CHEVRON CINCINNATI FACILITY

GROUNDWATER CORRECTIVE MEASURES STUDY (GWCMS)

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Abbreviations

AOC	Area of concern
API	American Petroleum Institute
AZ	Attenuation Zone
bgs	below ground level
CAMU	Corrective action management unit
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAO	corrective action objectives
CAP	Community Advisory Panel
CCFS	Chevron Cincinnati facility site
cfh	cubic feet per hour
cfs	cubic feet per second
Chevron	Chevron Products Company
CMI	Corrective Measures Implementation
CMS	Corrective measures study
Consent Order	Administrative Order on Consent
COPC	Contaminants of potential concern
CPT	Cone penetrometer technology
CTW	constructed treatment wetland
DBCA	downflow bubble contact aerator
DE&S	Duke Engineering and Services
DNAPL	Dense non-aqueous phase liquid
DO	Dissolved oxygen
DRO	Diesel-range organics
EI	Environmental Indicators
EPA	Environmental Protection Agency
EW	Extraction well
FBR	fluidized bed bioreactor
FML	flexible membrane liner
GAC	granular activated carbon
GCL	geosynthetic clay liner
GCW	Groundwater Circulating Wells
gpy	gallons per year
GRO	Gasoline range organics
GW CMS	Groundwater Corrective Measures Study
HI	hazard index
HSVE	horizontal soil vapor extraction [well]
IAS	In Situ Air Sparging
ISCO	In Situ Chemical Oxidation
IM	Interim measures
IW	Injection well
LPG	liquified petroleum gas
LNAPL	Light non-aqueous phase liquid
MCL	Maximum contaminant level

Mini-QAPP	Miniature Quality Assurance Plan
MNA	Monitored natural attenuation
MPPE	macroporous polymer extraction
MW	Monitoring well
OEPA	Ohio Environmental Protection Agency
NPDES	National Pollution Discharge Elimination System
P&T	Pump and treat
PAH	Polycyclic aromatic hydrocarbons
PID	Photoionization detector
PITT	Partitioning interwell tracer test
POC	Point of compliance
PRG	Preliminary remediation goals
PSA	pressure swing adsorption [system]
PVC	Polyvinyl chloride
PW	Production well
QAPP	Quality Assurance Plan
RCRA	Resource Conservation and Recovery Act
RFI	RCRA facility investigation
ROST	Rapid optical screening tool
SEAR	Surfactant-Enhanced Aquifer Remediation
SPH	Six-Phase Heating
SR	State Route
SVE	Soil vapor extraction
SVOC	Semivolatile organic compound
SW	Southwest
SWMU	Solid waste management unit
Tech Memo	*Corrective Action Objectives and Regulatory Strategy Tech Memo*
TPH	Total petroleum hydrocarbons
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compound
Work Plan	*Draft Groundwater Correctives Measures Study Work Plan*

Definition of Terms[1]

Aquifer: A water-bearing layer of rock or sediment capable of yielding significant quantities of water to wells and springs. The USGS points out that the term includes the unsaturated part of the permeable unit. The term 'aquifer material' refers to the particles of sediment comprising the aquifer.

Dissolved-phase contamination: Contamination of groundwater by substances dissolved from the LNAPL.

Groundwater: Water occurring in the zone of saturation of the aquifer or soil.

Heterogeneity: Synonymous with non-uniformity in the texture of the aquifer material. A material is heterogeneous if its hydrologic properties, in particular its hydraulic conductivity, vary throughout the aquifer.

LNAPL: Light non-aqueous phase liquid. In this document, LNAPL refers to the hydrocarbon released at the Chevron Cincinnati facility. The zone of the soil or aquifer containing LNAPL is known as the LNAPL zone. Therefore the 'smear zone' is synonymous with LNAPL zone. Free-phase LNAPL is LNAPL under positive pressure and is therefore mobile. Residual LNAPL is LNAPL under negative pressure that is trapped by capillary forces exerted by the aquifer material or soil.

Mobile LNAPL: Synonymous with free-phase LNAPL or recoverable LNAPL, i.e., LNAPL under positive pressure. Therefore, free-phase or mobile LNAPL will flow downgradient to a recovery well provided that the alluvium along the path of migration of the LNAPL to the well is at a local saturation close to or above the residual LNAPL saturation.

Plume: Refers to a zone of dissolved-phase or vapor phase contamination. The term 'hydrocarbon plume' is used in this document to describe the zone of dissolved-phase contamination generated by the LNAPL zone. The use of the phrase 'LNAPL plume' is discouraged because of the connotation that the LNAPL is mobile at any particular time.

Smear Zone: See under LNAPL

Source Materials: Defined as materials that include or contain hazardous substances, pollutants or contaminants that act as a reservoir (either stationary or mobile) for migration of contamination to groundwater, to surface water, to air, or act as a source for direct exposure. Groundwater contaminated with dissolved phase is not considered to be a source material although NAPLs (occurring as residual- or free-phase) may be viewed as source materials. EPA's definition of source materials indicates that the LNAPL may be either stationary or mobile.

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[1] These definitions are taken from EPA (1992 & 2000); Freeze and Cherry (1979); and Lohman, S.W. et al. (1972).

Specific Capacity: The pumping rate during a well test divided by the drawdown, typically expressed in gpm/ft. All head losses in the well piping (well losses) are included.

Specific Yield: The volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table.

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient.

Executive Summary

Background

Chevron Products Company (Chevron) owns a former refinery site near Hooven, Ohio, 20 miles west of Cincinnati. The facility operated from 1931 to mid-1986. After the refinery was closed, most of the above-ground structures were removed. While the refinery was in operation, a significant amount of refined petroleum product apparently was released through spills and leaks. The petroleum product moved downward through soil, leaving residual hydrocarbons in soil. Where enough product accumulated, a layer of light non-aqueous phase liquid (LNAPL) formed on the water table. Water table fluctuations over the years have raised and lowered the LNAPL layer, smearing the LNAPL in the soil zone near the water table.

Currently, there is a 200-acre smear zone and dissolved phase plume. In addition, varying thicknesses of LNAPL are found floating on the groundwater. The thickness of the free-phase layer is greatest when the water table is lowest. Hydraulic containment of the plumes is achieved by extracting groundwater continuously, thus creating an inward hydraulic gradient. Free-phase LNAPL is also recovered.

In 1993, Chevron entered into an Administrative Order on Consent (Consent Order) with the U.S. EPA to perform a RCRA Facility Investigation (RFI) and Corrective Measures Study (CMS). With EPA concurrence, the CMS was divided according to media with one CMS for soils/sludges and another for groundwater (the Groundwater Corrective Measures Study or GWCMS). The soils/sludges CMS was originally submitted in May 2000. It was resubmitted in September 2000. The EPA approved the Work Plan for the GWCMS with modifications in July 2001, and the final Work Plan was submitted in September 2001. This document is the draft GWCMS.

Current Conditions

The hydrogeology of the Great Miami River buried valley aquifer is characterized by high permeability, textural heterogeneity, and rapid water level changes driven by river stage. Discontinuous surficial floodplain deposits and fill cover most of the Chevron site and are up to 15 ft thick. Below these are highly permeable sands and gravels up to 100 ft thick, which form the productive part of the aquifer. High transmissivity and significant textural heterogeneity characterize the aquifer materials. The water table is affected mainly by the river stage, which is typically high during the spring and declines over the summer into the fall. However, the river stage can change abruptly in response to storms. Groundwater flow is from north to south, generally parallel to the river when pumping is not taking place; velocities are typically in the range of 2 to 4 ft/day.

Two types of LNAPL are encountered at the site. Low density and low viscosity LNAPL underlies most of the facility; a heavier and more viscous LNAPL is found in the east central part of the facility. Tracer tests identified an average LNAPL saturation of 4% in an area of the facility presumed to be representative. LNAPL redistribution by the fluctuating water table causes the thickness and extent of free-phase LNAPL to vary seasonally, with maximum thickness usually encountered in fall and early winter. Benzene is the most widespread contaminant of potential concern. It is distinguished at this site by the fact that it is present at concentrations three orders of magnitude greater than the regulatory level (in this case the maximum contaminant level [MCL]). Arsenic and isobutyl alcohol have also been identified in localized areas at the facility.

A conceptual future land use plan for the facility has been prepared with significant input from the Community Advisory Panel. In general, the local community is eager to see the site redeveloped. The area southwest of the site is currently being developed commercially.

Ongoing Operations

Several operations are taking place at the site. Chevron operates a system of groundwater extraction wells to alter the natural hydraulic gradient and groundwater flow patterns, thereby preventing discharge of LNAPL and dissolved phase hydrocarbons to the river. Extracted groundwater contains dissolved-phase hydrocarbons. The water is treated in a fluidized bed bioreactor, then polished in lagoons before being discharged to the river. The lagoons are being replaced by a system consisting of a pond and a constructed treatment wetland. Free-phase LNAPL is recovered during low water table periods when the free-phase layer is thickest. The recovery varies considerably from year to year depending on average groundwater level; the greatest recovery occurs when the water table is the lowest. A Corrective Action Management Unit (CAMU) is planned for disposal of the remaining hazardous wastes and contaminated soils. This CAMU will be located in the eastern part of the facility. Soil vapor extraction (SVE) is taking place via three horizontal wells beneath the community of Hooven.

Regulatory Approach

Several meetings were held with the EPA to decide on the most desirable regulatory approach for a groundwater CMS. Chevron proposes an overall site strategy using a tiered approach of identifying Corrective Action Objectives (CAOs) in the form of Short-Term Protectiveness Goals, Intermediate Performance Goals, and Final Cleanup Goals. The short-term goals are: a) preventing unacceptable human exposure to contamination, and b) preventing migration of contaminants. The Environmental Indicators report submitted in 2001 indicate that these goals have been met for the current conditions at the facility.

A series of intermediate performance goals for the next 10 to 15 years is proposed in this CMS. These goals are:

- Protecting human health and the environment;
- Recovering liquid hydrocarbon along SR128 and under Hooven;
- Maintaining plume control; and
- Returning the site to a productive asset for the surrounding community.

Final cleanup goals include:

- Protecting human health and the environment;
- Achieving cleanup objectives; and

- Controlling the sources of releases to reduce or eliminate further releases of hazardous constituents.

Chevron will achieve the first of these final cleanup goals by ensuring that the Environmental Indicators are continuously met. Note that, at present, the Environmental Indicators are met, based on the existing land use. In this CMS, it is assumed that drinking water standards will have to be met to achieve the second final cleanup goal. Chevron has been diligently and successfully working toward control of releases (third goal) for over a decade.

Chevron proposes to negotiate a new Corrective Measures Implementation (CMI) order that will have a defined period of 15 years and will be focused on the intermediate performance goals. Periodically during the life of this CMI order, and at its end, Chevron will report on actions undertaken and progress made toward compliance with the short-term CAOs identified for this CMI order. Chevron also proposes to use a Point Of Compliance (POC) approach for managing the groundwater contaminants.

Approaches to Remediation

Chevron has evaluated a series of technologies that may be applicable to preventing the migration of LNAPL, reducing the size of the existing plume, and ultimately restoring the groundwater to beneficial use. The following technologies were evaluated:

- Containment, including pump and treat (P&T) and barrier walls;
- Soil Vapor Extraction (SVE);
- In Situ Air Sparging (IAS);
- Thermal enhancements, including Six Phase Heating, which was tested at the site;
- Groundwater Circulating Wells (GCWs);
- Surfactant-Enhanced Aquifer Remediation (SEAR);
- In Situ Chemical Oxidation (ISCO);

- Monitored Natural Attenuation (MNA); and
- Institutional controls.

Containment, SVE, IAS, SEAR, MNA, and institutional controls were retained for further evaluation. The other technologies were not retained, as described in this CMS. Four remediation alternatives were identified:

1) Containment;
2) Containment supplemented with SVE;
3) Containment supplemented with SVE and IAS; and
4) Containment supplemented with SVE and SEAR.

These alternatives represent a range of options ranging from containment to very aggressive removal of LNAPL.

Comparison of Alternatives

A dissolution model was used to estimate how long it would take for dissolution to bring down the concentration of benzene to a target level. For modeling purposes, it was assumed that the target level would be the benzene MCL of 5 μg/L. The estimated durations for meeting the long-term objective range from 101 years for the most aggressive option (Alternative 4) to 458 years for the base-case containment alternative.

The present worth of all costs associated with each alternative were also estimated. These costs range from $50 million for the containment alternative to $150 million for Alternative 4. The alternatives were further evaluated according to the nine criteria specified in the Consent Order. Each alternative was assigned a score for each criterion and then the scores were tallied.

Alternative 1 (Containment) had the highest total score and the lowest present worth cost and is, therefore, the alternative proposed by Chevron in this GWCMS. The high score is due in large part to the fact that containment is proven and effective at this site, based on ongoing full scale operation. The low present worth cost is largely due to low initial capital expenditures. Chevron proposes to implement this alternative and focus on the short-term protectiveness goals and intermediate performance goals in the upcoming CMI order.

1.0 Introduction

1.1 Overview

On May 13, 1993, Chevron Products Company (Chevron), formerly Chevron U.S.A. Products Company, entered into an Administrative Order on Consent (Consent Order) with U.S. Environmental Protection Agency Region V (EPA) to perform a Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) and Corrective Measures Study (CMS) under Section 3008(h) of RCRA at its Cincinnati, Ohio, facility. Phases I and II of the RFI (Environmental Science and Engineering, 2000), and a facility-wide risk assessment report (Ecology and the Environment, April 2000) have been completed and approved by the EPA.

The Consent Order requires Chevron to prepare and submit a CMS Work Plan to the EPA. Chevron, with EPA approval, decided to separate the soils/sludges issues from the groundwater issues, and to submit two separate CMS reports. In May 2000, Chevron submitted a CMS report addressing contaminated soils and solid wastes at the Chevron Cincinnati facility *(Corrective Measures Study for Sludges and Contaminated Soils at the Chevron Cincinnati Facility, May 2000)*. A modified soils CMS was submitted to USEPA in September 2001 (URS, September 2001).

This document is the groundwater CMS (GWCMS), which was prepared to address the contaminated groundwater at the Chevron Cincinnati Facility.

1.2 Work Plan Development

Chevron began discussions concerning the GWCMS with both the U.S. EPA Region V and the Ohio EPA (OEPA) in 1999. A joint meeting with both agencies was held on May 25, 1999, to determine the relationship that the two agencies would have concerning groundwater issues at the Chevron Cincinnati Facility Site (CCFS). During this meeting and in follow-up conversations, it was confirmed that Ohio would not be adopting a Comprehensive State Groundwater Protection Program. Therefore, the U.S. EPA would have primacy in establishing groundwater remediation objectives, and in reviewing and approving the GWCMS.

A GWCMS Work Plan was developed, based in part on information in the *Handbook of Groundwater Policies for RCRA Corrective Action (updated 4/20/2000), EPA530-D-00-001* and on input received in two different meetings with the EPA (USEPA, 2000). The first meeting was held with Mr. Chris Black of the EPA at the CCFS on June 7, 2000. The second meeting was held with Mr. Chris Black and Mr. Gerry Philips at EPA's Chicago office on July 11, 2000. During these two meetings, the parties discussed regulatory strategy and how that strategy may affect the GWCMS. On November 15, 2000, Chevron submitted the *Draft Groundwater Correctives Measures Study Work Plan* (Work Plan) to EPA as required in the Consent Order (URS, 2000b). The Work Plan described the general approach that Chevron proposed to take in developing the GWCMS.

Following submittal of the Work Plan, a meeting was held in Cincinnati on April 19, 2001, to further discuss Corrective Action Objectives and regulatory strategy. This meeting included Mr. Chris Black and Mr. George Hamper from the EPA and representatives from Chevron. A technical memo was submitted in June 2001 (URS, May 2001). The regulatory strategy proposed in Section 5 of this GWCMS is based in part on the input received at these meetings.

On July 27, 2001, the EPA approved, with modifications, the Draft Work Plan. The Final GWCMS Work Plan was submitted to the EPA in September 2001.

1.3 GWCMS Organization

Section 1 of the GWCMS contains an overview of this CMS, a discussion of the purpose of this document, and its organization.

Section 2 contains a description of current site conditions. This description of current site conditions is intended to be the basis for the development and evaluation of the alternatives in the GWCMS.

Section 3 presents the conceptual redevelopment plan for the facility.

Section 4 describes the ongoing operations at the site and in its immediate vicinity.

Section 5 outlines Chevron’s proposed regulatory approach to the GWCMS and identifies the proposed remediation objectives.

Section 6 identifies the applicable technologies. The intent of this section is to identify the technologies that could potentially be applied at this site.

Section 7 identifies four potential remediation alternatives for the site, analyzes them for efficacy and cost effectiveness, and makes a recommendation.

Section 8 identifies design tasks planned for the site.

Section 9 describes the proposed monitoring program.

Section 10 identifies the proposed schedule for implementation of the recommended alternative.

Section 11 lists the literature references used in the CMS.

2.0 Description of Current Conditions

2.1 Introduction

In this section, the general geographical and historical background information is provided about the site. Then an overview is provided of major studies conducted so far that are relevant to the GWCMS.

2.1.1 Location

Chevron owns a former fuels and asphalt petroleum refinery near Hooven in Whitewater Township, Ohio, north of the intersection of State Route (SR) 128 and By-pass U.S. Route 50, approximately 20 miles west of Cincinnati, Ohio. The site occupies approximately 600 acres. It includes Islands No. 1 and No. 2 in the Great Miami River. The former refinery is bordered by the Great Miami River to the east, northeast, and southeast, and by the community of Hooven and State Route 128 to the west (Figure 2-1). U.S. Highway 50 runs just south of the site. Refinery operations occurred on approximately 250 acres consisting of buildings, storage tanks, and roads as shown on Figure 2-2, a 1975 aerial photo. The remainder of the site consists of tracts of upland and bottomland forest, open brushy areas, and isolated wetlands, which served as a buffer zone along the river.

2.1.2 Site History

Gulf Oil Corporation constructed and operated the refinery from 1931 to 1985. In 1985, Chevron acquired and assumed operation of the refinery. Chevron ceased refining operations in May 1986. The major products produced at the refinery were gasolines, jet fuels, diesel, home-heating fuels, liquified petroleum gas, asphalt, and sulfur.

Decommissioning, dismantling, and environmental remediation have been underway since May 1986. Nearly all of the above-ground buildings and structures have been demolished and removed from the facility. Only a few structures currently remain on the site. Voluntary removal actions have been conducted at several high priority Solid Waste Management Units (SWMUs) and Areas of Concern (AOCs). The former operating

Figure 2-1 Site Location Map

Figure 2-2 Aerial Photograph of the Chevron Cincinnati Facility in March 1975

portion of the facility now consists of a variety of lagoons, foundations, land disposal areas, ditches, disturbed open space, and groundwater remediation facilities, largely surrounded by a flood protection berm.

Interim Measures (IM) remediation performed at the facility since early 1985 include hydraulic control of the dissolved hydrocarbons in the groundwater and LNAPL recovery. Soil vapor extraction at Islands No. 1 and No. 2 and Hooven has been added in recent years. While these measures have successfully controlled contaminant movement and have accomplished substantial source removal, they also demonstrate the potential magnitude and complexity of site-wide corrective measures implementation.

Ongoing groundwater monitoring is performed under the terms of the Consent Order to verify hydraulic containment and assess changes in LNAPL thickness and dissolved contaminant concentrations over time. Figure 2-3 shows the network of wells currently used for compliance monitoring, as well as recovery wells, former water supply wells for the Village of Cleves, and other site features.

2.1.3 Study Summaries

The RFI was performed using a phased, facility-wide approach. The major objectives of Phase I of the RFI were to investigate conditions at the perimeter of the facility, and to evaluate the extent of possible off-site contamination where the perimeter investigation indicated that contamination originating at the facility might extend off site. The results of the Phase I investigations were presented in *Technical Memorandum for the Phase I RCRA Facility Investigation at the Chevron Facility, Hooven, Ohio, Revision 2,* (QST, et al., May 1998). The major objective of Phase II of the RFI was to investigate surficial areas and groundwater conditions around selected SWMUs and to perform a facility-wide human health and ecological risk assessment. The results of Phase II of the RFI are presented in *RCRA Facility Investigation Report for the Chevron Cincinnati Facility, Revision 0,* (ESE, April 2000), and *Chevron Cincinnati Facility Phase II Facility-Wide Human Health and Ecological Risk Assessment, Revision 0*, (E&E, April 2000).

Figure 2-3 Facility Diagram

During the *Chevron Cincinnati Facility Risk-Based Prioritization*, (E&E, February 1999), Ecology and Environment, Inc., (E&E) identified several high priority SWMUs and AOCs for additional consideration. The prioritization was based on a review of existing data and initial categorization; sampling of SWMUs and AOCs in the two highest priority category groups; risk-based screening in consideration of the potential future land reuse; and ranking of the SWMUs and AOCs into four groups on the basis of set criteria. The risk-based prioritization did not indicate the need for additional interim measures; however, some of the larger SWMUs and AOCs were aesthetically incompatible with potential future land reuse scenarios. Chevron therefore proceeded voluntarily with removal of several SWMUs and AOCs prior to or concurrent with the Phase II RFI.

A conceptual land-use plan, as presented in the *Market Analysis and Land Use Plan for the Chevron Cincinnati Facility, Hooven, Ohio,* (E&E, July 1997), hereafter referred to as the *Market Analysis and Land Use Plan*, was prepared with significant community input. This plan provided a sound basis for the Phase II Risk Assessment and presents options for the reuse of the site. The preferred land use identified in this plan is a mixed-use scenario, including potential industrial/commercial, open space, and recreational uses. Three major types of reuse areas were identified: industrial, passive recreational, and active recreational. The area designated for potential industrial reuse includes areas inside the flood protection berm. The area designated for active recreational reuse includes the approximate area of the north tank farm. The area outside the industrial and active recreational reuse areas, bordering the Great Miami River, was designated for passive recreational reuse. Due to seasonal flooding and a relatively undisturbed natural setting, the passive recreational area is unsuitable for industrial or commercial development.

For the purpose of the facility-wide risk assessment, the active recreational reuse area was classified as an industrial/commercial reuse area. Even though this area is located outside the flood protection berm, industrial/commercial reuse could be an alternative scenario for this area, and the industrial/commercial exposure scenario is more conservative than that of active or passive recreational use.

According to the *Chevron Cincinnati Facility Phase II Facility-Wide Human Health and Ecological Risk Assessment* (E&E, April 2000), the analytical results of environmental sampling of surface and subsurface soils indicate the presence of carcinogenic and non-carcinogenic polycyclic aromatic hydrocarbons (PAHs) at concentrations above risk-based screening criteria at some locations (i.e., in SWMUs). Arsenic, chromium, and lead were also found to be above appropriate risk-based screening criteria. These exceedances led to the detailed *Human Health Risk Assessment*, which evaluated short- and long-term exposures through direct contact and ingestion of soil, and through inhalation of vapors and particulates from surface and subsurface sources. For receptors in open air spaces or buildings at the ground surface, no unacceptable facility-wide human health risks were identified. Excess cancer risks were less than 1E-5, and hazard index (HI) values were less than 1. Basement indoor exposure for future industrial workers resulted in unacceptable risk from benzene exposure. Therefore, construction of basements is not currently recommended at the facility.

The *Chevron Cincinnati Facility Phase II Facility-Wide Human Health and Ecological Risk Assessment*, (E&E, April 2000) found that no endangered species are present at the site. Exposure pathways for soil contamination were evaluated for terrestrial plants and invertebrates, and for common species of birds and mammals likely to be found on site. For wildlife, ingestion of contaminants from food was considered, as well as ingestion of drinking water and incidental ingestion of soil. Inhalation exposure was considered for burrowing mammals. Ecological risks are largely based on elevated concentrations of lead, chromium, and/or PAHs in surface soil and sludges within SWMUs 7, 8, and 10, and on volatile organic chemicals in the subsurface outside the SWMUs. These are some of the SWMUs addressed by the Corrective Action Management Unit (CAMU).

The *Environmental Indicators Documentation Report Migration of Contaminated Groundwater Under Control RCRIS Code 750* (CEC, 2001) was submitted in May 2001 to the EPA Region 5 and is hereafter referred to as the EI report. This document demonstrated that groundwater contamination above levels of concern are not moving beyond the furthest three-dimensional extent to which the contaminants in the groundwater have migrated. It also presented the comprehensive groundwater monitoring program currently in place that will confirm that the plume of impacted groundwater remains stable (CEC, 2001).

