vapor-phase GAC consumption rates for soil vapor treatment are based on conservatively modeled soil vapor extraction of TCE vapor concentrations. As discussed in detail in Appendix F, we assumed the initial mass of TCE in the vadose zone is about 266 lb and a total vapor extraction rate of 250 scfm from the extraction wells. We assumed carbon consumption was 20% higher to account for extraction of other VOC vapors present in the vadose zone. Using 1,000-lb GAC canisters, we estimated change-out about every 20 days for Alternative 3, and about every 17 days for Alternatives 4 and 5 (and Alternative 6 if contingent BAT is required) for the first year of operation. We estimated reduced change-out frequency based on modeling presented in Appendix F. Actual vapor-phase GAC consumption may fluctuate in Alternatives 4 and 5 (and Alternative 6) as the saturated zone becomes exposed from dewatering.

12. The conceptual design for each alternative that includes ground water extraction is based on achieving the stated concentrations for treated effluent water at a flow rate based on total estimated well yield and average VOC concentrations for the extracted ground water. The equipment sizing and selection for the cost estimation are based on this conceptual design. Under expected flow and contaminant concentrations, the treatment should generally reduce total VOCs to concentrations at or below 0.5 µg/L (ppb) for all remedial alternatives.

13. The conceptual design for the ground water extraction and treatment systems for Alternatives 4 and 5 consists of pneumatic total fluids pumps, air compressor(s), a particulate filter, transfer drums and pumps, a low-profile air stripper, and two vapor-phase GAC vessels connected in series, a blower to remove air-stripper vapors, an air heater, water discharge piping, an air-misting array, piping, pneumatic and fluid lines, electrical supply and controls, and instrumentation. The treatment system will also include two aqueous-phase GAC vessels after the air stripper to remove trace diesel and/or T-BOS concentrations. The system will be placed in the same building as the soil vapor extraction system. The downgradient treatment system will be placed in a separate building located near the W-834-T4 well cluster.

14. Tables G-2 and G-3 provide the design bases for air stripping in Alternatives 4 and 5. These tables present anticipated average ground water flow rates, and the average ground water chemical concentrations, countercurrent air flows, and mass removal and carbon loading rates. We used TCE, cis-1,2-DCE and diesel-fuel concentrations to specify the model of air stripper and estimate carbon consumption because TCE and cis-1,2-DCE concentrations are about three orders of magnitude greater than the other chlorinated VOCs, and diesel fuel has been detected as floating product in one extraction well (W-834-D8). We assumed that, because T-BOS is relatively insoluble with water, it will be mostly removed by the phase separator and will not significantly affect carbon consumption calculations.

15. For vapor-phase GAC consumption from ground water stripping, we conservatively assumed 100% volatilization from the ground water and a vapor flow rate of 150 cfm (as specified by the air-stripper manufacturer). The GAC consumption rate will decline as a result of the decreased concentrations in the inlet water. The first year carbon consumption rate is based on the design flow rate and average inlet concentrations listed in the design-basis table for the system to which the alternative applies. Then a decline is assumed to occur in step fashion. For years 2 to 5, we estimated the carbon consumption rate will be one-half of what it is during the first year. For years 6 to 10, one-half of the rate during years 2 to 5, and for years 11 to 30, one-half of the rate during years 6 to 10. These consumption rates are based on a 15% adsorption capacity for the first year and a 5% adsorption capacity for the following years because of declining VOC concentrations. We assumed 90% operating time.

16. Aqueous-phase GAC (placed as contingency treatment after the air stripper effluent) consumption is conservatively estimated based on a continuous influent concentration of 10 ppb diesel with a carbon adsorption capacity of 2.8%.

17. An air-misting array will be installed to discharge treated ground water, thereby eliminating the need for additional surface discharge controls.

G-3.2. Capital Cost Estimation

The following assumptions apply to the estimation of capital costs for all treatment alternatives:

1. Vendor quotes, vendor catalog prices, or LLNL cost experience are used to develop the costs for major purchased equipment.

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 LLNL's experience in installing chemical process equipment.

3. LLNL Plant Engineering planning and Title I, II, and III services are assumed to be 33% of all total field costs, which include materials and construction.

4. Professional environmental services are estimated as follows:

   - $10,000 for each environmental permit (treated water discharge and air permits).
   - $20,000 for SVE tests.

- $5,000 for Alternative 2 system start-up.
- $30,000 for Alternative 3 system start-up.
- $40,000 for Alternative 4 system start-up.
- $60,000 for Alternative 5 system start-up.
- $50,000 for SVE performance evaluation.

5. One full time employee (FTE) per treatment system facility in included at $120,000/year to cover potential additional work (such as extra reporting, system evaluation, modeling, etc.).
6. Start-up monitoring for the SVE system in Alternatives 3, 4, and 5 and the air stripping vapor treatment system assumes sampling daily for the first ten days and weekly for the next six weeks.
7. LLNL material procurement charge on major equipment costs is estimated to be 18%, for costs less than $500,000.
8. LLNL material procurement charge on professional contract services is estimated to be 9.7%, assuming the services contract is greater than $500,000.
9. The costs to install the remediation systems 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 factors account for the labor and materials for items such as installation (58% major equipment costs), instrumentation and electrical (20% of major equipment costs), and contractor's overhead and profit (15% of total field costs). Experience with the construction of treatment facilities, similar to those analyzed here, was used to develop the factors applied in the cost estimation procedure for this report. This procedure is considered adequate for alternative cost comparisons because it was applied similarly for all alternatives.
10. Cost to install an extraction well, up to 50-ft deep, is estimated to be $10,000. This includes labor and materials for soil boring, well construction, and well development. An additional $8,000 is estimated for soil boring samples and initial ground water samples.
11. Cost to destroy an existing monitoring well is estimated to be $10,000. This includes labor, materials, expenses for drilling out the well casing and borehole materials, backfilling with cement, and waste disposal.
12. Pump tests are estimated at $3,000 for each new extraction and monitor well. One- to two-day pump tests are assumed.
13. Cost to install a shallow soil vapor monitor point is estimated to be $5,000. This includes labor, materials, and soil boring and well/point installation.
14. Costs to drill final confirmatory soil boring after SVRLs are achieved are estimated at $3,000 each. This assumes a boring depth of up to 12 feet and includes analytic costs.

15. Costs for a 3-ft-deep trench are estimated at $30/ft in unpaved areas and $40/ft in paved areas.
16. Because access to Building 834 is restricted, protective service escorts are required for all workers. LLNL protective services provide an escort at $40/hour. We assumed two escorts would be required during the construction phase.
17. Costs to retrofit the ventilation systems in Buildings 834A, D, O, and J include engineering and design, project and construction management, and construction costs that include demolition of existing work, installation of air ducts and carbon filters, raising the air intake height, and adjusting and testing mechanical equipment.
18. Cost for preparing the required Remedial Design (RD) report is estimated at $100,000 for Alternative 2, $300,000 for Alternatives 3 and 4, and $400,000 for Alternative 5. This includes costs for treatability studies, which may be required as a component of the RD.
19. Costs for implementing innovative technologies are not included in the cost estimates of any alternative.

G-3.3. Operating Cost Estimation

The following assumptions were used to develop operating cost estimates for all alternatives:

1. The estimates for operating cost are based on treating the expected flow rate of extracted soil vapor and ground water containing the average concentrations of contaminants.
2. The cost estimates are developed assuming the following treatment system lifetimes:
   - Alternatives 2 and 3: LNAPL recovery for two years.
   - Alternatives 3, 4, and 5: soil vapor extraction for five years.
   - Alternative 4: dewatering for five years.
   - Alternative 5: total fluids extraction for 5, 10, 20, and 30 years.

   A 3.5% discount rate was applied to calculate present-worth costs. The discount rate is based on Office of Management and Budget estimate of government's long-term opportunity costs (OMB, 1992). Operating cost estimates are discounted to 1993 present-worth costs following procedures described in U.S. EPA (1987).
3. The unit price for soil vapor monitoring includes on-site measurement of vapor concentrations for total VOCs using an FID or PID, with 20% of monitoring samples also being analyzed by EPA Method T-014 at $275/per sample.
4. The unit price for ground water monitoring includes analysis by EPA Method 8010 at $50/sample. Ground water monitoring costs also include labor for sample collection, purge water disposal, and QA/QC. Maintenance of monitoring systems includes labor for pump repair and pump replacement costs. The unit price for water-level measurements is presented as a separate line item.
5. An operating factor of 90% is assumed for all treatment systems.

6. 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.
7. An annual cost of about 10% of the major equipment installed cost (MEIC) is included in the operating cost for all alternatives to cover routine equipment maintenance.
8. The estimates for operating costs reflect conservative estimates of the decline in contaminant concentrations in the extracted soil vapor and ground water over the lifetime of the project. Operating costs have been adjusted to reflect this decrease in contaminant concentrations.
9. The cost for replacement of spent GAC is based on vendor quotes applicable to servicing the specific GAC treatment units used in the conceptual design. This cost estimate of $2.30/lb of GAC includes removal of spent unit, off-site thermal regeneration, and replacement with fresh GAC, as well as all freight and labor costs.
10. The following annual labor hours and hourly rates, including indirect labor costs, will apply to all alternatives:
    - Supervision labor: 200 h at $75/h.
    - Reporting labor: variable at $68/h.
    - Operating labor: 500 h at $55/h.
11. The costs for analysis of vapor and water samples include those samples necessary for monitoring the performance of aboveground treatment alternatives. Costs for sample collection and analysis associated with extraction system performance monitoring and compliance with discharge permit requirements are included in the operating cost estimates. We assume that each treatment facility will be monitored monthly. The following costs apply:
    - Vapor samples will be measured for total VOCs using a FID, and this cost is included in the operation labor cost.
    - Of vapor samples, 20% will also be analyzed for VOCs in a laboratory by EPA Method T-014 at $275/sample, plus labor for sample collection.
    - VOC analysis for water is estimated at $50/analysis/sample, plus labor for sample collection. Up to five water samples will be collected from the water treatment system and analyzed for VOCs by EPA Method 8010 and for diesel by EPA Method 8020.
12. To account for QA/QC, such as field blanks and duplicate samples, 10% is added to the total analytical cost per alternative.
13. Cost during and after remediation includes measuring water levels monthly and collecting soil vapor and ground water samples according to the program outlined on Table G-1.
14. Costs for operating and maintaining innovative technologies are not included in the cost estimates of any alternative.

