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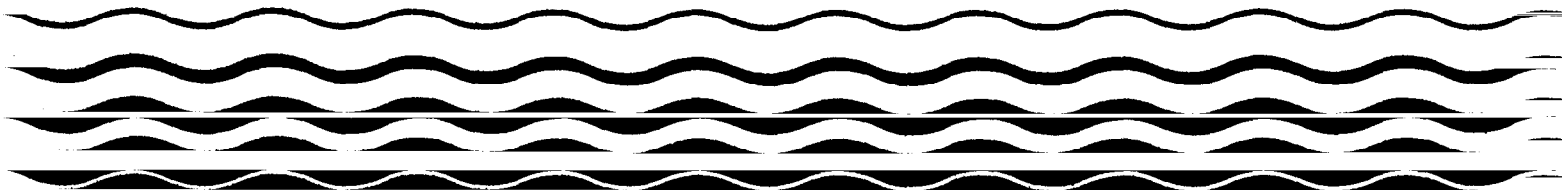
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Evaluation of Ground-Water Extraction Remedies: Phase II

Volume 1 Summary Report



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EVALUATION OF GROUND-WATER EXTRACTION REMEDIES: PHASE II

Volume 1 Summary Report

Office of Emergency and Remedial Response
U. S. Environmental Protection Agency
Washington, D.C.

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INTRODUCTION TO VOLUME 1

This report is the second phase of a study to evaluate the effectiveness of ground-water extraction systems being used to remediate ground-water contamination at hazardous waste sites. This report was prepared in the volumes. Volume 1: Summary Report, contains an Executive Summary and chapters which discuss the purpose, methodologies, and conclusion of the project. Volume 2: Case Studies, contain the individual analyses of each of the 24 sites associated with this project.

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EXECUTIVE SUMMARY

This summary report describes the second phase of an evaluation of the current effectiveness of ground-water extraction in remediating contaminated aquifers at several hazardous waste sites. This project involved reviewing data from existing extraction systems and should not be viewed as a "technology evaluation" in the typical sense because no attempt was made to select sites where the extraction systems had been optimized. Due to the limited number of sites with operating extraction systems, selection criteria were limited to identifying those sites where extraction systems had been in operation long enough to generate initial performance data.

This report does not go beyond describing the operation and conclusions associated with the 24 sites in the study. However, analysis of these findings provides part of the basis for identifying other guidance needs, determining modifications to our approach to ground-water remediation, and assessing the need for future studies and research. A data collection guide, a screening guide for assessing the likelihood of DNAPLs, and a Directive clarifying EPA's approach to ground-water remediation will be developed by EPA over the next year.

Phase I of the study was completed in 1989 (U.S. EPA, 1989). In this second phase, data from 17 of the original 19 case studies were updated, and new case studies were prepared for five additional sites. Two of the original case studies were not updated because more current site data either had not been generated or could not be obtained. The second phase of the study put special emphasis on nonaqueous phase liquids (NAPLs), which can increase the time frame and complexity of ground-water remediation.

The 24 case studies (U.S. EPA, 1991) that now comprise the results of this evaluation must still be considered a very small database from which to draw general conclusions. The case-study sites represent a variety of subsurface contamination situations, geologic environments, and remedial approaches. Records of extraction system operation vary in length, but in most cases are relatively short compared to the time that may be required to complete aquifer remediation (aquifer

remediation is not always the declared remedial objective). Because these sites represent some of the few sites where extraction systems have actually been in operation, they also represent some of the earliest ground-water investigations. Consequently, those investigations predate application of recent advances in site characterization methods and approaches. In most of the cases, site data that were obtained for this evaluation leave important questions unanswered. These are described in more detail in Chapter 3. Despite these shortcomings, it is possible to draw some tentative conclusions from the results reported here. Continued monitoring of remedial progress at these and other ground-water extraction sites, together with results from other ongoing research in the field, can be expected to lead to more effective application of ground-water extraction technology in the future.

CONCLUSIONS

The results of the phase II study reinforced the main conclusions of phase I and led to some additional conclusions concerning impacts of NAPLs on ground-water remediation. The first four conclusions are the same conclusions drawn in the initial study and are presented here to re-emphasize these findings.

Conclusion 1: Data collected, both site characterization data prior to system design and subsequent operational data, were not sufficient to fully assess contaminant movement or ground-water system response to extraction.

Conclusion 2: In the majority of cases studied (15 of the 24 sites), the ground water extraction systems were able to achieve hydraulic containment of the dissolved-phase contaminant plume.

Conclusion 3: Extraction systems were often able to remove a substantial mass of contamination from the aquifer.

Conclusion 4: When extraction systems were started up, contaminant concentrations usually showed a rapid initial decrease, but then tended to level off or decrease at a greatly reduced rate.

This may be a result of the type of monitoring data collected as much as a reflection of an actual phenomenon of ground-water extraction systems. For example, it can reflect successful remediation as the contaminated zone shrinks and less-contaminated ground water is pulled into the extraction system, or poor placement of ground-water monitoring wells.

Conclusion 5: Based on the available information, potential NAPL presence was not addressed during site investigations at 14 of the 24 sites. At 5 sites they were "addressed" because they were encountered unexpectedly during the investigation. As a result, it is difficult to determine NAPL presence conclusively from available site data. Because NAPLs were not addressed in the site investigation, they also were not addressed in the remedial design. Consequently, a ground-water extraction system may be performing as designed (removing dissolved phase contaminants) even though it will not achieve the cleanup goals within the predicted timeframe.

Conclusion 6: At 20 of the 24 sites, chemical data collected during remedial operation exhibited trends consistent with the presence of dense nonaqueous phase liquids (DNAPLs). However, even where substantial soil and water quality data were available, a separate immiscible phase was rarely sampled or observed. This is consistent with DNAPL behavior; i.e., they can move preferentially through very discrete pathways that may easily be missed even in thorough sampling schemes. DNAPL was observed at sites where contaminant concentrations in ground water were less than 15% of the respective solubilities.

Conclusion 7: The importance of treating ground-water remediation as an iterative process, requiring ongoing evaluation of system design, remediation time frames, and data collection needs, was recognized at all of the sites where remedial action was continuing.

SITE BACKGROUND INFORMATION

With the completion of phase II, moderately detailed case studies of 24 hazardous waste sites have been produced. Remedial performance histories range from 1 to 12 years, involving contaminant plumes ranging in size from less than 1 acre to more than 7,000 acres. In 19 of cases,

the contaminants of concern included volatile organics, usually chlorinated solvents.

Ground-water remediation systems installed at these sites reflected a wide range of intensity of remedial effort. The number of extraction wells per site ranged from 1 to 203, and total extraction rates of up to 9,200 gallons per minute were reported. The number of monitoring wells at individual sites ranged from six to 250.

Ground-water extraction systems at several sites were supplemented by additional remedial technologies. The most common of these were ground-water reinjection and soil vapor extraction, each of which were used at six sites. Soil vapor extraction systems usually removed significant quantities of contaminants, but the effect of this removal on reducing aquifer cleanup time could not be quantified. Reinjection was sometimes used more as a means of ground-water disposal than to increase the rate of contaminant migration. Slurry wall containment was used at three sites; French drains, fracture enhancement, and intermittent pumping were used at one site each.

REMEDIAL PERFORMANCE

As of the conclusion of this second phase evaluation, a successful aquifer cleanup has been reported for only one of the subject sites (Emerson Electric in Altamonte Springs, Florida). An apparent remedial success was reported in the first phase evaluation. However, remedial success claims were based on limited monitoring data, and may therefore be open to question. No new data were available for this site during the second phase evaluation.

Plume containment appeared effective at 15 of the 24 sites. At six other sites, the containment effectiveness was uncertain because of insufficient plume monitoring (chemical or water level) or contradictory site data. Plume containment appeared incomplete at only three sites.

Fifteen sites had data on contaminant mass removed by the extraction systems. Amounts removed ranged from 10 pounds to more than 203,000 pounds. Removal estimates were provided by the parties responsible for remediation, or were calculated as part of the Phase II study. Information needed to make such an estimate was unavailable for nine sites.

In light of the observation that contaminant concentrations frequently appear to stabilize above the cleanup goals, an effort was made to identify these levels in the performance records for each site. Based on data availability, this trend was identified in either the influent to the treatment system (11 cases), or in individual wells (9 cases). The identification of stabilization required some subjective judgment as to what constituted a stable concentration and what did not. Stabilized concentrations appear to have occurred at 17 sites. The apparent stabilization of contaminant concentrations may be due to a number of factors not necessarily related to technical limitations of ground-water extraction. These include non-representative monitoring techniques, other contaminant sources not previously identified, inadequate extraction network design, and/or inefficient operation of the extraction network.

OCCURRENCE OF NAPLS

At nine case-study sites, parties responsible for remediation acknowledged the presence of NAPLs. NAPLs were observed directly in eight of these cases, and in the ninth, the determination was based on circumstantial evidence. For at least seven of the other 15 sites, NAPLs appeared likely even though there was no direct confirmation or mention of them in the site reports. The likelihood of NAPL presence at all 24 sites was estimated using a rating scale of 1 through 5. Ratings were based on indirect evidence such as high contaminant concentration in ground water, depth of contamination in the aquifer, persistence of contaminant plume during remediation, and contaminant source characteristics.

Analyte concentrations in excess of the contaminant aqueous phase solubility were reported for ground-water samples at three sites. This provides a strong indication of the presence of NAPLs. One of these instances occurred at a site where the presence of NAPLs has not been acknowledged. At some sites where NAPL presence was acknowledged, the maximum contaminant concentrations reported were less than 15 percent of contaminant solubility. It is possible that in some cases, NAPL is being removed by the ground-water extraction systems without this being recognized by the system operators.

Chapter 1

INTRODUCTION

PROJECT HISTORY

In 1989, EPA's Office of Emergency and Remedial Response (OERR) completed a study of 19 hazardous waste sites at which ground-water extraction systems were being used to remediate aquifer contamination. The study utilized available site-investigation documents, such as remedial investigation (RI) and feasibility studies (FS) reports, and annual or quarterly performance monitoring reports that were generally current through late 1988. A project report was issued as three volumes (U.S. EPA, 1989): Volume 1, Summary Report; Volume 2, Case Studies; and Volume 3, General Site Data--Data Base Reports. That study and the reports produced comprise the first phase of the evaluation.

In late 1990, OERR initiated a second phase of the ground-water extraction evaluation. In it the original case studies were to be updated, and five new case-study sites were to be evaluated with special emphasis on the occurrence of contaminants in the form of NAPLs.

PHASE II METHODS AND OBJECTIVES

In general, the second phase objective was to evaluate the remedial effectiveness of ground-water extraction systems that had sufficient operational data to allow an initial assessment of system performance. These evaluations focused on the capability of the extraction systems to control and remove ground-water contamination. Evaluation of subsequent treatment and disposal of the extracted ground water is beyond the scope of this evaluation, except for instances where treatment or disposal issues affected the performance of the extraction system. In this regard, the objectives of the first and second phases of the evaluation are the same. The second phase updates the original 19 case studies using current performance information and provides five new case studies.

Site information updates covering the period from late 1988 through 1990 was obtained from the

same regulatory and responsible-party contacts who provided site data in the first phase. Remedial performance information generally was received in the form of annual or quarterly monitoring reports. Commonly, the annual reports for the preceding year are compiled and released in the first half of the following year. The timing of these reports caused problems for some site evaluations, because 1990 annual reports were not always available. For most sites, performance data were obtained through the third or fourth quarter (September or December, respectively) of 1990.