2.2 Hydrogeological Conditions

The hydrogeology of the Great Miami River buried valley aquifer is characterized by high permeability, textural heterogeneity, and rapid water level changes in the aquifer, driven by the river stage. All of these characteristics complicate remedial action at the site. The aquifer is composed of sand and gravel derived from glacial outwash, giving it a high permeability. Rapidly varying depositional conditions also resulted in heterogeneous conditions in the outwash, especially in the upper part of the aquifer. The aquifer is hydraulically connected to the river along three sides of the Chevron facility, so that changes in river stage are communicated relatively rapidly to the aquifer beneath the former refinery. These conditions cause the facility's pump and treat (P&T) system to manage large volumes of water, but also help retain LNAPL in the upper part of the aquifer.

2.2.1 Regional Setting

According to studies conducted by the US Geological Survey (Spieker and Durrell, 1961; Spieker, 1968; Watkins and Spieker, 1971), the Chevron site lies in a valley cut into the shale bedrock by the ancestral Great Miami River during inter-glacial periods, and then partially filled with glacial outwash and alluvium. The Ordovician shale bedrock has a low permeability, but contains fine cracks, joints, and thin layers of interbedded limestone. Regionally, the steep-walled valley is approximately 0.5 miles (0.8 km) wide and 100 ft (30 m) deep. Silt and sand derived from more recent floods cover the glacial outwash.

Several groundwater modeling studies have been undertaken in the Great Miami River aquifer since the earlier work of the US Geological Survey. Ward et al. (1987) presented an early example of grid-block mesh refinement in their aquifer model of the Chem-Dyne hazardous waste site in Hamilton, Ohio, located approximately 20 miles upstream of Hooven. They described the Chem-Dyne site as being predominantly sand and gravel without interstratified clay layers. They reported that an aquifer test at the Chem-Dyne site yielded transmissivities in the range of 13,000 to 40,000 ft^2/day (1200 to 3700 m^2/day). Aquifer sediments at Chem-Dyne fine upwards over a thickness of 150-200 ft. Ward et al. used a horizontal hydraulic conductivity (K_H) of 350 ft/day (1×10^{-3} m/s) and a vertical hydraulic conductivity (K_V) of 1.75 ft/day (6×10^{-6} m/s) beneath the site. However, they identified a poorly-sorted zone along the river channel that was set at K_H=100 ft/day (3×10^{-4} m/s) and K_V=0.5 ft/day (2×10^{-6} m/s).

Hydrogeologists at Wright State University in Dayton, Ohio, used geostatistics to conduct an extensive hydrostratigraphic analysis of the Great Miami River aquifer. Their areas of interest were the Montgomery County wellfield just south of Dayton (Ritzi et al., 1994) and the area around the US Department of Energy's facility near Fernald (Ritzi et al., 1995). Both studies adopted a three-layer aquifer model of upper aquifer, aquitard, and lower aquifer. The aquitard at DOE Fernald was identified by Ritzi et al. (1995) as a proglacial lake deposit at 430-440 ft above mean sea level. This three-layer model of the aquifer at Fernald, which is only 10 miles upstream of the Chevron facility, is also shown by Sidle and Lee (1996, Figure 1) of the US EPA in their study of uranium contamination of the aquifer.

Annual precipitation of 35 to 45 in. (900-1150 mm) was measured from 1931 to 1990, and annual recharge to the aquifer was estimated by Ward et al. (1987) to be approximately 6 in./year (150 mm/yr). Streamflow in the Great Miami River is gauged up river of the facility at a site below Hamilton and will likely be higher at the Chevron facility assuming that tributary inflows exceed industrial and municipal withdrawals. Typical daily flows below Hamilton are of the order of 3,300 cubic feet per second (cfs) (Spieker and Durrell, 1961). The annual peak flows below Hamilton for the period from

1985 to 1998 have averaged 42,300 cfs with a standard deviation of 13,800 cfs. Stormwater modeling was conducted as part of the design for the constructed treatment wetland (CTW) found in the *Conceptual Design Report for Groundwater Polishing and Treatment of Storm Water at the Chevron Cincinnati Facility, Hooven, Ohio* (E&E, Dec 2000).

2.2.2 Site Hydrogeology

Hydrostratigraphy

The unconsolidated sediments overlying the shale bedrock have been divided into two zones (Radian International and Duke Engineering & Services, 1999; Environmental Science & Engineering, Inc., 2000):

1. Surficial floodplain deposits and fill. This zone is discontinuous over the site, and is up to 15 ft thick, especially in the southern part of the site. It consists of low-permeability overbank silts. The lower portion of the surficial zone is water-saturated for brief periods, especially during spring floods.
2. Glacial outwash sand and gravel. The lower zone is up to 100 ft thick at the site and forms the productive part of the aquifer. The glacial outwash, deposited as a series of gradational systems of sands and gravels, has a high permeability. The upper portion of the outwash contains interbedded sand, silt, and gravel, and generally has a lower hydraulic conductivity than the deeper portion of the aquifer, which is composed of cleaner sand and gravel.

The cross section D-D’ in Figure 2-3 and in detail in Figure 2-4 shows the relationships between these zones along a line running west to east through the eastern portion of Hooven and the southern portion of the Chevron facility. The aquifer sediments tend to get finer upwards over the entire sedimentary thickness at the facility, a trend that can be associated with the northward retreat of the Pleistocene glaciers.

Figure 2-4 Cross-Section D-D' through Hooven and Plant Site

Radian International and Duke Engineering & Services (1999) undertook detailed hydrostratigraphic mapping of the first 35 feet of aquifer sediment beneath a site in the middle of the former refinery known as the Tracer Test Site (see Figure 2-3), and made comparisons with site-wide information. The Tracer Test Site was divided into three stratigraphic units. The upper zone from 0-12 ft below ground surface (bgs) is principally composed of fine-grained materials such as silts, clays, and some fine sand.

A transition zone occurred between 12 to 22 ft bgs, comprised of gravelly silts, fine sands, silty gravels, and small cobbles intermixed in a silt or sandy silt matrix. This zone is distinguished from the overlying silts and clays by the presence of 1-in. diameter or larger pebbles and cobbles embedded in the sediment matrix or present as distinct cobble zones. The lower zone (22 to >34 ft bgs) is a complex sequence of sands and sandy gravels that tend to fine upward.

The texture of the sediments from the Tracer Test Site was compared with sediments collected from 13 to 38 ft bgs during the installation of 16 monitoring wells distributed across the site (ES&E, 2000). Grain-size curves presented by Radian International and Duke Engineering & Services (1999) show the first 30 ft beneath the Tracer Test Site to be relatively fine-grained. For the site-wide samples, the percentage of gravel (>2mm) is greater, approximately 80%, whereas only 40-60% of the sediment from the Tracer Test Site exceeded 2 mm. At the other end of the textural scale, fine-grained materials, i.e., <0.25 mm in diameter, which include fine sand, silts, and clays, comprised about 5% of the site-wide materials and 10-15% of the materials beneath the Tracer Test Site. An additional 50 soil samples analyzed by PTS (1996) yielded permeability values that, when converted to hydraulic conductivities (10^{-2} to 10^{-4} cm/s), also indicated the presence of finer-grained materials in the first 30-40 ft of the subsurface. It is possible that the process of sampling cohesionless sand with split spoon and Shelby tubes favored the collection of finer-grained or more cohesive materials, which explains why the hydraulic conductivities obtained by pumping tests are so much higher than those determined from laboratory cores by PTS. In conclusion, it appears that the site is underlain by sediments that coarsen downwards across the site and that the Tracer Test Site is not unique in this aspect.

Hydraulic Properties of the Aquifer Materials

High overall transmissivity and significant textural heterogeneity characterize the aquifer materials found beneath the surficial floodplain deposits. Several methods ranging from laboratory permeameter studies to large-scale well tests with monitoring at several monitoring wells were used to measure the hydraulic properties of the aquifer.

Permeameter measurements of the 50 core samples by PTS taken from approximately 7 to 37 ft below grade (collected from five boreholes distributed across the site), range in permeability over two orders of magnitude from 130 millidarcies to approximately 12 darcies (PTS Laboratories, 1996). This is equivalent to a hydraulic conductivity range from 0.36 to 33 ft/day (0.00013 to 0.012 cm/sec). The locations of these boreholes (CH02, 3, 6, 8, 16) are shown on Figure 2-3, and plots of permeability versus depth in each borehole are shown in Figure 2-5. These laboratory data indicate the small-scale heterogeneity of the upper portion of the aquifer beneath the Chevron facility that contains the LNAPL or ‘smear’ zone.

Well tests have provided larger-scale measurements of the hydraulic properties of the aquifer, such as its specific capacity and transmissivity. Lyverse (1991) undertook the first of such tests at Production Well No. 14 (PW-14), which is adjacent to Recovery Well No. 14 (RW-14), near the main entrance gate to the facility (see Figure 2-3 for location). The test involved 24 hours of pumping at 1200 gallons per minutes (gpm) from the fully-penetrating well and the observation of drawdown at 10 partially penetrating monitoring wells with a screened interval of 15-55 ft at a depth of 40-75 ft bgs. The distance-drawdown analysis of the pumping test yielded a transmissivity of 532,000 gallons per day per foot (gpd/ft) and a specific yield of 0.15. Lyverse stated that the sedimentary deposits at PW-14/RW-14 are approximately 70 ft thick with a saturated thickness of 40 ft. Therefore the average hydraulic conductivity for this part of the aquifer is approximately 1780 ft/day (0.6 cm/s).

Figure 2-5 Permeability Versus Depth from Borings CH2-CH16

Handex (1996) undertook a study to determine the efficacy of partially penetrating pumping wells for improving free-phase LNAPL recovery. They installed a 10-inch diameter well screened from 19 to 48 ft bgs. Production Well No. 16, or PW-16 (named RW-1 in the Handex report) was installed 300 ft southeast of the wastewater treatment plant and is a similar distance from the river (see Figure 2-3 for location). The pumping rate was 394 gpm for 1400 minutes. The distance-drawdown analysis of the test yielded a transmissivity of 139,000 gpd/ft and a specific yield of 0.22. The specific capacity of this well was reported as 68 gpm/ft. Assuming the well pumped from the 29 ft screened interval of saturated aquifer materials, the hydraulic conductivity is approximately 640 ft/day (2 x 10^{-1} cm/s).

Aquifer testing in 1998 at the Tracer Test Site indicated transmissivities of 40,000 to 160,000 gpd/ft at depths between 23-33 ft bgs (Radian International and Duke Engineering & Services, 1999). These values are equivalent to hydraulic conductivities in the range of 260 to 540 ft/day (0.09 to 0.19 cm/s). Discharge during the test was maintained at 21 gpm and the drawdowns analyzed using the Cooper-Jacob method. Specific capacities of these four shallow wells were in the range of 3.7 to 4.6 gpm/ft, much smaller than the values obtained in the deeper aquifer materials pumped at PW-14. A summary of hydraulic conductivity data is presented in Table 2-1.

Table 2-1

Summary of Measured Hydraulic Conductivities (K)

Location in Plant and Well No.	Depth[1] (ft bgs)	K (ft/day)	K (cm/s)
Permeameter data from 50 cores collected from 5 boreholes	7 - 37	0.36 - 33	10^{-2} – 10^{-4}
Pumping test, PW-14	43-73	1780	6 x 10^{-1}
Pumping test, PW-16	19 - 48	640	2 x 10^{-1}
Pumping test, Tracer Test Site	23 - 33	260 – 540	2 x 10^{-1} – 9 x 10^{-2}

[1] Indicates depth of cores or the depth interval of the well screens of the pumping wells.

The most recent series of pumping tests took place at three new wells that were installed and initially tested in 1998 (PW-19) and 2000 (PW-20, -21). These wells are shown on Figure 2-3. The specific capacity of PW-19 was measured at 350 gpm/ft. It is very clear these wells are completed in a high-permeability zone or 'paleochannel' of the aquifer. This is apparent in the stratigraphic log of MW-20D shown in Figure 2-6, which is 70 ft

Figure 2-6
Lithology Log of MW-20D

from PW-19. The screened interval of PW-19 (i.e., 25 to 75 ft bgs) is comprised of cobbles, gravel, and sands with an LNAPL smear zone present from 20 to 43 ft bgs. At approximately 65 ft bgs, the sand and gravel give way to fine sand and then, at 70 ft bgs, to silty coarse sand and gravel. Weathered shale that is described as “soft, clayey” is encountered at 75 ft. Therefore, with the exception of 4 ft of fill at the ground surface and some fine sand at 35 to 38 ft bgs, the paleochannel of cobbles, gravel and medium-to-coarse sands extends from beneath the fill to 65 ft bgs, a total thickness of approximately 60 ft.

Original specific capacity data for various wells at the Chevron facility is provided in Table 2-2. Following Lohman et al. (1972), the duration of discharge is noted where known. The well locations are shown on Figure 2-3, with the exception of ML-2, which is located in the Tracer Test Site. The specific capacity values shown in Table 2-2 should be considered as very approximate indicators of permeability and can vary with duration of pumping, relative permeability effects due to LNAPL, well losses, etc.

Table 2-2
Specific Capacity Data for Pumping Wells

Pumping Well	Specific Capacity (gpm/ft)	Year of SC Test	Duration of Test (mins)	Screened Interval (ft)	Depth of Pump Set (ft)
PW-4	1580 gpm/9.5 ft = 158	1937	Unknown	50-73	B*
PW-5	1600 gpm/18 ft = 200	1945	Unknown	70-93	B*
PW-7	1500 gpm/15 ft = 100	1953	Unknown	Unknown	B*
PW-8	1500 gpm/14.5 ft = 103	1953	Unknown	68-93	B*
PW-9	1500 gpm/10.58 ft = 142	1957	Unknown	68-93	B*
PW-12	1324 gpm/5/33 ft = 248	1991	240	25-61	60
PW-14	1000 gpm/29.67 ft = 316	1985	480	43.5-73	B*
PW-15	1385 gpm/3.83 ft = 362	1991	480	42.6-81.5	B*
PW-16 (RW-1)	400 gpm/5.88 ft = 68	1995	70	29-53.5	B*
PW-18	285 gpm/3 ft = 95	1999	Unknown	12-39	B*
PW-19	1500 gpm/4.0 ft = 370	1998	390	25-75	50
PW-20	385 gpm/0.9 ft = 425	Aug 2001*	~ 60	25-70	50
PW-21	746 gpm/1.35 ft = 553	Sept 2001*	~ 60	25-70	50
Tracer Test Site (ML-2)	21.8 gpm/5.83 ft = 3.7	1998	131	14-34	33

B* = Estimated to be near base of screened interval.
* = The information for PW-20 and -21 is from the most recent specific capacity test, not the original specific capacity data collected.

Notwithstanding this caveat, the highest permeabilities measured at the site appear to be at the southern end of the former refinery and are indicated by PW-14, PW-15, and PW-19. These wells all have specific capacities greater than 300 gpm/ft and indicate that the paleochannel likely connects these wells.

2.2.3 Groundwater Flow System

Under natural conditions, groundwater flow at the site is from north to south with discharge to the Great Miami River near U.S. Highway 50. Currently, the groundwater flow system is controlled by groundwater extraction. Groundwater is pumped consistently all year from a series of high-capacity wells situated in the southern end of the facility. Flow is typically from the facility boundary and the river toward the extraction areas in the interior of the facility.

Streamflow-Aquifer Interactions

Flow conditions driven by seasonal difference in groundwater recharge and by changes in the river's water level change seasonally. The stage (hydraulic head) of the Great Miami River and the heads within the aquifer are closely correlated. The river stage typically varies 10 to 15 ft (3 to 5 m) over the course of a year, while heads in the aquifer typically fluctuate between 2 to 5 ft (0.6 to 1.5 m). Historical records have shown aquifer fluctuations up to 14 ft since the mid-1980s and up to 18 ft since the spills occurred some time after the 1930s. Flood waves in the river generally are of short duration – lasting as little as a week or as much as a month – during which time positive head differences of 2 to 9 ft (0.6-3 m) may exist from the river to the aquifer. These flood events may occur at any time of year, but typically occur with precipitation in the spring. Figure 2-7 shows water table contours for March 1999 that represent typical high-water conditions. The groundwater flow pattern then resembles natural conditions, except that groundwater discharge to the river is prevented as a result of the hydraulic control exerted by two or more wells at the south end of the facility.

The river stage typically falls through the summer and may remain low throughout the fall, although this trend typically is disrupted by runoff from storms within the Great

Figure 2-7 Water Table Contour Map, March 31, 1999

Figure 2-8 Water Table Contour Map, September 24, 1999

Miami River watershed. During the fall and other periods of low river stage, groundwater pumping from the production wells is increased, and induces a depression in the water table around the pumping wells. This causes groundwater flow to converge on these areas and LNAPL recovery is increased. Figure 2-8 shows water table elevations for typical low water conditions in September 1999. During periods of extreme drought, water levels in the river and aquifer drop even lower, expanding the area of influence of the production wells at the southern end of the facility. Figure 2-9 shows water table contours for November 1999. These contours appear to represent the lowest water levels observed in recent years.

Vertical Groundwater Flow

Vertical groundwater movement does not appear to play a significant role under current conditions but vertical flows could be important in evaluating corrective actions such as partially penetrating barriers that may induce gradients within the aquifer.

Groundwater Velocity

Despite the high hydraulic conductivity of the aquifer, average groundwater velocities at the site are moderate as a result of the generally low gradient. Groundwater velocities were calculated for both the northern and southern areas of the site during periods of both high and low water-table conditions (i.e., fall and spring 1999). Three calculations were made for each area during both periods using low, high, and mean values for porosity (0.22, 0.42, and 0.33 respectively) and hydraulic conductivity (260, 1100, and 550 ft/day respectively). These calculations indicate that groundwater velocities do not vary greatly from the north to the south, or from season to season, and are typically in the range of 2 to 4 ft/day in the glacial outwash sand and gravel (URS and Duke, 2001).

2.3 Groundwater Contamination

Both LNAPL and dissolved-phase contamination occur at the Chevron facility. The two types of contamination are closely related, but behave differently as a result of their differing physical and chemical properties, and are discussed separately.

Figure 2-9 Water Table Contour Map, November 22, 1999

2.3.1 LNAPL

Accidental spills, pipeline failures, and tank leaks during historical operations at the facility released several million gallons of LNAPL to the aquifer. Approximately 3.5 million gallons of LNAPL have been recovered from 1985 through 2000. The exact amount of hydrocarbon remaining in the aquifer has not been determined. However, based on the historical recovery curves, more than half of the hydrocarbon has already been removed. The LNAPL smear zone was observed to be from 12 to 30 ft bgs at the Tracer Test Site. This indicates the zone of fluctuation of the water table since the first spills occurred at the site.

LNAPL Properties

LNAPL properties largely determine its mobility and recoverability. These properties have been determined by 12 site-wide LNAPL samples analyzed by Arthur D. Little (1999) and 17 LNAPL samples taken from the Tracer Test Site by Radian International and Duke Engineering & Services (1999, p. 75). Figure 2-10 shows the benzene concentrations in the site-wide LNAPL samples analyzed by A.D. Little (1999) and Radian International and Duke Engineering & Services (2000b). The locations for these LNAPL samples are identified on Figure 2-3.

The LNAPL at the facility has been described as a mixture of approximately 80% leaded gasoline and 20% diesel fuel. Recent data from LNAPL samples analyzed by Arthur D. Little were interpreted to indicate “gasoline in the southwest corner, diesel along the western perimeter, and crude or diesel on the east side of the property” (M. Moir, CRTC memo dated 3/16/2000).

On the basis of physical-chemical properties, two types of LNAPL are identifiable:

- Type 1 LNAPL—a low viscosity and low density LNAPL that underlies most of the facility and has migrated beneath Hooven. The greatest amounts of Type 1 LNAPL are found at the southern end of the facility and beneath Hooven.

Figure 2-10 Summary of Benzene Analyses of LNAPL samples

- Type 2 LNAPL—a higher viscosity and higher density LNAPL. This LNAPL contains heavier hydrocarbons, and approximately half of the Type 2 LNAPL is heavier than C_{14}. Type 2 LNAPL occurs in the vicinity of SWMUs 2, 3, 7, 8, and 10 at the eastern edge of the facility.

Physical-chemical data for these two LNAPL types are shown in Table 2-3, based on the analyses of the 12 LNAPL samples collected at various monitoring and production wells and the 17 samples taken at the Tracer Test Site.

Table 2-3

Physical/Chemical Properties of Chevron LNAPL

Property	Units	Type 1	Type 2
Density	g/cm^3	<0.85	>0.85
Viscosity	Cp	<2	>5
Interfacial Tension	dynes/cm	~24	~12
Benzene	wt %	0.1 – 0.45[1]	0 – 0.03
Xylenes	wt %	~5	<0.8
Compounds > C_{14}	wt %	~7	~53

Site-wide data from Radian International and Duke Engineering & Services (2000b) and Arthur D. Little (1999).

[1] Mean value taken from 17 values measured at the Tracer Test Site by Radian International and Duke Engineering & Services (1999, p. 75).

Figure 2-11 shows the distribution of hydrocarbons heavier than C_{14} in the LNAPL, roughly defining the areas of Type 1 and Type 2 LNAPL. These two types of LNAPL comprise the composition of all LNAPL at the site. Mixing of the two types of LNAPL is evident adjacent to the SWMUs where intermediate amounts of heavier hydrocarbons are found. Tetraalkyl lead, benzene, and other monoaromatics are contained largely in the Type 1 LNAPL. The Type 2 LNAPL contains more polyaromatics and heavier hydrocarbons, up to and exceeding C_{40}.

LNAPL Distribution and Mobility

A LNAPL smear zone extends from a depth of 10 ft to a maximum depth of approximately 30 ft bgs over the area described in Figure 2-16. This zone coincides with the historical range of periodic fluctuations in groundwater levels since LNAPL has been

Figure 2-11 Distribution of Hydrocarbon Fractions Heavier Than C_{14}

present. Results from a partitioning interwell tracer test (PITT) at the Tracer Test Site showed an average LNAPL saturation of approximately 4.3% from 22 to 32 ft bgs.

ROST^{TM} measurements and soil cores from the same site showed significant centimeter-scale vertical variability in the LNAPL saturation, with localized LNAPL saturations ranging as high as 13% (Radian International and DE&S, 1999). Assuming 4% average LNAPL saturation, 0.1 to 0.45 weight percent benzene in the LNAPL (see Table 2-3), and mg/L levels of benzene in the groundwater (see Table 2-4), estimates indicate that there is easily one order of magnitude more benzene mass in the LNAPL than in the groundwater. Since the retention time of the groundwater in the LNAPL zone may be several years, it suggests the LNAPL will remain a source of dissolved benzene above the maximum contaminant level (MCL) for decades or centuries. (See also dissolution modeling in Section 7.4.1).

Seasonal fluctuations in the water table cause the LNAPL to be redistributed vertically within the LNAPL smear zone. This results in the difference between the residual or immobile LNAPL saturations in two-phase (oil/water - saturated zone) and three-phase (oil/water/air - vadose zone) systems. Laboratory measurements using soil cores indicate that two-phase residual saturation is approximately 5% while three-phase residual saturation is 0.5%. The lower three-phase residual LNAPL saturation suggests that, when the water table falls, LNAPL that was previously immobilized in a two-phase system becomes mobile and drains to the water table.

LNAPL redistribution by the fluctuating water table causes the observed thickness and extent of LNAPL at the Chevron facility to change seasonally. At high water, LNAPL is largely trapped in the formation and does not appear in some monitoring wells. As groundwater levels decrease, LNAPL drains from the vadose zone to the water table until it reaches three-phase residual saturation. The mobilized free-phase LNAPL appears in more monitoring wells, causing the observable extent of LNAPL to increase. Figures 2-12, 2-13 and 2-14 show the observed extent and thickness of LNAPL under typical high-water, typical low-water, and extreme low-water conditions, respectively.

2.3.2 Groundwater Contamination

Groundwater contamination at the Chevron facility is believed to be limited to shallow portions of the saturated zone of the aquifer, i.e., within and beneath the LNAPL smear zone.