G-3. LLNL Taxes and Contingency

1. A LLNL General and Administration (G&A) tax of 7.5% is applied to O&M material and labor costs.
2. A LLNL Lab-Directed Research and Development (LDRD) tax of 6.0% is applied to O&M material and labor costs and G&A.
3. A contingency of 20% is applied to the cost estimate.

G-4. Building 834 Treatment Facilities

The costs for the Building 834 Alternatives are given in Tables G-4 through G-8. The chemicals of concern in the ground water at the Building 834 treatment facilities are VOCs, diesel fuel, and T-BOS. The alternatives considered for these treatment facilities are no action, inhalation exposure controls, LNAPL recovery, soil vapor extraction using vapor-phase GAC treatment, and air stripping with vapor-phase GAC treatment. Cost estimates are summarized below, and are also shown in Table 5-2 and presented in cumulative 5 year intervals on Figure G-5.

G-4.1. Alternative 1: No Action

The costs for this alternative are presented in Table G-4. The capital requirement for this alternative is estimated to be $223,281. The present-worth cost of monitoring is $2,838,077. The total present-worth cost of the alternative, including LLNL taxes and 20% contingency, is $4,186,101 for a 30-year project life.

G-4.2. Alternative 2: Inhalation Exposure Controls, Drainage Controls, and LNAPL Recovery

The process flow diagram for this alternative is shown in Figure G-1. The description and costs for the major equipment items are given in Table G-5. The capital requirement for this alternative is estimated to be $1,250,077. The present worth of the operating cost is estimated to be $63,183. Present-worth monitoring costs are $2,844,856. The total present-worth cost of the alternative, including LLNL taxes and 20% contingency, is estimated to be $5,685,574 for a 30-year project life.

G-4.3. Alternative 3: Source Mass Removal by SVE and LNAPL Recovery

The process flow diagrams for this alternative are shown in Figures G-1 and G-2. The description and costs for the major equipment items are given in Table G-6. The capital requirement for this alternative is estimated to be $2,605,855. The present worth of the operating cost is estimated to be $851,434. The present-worth cost of monitoring is $2,920,895. The total present-worth cost of the alternative, including LLNL taxes and 20% contingency, is estimated to be $8,721,528 for a 30-year project life.

G-4.4. Alternative 4: Source Mass Removal by SVE with Dewatering and LNAPL Recovery

The process flow diagrams for this alternative are shown in Figures G-2 and G-3. The description and costs for the major equipment items are given in Table G-7. The capital requirement for this alternative is estimated to be $3,077,231. The present worth of the operating cost is estimated to be $1,571,321. The present-worth cost of monitoring is $2,944,183. The total present-worth cost of the alternative, including LLNL taxes and 20% contingency, is estimated to be $10,382,306 for a 30-year project life.

G-4.5. Alternative 5: Source Mass Removal with Dewatering and LNAPL Recovery; Downgradient Dewatering

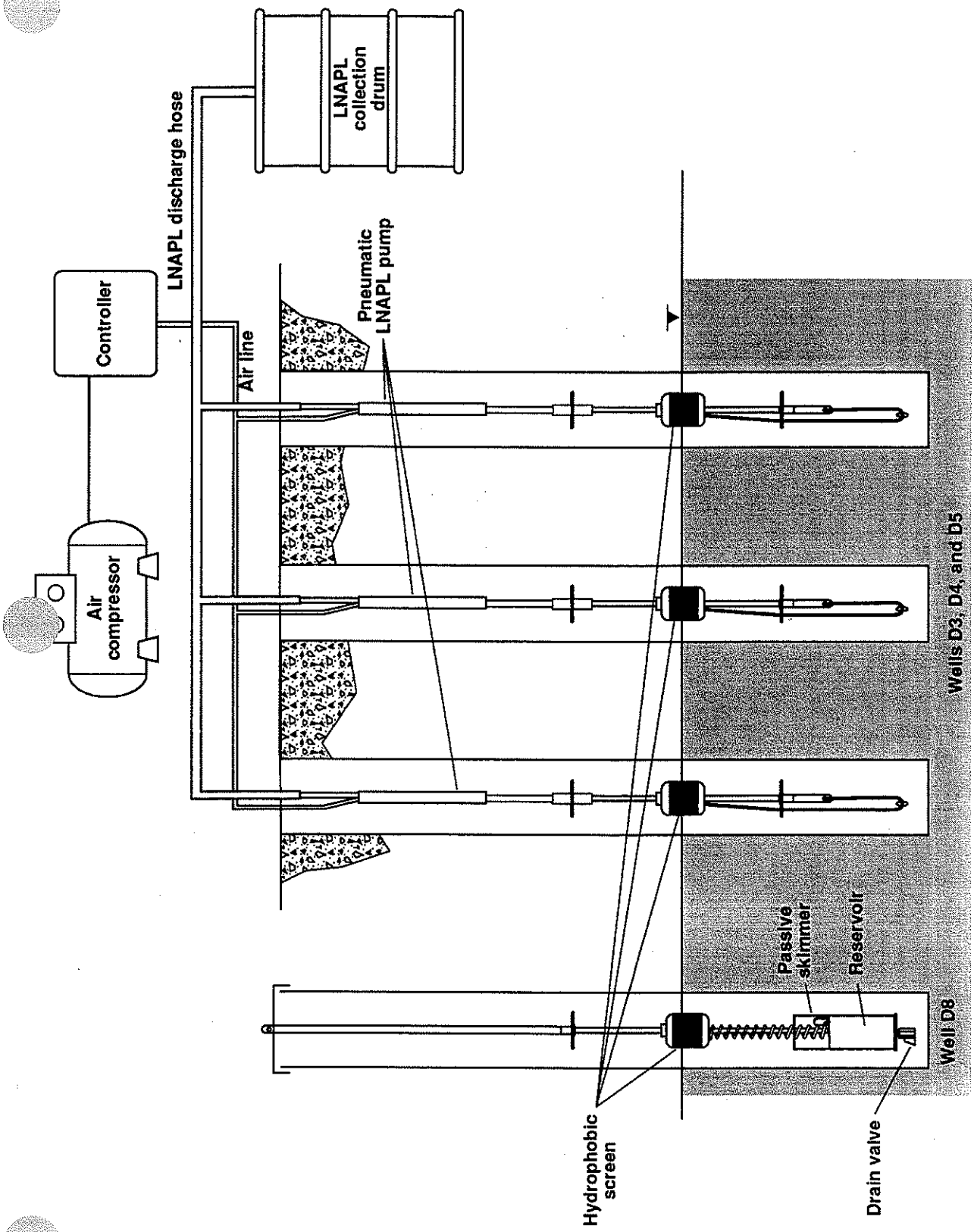
The process flow diagrams for this alternative are shown in Figures G-2 and G-3. The description and costs for the major equipment items are given in Table G-8. The capital requirement for this alternative is estimated to be $3,662,693. The present worth of the operating cost is estimated to be between $3,782,627 and $5,319,660 for 5 years and 30 years of operation, respectively. The present-worth cost of monitoring is $3,049,485. The total present-worth cost of the alternative, including LLNL taxes and 20% contingency, is estimated to be between $11,802,486 and $16,452,336 for project lives of 5 and 30 years, respectively.

G-5. References

Office of Management and Budget (1992), *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs,* Washington, D.C. (OMB Circular A-94).

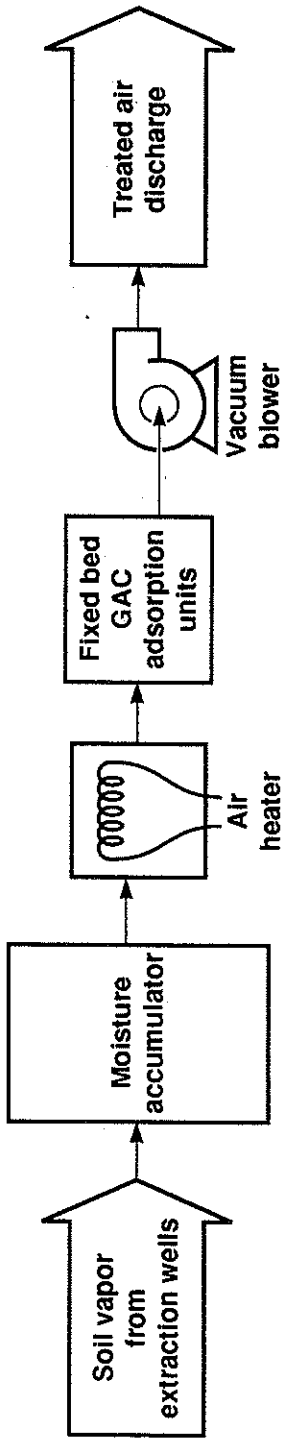
U.S. EPA (1987), *Remedial Action Costing Procedures Manual,* U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, D.C. (EPA-600/8-87-049).