Effort was made to locate new case-study sites that satisfied the second phase selection criteria: Superfund sites at which NAPLs were known to be present and at which aquifer remediation had been in progress long enough to produce initial performance data. These criteria proved difficult to satisfy. In the end, five sites were selected, four of which were Superfund sites. The fifth, Occidental Chemical, predates the Superfund legislation and is therefore, strictly speaking, not part of the program. However, it is being administered by the State of California and the EPA National Enforcement Investigation Center using procedures comparable to those of Superfund. The presence of NAPLs was acknowledged at three of the five new case-study sites, and NAPLs are quite likely to be present at one of the others.

The reporting format used in Phase II is similar to that of the first-phase evaluation. Background information on site history, geology, hydrogeology, and waste characteristics is presented first. This is followed by a description of the ground-water extraction system, remedial objectives, and some of the pertinent design considerations. The next section presents a review of system performance data. This review is based only on the site information obtained. This information was not always conclusive, and disagreements regarding data interpretation has sometimes been noted among various parties involved in the response action. Statements presented in the performance-evaluation sections of the case studies reflect judgements (by others) contained in site information packages and were not the result of

this study. Conclusions drawn in the course of this evaluation are contained in the "Summary of Remediation" or the "Summary of NAPL-Related Issues" sections.

Records for many sites contain no explicit mention of NAPLs or the possibility of their presence. Nonetheless, site data frequently contain clues indicating that NAPLs may be present, and these data are discussed for each case study. In the "Summary of NAPL-Related Issues" section, the Phase II authors of the case studies speculated on this possibility in light of the evidence in the site background and performance data. This should not be construed as an official determination by EPA concerning the nature of the contaminants at the site.

The format used for case study updates is similar to that used in the original case studies, but background issues are presented in less detail. The updates are meant to be readable as stand-alone documents, but to gain the fullest understanding of the sites it is necessary to read both the original and the update of the case study.

BACKGROUND ON THE IMPORTANCE OF NAPLs

Phase I of this study identified several factors that potentially increase the time frame and complexity of ground-water remediation. These factors include: hydrogeological factors (e.g., subsurface heterogeneity, presence of low-permeability zones, and presence of fractures); contaminant-related factors (e.g., sorption to soil, presence of NAPLs); continued leaching from source areas; and system design parameters (e.g., pumping rate, screened interval, and location of extraction wells). Phase II of the study again recognizes the importance of these factors as affecting the remediation of ground water, and focuses on the role of NAPLs in particular.

NAPLs have become a subject of special interest for those involved in ground-water remediation. In the early days of the Superfund program, contaminants present in the subsurface in immiscible form were not necessarily recognized as a special threat to ground-water quality. References can frequently be found in early site investigation documents to "visible soil contamination" or "soil staining," but these

conditions were not interpreted as evidence of NAPLs.

With increased experience in the application of pump and treat technology there has developed a greater understanding of factors that may impede progress in remediation of ground water. NAPLs are now frequently identified as a key factor in the longer-than-anticipated time frames for aquifer restoration. NAPLs present in the subsurface act as a residual source of ground-water contamination that typically takes a very long time to deplete solely by ground-water extraction. This is because the aqueous solubility of NAPL-forming compounds is a limiting factor; consequently, large quantities of ground water must be pumped to remove a significant quantity of the contaminant. Even so, the solubility of many of these compounds is much higher (e.g., 5 or 6 orders of magnitude) than their health-based water quality criteria.

A more efficient way to deal with NAPL contamination is to remove the contaminants in the immiscible phase rather than in the dissolved phase. To some extent this is practical for light nonaqueous phase liquids (LNAPLs), which are often found floating on the water table. However, the physical behavior of dense nonaqueous phase liquids (DNAPLs) makes them difficult to locate and even more difficult to control, given the current state of the science.

The emphasis on NAPLs in Phase II of the ground-water extraction evaluation is intended to be more empirical than theoretical. Several recent studies present theoretical explanations and observations on the behavior of NAPLs in fractured and porous media (Feenstra and Cherry, 1988; Huling and Weaver, 1991; Mercer and Cohen, 1990). The intent in this evaluation was to utilize field data obtained during actual ground-water remediations to develop a sense of the pervasiveness of the problem, and to illustrate some of the special features associated with NAPLs.

Chapter 2

OVERVIEW OF CASE STUDIES

SITE BACKGROUND CHARACTERISTICS

The Phase II study includes 24 case-study sites. Table 2-1 provides a summary of their background characteristics. The geographic distribution is shown in Figure 2-1. The majority of the sites, 18 of 24, are east of the Mississippi River. Although some consideration was given to geographic distribution, the availability of performance data for the ground-water extraction system was considered a higher priority in site selection.

LENGTH OF HISTORICAL RECORD

Startup dates for the ground-water extraction systems at the case-study sites range from 1974 to December 1989.

The site with the longest record of ground-water extraction is believed to be the Olin Corporation facility in Brandenburg, Kentucky. Because the process-water supply wells at Olin have gradually evolved into a ground-water remediation system, it is difficult to pinpoint the date when their use became comparable to the extraction systems at the other case-study sites. Olin's radial collector wells have been in operation since the early 1950s, but it was not until 1974 that their effectiveness in controlling the spread of contaminated ground water was recognized. In 1984 the wells were specifically operated as part of a ground-water remediation system. Performance data used here to evaluate the effectiveness of the system begins in 1984.

The IBM-Dayton site, which has the second longest record of extraction for ground-water remediation, began operation in 1978. After 6 years of operation, the system was shut down, with the expectation that natural processes would complete the restoration of the aquifer. Instead, the contaminant plume began to expand again, and in October 1990 ground-water extraction was resumed.

At the Sylvester/Gilson Road Superfund site, a ground-water extraction and recirculation system was put into operation in December 1981. In

1982, the system was enclosed by a slurry wall. For several years the slurry wall and pumping system was used for containment only, and the extracted ground water was reinjected without treatment. In April 1986 a treatment system was put into operation to remediate ground water within the enclosure to alternate concentration limits set forth in the Record of Decision (ROD).

PLUME SIZE

Table 2-1 lists the number of aquifers or aquifer zones affected at each site and the thickness and areal extent of the dissolved phase plume. This information gives some indication of the relative magnitudes of individual ground-water contamination problems.

More than half (14 of 24, or 58%) of the sites are listed as multi-aquifer remediation sites. In some cases, the aquifers are composed of different materials and have different water transmitting properties but are not hydraulically separated. These may more properly be considered as separate aquifer zones. At other sites aquifer materials are similar, but there is a significant hydrologic distinction caused by intervening layers of lower hydraulic conductivity. The distinguishing feature at these sites is that separate extraction and monitoring wells are dedicated to individual aquifers or aquifer zones. All these sites, therefore, require more complex extraction and monitoring systems than might a single-aquifer site with an otherwise similar magnitude of contamination.

Plume thicknesses listed in Table 2-1 are estimated maximum thicknesses of the contaminant plume. The estimate includes the saturated thicknesses of all aquifer zones and intervening layers between zones. Estimates range from 20 feet for the GenRad Corporation site to 365 feet at Tyson's Dump.

Plume areas listed in Table 2-1 refer to the estimated maximum lateral extent of the plume,