Contaminants of Potential Concern

The Environmental Indicators (EI) report (CEC, May 2001) has identified contaminants of potential concern (COPCs) for the groundwater listed below in Table 2-4. These COPCs, the proposed action levels, and the highest concentration reported for groundwater at the site are summarized in Table 2-4 Site concentrations are compared to the MCL, where available, or to EPA Region IX Preliminary Remediation Goals (PRGs) where no MCL is available. Neither the LNAPL itself, nor specific chemical constituents detected in the LNAPL, but not in the groundwater, are identified as COPCs.

Table 2-4

Contaminants of Potential Concern (COPC)

Chemical Constituent	MCL/PRG	Max. Detected	Well Number	Factor Above MCL/PRG
Benzene (µg/1)	5[1]	5,000	Tracer Test Site	1,000
Ethylbenzene (µg/1)	700[1]	2,000	MW-1R	2.9
1,4-DCB (µg/1)	75[1]	440	MW-48S	5.9
Acetophenone (µg/1)	0.042[2]	21	MW-101S	500
DEHP[5] (µg/1)	6[1]	46	MW-94S	7.7
Naphthalene (µg/1)	6.2[2]	450	MW-81S	72.6
Pyrene (µg/1)	180[2]	630	PROD-18	3.5
Dissolved Lead (mg/1)	0.015[3]	0.039	MW-48S	2.6
Total Arsenic (mg/1)	0.05[4]	0.081	MW-93S	1.6

[1] Federal Safe Drinking Water Act Maximum Contaminant Level (MCL), [2] U.S. EPA Region 9 Preliminary Remediation Goal (PRG) [3] U.S. EPA Drinking Water Standards and Health Advisories list an action level of 0.015 mg/1, [4] U.S. EPA has proposed an MCL of 0.005 mg/1, subject to public comment, [5] Bis (2-ethylhexyl) phthalate

Inorganic groundwater quality parameters measured within the smear zone at the Tracer Test Site are summarized in Table 2-5. The groundwater pH is near neutral and the electrical conductivity indicates a low-to-moderate total dissolved solids content. The shallow groundwater is generally anoxic as a result of hydrocarbon biodegradation. Consequently, dissolved iron is present and nitrate is below detection limits. Aside from the well demonstrated iron fouling at this site, the groundwater chemistry is suitable for most treatment technologies applicable to the site.

Figure 2-12 Extent of Free-Phase LNAPL, March 31, 1999

Figure 2-13 Extent of Free-Phase LNAPL, September 24, 1999

Figure 2-14 Extent of Free-Phase LNAPL, November 22, 1999

Table 2-5

Water Quality Parameters within the LNAPL Smear Zone

Parameter	Value
Depth (ft below ground surface)	27 – 32
pH	6.7 – 7.0
E_H (mV)[1]	+130 - +160
Electrical Conductivity (mS-cm)	520 – 1070
Dissolved oxygen (mg/L)	0.02 – 0.09
Nitrate (mg/L)	<0.5
Iron (mg/L)	4 - >10

[1] Corrected to the hydrogen electrode scale

Limits of Groundwater Contamination

Benzene is the most widespread COPC and exceeds regulatory action levels by the highest factor (Table 2-4). The distribution of dissolved benzene is believed to be limited to the area of the smear zone except near groundwater production wells where pumping has increased vertical gradients, drawing some dissolved-phase hydrocarbons deeper into the aquifer (see Figure 2-15). Dissolved benzene generally is not detected outside the area containing residual LNAPL because of the inward gradients maintained by the groundwater production wells. Low levels of benzene occasionally are detected outside the estimated area of the LNAPL smear zone in the southwestern end of the facility and beneath Hooven (see Figure 2-16) as a result of water table fluctuations (see EI report, Figure 13, CEC, 2001).

Ethylbenzene and 1,4-dichlorobenzene are also identified as COPCs in the EI report (CEC, May 2001). As with benzene, the extent of these VOCs generally is limited to the area of the LNAPL smear zone. These VOCs also originate in the LNAPL, and the LNAPL contains the overwhelming majority of the total mass of these contaminants at the site. However, these COPCs generally are present at lower concentrations than benzene and also have higher regulatory action levels. The semivolatile organic compounds (SVOCs) bis (2-ethylhexyl) phthalate, naphthalene, and pyrene have been detected in a few locations at concentrations exceeding MCLs or PRGs, and are included as COPCs.

Figure 2-15 Benzene Distribution in Groundwater

Figure 2-16 Estimated Extent of LNAPL Smear Zone and Dissolved-Phase Plume

Lead has been detected at elevated concentrations in historical sampling at the Chevron facility. However, in recent data from the Phase 2 RFI (ESE, April 2000), lead does not exceed any applicable regulatory action level for groundwater. Although LNAPL at the site remains a source of lead contamination, it is not clear that there is a detectable dissolved lead plume in the groundwater.

Arsenic has been detected at concentrations exceeding the current maximum contamination level under Hooven and the south central part of the facility, as shown in Figure 2-17. The elevated levels of arsenic are not believed to be a direct result of refinery operations and could be from a number of sources: naturally occurring, foundry, or other unknown sources either on-site or off-site. The arsenic plume is within the hydrocarbon plume boundary. However, anoxic conditions created by the LNAPL smear zone may lead to the dissolution of ferric oxides and the release of sorbed arsenic.

Isobutyl alcohol has been identified in the soil and groundwater in a small area at the northwestern end of the facility. This is an area that was leased to Elco Corporation for production of lubricating oil additives. The isobutyl alcohol contamination is being addressed separately from this GWCMS.

2.4 Conceptual Site Model

Figure 2-18 shows the overall conceptual model of the entire site including property lines, edge of the aquifer and local roads, in addition to the Great Miami River, the islands and the extent of the hydrocarbon plumes during high and low water tables. The hydrocarbon contamination extends off site to the west under Hooven and a contiguous area to the south of Hooven. Continuous groundwater pumping ensures that the hydraulic gradient is inward, into the site. This pumping was focused in 1985 to mitigate hydrocarbon seepage into the Great Miami River. Because of the inward hydraulic gradient, the dissolved phase plume covers approximately the same area as the smear zone.

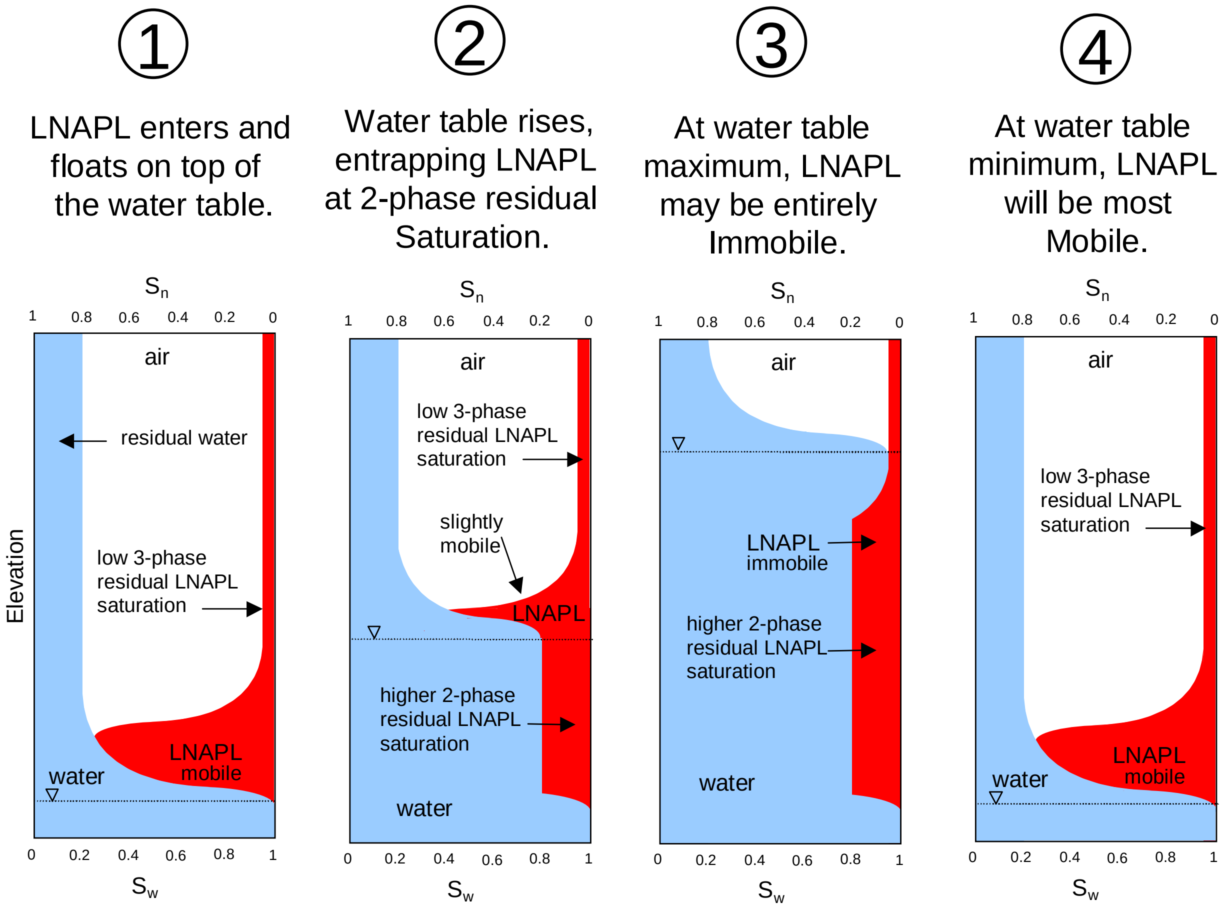
Figure 2-17 Arsenic Distribution in Groundwater

Figure 2-18 Site Map

A portion of the site is shown in more detail in the Site Conceptual Model in Figure 2-19. This figure shows the location of the horizontal SVE wells, pumping wells, smear zone, dissolved phase, hydrocarbon vapors, location of bedrock and other site conditions, and how they are all interrelated. Groundwater flow is directed by hydraulic control from the boundaries of the facility inward to the pumping wells for recovery. There is also evidence that natural attenuation occurs outside the smear zone both under Hooven and at the islands. Monitored natural attenuation degraded the dissolved hydrocarbons from the islands before ever reaching the Cleves wells. Therefore, natural attenuation is a natural enhancement to containment for any hydrocarbons that leave the site.

The site is underlain by a smear zone of LNAPL created by the up and down movement of a floating layer of free product. The conceptual behavior of the LNAPL is described on Figure 2-20. Steps 1 through 4 describe how the LNAPL is redistributed with the changes in the water table. The free product drains from the vadose zone when the water table drops, creating the thickest layer of free product when the water table is lowest.

Figure 2-19 Site Conceptual Model



Note: S_w = Saturation of water, S_n = Saturation of LNAPL

Figure 2-20

Schematic of LNAPL Redistribution by a Fluctuating Water Table

3.0 Redevelopment Plans

3.1 Proposed Redevelopment Plan for the Site

In 1997, Ecology and Environment prepared a market analysis and land use plan for the Chevron Cincinnati Facility (Ecology & Environment 1997). This study included the following elements:

- A review of demographic and economic conditions and trends, including population, personal income, and employment.
- A review of transportation and infrastructure, including transportation by air, river, and land; utilities in the area; and on-site infrastructure.
- An analysis of the real estate market, including real estate trends for different land uses; industry development trends; real estate valuation and taxes; and land use and policies.
- A conceptual land use plan for the site.

Land use options were developed for three scenarios: industrial, commercial/office, and open space. The Community Advisory Panel (CAP) voted on these options in 1997 and the mixed-use land use plan was selected as the preferred land use plan.

In April 2001, this land use plan was updated and approved by the CAP. The current conceptual land use plan is shown in Figure 3-1.

In general, the community is eager to see the site redeveloped for economic and aesthetic reasons. Additionally, the expected future activities at the site would greatly enhance the area's tax base and could provide local employment.

3.2 Development in the Southwest Quadrant

Chevron has designated the property located south of Hooven, west of SR 128, and the property adjoining the southwestern portion of the Chevron facility, east of SR 128 as the Southwest (SW) Quadrant. The location of the SW Quadrant is shown on Figure 3-2. The portion of the SW Quadrant located to the west of SR 128 was formerly a gravel pit.

During past operations, some of the mined area was backfilled with hard fill and spoilage from gravel mining operations. The remaining gravel pit excavation, located just southeast of the Hooven school, was recently (April-May 2001) filled in.

Most of the property designated as the SW Quadrant belongs to one owner. The property is divided into parcels that are in various phases of commercial and retail development. The proposed development layout is shown on Figure 3-3. Currently, at least two of the parcels of land west of SR 128 are in various stages of development. A Kroger grocery store opened in July 2001 on the parcel located the farthest to the south; Kroger is leasing this parcel from the owner. Parcel 6 has been sold to a developer who plans to install a Burger King restaurant. Parcel 1 was sold to a bank.

Figure 3-1 Mixed-Use Scenario Conceptual Land Use Plan - Updated April 2001

Figure 3-2 Location Map of Southwest Quadrant

Figure 3-3 Southwest Quadrant and Hooven Area

4.0 Ongoing and Planned Remediation Operations

In this section, current activities at the site are summarized. They include:

- Hydraulic containment via pumping of groundwater;
- Treatment of the extracted groundwater;
- The pond/constructed treatment wetland that is presently (late 2001) in construction and that will be part of the extracted water treatment system;
- The recovery of LNAPL;
- The Corrective Action Management Unit (CAMU) that is being designed; and
- The SVE system currently in operation under Hooven.

This overview does not include the extensive monitoring operations at the site.

4.1 Hydraulic Containment

There are currently 14 high-volume water production wells (PW) at the site (see Figure 4-1). Several of them are in operation at various locations within the property boundary, as described below. The number of wells in use varies depending on containment and LNAPL recovery needs. The purpose of these production wells is to create an inward hydraulic gradient that captures free-phase LNAPL and prevents further lateral expansion. The inward hydraulic gradient also inhibits migration of dissolved hydrocarbons from the site. Free-phase LNAPL recovery is carried out mainly during the fall low water-table season. At other times, the water level rises high enough to trap and immobilize most of the LNAPL in soil pores, so pumping rates can be decreased, and no free-phase LNAPL is recovered. Typical high water table pumping rates are approximately 2.5 million gallons per day (mgd), while low water table pumping rates are up to 5 mgd.

Figure 4-1 Groundwater Production Wells

From 1998 to May 2000, the LNAPL recovery system consisted of the almost continuous pumping of PW 12, 14, and 15, with periodic pumping from PW 19. PW 4 or 5 is pumped continuously. Only PW 14 and 15 are pumped during high water-table periods.

The effectiveness of the hydraulic containment system to control the hydraulic gradients is evaluated by gauging 115 monitoring wells and two river measuring points six times per year for water level and LNAPL thickness.

During low water conditions (typically August through December), other production wells are also pumped to accelerate LNAPL recovery, but are not necessarily required for hydraulic control. These may include wells PW-16, -18, -19; PW-20, -21 (installed in November 2000); and PW-22 and -23 (installed in 2001).

Measurement of groundwater levels every two months indicates that the LNAPL and associated phase hydrocarbons are hydraulically contained at high and low groundwater levels. The influence of pumping on the water table can be seen as cones of depression around operating production wells. See for example the water table depression around PW-15 on Figure 2-8. Containment has also been confirmed using a numerical model for the facility (GeoSyntec 1992). The radius of influence of PW-15 and 20 is estimated at 600 to 1200 ft, based on recent pumping tests (CEC 2001b).

Finally, natural attenuation has been shown to occur on the periphery of the dissolved hydrocarbon plume, specifically at Island No. 1 and in Hooven (CEC 2001). At the Island No. 1 site, the groundwater gradient was historically toward the former Village of Cleves production wells, yet dissolved hydrocarbons never reached the wells because of natural attenuation. A similar situation has been observed under Hooven. Natural attenuation thus contributes to containment of dissolved hydrocarbons, and may potentially allow interruptions of containment pumping in the future.

4.2 Treatment of Extracted Groundwater

The extracted groundwater is treated in a granular activated carbon fluidized bed bioreactor (FBR) system to meet a benzene standard of 0.5 mg/L in the FBR effluent. The FBR is a type of bioreactor optimized for the treatment of water with a low concentration of contaminants. It contains mm-size particles of GAC coated with a thin film of microbes. The particle bed is expanded by the continuous upward flow through the reactor. This ensures that the particles do not clump together and maximizes contact between the water and the microbes. The particles stay in the reactor, thus ensuring a very long biomass retention time in the reactor. The FBR design maximizes the surface area of microbial biomass. The combination of high biomass retention time and large surface area allows the FBR to treat low concentrations of contaminants.

The system at the Chevron facility consists primarily of two FBRs, approximately 14 ft in diameter and with a 14-ft working bed depth; two oxygen diffusers; and a high-purity oxygen generation system. In the FBR(s), dissolved hydrocarbons are oxidized to CO_2 and water, or partially metabolized and incorporated in the reactor microbial biomass. High purity oxygen is generated by pressure swing adsorption (PSA) systems, and diffused in the water using downflow bubble contact aerators (DBCAs). Approximately 430 gpm of clean groundwater from PW-4 or PW-5 is used as the oxygen carrier stream for each FBR. This carrier stream is then mixed with the contaminated groundwater before entering the FBR.

During spring and summer (high water-table periods), the focus of the pump-and-treat system is on hydraulic gradient management. Pumping is limited to approximately 1270 gpm of contaminated groundwater and 430 gpm of clean groundwater used as the oxygen carrier. The resulting combined groundwater flow of 1700 gpm is treated by one of the two FBRs. Approximately 550 gpm of FBR effluent is recirculated to maintain an overall flow rate of 2250 gpm through the FBR. This upward flow rate allows the FBR bed to remain fluidized. Approximately 130 cubic ft per hour (cfh) of high purity (89% O_2) oxygen is produced by the PSA system and diffused in the 430 gpm carrier stream; the total O_2 generation capacity is 170 cfh per FBR (340 cfh total). The system is controlled by measuring the effluent dissolved oxygen (DO) concentration and the oxygen feed is set so that the effluent DO remains at 1.5 mg O_2/L (see Figure 4-2).

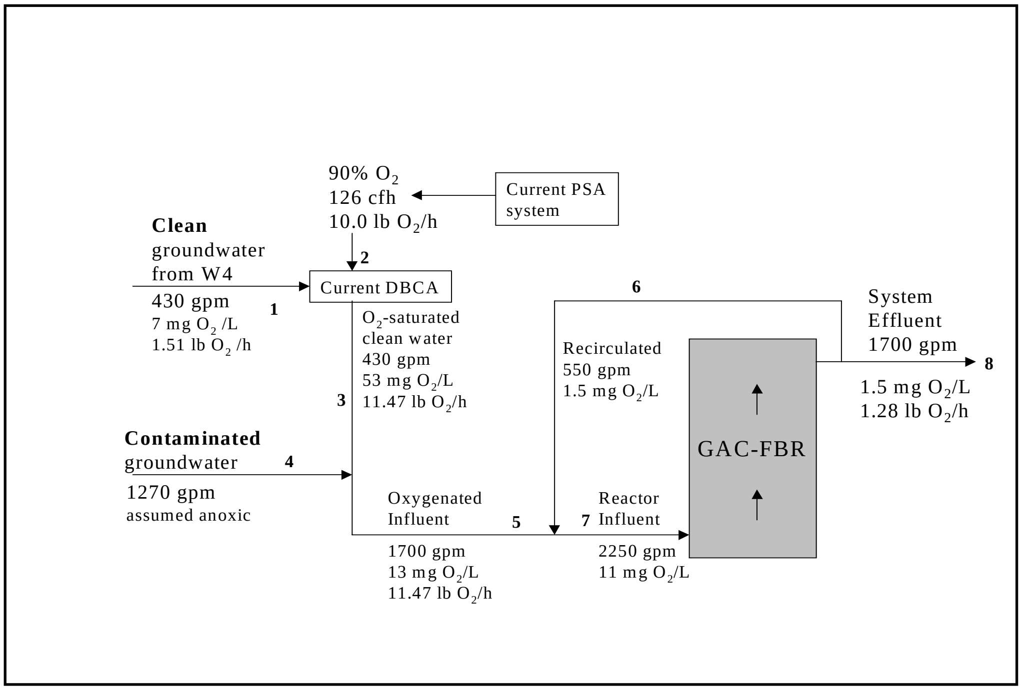


Figure 4-2

Chevron Cincinnati GAC-FBR System Schematic for High Water Table Operation

During fall and winter, the focus of the pump-and-treat operation shifts to free-phase LNAPL recovery. As a result, the groundwater pumping rate may double, to 3400 gpm, of which 860 gpm is clean oxygen carrier water from PW 4 or 5. This requires that both treatment trains be used; in essence two of the systems depicted in Figure 4-2 are operated in parallel. At times, the system is oxygen-limited, i.e., even with the full 340 cfh oxygen generating capacity in use, the water flow rate must be reduced to meet the 1.5 mg O_2/L parameter in the system effluent.

The effluent from the FBR system is conveyed to an impoundment where it is polished before discharge to the Great Miami River.

4.3 Pond/Constructed Treatment Wetland

A pond/constructed treatment wetland (CTW) system has been designed to provide polishing of treated groundwater and site storm water. It will replace the existing wastewater impoundment, which is being taken out of service to support construction of the CAMU (see Section 4.5). The location of the CTW can be found on Figure 3-1. The CTW is also designed to provide habitat and contribute to the ecological restoration of the facility. Construction began in September 2001 and will last through the spring of 2002. Wetland planting and startup is scheduled for spring 2002.

The system will consist of two major components. First, the 2-acre pond will receive treated groundwater via a pipeline from the fluidized bed reactor and an open channel carrying site storm water. The average depth of the pond will be 4 ft, with a smaller 6-ft-deep section at the inlet. The pond is designed to remove most of the incoming suspended solids. Water flows from the pond to the 6-acre CTW via two underground pipes.

The CTW consists of two 3-acre cells. The upstream part of each cell has several 3-ft-deep trenches to enhance mixing and provide even distribution of water. These trenches are separated by much larger 1-ft-deep sections planted with cattails and bullrush to provide treatment. The downstream end of the CTW cells is designed for habitat enhancement and treatment. This part of the CTW has a more varied, “natural” topography with depths varying from 0 to 3 ft deep. Simulated oxbows are separated by underwater ridges to minimize short circuiting. A variety of planting zones ranging from deep water plants to wet meadow vegetation to above-water shrub islands are provided.

After the CTW, the effluent flow rate will be measured and the water will be sampled for compliance with the facility’s NPDES permit, before flowing in an open channel to the Great Miami River.

The peak flow of groundwater to the system will vary seasonally from 2.5 to 4.9 MGD. This results in a retention time of just over one day. Storm water in a future land use scenario during a 25-year storm will contribute 5.8 MGD. The pond/CTW system is designed to accommodate flows from a 25-year storm event.

The primary design basis for removal of pollutants is Total Suspended Solids (TSS) in storm water, which has a peak value of 225 mg/L. The pond/CTW system is large enough to remove TSS to 30 mg/L, as will be required in the National Pollution Discharge Elimination System (NPDES) permit for this facility. In addition, the system will polish low levels of organics such as BTEX compounds and oil and grease.

4.4 LNAPL Recovery

LNAPL recovery began at the Chevron facility in 1985 in response to the observation of a petroleum hydrocarbon sheen on the Great Miami River. Approximately 3.5 million gallons of LNAPL have been recovered from the subsurface since 1985. Figures 4-3 and 4-4 show the history of LNAPL recovery at the site. From 1985 to 1989, large volumes of LNAPL were recovered annually because of the considerable depth of phase-separated hydrocarbons. During those initial years, all the easily recoverable LNAPL was recovered. Annual recovery after that time declined to baseline levels due to the limited depth of the free-phase LNAPL. Since 1989, LNAPL recovery has oscillated between 10,000 and 130,000 gallons per year, in response to water levels. The recovery is high in years with a very low water table, such as 1999. The reverse is true when the water table remains high, as in 2000.

Chevron currently operates high volume (500 to 900 gpm) fully penetrating production wells continuously to control the hydraulic gradient. This pumping ensures that the gradient is inward into the site and prevents LNAPL migration away from the area under hydraulic control. During low water-table periods, partially penetrating wells are brought on line. They create cones of groundwater depression that capture floating LNAPL. In these cones of depression, LNAPL is recovered by skimming it from recovery wells located within or adjacent to the production wells. The recovered LNAPL is pumped through metered lines for storage in above-ground tanks prior to off-site shipment.