U.S. EPA (1988), *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA,* Interim Final, Office of Emergency and Remedial Response, U.S. Environmental Protection Agency, Washington, D.C. (EPA/540/G-89/004, OSWER Directive 9355.3-01, October 1988).



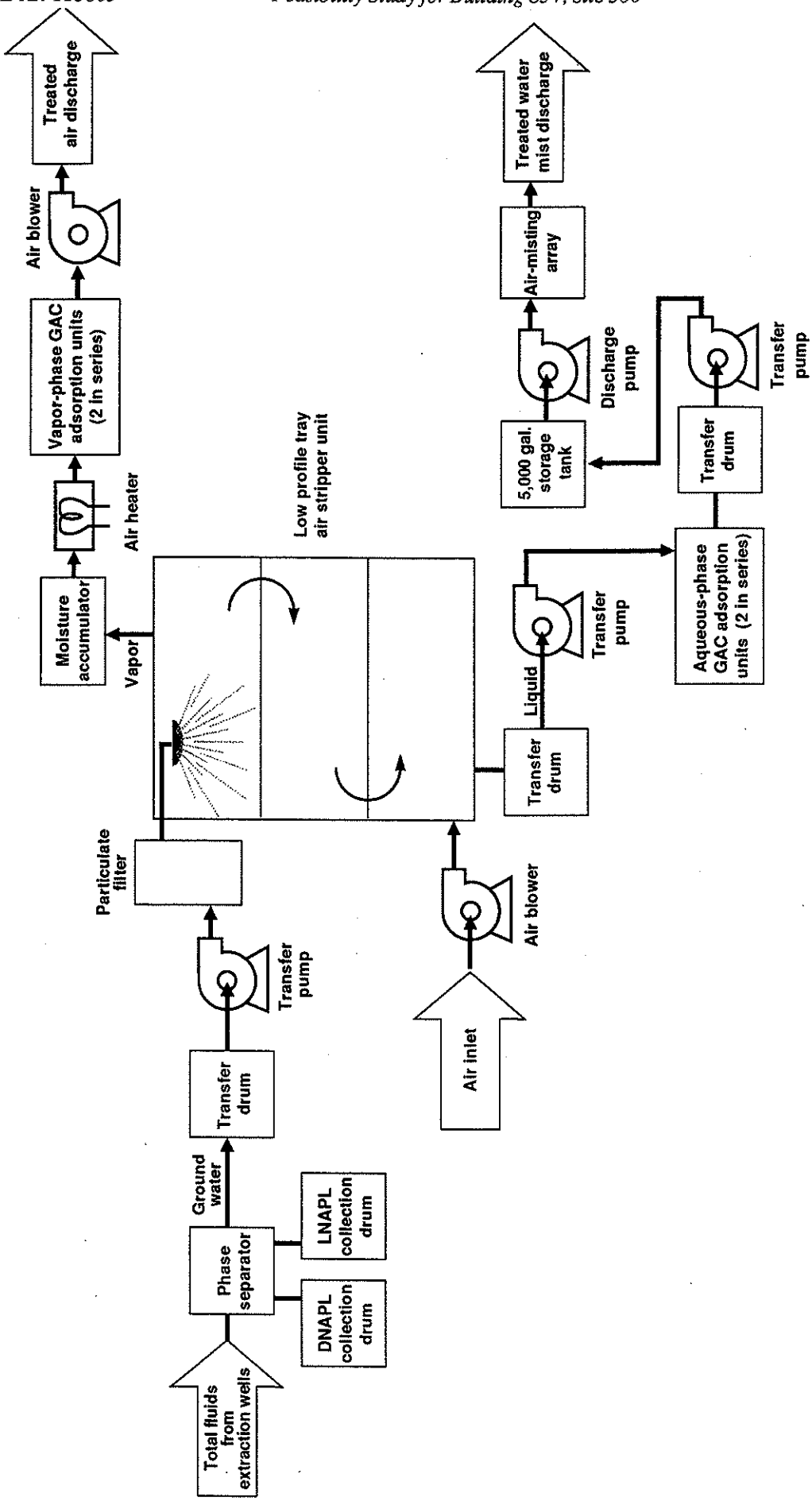
ERD-FS-834-3180

Figure G-1. LNAPL recovery system for Alternatives 2 and 3.



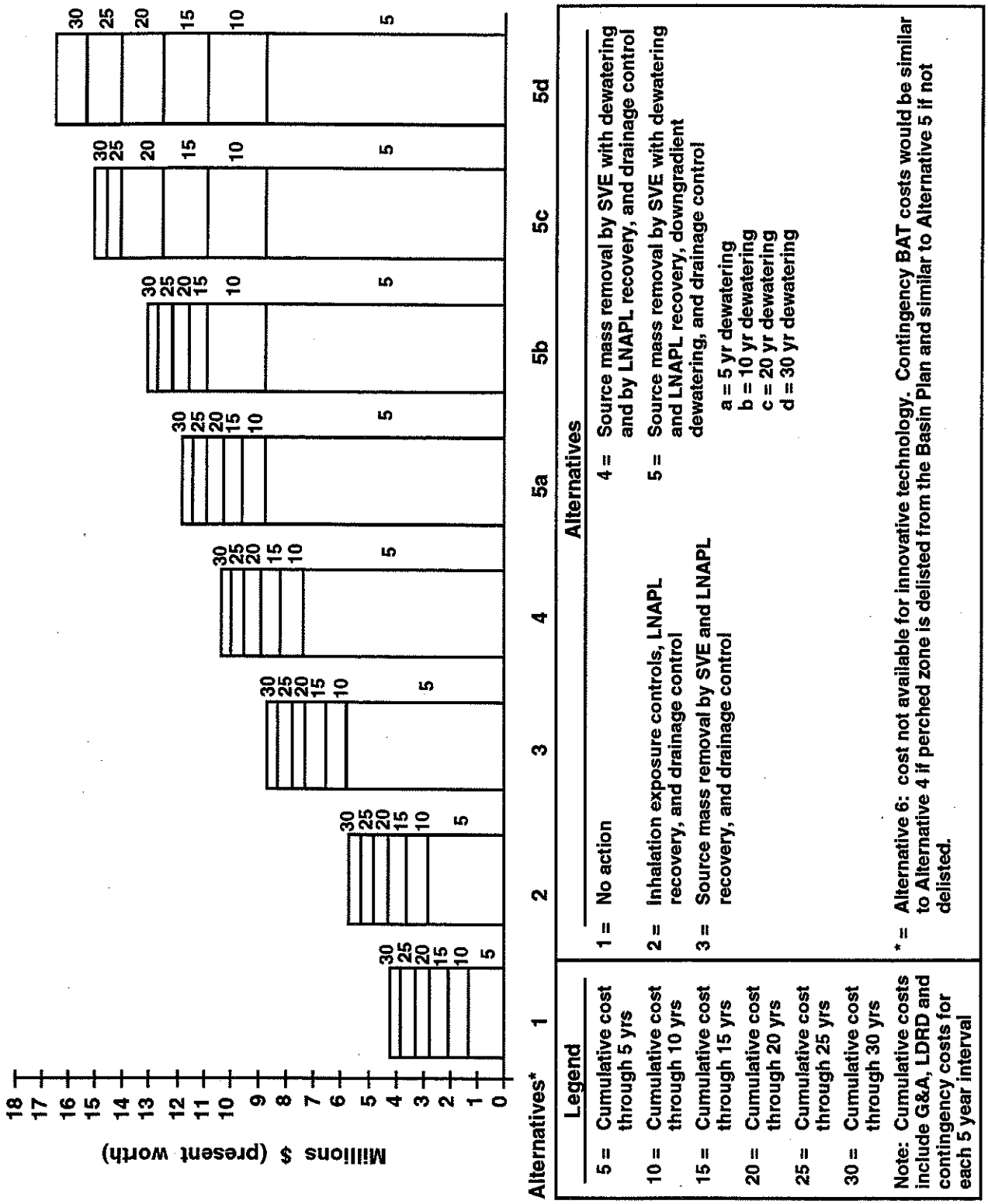
ERD-FS-834-3165

Figure G-2. Facility A soil vapor treatment system, Alternatives 3, 4, and 5.



ERD-FS-834-3179

Figure G-3. Air stripper with aqueous-phase and vapor-phase GAC for Alternatives 4 and 5.



ERD-FS-834-3190

Figure G-4. Cumulative cost for Building 834 remedial alternatives.

Table G-1. Soil vapor and ground water monitoring program for Building 834 operable unit.