Figure 2-1

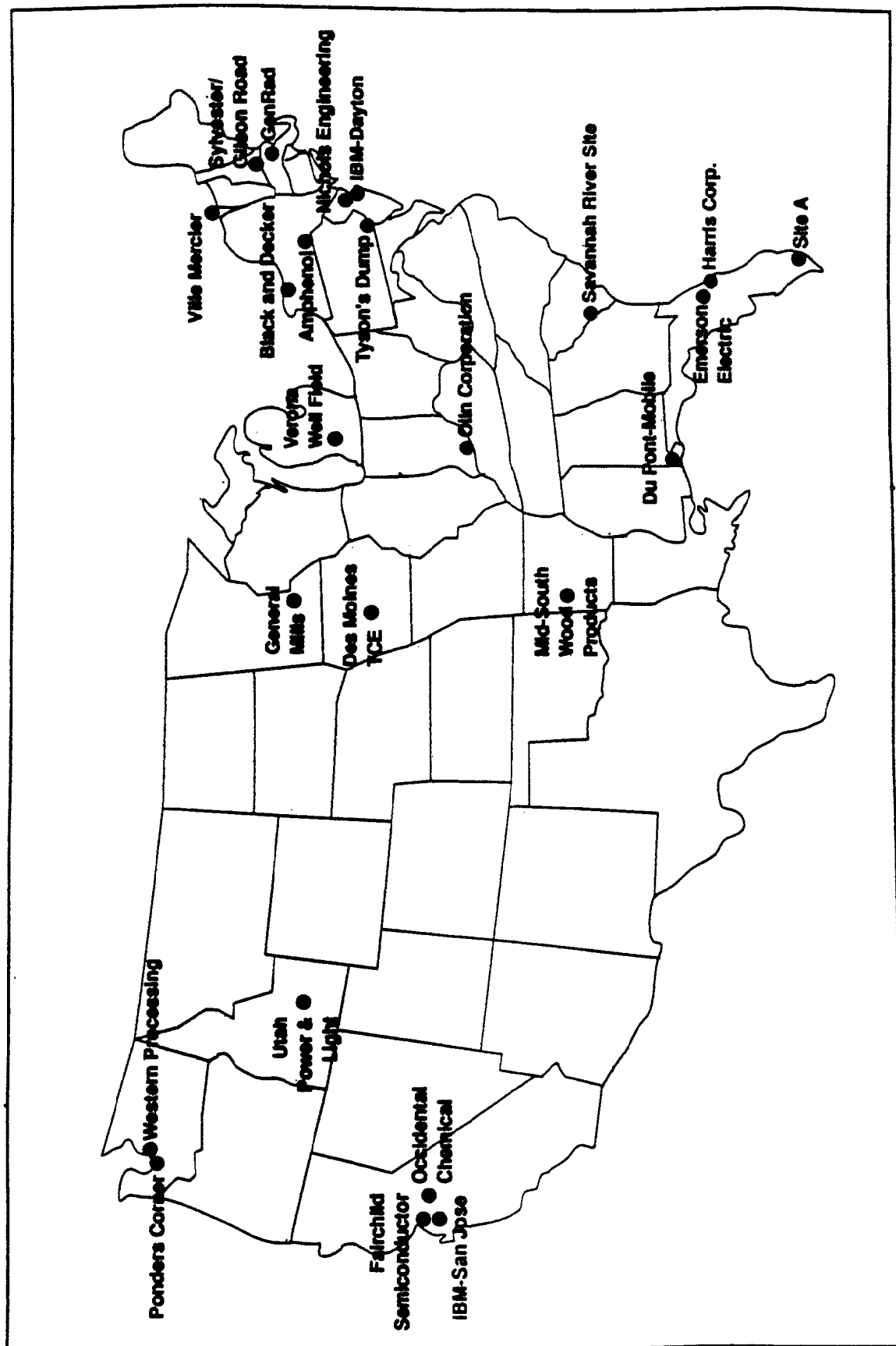


Figure 2-1
GEOGRAPHIC DISTRIBUTION OF
CASE-STUDY SITES
CASE STUDIES SUMMARY

Table 2-1
SITE BACKGROUND CHARACTERISTICS

Site No.	Name	Location	Date Problem Identified	Extraction Started	Administrative Program	No. of Aquifers Affected	Plume Area (Acres)	Plume Thickness (Feet)	Chemicals of Concern	Geologic Environment
1	Amphenol Corporation	Silkey, NY	1983	Jan. 1987	RCRA	2	9	100	PCE, TCE, Chloroform	Fluvial and glacial silt, sand and gravel
2	Black & Decker	Brookport, NY	1985	May 1988	RCRA	2	11	40	TCE, DCE, TCA, VC	Glacial till over fractured sandstone
3	Des Moines TCE	Des Moines, IA	1974	Dec. 1987	Superfund	1	130	50	TCE, DCE, VC	Silt, sand, clay, and gravel
4	Du Pont Mobile	Atch, AL	1983	Dec. 1985	RCRA	1	38	30	VOCs, Pesticides	Alluvial sand and clay
5	Emerson Electric	Altamonte Springs, FL	1981	Dec. 1984	State	1	3	50	VOCs	Sand
6	Fairchild Semiconductor	San Jose, CA	1981	Jan. 1982	State	3	75	180	TCA, DCE, Freon	Alluvial sand and gravel with silt and clay layers
7	General Mills	Minneapolis, MN	1981	Late 1985	State	3	110	50	TCE, PCE, TCA	Glacial drift over fractured sedimentary rock
8	GenRad Corporation	Bolton, MA	1984	Late 1987	State	1	10	20	VOCs	Glacial sand, silt, and gravel
9	Harris Corporation	Palm Bay, FL	1982	April 1984	State & Superfund	2	60	90	VOCs	Sand and shell with clay layers
10	IBM Dayton	Dayton, NJ	1977	March 1978	State	2	60	80	VOCs	Sand and silt with clay layers
11	IBM San Jose	San Jose, CA	1978	May 1982	State	5	760	250	VOCs, Oil	Alluvial sand and gravel with silt and clay layers
12	Nichols Engineering	Hillsborough Township, NJ	1987	Jan. 1988	State	2	2	100	VOCs	Fractured shale, siltstone, sandstone, and conglomerate
13	Ohio Corporation	Brandenburg, KY	Early 70s	1974	State	1	240	80	DCE, DCE, DCE	Silt and sand with interbedded clay
14	Pumkin Corner	Toonawa, WA	1981	Sept. 1984	Superfund	2	23	80	PCE, TCE, DCE	Glacial sand, silt, gravel, and clay
15	Savannah River Site	Altoona, SC	1981	Sept. 1985	State	4	1,000	150	PCE, TCE, TCA	Layered sand, silt, and clay
16	Site A	(Location Confidential)	1985	Aug. 1988	County	1	0.7	25	VOCs	Sand and oolitic limestone
17	Utah Power & Light	Mahoning Falls, ID	1983	Oct. 1985	RCRA	3	810	175	Chromium	Alluvium and fractured basalt
18	Vermorel Well Field	Battle Creek, MI	1981	May 1984	Superfund	2	125	120	VOCs	Glacial sand and gravel over fractured sandstone
19	Ville Mercier	Quebec, Canada	Early 70s	1983	Province	2	7,600	80	Organics	Glacial sand, gravel and clay over fractured sandstone
20	Mid-South Wood Products	Meigs, AR	1976	Early 1985	Superfund	1	10-20	170	PCP, CCA, Chromium	Fractured sandstone and shale
21	Occidental Chemical	Lathrop, CA	1977	June 1982	State	1	770	190	Pesticides	Interbedded alluvial sand, silt, and clay
22	Sylvestre/Oilco Road	Nashua, NH	1970	Dec. 1981	Superfund	2	16	110	VOCs, Arsenic	Glacial sand, gravel, and till over fractured schist
23	Tyson's Dump	King of Prussia, PA	1973	Nov. 1988	Superfund	1	65	365	TCF, styrene, toluene	Thin sand and clay over fractured sandstone
24	Western Processing	Kear, WA	1983	July 1988	Superfund	1	14	65	Mercury, Organics	Interbedded sand, silt, and clay over medium silty sand

PCE = Tetrachloroethylene
 TCE = Trichloroethylene
 TCA = 1,1,1-Trichloroethane
 VC = Vinyl chloride
 DCE = Trans 1,2-Dichloroethylene
 DCEHE = Dichloroethyl ether
 DCEHE = Dichloroethyl ether
 PCP = Pentachlorophenol
 CCA = Chromium copper arsenate
 TCF = 1,1,1-Trichloroethylene
 TCF = 1,1,1-Trichloroethylene

Source: U.S. EPA, Superfund Site Information System, 1988-1990.

generally measured before the start of remediation. Areas range from less than 1 acre at Site A to 7,600 acres at Ville Mercier.

Area estimates were made from concentration contour maps, where these were available. At the Mid-South Wood Products site no plume map was available, so the estimate was based on the area of contaminated soil. The actual plume area is unknown and may not conform to the area of contaminated soil. At the Emerson Electric site, the contaminant plume was never delineated. The extent of the plume was roughly estimated as a circular area centered on the contaminated monitoring well with a radius equal to the distance to the nearest "clean" monitoring well.

CONTAMINANTS OF CONCERN

At 20 out of 24 sites, the primary contaminants were volatile organic compounds (VOCs). Where only a few specific compounds are significant, they are listed by name. However, at many sites, the number of VOCs is too great for individual listing, and the generic abbreviation, VOCs, is used. At a few sites, other organic compounds in addition to VOCs are important, and the contaminants are listed as "organics." Many of these organic compounds are not miscible with water, and therefore have the potential to be present in the aquifers as a NAPL.

The case studies include two wood-treating sites, with PAH compounds, and two pesticide sites. Metals were significant contaminants of concern only at the Western Processing site. The metals involved were nickel, cadmium, zinc, chromium, arsenic, copper, and lead. This site also had a wide variety of organic contaminants.

GEOLOGIC ENVIRONMENTS

Various geologic environments are represented in the collection of case studies. The sites with the simplest hydrogeologic conditions are Emerson Electric and Site A. In both cases, the zones with known contamination were relatively uniform sand of marine origin. It is interesting to note that these two sites appear to have progressed most rapidly toward aquifer restoration.

The remaining 22 sites had greater hydrogeologic complexity than the two mentioned above. Many of the aquifers are layered or interbedded

combinations of sand, silt, and clay deposited in alluvial or glacial environments. Aquifer restoration using extraction wells is less efficient in heterogeneous formations than in more uniform materials. Ground-water flow toward extraction wells tends to take place mainly in the higher-conductivity materials. Low-conductivity zones, which may contain significant quantities of contaminants, are largely bypassed. Difficulties in remediating heterogeneous aquifers are presented in the Phase I report (U.S. EPA, 1989), and discussed in greater conceptual detail by Keely (1989).

Nine sites involve contamination of fractured rock aquifers, which are especially difficult to remediate. The movement of ground water in fractured rock takes place mainly in the fractures. Usually, the fracture density is uneven, which results in nonuniform, direction-dependent flow. Fractured bedrock aquifers are especially difficult to remediate as shown in several of the case study sites, particularly at Black & Decker, Nichols Engineering, Mid-South Wood Products, and Tyson's Dump.

ISSUES RELATED TO SYSTEM DESIGN

Table 2-2 summarizes information used to evaluate extraction system design for the case study sites. This information includes the number of monitoring and extraction wells and the maximum rate of extraction, which give an indication of the level of effort expended to remediate ground water at each site.

REMEDIAL OBJECTIVES

The remedial objectives generally have an important influence on the design and operation of the overall remedial system. Therefore, it is important to recognize that the remedial objectives for the extraction systems may differ for different sites.

Aquifer restoration is a remedial goal for 17 out of 24 of the sites. Restoration is understood to mean that the concentrations of contaminants in the aquifer are to be reduced to levels that would allow ground water to be used as it could have been before being contaminated. The implicit assumption is that, when these concentrations are achieved, no further action aside from

ground-water monitoring will be required. Cleanup goals are usually maximum concentration levels (MCLs) or other health-based criteria, such as 10^{-6} excess cancer risk concentrations. However, in some cases, alternative concentration goals have been established on a site-specific basis.

At the Amphenol site, the restoration goal is a total VOC concentration of less than 5 ppb. The General Mills site cleanup goal is 270 ppb for trichloroethylene (TCE) in the shallow aquifer and 27 ppb in the underlying aquifers. At the Sylvester/Gilson Road site, alternative concentration limits for 16 key contaminants, based on a site-specific risk assessment, are the cleanup goals.

Remedial goals at the Savannah River Site are similar to that for aquifer restoration but are expressed in terms of reduction of contaminant mass. Specifically, the goal is to remove 99 percent of the contaminant mass from affected aquifers in 30 years. Goals stated in this manner have proven to be a problem, because efforts to quantify the mass of contaminants in the aquifers using sampling data from monitoring wells have produced highly variable results. Recent (February 1991) discovery of contaminants in NAPL form will make accurate estimation of total contaminant mass even more difficult.

The remedial objective at seven sites is plume containment. This means ground-water quality restoration is not expected within the site containment area using the existing extraction system.

At the Verona Well Field site, two separate, but related, remediations are in progress. At the Thomas Solvent Raymond Road (TSRR) source area, aquifer restoration is being pursued. In the well field itself, current remedial action includes a system of blocking wells to contain the spread of the plume and protect the remaining unaffected wells. It may eventually be possible to discontinue the blocking system if final remedial actions are successful in all contaminant source areas.

Remedial objectives at the Fairchild Semiconductor site were changed from plume containment to aquifer restoration in 1988 when

the remedial action at the site changed from an interim remedial measure to a final remedial action.

At the IBM-Dayton site, the goal was changed from aquifer restoration to plume containment in response to the determination that contaminants are present in NAPL form. This change was reported in Phase I.

Three case-study sites (Harris, IBM-Dayton, and Ponders Corner) have well-head treatment systems. At Ponders Corner, the extraction system consists of two municipal production wells with treatment for VOCs. These wells serve both to remediate the aquifer and as a source of potable water. At Harris and IBM-Dayton, separate ground-water remediation systems have been installed in contaminant source areas in addition to the well-head treatment systems that are in operation at down-gradient production wells.

PROJECTED CLEANUP TIME

At several aquifer restoration sites, extraction system designers have predicted time frames required to complete the remediation. For three of the sites, the predicted cleanup time has passed. Our experience with ground-water remediation and the science involved in projecting remediation time frames has progressed significantly since these original estimates were made. These cleanup timeframes were underestimated due, in part, to a lack of knowledge of factors affecting ground-water remediation. Projections made based on the current understanding of fate and transport processes and subsurface characteristics are expected to be more representative.

At Site A, the cleanup was expected to be complete in 60 days, but monitoring records show that concentrations above the remedial goals were still present at least 2 years after the onset of pumping.