4.5 CAMU

The Corrective Action Management Unit (CAMU) will help facilitate corrective action for treatment/disposal of remaining sludges and contaminated soils at the Chevron Cincinnati facility. Once it is installed, the CAMU will preclude most groundwater treatment methods under its footprint (see Section 7). The CAMU selected is a unit designed for the disposal of stabilized remediation wastes generated during the implementation of the CMI phase of the RCRA Corrective Action Order.

Figure 4-3 Summary of Chevron Cincinnati Facility LNAPL Annual Recovery

Figure 4-4 Cumulative Free-Phase LNAPL Recovery

The EPA has determined that the CAMU can be designed and constructed to provide adequate protection. Chevron will submit detailed design documents for this CAMU to the EPA for review.

The location of the CAMU can be found on Figure 2-3. The conceptual design specifies that dikes comprising the outer rim of the containment unit will be constructed using existing dikes around SWMU 10 where possible. Other areas within the footprint of the repository, but not associated with SWMU 10, will be cut down (or filled) to the proposed finished bottom elevation to prepare for liner placement.

The finished bottom configuration, before liner placement, within the disposal unit will be designed to provide a minimum 2% slope toward sump locations. A double liner system will then be placed on top of the finished bottom and sidewalls will be composed of (from the bottom up): a geosynthetic clay liner (GCL), a flexible membrane liner (FML), a drainage geocomposite/geonet (leak detection), a second GCL, a second FML, a geotextile cushion, 1 ft of coarse-grained material (leachate collection), and a geotextile. Both drainage layers will drain to sumps, the number and configuration of which will be determined during the design process based on predicted inflow volumes and characteristics of available drainage materials.

After the containment cell is prepared for waste placement, contaminated sludges and soils throughout the Chevron facility will be excavated and hauled to the CAMU treatment and staging area, and stabilized. Waste will be placed according to project specifications up to a final surface configuration.

Once the total volume of stabilized material is placed in the unit, the surface will be covered with a low-permeability composite cap consisting of the following layers (from bottom to top): GCL, FML, geocomposite drainage layer, and 24 in. of protective soil cover. This cap design is in general accordance with Ohio EPA’s current and draft guidance as well as recent experience with similar corrective action sites in Ohio. Vegetation will be established on the finished cap, and erosion control measures will be incorporated as necessary.

Since the groundwater in the vicinity of the CAMU location is impacted with a free-phase hydrocarbon plume, any migration of leachate from the unit may not be detected in perimeter monitoring wells. Therefore, a leak detection layer will be incorporated into the liner (resulting in a double liner) to monitor the performance of the containment system. Any groundwater monitoring will be performed in conjunction with the currently established groundwater remediation and monitoring activities.

After closure, Chevron will routinely inspect and maintain the cap. Leachate accumulation in the collection system will be removed and treated as applicable.

4.6 Soil Vapor Extraction

Free-phase LNAPL has been found to extend off site under the eastern half of Hooven. Soil vapor extraction (SVE) is used in that area to remove LNAPL. The extracted vapors are oxidized in a thermal oxidizer. Horizontal well technology was selected because it minimized intrusion into the off-site area during construction; eliminated the need for construction and maintenance of conveyance structures off site; and allowed the thermal oxidation unit to be located on Chevron property.

One horizontal SVE (HSVE) well was installed and brought on-line in November 1999. Two additional wells were installed in late 2000 and have been operating since then (see Figure 2-3). Operation of all wells is intermittent depending on the height of the water table.

5.0 Regulatory Strategy and Corrective Action Objectives

5.1 Introduction

One of the key elements in developing a regulatory strategy and corrective action objectives is to determine final cleanup goals for the groundwater. In preparing this GWCMS, the *Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action* (USEPA, April 2001) was used to provide guidance in preparation of this regulatory strategy and the proposed Corrective Action Objectives. This document indicates that "EPA expects final remedies to return 'usable' groundwater to their maximum beneficial use, wherever practicable, within a time frame that is reasonable given the particular circumstances of the facility." It is not Chevron's intent to define maximum beneficial use at this time. However, in order to develop and evaluate alternatives, this GWCMS assumes that the maximum beneficial use of the impacted groundwater may be as a drinking water resource.

The Chevron Cincinnati Facility is a large, complex site that does not lend itself to any quick fixes. As part of the GWCMS, Chevron has been evaluating numerous technologies, both proven and innovative, to remediate the site and return the aquifer to its maximum beneficial use. These investigations indicate that even under optimistic conditions, it could take nearly 100 years to return the aquifer to its maximum beneficial use. Under more realistic assumptions, it could take several centuries. Therefore, there does not appear to be any reasonable approach that will restore the aquifer to its maximum beneficial use within the foreseeable future.

5.2 Corrective Action Objectives

Given the above situation, Chevron proposes an overall site strategy using a tiered approach of identifying Corrective Action Objectives in the form of short-term protectiveness goals, intermediate performance goals, and final cleanup goals. This is consistent with the approach outlined in the *Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action* (referred to hereafter as the "Handbook"). The Handbook refers to cleanup "goals" while typical CMS protocols refer to cleanup "objectives." For the purposes of this GWCMS, the "goals" and "objectives" terms will be assumed to be interchangeable and "goals" will be used throughout the rest of the document for consistency.

5.2.1 Short-term Protectiveness Goals

EPA's short-term goals associated with groundwater are to:

1. Ensure that humans are not being exposed to unacceptable levels of contamination; and
2. Ensure that contaminated groundwater is not migrating above levels of concern beyond its current extent.

These short-term goals can be measured by the Environmental Indicators reports. Chevron has demonstrated that it is meeting the first short-term goal by answering "Yes" in the Human Health Environmental Indicators Report that was submitted to the EPA in 2001. Chevron has demonstrated that it is meeting the second short-term goal by answering "Yes" in the Groundwater Environmental Indicators Report that was submitted to EPA in 2001 (CEC, 2001). Therefore, Chevron has met both of these short-term protectiveness goals.

Intermediate Performance Goals

Intermediate performance goals are facility-specific environmental conditions or measures that demonstrate progress toward achieving the final cleanup goals. Since the Environmental Indicators have been met, Chevron will concentrate on intermediate performance goals that will focus on maintaining positive Environmental Indicators and preparing the site for redevelopment while working toward meeting the Final Cleanup Goals. The proposed intermediate performance goals that Chevron will concentrate on over the next 10-15 years are:

1. Protect human health and the environment.
2. Remove the recoverable liquid hydrocarbon, to the extent practicable, concentrating on the area along SR 128.
3. Remove the recoverable hydrocarbon under Hooven, to the extent practicable, using the HSVE system.
4. Maintain plume control to prevent migration of either liquid hydrocarbon or dissolved phase constituents.
5. Begin site redevelopment within the next few years to return the area to productive use for the surrounding community. (This will be based on market demand and the ability to adequately safeguard the transition to development, while maintaining necessary remediation and monitoring in place.)

Final Cleanup Goals

As stated earlier, EPA expects final remedies to return 'usable' groundwater to their maximum beneficial use, wherever practicable, within a time frame that is reasonable given the particular circumstances of the facility. Specifically, EPA's goals for final cleanup are to:

1. Protect human health and the environment.
2. Achieve media cleanup objectives established to ensure protection.
3. Control the sources of releases so as to reduce or eliminate, to the extent practicable, further releases of hazardous constituents that may pose a threat to human health and the environment.

Protecting human health and the environment is of paramount importance and will be achieved by ensuring that the human health and groundwater Environmental Indicators are met based on the current or projected land use.

The media cleanup objectives are related to the maximum beneficial use of the groundwater. Given that the impacted aquifer has been designated as a sole-source aquifer, it is assumed that the ultimate media cleanup objectives would be drinking water standards. For the purposes of this GWCMS, MCLs have been used as the groundwater cleanup criteria. Even when MCLs are met, however, there will be residual hydrocarbon contamination in the smear zone and the aquifer will not have been restored to its pre-impacted condition. It is also important to note, as will be shown in Section 7, that it may be centuries before these cleanup criteria can be met throughout the impacted portion of the aquifer.

Chevron has been diligently working toward control of the releases for over a decade. Specifically, Chevron has taken significant actions toward achieving the first and third final cleanup goals. These actions include:

1. Refining operations at the facility were terminated in 1986, and almost all process equipment, storage tanks, and pipelines (except the former crude oil pipeline that discharges stormwater collected at the Land Treatment Unit to the oily water sewer system) have been dismantled and removed from the site. Only storage tanks and structures related to remediation activities remain at the site. The facility has a continuing program to remove the remaining subsurface infrastructure associated with the former refinery (foundations, sewers, pipelines, etc.).
2. SWMUs 1, 2, 3, 4, 9/13, 11, 22, X, parts of SWMU Y, all known areas of leaded tank bottoms, some areas with surficial lead contamination and Tank 61/62/63 area have been excavated and disposed of off-site.
3. SWMUs 7, 8, 10, and other areas of remaining soil contamination and waste will be incorporated into the CAMU that is planned for the site.
4. Groundwater pumping wells and a groundwater treatment system have been installed to hydraulically contain the dissolved phase plume.
5. Recovery wells have been installed to recover liquid hydrocarbons from the aquifer.
6. A horizontal SVE system has been installed to recover off-site hydrocarbons under Hooven.

7. The existing water supply well field for the Village of Cleves has been relocated to a different river valley.
8. A remediation system to address the separate hydrocarbon plume on Islands No. 1 and 2 has been operating since the mid 1990s.

5.3 Regulatory Strategy

As stated earlier, this is a large, complex site that does not lend itself to any quick fixes. Given the site-specific geology, hydrogeology, and contaminant types and distribution, it is unlikely that the groundwater can be restored to potential beneficial uses in the foreseeable future. The regulatory strategy must be workable within this context.

Chevron proposes to negotiate a new Corrective Measures Implementation (CMI) Order that will have a defined period of 10-15 years and will focus specifically on the intermediate performance goals listed in Section 5.2. At the end of that time, Chevron will submit a report that documents the actions undertaken to comply with the intermediate performance goals and to propose the path forward toward meeting the final cleanup goals. Chevron would then expect to enter into a new order that would be focused on the efficient long-term monitoring of the controls and property use.

During the life of the CMI Order that will be negotiated at the end of the CMS, Chevron proposes to use the Point of Compliance (POC) approach for monitoring and managing the groundwater contaminants. The POC will be established around the dissolved-phase and liquid hydrocarbon plumes. Chevron will maintain COCs below action levels (MCLs where they exist, otherwise preliminary remediation goals) at the POC by controlling the dissolved-phase and liquid hydrocarbon plumes with hydraulic controls or other technologies.

Figure 5-1 shows a conceptual idea of how the POC would be employed. The POC is defined as the line shown on Figure 5-1 and represents the location at which Chevron will meet the action levels for all COCs in the groundwater. The exact location of the POC will be somewhat influenced by the groundwater alternative that is ultimately selected.

Therefore, Chevron proposes to submit a Tech Memo that addresses the POC in more detail after EPA concurrence on the proposed groundwater alternative. This Tech Memo would define the specific location of the POC, proposed monitoring locations, and a specific POC monitoring plan.

Figure 5-1 Conceptual Location of Point of Compliance

6.0 Remedial Technology Screening

A wide range of site cleanup technologies is available, targeting different environmental media, classes of contaminants, scales of application, and treatment end-points. To identify the technologies best suited to the site and determine what function these technologies can best play in the overall cleanup process, this section examines a spectrum of cleanup technologies potentially applicable to hydrocarbon-contaminated sites.

This section first describes the approach that will be followed in the GWCMS to address all the technologies reviewed. A description of site-specific remediation needs follows, as well as a listing of constraints. Ten candidate technologies are described, followed by general considerations about applicability to this site.

6.1 Remediation Activities and Available Technologies

Several general types of activities are necessary to remediate the Chevron Cincinnati Facility. They include containment, source removal, and remediation of dissolved contaminants. No single technology will accomplish all of these functions. In this section, the capabilities of the technologies to perform the required remediation services are briefly discussed. An overview is presented in Table 6-1, which lists possible remediation activities compared with available technologies. Possible matches between the two are indicated in the body of the table. Each technology is most effective in treating a specific range of contaminant concentrations; several different methods may be needed to achieve the cleanup objectives for this site.

6.1.1 Containment

Containment must address contaminants in the groundwater, primarily dissolved phase hydrocarbons, and free-phase LNAPL. These two phases are related since the LNAPL is the source of the dissolved phase, but they can require distinctly different remediation strategies.

Table 6-1

Remediation Activities and Available Technologies

Activity	Medium	Containment with LNAPL recovery	Soil vapor extraction	In situ air sparging	Subsurface Heating	Six-phase heating	Recirculating wells	SEAR	Chemical oxidation	Monitored natural attenuation	Institutional Controls
Containment	Groundwater	P									
	Free-phase LNAPL	P									
Source removal	Residual immobile LNAPL, vadose		P	P	P	h		h	h	m	
	Free-phase LNAPL	P	P	P	P	P		P	P	m	
	Residual immobile LNAPL, saturated zone			P	P	P	m	P	P	m	
Vapor control	Soil vapor		P							P	
Dissolved hydrocarbon removal	Groundwater			P	P	P	P		P	P	
Exposure Prevention	Groundwater, LNAPL										P

P = This technology is potentially applicable for the activity listed.

m = This technology contributes to the activity listed, but only in a minor way.

h = This technology may be potentially applicable for the activity listed, but only if performed at high water table.

Note: Empty cells mean that the technology is not applicable to this activity.

6.1.2 Source Removal

Source removal must address the variable LNAPL conditions affected by groundwater fluctuations that smear LNAPL. The LNAPL is present in the subsurface in at least three states. Free-phase mobile LNAPL exists on top of the water table. Immobile LNAPL is present up to the two-phase (oil/water) residual saturation in the groundwater-saturated zone. Immobile LNAPL also is found at concentrations up to the three-phase (air/oil/water) residual saturation in the vadose zone. The source removal technologies selected must be suited for addressing one or more of these LNAPL states, and implementation plans must account for the dynamic processes that continually redistribute LNAPL between these states. At least one technology will be required that can remove free-phase LNAPL or prevent its accumulation at low water table.

6.1.3 Treatment of Dissolved-Phase Contamination

Dissolved-phase contamination can be treated in situ, or the groundwater can be extracted and treated above ground as now happens in the on-site extracted water treatment facility. Physical, chemical, and biological technologies are available for such treatment.

6.2 Site-Specific Constraints

Site-specific constraints make this an extremely challenging cleanup project. The ultimate cleanup to the proposed action levels may take decades to centuries or be impracticable. Site conditions that influence the selection and implementation of remedial technologies include:

- The LNAPL zone lies within a highly transmissive sand and gravel aquifer.
- The water table fluctuates by up to 14 ft in response to river stage changes and recharge from precipitation.
- More than one million gallons of LNAPL are present under both two-phase (saturated zone) and three-phase (vadose zone) conditions.
- The aquifer thickness ranges from a few ft along the northern part of the western boundary of the site, to 80 ft along the eastern side.

- Pumpable accumulations of LNAPL are present only seasonally over much of the site.
- Portions of the LNAPL zone extend off site to the west and southwest of the southern part of the site (Hooven and the Southwest Quadrant).
- The site lies entirely over a sole-source aquifer of the state of Ohio.
- The hydrocarbon plume has extended to the bank of the Great Miami River and has been hydraulically controlled since 1986 to prevent it from seeping into the river.
- The LNAPL smear zone extends over a broad area, covering approximately 200 acres, and extending from approximately 15 to 30 ft below ground surface (bgs).
- The LNAPL properties generally are consistent over the site, except for a local area of more viscous, higher molecular weight hydrocarbons near SWMUs 4, 7, 8, 10, and southerly to the vicinity of MW-88.
- There is a conceptual redevelopment plan for the site.

6.3 Discussion of Candidate Technologies

This section describes each of the candidate technologies that may be used to develop overall cleanup alternatives. For each technology, a brief description of the process is presented, followed by a discussion of available data and an evaluation of its applicability in light of site-specific factors. The following technologies are discussed:

1) Containment with LNAPL recovery;
2) Soil vapor extraction;
3) In situ air sparging;
4) Thermal enhancements to other technologies;
5) Six-phase heating;
6) Groundwater circulating wells;
7) Surfactant-enhanced aquifer remediation;
8) In situ Chemical oxidation;

9) Monitored natural attenuation; and
10) Institutional controls.

6.3.1 Containment with LNAPL Recovery

Containment Pumping

Brief Description

Groundwater is extracted year-round to achieve hydraulic containment and assist in the recovery of free-phase LNAPL. The extracted water is treated on site using an FBR, followed by polishing in aerated lagoons before release to the river under an NPDES permit. The lagoons will be replaced with a combination of a pond and an engineered wetland to facilitate construction of the CAMU as part of the soils CMI.

During low water-table intervals, LNAPL is recovered using skimming pumps. The extracted hydrocarbon-water mixture is separated in wellhead oil/water separators, and the oil is directed to and collected in large tanks for disposal. The small stream of separated water is treated in the facility’s API oil/water separator and in aerated lagoons prior to discharge.

Containment pumping is a mature technology, even at this scale of operation; design and operation are well defined.

Site-Specific Application

Containment pumping fulfills the site needs for hydraulic containment and free-phase LNAPL recovery. No matter what cleanup alternative is selected, groundwater pumping will continue to be a component of containment for some time. The rate of pumping may be reduced in the future; alternatively, it may become possible to pump intermittently. The limitation of pumping is that LNAPL recovery is dependent upon low water-table conditions and is limited by the need to pump large volumes of groundwater to produce favorable hydraulic gradients toward extraction wells in this very permeable formation. The pumping rate is limited by the current capacity of the treatment facility.

Site-Specific Effectiveness

Containment pumping is an effective, relatively low-cost containment technology. Detailed groundwater and contaminant transport modeling will allow Chevron to design an optimized system in terms of overall system performance, schedule, and cost. Numerical simulation should address free-phase LNAPL removal, and the dissolution, transport, and biodegradation of benzene and other hydrocarbons, with optimization constrained by physical and chemical limitations, and operational costs. An additional discussion of containment pumping is included as part of the remedial alternatives evaluation included in Section 7.

Discussion

Three aspects of the current pumping operation are discussed: hydraulic control, treatment of extracted water, and free-phase LNAPL recovery.

Hydraulic control – Hydraulic control will be applied to the entire area within the POC except for Islands No.1 and No. 2, and will be used to maintain compliance at the POC wells. Hydraulic control has been effectively established along the Great Miami River since 1986. Two additional production/recovery wells (PW-19 and -20) were installed in the fall of 2000. PW-20 helps achieve hydraulic control for the portion of the plume that extends under Hooven, and to the area south of Hooven as well. Two additional production wells were added in this area in 2001 (PW-22 and -23).

Containment pumping is the primary means of achieving hydraulic control of the LNAPL and the dissolved hydrocarbon plume. This in turn maintains the COCs below the action level concentrations at the POC. The distribution of future pumping wells, their well screen intervals, and the pumping schedule will be optimized using a groundwater model of the site.

The groundwater pumping program will be evaluated using this model and validated by field measurements during operation of the hydraulic control program. The modeling effort will help optimize the remediation monitoring program for wells within the POC.

The monitoring program will track the effectiveness of the hydraulic controls and LNAPL removal. Reinjection of treated water will also be considered as a means of achieving hydraulic control.

Treatment of Extracted Water – In conjunction with the optimization of the hydraulic controls, the capacity of the current water treatment system is a constraint on the volume and quality of water that can be pumped to achieve hydraulic control. The current GAC-FBR system can handle approximately 3400 gpm (4.9 mgd) of extracted groundwater. A pond/ CTW is being built (see Section 4.3) to treat storm water runoff and the effluent from the GAC-FBR system. Its capacity is similar to that of the FBR system, i.e., 5 mgd.

Free-Phase LNAPL recovery – LNAPL recovery started in 1985. By early 1986, PW-14 and -15 were on line and basically established the hydraulic gradient. Later wells did not fundamentally alter the gradient control established in 1986. For decades, the refinery had pumped process water from the central and north part of the site at a rate of 1 to 2 mgd, thus establishing some hydraulic gradients. During the first year of LNAPL recovery, approximately 1.4 million gallons of LNAPL were recovered; the recovery remained above 400,000 gallons per year until 1989. Afterwards, production declined rapidly to a baseline level of 10,000 to 130,000 gallons per year because all the easily accessible LNAPL had been removed. Since 1990, the efficacy of LNAPL recovery has been largely determined by low water levels: the lower they are, the better the recovery. Historical LNAPL recovery is illustrated on Figures 4-3 and 4-4. Recently, well positioning has also been seen to have an impact. This is illustrated by the fact that one-third of the unusually high 1999 LNAPL recovery came from the newly installed Well PW-19 in the fall of 1999.

Containment pumping with LNAPL recovery is compatible with redevelopment, provided the wellheads remain accessible, and the oil and water pipelines are routed around buildings.

Barrier Walls

Brief Description

Although barrier walls can only be part of an overall remediation scheme for a site, they can be an effective component for achieving the short-term remedial goals of controlling contaminant migration and removing LNAPL. The performance of the pumping system may be enhanced by the installation of various subsurface barrier walls to reduce the lateral recharge of groundwater. Barrier walls may increase the effective radius of the groundwater pumping program without increasing the volume of water pumped. The use of barrier walls may also increase the rate at which recoverable LNAPL can be removed by extending the seasonal low water-table conditions under which LNAPL is most readily removed. Barriers may reduce the volume of groundwater that needs to be pumped, allowing active containment systems to be replaced with passive or semi-passive systems better suited for long-term operation.

Barrier technologies are mature and various techniques are available for installing different types of barriers under varying site conditions. Barriers will probably be partially penetrating since the aquifer is typically 80 ft thick and only the top 20-30 ft of the aquifer is contaminated. Detailed groundwater modeling is required to design any barrier system. The conceptual design of a partially penetrating impermeable barrier is shown in Figure 6-1. Reactive barriers (e.g., oxygen-releasing compounds, sparging curtains, etc.) are probably not applicable in the presence of significant quantities of potentially mobile LNAPL, but could be considered in a funnel-and-gate arrangement with upstream LNAPL controls.

Partially permeable capillary barriers that allow groundwater flow through the barrier but prevent LNAPL migration can also be constructed as part of a containment system. Such permeable barriers only need to extend past the base of the LNAPL smear zone to be effective. The design of capillary barriers needs to take into account the LNAPL and aquifer properties to ensure effectiveness. The barriers would be installed in an area of LNAPL. LNAPL removal would then occur downstream of the barrier, while the barrier itself would prevent reentry of mobile LNAPL from upgradient. LNAPL would pool on

Figure 6-1 Conceptual Design of a Partially-Penetrating Barrier at the Chevron Cincinnati Facility

the upgradient side of the barrier and would have to be removed; groundwater pumping potentially would also be necessary to maintain a gradient toward the barrier. Barriers can also act to focus LNAPL flow into collection areas, facilitating skimming operations. The conceptual design of a capillary barrier system is shown in Figure 6-2.

Site-Specific Application

Once installed, barriers are passive elements of a treatment system and are compatible with conceptual site redevelopment plans. Barrier placement is invasive and disrupts surface facilities, which puts limits on its application to off-site areas like Hooven.

Groundwater modeling will be used to determine the location, depth, and length of barriers that could be used at the site. The following barrier types could be considered through computer modeling:

- Longitudinal impermeable walls along the Great Miami river;
- A longitudinal impermeable wall along SR 128 adjacent to Hooven;
- A trans-valley impermeable wall upgradient of the LNAPL plume; and
- Capillary barrier walls to prevent LNAPL migration.

Site-Specific Effectiveness

Barriers can be an effective means of achieving short-term protectiveness goals, but are not effective themselves in achieving long-term cleanup objectives. Barriers can be used to increase the effectiveness of other treatment technologies by focusing the flows of LNAPL or contaminated groundwater into treatment or recovery areas, thus helping to meet long-term cleanup goals including source removal and reduction of COC concentrations to action levels.

Barriers are most likely to be implemented as part of a long-term remediation strategy. They would not be cost effective as a means of providing interim containment during primary source removal since hydraulic containment could be implemented at much

Figure 6-2 Conceptual Design of Capillary Barrier System at the Chevron Cincinnati Facility

lower capital cost. If limited source removal is conducted and containment is needed over a long period, barriers may be the preferred method of containment.