Alternative	1				2				3							4						5						
Phase	Soil vapor		Ground water		Soil vapor		Ground water		Soil vapor				Ground water			Soil vapor				Ground water		Soil vapor				Ground water		
Monitoring period (years)	1–5	6–30	1–5	6–30	1–5	6–30	1–5	630	1	2–5	6–10	11–30	1	2–5	6–30	1	2–5	6–10	11–30	1–5	6–30	1	2–5	6–10	11–30	1–5	6–30	Comments
Well ID																												
W-834-B2	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-B3	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-B4 (new)	NA	NA	NA	NA	NA	NA	NA	NA	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-C2	—	—	A	A	—	—	A	A	Q	B	A	—	A	B	A	Q	B	A	—	A	A	Q	B	A	—	A	B	GWE,* SVE
W-834-C3 (new)	NA	NA	NA	NA	NA	NA	NA	NA	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D2	—	—	A	A	—	—	A	A	—	—	—	—	Q	A	A	—	—	—	—	Q	A	—	—	—	—	Q	A	Guard well*
W-834-D3	—	—	B	A	—	—	Q	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D4	—	—	B	A	—	—	Q	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D5	—	—	B	A	—	—	Q	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D6	—	—	B	A	—	—	B	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D7	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D8	—	—	A	A	—	—	Q	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D9A	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	A	Guard well
W-834-D10	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	A	B	A	—	Q	A	Q	B	A	—	A	B	GWE,* SVE
W-834-D11	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D12	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D13	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-D14	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-G3	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	*
W-834-H2	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-J1	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-J2	—	—	A	A	—	—	A	A	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-J3 (new)	NA	NA	NA	NA	NA	NA	NA	NA	Q	B	A	—	Q	B	A	Q	B	A	—	Q	A	Q	B	A	—	Q	B	GWE, SVE
W-834-K1	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-M1	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-M2	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-S1	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	GWE
W-834-S2	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-S2A	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	To be destroyed
W-834-S3	—	—	A	A	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	To be destroyed
W-834-S4	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-S5	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-S6	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	A	
W-834-S7	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	*

Table G-1. (Continued)

Alternative	1				2				3							4						5						
Phase	Soil vapor		Ground water		Soil vapor		Ground water		Soil vapor				Ground water			Soil vapor				Ground water		Soil vapor				Ground water		
Monitoring period (years)	1–5	6–30	1–5	6–30	1–5	6–30	1–5	630	1	2–5	6–10	11–30	1	2–5	6–30	1	2–5	6–10	11–30	1–5	6–30	1	2–5	6–10	11–30	1–5	6–30	Comments
Well ID																												
W-834-S8	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	A	A	
W-834-S9	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	
W-834-S10 (new)	—	—	NA	NA	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	A	
W-834-S11 (new)	—	—	NA	NA	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	B	GWE
W-834-S12 (new)	—	—	NA	NA	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	B	
W-834-T1	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	B	Guard well
W-834-T2	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	GWE
W-834-T2A	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	GWE
W-834-T2B	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	
W-834-T2C	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	
W-834-T2D	—	—	A	A	—	—	A	A	—	—	—	—	A	A	A	—	—	—	—	A	A	—	—	—	—	Q	B	GWE
W-834-T3	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	B	Guard well
W-834-T4	—	—	B	A	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	B	GWE
W-834-T4A	—	—	B	A	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	B	
W-834-T4B	—	—	B	A	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	B	
W-834-T4C	—	—	B	A	—	—	B	A	—	—	—	—	B	B	A	—	—	—	—	B	A	—	—	—	—	Q	B	GWE
W-834-T5	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	B	Guard well
W-834-T7A	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	B	Guard well
W-834-T8	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	B	Guard well
W-834-T9	—	—	Q	A	—	—	Q	A	—	—	—	—	Q	Q	A	—	—	—	—	Q	A	—	—	—	—	Q	B	Guard well
10 new shallow soil vapor points	B	A	NA	NA	B	A	NA	NA	Q	B	A	A	NA	NA	NA	Q	B	A	A	NA	NA	Q	B	A	A	NA	NA	
Total samples																												
Quarterly			8Q				12Q		29Q				28Q	8Q		29Q				28Q		29Q				40Q		
Biannually	10B		11B		10B		8B			29B			7B	26B			29B			7B			29B				38B	
Annually		10A	30A	49A		10A	29A	49A			29A	10A	17A	18A	52A			29A	10A	17A	52A			29A	10A	12A	14A	

Legend: Q = quarterly, B = biannually, A = annually, — = no sampling, GWE = ground water extraction, SVE = soil vapor extraction, NA = not applicable, * = well is historically dry.

Note: Wells W-834-C2 and W-834 -D10 will be used for GWE if water table rises.

Table G-2. System design criteria for Alternative 4, ground water treatment by air stripping.

Parameter	Trichloroethylene	cis-1, 2 Dichloroethene	Diesel fuel
Ground water flow rate = 1,900 gpd (1.3 gpm)			
Average influent concentration, ppb	84,000	16,000	3,000
Air flow rate = 150 scfm			
Average mass removal rate, lb/h	0.054	0.010	0.002
Initial vapor-phase carbon loading rate, % (lb VOC/100 lb carbon)	15	15	20
Initial average vapor-phase carbon consumption rate, lb/d	8.64	1.6	0.24

Table G-3. System design criteria for Alternative 5, ground water treatment by air stripping.

Parameter	Trichloroethylene	cis-1, 2 Dichloroethane	Diesel fuel
Ground water flow rate = 2,600 gpd (1.8 gpm)			
Average influent concentration, ppb	73,500	11,500	2,200
Air flow rate = 150 scfm			
Average mass removal rate, lb/h	0.066	0.010	0.002
Initial vapor-phase carbon loading rate, % (lb VOC/100 lb carbon)	15	15	20
Initial average vapor-phase carbon consumption rate, lb/d	10.56	1.6	0.24

Table G-4. Alternative 1: No action.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Capital costs for well installation				
Wells				
Dedicated soil vapor monitoring points	10	point	5,000	50,000
Well installation and development	3	well	10,000	30,000
Soil boring and initial water sample analyses	3	well	8,000	24,000
Pump test	3	well	3,000	9,000
Well destruction	2	well	10,000	20,000
Subtotal field costs				**133,000**
Contractor overhead and profit (15% of subtotal field costs)				19,950
Subtotal contractor field costs				**152,950**
LLNL material procurement charge (MPC) (18% of contractor field costs)				27,531
LLNL Protective Services				
Escort service (1 guard for 8 weeks)	40	day	320	12,800
Total Field Costs				**193,281**
LLNL ERD team				
Full time employee	0.25	year	120,000	30,000
Total LLNL ERD team				**30,000**
Total capital costs				**223,281**
Ground water monitoring				
Annual costs, years 1–5				
Quarterly water-level measurements	49	well	55	2,695
Quarterly ground water monitoring and analyses	8	well	640	5,120
Biannual ground water monitoring and analyses	11	well	320	3,520

Table G-4. Alternative 1: No action.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Annual ground water monitoring and analyses	30	well	160	4,800
Maintenance of ground water sampling system	49	well	430	21,070
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 1–5				**157,305**
Total present worth, years 1–5 (factor = 4.52)				**711,019**
Annual costs, years 6–30				
Quarterly water-level measurements	49	well	55	2,695
Annual ground water monitoring and analyses	49	well	160	7,840
Maintenance of ground water sampling system	49	well	430	21,070
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 6–30				**151,705**
Total present worth, years 6–10 (factor = 3.80)				**576,479**
Total present worth, years 11–15 (factor = 3.20)				**485,456**
Total present worth, years 16–20 (factor = 2.69)				**408,086**
Total present worth, years 21–25 (factor = 2.27)				**344,370**
Total present worth, years 26–30 (factor = 1.91)				**289,757**
Total present worth, years 6-30				**2,104,148**
Total present worth for ground water monitoring for 30 years				**2,815,167**

Table G-4. Alternative 1: No action.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Soil vapor monitoring				
Annual costs, years 1–5				
Biannual shallow soil vapor point monitoring and analyses	10	point	200	2,000
Total annual costs, years 1–5				**2,000**
Total present worth, years 1–5 (factor = 4.52)				**9,040**
Annual costs, years 6–30				
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 6–30				**1,000**
Total present worth, years 6–10 (factor = 3.80)				**3,800**
Total present worth, years 11–15 (factor = 3.20)				**3,200**
Total present worth, years 16–20 (factor = 2.69)				**2,690**
Total present worth, years 21–25 (factor = 2.27)				**2,270**
Total present worth, years 26–30 (factor = 1.91)				**1,910**
Total present worth, years 6-30				**13,870**
Total present worth for soil vapor monitoring for 30 years				**22,910**
Subtotal present worth of Alternative 1				**3,061,358**
LLNL General & Administrative Tax (7.5%)				229,602
Subtotal				**3,290,960**
LLNL Lab-Directed Research & Development Tax (6.0%)				197,458
Subtotal				**3,488,417**

Table G-4. Alternative 1: No action.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Contingency (20%)				697,683
Total present worth of Alternative 1				**4,186,101**

Table G-5. Alternative 2: VOC exposure control, LNAPL recovery, and institutional controls.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Capital costs for exposure control systems and LNAPL recovery system				
LNAPL recovery system MEC				
Pneumatic skimming unit (including controls and one pump for D3)	1	each	4,000	4,000
Skimming pumps (D4 and D5)	2	each	2,000	4,000
Passive skimmer (D8)	1	each	900	900
Pneumatic and product tubing	200	foot	6	1,200
Air compressor (2 hp)	Previously installed			
Miscellaneous fittings	1	lot	1,000	1,000
Total MEC for building ventilation and LNAPL recovery systems				**11,100**
Electrical components (20% of MEC)				2,220
Installation cost (58% of MEC)				6,438
Major equipment installed cost (MEIC)				**19,758**
Drainage control				
Grading, asphalt paving, curbs, culverts, drainage pipe installation	1	bid	325,500	325,500
Wells				
Dedicated soil vapor monitoring points	10	point	5,000	50,000
Well installation and development	3	well	10,000	30,000
Soil boring and initial water sample analyses	3	well	8,000	24,000
Pump test	3	well	3,000	9,000
Well destruction	2	well	10,000	20,000
Subtotal field costs				**478,258**
Contractor overhead and profit (15% of subtotal field costs)				71,739