At Sylvester/Gilson Road, it was expected that the alternate concentration levels (ACLs) would be reached 1.7 years after the ground-water treatment plant started operating in April 1986. However, monitoring data show that 7 of the 16 ACL compounds are still above the target concentrations after more than 2 years. During this time, the maximum concentration of one compound

Table 2-2
SUMMARY OF DESIGN-RELATED INFORMATION

Site No.	Name	Remedial Objective	Projected Cleanup Time	No. of Monitoring Wells	No. of Extraction Wells	Maximum Extraction Rate (gpm)	Applier Train (Y/N)	Flow Model (Y/N)	Travel Time Analysis (Y/N)	Multiwell Monitoring (Y/N)	Soil Sampling (Y/N)	Scraping Considered (Y/N)	Enhancement Technologies
1	Asphalted Corporation	Restoration	5-10 years	40	2	260	Y	Y	Y	Y	Y	Y	None
2	Black & Decker	Restoration	None	54	1	10-15	Y	N	N	Y	N	N	Fracture enhancement
3	Des Moines TCE	Restoration	None	46	7	1,300	Y	Y	Y	Y	Y	Y	None
4	DePue-Mobile	Containment	N/A	43	3	180	Y	N	N	N	Y	Y	None
5	Emerson Electric	Restoration	9 months	6	5	30	N	Y	Y	Y	Y	Y	None
6	Fairchild Semiconductor	Restoration	1994	124	36	9,200	Y	Y	Y	Y	Y	Y	Sherry wall, vapor extraction, reinjection
7	General Mills	Restoration	None	32	6	390	Y	Y	N	Y	Y	N	None
8	OenRad Corporation	Restoration	>5 years	16	2	40	Y	Y	N	Y	Y	Y	Intermittent pumping, reinjection
9	Harris Corporation	Restoration ¹	None	125	24	310	Y	Y	N	Y	Y	N	None
10	IBM Dayton	Containment ¹	N/A	-100	21	1,000	Y	Y	Y	Y	Y	Y	Reinjection
11	IBM San Jose	Restoration	None	276	30	6,000	Y	Y	N	Y	Y	Y	Reinjection, vapor extraction
12	Nichols Engineering	Restoration	Uncertain	14	4	65	Y	N	N	Y	Y	Y	None (intermittent pumping proposed)
13	Olin Corporation	Containment	N/A	33	10	6,200	Y	Y	N	N	Y	N	None
14	Pondent Corner	Restoration ¹	>10 years	51	2	2,000	Y	N	N	Y	Y	Y	Vapor extraction
15	Savannah River Site	Mass refection	30 years	250	12	550	Y	Y	Y	Y	Y	Y	Vapor extraction
16	Site A	Restoration	60 days	28	1	50	N	Y	Y	Y	Y	N	None
17	Utah Power & Light	Containment	N/A	31	17	200	Y	Y	N	Y	Y	Y	None
18	Vermont Well Field (TSRR) (Blocking Wells)	Restoration Containment	None N/A	123 6	9 6	400 2,000	Y	Y	Y	Y	Y	Y	Vapor extraction
19	Ville Mercier	Containment	N/A	7	3	750	Y	Y	Y	Y	Y	Y	None
20	Mid-South Wood Products	Restoration	None	40	15	42	N	N	N	Y	Y	N	French drains
21	Occidental Chemical	Restoration	N/A	49	6	600	Y	Y	Y	Y	Y	Y	None
22	Sylvester/Gilson Road	Restoration	1.7 years	183	8	300	Y	Y	Y	Y	Y	Y	Sherry wall, reinjection
23	Tyson's Dump	Containment	N/A	75-80	7	120	Y	Y	Y	Y	Y	N	Vapor extraction
24	Western Processing	Restoration	>5 years	55	206	200	N	Y	N	Y	Y	Y	Well points, reinjection, sherry wall

¹ Remediation includes well head treatment

Note: NMR refers to the Thomas Subent Raymond Road facility at the Vermont Well Field site

(toluene) appears to be higher now than before ground-water treatment began. Toluene is suspected to be present in NAPL form.

Remediation at the Emerson Electric site was judged to be complete in June 1987, after 2.5 years of ground-water extraction. However, the original estimates were that the cleanup would take only 9 months. It should be noted that the determination of remedial effectiveness at Emerson Electric was based on limited monitoring data (samples mainly from extraction wells and little post remediation monitoring). This site was discussed in greater detail in Phase I (U.S. EPA, 1989).

At three other case-study sites, definite cleanup times have been projected that have not yet expired. Designers of the ground-water extraction system at the Amphenol site predicted the aquifer would be restored to the desired water quality in 5 to 10 years after system startup. This projection was based on the estimated volume of the dissolved contaminant plume and the assumption that flushing several complete plume volumes of ground water would exhaust the supply of adsorbed contaminants. After approximately 4 years of extraction, it appears that ground-water contaminant concentrations are being reduced at a rate that may be consistent with projected cleanup time.

At the Fairchild Semiconductor site, a projection was made that aquifer restoration goals (achieving drinking water standards in the ground water) would be met in 1994. This estimate was based on observed water quality improvement since remedial extraction started in 1982.

Designers of the extraction system at the Savannah River Site initially expected to achieve aquifer restoration goals within 30 years of system startup. In the six years of operation, both the system design and the understanding of the contamination problem have changed. No new cleanup time projections have been made, but the system operators now describe the 30-year timeframe as a standard for evaluation of remedial progress rather than a firm objective.

EXTRACTION AND MONITORING SYSTEM SIZES

Table 2-2 lists the number of monitoring and extraction wells at each site, as well as the maximum ground-water extraction rate for all wells. The number of extraction wells represents the maximum because, at several of the sites, the size of the system has changed over the years.

The Western Processing site has the largest number of extraction wells with 203 well points installed in rows coupled to a common vacuum header. Each well point is designed to withdraw at approximately 1 gpm.

The highest combined pumping for the case study sites (9,200 gpm for 36 extraction wells) occurred at the Fairchild Semiconductor site. The Fairchild system operated at this rate for only a short time in 1983. Since then, the extraction rate has been steadily cut back in an effort to balance remedial effectiveness with the need for water conservation. Likewise, at the nearby IBM-San Jose site, extraction rates have been reduced from 6,000 gpm (30 extraction wells) to less than 1,000 gpm. The highest sustained extraction rate (6,200 gpm for 10 extraction wells) is at the Olin Corporation site, where the ground water is pumped from wells and radial collectors next to, and extending under, the Ohio River.

ENHANCEMENT TECHNOLOGIES

The term "enhancement technologies" as used here and in Table 2-2 refers to remedial activities used to augment or assist ground-water extraction in the removal of subsurface contamination. These technologies are not necessarily new or innovative. Examples include:

- Soil vapor extraction can reduce cleanup times by removing residual contaminant sources in the vadose zone.
- Slurry wall containment can limit the amount of water requiring treatment or reduce the quantity of water pumped to maintain a containment system.
- Re-injection of treated ground water can increase hydraulic gradients and saturated thickness in the aquifer being remediated, and block plume movement.

- Variations on the standard extraction well design, such as French drains, enhanced fracture zones, well-point systems, and horizontal wells can increase extraction effectiveness.

The most common enhancement technologies were reinjection and soil vapor extraction, which are used at six sites each. At the Fairchild Semiconductor and IBM-San Jose sites, both enhancement technologies are used. Treated ground water was reinjected at the Harris Corporation and Occidental Chemical sites. However, it is not considered an enhancement technology here because it was done solely for disposal purposes, and the injection was to deep aquifers that are not hydraulically connected to the aquifers being remediated.

The next most frequently used enhancement is slurry wall containment. The Sylvester/Gilson Road and Western Processing sites are enveloped by slurry walls that are not keyed into an underlying aquitard. At Fairchild Semiconductor, the most contaminated portion of the upper two aquifers is enclosed by a slurry wall keyed into a continuous low-permeability layer.

French drains are listed as an enhancement technology at the Mid-South Wood Products site. The extraction system at this site includes both conventional wells and wells combined with French drains. French drains were added to provide an improved hydraulic connection to the fractured rock aquifer.

A similar concern for improving hydraulic communication in fractured rock exists at the Black & Decker site. Here a single extraction well was drilled in an artificially enhanced fracture zone that was created using explosives.

Intermittent pumping is listed as an enhancement at the GenRad site, because the extraction system is turned off for three months every winter. However, this is done more to prevent freezing damage to the system than to improve the efficiency of contaminant removal.

SYSTEM DESIGN INFORMATION

The remaining columns of Table 2-2 provide a checklist of commonly used analytical techniques for the design of extraction systems. Aquifer

testing is a basic method of determining the hydraulic responsiveness of the aquifer to pumping. It is believed to have been used at all but four of the sites. (The Ville Mercier site was not treated in detail in this phase of the study, and information about the design techniques used there was not available.)

At 18 sites, some form of ground-water flow modeling was used to help select locations and pumping rates of extraction wells. In most cases, numerical or semi-analytical computer models were used.

Some form of travel-time analysis was used for at least ten of the sites. This analysis basically consisted of estimating the time it would take for the distant portion of the plume to be drawn into an extraction well and was used as part of the process for estimating restoration time frames. Details of the analysis were usually not explained in site documents obtained for this study. In a few cases, particle tracking or streamline-generation techniques were used to evaluate the flow of ground water to extraction wells. In other cases, travel-time estimates were based on comparisons of the extraction well-pumping rate to the estimated plume volume.

Numerical contaminant transport modeling appears to have been used rarely.

Documents reviewed for 17 sites, explicitly mention the importance of solute adsorption to aquifer materials. However, it was not always clear how this consideration was used in judging the potential effectiveness of the extraction system. In some cases, the estimated travel time for contaminants to reach the extraction wells from remote portions of the plume was increased to account for adsorptive retardation. In other cases, the estimate of total contaminant mass was adjusted to account for adsorption. A third common approach was to increase the estimated number of pore volumes of ground water that would have to be removed to complete the remediation. The overall effect of all three methods is roughly equivalent.

OCCURRENCE OF NAPLs

The occurrence of contaminants as NAPLs at the case-study sites was of special interest in Phase II. In Phase I, NAPLs were identified as residual

sources of contamination at the sites where they were known or suspected to be present. However, conditions associated with their presence and reasons for suspecting it were not discussed in detail.

Table 2-3 gives a summary of issues associated with the presence of NAPLs at the case-study sites.

At most sites studied, it was difficult to establish NAPL presence conclusively. The exceptions were sites where NAPLs had been directly observed and reported in monitoring wells or soil samples. Even though NAPLs are suspected, to some extent, at 20 of the 24 sites, they have been directly observed at only 8. Certain features of NAPL behavior in the subsurface make it possible for them to remain undetected by traditional site-investigation procedures. This is especially true of compounds having a density greater than that of water (DNAPLs). Some of the more important aspects of DNAPL behavior will be discussed briefly in Chapter 4.

At nine sites, parties responsible for remediation acknowledge that NAPLs are present. At three others, it is acknowledged that NAPLs may be present. Frequently, however, site information contains clues indicating that NAPLs may be present, even though this possibility was not mentioned in site documents. This is not surprising for older sites, because the issue of NAPLs was not emphasized by the scientific community until the early 1980s, and even now the concept is relatively new.

Table 2-3 includes a column labeled "Likelihood of NAPL Presence (1-5)". Entries in this column give a rough quantification of NAPL likelihood on a scale of 1 through 5. An entry of 1 indicate that the site probably does not have NAPLs. A likelihood of 5 was assigned only when NAPLs have been directly observed or the parties responsible for site remediation assert that they are present. Entries of 2, 3, or 4 provide a range of relative likelihoods between these extremes but do not have precise definitions in terms of quantitative site data.

Table 2-3 also lists several types of evidence that were used to judge the relative likelihood of NAPL presence. The most conclusive is direct

observation. Less conclusive, but still suggestive, clues include the following observations:

- High concentrations in the ground water compared to the aqueous solubilities of the compounds,
- Unusually deep (for DNAPLs) or shallow (for LNAPLs) concentration distributions that do not seem to be attributable to other hydrogeologic influences,
- Persistence of contamination in spite of the remediation efforts,
- Source characteristics or methods of waste disposal that would be likely to result in the presence of NAPLs in the aquifer.

All of these circumstantial clues are relative, being more or less persuasive depending on the degree to which they appear. Ground-water concentrations greater than 100 percent of solubility, for instance, would be considered very strong evidence of NAPL presence, whereas concentrations in the range of 1 to 5 percent give a questionable indication. The relative and cumulative nature of these clues were considered in assigning likelihood scores in the range of 1 through 4 in Table 2-3.

To provide insight into the importance of ground-water concentrations as an indicator of NAPL presence, a column has been included in Table 2-3 listing the highest reported concentration as a percentage of aqueous solubility for each site. In several cases, concentrations greater than 100 percent of aqueous solubility were reported in ground-water samples. Although the co-solvent effect is a possible explanation, this is most likely to be an indication that the compound was present in the sample in colloidal-size NAPL droplets. It was considered strong evidence for NAPL presence in the aquifer.

The final column in the table lists the chemical species for which the relative concentration in the preceding column was reported.