Discussion

Preliminary modeling of potential barriers in a funnel and gate configuration determined that there were potential problems with head build-up inside the barrier, inducing vertical gradients that transported dissolved-phase contaminants beneath the barriers meant to contain them. These preliminary conclusions will be reexamined based on a refined model of the site hydrogeology. Alternative barrier configurations will also need to be assessed. Once the design requirements for the barrier are established, an actual barrier type may be selected. The barrier wall construction method will be based on the anticipated surface use at the wall location, its depth, the access to the area required by the wall installation technology, and maintenance of the wall.

6.3.2 Soil Vapor Extraction

Brief Description

SVE systems use a blower to remove contaminated soil gases from the vadose zone. The extracted vapor is treated, typically by combustion in a thermal oxidizer or in a catalytic oxidizer, or by adsorption. Combustion in a thermal oxidizer is most applicable for this site because the vapors typically are flammable and the hydrocarbons easy to oxidize. In the soil, gaseous VOCs are removed by advection, and LNAPL trapped in the vadose zone is stripped, preferentially removing the most volatile components. Some diffusion of VOCs from the free-phase LNAPL at the base of the vadose zone will also occur, but is limited by the relatively small surface area/mass ratio of the pooled LNAPL. SVE has no significant impact on trapped LNAPL below the water table. Atmospheric air is pulled into the vadose zone to replace the extracted vapor, increasing the oxygen flux to the system. Over time, the extracted VOC concentration diminishes, so SVE systems are eventually shut down, typically after one to five years of operation. SVE usually is followed by bioventing, a much milder form of soil gas extraction that maintains the subsurface aerobic for optimal biodegradation.

The typical design and operation of an SVE system is illustrated in Figure 6-3. SVE is a mature technology for smaller sites and can be implemented via a network of vertical or horizontal wells. Application to the whole site would require an unusually large SVE system and would probably be implemented in a modular fashion. Such an SVE installation would require an extensive array of above-ground piping, blowers, oxidizers, power cables, and control systems that could interfere with long-term plans for site redevelopment. Horizontal wells would minimize surface disruption.

Site-Specific Application

SVE fulfills the need for control of soil vapor emissions and removal of the volatile fraction of LNAPL trapped in vadose soil pores. More volatile hydrocarbons will be preferentially removed. SVE is compatible with the type of LNAPL present over most of the site; this LNAPL is predominantly a lighter, gasoline range fraction. However, SVE will only directly affect vadose-zone trapped LNAPL. The next high water-table period will redistribute LNAPL throughout the vadose zone, requiring reapplication of SVE during the next low water season. This pattern would continue, with diminishing returns, until all volatile LNAPL is removed. Thermal enhancements (injection of oxidizer offgas or steam) could be used to speed remediation. SVE could also be used in conjunction with a low water-table technology focused on the free-phase LNAPL and the saturated zone, such as surfactant-enhanced aquifer remediation (SEAR), to complete the cleanup in a shorter time.

SVE using vertical wells has been in seasonal operation at the Islands No.1 and No. 2 sites since October 1995. It is estimated that by 2000 this system had removed 21,000 pounds of hydrocarbons via stripping and 7500 pounds via biodegradation; this includes the SPH test (see Section 6.3.5). This SVE operation has since been switched to bioventing with limited SVE. SVE was tested under Hooven in August 1998 using a 30-ft and a 60-ft vertical well to estimate radius of influence and VOC concentrations. In 1999, a large horizontal well was installed under Hooven and SVE operation started in November 1999. Between November 1999 and March 2000, this well removed

Figure 6-3 Conceptual Design of SVE at the Chevron Cincinnati Facility

approximately 180,000 pounds or 26,000 gallons of hydrocarbons (measured as total petroleum hydrocarbons or TPH). These high recoveries were achieved under unusually low water-table conditions, and have not been repeated since then. Two similar wells, running parallel to the first one, were brought on line in late 2000.

Site-Specific Effectiveness

SVE typically addresses only the LNAPL trapped in the vadose zone, and has minimal impact on the submerged LNAPL. At this site, however, the fluctuating water table periodically redistributes LNAPL over the vadose zone, thus making fresh LNAPL available for SVE. Therefore, the seasonal rise and fall of the water table transforms SVE into a technology that has the potential of impacting the LNAPL from most of the smear zone depth, not just the vadose zone.

At most sites, the hydrocarbon yield of SVE falls off sharply after the first few years. The same is to be expected here.

Discussion

The LNAPL plume extends under Hooven. Chevron has implemented an SVE program using three horizontal wells to reduce the perceived risk of vapors rising from this LNAPL plume and affecting residents and businesses in Hooven (note that the Hooven risk assessment showed no unacceptable risk). In the process, the SVE system is also removing a significant quantity of hydrocarbons. This SVE operation is described in Section 4.6.

SVE using horizontal wells can be compatible with redevelopment, provided it is designed so that the wellheads remain accessible. It would provide the ability to actively control soil vapor emissions after the site is built up.

6.3.3 In Situ Air Sparging

Brief Description

In situ air sparging (IAS) is designed primarily for groundwater remediation, but may also accomplish some direct LNAPL removal. Air is injected into the saturated zone, which causes physical stripping of VOCs from the groundwater and the LNAPL, and biodegradation of dissolved VOCs due to the supply of heretofore limiting oxygen. If only a stoichiometric amount of air is added (the amount needed to fully degrade hydrocarbons, no more), then negligible physical stripping will occur and biodegradation will be the main remediation mechanism. This is referred to as biosparging. Note that air sparging is by far the most efficient way of delivering a terminal electron acceptor to the saturated zone. Additionally, the turbulent flow of air enhances mass transfer of oxygen from air to water (Brown et al. 1994).

If air is added at a greater than stoichiometric rate, physical stripping becomes the main removal mechanism and an SVE system is usually needed to capture stripped VOCs and control atmospheric emissions. Vertical or horizontal wells have been used for sparging. An array of vertical wells is preferable because a horizontal well is more subject to channeling and release of all the air from a few sections of the screen. IAS is a mature technology for smaller sites. It is also used at large scale in the form of a curtain of sparging wells to intercept a migrating plume of dissolved hydrocarbons.

Site-Specific Application

IAS provides a means to strip hydrocarbons from the groundwater and from the LNAPL. Possible complications at this site include iron fouling since the water is iron-rich. IAS and SVE are mutually synergistic, and most IAS systems are operated in conjunction with SVE. The reverse is not true, i.e., most SVE systems operate without IAS.

Pilot-scale biosparging tests were conducted at Gulf Park, southeast of the site, in 1998. Injection and monitoring wells were installed using direct push technology. These tests showed that injection points should be no more than 15 ft apart for the injection depth used (29 ft bgs or 14 ft below the groundwater table). A six-month IAS test was conducted at Gulf Park during the second half of 1999 (CEC 2000) and it achieved 99% removal of dissolved BTEX. There was no SVE system so injection rates were limited to 4 to 5 scfm per sparge point; at these rates, the radius of influence was estimated at 10 to 15 ft. It may be higher at higher flow rates. Experience at Chevron's Bakersfield, CA, site indicates that the radius of influence can also be substantially larger if the injection point is completed at a greater depth below the water table. At this site, the water mounding zone of influence of an IAS well screened 45 to 50 ft below the water table was estimated at 60 to 80 ft (Goulding 2001, personal communication).

Site-Specific Effectiveness

On a purely stoichiometric and mass balance basis, IAS theoretically can deliver enough air to strip and biodegrade all site LNAPL in a few years. However, this assumes that the injected air is perfectly distributed over the entire targeted volume and no air channeling occurs, which is highly unlikely in this heterogeneous environment. IAS will preferentially strip more volatile and less water-soluble hydrocarbons. This is compatible with the type of LNAPL present over most of the site, which is predominantly a lighter, gasoline-range fraction. A site-wide IAS system would most likely require a site-wide SVE system, so it will be more costly than SVE alone. Then again, a combined system has the potential to address the entire depth of the smear zone. The radius of influence of IAS is generally smaller than that of SVE so the number of IAS wells will be larger than the number of SVE wells.

Discussion

The typical design and operation of an air sparging system is illustrated in Figure 6-4. In a homogeneous formation, IAS creates an aerated paraboloid of influence around the point of injection (Wilson & Norris 1997). Actual air distribution can vary greatly depending on site stratigraphy. The radius of influence is also a function of depth of injection and texture of the formation. So it is desirable to inject air at the greatest depth possible to maximize the radius of influence and thus minimize the number of wells, although greater depth translates into higher per-well costs. Pulsing the airflow improves long-term removal efficiency, channel density, and dispersivity, and minimizes the

Figure 6-4. Conceptual Design of In-Situ Air Sparging at the Chevron Cincinnati Facility formation of preferential channels, resulting in more effective air distribution (Wilson & Norris 1997). In other words, the air should only be flowing intermittently. In current industrial practice, air flow is generally off in any given well most of the time. IAS operations would have to be completed before redevelopment can occur because an array of vertical wells is not compatible with redevelopment.

6.3.4 Thermal Enhancements to Other Technologies

Brief Description

Heating the vadose zone or the entire soil profile will speed contaminant removal by increasing the volatility of hydrocarbons, their diffusion out of low permeability zones, and their biodegradation rates. If the temperature rise is sufficient, as in six-phase heating, boiling and steam stripping will occur. Direct thermal oxidation of in situ contaminants is not considered applicable here because of the presence of groundwater in a very permeable matrix and the very large size of the LNAPL zone.

Various means of applying heat are applicable. Hot SVE thermal oxidizer offgas could be injected, or steam could be generated from the thermal oxidizer and injected (see Figure 6-3). Vertical or horizontal wells could be used to inject these hot fluids, provided the materials of construction are compatible with the temperatures expected. Alternatively, the soil could be electrically heated (Six-Phase Heating, see Section 6.3.5).

Thermal technologies are fairly well developed for small-scale applications; for site-wide application at this 200-acre site, they should be considered experimental.

Site-Specific Application

Thermal enhancements can facilitate vadose zone or full profile remediation if used in conjunction with LNAPL removal technologies. Some caveats apply:

- The temperature increase must be carefully controlled, and the injection points located a safe distance from any PVC-cased wells. The monitoring wells on site are PVC-cased and could be damaged or destroyed by excessive heat. Alternatively, PVC wells in the path of a thermal enhancement could be replaced by heat-resistant wells.

- Increased LNAPL migration is a possibility since higher temperatures lower viscosity and increase mobility. This could conceivably be turned into an advantage to recover more free-phase LNAPL.
- If thermal oxidizer offgas is injected directly into the groundwater, scaling and pH problems are possible due to the high CO_2 concentration. Any gas injected, such as hot air or oxidizer offgas, will also add to the volume that must be handled by the SVE system. This is not the case with steam, which would condense in the subsurface. Only part of the offgas can be injected; a substantial bleed stream must be released to the atmosphere to prevent CO_2 buildup in the system.

Thermal enhancements would obviously improve the performance of SVE and are compatible with IAS. Steam flooding of the vadose zone could complement a low-water table SEAR (see Section 6.3.7).

Site-Specific Effectiveness

Site-wide thermal enhancements could greatly increase the rate of hydrocarbon removal, but would do so at a high cost. Major cost elements include the energy consumed to produce the heat and the potentially large number of horizontal or vertical wells needed for subsurface access. The cost could be controlled by targeting selected areas, such as the heavier oil area, that would benefit particularly from thermal enhancement. The site has an unfavorable characteristic with regard to heating. Due to the high permeability of the formation, groundwater levels rise and fall rapidly in response to changes in river elevation or weather events. The heating can also induce convection currents that bring in cold water, as observed during the Six Phase Heating™ (SPH) test on Island No. 1 (CEC 1999). All this mixing imposes an additional heating load on any thermal system and creates a heat loss pathway. Finally, cold water could enter any heated area at 2 to 4 ft per day, the estimated horizontal groundwater velocity.

Discussion

If a hot fluid is used to heat the subsurface, a choice of fluids is available. The thermal oxidizer used in conjunction with the SVE system produces offgas that could be injected. This would be simple because an existing hot fluid would be used. Steam could also be generated, which would be more complicated, but would have the following advantages:

- Steam has a much higher heat capacity than thermal oxidizer offgas or air so smaller flows would have to be handled and injected.
- Steam will condense in the subsurface so no additional soil vapor would be produced for the SVE system to handle.
- Steam opens the possibility of steam flooding in the vadose zone.

Thermal technologies have the disadvantage that they will preferentially enhance removal of the lighter fraction of the hydrocarbons, leaving heavier LNAPL in place. In essence a form of in situ distillation will occur. Thermal enhancement projects would have to be completed before redevelopment can occur.

6.3.5 Six-Phase Heating (SPH)

Brief Description

SPH is a form of thermal enhancement; it is highlighted here because it is the only thermal enhancement for which a pilot study was conducted on site. Electrical resistive heating is one way of thermally enhancing SVE. It consists of applying a current between two or more electrodes, resulting in ohmic heating of the affected soil. SPH is a particular implementation of resistive heating that consists of applying electrical current to a portion of the site via vertical electrodes installed in a hexagonal pattern. The resulting resistive or ohmic heating warms the subsurface to the point that groundwater boils, and the resulting steam flow strips off VOCs. The escaping vapors are captured via an SVE system, which is a necessary component of a SPH system.

Like other thermal enhancements, SPH causes increased solubilization and volatilization of VOCs, and can increase the rate of biodegradation.

Site-Specific Application

SPH was demonstrated at Island No.1 in the fall of 1998 (CEC 1999). An electrical current was applied for 52 days; near the groundwater level, the water was boiling for approximately 30 days. Benzene removals were in the 95 to 100% range, gasoline range organics (GRO) were typically removed at 84 to 98%, while only 29 to 66% of the diesel-range organics (DRO) were removed. Some apparent dissolved hydrocarbon migration was observed. The increased temperatures led to a flourishing of microbes in the months that followed the demonstration. SPH could in theory be applied to larger areas of the site by using multiple adjacent hexagonal cells.

Site-Specific Effectiveness

In a very permeable aquifer such as this one, SPH suffers from intrusion of cold water and convective circulation of water at the edges of the hexagonal SPH cell. This prevents groundwater from heating up much below the water table. Some migration of dissolved hydrocarbons was observed. These inherent weaknesses could be mitigated if SPH is applied over a large area since this would reduce water intrusion, edge convection, and LNAPL migration. A complementary approach would be to minimize water intrusion with barrier walls. Large-scale application of SPH will still require a very high boring density due to the small radius of influence of each electrode; the bore hole diameter is typically 10 in.

SPH involves using electricity to boil groundwater for an extended period of time. The electrical power demand for SPH is considerable, which is a major disadvantage of this technology. Based on vendor data, the ideal power input for the SPH test was 600 kW to treat 2000 sq ft from 3 to 27 ft bgs, or 1800 cubic yards. Heat was applied for 42 days, but the ideal duration would have been approximately 50 days. This translates to 720,000 kWh or 400 kWh per cubic yard. At this rate, if the technology were applied to the entire 200-acre site, continuous application of 71 megawatts would be required over five years, requiring the construction of a small generation plant. At $0.1 per kWh, the cost of generation would be on the order of $300 million. SPH also requires a very large density of large diameter (typically 10 in.) boreholes. At this site, the total number of borings could easily exceed 20,000.

Resistive heating allows an even distribution of heat throughout the affected formation, irrespective of heterogeneities. This is a clear advantage of SPH over the application of hot fluids (offgas, steam, or hot water), which tend to bypass tighter soil pockets. SPH also requires considerable vapor handling capacity.

Discussion

SPH has the disadvantage of using electricity to generate heat, which is thermodynamically inefficient compared to the injection of a hot fluid. The main advantage of SPH is that it heats the subsurface uniformly, whereas injected fluids tend to bypass tighter formations.

Overall, SPH is not an optimal remediation technology at this site because of the site's high permeability, SPH's high power demand, and the very high density of large diameter boreholes required.

6.3.6 Groundwater Circulating Wells

Brief Description

Groundwater circulating wells (GCWs) are an emerging technology for in situ stripping of VOCs from groundwater. In the GCW, water is drawn into an inner casing where it is mixed with injected air. This results in the stripping of the VOCs, which are released into the outer casing, brought to the surface, and treated. Meanwhile, the treated water is discharged into the vadose zone through a screened section of the outer casing and returns to the saturated zone via gravity flow. Thus a circulation of groundwater is established around the well with water entering the well at the bottom and exiting above the static water level. This circulation and stripping continues until adequate treatment is achieved. The typical design and operation of a GCW is illustrated in Figure 6-5.

Figure 6-5. Conceptual Design, Groundwater Circulating Well Technology

Several GCW technologies exist and they all require vertical wells. The technology is emerging, especially at large scale. Most GCW experience is with dense non-aqueous phase liquid (DNAPL) contamination, not LNAPL contamination. Fundamentally, GCWs are comparable to IAS + SVE: volatiles are stripped out of the water in situ, and are brought to the surface in the vapor phase for final treatment. The main difference with IAS + SVE is that GCWs achieve this with one vertical well, rather than requiring separate IAS and SVE wells.

Site-Specific Application

A GCW system would be implemented by installing an array of vertical GCW wells covering the area to be treated. The wells would be connected to a pressurized air piping system fed by one or several compressors. The extracted VOCs would be conveyed to thermal oxidizers via a different piping network, similar to what would be done with the extracted soil vapor from an SVE system. The vapor collection system would be more complicated than for an SVE system using horizontal wells, due to the much larger number of wells. Free-phase LNAPL entry into a GCW would be undesirable because it would redistribute LNAPL, so the top screen of the GCWs would have to be above the highest groundwater level and the bottom screen below the lowest groundwater level. In estimating highest and lowest water levels, the impact of the GCWs on the water table would have to be taken into account.

Alternatively, a curtain of GCWs could be installed around all or part of the perimeter of the contaminated zone to prevent migration of dissolved hydrocarbons.

Site-Specific Effectiveness

A GCW system would remove dissolved VOCs, but not LNAPL, from groundwater. Consequently, the system's source removal action would be indirect: it would maintain a concentration gradient and thus provide a driving force for LNAPL to dissolve into the groundwater. So, it could accelerate LNAPL dissolution, but would still take a long time to substantially reduce the LNAPL saturation or the quantity of free-phase LNAPL.

Discussion

A vertical well-based system covering the entire site will require a massive amount of drilling. Additionally, GCWs require large diameter borings and specific hardware. The cost per GCW has been estimated to range from $25,000 to $100,000 (J. Mueller 2001, personal communication). A GCW system would thus consist of a large array of vertical wells operated over a long time period. That makes the system particularly incompatible with redevelopment. A GCW system would be complicated, requiring two different piping networks: one for compressed air and one for vapors extracted from groundwater. GCWs have not been considered for this site and have not been tested there, so no site-specific information exists.

6.3.7 Surfactant-Enhanced Aquifer Remediation (SEAR)

Brief Description

Surfactant-Enhanced Aquifer Remediation (SEAR) involves the injection of an aqueous surfactant formulation into one or more wells followed by the extraction of either solubilized contaminant or mobilized LNAPL from extraction wells.

Surfactant mobilization, as opposed to solubilization, is desirable from the standpoints of chemical costs and effluent treatment. However, the success of surfactant flooding rests on choosing an appropriate surfactant and delivery system. Large-scale SEAR at the site would be geared toward maximizing LNAPL recovery and reducing residual LNAPL saturation to between 0.5% and 1%, at which level it would be immobile.

SEAR could be applied either at a high water table or at a low water table. At a high water table, it would sweep most of the smear zone and achieve very thorough LNAPL removal. However, this would maximize the volume swept, and thus the amount of surfactant needed, which would maximize the cost of the operation because the cost of surfactant is the largest cost element in large-scale SEAR application. The cost of surfactant would be minimized by operating at low water table, which would minimize volume swept and thus amount of surfactant. A low water-table surfactant flood can be timed such that much of the LNAPL trapped in the smear zone will have drained and collected on top of the water table. Surfactants will then mobilize and recover the LNAPL trapped in the saturated zone as well as the free-phase LNAPL.

The conceptual approach for implementing surfactant flooding across the Chevron site is illustrated in Figure 6-6. This figure shows a dual line drive system, in which there is a row of central injection points for surfactant with two rows of extraction points. Peripheral wells are used for injection of clean water from any one of several clean water wells to achieve hydraulic control and confine SEAR to the target area. The extracted fluids can contain LNAPL and percent levels of dissolved or emulsified surfactant and hydrocarbons. Treating these fluids at high flow rates to the point where they can be discharged to the water treatment facility or the river would require reducing these concentrations by three to six orders of magnitude. This is probably uneconomical, so it is essential that 100% on-site reinjection of extracted fluids be pursued, after appropriate treatment. This treatment would remove 95+% of hydrocarbons, especially benzene. Note that experience has shown that biofouling is not a concern at the high chemical concentrations typical of SEAR. A treatment train could consist of phase separation followed by macroporous polymer extraction (MPPE).

The environmental application of SEAR is relatively new and has been restricted to several demonstrations, primarily at small chlorinated solvent sites. Extracted liquids treatment is at an early stage of development. SEAR is not a proven technology for sites such as this and would require developmental work.

Site-Specific Application

SEAR could be conducted under low water-table conditions in 500-ft long, 100-ft wide panels. Each panel would have between 50 and 100 central injection wells, and a similar number of extraction wells. The exact number of wells will be determined from large-scale computer simulations.

Accurate characterization of LNAPL drainage rates is critical to the success of low water-table surfactant flooding. LNAPL from different site locations was characterized for

Figure 6-6 Illustration of Dual Line Drive for Surfactant Flooding

SEAR feasibility in late 1999 and early 2000, and an effective surfactant was identified that will mobilize the LNAPL (URS, 2000). No bench-scale water treatment work has been conducted at this point.

Site-Specific Effectiveness

The pumping tests indicate high aquifer permeabilities (on the order of 0.1 cm/sec or 100 Darcies), contrary to the permeameter tests, which may have been skewed due to loss of coarse material. These high permeabilities are favorable for SEAR and allow easy propagation of a viscous surfactant polymer solution through the subsurface. The surfactant flood can effectively be constrained to the targeted depth interval by the use of polymers, foams, or the injection of water under the flood to prevent downward channeling. (This technique was used during the tracer tests at the site, see Radian International & DE&S, 1999.) SEAR would be most economical if applied at low water table to minimize the aquifer volume to be treated and hence the cost of chemicals. The vadose zone would not be treated, but much of its LNAPL would have drained down as free product that would also be captured. SEAR may be used to remediate the entire site or certain portions of it. It can be used in conjunction with other technologies such as soil-vapor extraction in the vadose zone.

Discussion

Bench-scale studies indicate that SEAR can potentially reduce LNAPL saturations to less than 1% at the site. It can be conducted under both low and high water-table conditions, and therefore can potentially be conducted throughout the year. On the other hand, surfactant flooding is a sophisticated technology and requires considerable design and associated costs and time. If performed at a low water table, it will not address trapped LNAPL in the vadose zone. Surfactant costs may be very high, especially if a high water table flood is implemented. Finally, the fate of the extracted fluids significantly impacts the overall cost of SEAR because treatment of these fluids can be very costly.

SEAR would have to be completed before redevelopment can occur.

6.3.8 In Situ Chemical Oxidation

Brief Description

In-situ chemical oxidation (ISCO) involves delivering a chemical oxidant into the impacted interval and contacting the oxidant with the contaminant, resulting in destruction of the organic contaminant. The most widely used oxidants are Fenton's reagent (hydrogen peroxide [H_2O_2] plus iron catalyst), permanganate (either as potassium permanganate [$KMnO_4$] or sodium permanganate [$NaMnO_4$]), and ozone (O_3).

Each ISCO system is different. Fenton's reagent is injected into the contaminated soil, which generates a hydroxyl-free radical. This hydroxyl-free radical is extremely reactive and destroys the contaminants. Permanganate treatment involves injecting aqueous solutions of varying concentrations of permanganate (typically 1 to 40%) to distribute permanganate ion (MnO_4^-), which is a longer-lasting but less powerful oxidant than hydroxyl free radical. Ozone treatment involves injecting ozone gas (also a powerful oxidant) to the aquifer. Each of these technologies requires a network of injection wells in an array across the impacted interval. In contrast to other technologies described in the GWCMS, the organic contaminants are destroyed in situ and surface treatment of extracted fluids or vapors is generally not required.