Table G-5. Alternative 2: VOC exposure control, LNAPL recovery, and institutional controls.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Subtotal contractor field costs				**549,997**
LLNL material procurement charge (MPC) (18% of contractor field costs)				98,999
LLNL Protective Services				
Escort service (2 guards for 12 weeks)	120	day	320	38,400
check # **Total Field Costs (TFC)**				**687,396**
Professional environmental services				
Design				10,000
Permitting				5,000
Start-up labor and analyses				5,000
Subtotal professional environmental services				**20,000**
LLNL MPC (9.7% of professional environmental services)				1,940
Total professional environmental services				**21,940**
LLNL technical support services				
LLNL Plant Engineering planning and Title I, II, and check # III services (33% of TFC)				226,841
Implementation of institutional controls				50,000
Total LLNL technical support services				**276,841**
LLNL ERD team				
Full time employees	1	year	120,000	120,000
Total LLNL ERD team				**120,000**
Building ventilation system retrofit construction costs				
Building 834A	1	each	10,000	10,000
Building 834D	1	each	5,000	5,000
Building 834 J	1	each	4,500	4,500

Table G-5. Alternative 2: VOC exposure control, LNAPL recovery, and institutional controls.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Building 834O	1	each	4,500	4,500
Seal cracks/epoxy-coat floors				20,000
Total building ventilation retrofit cost				**44,000**
Remedial Design Report/Treatability study	1	each	100,000	100,000
Total capital costs (TCC)				**1,250,177**
O&M costs for LNAPL recovery system				
Annual O&M costs, years 1–2				
Electricity for 2 hp air compressor	12,000	kw•h	0.07	840
Electrical capacity charge	1.5	kw	36	54
Waste disposal (55 gallons)	1	each	750	750
Project management	200	hour	75	15,000
Operating labor	200	hour	55	11,000
Clerical	100	hour	45	4,500
Maintenance (10% of LNAPL recovery system MEC)				1,110
Total annual O&M costs, years 1–2				**33,254**
Total present worth of O&M for LNAPL recovery system, years 1–2 (factor = 1.90)				**63,183**
Ground water monitoring				
Annual costs, years 1–5				
Quarterly water-level measurements	49	well	55	2,695
Quarterly ground water monitoring and analyses	12	well	640	7,680
Biannual ground water monitoring and analyses	8	well	320	2,560
Annual ground water monitoring and analyses	29	well	160	4,640
Maintenance of ground water sampling system	49	well	430	21,070
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000

Table G-5. Alternative 2: VOC exposure control, LNAPL recovery, and institutional controls.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total annual costs, years 1–5				**158,745**
Total present worth, years 1–5 (factor = 4.52)				**717,527**
Annual costs, years 6–30				
Quarterly water-level measurements	49	well	55	2,695
Annual ground water monitoring and analyses	49	well	160	7,840
Maintenance of ground water sampling system	49	well	430	21,070
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 6–30				**151,705**
Total present worth, years 6–10 (factor = 3.80)				**576,479**
Total present worth, years 11–15 (factor = 3.20)				**485,456**
Total present worth, years 16–20 (factor = 2.69)				**408,086**
Total present worth, years 21–25 (factor = 2.27)				**344,370**
Total present worth, years 26–30 (factor = 1.91)				**289,757**
Total present worth, years 6–30				**2,104,148**
Total present worth of ground water monitoring for 30 years				**2,821,676**

Soil vapor monitoring

Annual costs, years 1–5				
Biannual shallow soil vapor point monitoring and analyses	10	point	200	2,000

Table G-5. Alternative 2: VOC exposure control, LNAPL recovery, and institutional controls.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total annual costs, years 1–5				**2,000**
Total present worth, years 1–5 (factor = 4.52)				**9,040**
Annual costs, years 6–30				
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 6–30				**1,000**
Total present worth, years 6–10 (factor = 3.80)				**3,800**
Total present worth, years 11–15 (factor = 3.20)				**3,200**
Total present worth, years 16–20 (factor = 2.69)				**2,690**
Total present worth, years 21–25 (factor = 2.27)				**2,270**
Total present worth, years 26–30 (factor = 1.91)				**1,910**
Total present worth, years 6-30				**13,870**
Total present worth for soil vapor monitoring for 30 years				**22,910**
Subtotal present worth of Alternative 2				**4,157,945**
LLNL General & Administrative Tax (7.5%)				311,846
Subtotal				**4,469,791**
LLNL Lab-Directed Research & Development Tax (6.0%)				268,187
Subtotal				**4,737,979**
Contingency (20%)				947,596
Total present worth of Alternative 2				**5,685,574**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Capital costs for exposure control, LNAPL recovery, and soil vapor extraction (SVE) and treatment systems				
LNAPL recovery system MEC				
Pneumatic skimming unit (including controls and one pump for D3)	1	each	4,000	4,000
Skimming pumps (D4 and D5)	2	each	2,000	4,000
Passive skimmer (D8)	1	each	900	900
Pneumatic and product tubing	200	foot	6	1,200
Air compressor (2 hp)	Previously installed			
Miscellaneous fittings	1	lot	1,000	1,000
SVE and treatment MEC				
Wellhead modifications	9 previously installed			
Additional wellhead modifications	10	each	500	5,000
Electrical supply line	Previously installed			
2-1/2-in. PVC piping	700	foot	4.40	3,080
PVC pipe fittings, unistrut	1	lot	5,000	5,000
Pitot tubes, vacuum gauges, sampling ports, valves, manifold	9 previously installed			
Pitot tubes, vacuum gauges, sampling ports, valves, manifold	10	well	1,000	10,000
Knockout drum, demister, and carbon bed hookup	1	each	1,100	1,100
SVE blower system, 10 hp	Previously installed			
Air heater (700 W)	1	each	500	500
Vapor phase carbon beds (2,000 lb)	3	each	7,700	23,100
Valves, gauges, sampling ports, controls	1	lot	10,000	10,000
Manifold piping and exhaust	1	lot	10,000	10,000
Total MEC for exposure control, LNAPL recovery, and SVE				**78,880**
Electrical components (20% of MEC)				15,776
Installation cost (58% of MEC)				45,750
Major equipment installed cost (MEIC)				**140,406**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Drainage control				
Grading, asphalt paving, curbs, culverts, drainage pipe installation	1	bid	325,500	325,500
Trenching for SVE system				
Trenching in paved areas (2 ft deep x 2 ft wide)	150	foot	40	6,000
Soil analyses and aeration	20	cu. yard	200	4,000
Wells/borings				
Dedicated soil vapor monitoring points	10	point	5,000	50,000
Well installation and development	6	well	10,000	60,000
Soil boring and initial water sample analyses	6	well	8,000	48,000
Pump test	6	well	3,000	18,000
Well destruction	2	well	10,000	20,000
Final confirmatory soil borings and analyses	10	boring	3,000	30,000
Structures				
Equipment building	1	each	300,000	300,000
Geotechnical	1	each	10,000	10,000
Subtotal field costs				**1,011,906**
Contractor overhead and profit (15% of subtotal field costs)				151,786
Subtotal contractor field costs				**1,163,692**
LLNL material procurement charge (MPC) (18% of contractor field costs)				209,465
LLNL Protective Services				
Escort service (2 guards for 16 weeks)	160	day	320	51,200
Total field costs (TFC)				**1,424,357**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Professional environmental services				
Design				50,000
Permitting				30,000
Start-up labor and analyses				30,000
SVE tests				20,000
SVE performance evaluation				50,000
Subtotal professional environmental services				**180,000**
LLNL MPC (9.7% of professional environmental services)				17,460
Total professional environmental services				**197,460**
LLNL ERD team				
Full time employee	1	year	120,000	120,000
Total LLNL ERD team				**120,000**
LLNL technical support services				
LLNL Plant Engineering planning and Title I, II, and III services (33% of TFC)				470,038
Implementation of institutional controls				50,000
Total LLNL technical support services				**520,038**
Building ventilation system retrofit construction costs				
Building 834A	1	each	10,000	10,000
Building 834D	1	each	5,000	5,000
Building 834 J	1	each	4,500	4,500
Building 834O	1	each	4,500	4,500
Seal cracks/epoxy-coat floors				20,000
Total building ventilation retrofit cost				**44,000**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Remedial Design Report/Treatability study	1	each	300,000	300,000
Total capital costs (TCC)				**2,605,855**
O&M costs for LNAPL recovery system				
Annual O&M costs, years 1–2				
Electricity for 2 hp air compressor	12,000	kw•h	0.07	840
Electrical capacity charge	1.50	kw	36	54
Waste disposal (55 gallons)	1	each	750	750
Project management	200	hour	75	15,000
Operating labor	200	hour	55	11,000
Clerical	100	hour	45	4,500
Maintenance (10% of LNAPL recovery system MEC)				1,110
Total annual O&M costs, years 1–2				**33,254**
Total present worth of O&M for LNAPL recovery system, years 1–2 (factor = 1.90)				**63,183**
Fixed O&M costs for SVE and treatment system				
Fixed annual O&M costs				
Electricity	64,500	kw•h	0.07	4,515
Electrical capacity charge	8.2	kw	36	295
Project management	300	hour	75	22,500
System optimization, engineer	400	hour	75	30,000
Well field optimization, hydrogeologist	400	hour	68	27,200
Clerical	200	hour	45	9,000
Operating labor	500	hour	55	27,500
Air permit compliance reporting (monthly)	12	report	2,000	24,000
Maintenance (10% of MEIC)				14,041
Total fixed annual O&M costs				**159,051**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total present worth, years 1–5 (factor = 4.52)				**718,910**
Total present worth of fixed operating costs for LNAPL recovery and SVE and treatment for 5 years				**782,092**
Variable operating costs for SVE and treatment system				
Annual costs, year 1				
SVE replacement of GAC	17,860	lb	2.30	41,078
SVE air sampling	36	sample	100	3,600
Total annual costs, year 1				**44,678**
Total present worth, year 1 (factor = 0.97)				**43,338**
Annual costs, year 2				
SVE replacement of GAC	3,040	lb	2.30	6,992
SVE air sampling	36	sample	100	3,600
Total annual costs, year 2				**10,592**
Total present worth, year 2 (factor = 0.93)				**9,851**
Annual costs, year 3				
SVE replacement of GAC	1,985	lb	2.30	4,566
SVE air sampling	36	sample	100	3,600
Total annual costs, year 3				**8,166**
Total present worth, year 3 (factor = 0.90)				**7,349**
Annual costs, year 4				
SVE replacement of GAC	860	lb	2.30	1,978
SVE air sampling	36	sample	100	3,600
Total annual costs, year 4				**5,578**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total present worth, year 4 (factor = 0.87)				**4,853**
Annual costs, year 5				
SVE replacement of GAC	480	lb	2.30	1,104
SVE air sampling	36	sample	100	3,600
Total annual costs, year 5				**4,704**
Total present worth, year 5 (factor = 0.84)				**3,951**
Total present worth of variable operating costs for SVE and treatment for 5 years				**69,341**
Total present worth of fixed and variable O&M costs				**851,434**
Ground water monitoring				
Annual costs, year 1				
Quarterly water-level measurements	52	well	55	2,860
Quarterly ground water monitoring and analyses	28	well	640	17,920
Biannual ground water monitoring and analyses	7	well	320	2,240
Annual ground water monitoring and analyses	17	well	160	2,720
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, year 1				**168,200**
Total present worth, year 1 (factor = 0.97)				**163,154**
Annual costs, years 2–5				
Quarterly water-level measurements	52	well	55	2,860
Quarterly ground water monitoring and analyses	8	well	640	5,120