Table 2-3

Site No.	Name	NAPL Presence Acknowledged (Y/N/Maybe)	Likelihood of Presence (1-5)	LNAPL or DNAPL	Nature of the Evidence for NAPLs				Source Characteristics	Max. Conc. vs. Solubility (%)	Compound
					Direct Observation	High Concentration	Depth of Contamination	Resistance to Remediation			
1	Amphical Corporation	N	1							0.02	TCE
2	Black & Decker	N	3	DNAPLs		X	X			5.5	TCE
3	Des Moines TCE	Maybe	3	DNAPLs			X	X	X	0.8	TCE
4	De Post Mobile	N	3	DNAPLs		X		X	X	21	1,2,4-TCB
5	Emerson Electric	N	2	LNAPLs		X				6.0	Toluene
6	Fairchild Semiconductor	N	4	DNAPLs		X		X	X	>100	1,1,1-TCA
7	General Mills	N	3	DNAPLs			X	X	X	0.2	TCE
8	GenRad Corporation	N	2	DNAPLs			X			0.5	TCE
9	Harris Corporation	N	2	DNAPLs		X		X		1.3	TCE
10	IBM-Dayton	Y	5	DNAPLs		X	X	X	X	4.1	PCE
11	IBM-San Jose	Y	5	LNAPLs	X	X		X	X	>9	From 113
12	Nichols Engineering	N	1							0.06	CCl4
13	Ohio Corporation	Maybe	3	DNAPLs		X		X	X	37	DCIPE
14	Pondora Corner	N	2	DNAPLs		X		X	X	3.2	PCE
15	Savannah River Site	Y	5	DNAPLs	X	X	X	X	X	22	TCE
16	Site A	N	1							0.1	T-1,2-DCE
17	Utah Power & Light	Y	5	DNAPLs	X	X	X		X	>100	PAHs
18	Verona Well Field	Y	5	LNAPLs	X	X	X	X	X	11.3	PCE*
19	Ville Meridier	Y	5	Both	X	X	X	X	X	7	?
20	Mid-South Wood Products	Y	5	Both	X	X	X		X	>100	PCP
21	Occidental Chemical	N	1							0.3	DBCP
22	Sylvester/Gilson Road	Maybe	4	LNAPLs		X	X	X	X	26	Toluene
23	Tyson's Deep	Y	5	DNAPLs	X	X	X	X	X	74	TCP
24	Western Processing	Y	5	Both	X	X	X		X	65	DCE

*PCE is dissolved in toluene, and therefore floats.

1,1,1-TCA = 1,1,1 Trichloroethane
 1,2,4-TCB = 1,2,4 Trichlorobenzene
 CCl4 = Carbon Tetrachloride
 DBCP = Dichlorobenzene propene
 DCEB = Dichloroethyl ether
 DCIPE = Dichloroisopropyl ether
 PAHs = Polycyclic aromatic hydrocarbons
 PCE = Tetrachloroethylene
 TCP = Trichloroethylene
 TCE = 1,1,2 Trichloroethane
 T-1,2-DCE = Trans 1,2 Dichloroethylene

Note: The solubility referred to in this table is the solubility of the pure compound in contact with pure water, as published in standard technical reference works.

Chapter 3

SUMMARY OF REMEDIAL PROGRESS

In the first phase of the study, four conclusions were reached concerning the remedial performance of the extraction systems at the sites studied.

1. The ground-water extraction systems at most of the sites studied appeared to be achieving hydraulic containment of aqueous contaminant plumes.
2. Most of the extraction systems were removing, or had removed, substantial quantities of contaminants.
3. When extraction systems are first turned on, contaminant concentrations usually show a rapid initial decrease, but then tend to level off or decrease at a greatly reduced rate.
4. The data collected prior to system design and during operation were often not adequate to fully assess contaminant movement and the response of the ground-water system to extraction.

The information obtained in the second phase of the study seems to generally confirm these conclusions. However, the collection of case studies contains enough variety to provide exceptions to each of the general conclusions. Table 3-1 gives a concise summary of the major indicators of remediation effectiveness at the case-study sites.

PLUME CONTAINMENT

As shown in Table 3-1, containment of the aqueous plume appeared to be effective at 15 of the 24 sites. This judgment was made by comparing the extent of known ground-water contamination, based on ground-water monitoring, to the capture zone of the extraction system, as indicated by water-level measurements in monitoring wells and piezometers.

Containment effectiveness is listed as uncertain for six sites in Table 3-1. In each case, this is because of a lack of enough site data on which to base a firm determination. At the Du Pont-Mobile and General Mills sites, the delineation of capture

zones was uncertain, because there were not enough piezometers on the downgradient side of the extraction wells. At Emerson Electric, Site A, and Mid-South Wood Products, both the extent of the ground-water contamination and the hydraulic effects of the extraction system were unclear. At Utah Power & Light, the main problem was the difficulty in determining the boundary of the contaminant plume in the fractured rock aquifer.

It should be emphasized that both water-level and water-quality measurements are required to demonstrate that the extraction system is effectively containing the aqueous contaminant plume. Observation of water-quality trends alone is insufficient.

At three of the case-study sites, the available data indicated that hydraulic containment was not completely effective. These sites were the Savannah River Site, Sylvester/Gilson Road, and Tyson's Dump.

At the Savannah River Site, the contaminant plume extends beyond the zone of influence of the recovery system. In the Phase I report, it was noted that the capacity of the recovery system did not seem to be commensurate with the magnitude of the contamination problem. Since 1988, the total pumping rate for the system has been increased from an average of 436 gpm to as much as 550 gpm. In addition, new extraction wells have been installed in areas that were not previously being remediated. However, it appears that there are still portions of the plume that are not being captured. Also, downward migration of the plume has not been completely reversed.

At the Sylvester/Gilson Road site, the extraction rates apparently have not been high enough to maintain inward gradients around the entire periphery of the slurry wall that encloses the site. In addition, observation of vertical gradients within the enclosed area indicate that contaminants may be escaping by vertical migration to lower aquifer zones. In response to these observations, new extraction wells are to be added to the ground-water recirculation system inside the slurry wall. Also, consideration is being given to

Table 3-1

Table 3-1
SUMMARY OF REMEDIAL EFFECTIVENESS

Site No.	Name	Contaminant Effectiveness	Estimated Initial Mass (lbs)	Estimated Mass Removed (lbs)	Indicator Compound	Maximum Reported Concentration	Initial Recovery Concentration	Concentration Plateau	Location of Observed Plateau	Time to Reach Plateau	Cleanup Goal
1	Amphenol Corporation	Effective	Not given	Not given	Total VOCs	329	Not given	30	Well 1-D	1.7 yrs	5
2	Black & Decker	Effective	Not given	15 ^a	TCE	86,000	7,900	800	Influent	1 yr	5
3	Das Motors TCE	Effective	50-90	15,860	TCE	8,467	2,800	800	Influent	0.4 yrs	5
4	Du Pont-Mobile	Uncertain	Not given	1,440	TOX	10,450	Not given	None	N/A	N/A	N/A
5	Emerson Electric	Uncertain	Not given	12 ^a	MBIX	90,000	150	None ^b	N/A	N/A	Detection
6	Fairchild Semiconductor	Effective	Not given	90,000	TCA	1,900,000	11,000	1,000	RW-2B	1 mo	200 ^c
7	General Mills	Uncertain	100,000	2,000 ^a	TCE	2,300	1,200	100	Well 10	0.5 yrs	27
8	GenRad Corporation	Effective	Not given	10 ^a	TCE	>5,000	31	250	G-111-14A	3.5 yrs	5
9	Harris Corporation	Effective	Not given	16,000	Total VOCs	37,120	6,000	1,100	Influent	3.8 yrs	N/A
10	IBM-Dayton	Effective	Not given	Not given	TCA	9,500	200	30	SB-11	6 yrs	N/A
11	IBM San Jose	Effective	Not given	>8,000 ^a	Freon 113	16,000	Not given	7	?	?	N/A
12	Nichols Engineering	Effective	Not given	Not given	CCl4	980	1.8	100	MW-1	0.8 yrs	5
13	Onix Corporation	Effective	Not given	Not given	DCIPE	632,000	Not given	-6,000	RW-1	?	N/A
14	Ponders Corner	Effective	1,500	1,700 ^a	PCE	4,866	492	50	Well H2	1 yr	N/A
15	Savannah River Site	Partial	444,800	203,762	TCE	223,000	33,000	None	Influent	N/A	N/A
16	Site A	Uncertain	Not given	-15	T-1,2-DCE	7,200	7,200	None	Influent	N/A	70
17	Utah Power & Light	Uncertain	Not given	Not given	Total PAHs	58,000	0	Variable	Influent	N/A	N/A
18	Venona Well Field	Effective	Not given	14,000 (TSRUR) ^c	Total VOCs	85,960	19,000	2,500	Influent	0.3 yrs	N/A
19	Ville Mercier	Effective	Not given	Not given	1,2-DCA	11,500	11,500	1,000	Influent	0.7 yrs	N/A
20	Mid-South Wood Products	Uncertain	Not given	Not given	PCP	65,000	15,000	None	N/A	N/A	200 ^d
21	Occidental Chemical	Effective	Not given	-5,000 ^a	DBCP	4,200	4,200	20	Influent	6 yrs	N/A
22	Sylvester/Citron Road	Partial	Not given	Not given	Toluene	140,000	17,000	10,000	Influent	0.7 yrs	2,900
23	Tysons' Dump	Partial	Not given	101,000	1,2,3-TCF	1,400,000	340,000	50,000	Influent	2 yrs	N/A
24	Western Processing	Effective	Not given	Not given	TCE	210,000	13,000	5,000	Cell 5	1 yr	Not given

^aMass of the indicator compound only. Unfootnoted entries in this column are for total contaminant mass.

^bConcentrations were reduced below the cleanup criteria in less than 3 years.

^cCleanup goal in the absence of other contaminants. (Several recovery wells are below this goal.)

^dFrequency MCL, not explicitly specified as a goal for this site.

^eINRR refers to the Thomas Solvent Recovery Road facility at the Venona Well Field site.

All concentrations in ppb

increasing the rate at which treated ground water is removed from recirculation and discharged outside the wall.

The interim ground-water extraction system at the Tyson's Dump site captures most, but not all, of the solute plume. That is all that the interim extraction system was intended to do. An expanded extraction system designed for complete hydraulic control of the solute plume is presently in the final stages of construction.

Table 3-1 lists containment effectiveness as uncertain at six of the case-study sites. This judgment was generally reached because of lack of information about either the extent of the contaminant plume or the hydrodynamic conditions generated by the extraction system.

At the Emerson Electric site, it was impossible to judge the containment effectiveness of the extraction system, because the extent of the contaminant plume was never defined and no water-level measurements were reported.

Containment effectiveness is listed as uncertain for the General Mills site, because the site documents that were obtained for review do not show enough water-level measuring points to support accurate delineation of the capture zone. The extraction system operators assert that the portions of the plume that exceed the cleanup levels are being captured. In the lower of the two aquifers being remediated, however, concentrations in excess of the cleanup standards are consistently being detected at monitoring wells that appear to be outside the likely zone of influence of the extraction well.

At Site A, no water-level measurements have been presented to support the contention that the recovery well has captured the contaminant plume. The hydraulic design of the extraction well seems to have been based on the assumption of horizontal radial flow to the well. There is no indication that the effects of vertical flow or regional gradients were considered. The only indication of the actual hydrodynamic performance of the well is the assertion, appearing in the early performance reports, that no drawdown could be detected in any of the monitoring wells when the extraction system was turned on.

Table 3-1 lists the containment effectiveness at the Utah Power & Light site as uncertain, because the available site data do not support an accurate delineation of the extent of the contaminant plume in all aquifer zones. Water-level measurement data indicate that the extraction system's capture zone does include all of the monitoring wells currently reported to be contaminated.

Capture effectiveness at the Mid-South Wood Products site is listed as uncertain, because the available site documentation does not indicate either the extent of the contaminant plume or the ground-water flow patterns induced in the aquifer by the extraction system.