Fenton's reagent is the most mature ISCO technology and has been used for at least eight years, including at multi-acre sites impacted by petroleum-related hydrocarbons and chlorinated solvents under NAPL concentrations. Bench-scale testing has been performed on soil and groundwater samples collected from the Chevron Cincinnati facility, and a draft report was issued in July 2000 (GeoCleanse 2000). The primary focus of the bench test was to determine if Fenton's reagent ISCO could destroy the contaminants present and to determine if any potentially hazardous intermediate products were formed.

Permanganate and ozone technologies are relatively newer. In particular, permanganate ISCO generally is applied to sites impacted by chlorinated solvents, and application to petroleum hydrocarbons must be further evaluated. Permanganate ISCO generates precipitation of solid manganese dioxide (potentially clogging pore spaces and reducing permeability) and may contain high levels of soluble heavy metals including hexavalent chromium.

Site-Specific Application

This technology may address the need for destroying LNAPL, primarily trapped LNAPL in the saturated zone, as well as dissolved VOCs. The oxidant demand is primarily controlled by contaminant mass and chemical inefficiencies in the subsurface. Reductants naturally present in the aquifer matrix, including organic matter and some minerals, may also consume oxidant. Application of the technology may be most beneficial under high water conditions when the LNAPL is trapped and most susceptible to oxidant contact and resulting destruction. The tradeoffs between high and low water table application are the same as for SEAR (see previous section). Fenton’s reagent treatment is very sensitive to aquifer chemistry, and a mildly acidic pH (pH less than 6) and elevated iron concentration (generally greater than 10 mg/L) must generally be achieved for effective treatment. These conditions are difficult to achieve in an alkaline aquifer such as at the facility, but Fenton’s reagent has been effectively implemented in limestone bedrock aquifers and under moderately alkaline groundwater conditions, including elsewhere in the Ohio River Valley in Cincinnati.

Chemical oxidation is an exothermic process and produces oxygen and carbon dioxide gas, particularly with Fenton’s reagent. Runaway reactions have occurred. The heat and gas formation can be controlled, and can be effectively used in conjunction with other technologies (particularly SVE) to increase contaminant mass removal from the vadose zone. Increased temperature and aquifer circulation can also improve LNAPL recovery of the existing P&T system during periods of high water level. Chemical oxidation with Fenton’s reagent also results in saturated oxygen levels in groundwater, which is conducive to aerobic degradation and natural attenuation; in fact, hydrogen peroxide is occasionally used as an injectable oxygen source. Fenton’s reagent treatment will temporarily reduce microbial activity, but does not sterilize the aquifer.

Site-Specific Effectiveness

ISCO has been effective at removing hydrocarbons at other sites, and generally is used for removal of concentrated NAPL source areas. High aquifer permeability is conducive to ISCO for injection of the aqueous reagents. ISCO may be best applied at times of high water level to improve oxidant contact; however, ISCO has also been applied directly for vadose zone treatment. At sites with strong geological heterogeneity, there may be difficulties in achieving complete contact between the oxidant and contaminants. More than one application may be necessary to achieve complete LNAPL removal. Preliminary estimates indicate high chemical costs.

Discussion

The bench-scale testing showed poor oxidation efficiency, attributed to the coarse nature of the aquifer material, which resulted in a short contact time between oxidant and hydrocarbons. The vendor claimed that this would not be an issue in the field and indicates that injected chemicals will travel far from this injection point, thus reducing the number of injection points. As is the case with every fluid injection, there is a concern that the fluids may bypass tight formations. The pH remained above 6, which is not optimal for this process (Geo-Cleanse 2000).

The process has the advantage that contaminant destruction occurs in situ, no fluids (vapor or water) are extracted, and no ex situ treatment is necessary. It has the disadvantage of requiring the handling of large amounts of a very corrosive chemical (hydrogen peroxide). The chemicals to be injected are also costly; the total cost for treating the facility was estimated at $180 million (Geo-Cleanse 2000, personal communication).

6.3.9 Monitored Natural Attenuation

Brief Description

Natural attenuation will remediate soil vapor and dissolved hydrocarbons outside of areas of free-phase LNAPL accumulations. At this site, the abundant LNAPL source currently depletes any terminal electron acceptors and maintains equilibrium concentrations of dissolved hydrocarbons inside the LNAPL zone. However, monitored natural attenuation (MNA) will be a necessary final polishing step after removal of most of the LNAPL.

MNA involves collecting data on changes in groundwater chemistry along flow paths through the area of contamination and over time. Contaminant species, nutrients, electron acceptors, electron donors, and breakdown products may be included in the monitoring program. MNA is a technically mature approach and is applied to large sites such as this one. The typical design and operation of a MNA program is illustrated in Figure 6-7.

Site-Specific Application

The potential for natural attenuation was evaluated in detail at the Island No. 1 site in 1995 and again in 1998. The 1995 study (CEC 1995) showed that there is a robust population of aerobic heterotrophic bacteria; that microbial inhibition should not be a problem; and that bioavailable nitrogen may be limiting. The 1998 study (CEC 1998) showed that natural attenuation has stabilized the plume in the direction of Cleves, and that low Eh conditions are accompanied by increasing dissolved iron and decreasing NO_3, which suggests active biodegradation. Note that dissolution of hydrocarbons is the first step in natural attenuation.

Discussion

Wiedemeier et al. (1999) define natural attenuation of contaminants in groundwater as an observed reduction in contaminant concentrations as a result of fate and transport processes including simple dilution, dispersion, sorption, volatilization, and biotic and abiotic transformations. As noted above, biodegradation is expected to be the dominant mechanism of natural attenuation on site after the removal of most of the LNAPL using more aggressive approaches.

Almost all fuel hydrocarbons are biodegradable once dissolved in water. The monoaromatic benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds

Figure 6-7. Conceptual Design for Monitored Natural Attenuation

historically have been the regulatory risk drivers. They are also the most soluble hydrocarbons so they are disproportionately represented in groundwater compared with their mole fraction in the LNAPL. A wide variety of microorganisms can biodegrade petroleum hydrocarbons and are ubiquitous in the subsurface. Over the years and decades that hydrocarbon contamination exists at a typical site, microbes form consortia that are optimally adapted to site conditions.

The primary mechanism of hydrocarbon biodegradation is oxidation, in which electrons are transferred from the hydrocarbon (the electron donor) to an electron acceptor in the aqueous phase. Electron acceptors including oxygen, nitrate, manganese (IV), ferric iron, sulfate, and carbon dioxide can be used in the order of preference listed. The microorganisms derive energy and carbon from these conversions. Thermodynamically, oxygen provides the most energy per mole. As a result, it is used first and is quickly exhausted by the microbiota in the presence of dissolved hydrocarbons, especially since it is only sparingly soluble in water. There is some evidence of sulfate reduction at the site; however, the amount of sulfate present in the groundwater is limited.

6.3.10 Institutional Controls

Institutional controls can limit potential human exposure to contamination. EPA Region V categorizes institutional controls as follows (EPA 2000):

- Informational Devices: Provide information of notification. Examples include state registries of contaminated properties, deed notices, and advisories. They may often be unenforceable.
- Governmental Controls: Are usually implemented by a state or local government and restrict property use. Examples include restrictions on the use of land and water, zoning restrictions, ordinances, building permits, or other permit requirements. Their effectiveness is dependent on enforcement by the competent government entity.

- Proprietary Controls: Legal instruments placed in the chain of title for the property that convey a property interest from the owner to a second party for the purpose of limiting use or imposing restrictions on land and/or water. They include easements and covenants. These controls are binding on subsequent purchasers of the property.
- Enforcement Actions with Institutional Control Components: Including EPA administrative orders and consent decrees that limit or allow certain long-term site activities. Most of these are binding only on the signatories and not on a future buyer. However, EPA may require that the prior land owner remain responsible for adherence to the institutional control.

Potential uses of institutional controls include the following:

- Prevention of the use of impacted groundwater; and
- Restriction on the construction of basements in certain areas with high concentrations of hydrocarbon vapors.

Chevron is currently in discussions with local governmental agencies to determine what institutional controls may be available and how they could be enforced.

6.4 Subsurface Access and Radius of Influence – Water Level

The large area of the LNAPL smear zone (200 acres) imposes practical limits on the technologies that can be implemented at the site. In situ soil and groundwater treatment technologies, such as air sparging, bioventing, SEAR, oxidant injection, Six Phase Heating, etc., are potentially applicable to the site based on the nature of the contaminants, the hydrogeology, and the depth of contamination. However, their applicability is only as good as the degree of access to the contamination. The degree of access achieved is affected by three factors: the areal extent of the LNAPL zone; the seasonal vertical movement of the LNAPL; and the phase (aqueous or non-aqueous) in which the technology reacts with the contaminant. Also, heterogeneities affect some technologies more than others.

No matter which of these technologies is chosen, many wells will be needed to cover the entire 200-acre LNAPL zone. The number of wells is inversely proportional to the square of the radius of influence of each technology. For example, at 50-ft centers (corresponding to a radius of influence of 35 ft), 3,300 wells are needed, while at 100-ft centers (71-ft radius of influence), only 800 are needed. For technologies like air sparging or Six Phase Heating, it is questionable that a 71-ft radius of influence per boring can be achieved. Consequently, the radius of influence of each technology is an essential variable.

Seasonal LNAPL movements also impose tradeoffs between efficiency and effectiveness. Prolonged periods of low water concentrate the LNAPL in a layer on top of the groundwater, providing opportunities for more efficient recovery. This phenomenon presently is exploited to recover LNAPL at the extraction wells on site. LNAPL extraction at low water levels can be enhanced with various technologies such as surfactant and/or polymer floods. Low-water treatment would not directly remove contaminants from the vadose zone. However, natural drainage of LNAPL under three-phase conditions would reduce the residual saturation in the smear zone, thus reducing the likelihood that free-phase LNAPL would reoccur in treated areas.

LNAPL extraction under high water table conditions, on the other hand, offers maximum access to the smear zone for technologies like SEAR or chemical oxidation, but also maximizes the amount and cost of reagents that must be injected.

6.5 Summary Technology Screening

The potentially available technologies discussed in Section 6 were screened based on the preceding review, to decide which ones should be eliminated at this stage and which ones should be further explored in Section 7, where treatment alternatives for the site are examined. The screening can be summarized as follows:

- **Containment:** Containment pumping and seasonal LNAPL recovery is the current practice at the site. It has been successful at preventing reoccurrence of a hydrocarbon sheen on the Great Miami River. A groundwater model (see Section 8) will be used to evaluate the effectiveness of containing LNAPL and the dissolved plume under Hooven and southwest of the facility. Barriers could enhance P&T and will be investigated using the model. Natural attenuation is active in degrading hydrocarbons at the site and thus supplements containment. It may make it possible to seasonally interrupt pumping. Note that containment will have to continue during the implementation of any of the other technologies discussed; it will also have to continue after this until the aquifer is restored to beneficial use. Containment is an essential component of any remediation approach, at least initially, so it will be investigated further in Section 7.
- **Soil Vapor Extraction (SVE):** SVE has been proved to be feasible and effective at full scale in the vicinity of the site, and is a mature technology for vapor control, partial LNAPL removal, and enhancing biodegradation. Consequently, it will be investigated further in Section 7.
- **In Situ Air Sparging (IAS):** IAS has been proved to be feasible in the vicinity of the site (at Gulf Park), and is a mature technology for stripping VOCs from the saturated zone and enhancing biodegradation; will be further evaluated in Section 7.
- **Thermal enhancements, including Six-Phase Heating (SPH)**: Based on a pilot test, it appears that thermal enhancements are problematic at this site because of the high permeability of the aquifer. The relatively free movement of water into and out of the volume being heated increases the energy demand and makes it difficult to achieve sufficient heating. The lateral movement of water may be mitigated by barriers, but they would not affect vertical convective movement. Large-scale application of SPH would require the construction of a small generating plant on the site. It would also require a very large number of borings on site, which would

maximize disruption. For these reasons, thermal enhancements will not be considered as part of the remediation alternatives at the site.

- **Groundwater Circulating Wells (GCWs):** The operation of GCWs is complicated by the presence of a vertically fluctuating LNAPL layer. The ex situ infrastructure would be the same as for a combined SVE and IAS system, but the wells and in-well equipment would be costly. GCWs will not remove LNAPL, and have not been tested at the site in the field or in the lab. For these reasons, they will not be further considered here; the preference will be given to a combined SVE and IAS system.
- **Surfactant-Enhanced Aquifer Remediation (SEAR):** SEAR is unproven for LNAPL at a scale of 200 acre. Questions remain about treatment and recycling of extracted fluids. Laboratory evidence indicates efficacy; SEAR has the potential to remove all mobile LNAPL, leaving a lower residual than other technologies. Because of its potential and the existing site-specific evidence, SEAR will be considered in Section 7.
- **In Situ Chemical Oxidation (ISCO):** Lab tests indicate problems with permeability and pH, and it would be extremely costly. Will not be considered further.
- **Monitored Natural Attenuation (MNA):** MNA will not be investigated per se in this study, but it is understood that MNA is a necessary polishing component of any technology. It also contributes to containment.
- **Institutional Controls:** These controls will be applied irrespective of the technology or combination of technologies chosen. They do not remediate, but they prevent exposure to contaminated soil, groundwater, or LNAPL.

An overview of this screening is provided in Table 6-2.

Table 6-2

Summary Screening of Technologies

Technology	Description	Considered for further Evaluation	Rationale
Containment	Containment pumping, barrier walls, natural attenuation.	Yes	Proven effective at full scale at this site; essential to prevent migration of contaminants.
Soil vapor extraction (SVE)	Extraction of soil vapor, causing stripping of vadose hydrocarbons and enhanced biodegradation.	Yes	Proven effective at full scale to remove or biodegrade hydrocarbons from the vadose zone at this site.
In situ air sparging (IAS)	Injection of air below the water table, causing stripping of hydrocarbons and enhanced biodegradation	Yes	Proven effective in removing hydrocarbons from the saturated zone at nearby site; complements SVE
Thermal enhancements other than Six-Phase Heating	Injection of heated air or steam to reduce viscosity, and enhance stripping of hydrocarbons.	No	Very permeable formation causes large heat losses; energy-intensive; bypasses lenses of tight soil; unproven at this site.
Six-Phase Heating (SPH)	Resistive heating with electrodes in hexagonal pattern; boils water, driving off dissolved hydrocarbons and LNAPL	No	Very permeable formation causes large heat losses; energy-intensive; requires very large number of large diameter borings.
Groundwater Circulating Wells (GCWs)	In situ stripping of groundwater, removes volatiles with exhausted air.	No	Poorly compatible with vertically fluctuating LNAPL layer; expensive infrastructure; does not remove LNAPL; unproven at this site.
Surfactant-Enhanced Aquifer Remediation (SEAR)	Surfactant flooding to mobilize LNAPL.	Yes	The only technology that has the potential to rapidly and thoroughly remove free-phase and residual LNAPL.
In Situ Chemical Oxidation (ISCO)	Injection of oxidant to destroy hydrocarbons in situ.	No	According to site-specific lab tests, poorly compatible with site permeability and pH, very costly.
Monitored Natural Attenuation (MNA)	Sorption, dispersion, and biodegradation	Yes	Essential in final polishing of the site; complements containment.
Institutional Controls	Official notification, government controls, legal instruments that restrict access to the site.	Yes	Will be used in any case to prevent exposure to the contaminants.

7.0 Remediation Alternatives

7.1 Introduction

In this section, four remediation alternatives have been developed from the technologies discussed in Section 6. The time necessary to remediate the groundwater was estimated using a dissolution model. The cost of each alternative is described and some cost sensitivities are explored. The compatibility of these alternatives with the redevelopment of the site is discussed. Finally, the alternatives are evaluated according to a set of criteria prescribed in the Consent Order and the selected alternative is proposed.

7.2 Alternative Descriptions

The technologies that appear to be the most appropriate for the site conditions include:

- Institutional controls
- Containment;
- SVE;
- Inductive Air Sparging (IAS); and
- SEAR.

These technologies have been developed into four different alternatives:

- Alternative 1: Containment
- Alternative 2: Containment + SVE
- Alternative 3: Containment + SVE + IAS
- Alternative 4: Containment + SVE + SEAR

As will be discussed in the following sections, these alternatives generally build upon one another, starting with the least aggressive remedial technology and progressing to the most aggressive combinations of remedial technologies. These alternatives all provide similar levels of protection to human health and the environment, the main difference being the length of time that it will take to reach the cleanup criteria. The alternatives are described below and developed in more detail in Section 7.3.

- **Alternative 1: Containment -** This is the base case alternative on which all the other alternatives are built. This alternative consists of containing the dissolved phase and LNAPL plumes to prevent contaminant migration, continuing LNAPL recovery to the extent practicable, relying on monitored natural attenuation to help reach ultimate remediation goals, and using institutional controls to prevent the use of impacted groundwater.
- **Alternative 2: Containment + SVE –** Alternative 2 builds on Alternative 1 by starting with containment, LNAPL recovery, MNA, and institutional controls. It then adds SVE across the entire site using horizontal SVE wells similar to the HSVE wells under Hooven.
- **Alternative 3: Containment + SVE + IAS –** Alternative 3 builds on Alternatives 1 and 2 by starting with containment, LNAPL recovery, MNA, institutional controls, and HSVE. It then adds IAS across the entire site using vertical air injection wells.
- **Alternative 4: Containment + SVE + SEAR –** Alternative 4 builds on Alternatives 1 and 2 by starting with containment, LNAPL recovery, MNA, institutional controls, and HSVE. It then adds SEAR across the entire site.

7.3 Alternative Development

7.3.1 Alternative 1: Containment

This alternative is the base case and includes use of containment, LNAPL recovery, and institutional controls (see Figure 7-1). The primary objective of the containment alternative is to prevent the migration of either the dissolved phase or LNAPL plumes beyond the point of compliance while meeting all of the Corrective Action Objectives discussed in Section 5.

Figure 7-1 Alternative 1

Containment

Containment potentially could be accomplished in a number of ways. One option would be to continue using pump and treat as is the current practice at the site. Another option would be to use barrier walls or a combination of barrier walls and pumping wells to contain the plumes. Still another option may be to remove LNAPL to the point that it is no longer mobile and then rely on natural attenuation to control the migration of the dissolved phase plume.

At present, hydraulic containment is achieved by extracting large volumes of groundwater to manage the hydraulic gradient. The production wells currently used for this purpose are shown on Figure 4-1. The purpose of this containment is to create an inward hydraulic gradient to prevent free product from migrating off site. This also contains the dissolved hydrocarbons, preventing the migration of a plume of dissolved hydrocarbons. The aquifer is permeable and the area of containment is large, so large flows of water have to be extracted and processed. During high water periods (typically late winter to late summer), little or no free product is encountered because the LNAPL is distributed over a greater depth at high two-phase saturations. Consequently, there is less need for containment and little opportunity for free-product recovery, and a total flow on the order of 1700 gpm (2.4 mgd) is extracted and processed (see Section 4.2). At low water levels (typically early fall to midwinter), free product drains out of the vadose zone and accumulates on the water table in significant amounts. In fact, experience shows that the lower the water table, the greater the free-product recovery. This increases the need for containment and the opportunity for free-product recovery. As a result, extracted flow approximately doubles to 3400 gpm (4.9 mgd) during low water-table conditions. Extracted groundwater is treated in an FBR and a lagoon system before being discharged to the Great Miami River.

If the Containment Alternative is selected, an options analysis would be conducted to determine the optimum way to implement the containment of the dissolved phase and LNAPL plumes. This would involve the use of a groundwater model to optimize flow rates from existing production wells and possibly locate new wells, including injection wells. Note that the location of new wells is not just constrained by hydrogeology but also by the fact that they have to be on Chevron property. Water injection could supplement the hydraulic gradient management. The groundwater model could be used to model the efficacy of barriers. Several barrier configurations are possible. Barriers may make it possible to hydraulically isolate part of the site. Within the barrier, it may be possible to depress the water table, thus enhancing free-product recovery. Conversely, it may be possible to reduce pumping and groundwater treatment while maintaining the same groundwater level.

For the purpose of comparing alternatives in this GWCMS, an assumption is made that the existing P&T operation is continued without barriers or injection wells.

Source Removal

As discussed in Section 2, the LNAPL remaining within the impacted area represents a continuing source of contamination for the groundwater. A finite amount of LNAPL exists under the site so the production of free-phase hydrocarbons using pump and treat techniques is expected to gradually taper off. The production figures for the last decade (see Figures 4-3 and 4-4) indicate that the incremental recovery of free product is already fairly low. Under this alternative, efforts will be made to recover LNAPL to the extent practicable by using the existing LNAPL recovery wells as well as by installing new LNAPL recovery wells. The greatest success with LNAPL recovery recently has been in the area along SR 128. However, at some point it will become uneconomical to continue with LNAPL recovery.

The HSVE wells under Hooven will continue to be operated as long as it is practicable to recover hydrocarbon using them.

Over the long term, dissolution of LNAPL hydrocarbons and MNA will lower the groundwater benzene concentration to the MCL of 5 μg/L. Simulations show that it could take centuries to reach this point.

Finally, it must be noted that remedial activities will have to be designed and operated to be compatible with redevelopment of the site.

Institutional Controls

Institutional controls will have to be put in place to prevent the use of contaminated groundwater and prevent the construction of basements on site. Chevron can manage development on site to ensure that impacted groundwater is not used and that basements are not constructed. Chevron is also investigating various methods of using institutional controls to prevent use of contaminated water off site where Chevron has no control over development.

7.3.2 Alternative 2: Containment + SVE

This alternative builds on all the elements of Alternative 1 and then adds HSVE site-wide (see Figure 7-2). The primary objective of this alternative is to prevent the migration of either the dissolved phase or LNAPL plumes beyond the point of compliance and facilitate the removal of hydrocarbons with SVE while meeting all of the corrective action objectives discussed in Section 5.

Containment

The containment elements of Alternative 2 are essentially the same as those of Alternative 1.

Source Removal

The source removal under Alternative 2 contains all of the source removal elements that are included in Alternative 1. In addition, SVE would be implemented across the site. SVE at the site would be implemented via a network of mostly parallel horizontal wells underlying the whole site (see Figure 7.2). It is assumed that these wells would be drilled from the existing north-south site roads and that they can be spaced 300 feet apart. This would result in approximately 17 horizontal wells on site and 3 or 4 wells off site south of Hooven. The wells would be manifolded together to negative pressure blowers and thermal oxidizers. The depth of the horizontal wells is determined by two opposing

Figure 7-2 Alternative 2: Containment + SVE

constraints: they have to be deep enough to affect a significant portion of the unsaturated profile, but not so deep that they are frequently submerged.

SVE would be operated until diminishing returns are reached, probably in 5 to 10 years. It is assumed that 99% of the benzene in the vadose zone would be removed by that time. Note that the efficacy of SVE will vary from location to location based on soil heterogeneities and the molecular weight of the hydrocarbons. In particular, SVE is likely to be less effective in the area of heavier hydrocarbons in the central eastern portion of the site (see Section 2.3.1 and Figure 2-11). Note also that SVE is incompatible with the planned CAMU since the bottom of the CAMU will be close to the high water table, leaving insufficient room for HSVE wells. SVE will only be possible outside the footprint of the CAMU or before its construction. SVE will have to be harmonized with future redevelopment of the site; in other words, the placement of the wellheads, ductwork, blowers, and oxidizers will have to be compatible with the redevelopment.

Institutional Controls

The institutional controls in Alternative 2 will be the same as those in Alternative 1.

7.3.3 Alternative 3: Containment + SVE + IAS

This alternative builds on all the elements of Alternatives 1 and 2 and then adds IAS site-wide (see Figure 7-3). The primary objective of this alternative is to prevent the migration of either the dissolved phase or LNAPL plumes beyond the point of compliance and facilitate the removal of hydrocarbons with SVE and IAS while meeting all of the corrective action objectives discussed in Section 5.

Containment

The containment elements of Alternative 3 are essentially the same as those of Alternatives 1 and 2.