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Biannual ground water monitoring and analyses	26	well	320	8,320
Annual ground water monitoring and analyses	18	well	160	2,880
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 2–5				**161,640**
Total present worth, years 2–5 (factor = 3.55)				**573,822**
Annual costs, years 6–30				
Quarterly water-level measurements	52	well	55	2,860
Annual ground water monitoring and analyses	52	well	160	8,320
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 6–30				**153,640**
Total present worth, years 6–10 (factor = 3.80)				**583,832**
Total present worth, years 11–15 (factor = 3.20)				**491,648**
Total present worth, years 16–20 (factor = 2.69)				**413,292**
Total present worth, years 21–25 (factor = 2.27)				**348,763**
Total present worth, years 26–30 (factor = 1.91)				**293,452**
Total present worth, years 6–30				**2,130,987**
Total present worth of ground water monitoring for 30 years				**2,867,963**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Soil vapor monitoring				
Annual costs, year 1				
Quarterly soil vapor monitoring and analyses from extraction wells	19	well	400	7,600
Quarterly shallow soil vapor point monitoring and analyses	10	point	400	4,000
Total annual costs, year 1				**11,600**
Total present worth, year 1 (factor = 0.97)				**11,252**
Annual costs, years 2–5				
Biannual soil vapor monitoring and analyses from extraction wells	19	well	200	3,800
Biannual shallow soil vapor point monitoring and analyses	10	point	200	2,000
Total annual costs, years 2–5				**5,800**
Total present worth, years 2–5 (factor = 3.55)				**20,590**
Annual costs, years 6–10				
Annual soil vapor monitoring and analyses from extraction wells	19	well	100	1,900
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 6–10				**2,900**
Total present worth, years 6–10 (factor = 3.80)				**11,020**

Table G-6. Alternative 3: Source mass removal at core of complex using soil vapor extraction and LNAPL recovery.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Annual costs, years 11–30				
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 11–30				**1,000**
Total present worth, years 11–15 (factor = 3.20)				**3,200**
Total present worth, years 16–20 (factor = 2.69)				**2,690**
Total present worth, years 21–25 (factor = 2.27)				**2,270**
Total present worth, years 26–30 (factor = 1.91)				**1,910**
Total present worth for soil vapor monitoring for 30 years				**52,932**
Subtotal present worth Alternative 3				**6,378,183**
LLNL General & Administrative Tax (7.5%)				478,364
Subtotal				**6,856,547**
LLNL Lab-Directed Research & Development Tax (6.0%)				411,393
Subtotal				**7,267,940**
Contingency (20%)				1,453,588
Total present worth of Alternative 3				**8,721,528**

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Capital costs				
Total fluids and soil vapor extraction (SVE) system major equipment costs (MEC)				
Wellhead modifications	9 previously installed			
Additional wellhead modifications	10	each	500	5,000
Electrical supply line	Previously installed			
4-in. PVC piping	700	foot	8.20	5,740
2-1/2-in. PVC piping	700	foot	4.40	3,080
Nalgene tubing	1,000	foot	1.41	1,410
Pneumatic total fluids pumps	3 previously purchased			
Pneumatic total fluids pumps	16	each	2,400	38,400
Pneumatic lines in wells	16	each	250	4,000
Air compressors (7.5 hp)	1	each	5,000	5,000
Air compressor lines in trenches	1,000	foot	1.40	1,400
PVC pipe fittings, unistrut	1	lot	5,000	5,000
Ground water extraction system valves, sampling ports, gauges	3 previously purchased			
Additional GWE valves, sampling ports, gauges	16	well	500	8,000
SVE pitot tubes, vacuum gauges, sampling ports	9 previously installed			
SVE pitot tubes, vacuum gauges, sampling ports	10	well	1,000	10,000
Ground water treatment MEC				
Phase separator (with LNAPL and DNAPL collection drums)	1	each	15,000	15,000
Transfer drum (55 gallons)	3	each	200	600
Air misting storage tank (5,000 gallons)	1	each	5,000	5,000
Transfer pump (1/6 hp)	2	each	300	600
Transfer pump (1-1/2 hp)	2	each	500	1,000
Particulate filter assembly	Previously installed			
Low profile tray air stripper, Model 1321	1	each	13,000	13,000
Knockout drum, demister, carbon bed hookup	1	each	1,100	1,100
Air heater (700 W)	1	each	500	500
Aqueous-phase carbon beds (200 lb)	2	each	500	1,000
Vapor-phase carbon beds (1,000 lb)	2	each	6,000	12,000

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Air stripper vapor exhaust blower (2 hp)	1	each	3,500	3,500
Manifold, piping, valves, gauges, sampling ports, totalizer, controllers	1	lot	10,000	10,000
Discharge piping and fittings	Previously installed			
Pipe heating tape	2,000	foot	2	4,000
Addition to existing air misting discharge unit	1	each	10,000	10,000
SVE treatment MEC				
Knockout drum, demister, carbon bed hookup	1	each	1,100	1,100
SVE blower system (10 hp)	Previously installed			
Air heater (700 W)	1	each	500	500
Vapor-phase carbon beds (2,000 lb)	3	each	7,700	23,100
Valves, gauges, sampling ports, controllers	1	lot	10,000	10,000
SVE manifold, piping, exhaust	1	lot	10,000	10,000
Total MEC for exposure control and ground water and SVE treatment systems				**209,030**
Electrical components (20% of MEC)				41,806
Installation cost (58% of MEC)				121,237
Major equipment installed cost (MEIC)				**372,073**
Drainage control				
Grading, asphalt paving, curbs, culverts, drainage pipe installation	1	bid	325,500	325,500
Trenching				
Trenching in paved areas	500	foot	40	20,000
Soil analyses and aeration	20	cu. yard	200	4,000
Wells/borings				
Dedicated soil vapor monitoring point	10	point	5,000	50,000
Well installation and development	6	well	10,000	60,000
Soil boring and initial water sample analyses	6	well	8,000	48,000
Pump test	6	well	3,000	18,000

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Well destruction	2	well	10,000	20,000
Final confirmatory soil borings and analyses	10	boring	3,000	30,000
Structures				
Equipment building	1	each	300,000	300,000
Geotechnical	1	each	10,000	10,000
Subtotal field costs				**1,257,573**
Contractor overhead and profit (15% of subtotal field costs)				188,636
Subtotal contractor field costs				**1,446,209**
LLNL material procurement charge (MPC) (18% of contractor field costs)				260,318
LLNL Protective Services				
Escort service (2 guards for 20 weeks)	200	day	320	64,000
Total field costs (TFC)				**1,770,527**
Professional environmental services				
Design				50,000
Permitting				30,000
Start-up labor and analyses				40,000
SVE tests				20,000
SVE performance evaluation				50,000
Subtotal professional environmental services				**190,000**
LLNL MPC (9.7% of professional environmental services)				18,430
Total professional environmental services				**208,430**

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
LLNL ERD team				
Full time employee	1	year	120,000	120,000
Total LLNL ERD team				**120,000**
LLNL technical support services				
LLNL Plant Engineering planning and Title I, II, and III services (33% of TFC)				584,274
Implementation of institutional controls				50,000
Total LLNL support services				**634,274**
Building ventilation system modification major equipment costs (MEC)				
Building 834A	1	each	10,000	10,000
Building 834D	1	each	5,000	5,000
Building 834J	1	each	4,500	4,500
Building 834O	1	each	4,500	4,500
Seal cracks/epoxy-coat floors				20,000
Total building ventilation retrofits				**44,000**
Remedial Design Report/Treatability study	1	each	300,000	300,000
Total capital costs (TCC)				**3,077,231**