At the Du Pont-Mobile site, no new information on the hydrodynamic effects of the extraction system has been obtained since the first phase of the study. The potentiometric surface map presented in the first case study appeared to show that the contaminant plume was entirely captured. However, some uncertainty was cast on this conclusion by some rough, contaminant mass-balance calculations, which indicated that only about half of the contamination approaching the line of extraction wells could be accounted for by the concentrations and flow rates being extracted. It is likely that the discrepancy is due to inaccuracies in estimating the contaminant flux in the plume. But, it is also possible that contaminants are bypassing the extraction wells in the deeper portions of the aquifer that are not monitored.

AQUIFER RESTORATION EFFECTIVENESS

CONTAMINANT MASS REMOVAL

Table 3-1 lists the available estimates of the initial contaminant mass and the mass removed to date for each of the case-study sites. In most cases, no estimate was available for the initial mass in place. Where such estimates were available, they have often been proven wrong.

For instance, at the Des Moines TCE site, the representatives of the responsible parties have, in the past, contended that the ground-water contamination was caused by the former practice of pouring contaminated sludges on the ground for dust control at the rate of 100 to 200 gallons per

year. Considering the maximum measured TCE concentration in the sludge and the period of years over which this practice was followed, the total mass of TCE disposed of can be estimated at 50 to 90 pounds. Influent concentration records for the ground-water treatment plant, however, show that more than 9,100 pounds of TCE were removed from the aquifer during the first 9 months of operation. By the end of 1989, the total mass of TCE removed was estimated at 15,860 pounds. This discrepancy highlights the obvious uncertainty about the true nature of the contaminant source.

Another example is the Savannah River Site, where the initial estimate of contaminant mass in place was based on volume integration of the contaminant concentrations in the plume, as measured by the extensive ground-water monitoring system. This calculation of contaminant mass in place has been repeated regularly at the Savannah River Site and used in conjunction with estimates of the quantity of contaminants removed as a means of monitoring the performance of the extraction system. Experience with this procedure has shown that the quantity of contamination actually removed is greater than the estimated change in contaminant mass in the aquifer. The recent discovery of DNAPL contamination in the aquifer provides one explanation for this discrepancy, and highlights the difficulty of determining what is actually present in the subsurface.

The estimates given in Table 3-1 for the mass of contaminants removed by the extraction system are expected to be more reliable than the estimates of mass in place. In some cases, the estimates of mass removal were made by the parties responsible for the remediations. However, most of the estimates were made as part of this study, and were based on treatment plant influent records presented in the case studies.

The quantity of contaminant mass removed is presented in Table 3-1 as a measure of extraction system performance because it represents an accomplishment that can be attributed unambiguously to the system. In effect, however, it seems to be a measure more closely associated with the magnitude of the problem than with the degree of remedial success. The two case-study sites that appear to be closest to successful remediation, Emerson Electric and Site A, are

among the three with the lowest estimates of contaminant mass removed.

CONTAMINANT CONCENTRATIONS

The last seven columns of Table 3-1 deal with the concentration of an indicator compound (or a composite contamination parameter) that has been selected for each site to serve the illustrative purposes of the table. In many cases, the indicator compound is also the primary contaminant at the site, but this is not true in every case. The indicator compounds were chosen only for use in this table and have no official status as indicators at the sites themselves.

The maximum reported concentration of the indicator compound, as listed in Table 3-1, was culled from the site records made available for this study. In a few cases, a nearly complete record of site-monitoring data was available, and was used to identify the highest reported concentration. More often, the concentration listed was the highest mentioned either in text, tables, or figures in a remedial investigation report for the site. Higher concentrations may have been measured, but were not reported in the documents made available for the case study.

At three sites--Fairchild Semiconductor, Utah Power & Light, and Mid-South Wood Products--the maximum reported concentration exceeded the aqueous solubility of the indicator compound. These occurrences were taken as a strong indication of the presence of NAPLs.

At three other sites--Ville Mercier, Occidental Chemical, and Site A--the maximum reported concentration was the initial recovery concentration. For the first two sites, this was probably because the information collected for the case studies consisted mostly of summary reports. If a complete data base of ground-water monitoring results had been available, higher concentrations than those reported for the treatment plant influent probably would have been found. At Site A, however, a fairly complete record of site-monitoring data was made available, and none of the reported monitoring-well concentrations were as high as the initial concentration reported in the treatment plant influent.

At several sites (particularly Utah Power & Light, Nichols Engineering, and GenRad) the initial recovery concentrations were very low. This is simply the result of the extraction wells initially not being in a high concentration portion of the plume. In each case, however, the extraction wells later produced at higher concentrations as contaminants were drawn toward them.

One of the general conclusions drawn in the first phase of the study was that ground-water extraction frequently produces a rapid initial drop in concentration and then levels out to relatively constant, or slowly declining, contaminant levels. This leveling out in concentration reduction can result from a number of factors and can, in fact, reflect progress in cleaning up a plume. Before any conclusions can be drawn from looking at concentration reduction trends, a thorough review of extraction system design should be performed. This was not done as part of this study; consequently, it is not possible to determine if the plateaus observed and described in the following paragraphs reflect a true limitation or inefficient design of the extraction system or sampling that does not represent the full impact of remediation. In most cases, the latter two occurrences are associated with dilution of contaminant concentrations at the monitoring point through one of the following mechanisms:

- Selective pumping of wells in less contaminated areas at relatively high flow rates.
- The well is constructed such that the water table is quickly lowered below the contaminated zone.
- The outer edge of the plume is cleaned up and individual monitoring wells reflect a continuing decline in contaminant concentrations, yet monitoring samples are taken from a point at which ground water from all extraction wells is combined.

This dilution of samples with surrounding clean ground water can mask the fact that ground-water is being cleaned up.

Assuming the above design limitations have been addressed, the occurrence of a stabilized concentration can indicate that the clean up of the

affected portion of the aquifer is limited by the kinetics of contaminant desorption or dissolution. This could be due to the release of contaminants from a residual source, such as adsorbed contaminants or a NAPL.

As shown in Table 3-1, an attempt was made to identify such a concentration plateau at each case-study site. This identification was entirely a matter of perception, and required the application of subjective judgment as to what constituted a stabilized concentration and what did not. No precise mathematical or statistical definition of the stabilized concentration was used. Where leveling out of the concentration record was noted, it frequently occurred in only part of the contaminant plume, or in the extraction wells. The identification of a stabilized concentration in Table 3-1 does not constitute a prediction that it will persist for a very long time. In several instances in which concentrations seemed to have stabilized in the first phase case studies, additional data gathered in the second phase showed concentration reductions. Examples of this are Monitoring Well 1-S at the Amephenol site and Extraction Well ERW-8 at Des Moines TCE (see Case Studies 1 and 3).

No concentration plateau could be identified for some of the sites. At the Du Pont-Mobile and Utah Power & Light sites, the concentration records showed too much variability for plateau identification. At the Emerson Electric site, the initial high rate of concentration reduction was not maintained, but the concentrations did continue to decline steadily until the cleanup goals were reached. The concentration records at Site A showed a similar pattern, at least for the selected indicator compound. At the Savannah River Site, the record of concentration in the treatment plant influent showed a slow, but fairly continuous, downward trend with no obvious leveling off. At the Mid-South Wood Products site, the performance record was too short and available data too limited for trends to be identified.

The initial effort at each site to identify a concentration plateau focused on the treatment plant influent record since this allowed the selection of a single point for each site. (This does not mean that treatment plant influent concentrations are the best measurement of pump and treat performance as indicated above.) In 10 cases, concentration plateaus were found in the

influent records. Where plateaus could not be found in the influent records, either because the records were unavailable or the concentrations did not level off, records from individual wells were scrutinized. Several instances of leveling off were identified in monitoring wells or individual extraction wells, even though concentrations were not stable for the extraction system as a whole.

Table 3-1 also lists both the approximate time after the beginning of extraction when the concentration plateau was reached and the remediation goal for the indicator compound, where applicable. The cleanup goals for the indicator compounds were listed here primarily for comparison with the maximum, initial recovery and plateau concentrations. The cleanup goal is listed as "N/A" (not applicable) when the indicator compound is total VOCs or the remedial goal at the site is containment rather than aquifer restoration. For the IBM-San Jose site, the cleanup goal for Freon 113 is different for the different aquifers, and because no point measurements of concentration are listed, there is nothing to compare. At the Western Processing site, the cleanup goal for TCE is expected to be an ACL that is to be specified in a future record of decision. For the Savannah River Site, the remediation goals have not been specified in terms of cleanup levels.

PLUME AREA REDUCTION

Reduction of the area of a contaminated aquifer is an alternative measure of restoration effectiveness. Remedial progress is less commonly viewed in this way, probably because this kind of evaluation requires mapping of contaminant concentration values, usually in the form of concentration isopleths. One reason such maps are not more widely relied on to evaluate remedial progress is that their construction makes use of interpolated concentrations between the monitoring wells. Consequently, the maps are partly the result of interpretation as opposed to being a direct measurement. The advantage of this format, however, is that it shows the extent to which aquifer restoration has been partially achieved.

Plume mapping is usually done as part of the remedial investigation, but is less commonly encountered in status reports for operating remedial systems. At nine of the case-study sites, contaminant plume maps were available in the

operational data reports and have been presented in the case studies. In each of these cases, the maps demonstrated that the area of groundwater contamination has been reduced for some or all of the contaminants of concern. The sites for which plume maps were produced are:

- Fairchild Semiconductor
- GenRad Corporation
- Harris Corporation
- IBM-Dayton
- IBM-San Jose
- Nichols Engineering
- Occidental Chemical
- Sylvester/Gilson Road
- Verona Well Field
- Western Processing

Of these sites, Fairchild Semiconductor and IBM-San Jose show the most marked reduction in plume size.

USE AND EFFECTIVENESS OF ENHANCEMENT TECHNOLOGIES

Supplemental remediation techniques that are being used in addition to basic ground-water extraction at the case-study sites, and that have the potential to improve the ground-water remediation, are referred to here as enhancement technologies. These techniques are not necessarily new or innovative. Various enhancement technologies, including soil vapor extraction, reinjection, and slurry wall containment are being used at several sites. In addition, fracture enhancement was used at the Black & Decker site. Many other enhancement technologies are available that were not used at the case-study sites.

SOIL VAPOR EXTRACTION

At the Fairchild Semiconductor site, soil vapor extraction was begun as a pilot system in October 1988 and was expanded to full scale in January 1989. The system consists of 32 vapor wells installed in the dewatered upper aquifer, in the partially dewatered underlying aquifer, and in the aquitard layer that separates them. Eight air inlet wells have also been installed to facilitate vapor sweeping in the deeper zones. By September 1990, after approximately 1 year of operation, the system had removed 14,700 pounds of VOCs.

A pilot scale system was tested in five separate areas of the IBM-San Jose site in 1990. Both LNAPL petroleum hydrocarbons and VOCs were successfully recovered. As a result of the test, a full-scale vapor extraction system was planned for the site.

At Ponders Corner, a vapor extraction system was installed around the contaminant source area in December 1987. The system consisted of 10 vertical wells and 3 horizontal vapor extraction headers. When the system was turned on in March 1988, it recovered tetrachloroethylene (PCE) at a rate much higher than had been foreseen by the designers of the vapor treatment system. Consequently, the system operated only intermittently, with interruptions for replacement of the treatment system's activated carbon. During the first month of operation, the system removed 360 pounds of PCE from the soil. Operation of the system was permanently discontinued in April 1988, by which time it had recovered an estimated 775 pounds of PCE. Even though this mass of contaminants is large, compared to the estimated total of 1,500 pounds recovered in 6 years by the ground-water extraction system, it had no obvious effect on the PCE concentrations pumped by the extraction wells.