Figure 7-3 Alternative 3: Containment + SVE + IAS

Source Removal

Alternative 3 builds on Alternatives 1 and 2, and adds IAS to remediate hydrocarbons in the saturated zone and LNAPL. Like SVE, IAS has a physical stripping component and a biodegradation component achieved through aeration of the subsurface. Consequently it also preferentially removes lighter hydrocarbons. Horizontal wells are not the preferred option for IAS because of the probability that air injection would be very unequal along the length of the well. Instead, the air would be injected via a network of vertical wells laid out in an orthogonal grid. The wells would be manifolded to a set of positive pressure blowers. Each injection well would only be operated intermittently to minimize the formation of air channels. IAS will greatly increase the required SVE offgas handling capacity as the extracted flow (SVE) is typically three times the injected flow (IAS). Therefore, more and larger air ducts will be needed as well as more blower and oxidizer capacity.

Chevron has IAS experience at Gulf Park, near the site (see Section 6.3.4). For this evaluation of alternatives, it was assumed that the IAS wells would have a greater radius of influence at the site than at Gulf Park because of much higher per well injection rates made possible by the existence of an SVE system at the site as well as greater injection depth. The IAS wells would be installed at 50-ft centers which would result in approximately 3500 wells for the whole 200-acre plume area. Because the drilling is vertical, IAS would be limited to Chevron property. IAS would be impossible on the site of the planned CAMU and the treatment pond. It could be implemented over the CAMU footprint before the CAMU’s construction. IAS and SVE would be less effective in the area of heavier hydrocarbons in the east-central part of the site. For modeling purposes, it was assumed that IAS would remove 80% of the benzene from the saturated zone. Like SVE, IAS would be operated until diminishing returns force its closure, typically after 5 to 10 years. The vertical IAS system is incompatible with redevelopment and will have to be dismantled before such redevelopment can take place.

Institutional Controls

The institutional controls in Alternative 3 will be the same as those in Alternatives 1 and 2.

7.3.4 Alternative 4: Containment + SVE + SEAR

This alternative builds on all the elements of Alternatives 1 and 2 and then adds SEAR site-wide (see Figure 7-4). The primary objective of this alternative is to prevent the migration of either the dissolved phase or LNAPL plumes beyond the point of compliance, and aggressively remove hydrocarbons with SVE and SEAR while meeting all of the corrective action objectives discussed in Section 5.

Containment

The containment elements of Alternative 4 are essentially the same as those of Alternatives 1, 2, and 3.

Source Removal

This alternative represents the most aggressive approach to remediating the site. SEAR would be used to flush most of the LNAPL from the saturated zone and remove the free phase, while SVE would attack the vadose zone. SEAR would be implemented at a low water table to take advantage of the vertical natural drainage of LNAPL and minimize the volume of aquifer to be treated, and thus the volume and cost of surfactant to be used. SEAR is different from the other technologies considered because it would be implemented in small blocks referred to as panels. A panel would be treated in a few weeks, after which time the operation would move to the next downgradient panel. This process would extend over several low water seasons, progressing downgradient until the entire site is treated.

The surfactant mix would be injected through a row of injection wells spaced 10 to 15 ft apart and extracted through a similar and parallel row of wells 50 ft from the injection row. Under these assumptions, approximately 17,000 wells may have to be drilled, a truly enormous and unprecedented operation. The SVE system, as described in 7.3.2,

Figure 7-4 Alternative 4: Containment + SVE + SEAR

would be installed and operated immediately after SEAR is completed in a particular area. Because of the intense drilling required, SEAR could only be implemented on site. SEAR would require substantial development before it could be implemented at the site. The spacing of the wells would have to be defined. It has been assumed that the extracted fluids will be treated and entirely recycled or removed. The feasibility of this concept must be proven. A flexible design will have to be developed to allow the system to function despite the sudden fluctuations in the water level that are observed at the site. The application of SEAR to this site is two orders of magnitude larger than the largest SEAR operations conducted to date. To bridge this experience gap will also require substantial technology development.

SEAR would leave very low residual LNAPL saturations and would be equally effective against the heavier oil found in the east-central part of the site. It would be incompatible with the CAMU and the treatment pond because of the close spacing of wells that would be required. It could be implemented over the CAMU footprint before the CAMU's construction. Only after SEAR has been completed in a given area can redevelopment begin in that area. In that regard, it may be observed that the southern area that will support the most intensive commercial development is also downgradient, and will thus be treated last. After SEAR, SVE would be applied until it becomes ineffective after 5 to 10 years.

Institutional Controls

The institutional controls in Alternative 4 will be the same as those in the other Alternatives.

7.4 Analysis of Alternatives

In this section, the alternatives are analyzed based on the length of time that it will take to reach the final cleanup goals; the cost of implementing the alternatives; and the compatibility of each alternative with redevelopment of the site.

7.4.1 Time to Reach the Final Cleanup Goals

For the purpose of this evaluation, it was assumed that the final cleanup goals were drinking water standards, in this case, MCLs. Modeling indicates that benzene is the primary contaminant of concern and that if benzene can be reduced to its MCL, all other contaminants should also be at or below drinking water standards.

The LNAPL represents a source for all the contaminants of concern. All of the alternatives, except Alternative 1, include an initial source removal phase (SVE, SVE + IAS, or SVE + SEAR), followed by a lengthy application of containment until dissolution brings the concentration of benzene down to the MCL of 5 micrograms per liter. How long this subsequent containment period will last depends on how much benzene and how much LNAPL are left after the initial source removal phase. A dissolution model was used to estimate how long containment would have to be applied after the initial source removal phase. This model is presented in Appendix A; the assumptions used are also described there.

The results of the dissolution modeling are presented in Table 7-1. The first two columns list the alternative that was modeled. Column 3 lists the assumed benzene removal efficiency achieved by implementing the source removal technology listed. In the case of Alternative 1, there is no initial application of a source removal so there is no initial benzene removal. For Alternative 3, SVE + IAS, the assumed benzene removal efficiencies of SVE and IAS are listed separately.

Table 7-1

Estimated Time needed for the Groundwater Benzene Concentration to Drop Below the MCL (5 μg/L), After Initial Source Removal

Alternative	Initial Source Removal Technology	% Benzene Removed Initially	Residual LNAPL (% saturation)	Estimated Duration[1] (yrs)
1	None	0	No initial impact on residual saturation	458
2	SVE	99%		294
3	SVE + IAS	99% / 80%		233
4	SVE + SEAR	99%	1%	93

[1] After the initial source removal (SVE, SVE + IAS, SVE + SEAR) has been completed.

Column 4 shows the residual LNAPL saturation after implementation of the initial source removal technology. Investigations indicate that the average residual LNAPL saturation across the site is approximately 8%. Note that SVE and IAS have some impact on residual LNAPL saturation, but this impact was assumed to be negligible for the purpose of this modeling exercise. The only technology that would have a significant impact on LNAPL saturation was assumed to be SEAR, which would achieve a residual LNAPL saturation of approximately 1%. Better results may have been obtained in lab and small-scale field studies. However in this case, SEAR will not be able to reach the entire smear zone, whether applied during high or low water periods, so 1% seems to be a reasonable average for the entire smear zone. All of the alternatives include an effort to continue removing LNAPL, to the extent practicable, using pump and treat as discussed in Section 7.3.1. These removal efforts were assumed to be similar for all alternatives and have been factored into the evaluation.

Finally, Column 5 shows the results of the dissolution modeling in terms of years of containment needed to reach the benzene MCL, after the initial source removal (SVE, SVE + IAS, or SVE + SEAR) has been completed. For the base case, Alternative 1 – Containment, there is no initial source removal (other than the continued free phase LNAPL recovery through pump and treat that is common to all the alternatives) so the duration listed in Column 5 is the total time from the present to the achievement of the benzene MCL.

The modeling results are also shown in Table 7-2. In this table, the estimated duration of initial source removal was added to the subsequent containment duration calculated by the model. It was assumed that SVE would be implemented site-wide for 12 years; SVE + IAS would only take 10 years because of the enhancement due to sparging; and SEAR + SVE would require 8 years of field work. It was further assumed that no significant biodegradation would occur as long as there was significant residual LNAPL present. These results are displayed in Table 7-2 and Figure 7-5.

Table 7-2

Estimated Time from Present Needed for the Groundwater Benzene Concentration to Drop Below the MCL (5μg/L)

Alternative	Initial Source Removal Technology	Time after Initial Source Removal	Duration of Initial Source Removal	Total Duration
		Years	Years	Years from Present
1	None	458	0	458
2	SVE	294	12	306
3	SVE + IAS	233	10	243
4	SVE + SEAR	93	8	101

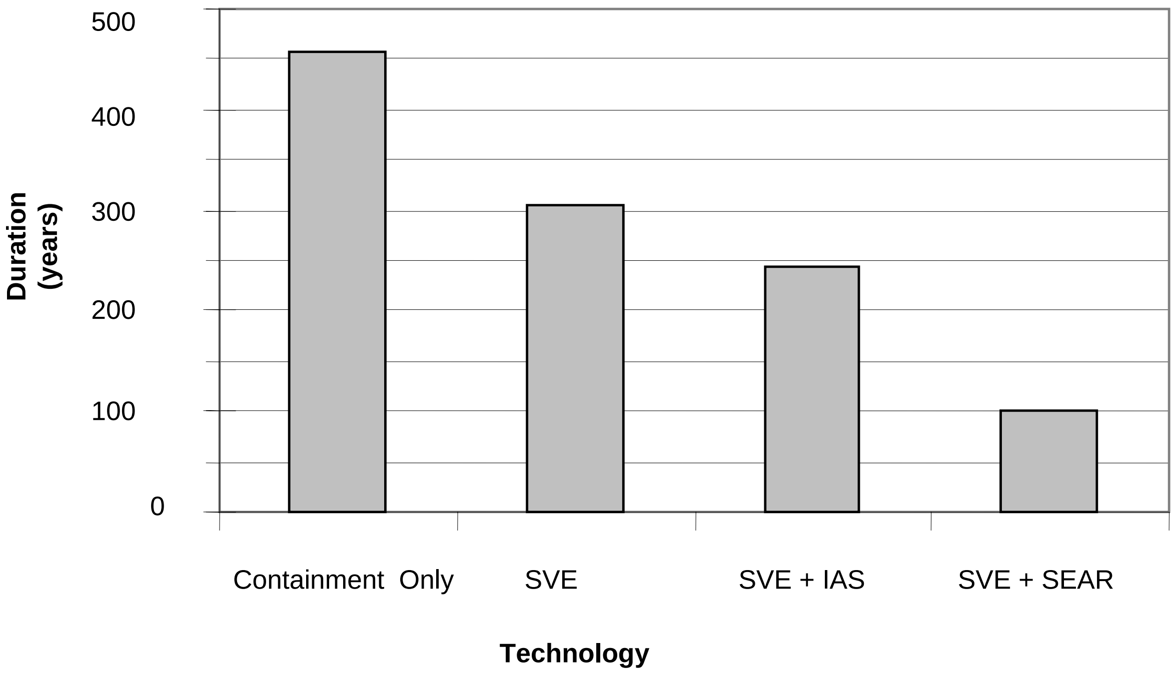


Figure 7-5

Projected Durations from Present to 5 μg/L Benzene, versus Technology

The following observations can be made:

- Compared to the containment alternative (Alternative 1), the addition of site-wide SVE (Alternative 2) has limited impact on remediation duration because the SVE does not affect the saturated zone directly.
- SVE + SEAR (Alternative 4) allows the shortest remediation duration, but it is still close to 100 years assuming that no significant biodegradation takes place as long as residual LNAPL is present.

7.4.2 Cost Analysis

The costs associated with each alternative were estimated using the approach documented in Appendix B. It lists the following cost inputs and assumptions:

- Financial assumptions;
- Fixed costs for short term operations;
- Annual operating costs for containment (in this case, assumed to be pump and treat) including the cost of periodic replacement of the water treatment plant;
- The cost of free-product recovery (this is the LNAPL removal associated with the pump and treat that is common to all the alternatives); and
- The cost of initial source removal (via SVE, SVE + IAS, or SVE + SEAR).

Ongoing Site Operations

Ongoing site operations are those items that are common to all the alternatives. For the purposes of this GWCMS, it is assumed that containment would initially be achieved with continued P&T and the costs are developed accordingly. If a later options analysis indicates that barriers or other technologies could reduce the overall containment costs, these costs savings would be similar across all the alternatives and would not affect the overall evaluation of alternatives.

Continued P&T, replacement of the GAC FBR every 25 years, and free-product recovery are combined under the heading "Ongoing Site Operations." These operations are currently underway at the site, except for the replacement of the GAC FBR, which has not yet taken place because the system has not been in operation for its estimated useful life of 25 years. This section examines the cost of these operations over the life of the remediation at the site, which is discussed in Section 7.4.1 and shown in Table 7-2 and Figure 7-5. The ongoing site operations costs are summarized in Table 7-3.

Table 7-3

Present Worth Cost of Ongoing Operations over the Life of the Remediation at the Site

Alternative	Initial Source Removal Technology	Present Worth of Costs ($ millions)			
		P&T	GAC FBR Replacement	Free-product recovery	Total
1	None	43.68	4.97	0.55	49.20
2	SVE	43.57	4.96	0.55	49.08
3	SVE + IAS	43.28	4.95	0.41	48.64
4	SVE + SEAR	37.43	4.52	0.27	42.22

The P&T column lists the present worth of the annual P&T cost of $848,333 (see Appendix B) over the total duration of the remediation, as listed in Table 7-2. The GAC FBR column shows the present worth cost of replacing the GAC FBR in 10 years and every 25 years thereafter. The Free-Product Recovery column lists the present worth cost of recovering free product over the next 16 years, as described in Appendix B. The total of these present worth costs is nearly the same for Alternative 1, 2 and 3 and only slightly less for Alternative 4.

Overall Present Worth of Costs

In this section, the present worth of short-term and long-term costs is combined to provide an overall present worth cost. To simplify the costing, the capital cost of the initial source removal is not discounted; in other words, the installation and operation of the initial source removal infrastructure is assumed to be instantaneous.

The present worth of all costs is summarized on Table 7-4 and displayed on Figure 7-6.

Table 7-4

Present Worth of All Costs Associated with Alternatives 1 through 4

Alternative	Initial Source Removal Technology	Present Worth ($ millions)			
		Initial Source Removal		Ongoing Site Ops.	Grand Total[1]
		Capital	O&M		
1	None	0.00	0.00	49.20	50.45
2	SVE	18.74	23.77	49.08	92.84
3	SVE + IAS	24.78	32.08	48.64	106.74
4	SVE + SEAR	89.76	16.45	42.22	149.68

[1] Includes $1.25 million in fixed costs, as discussed in Appendix B.

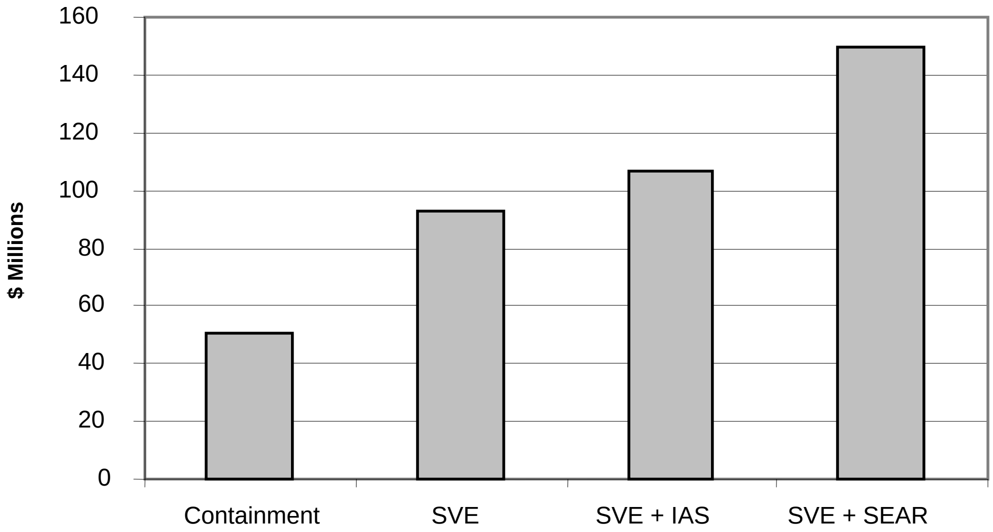


Figure 7-6 Present Worth of Alternatives

The following observations can be made:

- Total present worth costs increase significantly as increasingly aggressive source removal technologies are applied: Alternative 1 (Containment) < Alternative 2 (Containment + SVE) < Alternative 3 (Containment + SVE + IAS) < Alternative 4 (Containment + SVE + SEAR).
- Alternative 4 (Containment + SVE + SEAR) is the fastest alternative, as discussed in Section 7.4.1. It is also the most expensive alternative.

- Alternative 1 (Containment only) is the slowest alternative (see Section 7.3.2), but it is also the least expensive in terms of present worth.

7.4.3 Sensitivity Analyses

The impact of biodegradation rate on cost was evaluated and it turned out that this rate has little impact on the present worth of costs. This is due to the fact that biodegradation generally only affects duration far in the future when the changes in discounted value are minimal. Additionally, it does not affect front-end costs.

Second, the sensitivity of present worth costs to groundwater velocity was examined. The base case assumes a groundwater velocity of 4 ft/day, which is at the high end of the estimated site velocity range of 2 to 4 ft/day. Groundwater velocity is inversely proportional to duration of containment after initial source removal. So, halving the velocity will double the time to achieve 5 μg/L of benzene after the initial source removal is completed. For example, Alternative 1 (Containment) without biodegradation takes 458 years to achieve the treatment objective at 4 ft/day (see Table 7-1). At 2 ft/day, it would take 916 years. The effect on present worth of halving the groundwater velocity to 2 ft/day is small because the additional costs are generally so far in the future that they are discounted to infinitesimal levels.

7.4.4 Short-Term, Intermediate and Long-Term Focus

The estimated remediation times for the alternatives range from 101 years for the most aggressive alternative to 458 years for the containment alternative. Chevron believes that regulations will continue to evolve over the next 100 years and there will undoubtedly be huge advances in remediation technologies. Therefore, it is unlikely that a final remedy selected today requiring a century or more to complete will remain unchanged as regulations evolve and technologies change. Given this, Chevron proposes to focus on the short-term protectiveness goals and intermediate performance goals as discussed in Section 5. Therefore, the primary focus of the alternative evaluation is the impact that these alternatives would have over the short- and intermediate-term, the next 15 years.

7.4.5 Compatibility of Remediation with Site Redevelopment

As discussed in Section 3, the conceptual development plan includes a commercial/light industrial area in the southern half of the site. How compatible are the various alternatives with the development plan?

All alternatives involve continued containment (P&T has been assumed for evaluation purposes) including free-product recovery. Continued P&T is reasonably compatible with redevelopment, provided the detailed redevelopment plan takes into account the existing and planned production and monitoring wells. The oil and water pipelines may have to be rerouted around planned construction, which is fairly straightforward. The wellhead equipment is fairly unobtrusive and quiet. Alternative 1 only involves containment and free product removal, and should be compatible with site redevelopment.

Alternatives 2, 3, and 4 involve the installation of a network of horizontal SVE wells over the entire site. Once the wells are installed, development could proceed without significant interference. There is some flexibility in the location of the blower systems and thermal oxidizers; however, they may have some impact on the layout of the proposed redevelopment.

Alternative 3 also involves the installation of an IAS system. Applying IAS using horizontal wells is unlikely because it would be difficult to ensure an equal flux of air over the entire length of the horizontal well. Because of much shorter screen lengths, a network of vertical wells would probably be more effective. This network will be dense and would probably include hundreds or thousands of vertical wells. Such a network of wells is clearly incompatible with redevelopment, therefore, redevelopment would have to be delayed until the IAS was completed and the IAS infrastructure could be removed. Significant redevelopment could not occur until after the anticipated 10-year duration of the IAS system.

SEAR (Alternative 4) may require an even denser network of vertical wells than IAS. However, SEAR would be applied in one small area at a time. After each small area is treated, SEAR operations would move on to the next parcel. Over a period of eight years, the entire site would be treated. Each local application of SEAR would only take a few weeks or months, after which the wells would be capped and the area vacated to allow redevelopment. However, SEAR would probably begin at the upgradient (northern) end of the site and progress downgradient (southward). This would mean that the southern end of the site that is proposed for commercial redevelopment would be the last area remediated. From a practical point of view, significant site redevelopment could not begin until after the eight-year period.

7.5 Evaluation of Alternatives

This section presents an analysis of the alternatives using the information developed in Section 7. The evaluation criteria are based on EPA guidance documents, including the *Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action* (EPA530-D-00-001).

Procedural guidance for remedy selection at the Chevron Cincinnati facility was included in the *Scope of Work for a Corrective Measures Study at Chevron USA—Cincinnati Refinery* given in the Consent Order. This guidance has two main evaluation criteria, which are broken down to a total of nine separate sub-criteria. The evaluation criteria are:

Technical/Environmental/Human Health/Institutional:

1. Effectiveness and useful life;
2. Reliability and O&M requirements;
3. Implementability and constructability
4. Duration;
5. Safety;
6. Environmental short term and long term;
7. Human health short term and long term;

8. Institutional (regulatory and community relations); and
9. Cost.

Remedial alternatives were evaluated and ranked using these evaluation criteria. Table 7-5 illustrates the type of grading scale used in evaluating and ranking the alternatives. This grading scale was used to grade all alternatives for each criterion.

7.5.1 Effectiveness and Useful Life

The potential for migration is the same for all alternatives since they all rely on the same containment measures. The potential for migration is small, so all alternatives will receive a score of 2.

7.5.2 Reliability and O&M Requirements

Alternative 1 relies on the existing P&T system, which is proven and ongoing; some O&M is required so this alternative receives a score of 2. Alternatives 2 and 3 are innovative at this scale so they will receive a score of 1. Alternative 4 is definitely developmental so it warrants a score of 0.

7.5.3 Implementability

Alternative 1 is already constructed so its implementability is not in doubt and its score is 3. Alternative 2 is an extrapolation of technology existing adjacent to the site so it gets a 2, whereas Alternative 3 gets a score of 1 because of the added complexity of an IAS system and the major drilling effort required. Alternative 4 will require a lot of development work so its score is 0.

7.5.4 Safety

Alternative 1 involves the handling of liquid hydrocarbons so it will be assigned a score of 2. Alternatives 2 and 3 require the additional handling of hydrocarbon vapors and produce air emissions from the oxidizers, resulting in a score of 1. Alternative 4 has all these concerns plus the handling and reinjection of very concentrated fluids so it will be given a score of 0.

Table 7-5

Remedy Selection Decision Factor Grading Scale

Remedy Selection Factor	Grade	Grade Points	Grade Definition
Effectiveness and Useful Life	Excellent	3	Completely prevents the potential for future migration through rigorous treatment, containment, or both. Excellent ability to perform intended function through design or performance standards. Unlimited useful service life.
	Good	2	Limited potential for migration due to less rigorous treatment or containment. May not fully address contamination. Good ability to perform intended function through design or performance standards. Prolonged useful service life.
	Fair	1	Incomplete or limited treatment. Limited ability to perform intended function through design or performance standards. Limited useful service life.
	Poor	0	No reduction in toxicity, mobility, or volume. Poor ability to perform intended function through design or performance standards. Inadequate useful service life.
Reliability and O&M requirements	Excellent	3	Highly effective and proven treatment. Minimal risk of failure, or failure would have insignificant impact on receptors. Little or no operation and maintenance required.
	Good	2	Effective treatment, used in similar conditions and applications. Low risk of failure or failure would have little impact on receptors. Operation and maintenance requirements are straightforward and/or infrequent.
	Fair	1	Innovative approach or technology. Operation and maintenance requirements are complex and/or frequent. Risk of failure or failure would have significant impact on receptors.
	Poor	0	Developmental or unproven approach. High risk of failure or failure would adversely impact receptors. O&M requirements are stringent.
Implementability	Excellent	3	No significant construction or regulatory issues. Technology, regulatory climate, and internal climate favorable. Benefits of treatment can be observed immediately. Expedites the timing of remedial activity implementation.
	Good	2	Site conditions do not interfere with constructability. Technology and climate mostly favorable. Some issues may require additional testing, evaluation, and negotiation. Remedial activity implementation is swift, and benefits of treatment are quickly apparent.
	Fair	1	Site conditions have some effect on constructability. Innovative approach or technology. Some regulatory hurdles. Remedial activity implementation and/or observable treatment benefits may be delayed.
	Poor	0	Site conditions adversely affect constructability. New or developmental technology or approach. Extensive regulatory and/or community input is required. Extensive negotiations may delay technology implementation, or technology takes a long time to produce beneficial effects.