Operation and Maintenance Costs

Fixed annual O&M costs for SVE				
Electricity	64,700	kw•h	0.07	4,529
Electrical capacity charge	8.2	kw	36	295
Project management	300	hour	75	22,500
System optimization, engineer	400	hour	75	30,000
Well field optimization, hydrogeologist	400	hour	68	27,200
Operating labor	250	hour	55	13,750

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Clerical	200	hour	45	9,000
SVE air permit compliance reporting (monthly)	12	report	2,000	24,000
Total fixed annual SVE O&M costs				**131,274**
Total present worth of fixed O&M for soil vapor extraction, years 1–5 (factor = 4.52)				**593,359**
Fixed annual O&M costs for dewatering				
Electricity	93,000	kw•h	0.07	6,510
Electrical capacity charge	11.8	kw	36	425
Project management	200	hour	75	15,000
System optimization, engineer	300	hour	75	22,500
Well field optimization, hydrogeologist	300	hour	68	20,400
Operating labor	500	hour	55	27,500
Clerical	200	hour	45	9,000
Ground water treatment system analyses (water only)	12	event	500	6,000
Ground water treatment air permit compliance reporting (monthly)	12	report	2,000	24,000
Ground water discharge reporting (monthly)	12	report	2,000	24,000
Maintenance (10% of MEIC)				37,207
Total fixed annual dewatering and plume control O&M costs				**192,542**
Total present worth of fixed O&M for ground water extraction, years 1–5 (factor = 4.52)				**870,290**
Total present worth of fixed O&M costs				**1,463,650**

Variable operating costs for source mass removal and plume control

Annual costs, year 1				
SVE replacement of GAC	17,860	lb	2.30	41,078
Ground water treatment system replacement of vapor GAC	3,440	lb	2.30	7,912
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 1				**56,282**
Total present worth, year 1 (factor = 0.97)				**54,594**
Annual costs, year 2				
SVE replacement of GAC	3,040	lb	2.30	6,992
Ground water treatment system replacement of vapor GAC	1,720	lb	2.30	3,956
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 2				**18,240**
Total present worth, year 2 (factor = 0.93)				**16,963**
Annual costs, year 3				
SVE replacement of GAC	1,985	lb	2.30	4,566
Ground water treatment system replacement of vapor GAC	1,720	lb	2.30	3,956
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 3				**15,814**
Total present worth, year 3 (factor = 0.90)				**14,232**
Annual costs, year 4				
SVE replacement of GAC	860	lb	2.30	1,978
Ground water treatment system replacement of vapor GAC	1,720	lb	2.30	3,956

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
GWT air sampling	36	sample	100	3,600
Total annual costs, year 4				**13,226**
Total present worth, year 4 (factor = 0.87)				**11,507**
Annual costs, year 5				
SVE replacement of GAC	480	lb	2.30	1,104
Ground water treatment system replacement of vapor GAC	1,720	lb	2.30	3,956
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
GWT air sampling	36	sample	100	3,600
Total annual costs, year 5				**12,352**
Total present worth, year 5 (factor = 0.84)				**10,376**
Total present worth of variable operating costs				**107,671**
Total present worth of fixed and variable O&M costs				**1,571,321**

Ground water monitoring

Annual costs, years 1–5				
Quarterly water level measurements	52	well	55	2,860
Quarterly ground water monitoring and analyses	28	well	640	17,920
Biannual ground water monitoring and analyses	7	well	320	2,240
Annual ground water monitoring and analyses	17	well	160	2,720
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring report	4	report	15,000	60,000
Project management	500	hour	75	37,500

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 1–5				**168,200**
Total present worth, years 1–5 (factor = 4.52)				**760,264**
Annual costs, years 6–30				
Quarterly water-level measurements	52	well	55	2,860
Annual ground water monitoring and analyses	52	well	160	8,320
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring report	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 6–30				**153,640**
Total present worth, years 6–10 (factor = 3.80)				**583,832**
Total present worth, years 11–15 (factor = 3.20)				**491,648**
Total present worth, years 16–20 (factor = 2.69)				**413,292**
Total present worth, years 21–25 (factor = 2.27)				**348,763**
Total present worth, years 26–30 (factor = 1.91)				**293,452**
Total present worth, years 6–30				**2,130,987**
Total present worth of ground water monitoring for 30 years				**2,891,251**

Soil vapor monitoring

Annual costs, year 1				
Quarterly soil vapor monitoring and analyses from extraction wells	19	well	400	7,600

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Quarterly shallow soil vapor point monitoring and analyses	10	point	400	4,000
Total annual costs, year 1				**11,600**
Total present worth, year 1 (factor = 0.97)				**11,252**
Annual costs, years 2–5				
Biannual soil vapor monitoring and analyses from extraction wells	19	well	200	3,800
Biannual shallow soil vapor point monitoring and analyses	10	point	200	2,000
Total annual costs, years 2–5				**5,800**
Total present worth, years 2–5 (factor = 3.55)				**20,590**
Annual costs, years 6–10				
Annual soil vapor monitoring and analyses from extraction wells	19	well	100	1,900
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 6–10				**2,900**
Total present worth, years 6–10 (factor = 3.80)				**11,020**
Annual costs, years 11–30				
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 11–30				**1,000**
Total present worth, years 11–15 (factor = 3.20)				**3,200**
Total present worth, years 16–20 (factor = 2.69)				**2,690**
Total present worth, years 21–25 (factor = 2.27)				**2,270**
Total present worth, years 26–30 (factor = 1.91)				**1,910**

Table G-7. Alternative 4: Source mass removal at core of Building 834 Complex soil vapor extraction enhanced by dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total present worth for soil vapor monitoring for 30 years				**52,932**
Subtotal present worth of Alternative 4				**7,592,735**
LLNL General & Administrative Tax (7.5%)				**569,455**
Subtotal				**8,162,190**
LLNL Lab-Directed Research & Development Tax (6.0%)				**489,731**
Subtotal				**8,651,921**
Contingency (20%)				**1,730,384**
Total present worth of Alternative 4				**10,382,306**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Capital costs				
Total fluids and soil vapor extraction (SVE) system major equipment costs (MEC)				
Wellhead modifications	9 previously installed			
Additional wellhead modifications	17	each	500	8,500
Electrical supply line	Previously installed			
Electrical supply line from core to S1 area	300	foot	0.96	288
Electrical supply line from T4 to T2 area	400	foot	0.96	384
4-in. PVC piping	2,000	foot	8.20	16,400
2-1/2-in. PVC piping	700	foot	4.40	3,080
Nalgene tubing	3,000	foot	1.41	4,230
Pneumatic total fluids pumps	3 previously purchased			
Pneumatic total fluids pumps	23	each	2,400	55,200
Pneumatic lines in wells	23	each	250	5,750
Air compressor (7.5 hp)	1	each	5,000	5,000
Air compressor (2 hp)	1 previously purchased			
Air compressor (2 hp)	2	each	3,500	7,000
Air compressor lines in trenches	1,250	foot	1.40	1,750
PVC pipe fittings, unistrut	1	lot	10,000	10,000
Ground water extraction system valves, sampling ports, gauges	3 previously purchased			
Additional ground water extraction system valves, sampling ports, gauges	24	well	500	12,000
SVE pitot tubes, vacuum gauges, sampling ports	9 previously installed			
SVE pitot tubes, vacuum gauges, sampling ports	10	well	1,000	10,000
Ground water treatment MEC				
Phase separator (with LNAPL and DNAPL collection drums)	1	each	15,000	15,000
Transfer tank (250 gallons)	1	each	500	500
Transfer drum (55 gallons)	5	each	200	1,000
Air misting storage tank (5,000 gallons)	1	each	5,000	5,000
Transfer pump (3 hp)	1	each	1,500	1,500
Transfer pump (1-1/2 hp)	2	each	500	1,000

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Transfer pump (1/2 hp)	1	each	400	400
Transfer pump (1/6 hp)	3	each	300	900
Particulate filter assembly	Previously installed			
Low profile tray air stripper	1	each	13,000	13,000
Knockout drum, demister, carbon bed hookup	1	each	1,100	1,100
Air heater (700 W)	1	each	500	500
Aqueous-phase carbon beds (200 lb)	2	each	500	1,000
Vapor-phase carbon beds (1,000 lb)	2	each	6,000	12,000
Air stripper vapor exhaust blower (2 hp)	1	each	3,500	3,500
Manifold, piping, valves, gauges, sampling ports, totalizer, controllers	1	lot	15,000	15,000
Discharge piping and fittings	Previously installed			
Pipe heating tape	2,000	foot	2	4,000
Addition to existing air misting discharge unit	1	each	10,000	10,000
SVE treatment MEC				
Knockout drum, demister, carbon bed hookup	1	each	1,100	1,100
SVE blower system (10 hp)	Previously installed			
Air heater (700 W)	1	each	500	500
Vapor-phase carbon beds (2,000 lb)	3	each	7,700	23,100
Valves, gauges, sampling ports, controllers	1	lot	10,000	10,000
SVE manifold, piping, exhaust	1	lot	10,000	10,000
Total MEC for exposure control and ground water and SVE treatment systems				**269,682**
Electrical components (20% of MEC)				53,936
Installation cost (58% of MEC)				156,416
Major equipment installed cost (MEIC)				**480,034**
Drainage control				
Grading, asphalt paving, curbs, culverts, drainage pipe installation	1	bid	325,500	325,500