At the Savannah River Site, a pilot scale vapor extraction system was tested in 1990. It recovered a total of approximately 1,500 pounds of contaminants in 3 weeks. As a result of the test, a full-scale system has been proposed.

A soil vapor extraction system has been in operation in the Thomas Solvent Raymond Road portion of the Verona Well Field site since 1987. It consists of 23 PVC wells of 2-inch and 4-inch diameter. After approximately 1 year of operation, the system had removed an estimated 45,000 pounds of VOCs from the vadose zone. However, the rate of removal had fallen off to less than 10 pounds per day, and the soil remediation goals had not been met. Several reasons were put forward by the system operators to explain this. They included many of the same effects that impede the restoration of aquifers by ground-water extraction systems. For instance, it was pointed out that VOC concentrations had been reduced to low levels in the soil vapor so that continued pumping resulted in low rates of mass extraction. The rate of mass transfer from residual LNAPL globules to the surrounding soil vapor had

apparently been reduced because the smaller globules, with their greater ratios of surface area to volume, had been exhausted. Also, the concentrations of volatile constituents within the residual LNAPL were reduced, so that they volatilized at lower rates. Finally, it was pointed out that the majority of the vapor flow in the vadose zone was following preferential flow paths, a situation that was exacerbated by the desiccation of the soil in these areas.

GROUND-WATER REINJECTION

Reinjection has been tried at several of the case-study sites. As reported in the first phase of the study, reinjection wells were used briefly at the IBM-Dayton site until their effectiveness was destroyed by clogging. The new extraction system at IBM-Dayton uses spray irrigation as a form of ground-water reinjection primarily to dispose of the treated water from the extraction wells. However, the spray field is upgradient of the contaminated portion of the unconfined aquifer and may also increase the rate of groundwater flow toward the extraction wells.

Reinjection is also being used at the Sylvester/Gilson Road site and at Western Processing. In both cases, the reinjection is through trenches rather than wells. Even so, there were problems with clogging of the trenches due to iron precipitation at Sylvester/Gilson Road. The ground-water treatment system, which came on line in 1986, includes iron removal, and no further problems with iron clogging are expected. At Western Processing, there has been no indication of any problems with the reinjection trenches.

At Fairchild Semiconductor, a system of reinjection wells was put into operation in September 1990. Their installation was preceded by pilot testing, which apparently indicated success. As yet, there has been no indication of the success of the full-scale system. A system of reinjection wells is also planned for the nearby IBM-San Jose site.

SLURRY WALL CONTAINMENT

Slurry walls are being used at the Fairchild Semiconductor, Sylvester/Gilson Road, and Western Processing sites. At Fairchild, the wall was constructed only around the most highly contaminated portion of the plume to isolate the

source areas. It was completed through the two uppermost aquifers and keyed into a continuous clay layer. Ground-water extraction within the wall has resulted in significant aquifer dewatering, and permitted soil vapor extraction to be conducted at depths below the normal water table.

At Sylvester/Gilson Road, the slurry wall encloses nearly the entire contaminant plume, but it is not keyed into a continuous underlying aquitard. Consequently, the containment effectiveness of the wall is highly dependent on maintenance of inward hydraulic gradients. It appears that the rate of net ground-water withdrawal in the enclosed area has not been high enough to produce inward gradients everywhere. Contamination is also thought to be escaping by vertical flow into the underlying bedrock in the interior portion of the site.

The slurry wall at the Western Processing site also depends heavily on hydraulic gradient control for its effectiveness. A fairly elaborate gradient-monitoring system is used to ensure that contamination does not escape under the wall. This system is probably effective for dissolved constituents. However, if DNAPLs were present, which has not been shown to be the case, the gradients being maintained across the wall probably would not prevent their migration to lower aquifer zones.

FRACTURE ENHANCEMENT

The ground-water extraction system at the Black & Decker site uses an artificially created, enhanced fracture zone to improve the effectiveness of extraction. It is probably due to this zone that the system seems to provide effective plume containment. DNAPLs have not been shown to be present at this site. However, if they were present, the deep fracturing produced when the enhanced fracture zone was created might permit them to penetrate more deeply into the bedrock than they would otherwise have done.

UPDATE ON SITE DATA REQUIREMENTS

In the summary of the first phase of the study, considerable attention was paid to the types of site information necessary for the design and operation of effective ground-water extraction systems. The emphasis in that discussion was on the design and

operation of systems to control and remediate plumes of dissolved contaminants. The new case studies and updates developed in the second phase tend to reinforce the observations made in the original study. In addition, with the present emphasis on NAPLs, some of the information requirements take on new importance.

It has been observed that a conclusive determination of the presence or absence of NAPLs is often difficult. At many of the sites where circumstantial evidence suggested that NAPLs were likely to be present, no confirmation in the form of direct observation has been forthcoming. Considering the important implications that the occurrence of NAPLs can have, it is obviously desirable to obtain the site data that would be most helpful in reaching the correct determination.

In this section, examples will be selected from the new site information gathered in the second phase of the study, to illustrate the importance of various types of field data with respect to the selection and design of ground-water remediation systems. The usefulness of this information in the search for NAPLs will also be discussed.

HYDROGEOLOGIC INFORMATION

Stratigraphy

For design of a successful ground-water remediation system, it is important to know the number of aquifers involved and the degree of hydraulic interconnection between them. At several of the case-study sites, the ground-water extraction system was installed in more than one aquifer. At sites like Fairchild Semiconductor and IBM-San Jose, the sand and gravel aquifers were clearly separated by layers of silt and clay, although these layers were not always continuous. At these sites, each of the contaminated aquifers had its own set of extraction wells, which could be operated more or less independently.

The contaminant plume at the Occidental Chemical site occurs in an upper aquifer that is divided into three permeable zones with partial hydraulic interconnection. Here, some of the extraction wells are screened in more than one zone, and pumping from a well in one zone creates hydraulic gradients in other zones as well. Even so, distinctions can be made between the behavior of

the plume in the separate zones. For instance, incomplete hydraulic containment has been observed in the deep zone during certain periods of high-volume pumping from nearby water-supply wells. This can only be distinguished because the monitoring system has been designed to permit observations in the individual zones. In contrast, the monitoring system at the Du Pont-Mobile site has not been designed to distinguish between zones. As a result, there are persistent questions about the effectiveness of plume capture.

Stratigraphy may also influence the movement and detectability of DNAPLs. When downward moving DNAPLs arrive at a layer of lower-permeability material, they may be unable to penetrate them. The nonaqueous liquid may then pool on top of the low permeability layer and flow laterally in the direction of dip. If the stratigraphic information identifies such a situation, it may provide an opportunity to sample the DNAPL and perhaps even to control its migration.

Aquifer Properties

An understanding of the hydraulic properties of the aquifer is very important for the design of the ground-water extraction system. An interesting example of this is the Western Processing site, where a system consisting of many low-capacity shallow wells was used to concentrate the capture zone in the highly contaminated shallow soils. This was done because it was recognized that the underlying soils had higher hydraulic conductivity and would yield large quantities of relatively clean water to a system composed of a few high-capacity extraction wells.

In dealing with NAPLs, several other hydrologic properties of the aquifer materials besides the saturated hydraulic conductivity are important. These include the porosity and the complex relationships between the degree of saturation, the capillary pressure, and the relative permeability for the wetting and nonwetting fluids. A consequence of these additional porous matrix flow properties is the phenomenon of residual saturation for NAPLs. This is the degree of saturation below which the NAPL is, for practical purposes, immobile. These properties can be measured in the laboratory, and some analytical and numerical modeling techniques are available for using them to predict the behavior of NAPLs. However, these techniques are not yet developed to the stage

where they are considered reliable for widespread practical application. More commonly, grain size analysis may be used to obtain rough predictions of the NAPL holding and transmitting capacity of the soil (Mishra, et al., 1980) (Carsel and Parrish, 1988).

Potentiometric Gradients

The ability of an extraction system to capture and remove contaminated ground water will depend partly on the potentiometric gradients that it creates in comparison to the external gradients. A simple manifestation of this relationship is illustrated in the case study for the Nichols Engineering site. The extraction system designers for this site have provided graphical depictions of several alternative capture zone estimates, depending on the magnitude of the regional gradient.

A somewhat less obvious illustration of the importance of the regional gradient is provided at the Sylvester/Gilson Road site. Here, the regional gradient has been strong enough to cause contaminated ground water to flow out from under the slurry wall containment system on the downgradient side of the site. In response to this problem, it may be necessary to increase the rate of net ground-water withdrawal from within the area enclosed by the wall.

The application of horizontal gradients by the ground-water extraction system usually has little effect on the movement of DNAPLs, which are primarily governed by gravitational forces. In some cases, changes in vertical gradients may reinforce or counteract the buoyancy forces and affect the vertical movement of the free phase. However, this cause and effect relationship would probably be difficult to detect, and the present study provides no examples of it.

CONTAMINANT CHARACTERISTICS AND DISTRIBUTION

Identification of Contaminants

An important step in evaluating the likelihood of NAPLs is the identification of the compounds that are present at the site and their potential to persist

in the nonaqueous phase. Creosote, toluene, and the chlorinated ethenes and ethanes are the contaminants that were most commonly found as NAPLs in this study. Other compounds with higher aqueous solubility, such as acetone, tetrahydrofuran, and 1,4-dioxane, are less likely to be found as NAPLs.

The solubilities of the compounds should be kept in mind when evaluating site data. At some of the case study sites, analytical data for ground-water samples were reported that indicated constituent concentrations higher than the solubility of the compounds. There was usually no indication that this had been noticed by the site investigators. These occurrences should be interpreted as a strong indication of the presence of NAPLs.

Attention should also be paid to the possibility that several compounds that are miscible with one another may be present as a NAPL. This is a very common at disposal sites for used solvents. The properties of a multicomponent NAPL may be significantly different from the properties of the individual constituent compounds. One effect is that the partitioning of each individual compound between the NAPL and the ground water will reduce the effective aqueous solubility for each compound.

Another effect is that compounds that are more dense than water in pure form may be caught up in a NAPL that floats. For instance, an LNAPL is present at the Verona Well Field site consisting of chlorinated ethenes and ethanes mixed with benzene, xylene, and toluene. The proportions of this mixture result in a NAPL that floats, even though several of the compounds of greatest concern would normally be expected to form DNAPLs. A similar situation exists at the Mid-South Wood Products site, where pentachlorophenol (PCP), a compound with a specific gravity of approximately 2.0, was mixed with a light carrier oil for use in wood treatment. The ground-water monitoring data show extensive PCP contamination, but do not mention the presence or nature of the carrier oil. Nonetheless, the extraction system is designed to deal with the resulting LNAPL.

Contaminant Distribution and Concentration

Concentrations in both the soil and the ground water are important clues to the likelihood of NAPL presence. Ground-water concentrations close to or greater than solubility indicate a high likelihood of NAPLs. However, as has frequently been noted, concentrations that are less than 10 percent of solubility may also indicate NAPL presence (Feenstra and Cherry, 1988; Huling and Weaver, 1991). At the case study sites with acknowledged NAPLs, the range of maximum detected ground-water concentrations was from 4.1 percent to over 100 percent of solubility.

Concentrations measured in soil samples may also be a good indicator of NAPL presence. High soil concentrations were noted in the update of the Verona Well Field case study and interpreted as an indication of NAPL presence. When soil concentrations are interpreted in this way, allowance must be made for the partitioning of the contaminant between the adsorbed, dissolved, and vapor phases that are included in the sample (Feenstra, et al., 1991).

The vertical distribution of contaminant concentrations may also be an indicator of NAPLs. Sampling from a well cluster in the suspected source area at the IBM-Dayton site showed contaminant concentrations increasing with depth. This was one of the clues used to support the contention of DNAPL contamination at this site, where there has been no direct observation of DNAPLs.