Table 7-5 (Continued)

Remedy Selection Factor	Grade	Grade Points	Grade Definition
Safety	Excellent	3	Minimal material handling or waste management activities. Waste handling/management performed under controlled conditions. Little or no threat to workers or nearby communities during implementation.
	Good	2	Some material handling/waste management. Activities well controlled. With proper controls, no threat to workers or nearby communities during implementation.
	Fair	1	Rigorous yet controlled material handling and waste management. Some risk of short-term release or exposure. Some potential threat to workers or nearby communities during implementation.
	Poor	0	Extensive material handling or waste management activities. Potential for short-term releases or exposures. Can pose a threat to workers or nearby communities during implementation.
Environmental effects (short and long term)	Excellent	3	Large (90-100%) reduction in toxicity or mobility. Waste is managed and contained so as to minimize future releases and optimize short-term efficacy. Eliminates contact and migration potential.
	Good	2	Reasonable (risk-based) reductions in toxicity or mobility. Short-term exposure risk is restricted. Reduces exposure risk by limiting contact and migration potential.
	Fair	1	Some reduction of toxicity or mobility, but not wholly effective for the contaminants of concern. Contact and/or migration potential if containment systems or other engineering controls fail. Some risk of short-term release or exposure.
	Poor	0	No reduction in toxicity or mobility. Will result in a release if the containment systems or other engineering controls fail. Contact and/or migration potential is persistent.
Human Health effects (short and long term)	Excellent	3	Large (90-100%) reduction in toxicity or mobility. Waste is managed and contained so as to minimize future releases and optimize short-term efficacy. Eliminates contact and migration potential.
	Good	2	Reasonable reductions in toxicity or mobility. Short-term exposure risk is restricted. Reduces exposure risk by limiting contact and migration potential.
	Fair	1	Some reduction of toxicity or mobility, but not wholly effective for the contaminants of concern. Contact and/or migration potential if containment systems or other engineering controls fail. Some risk of short-term release or exposure.
	Poor	0	No reduction in toxicity or mobility. Will result in a release if the containment systems or other engineering controls fail. Potential for short-term releases or exposures. Contact and/or migration potential is persistent.

Table 7-5 (Continued)

Remedy Selection Factor	Grade	Grade Points	Grade Definition
Institutional Concerns	Excellent	3	Community in full support of technology. Technology, regulatory climate, and internal climate favorable. No significant construction or regulatory issues. Expedites the timing of remedial activity implementation.
	Good	2	Public support for proposal is available. Technology and climate mostly favorable. Some issues may require additional testing, evaluation, and negotiation.
	Fair	1	Some community relations issues. Innovative approach or technology. Some regulatory hurdles.
	Poor	0	Community dislikes alternative. New or developmental technology or approach. Will require extensive regulatory negotiation. Remedial activity implementation may be delayed.
Construction Cost	None	None	Construction cost of implementing remedy.
O&M Cost	None	None	O&M cost of implementing remedy.

7.5.5 Environmental Effects (Short- and Long-Term)

For all alternatives, the mobile LNAPL and dissolved hydrocarbons are contained, so the efficacy of containment is not a differentiator, but it implies that no alternative should get a score below 2. Alternative 1 removes only free phase LNAPL and has no direct impact on benzene; of all the alternatives, it leaves the most LNAPL and benzene in the ground so it will be given a score of 2. Alternatives 2 and 3 have more impact on benzene and LNAPL but not to the point of warranting a higher score, so they also will be assigned a score of 2. Alternative 4 is the only one with the potential of removing most of the LNAPL and thus the source of benzene, so it will be given a score of 3.

7.5.6 Human Health Effects (Short- and Long-Term)

The scoring for this criterion will follow the same reasoning as for the environmental effects, i.e., a 2 for Alternatives 1, 2, and 3, and a score of 3 for Alternative 4.

7.5.7 Institutional Concerns

Alternative 1 is already in place and is well accepted, so it will be given a score of 3. Alternative 2 is fairly straight forward and should receive public support and will be given a score of 2. Alternative 3 precludes site redevelopment for the 10-year implementation of the IAS system which goes directly against the community desires to begin redevelopment as soon as possible. Therefore, Alternative 3 will be given a score of 1. Alternative 4 has the similar impacts on site redevelopment as Alternative 3 plus it is developmental and involves extremely intense drilling and reinjection of very concentrated fluids so it will be given a 0.

7.5.8 Costs

RCRA's overriding mandate is the protection of human health and the environment. However, the EPA believes that relative cost is a relevant and appropriate consideration when selecting alternatives that achieve the cleanup objectives. EPA has stated that cost may be one of the selection criteria for alternatives that offer equivalent protection of human health and the environment.

The total present worth of costs for the different alternatives was presented in Section 7.4.2.

7.6 Alternative Ranking

All the scores are tallied in Table 7-6. Note that the cost information is listed for information only, it is not used in computing the final score.

Alternative 1 has the highest final score (16), combined with the lowest present worth cost ($50 million). The high score is due in large part to the fact that containment is proven and effective at the site based on ongoing operations. Conversely, Alternative 4 has the lowest score (8) and the highest cost ($150 million). Its low score in turn is mainly due to the fact that it is the most developmental approach. The other two alternatives have scores and costs that fall between Alternatives 1 and 4; Alternatives 2 and 3 have similar scores and present worth costs.

Table 7-6

Composite Evaluation of Alternatives

Alternative No.	Effectiveness and Useful Life	Reliability and O&M Requirements	Implementability	Safety	Environmental Effects	Human Health Effects	Institutional Concerns	Present Worth Cost ($ millions)	Final Score
1	2	2	3	2	2	2	3	50	16
2	2	1	2	1	2	2	2	90	12
3	2	1	1	1	2	2	1	107	10
4	2	0	0	0	3	3	0	150	8

7.7 Conclusions

The estimated remediation times and estimated costs for the four alternatives are shown in Table 7-7.

Table 7-7

Estimated Remediation Times and Costs for Four Alternatives

Alternative No.	Present Worth Cost ($ millions)	Estimated Remediation Time
1	50	458 years
2	96	306 years
3	107	243 years
4	150	101 years

The four alternatives that have been developed comprise a range of approaches from continued containment (Alternative 1) to the most aggressive (Alternative 4). An analysis of these alternatives indicates that even with the most aggressive approach, it will take at least a century to meet the final cleanup goals. Practically speaking, it is not possible to return the aquifer to its maximum beneficial use in a reasonable time period.

Given this, Chevron proposes to implement Alternative 1, the containment alternative, and focus on the short-term and intermediate corrective action objectives identified in Section 5.

Chevron agrees that the long-term goal is to return the impacted portion of the aquifer to its maximum beneficial use and will continue to work toward that goal through the containment alternative.

8.0 Design Tasks

This section describes design tasks that are planned to optimize the selected alternative.

8.1 Optimization of Recommended Alternative

The recommended remedy for the next 15 years is Alternative 1, Containment. This alternative involves various combinations of features to contain LNAPL that will need to be configured to optimize containment. The principal design tool used to optimize containment will be a numerical groundwater flow model. Specifically, it will be used to optimize pumping and LNAPL recovery operations, and evaluate the effectiveness of barrier walls.

Chevron has begun preparing a numerical finite-difference groundwater flow model (MODFLOW). The MODFLOW model will be constructed and calibrated to a representative water-table map (representing steady-state conditions) as well as various pumping scenarios and river stages (transient conditions). In addition, the model will be calibrated to simulate measured well responses with aquifer tests that have been performed at the Chevron facility. The groundwater model will be used to optimize hydraulic containment by determining the minimum flow rate compatible with hydraulic containment. It may also be used to determine the optimal location of potential new production wells from the standpoint of hydraulic containment and LNAPL recovery.

In addition, the groundwater model will be used to evaluate the effectiveness of hydraulic barriers. These are discussed in more detail in Section 6.3.1. In summary, the following possible barrier locations will be investigated:

- Longitudinal walls along the Great Miami River. This type of barrier may be an alternative to hydraulic control or supplement hydraulic control efforts to prevent LNAPL discharge to the river. Longitudinal wall(s) may either obviate the need for pumping near the river or result in reduced pumping rates or durations. The groundwater flow model will be used to evaluate the effectiveness of this measure.

- A longitudinal wall along SR 128 adjacent to Hooven. The main purpose of such a wall would be to mitigate further migration of LNAPL off site into Hooven. However, this measure could interfere with any potential LNAPL movement from Hooven to on-site recovery wells. The existing horizontal wells will also interfere with this option.
- An east-west trans-valley wall upgradient (north) of the LNAPL plume. Such a wall could be fully penetrating due to the reduced depth to bedrock in that area. It could reduce groundwater influx into the southern part of the site, resulting in lower groundwater levels. As noted earlier, low groundwater levels promote gravity drainage of LNAPL into wells, thereby extending the LNAPL recovery season and enhancing annual free-product recovery.
- Capillary barrier walls to prevent LNAPL migration. These walls would have little impact on groundwater flow or levels but would intercept free product. They could be installed along SR 128 to prevent free product migration into Hooven. The design and operation of capillary walls will be evaluated, with special emphasis on long-term maintenance.

8.2 Compatibility of Recommended Remedy with Redevelopment

The existing hydraulic control operation will have to be modified so that it is compatible with the proposed land development. The water and oil piping system will have to be rerouted and may have to be buried to be compatible with redevelopment. On the other hand, the development plans may have to be modified to accommodate the wellhead infrastructure.

9.0 Groundwater Monitoring Program

Chevron has a comprehensive groundwater monitoring program (referred to as the Interim Measures or IM Program) in place at the facility to evaluate the horizontal and vertical extent of groundwater contamination as well as to verify that contaminated groundwater is not migrating.

The current monitoring program includes:

- Measuring water levels and LNAPL thickness six times a year from approximately 115 monitoring wells.
- Conducting semi-annual sampling of selected monitoring and production wells on the facility and Island No. 1. During the two semi-annual sampling events in 2000, 22 wells were sampled.
- Conducting quarterly sampling of selected monitoring wells in and adjacent to Hooven. During four quarterly sampling events in 2000, 23 wells were sampled. This program was updated to change the wells in Hooven from quarterly to semi-annual sampling in correspondence sent to the U.S. EPA on March 26, 2001. Monitoring wells in Hooven were sampled during the first semi-annual sampling event in 2001.

All groundwater measurements and sampling are performed in accordance with Chevron's revised Mini-Quality Assurance Project Plan (Mini-QAPP), dated October 1995, and approved with modifications by the EPA in a letter to Chevron dated November 3, 1995. The following presents the scope of work that will be performed during dissolved phase and LNAPL monitoring as detailed in Chevron's Mini-QAPP.

The current groundwater monitoring program will be updated based on the future agreement (CMI Order) with the EPA regarding the POC boundary. As discussed in Section 5.3, the point of compliance (POC) will be established around the dissolved phase and LNAPL plumes. The proposed groundwater monitoring program will specifically address intermediate performance goals (see Section 5.2). The location of the POC wells and sentinel wells will be identified as part of the Containment Options Analysis.

Chevron anticipates that this effort will include the use of a geostatistical approach to evaluate the current monitoring well system, and to develop an appropriate future system that will eliminate redundancies and promote the effective use of wells and analytical strategies to evaluate the performance of the hydraulic containment program.

10.0 Implementation Schedule

The proposed implementation schedule for the selected alternative is shown on the GANTT chart in Figure 10-1.

Figure 10-1. Chevron Cincinnati Groundwater Remedy Implementation Schedule

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Attachment A

Large-scale Dissolution Model

Large-scale Dissolution Model

[Summarized from DE&S 2001]

A.1 Upscaling

The two-dimensional geosystem developed for the Tracer Test Site area was scaled up to the approximate length (parallel to groundwater flow) of the LNAPL smear zone at the Chevron Cincinnati Facility (4,000 ft). The scaleup was accomplished by extrapolating the PITT area permeability and saturation distributions to the entire site. Based on results from the sensitivity analysis (DE&S 2001) that indicated the importance of vertical heterogeneity on the dissolution results, the vertical discretization of 1-ft gridblocks through the smear zone was not altered in the upscaling process. In contrast, the relative lack of sensitivity of dissolution results to horizontal heterogeneity allowed coarsening of the horizontal discretization to that of 21.6-ft gridblocks along the axis of flow throughout the model domain. A total of $nx \times ny = 184 \times 21 = 3{,}864$ gridblocks were used for the large-scale model.

A.2 Detailed Compositional Model

For the short time frames used in the column and Tracer Test area simulations, it was sufficient to approximate the LNAPL using five soluble contaminant components (benzene, toluene, ethylbenzene, o-xylene, and p+m-xylene) and one remaining insoluble pseudocomponent. At the longer time frames of interest for simulating the time for benzene to reach MCL levels in the groundwater (i.e., centuries), this simplistic approach was no longer sufficient. Instead, in addition to the 4 BTEX components (all three xylene isomers being grouped in this case), another 12 pseudocomponents were used to approximate the LNAPL.

These 12 components were chosen based on the High Temperature Simulated Distillation (HTSD) results for LNAPL sample P-I2-45 reported in the LNAPL characterization study (Radian and DE&S, 2000). Components with carbon numbers of 16 and greater were grouped into one component with an effective carbon number of 22 based on the centroid of the component distribution. Aqueous solubilities have not been measured or are not published for most of the components with carbon numbers greater than ten. To assign properties to these components, a log-linear fit of the solubility with respect to carbon number was made to published values for dodecane, hexadecane, and octadecane, and the values were either interpolated or extrapolated.

By including the mass fractions and solubilities of the LNAPL components in this way, it was possible to simulate the long-term effects of Raoult's Law on the benzene dissolution. Because benzene and the TEX components are among the most soluble components in the LNAPL, they are depleted fastest from the LNAPL. As they are depleted, however, the effective solubility (i.e., the product of the mole fraction in the LNAPL and the pure compound aqueous solubility) is reduced. The degree to which the LNAPL saturation changes is governed by the amount of lighter hydrocarbons in the LNAPL. Unless the NAPL consists largely of relatively soluble components, the overall saturation will not change significantly even over very long periods of time. More pronounced may be the "weathering" or depletion of lighter components from the LNAPL.

A.3 Simulation Results

The time required to reach the MCL for benzene will depend (with inverse proportionality) on the groundwater velocity at the site. For the range of groundwater velocities observed at the site, the model predicts that between 360 and 610 years will be required to reach the MCLs for benzene in a monitoring well adjacent to the downstream end of the LNAPL zone.

The LNAPL saturation is only mildly affected by dissolution even after 100 years. More profound is the change in the fraction of benzene within the LNAPL. The depletion of benzene from the LNAPL occurs primarily from the bottom of the smear zone upward and from the upgradient portion of the smear zone along the direction of groundwater flow. It is this process that results in lower benzene solubilities.

It should be noted that these simulations depend on the geosystem (i.e., the permeability and LNAPL distributions) as well as the LNAPL composition input into the model. Here, we have assumed that the geosystem in the Tracer Test area of the site is representative of conditions throughout the site as a whole. In addition, we have assumed that the LNAPL composition of the sample P-I2-45 from the Tracer Test area is representative of the LNAPL elsewhere at the site. Given these assumptions, the simulations indicate that dissolution will not greatly affect the LNAPL saturation in the smear zone due to the high percentage of low-solubility chemicals. Therefore, low-water table conditions every 5 to 10 years will cause the LNAPL to be mobile. In addition, several hundred years will be required before the MCL for benzene is reached through pump & treat alone.

A.4 Dissolution Modeling

Predictive simulations using the large-scale dissolution model were conducted to address the value of pursuing various remedial alternatives. The base case simulations correspond to the containment option (Alternative 1). For all simulations, an average groundwater velocity of 4 ft/day was assumed. Two scenarios of no biodegradation and a first order BTEX biodegradation rate of 0.44%/day were applied to the simulations of each remedial alternative.

Rather than explicitly simulating the remedial alternatives, assumptions were made about the effect of each alternative on the LNAPL saturation within the aquifer and the contaminant composition within that LNAPL. Furthermore, a range of three assumed levels of remediation (high, average, and low) were used to bracket the anticipated range for the effects of each remediation method. Figure A-1 illustrates the zones over which each remedial technology was assumed to have an influence.

Assuming a smear zone with a vertical extent of 15 ft, the zone of influence of SVE was assumed to encompass the top 12.5 ft of the smear zone (see Figure A-1). In reality, it can be expected that SVE would have a greater effect at the top of the smear zone, where air contacts the LNAPL the majority of time, and a diminished effect deeper and deeper into the smear zone where air contacts the LNAPL for increasingly shorter durations. Because this is difficult to quantify without explicitly simulating the SVE remediation process, a uniform removal efficiency was assumed over the entire zone of influence of SVE. The high, average and low remedial effects corresponded to 99.9%, 99%, and 90% benzene removal, respectively. To account for the effect of SVE on the other LNAPL components and on the overall LNAPL saturation, batch calculations were conducted so that the removal of each component was

Figure A-1: Schematic Illustrating the Smear Zone, the Assumed Vertical Zone of Influence of Each Remedial Technology, and the Vertical Extent of a Hypothetical 10-ft Monitoring Well

proportional to its vapor pressure and the sum of the removal of all components resulted in the net change to the LNAPL saturation.

IAS would be used in concert with SVE (Alternative 3) and its zone of influence was assumed to increase that of SVE by another 2.5 ft in the deepest portion of the smear zone. The high, average and low remedial effects corresponded to 90%, 80%, and 80% benzene removal, respectively. The effect of IAS on other LNAPL components and the LNAPL saturation was calculated similarly to SVE.

Surfactant-enhanced aquifer remediation (SEAR) was assumed to influence the saturated portion of the smear zone. The high, average, and low remedial effects corresponded to leaving LNAPL saturations of 0.1%, 1%, and 2%, respectively. It was assumed that SEAR would entail no preferential removal of benzene or any other component so the LNAPL composition remained unaffected. Because SEAR would be used in concert with SVE (Alternative 4), the effect of SVE on the LNAPL composition was also applied over the SVE zone of influence.

It should be noted that these simulations depend on the geosystem (i.e., the permeability and LNAPL distributions) as well as the LNAPL composition input into the model. Here, we have assumed that the geosystem in the tracer test area is representative of conditions throughout the site as a whole. In addition, we have assumed that the LNAPL composition of the sample P-I2-45 from the tracer test area is representative of the LNAPL elsewhere.

It is important to recognize that aqueous benzene concentrations are only one problem associated with the LNAPL. The simulations indicate that dissolution will not greatly affect the LNAPL saturation in the smear zone due to the high percentage of low-solubility chemicals.

A.5 Biodegradation

An attempt was made to cover the entire range of conceivable biodegradation rates. The upper value, 0.44%/day, is the median value reported for dissolved BTEX plumes at US Air Force sites in a study by Rifai and Newell (1998). In the presence of trapped and free-phase LNAPL, the rate of biodegradation is probably much lower than that.

Some evidence of substantial biodegradation rates in the immediate vicinity of NAPL can be found in recent literature (Yang & McCarty, 2000). In this paper, reductive dehalogenation is shown to occur in the presence of DNAPL, provided the availability of electron donor compound is not limiting. In the case of LNAPL, the typical limitation is the availability of electron acceptors such as oxygen or sulfate. In other words, biodegradation of LNAPL will proceed at the rate at which electron acceptors flow into the system. Electron acceptors include oxygen, nitrate, trivalent iron, sulfate, and carbon dioxide. All of these electron acceptors are present to some extent in the groundwater entering the LNAPL zone; this groundwater moves mostly horizontally from the north. Presumably, the dissolved electron acceptors are quickly depleted at the north rim of the LNAPL zone by the overwhelming amount of hydrocarbons. Additionally, the groundwater is known to be nitrate- and sulfate-poor. S o, it is likely that the rate of (vertical) diffusion of atmospheric oxygen into the smear zone will determine the rate of biodegradation. This diffusion is probably slow due to the relatively tight superficial soil. Furthermore, it is likely that most oxygen is used up by biodegradation in the upper part of the vadose zone. As a result, the total influx of electron acceptors into the smear zone is expected to be low enough to limit post-remediation biodegradation to rates much closer to zero than to 0.44% per day.

Attachment B

Cost Inputs to Present Worth Calculation

B.0 Cost Inputs

B.1 Financial Assumptions

The discount rate (i) was set at 5%/year, the inflation rate (i_i) at 3%/year. From these numbers, an effective discount rate (i_e) of 1.94% was calculated using the equation
$i_e = (i-i_i) / (1+i_i)$.

B.2 Fixed Costs

Several short-term operations now taking place at the site will have to continue in the near future and be completion. On the Island, bioventing will continue and be followed by monitored natural attenuation. Under East Hooven, three horizontal wells are in operation; they will be operated in SVE mode until this becomes uneconomical, after which they will be operated at a reduced flow for bioventing. The costs and durations assumed are summarized in Table B-1.

Table B-1

Fixed Costs

Location	**Islands**		**Hooven**	
Technology	**Bioventing**	**MNA**	**SVE**	**Bioventing**
Annual Cost	$40,000	$20,000	$100,000	$40,000
From	Year 0	Year 8	Year 0	Year 8
Until	Year 7	Year 14	Year 7	Year 14
Present worth*	$0.26MM	$0.11MM	$0.65MM	$0.23MM

* Present worth of costs at 1.94% effective discount rate.

The total present worth of these fixed costs is $1.25 million.

B.3 P&T Costs

The annual operating cost of the P&T system without free-product recovery is estimated in Table B-2.

Table B-2

Present Annual O&M Cost of the P&T System

Item	Annual Cost
Electrical (Wells)	$63,333
Electrical (GAC FBR)	$60,000
GAC FBR Consumables	$62,000
Maintenance labor	$117,000
NPDES fees	$6,000
Well rehabilitation, 9 wells	$33,000
Effluent monitoring	$12,000
Groundwater monitoring	$125,000
Non-P&T payroll	$200,000
Other utilities, O&M	$20,000
Consulting	$150,000
Total annual cost	$848,333

The alternatives have projected operating times that range from decades to centuries. During this time, it is likely that the GAC FBR water treatment facility will have to be replaced. It was assumed that the GAC FBR facility would have a life expectancy of 25 years and that the first replacement would have to occur in 10 years since the present facility was built 15 years ago. A new GAC FBR facility is estimated to cost $2.3 million.

B-4 Free-Product Recovery

As discussed in Section 4.4, the rate of free-product recovery since 1989 has oscillated based on water levels and shows no clear trend. LNAPL recovery will continue as long as substantial amounts can be recovered, but will be focused on the western edge of the facility, along S. R. 128. For the purpose of this cost analysis, we assumed that free-product recovery would continue for 16 years. The cost of disposing of the recovered free product is $0.67/gallon.

For Alternatives 1 (P&T only) and 2 (SVE), an annual free-product recovery of 60,000 gallons was estimated. This is the historical average for the past decade. The initial recovery rate in the 1985-1989 time frame was much higher, but has not reoccurred since.

In the case of Alternative 3, we assumed that the SVE + IAS system would remove some free product, leaving only 45,000 gallons per year to be recovered via the production wells. Finally, the SEAR + SVE system in Alternative 4 was assumed to remove a substantial amount of free product, leaving only 30,000 gallons per year for recovery via the production wells.

B-5 Cost of Initial Remediation

The capital and O&M costs of SVE, SVE + IAS, and SEAR + SVE were estimated (see Appendix B) and are summarized in Table B-3.

Table B-3

Estimated Costs of Initial Remediation

Alternative	**Initial Remediation Technology**	**Capital Cost**	**O&M Cost**	**Duration of Initial Remediation**	**Present Worth of O&M**
		$ millions	**$ millions/yr**	**years**	**$ millions**
1	None	0	0	0	0
2	SVE	18.74	2.24	12	23.77
3	SVE + IAS	24.78	3.56	10	32.08
4	SEAR + SVE	89.76	2.24 (*)	8	16.45

(*) Only O&M for SVE; O&M of SEAR incorporated in capital cost.

Note that, due to the complexity of the SEAR cost estimate, SEAR was assumed to be instantaneous for cost purposes, so its capital and O&M costs are combined in the capital cost column. The present worth of O&M for SEAR reflects only the cost for SVE operation during 8 years.