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Trenching				
Trenching in paved areas	550	foot	40	22,000
Trenching in unpaved areas	1,100	foot	30	33,000
Soil analyses and aeration	370	cu. yard	200	74,000
Wells/borings				
Dedicated soil vapor monitoring points	10	point	5,000	50,000
Well installation and development	6	well	10,000	60,000
Soil boring and initial water sample analyses	6	well	8,000	48,000
Pump test	6	well	3,000	18,000
Well destruction	2	well	10,000	20,000
Final confirmatory soil borings and analyses	10	borings	3,000	30,000
Structures				
Equipment building	1	each	300,000	300,000
Butler building for septic area (10' x 10')	1	each	5,000	5,000
Butler building for T2 area (10' x 10')	1	each	5,000	5,000
Butler building for T4 area (10' x 10')	1	each	5,000	5,000
Geotechnical	1	each	20,000	20,000
Subtotal field costs				**1,495,534**
Contractor overhead and profit (15% of subtotal field costs)				224,330
Subtotal contractor field costs				**1,719,864**
LLNL material procurement charge (MPC) (18% of contractor field costs)				309,576
LLNL Protective Services				
Escort service (2 guards for 28 weeks)	280	day	320	89,600
Total field costs (TFC)				**2,119,040**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Professional environmental services				
Design				50,000
Permitting				30,000
Start-up labor and analyses				60,000
SVE tests				20,000
SVE performance evaluation				50,000
Subtotal professional environmental services				**210,000**
LLNL MPC (9.7% of professional environmental services)				20,370
Total professional environmental services				**230,370**
LLNL ERD team				
Full-time employees	1	year	120,000	120,000
Total LLNL ERD team				**120,000**
LLNL technical support services				
LLNL Plant Engineering planning and Title I, II, and III services (33% of TFC)				699,283
Implementation of institutional controls				50,000
Total LLNL support services				**749,283**
Building ventilation system modification major equipment costs (MEC)				
Building 834A	1	each	10,000	10,000
Building 834D	1	each	5,000	5,000
Building 834J	1	each	4,500	4,500
Building 834O	1	each	4,500	4,500
Seal cracks/epoxy-coat floors				20,000
Total building ventilation retrofits				**44,000**
Remedial Design Report/Treatability Study	1	each	400,000	400,000
Total capital costs (TCC)				**3,662,693**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Operation and Maintenance Costs				
Fixed O&M costs for source mass removal and plume control				
Fixed annual O&M costs for SVE				
Electricity	65,000	kw•h	0.07	4,550
Electrical capacity charge	8.2	kw	36	295
Project management	300	hour	75	22,500
System optimization, engineer	400	hour	75	30,000
Well field optimization, hydrogeologist	400	hour	68	27,200
Operating labor	770	hour	55	42,350
Clerical	200	hour	45	9,000
SVE air permit compliance reporting (monthly)	12	report	2,000	24,000
Total fixed annual SVE O&M costs				**159,895**
Total present worth of fixed O&M for soil vapor extraction, years 1–5 (factor = 4.52)				**722,726**
Fixed annual O&M costs for dewatering and plume control				
Electricity	205,000	kw•h	0.07	14,350
Electrical capacity charge	17.5	kw	36	630
Project management	200	hour	75	15,000
System optimization, engineer	300	hour	75	22,500
Well field optimization, hydrogeologist	300	hour	68	20,400
Operating labor	1,020	hour	55	56,100
Clerical	200	hour	45	9,000
Ground water treatment system analyses (water only)	12	event	500	6,000
Ground water treatment system air permit compliance reporting (monthly)	12	report	2,000	24,000
Ground water discharge reporting (monthly)	12	report	2,000	24,000
Maintenance (10% of MEIC)				48,003
Total fixed annual dewatering and plume control O&M costs				**239,983**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total present worth, years 1–5 (factor = 4.52)				**1,084,725**
Total present worth, years 6–10 (factor = 3.80)				**911,937**
Total present worth, years 11–15 (factor = 3.20)				**767,947**
Total present worth, years 16–20 (factor = 2.69)				**645,555**
Total present worth, years 21–25 (factor = 2.27)				**544,762**
Total present worth, years 26–30 (factor = 1.91)				**458,368**

Variable operating costs for source mass removal and plume control

Annual costs, year 1				
SVE replacement of GAC	17,860	lb	2.30	41,078
Ground water treatment system replacement of vapor GAC	4,080	lb	2.30	9,384
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 1				**57,754**
Total present worth, year 1 (factor = 0.97)				**56,021**
Annual costs, year 2				
SVE replacement of GAC	3,040	lb	2.30	6,992
Ground water treatment system replacement of vapor GAC	2,040	lb	2.30	4,692
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 2				**18,976**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total present worth, year 2 (factor = 0.93)				**17,648**
Annual costs, year 3				
SVE replacement of GAC	1,985	lb	2.30	4,566
Ground water treatment system replacement of vapor GAC	2,040	lb	2.30	4,692
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 3				**16,550**
Total present worth, year 3 (factor = 0.90)				**14,895**
Annual costs, year 4				
SVE replacement of GAC	860	lb	2.30	1,978
Ground water treatment system replacement of vapor GAC	2,040	lb	2.30	4,692
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, year 4				**13,962**
Total present worth, year 4 (factor = 0.87)				**12,147**
Annual costs, year 5				
SVE replacement of GAC	480	lb	2.30	1,104
Ground water treatment system replacement of vapor GAC	2,040	lb	2.30	4,692
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
SVE air sampling	36	sample	100	3,600
Ground water treatment system air sampling	36	sample	100	3,600

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Total annual costs, year 5				**13,088**
Total present worth, year 5 (factor = 0.84)				**10,994**
Annual costs, years 6–10				
Ground water treatment system replacement of vapor GAC	1,020	lb	2.30	2,346
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, years 6–10				**6,038**
Total present worth, years 6–10 (factor = 3.80)				**22,944**
Annual costs, years 11–30				
Ground water treatment system replacement of vapor GAC	510	lb	2.30	1,173
Ground water treatment system replacement of aqueous GAC	40	lb	2.30	92
Ground water treatment system air sampling	36	sample	100	3,600
Total annual costs, years 11–30				**4,865**
Total present worth, years 11–15 (factor = 3.20)				**15,568**
Total present worth, years 16–20 (factor = 2.69)				**13,087**
Total present worth, years 21–25 (factor = 2.27)				**11,044**
Total present worth, years 26–30 (factor = 1.91)				**9,292**

Ground water monitoring

Annual costs, years 1–5				
Quarterly water-level measurements	52	well	55	2,860
Quarterly ground water monitoring and analyses	40	well	640	25,600

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Annual ground water monitoring and analyses	12	well	160	1,920
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 1–5				**172,840**
Total present worth, years 1–5 (factor = 4.52)				**781,237**
Annual costs, years 6–30				
Quarterly water-level measurements	52	well	55	2,860
Biannual ground water monitoring and analyses	38	well	320	12,160
Annual ground water monitoring and analyses	14	well	160	2,240
Maintenance of ground water sampling system	52	well	430	22,360
Quarterly monitoring reports	4	report	15,000	60,000
Project management	500	hour	75	37,500
Hydrogeologist	200	hour	68	13,600
Clerical	200	hour	45	9,000
Total annual costs, years 6–30				**159,720**
Total present worth, years 6–10 (factor = 3.80)				**606,936**
Total present worth, years 11–15 (factor = 3.20)				**511,104**
Total present worth, years 16–20 (factor = 2.69)				**429,647**
Total present worth, years 21–25 (factor = 2.27)				**362,564**
Total present worth, years 26–30 (factor = 1.91)				**305,065**
Total present worth for ground water monitoring for 30 years				**2,996,553**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Soil vapor monitoring				
Annual costs, year 1				
Quarterly soil vapor monitoring and analyses from extraction wells	19	well	400	7,600
Quarterly shallow soil vapor point monitoring and analyses	10	point	400	4,000
Total annual costs, year 1				**11,600**
Total present worth, year 1 (factor = 0.97)				**11,252**
Annual costs, years 2–5				
Biannual soil vapor monitoring and analyses from extraction wells	19	well	200	3,800
Biannual shallow soil vapor point monitoring and analyses	10	point	200	2,000
Total annual costs, years 2–5				**5,800**
Total present worth, years 2–5 (factor = 3.55)				**20,590**
Annual costs, years 6–10				
Annual soil vapor monitoring and analyses from extraction wells	19	well	100	1,900
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 6–10				**2,900**
Total present worth, years 6–10 (factor = 3.80)				**11,020**
Annual costs, years 11–30				
Annual shallow soil vapor point monitoring and analyses	10	point	100	1,000
Total annual costs, years 11–30				**1,000**

Table G-8. Alternative 5: Source mass removal at core of Building 834 Complex using soil vapor extraction enhanced by dewatering, and downgradient dewatering.

	Quantity	Unit type	Unit price (1994 $)	Total (1994 $)
Alternative 5d (5 years SVE, 30 years of dewatering, 30 years monitoring)				
TCC				3,662,693
Present worth for fixed operating costs				5,136,021
Present worth for variable operating costs				183,639
Ground water monitoring				2,996,553
Soil vapor monitoring				52,932
Subtotal				**12,031,838**
LLNL General & Administrative Tax (7.5%)				902,388
Subtotal				**12,934,226**
LLNL Lab-Directed Research & Development Tax (6.0%)				776,054
Subtotal				**13,710,280**
Contingency (20%)				2,742,056
Total present worth of Alternative 5d				**16,452,336**