Sorption Characteristics

The importance of contaminant sorption was emphasized in the first phase study, both as a retarding mechanism to aquifer restoration and as a form of residual contaminant source. These effects may complicate the determination of NAPL presence on the basis of resistance to remediation, because both adsorbed contaminants and NAPLs can prolong the aquifer-restoration process.

For instance, at the Ponders Corner site, the concentrations in the contaminant plume have been relatively steady over a period of approximately 6 years. This is an indication of a residual contaminant source, which could be due to NAPLs or adsorbed contamination. If the soil did not

have high sorption potential, more suspicion would be directed to NAPLs. However, at Ponders Corner, much of the contamination is believed to be adsorbed to the soil in a heavily contaminated till layer. This does not rule out NAPLs, but does tend to cloud the evidence for them.

Identification of Contaminant Sources

It has already been noted in this summary that a high proportion of the known NAPL sites in the case studies were the result of leakage from chemical storage and handling facilities and the direct disposal of solvents in the ground. Where these practices are known to have taken place, the likelihood of NAPLs resulting seems to be high.

Chapter 4

OCCURRENCE AND IMPLICATIONS OF NAPLS

NAPLs have been directly observed at eight of the case-study sites and their presence is suspected at several others. This chapter will discuss the waste-handling methods that led to release of NAPL contamination at these sites, the signs that revealed their presence, and their implications for aquifer remediation.

WASTE HANDLING PRACTICES LEADING TO NAPL CONTAMINATION

The following table enumerates the known or suspected sources of the NAPLs at the nine sites where they are acknowledged to be present:

IBM-Dayton	Suspected leaks or spillage from storage tanks
IBM-San Jose	Suspected DNAPL leaks from storage tanks; known spill of Shell Sol hydrocarbon
Savannah River Site	Leakage from liquid waste settling basin
Utah Power & Light	Leakage from underground pipeline
Verona Well Field	Leakage from buried storage tanks
Ville Mercier	Dumping in abandoned gravel pit
Mid-South Wood Products	Leakage from waste storage lagoon
Tyson's Dump	Dumping in abandoned sand pit
Western Processing	Dumping of liquid wastes

In six of the nine cases listed above, the problem was caused by faulty storage or handling of the nonaqueous liquids. This implies that the problems could have been avoided in two-thirds of the cases by better design, operation, and monitoring of the storage and handling facilities. At the other three sites, the NAPLs were In such cases, site investigation procedures toluene predominates. At Tyson's Dump, on the other hand, toluene is a constituent of a DNAPL dominated by the dense compound 1,2,3-trichloropropane introduced by dumping of waste liquids into pits as a means of disposal.

In such cases, site investigation procedures intended to detect the presence of NAPLs should generally be implemented. At some of the case-study sites, compounds that, by themselves, would be expected to sink were found to be present as LNAPLs. At Verona Well Field, for instance, chlorinated solvents are floating as LNAPLs on the water table because they are part of a mixture in which toluene is a constituent of a DNAPL dominated by the dense compound 1,2,3-trichloropropane.

IDENTIFICATION OF NAPL PRESENCE

Although the presence of NAPLs is acknowledged at several of the sites, there are several others

where they are uncertain or are the subject of contention. Because of their elusive nature, especially for DNAPLs, it is often difficult to prove beyond doubt that they are present; and, it is even more difficult to prove their absence. Some of the identifying signs and clues found at the case-study sites are discussed below.

Direct Observation

NAPLs have been observed directly at eight of the sites. At Verona Well Field, IBM-San Jose, Western Processing, Tyson's Dump, and the

Savannah River Site, NAPLS were discovered in ground-water samples.

In the first three cases, the contaminants were LNAPLs. LNAPLs are more likely to be discovered in this way because they are often present at greater than residual saturation at, and just above, the water table. It is common to screen monitoring wells across the water table, and if the LNAPL saturation of the soil is greater than the residual saturation, it can flow into the well. Once the LNAPL has entered the well, it is likely to be discovered during sampling.

DNAPLs are less likely to appear in ground-water samples because of their ability to penetrate below the water table. By penetrating deeper into the aquifer, they travel a greater distance through the porous material and are, therefore, less likely to be encountered at greater than residual saturation. Also, because of their propensity for vertical movement, they are more likely to spread vertically than laterally and are less likely to be intersected by a monitoring well. Furthermore, if they do enter a well, they tend to sink to the bottom where they may escape detection during sampling. In spite of these difficulties, DNAPLs were found by ground-water sampling at the Savannah River Site and Tyson's Dump.

The movement of DNAPLs in the subsurface is governed primarily by gravity and, where their downward movement is unobstructed, the depth of penetration depends on the residual holding capacity of the aquifer materials and the volume and rate of contaminant release. In many cases, the DNAPLs may not move laterally very far from the original source area. This seems to be the case at the IBM-Dayton site, where the residual source area is localized near the former solvent storage tanks. This situation is expected to facilitate the control of plume migration.

NAPLs may also be directly observed staining or flowing from soil samples, coating the outside of drill rods (as at Utah Power & Light), or seeping into surface water bodies (Mid-South Wood Products).

High Concentrations in Ground-Water or Soil Samples

A strong indication that NAPLs may be present is when the ground-water samples show

concentrations that are near the aqueous solubility of the contaminant. At three of the case-study sites, ground-water concentrations greater than the aqueous solubility were reported. These sites are Fairchild Semiconductor, Utah Power & Light, and Mid-South Wood Products. Fairchild is not a site where NAPLs have been acknowledged, but the other two are. One possible explanation for ground-water concentrations exceeding solubility would be the co-solvent effect, but this is not likely unless the concentration of some other constituent is extremely high. The most likely explanation is that NAPLs were present in colloidal form in the sample and were not noticed visually. This can be considered a strong indication that NAPLs are also present in the aquifer. It is possible that, in some cases, NAPLs are being removed with the ground water by the extraction systems.

The lack of any measured ground-water concentrations close to solubility, however, is not a good argument for the absence of NAPLs. At several of the case-study sites where NAPLs are acknowledged, the highest reported concentration of the contaminant in question is considerably below aqueous solubility. Examples are: IBM-Dayton at 4.1 percent for PCE, Savannah River Site at 12 percent for TCE, and Verona Well Field at 11.3 percent for PCE. Several factors that could account for this observation include reduction of effective solubility due to partitioning of the compound between water and a mixture of nonaqueous solvents, kinetic effects limiting the rate of dissolution of the compound from the NAPL, dilution by the flow of ground water in the aquifer, and dilution during the sampling process. Because of these effects, concentrations in the range of 1 to 10 percent of aqueous solubility may be high enough to lead to the suspicion of NAPL presence.

The detection of high concentrations of potential NAPL compounds in soil samples can also indicate that NAPLs are present. In this case, however, the relationship between the measured concentration and the likelihood of NAPL presence is not as direct as it is for ground-water samples. Analytical results for soil samples indicate the quantity of contaminant that was present in the sample in all forms. This includes the adsorbed phase, the vapor phase, dissolved constituents in the soil moisture, and the NAPL phase. By invoking the assumption of linear equilibrium

partitioning, Feenstra, Mackay, and Cherry (1991) have developed a procedure for assessing the meaning of high contaminant concentrations in soil samples. Using a procedure similar to this, it was determined that high concentrations of PCE measured at the Thomas Solvent Annex portion of the Verona Well Field site are an indication of potential DNAPL contamination there.

Depth of Contamination

Another indicator of the possible presence of DNAPLs is the observation of high concentrations at greater depths in the aquifer than would otherwise be expected in the absence of a strong vertical gradient. This is one indicator that led to the determination of DNAPL presence at the IBM-Dayton site, where DNAPLs have not been directly observed. At the Mid-South Wood Products site, high concentrations of pentachlorophenol also have been detected in the deepest monitoring well, indicating that this contaminant may have sunk deep into the bedrock in DNAPL form.

At the Sylvester/Gilson Road site, the highest concentrations of toluene were detected near the water table, even though there is a downward component of ground-water flow that has transported other contaminants to greater depth. This, together with the high toluene concentrations and their resistance to remedial efforts lends credence to the possibility that nonaqueous toluene is present.

Resistance to Remediation

The main reason for the determination that DNAPLs were present at the IBM-Dayton site was the persistence of the contaminant plume and the reappearance of high concentrations when the extraction system was turned off. It has frequently been noted that contaminant concentrations tend to increase when pumping is discontinued. This effect is considered to be an indication of a residual source of contaminants in the aquifer. Such a source could be of several kinds. It could be due to continued leaching from the vadose zone or leakage from the disposal area. It could be due to the release of adsorbed contaminants from highly sorptive aquifer materials or to a lessening of the hydrodynamic dilution after the extraction wells were turned off. At the IBM-Dayton site, these effects were judged not to have the potential

to explain the observed magnitude of plume resurgence, and it was concluded that DNAPLs must, therefore, be present.

IMPLICATIONS OF NAPL PRESENCE

The discovery of NAPLs at an aquifer restoration site usually marks a turning point in the course of the remediation. Aquifer restoration using ground-water extraction alone is likely to be a very slow process when NAPLs are present. Ground-water extraction is an inefficient method of removing NAPL compounds from the aquifer because, by definition, it removes only the dissolved constituent. Thus, to remove the NAPL, it is necessary to wait for it to dissolve so that it can be removed with the ground water. Because most NAPL-forming compounds have low solubility, large quantities of water must be removed to extract a small amount of the contaminant.

In a few instances, the pumping of free-phase DNAPLs from ground-water extraction wells has been reported. Globbs of creosote have been produced from extraction wells at the Utah Power & Light facility. This was an unexpected occurrence that required the retro-fitting of phase separation equipment in the ground-water treatment process. Phase separation has also been provided for at the Mid-South Wood Products site in anticipation of free-phase creosote and pentachlorophenol recovery from the ground-water extraction system.

There are several removal technologies that have been used with success at LNAPL sites. These include soil vapor extraction, free-product skimming, and enhanced biodegradation. Both vapor extraction and free-product skimming were used in the remediation of LNAPLs at the Verona Well Field site. It was estimated that 45,000 pounds of LNAPL constituents were removed by vapor extraction, and 1,200 pounds by free-product skimming. This should shorten the time required for aquifer restoration, but the ground-water concentrations are still above cleanup goals and further restoration is expected to be slow. Both of these removal techniques are also being applied to the LNAPL Shell Sol spill area at the IBM-San Jose site.

Where DNAPLs are concerned, the current established removal technologies are relatively ineffective. Many new technologies are currently being tested (e.g., use of surfactants, water flooding, air sparging) but none of them were used at the case-study sites.

At four of the case-study sites with acknowledged DNAPL contamination, the remedial goal is containment of the solute plume rather than aquifer restoration. This goal is usually feasible when the DNAPL has been located or there are strong indications that it is present, and it is immobile. Containment in the area where the DNAPL is located can be combined with restoration of portions of the ground-water plume that have migrated beyond the DNAPL zone. If the residual DNAPL source is limited to a relatively small area, the migration of the resulting solute plume may be fairly easy to control. At the IBM-Dayton site, for example, it is expected that only one extraction well located near the DNAPL source area will eventually be sufficient to control the migration of contaminants.

At several of the case-study sites, there seemed to be some resistance on the part of the responsible parties to acknowledging the existence of DNAPLs, even though the evidence for them is fairly strong. This resistance may be counter-productive. Failure to recognize the implications of DNAPL presence can result in a much more costly and less effective remedial action in the long run than recognizing the presence of the DNAPL and determining a more appropriate remedial strategy. In some cases (as at IBM-Dayton) the existence of a DNAPL source may only become apparent after an effort at aquifer remediation.